IDENTIFICATION AND ANALYSIS OF EXTERNAL EVENT COMBINATIONS FOR HANHIKIVI 1 PRA

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Fennovoima's nuclear power plant, Hanhikivi 1, 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 as an input for the Probabilistic Risk Assessment (PRA) of Hanhikivi 1. At first, a list of relevant single events and their probabilities shall be determined. The relevant event combinations are then identified by taking into account seasonal variation, preconditions related to different events and dependencies (fundamental and cascade-type) between events. By using this method, 30 relevant combinations of two events were identified and preliminary probabilities of each combination was evaluated. Event combinations with extremely low probability were excluded from further analysis. Event combinations of 3 or more events were identified by adding possible events to the remaining combinations of two events. In the end, 10 relevant combinations of two events and 3 relevant combinations of three events were identified. The identified event combinations and their probability estimates shall be considered preliminary and will be evaluated in more detail after the detailed effects on plant safety resulting from different events have been analyzed.

I. INTRODUCTION

The probabilistic risk assessment 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. In this paper, all the relevant external event combinations are identified and their preliminary probabilities are assessed.

The method for identifying and evaluating event combinations is described in section II of this paper. The relevant single events are listed and their seasonal variation, preconditions and effects on plant are evaluated in section III. The relevant event combinations are identified in section IV and their probabilities are estimated in section V.

The probability estimates presented in this paper are preliminary and based on simplified methods. The most important event combinations should be evaluated in more detail later when the plant design evolves. The main outcome of this paper is the identification of relevant combinations and exclusion of irrelevant ones.

II. METHODS

II.A. 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 nature phenomena shall be considered in the PRA.[1] External event combinations are not mentioned in the YVL guide A.7 related to Probabilistic risk assessment.[2]

In the international guides and standards the combined external events are rarely mentioned. The IAEA SSG-3 states that external event combinations shall be considered, but no methodologies are described.[3]

A short method description for combined external event evaluation is given in Ref. 4.

II.B. Method description

The method for creating a list of relevant event combinations for the PRA of Hanhikivi 1 is presented in Figure 1. The method includes similar elements as in Ref. 4.

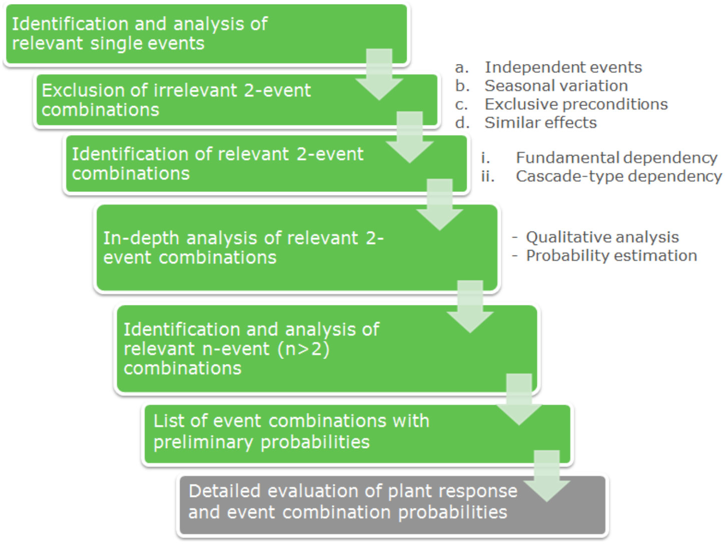


Fig. 1. Identification and evaluation of event combinations in the Hanhikivi 1 PRA.

The relevant single external events shall be identified by first creating a comprehensive list of all possible events. Irrelevant events are then screened out if they have a low probability, low damage potential, are irrelevant to the site or are included in another event. When event combinations are considered, a somewhat extended list of relevant external events shall be used as a starting point to cover also events that do not cause an initiating event themselves but however may have an effect on plant safety systems and functions.

At first, combinations of two events are identified and analyzed, and combinations of more than two events are included later. A large share of the 2-event combinations can be excluded by using the following screening criteria:

a. 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.
b. Seasonal variation. Some events have a strong seasonal variation and events occurring in different seasons cannot form a relevant combination.
c. Exclusive preconditions. Certain events require specific preconditions related to weather and sea conditions, and events that have opposite preconditions cannot form a relevant combination.
d. 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.

