Loviisa nuclear power plant spent fuel storage risk analysis

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Abstract: Spent fuel of Loviisa NPP is stored submerged in water pools of spent fuel storage (SFS) at Loviisa site at least 10 years and up to many decades. First 1 – 2 years the spent fuel is cooled in refueling pools in reactor buildings. After SFS the spent fuel will be moved to final repository at Olkiluoto. Loviisa NPP PRA covers level 1 and level 2 PRA for reactors and refueling pools for both unit 1 and 2 and common spent fuel storage for both units. Loviisa NPP PRA covers also all operating and shutdown states and all types of initiating events. Current seismic PRA is outdated and under significant update. Loviisa SFS PRA models SFS with highest design basis decay heat rate of current operating license from 2030. Mission times vary from no time to recover to up to 2 months. Criteria for result evaluation is fuel exposure or mechanical break. Equipment failures have only minor impact to the risk because of low heating rate. Seismic initiating events cause over 50 % of fuel damage frequency (FDF) and large release frequency. Also early release frequency (ERF) is considered. FDF 1,9E-7/a is about 1 % of combined Loviisa unit 1 and 2 core damage frequency.

1. INTRODUCTION

Loviisa Nuclear Power Plant (NPP) includes two VVER-440 type PWR (Pressurized Water Reactor) units located in southern coast of Finland. Commercial operation of the units started on 1977 (unit 1) and 1980 (unit 2). The power plant is a unique design with Russian reactor technology combined with western safety systems.

Loviisa NPP probabilistic risk assessment (PRA) covers level 1 and level 2 PRA for reactors and refueling pools for both unit 1 and 2 and common spent fuel storage for both units. Loviisa NPP PRA covers also all operating and shutdown states and all types of initiating events. Current seismic PRA is outdated and under significant update. For more details about Loviisa NPP PRA see e.g. reference [1] or [2]. The most recent results of the Loviisa NPP main PRA (Loviisa NPP units 1 and 2 PRA including reactors and refueling pools) will be presented in this paper and compared to spent fuel storage risk analysis results.

Chapter 2 shows level 1 PRA of Loviisa spent fuel storage, Chapter 3 includes level 2 additions to the analysis. Chapter 4 shows results. Chapters 5 and 6 presents the uncertainty and sensitivity analyses, and summary and conclusions.

1.1 Loviisa Spent Fuel Storage

For about the first 10 to 15 years of Loviisa NPP operation the spent fuel (SFS) was sent to Russia. The spent fuel storage at Loviisa was expanded due to legislation changes in 1990's, since it wasn't allowed to export used fuel anymore. Loviisa NPP spent fuel storage is common for both units and located at the site.

Loviisa SFS includes two units in two buildings. SFS1 is the original. Both units include one loading pool and multiple storage pools. All the pools can be separated from each other using gates between the pools. Any of pools can be emptied for example for maintenance or to install new fuel racks. Total amount of the water in the pools is reduced when one of the pools is empty. SFS1 has been built with same criteria as refueling pools in reactor building. SFS2 has been built in two stages: 1981 … 1984 and 1996 … 1999. New upgrades or changes are needed if Loviisa NPP continues operation after the current operating license expires in 2030. Building the SFS in many stages has resulted in multiple design features which all impact both the analysis and results of the SFS PRA. For example new fuel racks have been installed only as needed.

Loviisa spent fuel is stored submerged in water pools for at least 10 years and up to many decades. The first one to two years the spent fuel is cooled in refueling pools in reactor buildings. After SFS, the spent fuel will be moved to final repository at Olkiluoto (see e.g. Posiva Oy website [3] for more details). The current plan is to start moving used fuel from Loviisa to final repository in a few years. This would reduce the needed capacity of Loviisa SFS for the remaining operation lifetime of Loviisa NPP. Currently Loviisa unit 1 and 2 have operating licenses up to 2027 and 2030, respectively. Fortum announced in early 2022 that Loviisa NPP is applying for extension for the operating license until 2050 and this will impact also the needed capacity of Loviisa SFS.

1.2 Scope of the risk analysis

Loviisa SFS risk analysis was first introduced in 2018 and updated in 2021. The 2021 update of the risk analysis is complete including all types of initiating events and all the same risk metrics as the main PRA of Loviisa NPP. SFS cooling needs many of the same systems as cooling of the reactors and refueling pools. Because of the similarities, most of the initiating events including external and internal hazards are derived from the main PRA. Results of the analysis include

- level 1 results like fuel damage frequency, and
- level 2 results like large and early release frequency.

The analysis includes also sensitivity and uncertainty analysis. The analysis considers the maximum heating rate during the current operating license. The analysis will be updated to consider possible lifetime extensions, impact of moving fuel to final repository and updates to PRA inputs like hazard.

2. LEVEL 1 PRA

Level 1 PRA in this paper assesses accident scenarios leading to fuel exposure or mechanical break at the spent fuel storage.

