Frequency of early release requiring protective actions for the public at Loviisa VVER-440 NPP

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Abstract: This paper describes the probabilistic risk assessment of early releases requiring protective actions on people living near the nuclear power plant at Loviisa. The analysis raises importance of several accident scenarios, which would be considered minor or negligible risks based on analysis of core damage or large release frequencies.

Keywords: PRA level 2, Early release

1 INTRODUCTION

Loviisa Nuclear Power Plant (NPP) is a VVER-440 type PWR located in southern coast of Finland. The power plant is a unique design with Russian reactor technology combined with Western safety systems, ice-condenser containment and automation systems.

The level 1 PRA model of Loviisa NPP covers nowadays internal and external events including fires, floods, seismic and severe weather events as well as man-made events like transportation accidents for power operation and shutdown states taking into account also the fuel pool. Level 2 PSA has the same coverage as level 1 except for seismic events have been neglected due to their small significance. Until 2017 the results of level 2 PSA were only presented for large release frequency (LRF). [1], [2]

In 2015 Loviisa NPP received a decision from Radiation and Nuclear Safety Authority in Finland (STUK), which required the plant owner to provide information of accident scenarios, in which there would be no time to apply protective measures on people living close to the power plant. The usual approach considering early releases is to calculate large early release frequency (LERF), which has been defined in NRC document NUREG-1765 [3] as accidents leading to prompt fatalities. In the background material of the decision STUK specifically pointed out, that protective measures are being applied already at much lower dose rates in the environment, than what would be applicable in case of over 100 TBq release of Cs-137, which is defined as the threshold for large release . While in case of a large early release fatalities are being expected near the power plant, protective measures are being applied already at much lower dose rate levels. Therefore a new measure is defined: Early Release Requiring Protective Actions (ERRPA).

Scenarios, which would qualify for ERRPA, but not for LER are e.g. small leaks from containment and accidents, in which only the activity from gas gap is released to the environment. The latter type of accidents would also not be considered as large release in long term and not always as core damage either.

2 SAM STRATEGY AT LOVIISA

Development of severe accident management (SAM) strategy at Loviisa was done during 1990's and the last installations were completed in 2003. Before actual SAM project containment external spray system was installed to allow long term pressure control of the containment during severe accidents. An extensive research program was implemented to support the SAM program and to ensure the strategy will work as planned. [4], [5], [6]

SAM strategy is based on 5 functions, which are presented in Figure 1. By successfully achieving these functions, the consequences of an accident are mitigated and a large radioactive release to the environment is prevented. SAM systems have two dedicated diesel generators, which are shared between the units. One diesel generator is enough to operate SAM systems of both units. The SAM strategy relies on fixed (as opposed to mobile) systems.