After the obvious irrelevant combinations have been excluded, the remaining 2-event combinations shall be considered one by one. As stated in the method presented in Ref. 4, 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:

i. Fundamental dependency. The occurrence of events is related to same basic phenomenon or events are created by the same mechanism.
ii. 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 cut-off frequency (10^{-8} /y) used in the PRA. However, a lower cut-off frequency (10^{-9} /y) shall be applied if the conditional core damage probability after the event combination is close to 1.

After the list of relevant 2-event combinations is completed, event combinations with more than 2 events are identified by recognizing groups of events that are all dependent of each other. In practice, the 2-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 event A and B. Similarly, event combinations including more than three events can be assessed.

III. SINGLE EVENT ANALYSIS

III.A. Relevant single events

The relevant single external events that possibly need to be included in the Hanhikivi 1 PRA have been identified earlier[5] and are shown in Table I.

TABLE I. A list of relevant single external events.[5]

Meteorological	**Sea-related**	**Other**
Air humidity	Algae or other impurities	Earthquakes
Downbursts	Frazil ice	Geomagnetic currents
Freezing rain	High sea water level	Wildfires
High air temperature	High sea water temperature	
Lightning	Low sea water level	
Low air temperature	Meteotsunami	
Rain	Oil spills	
Snow	Sea ice	
Strong wind	Waves	
Trombs		

III.B. Independent events

The following events can be assumed independent of any other events:

- Earthquakes
- 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 surface or atmosphere.

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

III.C. Seasonal variation

The seasonal variation of each event is analyzed based on measurement data from nearby weather stations, weather simulations, documented observations and expert judgement. Detailed evaluation of some events is presented in this paper, and for other events, only the end result is shown in Table II.

III.C.1. High or low air temperature

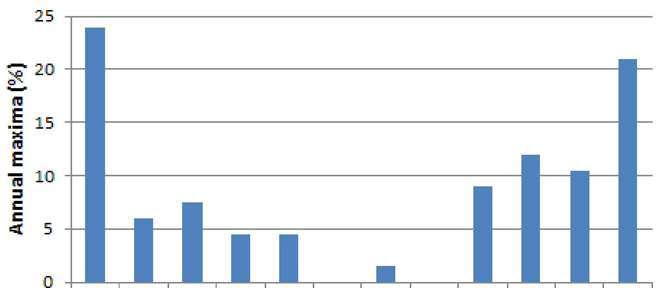
Seasonal variation of air temperature according to Oulu weather station measurements is presented in Figure 2. The warmest month is July and the coldest month January. In general, warm temperatures can be expected between June-August and cold temperatures between December-February.

	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.[6]

III.C.2. Strong wind

The monthly occurrence of strong wind in Hanhikivi is illustrated in Figure 3, which presents the monthly distribution of annual 10 minute mean wind speed maxima in the Oulu airport weather station in 1960-2010.[6] Strong wind is most probable in September-January and fairly common also in September and February-May, but rare in summer (June-August).



Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
24	6	7	4	4	0	1	0	9	12	10	21

Fig. 3. Monthly distribution of annual 10 min mean wind speed maxima in Oulu in 1960-2010.[6]

III.C.3. Algae

Algae and other organic material concentrations in the sea water are at highest in autumn when the vegetation grown during the summer starts to die. Large amounts of algae may be observed also in spring when the ice sheet melts (on average in May) and the growth of last summer starts to move. High algae concentrations can be observed also in mid-summer when the algae grows rapidly.

III.C.4. Summary

The relative occurrence of different external hazards during different months is presented in TABLE II. The following colour coding is used:

- Green: high relative probability (peak occurrence)
- Yellow: moderate relative probability (probability of occurrence roughly 10 % when compared to peak month)
- Red: low relative probability (probability of occurrence roughly 1 % when compared to peak month)
- White: very low relative probability (the event is practically non-existing)

TABLE II. The relative monthly probabilities of external events (green=high, yellow=moderate, red=low, white=very low).

	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												
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												

III.D. 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 III presents the preconditions required by different events.

TABLE III. Preconditions of external events.

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

Humid air requires high temperature because hot air can include more water vapour 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 due to 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.

III.E. Plant effects

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

TABLE IV. The general plant effects related to different external events.[4]

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

Structural effect can impact different plant parts, such as building roofs and walls, switchyard or to 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 wind 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 wind, downbursts or trombs blow material into the cooling water intake or due to low sea water level or high sea water 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 due to 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.

IV. IDENTIFICATION OF EVENT COMBINATIONS

IV.A. Exclusion of irrelevant combinations

The irrelevant combinations are identified according to the screening criteria presented in section II.B:

a. Independent events.
b. Seasonal variation
c. Exclusive preconditions
d. Similar effects.