Chapter 2.1 explains the success criteria and end state selections. Chapter 2.2 describes initiating event identification and details of screening and modelling. Chapter 2.3 includes seismic initiating events with description of their frequency estimation. Chapter 2.4 explains time delays, recovery actions and the selection of mission time.

2.1 Success criteria and end states

Normally the residual heat of the submerged used fuel is transferred to the ultimate heat sink which is sea. Three systems are needed in the normal cooling system:

- Pool cooling system TG
- Intermediate cooling system TF
- Service water system VF

An alternative heat sink is the cooling tower VT. It replaces and is independent from VF system and sea. Boiling and refilling the pools to replace evaporated water is also an option in case of emergency if cooling of the pools is unavailable. Only long unavailability, up to two months, of pool cooling systems requires refilling the pools. Chapter 2.4 includes more details about recovery times and probabilities related to recoveries. Note that some initiating events, like pool rupture due to earthquake, do not have any time for recovery.

Boiling with refilling the pools is considered as an acceptable end state because with refilling there is practically enough time to recover cooling of the pools. The pools can tolerate boiling water based on internal studies. SFS includes a normal system used to fill the pools when needed as a part of the pool cooling system TG. Recently also additional pool filling system (ALPO) with fire track connection has been built. Due to long recovery times, it is expected that also new systems can be built to refill the pools. No access to the SFS buildings are expected or considered after the water has started boiling.

Based on internal analysis, submerged used fuel in SFS cannot melt even when considering e.g. mechanical breaks of the fuel.

As a summary, an acceptable end state without fuel damage fulfills the following:

- Spent fuel rods are submerged.
- Residual heat is removed by normal cooling system or by boiling and pool refilling.

2.2 Initiating events

Only initiating events that cause long lasting loss of cooling of the fuel pools are considered in the analysis. If the cooling can be easily and quickly recovered, it will not have impact on the risk of SFS due to decayed heating rates of the used fuel. Initiating events matching the following criteria have not been considered due to minor contribution to risk:

- Failures with an average needed recovery time less than a few hours.
- Planned maintenance, even if in some cases planned maintenance may cause longer than a few hours of unavailability to the cooling systems.

Most of the initiating events are derived from Loviisa main PRA (see e.g. [1] or [2] for more details) with needed modifications to apply also for the SFS. Some initiating events are new and identified only for SFS. Identification of the initiating events follows the methodology of Loviisa main PRA. The SFS PRA includes following types of initiating events:

- internal events (e.g. transients and equipment losses),
- internal hazards (e.g. fire and flood),
- external hazards (e.g. weather, high sea water level and seismic),
- manmade events (e.g. oil accident and operator emptying wrong pool) and
- loss of offsite power.

The identified initiating events have been divided into three categories with all having different modelling. Number of modelled initiating events after screening and grouping is 13. Most of the initiating events have been modelled in four different scenarios (see Chapter 2.4 and Table 2 for more details) resulting total of 48 initiating event frequencies in the analysis.

First group of initiating events. Initiating events with short needed time to recover compared to time available for the recovery actions. This group of initiating events include the largest number of initiating events, over 30. This group has simplified modelling with one conservative recovery time assumed for all the initiating events. This group of initiating events results only one modelled initiating event in the total number of initiating events of 13 due to simplified modelling. Most of the initiating events in this group are from Loviisa main PRA.

Second group of initiating events. Initiating events screened out of the modelling due to low frequency. The screening limit is 1E-8/a. It is the same as with Loviisa main PRA. Risks in SFS are smaller compared to reactors, which would support a lower screening level. However, the main reason for the selection is that many uncertain phenomena need to be modelled if a lower screening limit is used. It is also easy to use same screening level as with the reactor because then the existing initiating events may be mostly used as is. What would be the reason to model SFS more accurately compared to the reactors knowing that SFS has only minor risk compared to reactor? The screening level needs to be considered when looking at the results. Still, most of the screened initiating events have much smaller initiating frequency than the screening level. It is expected that including the screened out initiating events would not impact the results significantly.

Third group of initiating event are the most important. This group includes initiating events that are difficult to recover from within the available time. Initiating events of this group produce most of the risk in SFS.

2.3 Seismic initiating events

SFS PRA has seismic initiating events in all the three groups described in Chapter 2.2. This paper includes an additional chapter about seismic initiating events due to their importance in the level 1 and 2 results. The seismic initiating events and their modelling has also many specific details of its own compared to other initiating events.

Loviisa NPP and SFS does not have an original seismic design basis, but seismic risks have been included in Loviisa NPP PRA since 1991. Loviisa main PRA currently uses a seismic hazard estimate from 2007. This hazard was included in the main PRA on 2010 [4]. Currently the seismic PRA of Loviisa NPP is under a major update and the estimate of seismic risk is expected to increase significantly mainly due to a significantly increased seismic hazard.

This SFS PRA is the first segment of Loviisa NPP PRA that includes the updated seismic hazard from 2018. The Loviisa seismic hazard has been since updated again in 2021, but changes between the 2018 and 2021 hazards are quite minor. SFS PRA will be updated to the new seismic hazard after the main Loviisa seismic PRA update has been finalized. For SFS it was quite easy to consider the new seismic hazard due to simple safety systems of the Loviisa SFS.

