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Evaluation of Impact of NEK Safety Upgrade Program Implementation on the Reduction of Total Core Damage Frequency

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ABSTRACT

The nuclear accident in Japanese plants in 2011 has initiated a quick response from the countries utilizing a nuclear power. Krsko Nuclear Power Plant (NEK) was required by Slovenian Nuclear Safety Administration (SNSA) to perform consequential actions to reduce the risk of severe accidents and their consequences as low as feasible. NEK have analyzed the response to the severe accidents, and based on the results of this analysis, proposed the measures to be implemented in the shortest possible time.

In response to SNSA request NEK has developed the Safety Upgrade Program (SUP) which contains a comprehensive set of measures for plant safety improvements. SUP Phase 1 has been implemented during the Outage 2013.

This paper presents the work done on the evaluation of impact of plant modifications planned for implementation in Phases 2 and 3 of NEK Safety Upgrade Program on the quantitative figure of merit for the plant risk significance – total core damage frequency (CDF). A significance of the most valuable measures in terms of contribution to the CDF reduction was determined and a new fractional contribution of initiators categories was obtained.

The quantification of total CDF was made by employment of RiskSpectrum PSA code and running a predefined set of analytical cases for all initiator categories covered by the scope of NEK PSA model.

The basis for analysis was NEK's most recent at-power PSA model which reflects the plant status with plant modernization implemented in SUP Phase 1. The analysis was done in two steps. In the first step plant modifications planned for SUP Phase 2 were addressed and in the second step plant modernization measures and upgrades planned in SUP Phase 3 were modeled in addition to those already modelled in the first step.

***Keywords**: Probabilistic Safety Assessment, PSA, Core Damage Frequency, Krsko, NEK, Safety Upgrade Program*

1 INTRODUCTION

Before the Fukushima accident, a certain plant modernization were in progress in NEK, such as installation of the third Emergency Diesel Generator, for power supply of safety systems, contributing to an increase in safety and at the same time also supports initiatives for modernization after the Fukushima accident. Thus, based on its own analysis, as well as on recommendations of international organizations and nuclear regulatory bodies, NEK has taken certain short-term and long-term actions.

Within the frame of short-term actions, the mobile equipment was purchased (e.g., diesel generators of different rated power, air compressors, water pumps, vehicles for transportation of mobile equipment). The modifications on some of the existing systems were done in order to allow connection of new mobile equipment to adequate connection points.

Within the frame of long-term actions, and due to the requirements from the SNSA Decree [1], NEK have analyzed the response to the severe accidents. Based on the results of the analysis documented in NEK technical report [2], the measures to be implemented in the shortest possible time were proposed. This results of analysis from [2] have shaped plant modernization program for severe accidents prevention and mitigation of their consequences, formally known as NEK Safety Upgrade Program, Rev. 0, [3]. In the meanwhile SUP was updated and reviewed, and the most recent design bases for additional structures, systems and components, as well as the list of plant modernization proposals were documented in SUP, Rev. 2, [4]. Document [5] establishes common understanding of design inputs, requirements and assumptions for all SUP modifications.

The paper analyzes the impact of the implementation of plant modifications in SUP Phases 2 and 3 on the total CDF, considering both internal and external initiators. The intention was to obtain a new total CDF which will reflect the impact of plant modifications taken integrally, as well as to determine a significance of the most valuable measures in terms of contribution to the total CDF reduction and obtain a new fractional contribution of initiators' categories.

2 METHODOLOGICAL APPROACH

The methodology used in this report is essentially the methodology used for evaluation of the risk from the plant in power operation mode. The methodology for assessment uses probabilistic approach, including the necessary engineering judgments. The Probabilistic Safety Assessment (PSA) is a methodology used to quantify risk based on the reliability of consequence-limiting equipment. NEK PSA procedure [6] defines methodology for application of a PSA. A PSA evaluation could be performed at several levels of scope. Two levels are used in the NEK PSA – Level 1 and Level 2. The scope of this paper is focused on the Level 1 PSA modelling and quantification.

Within the scope of this paper the total CDF, due to both external and internal initiators, was evaluated. The analysis was performed by employment of the second generation of Windows OS based RiskSpectrum PSA (RS PSA) code, version 1.2.1.1 with built-in RiskSpectrum Analysis Tool, version 3.2.3.1 [7]. Consequence-type analyses were performed by RS PSA for different initiators categories contributing to the total CDF. Analyzed initiators categories include:

- Internal initiating events (IIE) – 16 categories,
- Internal fire events,
- Internal flooding events,
- High energy line break (HELB) events,
- Seismic events and liquefaction, and
- Other external events (OEE) covering: aircraft accidents, turbine-generated missiles, external fire, external flooding, industrial and military accidents, pipeline (gas), release of chemicals, severe winds, transport. accidents, turbine missiles, glaze ice, extreme drought.

