PSA for Freezing of River Danube as Ultimate Heat Sink of NPP Paks, Hungary

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Abstract: Recirculation of discharge water to the cold water canal of the water intake plant is used as a preventive measure to avoid ice formation that could endanger water intake from the river Danube as the ultimate heat sink of the Paks Nuclear Power Plant, Hungary. Recent operational experience shows that this measure may not always be sufficient to prevent the water intake plant from the effects of ice formation. A special working group has been formed to examine and evaluate the mechanisms of ice formation, as well as to establish additional measures to increase the protection of the power plant against such effects. The need to assess plant risk due to possible ice formation and freezing of the cooling river water was also recognized. Probabilistic hazard assessment of water freezing was performed to support risk assessment. According to the forecasts, in the near future, the frequency and extent of freezing of rivers in the temperate zone will decrease as a result of climate change. The average water temperature of the Danube can be expected to rise in the next decades. However, weather extremes may become more frequent, so ice formation and glaciation cannot be ruled out in the coming decades, as the recent operational events already pointed out. Based on an analysis of historical events available since 1954, the probabilistic hazard assessment resulted in exceedance frequencies for four ice formation categories: low-concentration ice floes, high-concentration ice floes, ice cover, and ice jam. The analysis of plant response and vulnerability to these ice formation events supported the modeling of accident sequences in the probabilistic safety assessment for river water freezing. The plant response analysis placed emphasis on the preventive measures that can be taken to prevent loss of water intake, including the necessary human interventions as well as the equipment to be used for this purpose. To enable risk quantification, the likelihood of failure to successfully implement these measures was assessed as a special type of “fragility analysis”. The results of the probabilistic hazard assessment, and plant response analysis were used to develop and quantify a PSA model for ice formation. The core damage risk has been determined for full power as well as low power and shutdown states. This paper describes the risk assessment process and its results, with particular attention to the specifics of the external event analyzed and the findings regarding plant vulnerability to ice formation.

Keywords: External Events PSA, Ice Formation, Probabilistic Hazard Assessment, Loss of Ultimate Heat Sink.

1. INTRODUCTION

The river Danube ensures the ultimate heat sink for the four VVER-440/213 units of the Paks Nuclear Power Plant (NPP) in Hungary. Water from the Danube reaches the water intake plant through an open-surface, earth-bed canal, the freshwater (named cold water) intake canal. The cold water intake canal is common to all four units. It delivers cooling water to the water intake plant equipped with two condenser cooling water pumps and three essential service water pumps for each unit.

A fixed debris boom is installed in the cold water intake canal to capture large debris and prevent it from entering the water intake plant. However, the debris boom is not suitable for catching congested ice sheets in case of persistent and strong ice floes. Therefore, in such cases, barges are installed in front of the debris boom to protect the debris boom and thus the cold water intake canal from the effects of the ice sheets. In addition, ice breakers are also used to increase the protection of the debris boom and the cold water intake canal from ice floes. Excessive and thus dangerous ice formation in the cold water inlet canal itself is prevented by returning warmer water from the discharge water canal of the plant. If needed, discharge water level can be recirculated to the mouth of the cold water intake canal and to the forebay of the water intake plant. In this manner, cooling water temperature can be increased by about 1 °C at the mouth of the cold water intake canal, and by 2-4 °C at the forebay.

Between January 8 and February 6, 2017, due to icing caused by long-lasting low temperatures, extensive protection against freezing of river water was necessary at the Paks NPP. The low water level in the river significantly worsened the conditions for protective measures. The experience of this unprecedented operating event shows that the combination of low ambient temperature and low river water level can have the following consequences:

- despite the use of barges and icebreakers, a substantial amount of ice can flow into the cold water intake canal under the debris boom;
- sheets of ice can get congested in the cold water intake canal, and ice formation can also start in the canal as a result of the low ambient temperature;
- a large, continuous ice surface may form in the flow dead spaces of the cold water intake canal, and then the ice may break up, which may cause ice floes in the canal.

In response to this event, a special working group was set up in order to examine and evaluate the mechanisms of ice formation and to develop a concept for additional measures to increase the protection of the plant against such effects. The working group proposed fourteen technical and administrative measures for consideration by the plant management [1]. Detailed modelling of ice formation in the cold water intake canal helped to develop the method and assess the effectiveness of some preventive measures [2], [3]. Some of these measures have already been implemented and incorporated into plant's action plan for protection against excessive ice formation. Others are being further investigated as potential longer-term measures.