The following seismic initiating events have been identified for SFS PRA:
- Building collapse due to earthquake
- Leakage in stainless steel liner of the pool due to fuel rack sliding during earthquake
- Pool breaks due to earthquake
- Leakage in liner and concrete structures of the pool due to earthquake
- Pool cooling system failure due to earthquake

All but cooling system failure have specific deterministic seismic analysis based on which the seismic fragility has been developed. Cooling system failures allow a long time for recovery actions, so a conservative initiating event frequency can be used with only a minor impact on the results.

The Conservative Deterministic Failure Margin (CDFM) method is used for seismic fragilities. CDFM method is an easy way to generate most of the seismic fragilities. As described in reference [5], the most significant seismic fragilities can be later updated using more advanced methods like Separation of Variables (SV). First inputs to the CDFM method are HCLPF (High Confidence Low Probability of Failure) capacities from the deterministic analyses. Next inputs to the CDFM method are uncertainty parameters β_R and β_U. Generic values are in use for the parameters from reference [5], Table 6-2: β_R is 0.24 and β_U is 0.26.

Seismic capacities are linked from deterministic analyses to HCLPF capacities using reference ASCE 4-16 [6]. All the analyses have used or followed standard ASCE 4-16. Aim of the standard is to generate seismic capacity with about the same definition as HCLPF capacity in CDFM method (see references [5] and [6]). Acceptance criteria of pool liner seismic capacity is based on an accepted stretching limit of nuclear containment liner. In ASME standards the acceptance criterion for containment liner is 0.3 % [7]. Based on internal studies and expert judgement, stretching of 0.3 % is too conservative to meet HCLPF criteria with 1 % expected failure probability. Stretching value of 1 % is selected as the acceptance criterion based on expert judgement to reduce additional conservatism. Another expert judgement from strength analysis experts is that stretching of tens of percents is ok for liner before significant leakage. Using 1 % stretching limit with CDFM method produces better in line result for median seismic capacity, still resulting in a conservative capacity estimate.

The difficulty with seismic capacities and fragilities is that different configurations and modifications to the structures over the years may result in varying seismic capacities. As described in Chapter 1.1, SFS units 1 and 2 and fuel racks have been built in many stages and with a few different configurations. Currently no seismic capacity analysis is available for all the different configurations. For the missing capacities, capacity of the most similar configuration or lowest known capacity is in use.

All the deterministic analyses do not use the same seismic ground response spectra (GMRS). Figure 1 shows both of the used spectra from 2018 and YVL B.7 [8]. Figure 1 shows also GMRS from 2007 which is currently in use in Loviisa main PRA [4]. Most of the SFS analysis use Loviisa GMRS 2018. Some of the deterministic analysis use also GMRS from Finnish national regulatory guidance YVL B.7 (Appendix - An example of an acceptable spectrum) scaled to 0.1 g PGA minimum limit [8]. The current YVL B.7 guidance does not have the spectra anymore [9]. All the seismic capacities are scaled to meet the 2018 response spectrum when other GMRS have been used as an input. Figure 2 compares Loviisa 2018 and 2007 seismic hazard estimates using PGA (peak ground acceleration, 100 Hz) accelerations.