The evaluation was done in two consecutive steps. In the first step the plant modifications planned for implementation in SUP Phase 2 were modelled in PSA model and quantified. In the second step, in addition to the plant modifications modeled in the first step, the plant modifications planned for implementation in SUP Phase 3 were modelled and quantified.

Finally, the evaluation is concluded with results of quantification of NEK PSA model posterior to the implementation of both Phases 2 and 3, in which plant modifications, as seen and planned at the time of preparation of this paper, are addressed integrally.

3 EVALUATION

The starting point and the basis for the evaluation is NEK baseline at-power PSA model "NEKC28" (referential or baseline model), documented in technical report [8], and it reflects the plant status with modifications from SUP Phase 1 implemented, i.e. Passive Containment Filtering Vent System and Passive Autocatalytic Recombiners.

The total CDF obtained by quantification of referential PSA model "NEKC28" is estimated at 4.69E-5 /rcryr (baseline total CDF). These results in terms of contribution of all initiators' categories are, as well as the fractional contribution of initiator categories to baseline total CDF are illustrated by blue bars in Figure 1 and Figure 2 (baseline total CDF) in section 3.2.

3.1 Evaluation NEK Safety Upgrade Program Phase 2

The purpose of the evaluation performed in this section is to obtain insight on the impact of plant modifications planned for implementation in Phase 2 on the total CDF, as compared to the baseline total CDF. Plant modifications planned for implementation in Phase 2 were modelled in PSA model "NEKC28". Limitations and exceptions during modelling of modifications in Phase 2 were noted to the associated plant modification, where appropriate. Modelled plant modifications encompass the following:

1. SUP Phase 2 plant modifications per [4]:
   a. Construction of Emergency Control Room (ECR) and Technical Support Center (TSC) in BB1 building (Phase 2c).
   b. Additional PRZR PORV Bypass valves for RCS pressure relief (Phase 2d).
   c. Upgrade of flooding protection of NSSS island (Phase 2a).
   d. Upgrade Operating Support Center (OSC) with additional emergency power supply capacities and conditions for long term presence of operating personnel during accident (Phase 2b). These modifications were not addressed in PSA model since OSC is not a system for performing a safety function and directly mitigating a sequence leading to the core damage.
   e. Alternative Spent Fuel Pool (SFP) cooling (additional sprinklers for SFP cooling and connections for mobile heat exchanger). This modification was not addressed in PSA model; it should be reflected in the NEK SFP PSA model.
   f. Additional A-RHR heat exchanger for alternative long-term RCS / containment cooling and decay heat removal. An attempt was made to address the impact of installation of Alternative RHR system (A-RHR) on the CDF in NEK PSA model, and the result has shown no change in CDF. The importance analysis was carried out for the existing RHR system, and the highest risk decrease factor (RDF) estimated at 1.01 was obtained for a basic event "RHR MDPs failure to start due to CCF", by running the importance analysis of RH system's "No low pressure recirculation flow" top gate. Since this risk decrease potential is very small, installation of an additional RHR pump / train would have negligible contribution to further risk reduction (unchanged total CDF). The reason for this lies in the fact that a typical mission time of 24 hours, used in the standard PSA model, is considered to be sufficient to reach stable state after the accident. As the evolution of the accident takes more than 24 hours, the impact on CDF may not be demonstrated for long term low pressure recirculation mode. Consequently, the importance and benefit of installation of an alternative RHR train is not "visible" through the CDF metric which is "driven" by 24 hour mission time.
2. Installation of the shielding of ESW pumps' motors from the spray source.

   In the ESW Pumphouse, shielding can be accomplished with placing sturdy removable steel jacketing around the expansion joints that would protect the pumps from potential water spray. It has to be noted at this point that this modification as such is not a part of SUP Phase 2. Although, this modification is not explicitly stated as a SUP modification, it was identified during NEK analyses of potential safety improvements [2], as a measure with impact on CDF reduction with "High" risk significance, and as such has to be addressed in the PSA model.

The modifications stated in the paragraphs above were modeled in "NEKC28" model, and the resultant model is named "PNV2".

3.1.1 Analysis and Quantification Results (SUP Phase 2)

The results obtained by running the consequence analysis cases on "PNV2" model are provided in Table 1, Figure 1 and Figure 2 (red bars). They shows an impact on CDF reduction (per initiator category) of plant modifications defined by the scope of Phase 2 as compared to the baseline CDF obtained by the referential PSA model (with SUP Phase 1 addressed).