At present, the action plan against ice formation includes instructions to follow and measures to be taken regarding necessary activities [4]:

- on the Danube and at the debris boom installed at the mouth of the cold water intake canal;
- in the cold water intake canal and at the forebay of the water intake plant;
- at the water intake plant.

The action plan prescribes various tasks within each of these three action categories. These tasks have to be completed at the plant locations shown in Figure 1.

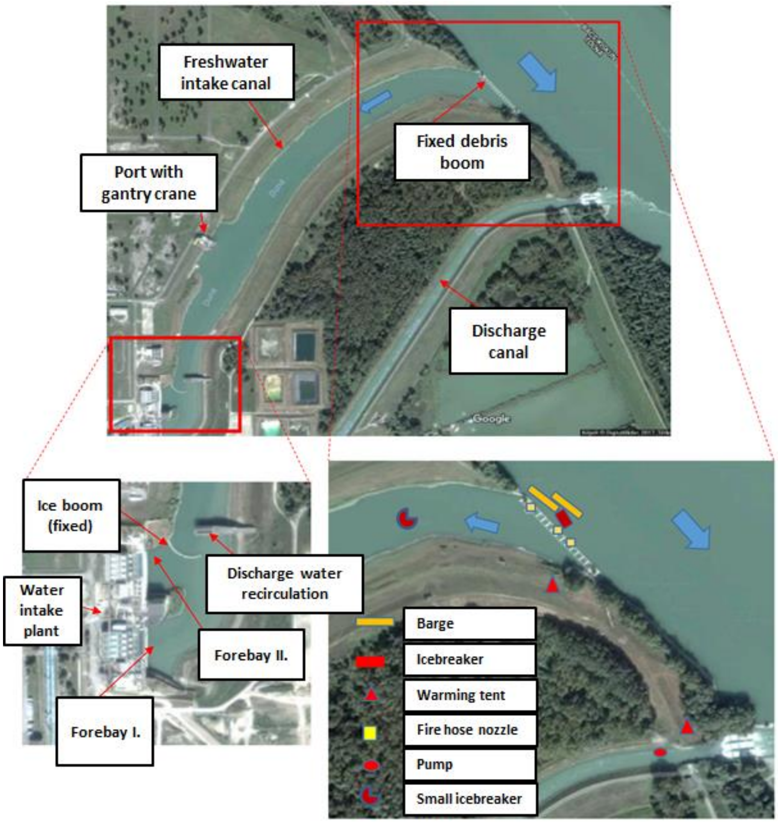


Figure 1. Plant Locations for Actions against Ice Formation

Given the challenges faced by the plant's personnel from the operational events experienced in early 2017, the need to assess plant risk due to possible ice formation and freezing of the cooling river water was also recognized. Accordingly, level 1 probabilistic safety assessment has been prepared for freezing of water in the Danube, an external event previously not included in the PSA of the plant. The main steps and most important results of the level 1 PSA for river freezing are discussed below. A concise evaluation of the results of the analysis is also carried out, with regard to the evaluated risk figures and their comparison with other risk contributors and regulatory requirements.

2. HAZARD ASSESSMENT

According to the forecasts that take into account the effects of climate changes, the average water temperature of the Danube can be expected to rise in the next decades. Simulations of icing predict a significant reduction in the number of icy days in winter [5]. However, weather extremes may become more frequent. Therefore, ice formation and glaciation cannot be ruled out in the coming decades, as the recent operational events have already shown. In addition, the decreasing number of ice formation events leads to the lack of experience and practice necessary to deal with such situations, which may negatively affect the effectiveness of protection in the case of less expected river ice. All these factors justify the need to assess the hazard of ice formation, that is the exceedance frequency of different degrees of ice formation.

Based on international experience, the possibility of frazil ice formation and water surface icing were also investigated as part of the hazard assessment. Use was made of publicly available data sources and technical literature to underpin the assessment.

Operational events suggest that frazil ice can significantly reduce cooling water flow and compromise water intake capability. Some notable examples are:

- shutdown to cold reactor state of Olkiluoto NPP, Unit 1 and hot shutdown of Unit 2 because of frazil ice affecting the plant, Finland, January 1995 [6];
- blockage of water intake plant and reactor shutdown due to frazil at the Rostov NPP, Russia, January 2005, [7];
- scram of Fitzpatrick 1 NPP due to frazil ice, January 2016, USA [8].