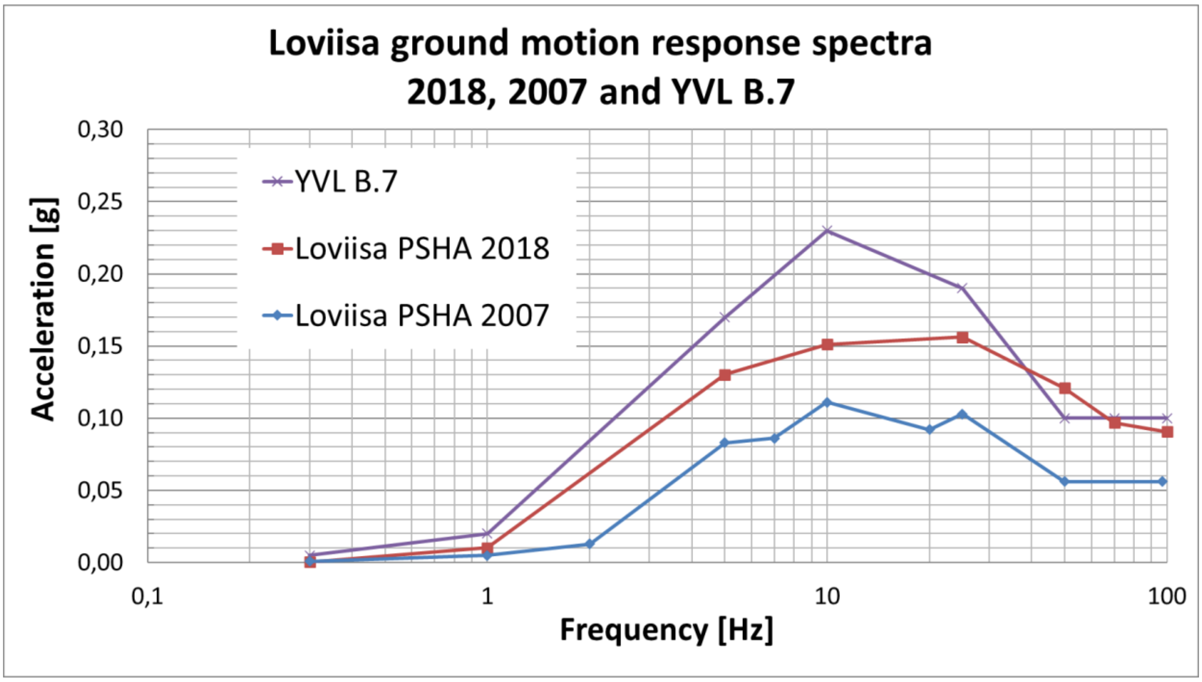

Figure 1: Loviisa NPP 2018 site specific ground motion response spectra compared to probabilistic seismic hazard assessment (PSHA) conducted at 2007 [4] and YVL B.7 design spectrum [8] scaled to PGA 0.1 g with annual frequency of exceedance of 1E-5/a.

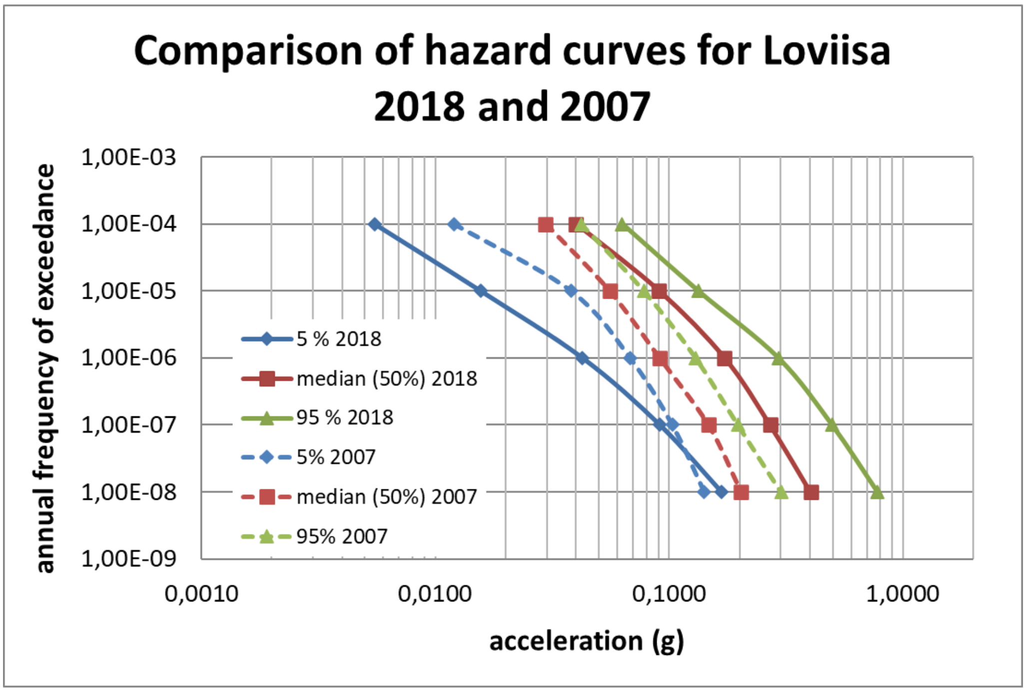

Figure 2: Comparing 100 Hz hazard curves for Loviisa NPP site. Comparing results from probabilistic seismic hazard assessments 2018 and 2007 [4].

Seismic initiating event frequencies are evaluated using the following procedure. 40 discrete frequency intervals are selected between annual frequency of exceedances (AFE) 1E-2 /a and 1E-8 /a. The mean value of the 2018 hazard in Figures 1 and 2 is used. The acceleration for the interval is chosen from the midpoint of the interval. The acceleration is then used to evaluate the failure probability due to earthquake for the interval using the CDFM method [5]. The failure frequency for the interval is the product of the frequency and the corresponding failure probability. The total seismic initiating event frequency is the sum of all the failure frequencies of the individual intervals.

2.4 Time delays and recovery failures

No specific mission times have been considered due to low heating rates and because of long times to recover the cooling of the pools in most scenarios. The selection of mission time would not have a significant impact on the results. The mission time impacts mainly the equipment failure probabilities. With a longer mission time, the failure probability is higher. However, due to long mission times, also more difficult and long repair and recovery operations can be expected and modelled. The most significant reason why the selection of mission time does not have a significant impact is because most of the risk is related to scenarios other than traditional equipment failures.