Table 1 Comparison of the CDF per Initiators' Group (Phase 2 Addressed vs. Phase 1 Addressed)

Initiators' Group	*Baseline CDF [/rcryr] (NEKC28)*	*CDF Posterior to SUP Phase 2 [/rcryr] (PNV2)*	*Abs. Delta CDF [/rcryr]*	*Delta CDF Rel. to Baseline CDF due to Initiators' Group [%]*	*Total CDF Reduction Factor (RF)*	*Delta CDF Rel. to Baseline Tot. CDF [%]*
IIE	1.22E-5	1.22E-5	0.00E+00	0.0%	1.0	0.0%
FIRE	1.26E-5	2.90E-6	-9.70E-6	-76.9%	4.3	-20.7%
FLOOD	4.88E-6	6.71E-7	-4.21E-6	-86.3%	7.3	-9.0%
HELB	1.48E-6	1.46E-6	-1.51E-8	-1.0%	1.0	0.0%
SEISMIC	1.12E-5	1.10E-5	-2.19E-7	-2.0%	1.0	-.5%
OEE	4.54E-6	3.73E-6	-8.06E-7	-17.8%	1.2	-1.7%
TOTAL	**4.69E-5**	**3.20E-5**	**-1.49E-5**	**-31.9%**	**1.47**	**-31.9%**

Based on the quantification of "**PNV2**" model, the total CDF posterior to the implementation of Phase 2 was estimated at **3.20E-5 /rcryr**, which represents a **reduction of 32%** (reduction factor of 1.5) as compared to the baseline total CDF (4.69E-5 /rcryr). The measures planned for implementation in Phase 2 with most dominant contribution to baseline total CDF reduction are:

- Construction of ECR – contribution to baseline total CDF reduction of 20.7%,
- Installation of ESW pumps shielding against spraying – contribution to baseline total CDF reduction of 9.0%,
- Upgrade of flooding protection of NSSS island – contribution to baseline total CDF reduction of 1.7%.

Consequently, the construction of ECR significantly reduces CDF due to Internal Fire to the value of 2.9E-6 /rcryr (reduction of 77% relative to the baseline CDF from internal fire events). Similarly, installation of SW pumps shielding against spraying reduced CDF due to Internal Flooding to the value of 6.7E-7 /rcryr (reduction of 86% relative to the baseline CDF from internal flooding events). The installation of flooding protection of NSSS island reduces CDF due to Other External Events (in particular "External Flooding" category) to the value 3.7E-6 /rcryr (reduction of 18% relative to baseline CDF from other external events).

CDF due to IIEs was calculated to be unchanged since the plant modernization measures in Phase 2 do not affect plant systems responsible for mitigation of sequences leading to CD due to internal initiators. Similarly, calculated CDF due to HELB as well as CDF due to seismic events are practically unchanged.

3.2 Evaluation of NEK Safety Upgrade Program Phase 3

The purpose of the evaluation performed in this section is to get an insight of the impact of the implementation of Phase 3 on the total CDF, as compared to both baseline total CDF and total CDF posterior to the implementation of Phase 2.

Plant modifications planned for implementation in Phase 3 were modelled in "PNV2" model. Limitations and exceptions during modelling of modifications in Phase 3 were noted to the associated plant modification, where appropriate. Plant modifications subject to Phase 3 [4] are:

1. Installation of Alternative Safety Injection (A-SI) pump and associated Alternative Borated Water Tank (A-BWT) for RCS injection with borated water (primary injection) in BB2 building (Phase 3a).
2. Installation of Alternative Auxiliary Feedwater (A-AF) pump and associated Alternative Condensate Water Tank (A-CYT) with water inventory for SG injection (secondary injection) in BB2 building (Phase 3b).
3. Construction of interconnections between BB1 and BB2 buildings and interconnections between BB2 building and NSSS island, which are seismically designed and resistant to liquefaction. This is not explicitly listed as a modification in Phase 3 per [4], but there is a requirement in [5] that equipment and interconnections from new DEC systems to the existing systems equipment shall be designed to meet seismic performance requirements during and after a DEC earthquake with Peak Ground Acceleration (PGA) intensity of 0.6*g*.
4. Plateau for mobile equipment seismically designed for 0.6*g* PGA for mobile equipment with mobile diesel generator mounted with seismic isolation.

The modifications listed above were modeled in the PSA model "PNV2", and the resultant model named "PNV3" reflects the plant status with both Phases 2 and 3 modifications addressed.