Studies on the mechanisms and processes that lead to the formation of frazil ice were looked at in detail including [9] in particular. This study helped to understand the environmental factors influencing the formation of frazil ice and the effect of these factors on the speed of frazil ice formation. Furthermore, the conditions defined for the formation of frazil ice in [10], [11] and [12]. For example, [11] cites the following prerequisites for the development and growth of frazil ice:

- ambient air temperature: below -10 °C;
- wind speed at ground level: greater than 10 m/s;
- wind in the direction of water intake plant;
- ice free water surface.

Moreover, [12] specifies clear, cloudless sky as an important precondition for the formation of frazil ice. Based on the criteria of frazil ice formation applied at other NNP sites, as well as the evaluation of ice formation mechanisms and related physical and environmental factors discussed in [9], it was concluded that the likelihood of frazil ice formation to a degree that endangers water intake at the Paks NPP is negligible. Thus frazil ice was excluded from detailed hazard and risk assessment.

Since the Paks NPP is a riverside plant, the publicly available international technical literature and data related to ice formation on the water surface were reviewed with focus on surface icing of rivers. References [13] and [14] were found most useful in understanding ice formation mechanisms, although reference [14] deals with ice formation in open surface canals and tunnels as opposed to rivers. Reference [15] contains some processed data on the frequencies of different types of ice formation. However, due to substantial hydrological and geological differences compared to the site of the Paks NPP, these data were not considered as generic data that can be used for hazard assessment. In summary, the literature review qualitatively supported the hazard assessment, but the quantitative analysis had to be performed solely on the basis of domestic data on ice formation events.

Detailed historical data on ice formation events affecting the Paks Danube section since 1954 were retrieved from the Central Hydrological Data Base of the General Directorate of Water Management [16]. In principle, older data collected since 1875 for the Danube section in Budapest (upstream the Paks Danube section) could also have been used. As the content of the earlier data differs significantly from the data available for the Paks Danube section, and the climate conditions have dramatically changed since the older data were collected, it was decided to make use of the more recent Paks data sets only.

The historical records include the water levels of the Danube, as well as the characterization of ice formation events according to the degree of ice formation. The degree of ice formation is broken down into 10 categories, the mildest being ice floes of very low concentration and border ice, and the strongest being ice jamming. This categorization was simplified by expert judgment making use of the findings of the literature review. As a result, 4 distinct groups of ice formation were defined for the purposes of hazard assessment:

- low-concentration ice floes;
- high-concentration ice floes;
- ice cover;
- ice jam.

Figure 2 depicts the number of days affected by the different ice formation categories between 1954 and 2022. The number of days affected by ice formation is important because the duration of an icing event largely determines if loss of water intake can be expected. For this reason, plant records of experiences with icing events in 2017 and 1985 were examined and evaluated. The results of this evaluation were used in combination with the results of the literature review to estimate the number of days leading to a loss of the water intake capability for the 4 categories of ice formation. Table 1 summarizes the numerical estimates derived.