Time available to recover cooling varies from 'no time to recover' to 2 months. For example a building collapse due to an earthquake allows no time to recover. Longest available times for recovery are with initiating events including only the loss of cooling of the pools in scenarios when all the pools are full of water. Water can boil up to 2 months in SFS2 before the water level in pools reaches the top of the fuel rods.

In case of loss of cooling of the pools the operator may be able to recover the cooling with two alternative methods:

- recover normal cooling systems of the pools, or
- refill the pools to compensate evaporation due to boiling.

In case of leakage of the pools, the operator may be able to isolate the leakage or fill the pools before exposure of the fuel.

Recovery actions include also repairing of the systems due to long recovery times. Human reliability assessment (HRA) methods (used to estimate the probability of an unsuccessful recovery) are usually optimized for short time periods with a maximum of a few hours for recovery. Consideration was needed in how to apply traditional methods for longer recovery times up to 2 months. Equation (1) was selected for long time recovery probabilities (probability of unsuccessful recovery)

$$P(T_0, T_1, T_2) = \begin{cases} e^{-\frac{T_2 - T_0}{T_1}}, & e^{-\frac{T_2 - T_0}{T_1}} > 10^{-6} \\ 10^{-6}, & e^{-\frac{T_2 - T_0}{T_1}} \leq 10^{-6} \end{cases}. \tag{1}$$

Time T_0 represents the delay between the initiating event and the start of the recovery action. T_1 represents the average time needed for the recovery action. T_2 represents the time available for the recovery action. Table 1 shows recovery failure probabilities using Equation (1) with different average times T_1 and T_2 using T_0 = 0. 1E-6 is a selected minimum value for the probability.

Delays T_0 are conservative expert judgements. The impact of T_0 values is small to the results even with the conservative values. The operator starts recovery actions only after having noticed the need for the action. For example in scenarios with core damage, SFS may not be in focus straight after the initiating event and then, as a conservative assumption, a few days (=T_0) have been assumed before the operator initiates recovery actions for the SFS.

Times T_1 are expert judgements. T_1 estimates consider that SFS pools have also backup cooling systems and their availability.

Times T_2 are mainly based on analysis on how long it takes for water to reach boiling temperature and to evaporate so much that fuel will be exposed. All the initiating events have been considered and the times available for recovery actions have been analyzed.

Table 1: Recovery failure probabilities using Equation 1 with different parameter values T_1 and T_2. T_0 selected to be 0 in the Table.

		Time needed T_1						
		3 h	6 h	12 h	24 h	2 d	4 d	8 d
Time available T_2	1,5 h	6,1E-01	7,8E-01	8,8E-01	9,4E-01	9,7E-01	9,8E-01	9,9E-01
	3 h	3,7E-01	6,1E-01	7,8E-01	8,8E-01	9,4E-01	9,7E-01	9,8E-01
	6 h	1,4E-01	3,7E-01	6,1E-01	7,8E-01	8,8E-01	9,4E-01	9,7E-01
	12 h	1,8E-02	1,4E-01	3,7E-01	6,1E-01	7,8E-01	8,8E-01	9,4E-01
	24 h	3,4E-04	1,8E-02	1,4E-01	3,7E-01	6,1E-01	7,8E-01	8,8E-01
	2 d	1E-06	3,4E-04	1,8E-02	1,4E-01	3,7E-01	6,1E-01	7,8E-01
	4 d	1E-06	1E-06	3,4E-04	1,8E-02	1,4E-01	3,7E-01	6,1E-01
	8 d	1E-06	1E-06	1E-06	3,4E-04	1,8E-02	1,4E-01	3,7E-01
	16 d	1E-06	1E-06	1E-06	1E-06	3,4E-04	1,8E-02	1,4E-01
	32 d	1E-06	1E-06	1E-06	1E-06	1E-06	3,4E-04	1,8E-02
	64 d	1E-06	1E-06	1E-06	1E-06	1E-06	1E-06	3,4E-04
	128 d	1E-06	1E-06	1E-06	1E-06	1E-06	1E-06	1E-06

The exponential function in Equation (1) is widely used to represent the distribution of repair times. The distribution of average repair times converges to the exponential distribution especially with difficult repair cases and when considering multiple failure modes. The exponential function is also easy to use in the recovery probability estimation.

The time available for operator recovery actions (T_2) depends e.g. on severity of the initiating event. The time needed for the recovery actions (T_1) depends on the initiating event but also conditions at the site. The initiating event itself may impact the site conditions, e.g. IEs with high sea water levels are considered. Many initiating events may also lead e.g. to core damage at the reactors. These kinds of more challenging scenarios have been considered at the site as separate initiating events. In case of a core damage, carrying out recovery actions at the SFS is considered to require more time due to the complex situation at the site.

Specific recovery probabilities have been estimated for both SFS units (SFS1 and SFS2) and for scenarios with all the pools full of water (SFS1/2) and with the scenario when one pool is empty (SFS1/2e) e.g. due to maintenance. All of these impact some of the parameter values T_0, T_1 or T_2 in some initiating events. For example having one pool empty reduces the amount of water in the pools. With less water, less time is needed for enough water to evaporate to expose the fuel. Table 2 includes examples of a few recovery failure probabilities used in the analysis.