3.2.1 Analysis and Quantification Results (SUP Phase 3)

The results obtained by running the same set of consequence analysis cases are provided in Table 2, Figure 1 and Figure 2 (green bars). They reflect an impact on CDF reduction (per initiator categories) of implementation plant modifications in Phase 3 as compared to CDF obtained by model with Phase 2 addressed.

Table 2 Comparison of the CDF per Initiators' Group (Phase 3 Addressed vs. Phase 2 Addressed)

Initiators' Group	***CDF Posterior to SUP Phase 2 [/rcryr] (PNV2)***	***CDF Posterior to SUP Phase 3 [/rcryr] (PNV3)***	***Abs. Delta CDF [/rcryr]***	***Delta CDF Rel. to Baseline CDF due to Initiators' Group [%]***	***Total CDF Reduction Factor (RF)***	***Delta CDF Rel. to Baseline Tot. CDF [%]***
IIE	1.22E-5	2.22E-6	-9.98E-6	-81.8%	5.5	-21.3%
FIRE	2.90E-6	1.18E-6	-1.73E-6	-59.5%	2.5	-3.7%
FLOOD	6.71E-7	2.86E-8	-6.42E-7	-95.7%	23.4	-1.4%
HELB	1.46E-6	1.05E-7	-1.36E-6	-92.8%	14.0	-2.9%
SEISMIC	1.10E-5	4.81E-6	-6.17E-6	-56.2%	2.3	-13.2%
OEE	3.73E-6	3.63E-6	-1.00E-7	-2.7%	1.0	-.2%
TOTAL	**3.20E-5**	**1.20E-5**	**-2.00E-5**	**-62.5%**	**2.67**	**-42.6%**

Based on the quantification of "**PNV3**" model, the total CDF posterior to the implementation of Phase 3 was estimated at **1.20E-5 /rcryr**, which represents a significant reduction of 63% (a reduction factor of 2.7) as compared to the total CDF obtained posterior to Phase 2, and reduction of 43% as compared to the baseline total CDF (4.69E-5 /rcryr). The measures planned for implementation in Phase 3 with the most significant contribution to reduction of baseline total CDF are:

- Installation of additional pumps (A-AF and A-SI) and associated tanks (A-CYT and A-BWT) – contribution to baseline total CDF reduction of 21.3%.
- Construction of interconnections between BB1 and BB2 buildings and interconnections between BB2 building and NSSS island, which are seismically designed to withstand PGA of 0.6*g* and resistant to liquefaction and mobile diesel generator mounted with seismic isolation – contribution to baseline total CDF reduction of 13.2%;

Consequently, the installation of alternative pumps A-AF and A-SI, as well as associated tanks A-CYT and A-BWT in BB2 building, would significantly reduce CDF due to IIEs to the value of 2.2E-6 /rcryr (reduction of 82% relative to the baseline CDF due to IIEs). Similarly, construction of seismically designed and liquefaction resistant interconnections between buildings BB1 and BB2 and interconnections between BB2 building and NSSS island would lead to reduced CDF due to seismic events to the value of 4.8E-6 /rcryr (reduction of 56% relative to the baseline CDF from seismic events).

In order to obtain an insight of the cumulative effect of plant modifications planned in both Phase 2 and 3 a comparison of contributions from all initiator categories to the total CDF between is summarized and presented in Table 3.

Table 3 Comparison of the CDF per Initiators' Group (Phase 3 Addressed vs. Phase 1 Addressed)

Initiators' Group	*Baseline CDF [/rcryr] (NEKC28)*	*CDF Posterior to SUP Phase 3 [/rcryr] (PNV3)*	*Abs. Delta CDF [/rcryr]*	*Delta CDF Rel. to Tot. CDF due to Initiators' Group [%]*	*Total CDF Reduction Factor (RF)*	*Delta CDF Rel. to Baseline Tot. CDF [%]*
IIE	1.22E-5	2.22E-6	-9.98E-6	-81.8%	5.5	-21.3%
FIRE	1.26E-5	1.18E-6	-1.14E-5	-90.7%	10.7	-24.4%
FLOOD	4.88E-6	2.86E-8	-4.85E-6	-99.4%	170.4	-10.3%
HELB	1.48E-6	1.05E-7	-1.38E-6	-92.9%	14.1	-2.9%
SEISMIC	1.12E-5	4.81E-6	-6.39E-6	-57.0%	2.3	-13.6%
OEE	4.54E-6	3.63E-6	-9.06E-7	-20.0%	1.2	-1.9%
TOTAL	**4.69E-5**	**1.20E-5**	**-3.49E-5**	**-74.5%**	**3.92**	**-74.5%**