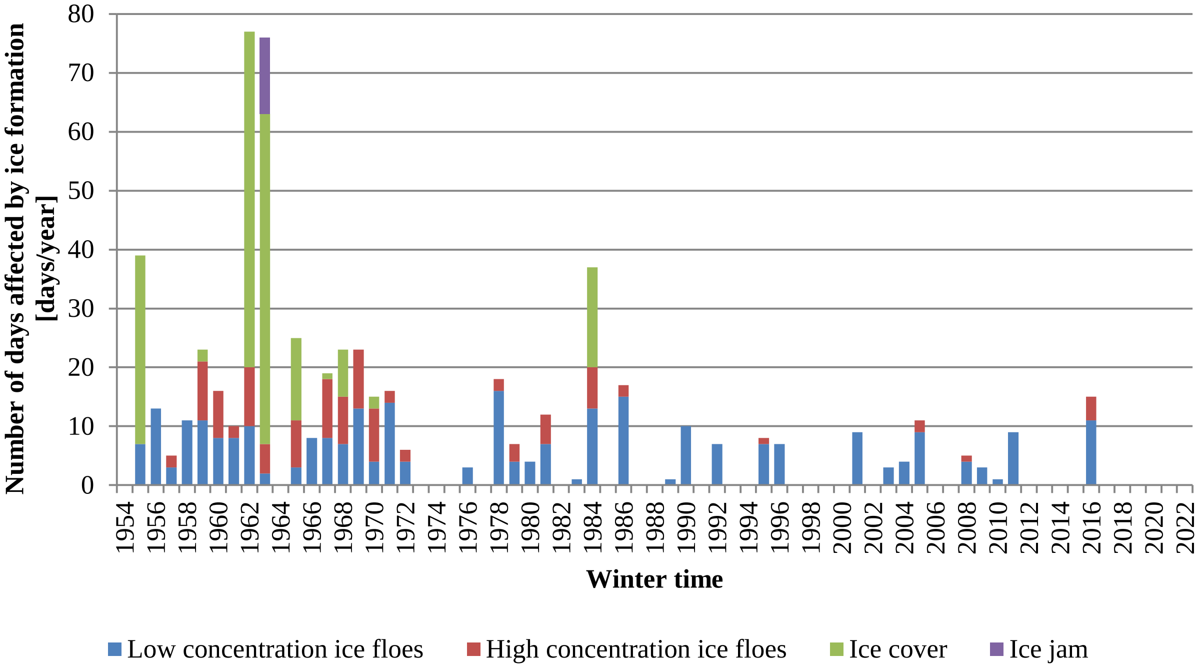


Figure 2. Duration of Ice Formation Events on the Danube (1954-2022)

Table 1. Duration of Ice Formation Events Leading to Loss of Water Intake

Ice formation category	Number of days to loss of water intake
low-concentration ice floes	6
high-concentration ice floes	3
ice cover	2
ice jam	1

Since the number of days with icing is significantly decreasing due to climate change, weights were subjectively assigned to the ice formation events dividing the years of observation into four disjunctive subsets, see Table 2. The number of ice formation events lasting longer than the number of days listed in

Table 1 was counted for all four ice formation categories within each subinterval given in Table 2. Then the frequencies of the different ice formation events were calculated by dividing the number of events by the number of years (17) and producing weighed averages using the weights in Table 2.

Table 2. Weighing of Ice Formation Events According to the Period of Their Occurrence

Period	1954-1971	1972-1988	1989-2005	2006-2022
Weight	0.05	0.15	0.3	0.5

The quantitative results of the hazard assessment are listed in Table 3. These are point estimates of the frequency of the various ice formation events. It is considered that there are substantial uncertainties in the ice formation hazard due to several factors, including, in particular, the uncertainty in the data listed in Table 1 and Table 2, respectively. However, information to quantify these uncertainties was lacking. For the time being, the ice formation frequencies were arbitrarily assigned a lognormal distribution with an error factor of 3 in the case of low-concentration ice floes, high-concentration ice floes and ice cover, and 10 in the case of ice jam.

Table 3. Quantitative Results of Hazard Assessment

Ice formation category	**Frequency of occurrence [1/year]**
low-concentration ice floes	$1{,}74 \cdot 10^{-1}$
high-concentration ice floes	$6.76 \cdot 10^{-2}$
ice cover	$2.65 \cdot 10^{-2}$
ice jam	$2.94 \cdot 10^{-3}$

3. ANALYSIS OF PLANT RESPONSE

Taking timely and appropriate measures to prevent the loss of plant capacity is extremely important to ensure safe operating conditions in the event of ice formation on the Danube. If these measures are not successful, the loss of water intake can lead to a series of events that are challenging to cope with, especially with ice formation and associated low ambient temperatures. Successful mitigation of ice-initiated plant transients is conditional upon the availability of plant systems and components to fight the loss of water intake scenarios and the effectiveness of the plant personnel to take the necessary actions in a timely manner.

3.1. Measures to Prevent Loss of Water Intake due to Ice Formation

Since the formation of ice in the cold water canal cannot be avoided if the Danube water freezes, the preventive measures should be aimed at mitigating the effects of icing in the cold water canal and in the forebay of the water intake plant in order to maintain the operation of the plant. As discussed briefly in Section 2, combating critical ice formation involves various actions at different locations in the plant, which requires the availability and use of dedicated equipment and coordination between competent plant staff and external personnel. Examples of anti-icing measures include the use of barges and icebreakers, the mixing of warm water back into the mouth of the cold water intake canal and to the forebay of the water intake plant, as well as the continuous monitoring of the ice condition. There are dedicated plant procedures in place to assist personnel in implementing the necessary preventive actions. These procedures utilize the lessons learned from past ice formation events and emergency drills to cope with ice formation.