The excluded event combinations according to screening criteria b, c and d are presented with a red colour in Table V. For some combinations, more than one screening criteria can be applied. Most of the event combination exclusions are obvious, but some explanations are provided below.

Air humidity & Wildfires: Fires can be considered improbable in humid conditions.

Freezing rain & Low air temperature: The occurrence of freezing rain requires a warmer atmosphere layer (> 0 ºC) which is highly improbable if the ground temperature is very low.

Lightning & Wildfires: This combination has not been excluded because lightning strikes may sometimes start ground and forest fires. Lightning is typically related to heavy rainfall, but it may occur also in relatively dry conditions.

The combinations of events that could cause loss of seawater cooling (algae, frazil ice, high sea temperature, low sea level, oil spill, sea ice) have not been considered because the consequence from only one event is practically the same as from several different events occurring simultaneously.

Low sea level & meteotsunami: The meteotsunami wave has only a little effect if the sea water level is already low. However, it shall be taken into account that the water level decreases temporarily after the meteotsunami. This could cause problems if the sea level is already low.

Low sea level & waves: The effect of waves is small if the sea water level is low.

Sea ice & wildfires: Both could occur in spring. However, sea ice requires a cold spring, whereas wildfires would require a dry and warm spring.

IV.B. Identification of relevant combinations

After the exclusion of irrelevant combinations, the remaining 2-event combinations are considered one by one to identify the following types of dependencies:

i. fundamental dependency
ii. cascade-type dependency

The dependent events have been marked with green colour in Table V. A large share of combinations is left blank (white colour). These combinations could not be excluded by using criteria a-d, but also no dependency (type i or ii) was identified. Thus, these combinations can be considered irrelevant.

To summarize, in the beginning 22 relevant single events were identified. Two of these events were considered independent from any other events. From the remaining 20 events, 190 different 2-event combinations can be formed. From these 2-event combinations, 80 were excluded by using screening criteria b, c and d. 30 dependent event combinations were identified. For 80 combinations, neither exclusion nor dependency criteria could be applied.

TABLE V. The exclusion of irrelevant event combinations (red colour, b=seasonal variation, c=exclusive preconditions, d=similar effects) and the identification of dependent combinations (green colour, i=fundamental dependency, ii=cascade-type dependency).

	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	

The potentially relevant 2-event combinations are listed in Table VI. Also short descriptions of the identified dependencies are provided.

TABLE VI. Potentially relevant 2-event combinations.

	Event 1	Event 2	Type	Justification
1	Air humidity	High air temp.	ii	High humidity worsens the effect of high air temperature by deteriorating HVAC equipment capacity (high enthalpy).
2	Downburst	Lightning	i	Both occur together with thunderstorms.
3	Downburst	Rain	i	Downbursts occur together with thunderstorms, which are also quite often accompanied by heavy rainfall.
4	Freezing rain	Snow	i	Snow load is at highest in wet and rainy conditions.
5	High air temp.	High sea temp.	ii	Hot air also heats sea water (with a delay) and sea temperature affects air temperature.
6	High air temp.	Wildfires	ii	Long-lasting heat waves increase the probability of wildfires.
7	Lightning	Rain	i	Lightning occurs together with thunderstorms, which are also quite often accompanied by heavy rainfall.
8	Lightning	Strong wind	i	Lightning occurs together with thunderstorms, which are also quite often accompanied by strong wind.
9	Lightning	Tromb	i	Lightning occurs together with thunderstorms. Also strongest trombs are typically related to thunderstorms (Mäkelä & Hyvärinen, 2014).
10	Lightning	Meteotsunami	i	Lightning occurs together with thunderstorms. Also meteotsunamis might occur together with thunderstorms.