The main reference for the minimum recovery probability 1E-6 (see Equation (1)) is NPSAG report from 2016 about dependencies in HRA [10]. Chapter 5.7 of the report summarizes suggestions for minimum total human error probability for many different HRA methods. The minimum limit is recommended regardless of the number of the human errors needed in the scenario. This kind of minimum limit is suggested due to possible dependencies between the different human errors. The methods have been mainly developed for reactor accident scenarios with much shorter time delays compared to scenarios related to SFS. Suggestions for the minimum probabilities are between 1E-7 and 1E-5 for various methods. Most common suggestion is 1E-5. The minimum value of 1E-6 was selected for the SFS analysis due to long time delays in SFS. Most of the recovery probabilities in the SFS analysis include expert judgements with significant uncertainties. Using a minimum value of 1E-7 is not considered justified because of the significant uncertainties.

Table 2: Example of recovery failure probabilities and their parameters T_0, T_1 and T_2.

					SFS1	SFS1e	SFS2	SFS2e		SFS1	SFS1e	SFS2	SFS2e
Initiating event	Description	T_0	T_1	Unit	T_2				Unit	Recovery failure probability			
IEQ_SFS_COOL	SFS pool TG-cooling fails due to EQ	2	2	d	34	32	63	29	d	1E-06	1E-06	1E-06	1E-06
ISEAL3	High sea level (>3,1 m)	2	2	d	34	32	63	29	d	1E-06	1E-06	1E-06	1E-06
ISEAL4	High sea level (>4 m)	4	4	d	32	30	61	27	d	4E-04	5E-04	1E-06	1E-03
ISFS_COOLSTOP_CD	SFS TG-cooling stop due to Lo1 or Lo2 reactor core damage, no large release	3	3	d	33	31	62	28	d	2E-05	3E-05	1E-06	1E-04
...	...												
Initiating event x	Description of initiating event x												

3. LEVEL 2 PRA

All the fuel damage (FD) sequences in SFS include melting fuel due to pools boiling empty. SFS does not have a containment, so all the FD sequences are also large releases (LR). The inventory of the releases differs significantly from reactor accidents due years or decades of cooling of the fuel. The nuclide inventory of the used fuel in the SFS includes an extremely large portion of long lasting nuclides like Cs-134 and Cs-137. SFS accidents can cause significant contamination to large areas around the site due to long lasting nuclides.

Level 2 results have also been estimated for early release. Criteria for early release frequency (ERF) is following [11]:

- Release before 5 hours after operator recognizes the initiating event and is able to start preparations for protections of surrounding environment and inhabitants.
- Maximum dose integrated over 24 hours exceeds 10 mSv for surrounding inhabitants.

Significant releases without melting fuel have been estimated almost impossible. Based on internal studies, it is almost impossible that submerged used fuel cooled more than one year melts even when considering possible damages to the fuel. Used fuel in the Loviisa SFS has been cooled at least one year at the reactor building before moving it to the SFS. Possible mechanical breaks of the fuel releases gaseous releases in the fuel. Based on internal studies, amount of the release is small compared to both ER and LR limits, even if all the used fuel in the SFS breaks and releases the gaseous releases. Amount of the releases related to mechanical breaks considers inventory of the gaseous releases and impact of water to the releases while the fuel is submerged.

4. RESULTS

Table 3 shows main results for both main PRA and SFS PRA on 2021. Table includes results for both levels (1 and 2) including fuel damage frequency (FDF) of the SFS, core damage frequency (CDF) of the main PRA and large (LRF) and early release frequencies (ERF). Table shows also fractions of ERF and LRF and fractions of SFS frequencies compared to main PRA. Table includes combined results for both SFS units. Loviisa main PRA refers to combined results of Loviisa unit 1 and unit 2 PRA including reactors and refueling pools. Values highlighted in the Table shows the main frequency results and other values are fractions derived from the results.

Figure 3 shows initiating event contribution to the level 1 and level 2 PRA results. Red sections in the Figure are also ERs. Table 4 shows description of the most important minimal cut sets of the analysis. Figure 4 shows initiating event contribution to Loviisa unit 1 level 1 PRA for comparison.

Table 3: PRA level 1 and 2 main results for Loviisa NPP main PRA and SFS PRA.