3.2. Events Induced by Loss of Water Intake

Critical ice formation leads to the loss of all condenser cooling water pumps, causing reactor shutdowns at all four NPP units. Although the Hungarian Transmission System Operator may be able to maintain the stability of the grid, the shutdown of the entire Paks NPP is expected to result in the loss of off-site power to the plant. In addition, due to the low ambient temperature, failures and physical damage can occur in the electric grid, making it difficult to restore off-site power. Excessive ice formation, unsuccessful preventative measures and low temperature-induced component failures may result in the loss of the essential service water supply. In such a case, recovery of the service water system should be started immediately.

3.3. Availability of Plant Systems and Equipment to Deal with Ice-Induced Accidents

If the anti-icing measures are not taken successfully, the ultimate heat sink, including the essential service water system (ESWS), is lost. Some measures were implemented recently at the plant to help mitigate loss of ultimate heat sink situations by enabling the use of the fire water system to provide:

1. direct water injection into the steam generators;
2. cooling water to some designated consumers of the ESWS;
3. water injection into the spent fuel pool (SFP).

In order to provide long-term heat removal through steam generators (i.e. measure 1 on the above list), the necessary conditions are ensured for feeding external cooling water through the existing connection points in the plant yard area via existing feed lines to the auxiliary emergency feedwater system. The key to recovering from the loss of ultimate heat sink is the connection between the ESWS, the technological service water system and the fire water systems (i.e. measure 2 on the above list). Supply of fire water to the ESWS via the normal service water system can be readily provided through built-in connections and assemblies. The loss of the ESWS would result in the loss of SFP cooling. An alternative pathway of supplying external water to the SFPs is provided (i.e. measure 3 on the above list). The required operations are specified in plant operating procedures.

4. DEVELOPMENT OF ACCIDENT SEQUENCE MODELS

4.1. Definition of Initiating Events

The results of the hazard assessment were used directly as input to the definition of initiating events for the purposes of accident sequence modelling. Accordingly, the four ice formation categories and the associated annual frequencies given in Table 3 represent the initiating events in the analysis. The subjectively determined uncertainties of the initiating event frequencies (see Section 2) were also used in the risk assessment.

4.2. Event Tree Analysis

Event trees of ice formation were developed for each relevant plant operational state (POS) that is made up of event sequences having either an endstate with stable core cooling conditions (full power or shutdown, cooled in long term) as success or core damage as the one and only pre-defined undesirable endstate in the level 1 PSA for NPP Paks. The “small event tree – large fault tree” approach was applied during event sequence development. A mission time of 168 hours was taken into account, since time to recovery of the ESWS can take several days, although full credit was given to successful recovery within a week

To illustrate the elaborated accident sequences, the event tree of ice formation events at full power and some low power states is shown in Figure 3. Briefly, event tree headers represent the following events:

RECIRC – Given the degree of ice formation, and timely and successful start of recirculation of discharge water into the cold water canal (mouth of water intake cannel and forebay), loss of water intake is prevented.
ICE_PROT – Successful recirculation of discharge water into the cold water canal and several additional preventive actions (use of barges, ice breakers, etc.) prevent the loss of water intake.
LOOP_ICE – Loss of off-site power does not occur despite the loss of water intake due to ice formation.
REC_LOOP – Off-site power is recovered within 48 hours, which prevents temperatures from dropping to the point where secondary side cooling systems cannot be restarted at certain plant locations.
SHR – Secondary side cooling is provided by open circuit cooling through 1 out of 6 steam generators until the demineralized water inventory is exhausted.
SG_SUPP – The plant operators reduce steam generator pressure below 3-5 bar and supply cooling water to the steam generators from low-pressure water sources.