11	Low air temp.	Strong wind	ii	Strong wind increases the freezing effect of low air temperature.
12	Low air temp.	Frazil ice	ii	The formation of frazil ice requires low air temperature, open sea and strong wind to enable effective heat transfer.
13	Low air temp.	Sea ice	ii	Low air temperature increases the amount of sea ice.
14	Rain	Strong wind	i	Storms in the summertime quite often involve both heavy rain and strong wind.
15	Rain	Tromb	i	Thunderstorms are quite often accompanied by heavy rainfall. Also strongest trombs are typically related to thunderstorms (Mäkelä & Hyvärinen, 2014).
16	Rain	Meteotsunami	i	Meteotsunamis might occur together with heavy rainfall.
17	Snow	Strong wind	i/ii	Storms in the wintertime quite often involve both heavy snow and strong wind (blizzard). In addition, strong wind may lift up snow from the ground (blowing snow).
18	Strong wind	Algae	ii	Strong wind and rough sea conditions could detach and transfer algae and other organic material.
19	Strong wind	Frazil ice	ii	The formation of frazil ice requires low air temperature, open sea and strong wind to enable effective heat transfer.
20	Strong wind	High sea level	ii	Sea water level is affected most by wind conditions, and thus it can be assumed that high sea level is also accompanied by heavy wind.
21	Strong wind	Low sea level	ii	Sea water level is affected most by wind conditions, and thus it can be assumed that low sea level is also accompanied by heavy wind.
22	Strong wind	Meteotsunami	ii	Meteotsunamis might occur together with moderate or strong wind.
23	Strong wind	Oil spill	ii	Rough sea conditions could cause ship accidents leading to oil spills.
24	Strong wind	Sea ice	ii	Sea ice is moved by wind (and currents).
25	Strong wind	Waves	ii	Waves are caused by strong wind.
26	Strong wind	Wildfires	ii	Wind causes rapid spreading of fires and smoke.
27	High sea level	Meteotsunami	ii	If the sea level is already high, a simultaneous meteotsunami raises the sea level even higher.
28	High sea level	Waves	ii	If the sea level is already high, waves may raise the sea level even higher.
29	Low sea level	Meteotsunami	ii	If the sea level is already low, the sea level might be lowered even more after a meteotsunami.
30	Oil spill	Waves	ii	Rough sea conditions could cause ship accidents leading to oil spills.

V. PROBABILITY EVALUATION

In this section, the event combinations identified as potentially relevant are analyzed. Detailed evaluation of one event combination (Strong wind and algae) is presented in this paper, whereas for other events only final results are provided in Table VII.

V.A. Strong wind and Algae

V.A.1. Single event frequencies

According to probability estimations based on measurement data from nearby weather stations[7], the gust wind speed (3 s) exceeds 30 m/s with a probability $3 \cdot 10^{-2}$ /y. A wind this strong can create high waves and rough sea conditions that detach sea vegetation and accumulate it to the sea water intake. The probability for exceeding grid design basis 39 m/s is $2 \cdot 10^{-4}$ /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 sea water cooling if no countermeasures are taken) in Hanhikivi is $1.05 \cdot 10^{-2}$ /y.[8]

V.A.2. Event combination frequencies

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 sea water intake and in the sea water system. The breakwaters around the sea water 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.[9] We may assume that wind cannot remove and carry large amounts of algae during this period. According to Figure 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 towards Hanhikivi. The probability for this is roughly 60 % according to Finnish wind statistics.[10] 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 is accumulated near the sea water 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:

$3 \cdot 10^{-2}$ /y $\cdot$ 0.50 $\cdot$ 0.60 $\cdot$ 0.50 = $4.5 \cdot 10^{-3}$ /y

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:

$2 \cdot 10^{-4}$ /y $\cdot$ 0.50 $\cdot$ 0.60 $\cdot$ 0.5 = $3.0 \cdot 10^{-5}$ /y

V.A.3. Conclusion

Fairly high probabilities were estimated for the event combinations “wind > 30 m/s & algae” and “wind > 39 m/s & algae”. The safety effects of these combinations and other respective combinations shall be estimated to determine if they shall be included in the PRA model.

V.B. Summary of 2-event combination probabilities

The event combinations that were quantified are summarized in Table VII. The event combinations that might be relevant according to the probability evaluation are marked with grey colour.

TABLE VII. A summary of 2-event combinations and their probabilities.