The **total CDF** evaluated on the basis of implemented plant modifications in Phase 1, as well as scope of modifications planned in Phases 2 and 3 is estimated, as mentioned before, at about **1.20-5 /rcryr**. Cumulative reduction of total CDF is about 3.5E-5 /rcryr, which is a significant decrease of total CDF for **75%** (reduction factor of nearly **4**), when compared to the baseline total CDF (32% in Phase 2 plus 43% in Phase 3). (Note: Overall RF of nearly 4 equals to product of RF of 1.5 after Phase 2 and RF of 2.7 after Phase 3.)

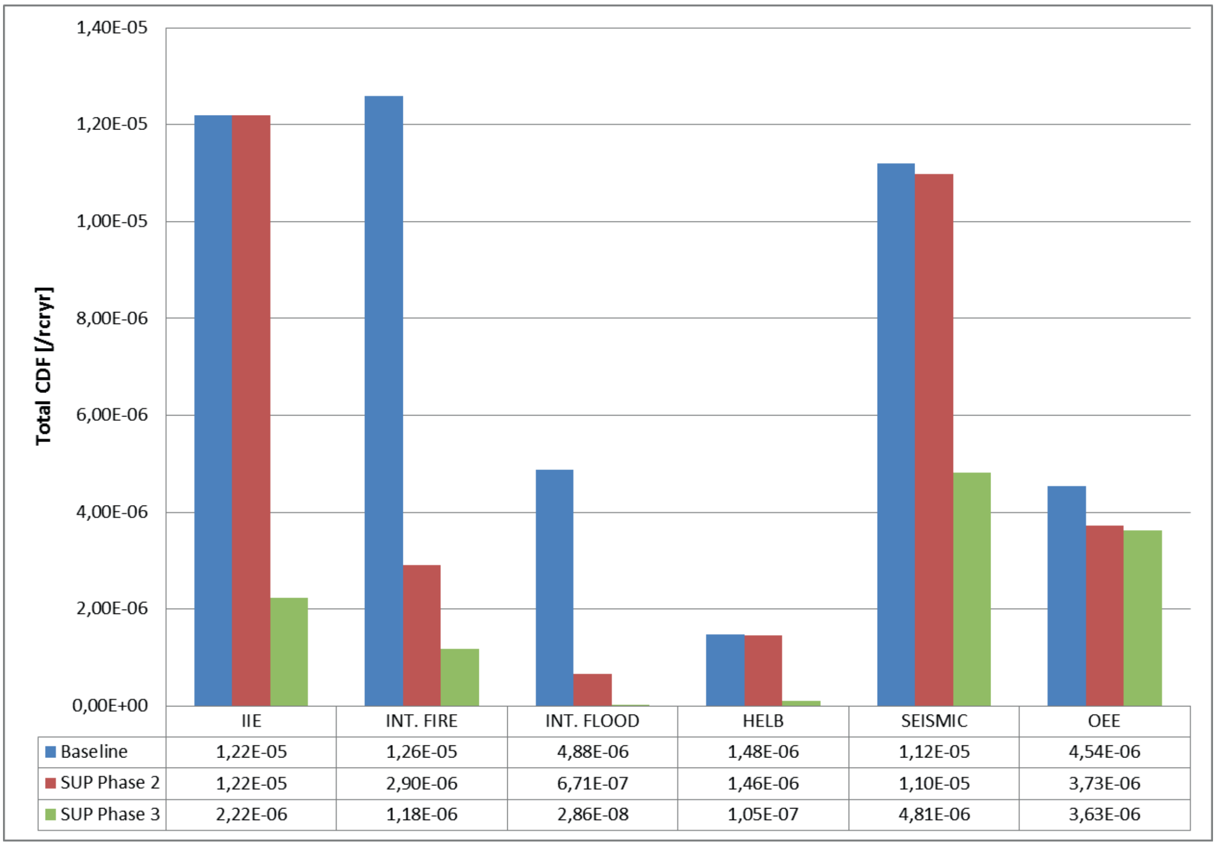
Upon a completion of Phases 2 and 3 the most dominant total CDF reduction is observed for internal fire events in absolute value of 1.1E-5 /rcryr, which represents reduction of baseline total CDF for 24%. This reduction is primarily due to installation of the Emergency Control Room as part of BB1 project in Phase 2 (21%).