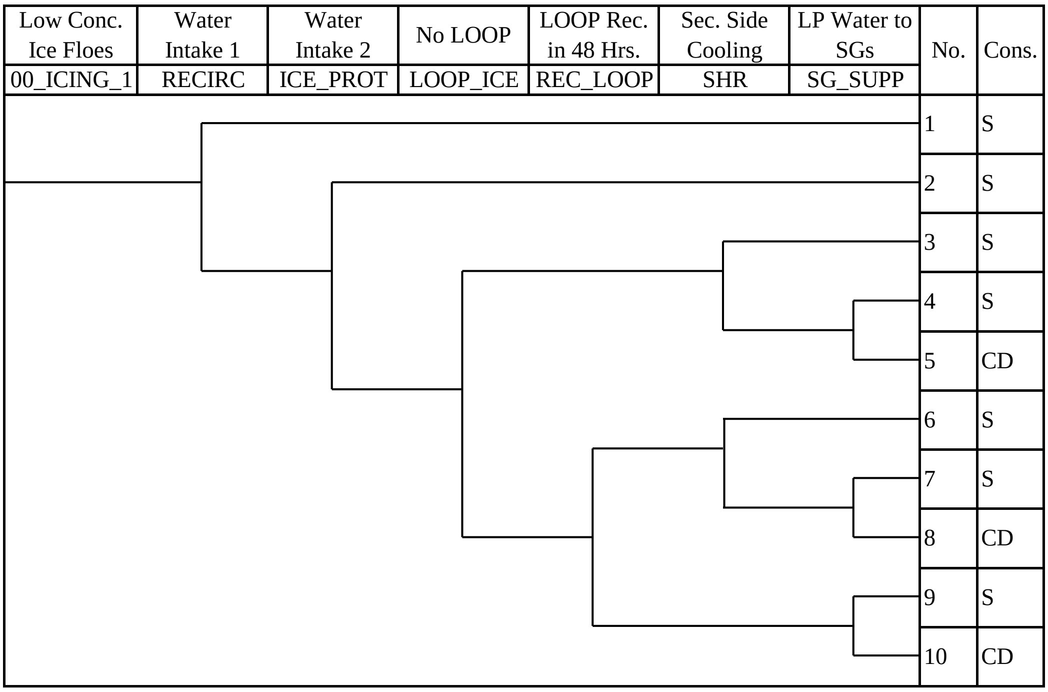


Figure 3. Example of Event Trees

4.3. Fault Tree Analysis

As usual, failures of system and human responses to prevent severe consequences by fulfilling the defined success criteria were linked as top events to the event tree nodes during event tree development. Main and support systems were modelled in detail according to the role they play in accident mitigation and their functional interconnections.

Use was made of fault trees elaborated earlier in the internal events PSA to model

- timely recovery of off-site power;
- decay heat removal by means of the emergency or the auxiliary emergency feed water systems;
- interventions using the fire water system and mobile equipment (including direct water injection into the steam generators and supply of cooling water to some designated consumers of the essential service water system).

In addition, anti-icing measures including e.g. the use of barges and icebreakers, the mixing of warm water back into the mouth of the cold water intake canal and to the forebay of the water intake plant, as well as the continuous monitoring of the ice condition had not been modeled in the original PSA. Therefore these systems had to be additionally modeled in the fault tree analysis.

4.4. Human Reliability Analysis

Use was made of human failure event definitions and probabilities from the internal events PSA for both pre-initiator (Type A) and post-initiator (Type C) actions, where performance conditions were considered largely similar for internal events and ice formation. However, the following responses to ice formation events required a dedicated analysis:

- recovery of off-site power caused due to icing;
- fighting against ice formation to prevent loss of water intake;
- supply of cooling water to the steam generators from low-pressure water sources.

It was assumed that the off-site power can be lost if all the four Paks NPP units shut down due to ice formation on the Danube. Other adverse effects of low ambient temperatures on the power grid were not considered, as these effects were separately taken into account in the PSA for extreme ambient temperatures [17]. Under these conditions, it was concluded that special efforts would be made for the recovery of off-site power to the plant. The mean and median recovery times of 2.38 h and 1.35 h used in the internal events

PSA were considered suitable for determining the probability of off-site power recovery, assuming lognormal distribution of time to recovery.