Event 1	Event 2	Prob.	Conclusion regarding PRA
High air humidity	High air temperature	*	More detailed evaluation needed
Lightning > 200 kA	Downburst F1-F3	9.5E-10	Exclusion due to low probability
Lightning > 200 kA	Downburst F1-F3 (power line area)	4.0E-09	Exclusion due to low probability (unless CCDP≈1)
Lightning (power line area)	Downburst F1-F3	1.2E-07	More detailed evaluation needed
Downburst F1-F3	Rain > 200 mm in 24 h	1.3E-10	Exclusion due to low probability
Air temperature > 43°C	Sea temperature > 30°C	5.0E-09	Exclusion due to low probability (unless CCDP≈1)
Air temperature > 43°C	Wildfire (power line area)	5.0E-10	Exclusion due to low probability
Lightning > 200 kA	Rain > 400 mm in 24 h	< 1.0E-9	Exclusion due to low probability
Lightning > 200 kA	Wind > 30 m/s	7.6E-11	Exclusion due to low probability
Lightning > 200 kA	Wind > 39 m/s (power line area)	~1E-11	Exclusion due to low probability
Lightning (power line area)	Wind > 30 m/s	1.0E-08	More detailed evaluation needed
Lightning > 200 kA	Tromb F1-F5	5.3E-10	Exclusion due to low probability
Lightning > 200 kA	Tromb F1-F5 (power line area)	4.0E-09	Exclusion due to low probability (unless CCDP≈1)
Tromb F1-F5	Lightning (power line area)	2.2E-09	Exclusion due to low probability (unless CCDP≈1)
Wind > 30 m/s	Low air temperature < -35°C for 24 h	1.7E-06	More detailed evaluation needed
Low air temperature	Sea ice	< 1.0E-9	Exclusion due to low probability
Rain > 200 mm in 24 h	Wind > 30 m/s	1.8E-08	More detailed evaluation needed
Rain > 200 mm in 24 h	Tromb F1-F5	< 1.0E-9	Exclusion due to low probability
Snow	Wind > 30 m/s	2.1E-03	More detailed evaluation needed
Snow	Wind > 39 m/s	1.4E-05	More detailed evaluation needed
Wind > 30 m/s	Algae	4.5E-03	More detailed evaluation needed
Wind > 39 m/s	Algae	3.0E-05	More detailed evaluation needed
Wind > 30 m/s	Frazil ice	2.6E-04	More detailed evaluation needed
Wind > 39 m/s	Frazil ice	1.7E-06	More detailed evaluation needed
Wind > 39 m/s	Oil spill	1.2E-06	More detailed evaluation needed
Wind > 30 m/s	Sea ice	9.5E-06	More detailed evaluation needed
Wind > 39 m/s	Sea ice	6.3E-08	More detailed evaluation needed

*The combination of high air humidity and temperature, i.e. high enthalpy, has been evaluated separately[11]

V.C. N-event combinations

In addition to the 2-event combinations, the following relevant 3-event combinations were identified:

- Wind + Snow + Algae
- Wind + Snow + Frazil ice
- Wind + Snow + Sea ice

The probabilities of the 3-event combinations are presented in Table VIII.

V.D. Summary of event combination probabilities

The event combinations that are significant enough to be taken into account in the PRA according to current understanding are listed in Table VIII. Also the preliminary probability estimates are presented.

TABLE VIII. Summary of event combinations that might be significant enough to be taken into account in PRA.

Event 1	Event 2	Event 3	Prob. (/y)
High air humidity	High air temperature	-	*
Lightning (power line area)	Downburst F1-F3	-	1.2E-07
Lightning (power line area)	Wind > 30 m/s	-	1.0E-08
Wind > 30 m/s	Low air temperature < -35°C for 24 h	-	1.7E-06
Wind > 30 m/s	Rain > 200 mm in 24 h	-	1.8E-08
Wind > 30 m/s	Snow	-	2.1E-03
Wind > 39 m/s	Snow	-	1.4E-05
Wind > 30 m/s	Algae	-	4.7E-03
Wind > 39 m/s	Algae	-	3.1E-05
Wind > 30 m/s	Frazil ice	-	2.6E-04
Wind > 39 m/s	Frazil ice	-	1.7E-06
Wind > 39 m/s	Oil spill	-	1.2E-06
Wind > 30 m/s	Sea ice	-	9.5E-06
Wind > 39 m/s	Sea ice	-	6.3E-08
Wind > 30 m/s	Snow	Algae	2.8E-04
Wind > 39 m/s	Snow	Algae	1.9E-06
Wind > 30 m/s	Snow	Frazil ice	2.6E-05
Wind > 39 m/s	Snow	Frazil ice	1.7E-07
Wind > 30 m/s	Snow	Sea ice	1.1E-06

*The combination of high air humidity and temperature, i.e. high enthalpy, has been evaluated separately[11]

VI. CONCLUSIONS

In this paper, all combinations of external events that could occur simultaneously in the Hanhikivi site were identified, and also preliminary probability estimates were 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, and based on qualitative assessment, 30 combinations of two events were identified as possibly relevant. A majority of these combinations were evaluated as highly improbable - annual probability less than 10^{-8} – and were excluded from further analysis. Event combinations of 3 or more events were identified by adding possible events to the remaining combinations of two events. In the end, 14 relevant combinations of two events and 5 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.

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