	Main PRA	SFS PRA	SFS frequency / Main PRA frequency
CDF or FDF (1/a)	1,3E-05	1,9E-07	1 %
LRF (1/a)	6,1E-06	1,9E-07	3 %
LRF / CDF or FDF	46 %	100 %	
ERF (1/a)	1,5E-07	5,2E-08	36 %
ERF / LRF	2 %	28 %	
ERF / CDF or FDF	1 %	28 %	

Table 4: Most important initiating events with their descriptions.[*]

Initiating event	Description
IEQ_SFS_RACK	SFS pool steel liner leak due to fuel rack movement and pool concrete structure crack due to EQ
ISFS_DRAIN_UH	SFS pool erroneous drainage due to operator error
ISFS_COOLSTOP	All SFS TG-cooling stop initiators (plant data)
IEQ_SFS_BUILDING	SFS building collapse due to EQ
ISFS_COOLSTOP_LR	SFS TG-cooling stop due to reactor CD and large release
ISFS_LINER	SFSpool liner leakage (plant data)
ISFS_WIND53	High wind speed (>53 m/s)
IEQ_SFS_LINER	SFS pool liner and concrete structure leakage due to EQ

[*] EQ: Earthquake

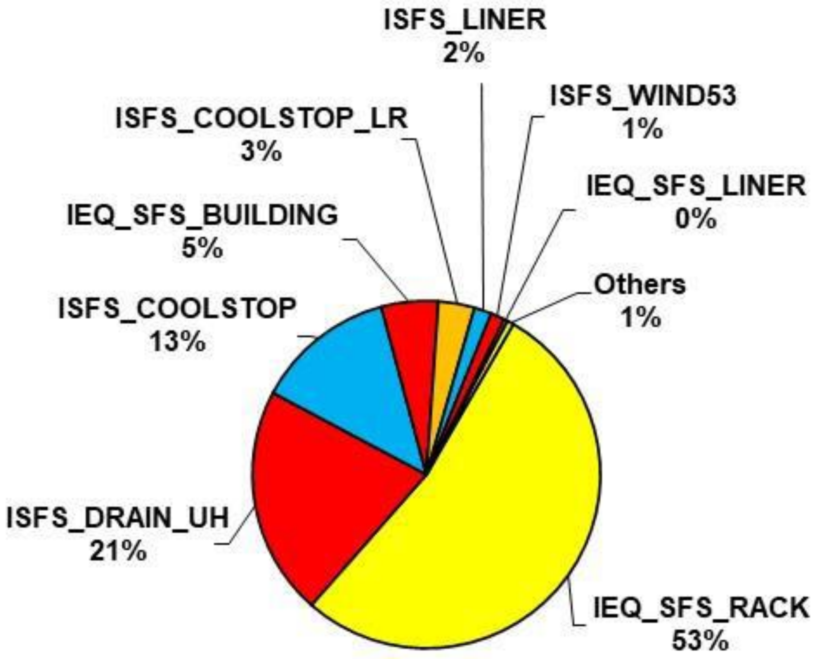

Figure 3: Contribution of initiating events to the SFS PRA level 1 and 2 results. FDF and LRF are the same including all the initiating events. Red sections are included also in ERF.

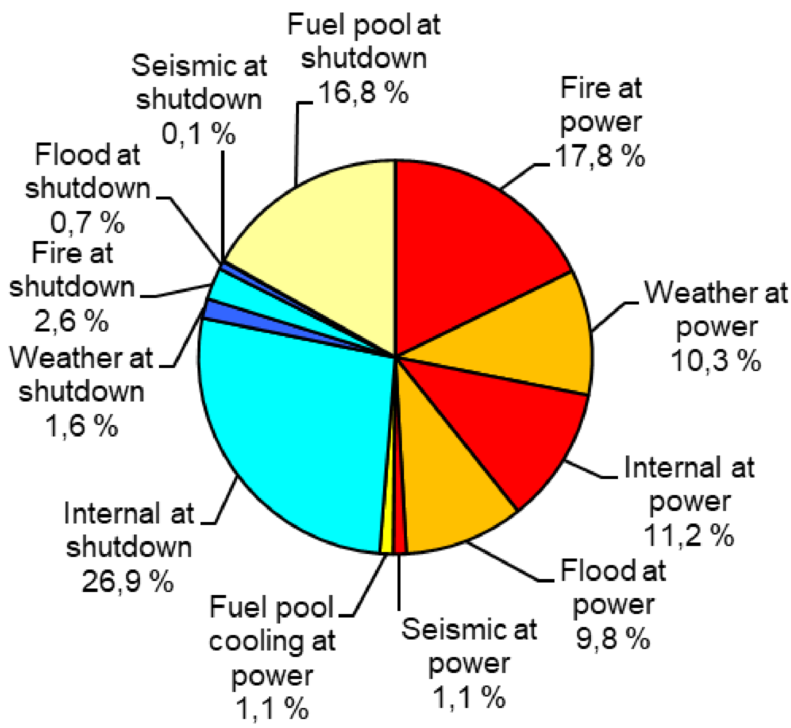

Figure 4: Contribution of initiating events to the Loviisa unit 1 level 1 PRA 2021.

5. UNCERTAINTIES AND SENSITIVITY ANALYSIS

SFS PRA includes significant uncertainties but absolute uncertainties are small compared to absolute uncertainties in reactor risk analysis.

SFS PRA includes qualitative uncertainty and sensitivity analysis. Due to the grouping of initiating events and recovery actions, the SFS PRA model is relatively simple and therefore the quantification has been carried out with MS Excel. Excel does not have built in sensitivity and uncertainty analysis tools. Quantitative assessment of uncertainties would also be difficult for the most important uncertainties listed below due to the difficulty of obtaining reliable uncertainty estimates. Qualitative uncertainty and sensitivity analysis is expected to cover all important aspects of the current analysis.