Combating ice formation and supplying cooling water to the steam generators from low-pressure water sources are complex interventions that require the coordinated and well-managed activities of different personnel, the availability and skillful use of special (stationary and mobile) equipment, and the reliance on instructions and guidelines from various plant procedures. Because of budgetary and time constraints of the analysis, a holistic approach was taken to determine human failure events for these interventions. A limited number of high level human failure events (HFEs) were defined, as opposed to decomposing the different activities into lower level actions. An example of this high level HFEs is the failure of all the interrelated preventive actions to avoid loss of water intake due to ice formation. The Success Likelihood Index Method (SLIM) [18] was used to assess the probability of the high level HFEs that are specific to icing. Without discussing the details of the analysis, Table 4 presents examples of the quantification of the HFE for preventing loss of water intake (ICE_PROT_EO) including the weights (W) and the ranks (R) applied, as well as the SLIM indices (SLI) and the human failure probabilities (HEPs) obtained.

Table 4. Quantification of HEP for Preventing Loss of Water Intake due to Ice Formation

Performance condition	**W**	**L.-conc. ice floes**		**H.-conc. ice floes**		**Ice cover**		**Ice jam**	
		ICE_PROT-EO1		**ICE_PROT-EO2**		**ICE_PROT-EO3**		**ICE_PROT-EO4**	
		R	**SLI**	**R**	**SLI**	**R**	**SLI**	**R**	**SLI**
Environment	0.05	6	0.3	5	0.25	4	0.2	3	0.15
Time pressure	0.2	7	1.4	6	1.2	5	1	4	0.8
Task complexity	0.2	5	1	4	0.8	3	0.6	2	0.4
HMI*	0.15	2.5	0.375	2	0.3	1.5	0.225	1	0.15
Training	0.1	6	0.6	5	0.5	4	0.4	3	0.3
Team work	0.2	3	0.6	3	0.6	3	0.6	3	0.6
Procedures	0.1	2	0.2	2	0.2	2	0.2	2	0.2
Total	1		4.475		3.85		3.225		2.6
HEP			**$3.24 \cdot 10^{-2}$**		**$6.01 \cdot 10^{-2}$**		**$1.11 \cdot 10^{-1}$**		**$2.06 \cdot 10^{-1}$**

*Human-Machine Interface

4.3. Assessment of Component Reliability Data

Mostly the component reliability data of the internal events PSA were used in the risk assessment for ice formation. In addition, the reliability of equipment specifically used to combat icing events was assessed by evaluating data from the existing plant PSA, collecting plant-specific information (e.g., testing and maintenance), and using generic industry data. Data on mechanical, electrical and instrumentation and control components not previously included in the plant PSA were assessed in this manner.

5. RISK QUANTIFICATION

The PSA model was prepared and risk quantification was performed by the use of the RiskSpectrum PSA software package. The core damage risk was determined, and the main risk contributors were identified and evaluated for each of the four units of NPP Paks.

The point estimate of the average core damage frequency due to ice formation on the river Danube is around $1.58 \cdot 10^{-6}$/year including risk at full power as well as low power and shutdown states of a refueling outage. There is very little variation in the risk estimate between the different plant units. Figure 4 shows the distribution of risk at unit 1 due to ice formation according to the different ice formation categories, while Figure 5 presents the core damage probability in the different plant operational states (POSs) and the POS durations. (POS durations are expressed as average durations over a year.) POS0 represents full power, and POS1 to POS24 are the low power and shutdown states distinguished in the analysis. Parametric uncertainty analysis of the core damage risk was also performed, and importance and sensitivity analyses yielded additional insights into the main risk factors and risk reduction possibilities, but discussion of these results is beyond the scope of this paper.