The second largest contributor to the reduction of total CDF are IIEs, for which a reduction about 1.0E-5 /rcryr is obtained, which represents reduction of baseline total CDF for 21%. All of it comes from the modifications in Phase 2, primarily due to installation A-AF and A-SI pumps and associated tanks (A-CYT and A-BWT) in BB2 building.

The third largest contributor to the reduction of total CDF are seismic events, for which an absolute reduction is about 6.4E-6 /rcryr, which represents reduction of baseline total CDF for 14%. This comes from the modifications in Phase 3, due to construction of an interconnections between BB1 and BB2 buildings and interconnections between BB2 building and NSSS island, which are seismically designed to withstand PGA of 0.6*g* and are resistant to liquefaction.

The fourth largest contributor to the reduction of total CDF are internal floods, for which an absolute reduction is about 4.9E-6 /rcryr, which represents reduction of baseline total CDF for 10%. This reduction is primarily due to installation of ESW pumps shielding against water spraying in Phase 2 (9%).

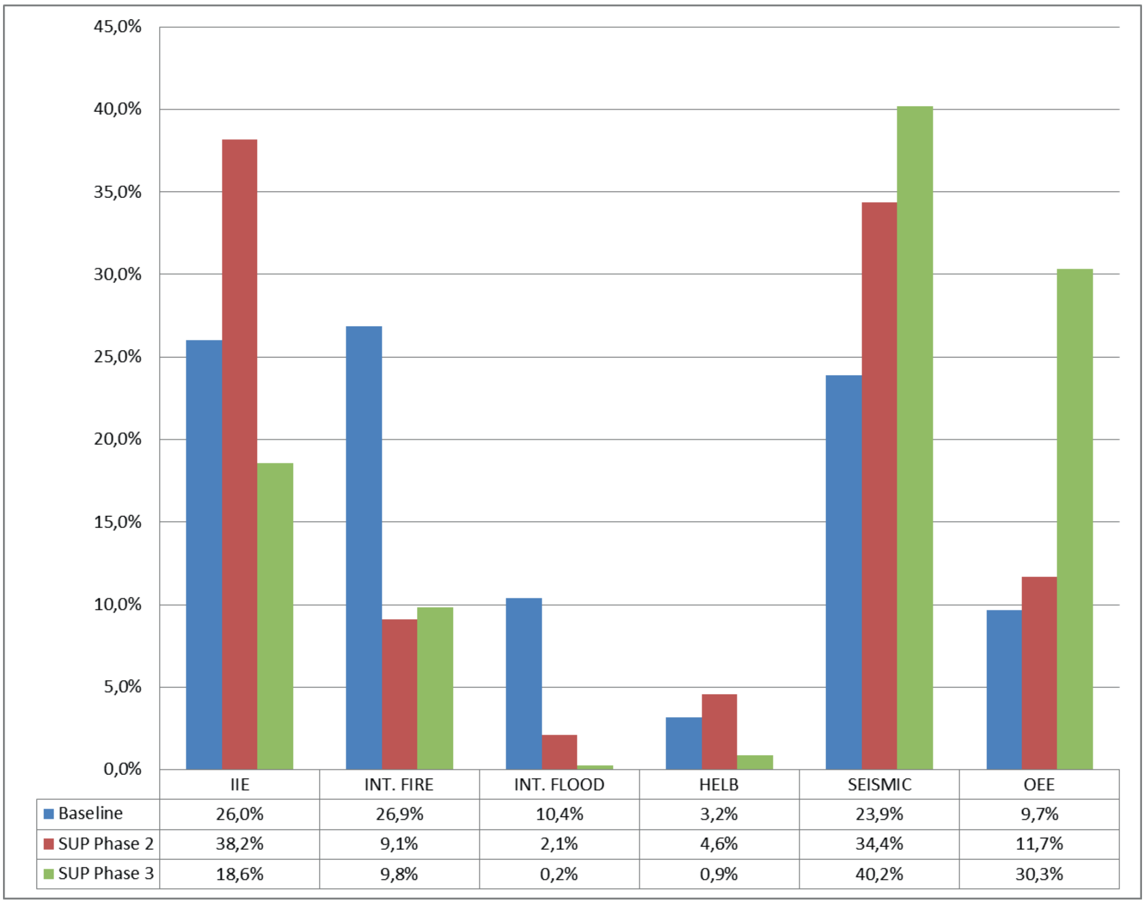
Figure 1 provides comparison of CDF profiles for all three analyzed cases (posterior to Phase 1 (baseline), posterior to Phase 2 and posterior to Phase 3). Figure 2 illustrates the comparison of fractional contributions CDF per contributors (initiators' groups) for the same three analyzed cases.