The most important uncertainties are related to seismic events. They cause 58 % of the total spent fuel storage fuel damage frequency. A few reasons have been identified to explain their importance:

- In seismic initiating events such as pool rupture or building collapse leading to emptying of the pools or direct fuel damage, no significant safety benefit is gained from low heating rates as with most of the other initiating events.
- Loviisa NPP does not have seismic design basis originally and then already quite small earthquakes can and/or are assumed to cause damage at the plant.
- Seismic hazard estimate has significantly increased since 2007.

The following most important uncertainties have been identified.

- The most significant initiating event is fuel rack moving because of earthquake causing 53 % of the FDF. Only two out of four different kinds of fuel racks have been seismically analyzed. One of the remaining two types of fuel racks is expected to have at least the same seismic capacity as the newer rack with available seismic analysis. The last and oldest remaining fuel rack is without seismic analysis and it is not easy to say without a proper analysis whether it has a lower or higher seismic capacity compared to the newer ones.
- SFS PRA is based on the 2018 seismic hazard estimate. Loviisa NPP has already a newer seismic hazard estimate from 2021. Differences between 2018 and 2021 seismic hazard estimates are not very significant, but already new research is ongoing related to the seismic hazard. The seismic hazard seems to include significant uncertainties for both lower and higher direction. In low seismic activity areas like Southern Finland, it is very difficult to justify a seismic hazard estimate due to a lack of data and proper models developed for the area. The bedrock in Southern Finland is very hard compared to most of the world making it difficult to apply methods developed for softer rocks.
- Assumptions related to correlations between seismic fragilities. All the seismic fragilities have been modelled fully dependent within one unit of the SFS and fully independent between the units 1 and 2. The selection between degrees of dependency impacts approximately ten percent to the FDF results in both directions.
- Correlations also between other than seismic events are important. All the initiating events have been modelled independently. Considering the dependencies would reduce FDF a few percent.

6. SUMMARY AND CONCLUSIONS

Fuel damage frequency (FDF) of the spent fuel storage (SFS) is 1,9E-7/a which is about 1 % of Loviisa NPP main PRA CDF. The risks at the SFS are small compared to main PRA. Uncertainties within the SFS analysis are high. Seismic initiating events cause 58 % of the spent fuel storage fuel damage frequency. Early release frequency (ERF) fraction of FDF is 28 % in SFS PRA. It is much higher compared to similar fraction (1 %) in main PRA. ERF of the SFS is also quite high fraction of main PRA ERF (36 %).

Most of the initiating events are from Loviisa main PRA, but their contribution to the risk is completely different. Note that Loviisa main PRA does not currently have up to date seismic PRA. Seismic risk estimate for Loviisa NPP main PRA is also expected to increase significantly in the ongoing seismic PRA update. Increase in seismic risk is mainly due to the significant increase in the seismic hazard estimate since 2007. High importance of seismicity in SFS PRA is mainly due to low heating rate. No significant safety benefit is gained in most of seismic initiating events from low heating rates.

References

[1] K. Jänkälä, "Analysing and decreasing external event risks of Loviisa NPP" in *13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13)*, Seoul, 2016.

[2] K. Jänkälä and S. Sirén, "Uncertainty analysis of Loviisa PRA" in *Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference*, Singapore, 2020.

[3] Posiva Oy, "Website of Posiva Oy" [Online]. Available: https://www.posiva.fi/en/index.html. [Accessed 29 04 2022].

[4] J. Helander and K. Jänkälä, "The Update of Seismic Probabilistic Risk Analysis for Loviisa Nuclear Power Plant" in *International Conference on Probabilistic Safety Assessment and Management PSAM11*, Helsinki, 2012.

[5] EPRI, ”Seismic Evaluation Guidance” Report 1025287, 2012.

[6] American Society of Civil Engineering, ASCE, Seismic Analysis of Safety-Related Nuclear Structures (4-16), 2017.

[7] American Society of Civil Engineering, ASME, Boiler and Pressure Vessel Code, Section III, Division 2 - Code for Concrete Containments, 2013.

[8] Radiation and Nuclear Safety Authority (STUK), ”YVL B.7, Provisions for internal and external hazards at a nuclear facility” 2013.

[9] Radiation and Nuclear Safety Authority (STUK), ”YVL B.7 Provisions for internal and external hazards at a nuclear facility” 2019.

[10] X. He, ”Dependences in HRA” NPSAG report 41-001:01 Version 2.0. Nordic Probabilistic Safety Analysis Group, NPSAG, Sundbyberg, 2015.

[11] T. Laato and K. Jänkälä, "Frequency of early release requiring protective actions for the public at Loviisa VVER-440 NPP" in *Probabilistic Safety Assessment and Management PSAM 14*, Los Angeles, 2018.