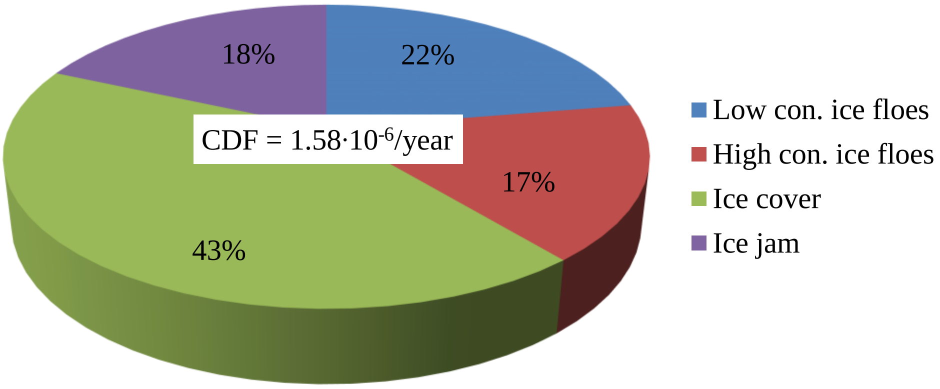
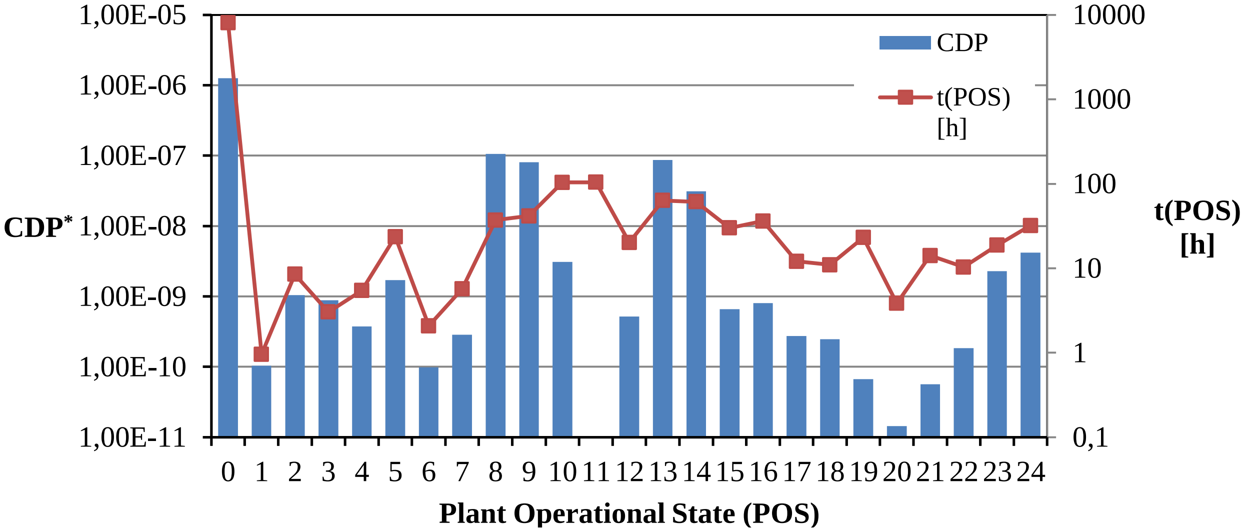


Figure 4. Distribution of Core Damage Risk among Ice Formation Categories



*Core damage probability attributable to the different Plant Operational States

Figure 5. Risk Breakdown by Plant Operational States

6. EVALUATION OF RESULTS

The core damage risk attributable to ice formation on the Danube is not negligible. However, it cannot be considered substantial, since the assessed core damage frequency of $1.58 \cdot 10^{-6}$/year is less than 3% of the total core damage frequency of the Paks NPP (approximately $6.0 \cdot 10^{-5}$/year) from all types of initiating events, including internal events as well as internal and external hazards. Two factors largely contribute to the relatively favorable result (1) several methods and tools are available to cope with ice formation and prevent the loss of water intake even in the case of intense icing on the Danube, (2) post-Fukushima measures implemented at the plant have largely increased the protection against loss the ultimate heat sink, including in particular the supply of cooling water to the secondary circuit from various low-pressure water sources. A detailed evaluation of the main risk contributors (POSs and accident sequences) helped to identify additional risk reduction measures that could be reasonably implemented, such as improving related plant procedures and the training of the personnel involved in the responses to ice formation events.

7. CONCLUSIONS

Recirculation of discharge water to the cold water canal of the water intake plant is used as a preventive measure to avoid ice formation that could endanger water intake from the river Danube as the ultimate heat sink of the Paks Nuclear Power Plant, Hungary. Recent operational experience shows that this measure may not always be sufficient to prevent the water intake plant from the effects of ice formation. Thus the need to assess plant risk due to possible ice formation and freezing of the cooling river water was also recognized. Based on an analysis of historical events available since 1954, the probabilistic hazard assessment resulted in exceedance frequencies for four ice formation categories: low-concentration ice floes, high-concentration ice floes, ice cover, and ice jam. The results of the probabilistic hazard assessment, and plant response and analysis were used to develop and quantify a PSA model for ice formation. The core damage risk was determined for full power as well as low power and shutdown states. The core damage frequency due to ice formation on the Danube is not negligible, although not significant. The PSA helped to identify additional measures that could further reduce the risk from icing.

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