	IIE	INT. FIRE	INT. FLOOD	HELB	SEISMIC	OEE
🟦 Baseline	1,22E-05	1,26E-05	4,88E-06	1,48E-06	1,12E-05	4,54E-06
🟥 SUP Phase 2	1,22E-05	2,90E-06	6,71E-07	1,46E-06	1,10E-05	3,73E-06
🟩 SUP Phase 3	2,22E-06	1,18E-06	2,86E-08	1,05E-07	4,81E-06	3,63E-06

Figure 1: Comparison of Total CDF Profiles with Phases 2 and 3 Addressed vs. Phase 1 Addressed

Due to significant reduction of baseline total CDF for internal fire (≈ 24%) and internal initiating events (≈ 21%), then moderate reduction of baseline total CDF for seismic events (≈ 13%), and floods (≈ 10%), and negligible baseline total CDF changes from HELB events (≈ 3%) and other external events (≈ 2%), a noticeable change in fractional contribution of initiators to total CDF posterior to Phase 3 is observed. Therefore, the largest total CDF contributor posterior to Phase 3 are seismic events with contribution of around 40% (before Phase 2 it was ≈ 24%), and other external events became the second largest with contribution of around 30% (before Phase 2 it was ≈ 10%).



	IIE	INT. FIRE	INT. FLOOD	HELB	SEISMIC	OEE
🟦 Baseline	26,0%	26,9%	10,4%	3,2%	23,9%	9,7%
🟥 SUP Phase 2	38,2%	9,1%	2,1%	4,6%	34,4%	11,7%
🟩 SUP Phase 3	18,6%	9,8%	0,2%	0,9%	40,2%	30,3%

Figure 2: Fractional Contribution of Initiators to Total CDF (SUP Phase 2 and 3 Addressed vs. Phase 1 Addressed)

An additional step was taken to get an insight and evaluate contribution of various events within the category of other external events. There were changes observed in contribution to CDF for two OEE subcategories:

(1) *External flooding*. An upgrade of flooding protection of NSSS island is planned for implementation in Phase 2. New design would ensure flood protection even in case of Sava River bank failure. The required margin level is 40 cm (upper edge of the existing river bank plus 40 cm yields protection to 157.53 m above sea level). This measure reduces CDF due to external flooding for factor of 5, consequently reducing external flooding contribution to total CDF due to OEE from 22% (before Phase 2) to 6% (after Phase 3).

(2) *Aircraft accidents*. Any civil adaptation to existing BB1 building or BB2 building planned for construction in Phase 3 would be designed and reinforced to be capable to sustain events related to external large commercial aircraft impact on the plant (dynamic forcing function equivalent to B.5.b U.S. NRC requirement or European Utility Requirements for LWR NPP and large fires) and would assure functionality of equipment located inside these buildings during and after DEC. Hence, a reduction of CDF for factor of 2 due to the aircraft accident is estimated, causing a minor change in aircraft accidents contribution to total CDF due to OEE from 4.4% (before Phase 2) to 2.8% (after Phase 3).

These two measures have very low impact on the reduction of the baseline total CDF of 1.93%. However, the largest contributor to the CDF due to OEE remains severe winds (tornados), whose contribution is shifted from 55% to 69% due to implementation of measures described in two paragraphs above.

3.2.2 Most Dominant Core Damage Sequences Posterior to SUP Phase 3

An additional analysis of the core damage sequences due to all initiating events covered by the scope of NEK at-power PSA model was performed. The core damage sequences with frequency above 2E-7 /rcryr for the plant status with Phase 3 implemented are listed in Table 4. There are 12 core damage sequences with frequency higher than or about 2E-7 per rcryr. Their absolute contribution is 1.0E-5 /rcryr, which makes approximately 85% of total CDF.

Table 4 Most Dominant Initiators Contributing to the Total CDF Posterior to SUP Phase 3

	Initiating Event Description	**Abs. Contribution to Total CDF [/rcryr]**	**Rel. Contribution to Total CDF [%]**
1	High winds – tornado strikes (induced station blackout)	2.50E-6	20.9%
2	Seismically induced transient without reactor trip	1.50E-6	12.5%
3	Earthquakes with PGA over 1.1*g*	1.27E-6	10.6%
4	Fire in the main control room	1.08E-6	9.0%
5	Steam line break due to IIE	9.18E-7	7.7%
6	Seismically induced station blackout	9.15E-7	7.6%
7	Seismically induced loss of offsite power	5.97E-7	5.0%
8	RPV failure due to IIE	3.42E-7	2.9%
9	SG tube rupture due to IIE	3.32E-7	2.8%
10	Seismically induced liquefaction (induced loss of ESW system)	2.80E-7	2.3%
11	Seismically induced loss of ESW system	2.04E-7	1.7%
12	External flooding	2.00E-7	1.7%
	...	...	...
	Total	***1.20E-5***	***100.0%***

There are 4 core damage sequences, with frequency above the value of 1E-6 /rcryr. They contribute roughly 53% to the total CDF. They stem from the following initiator categories:

a) *Severe winds – tornados (induced station blackout)* (contribution of 20.9% to total CDF)
It is possible to reduce the risk due to tornados by installation of shielding for coolers and air suction of Diesel Generator #3 against the missiles, which may be generated by tornadoes.

b) *Seismically induced transient without reactor trip* (contribution of 12.5% to total CDF)
It is not possible to reduce the risk from seismically induced transient without reactor trip. The analysis has shown that more than 98% of the seismic hazard comes from the area within the radius of 25 km from the plant. Thus, given the seismically triggered reactor trip protection would be successful for the earthquakes distanced from NEK for more than 28 km, it can be concluded that seismically triggered reactor trip protection is in most cases insufficient (too slow, considering the seismic waves propagation and time needed to successfully trip the reactor) and, therefore, implementation would not significantly improve the plant's seismic safety.

c) *Earthquakes with PGA over 1.1g* (contribution of 10.6% to total CDF)
It is not possible to reduce the risk from the earthquake with PGA over 1.1*g*. The frequency of earthquakes above 1.1*g* PGA is a natural characteristic of the plant site, evaluated by the seismic risk studies for NEK.

d) *Fire in the Main Control Room (MCR)* (contribution of 9.0% to total CDF)
A more detailed analysis should evaluate the residual risk due to fire upon construction of ECR. In this analysis the fire risk in the MCR was reduced for 90% (from 1.08E-5 to 1.08E-6) due to construction of ECR.

4 CONCLUSION

In this paper a Level 1 PSA was performed on NEK at-power PSA model in order to evaluate the impact of plant modernization and upgrades, Phases 2 and 3 of the NEK Safety Upgrade Program, on the total core damage frequency. Analysis was also used to identify the most dominant measures for reduction of total CDF.

Total CDF posterior to the implementation of Phase 3 was estimated at 1.20E-5 /rcryr, which represents a reduction of 63% (a reduction factor of 2.7) as compared to the total CDF obtained posterior to the Phase 2. The measures planned for implementation in Phase 3 with the most significant contribution to reduction of baseline total CDF are (1) installation of additional pumps for primary and secondary injection (A-SI and A-AF) and associated tanks (A-BWT and A-CYT) (21%), and (2) construction of in interconnections between BB1 and BB2 buildings and interconnections between BB2 building and NSSS island (13%).

Cumulative reduction of total CDF after Phase 3, when compared to the baseline total CDF (4.69E-5 /rcryr), is about 3.5E-5 /rcryr, which represent a significant reduction of total CDF for 75% (reduction factor of nearly 4). Upon a completion of Phase 3 the most dominant reduction of baseline total CDF for 24% is observed for internal fire events. This is primarily due to installation of the ECR as part of BB1 project in Phase 2 (21%). The second largest contribution comes from internal initiating events (reduction of baseline total CDF for 21%). It all comes from the modifications in Phase 2, primarily due to installation A-AF and A-SI pumps and associated tanks (A-CYT and A-BWT) in BB2 building. The third largest contribution is from seismic events (reduction of baseline total CDF for 14%). This comes from the modifications in Phase 3, due to construction of an interconnections between BB1 and BB2 buildings and interconnections between BB2 building and NSSS island.

A noticeable change in fractional contribution of initiators' groups to total CDF posterior to Phase 3 is observed. The largest total CDF contributor posterior to Phase 3 are seismic events with contribution of around 40% (before Phase 2 this was ≈ 24%), and other external events became the second largest with contribution of around 30% (before Phase 2 this was ≈ 10%).

As for the other external events, two measures, an upgrade of flooding protection of NSSS island (external flooding) and design change during civil adaptation of existing BB1 building or design of BB2 building capable to sustain events related to external large commercial aircraft impact (aircraft accidents), have very low impact on reduction of the baseline total CDF of 1.93%. High winds category remains the largest contributor to the CDF due to OEE, and its fractional contribution to OEE is shifted from 55% to 69%.

To conclude, a continuous two decade trend of total CDF reduction is present at NEK and is foreseen to be lowered even more in mid-term by additional safety measures and plant modernization defined by the scope of NEK SUP.

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