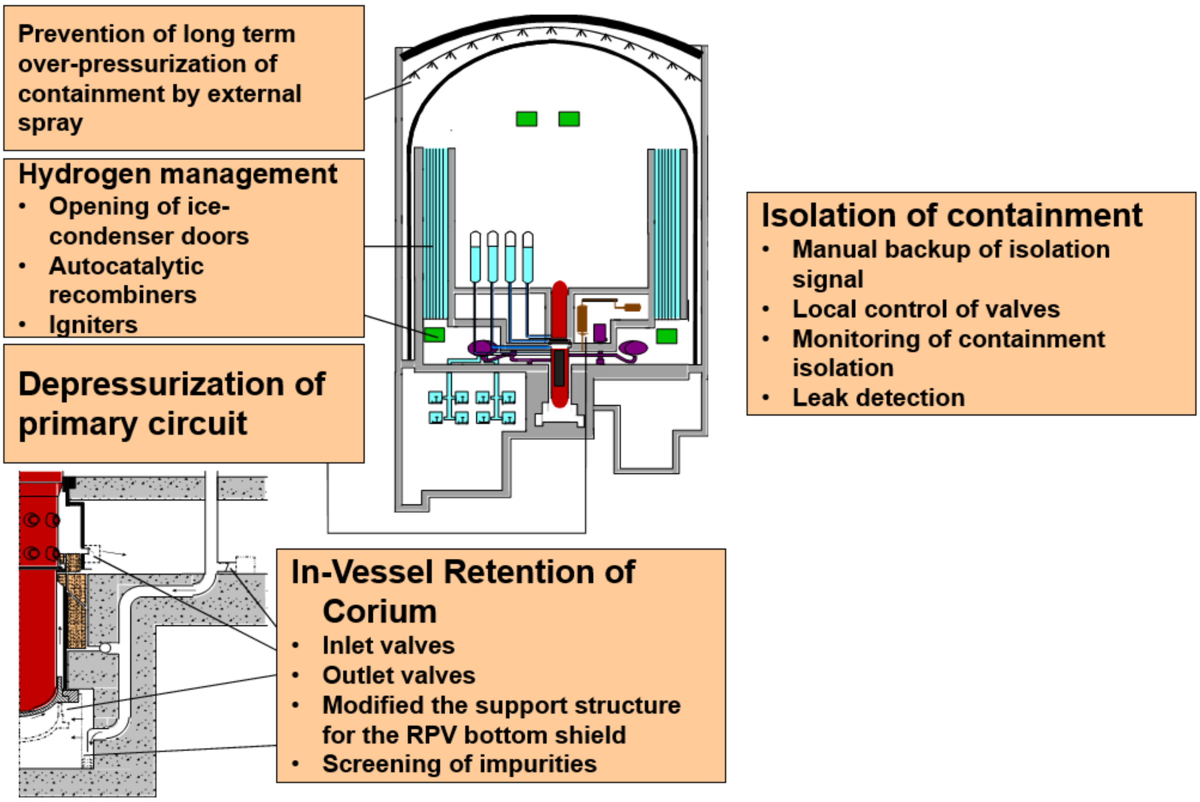

Figure 1: Severe accident management at Loviisa.

The isolation of the containment is done automatically at an early phase of an accident. The isolation signals are backed up by manual activation of isolation signals. Selected valves can be closed also at local control centers backed up by SAM diesel generators.

Depressurization of the primary circuit is done, when the core is uncovered from water. The depressurization allows water from the hydro accumulators to inject water into the primary circuit and reduces loads inflicted to the reactor pressure vessel (RPV) wall. This is necessary at a later stage of the accident, when the molten corium has partially melted the RPV wall.

Hydrogen management at Loviisa is implemented by removing hydrogen with passive autocatalytic recombiners. The high local hydrogen concentrations are diluted by forcing the ice-condenser doors open to create a natural circulation air flow between upper and lower compartments of the containment. To counter the threat of rapid hydrogen generation e.g. during reflooding of an over-heated core, ignition capability has been installed to the steam generator compartment to ignite the hydrogen in small quantities. [7]

The chosen method for stabilizing molten corium is in-vessel melt retention. In most of the accident scenarios the reactor cavity is passively flooded by water from primary circuit and melting ice-condensers. The thermal shield at the bottom of the RPV is lowered to ensure sufficient space for the cooling water flow. The in-vessel melt retention approach leaves hydrogen as the only non-condensable gas to be dealt with. [8]

Prevention of long term over-pressurization has been implemented using containment external spray system. The system sprays water on the steel dome of the containment leading to condensation of the steam inside the containment. The system has its own sea water cooling system and there are connections to enable use of a mobile pump, e.g. fire truck. [9]

3 DEFINITION OF ERRPA AT LOVIISA

3.1 Time delay and limits for release of fission products

In the emergency response procedures it is defined, that the design time for the emergency personnel to execute protective measures in the emergency planning zone is 4 hours in case of a radiation emergency. To allow plant personnel enough time to find out and communicate the situation at the NPP to the authorities, one hour is added to the time constraint. Therefore only accident scenarios, in which the release begins within 5 hours since the start of the accident scenario are considered in this paper.

For Loviisa NPP maximum doses to the nearby people have been analyzed at different integration times. The shortest integration time available at the time of this analysis was 24 hours and therefore it has been used as the basis for the analysis. It is estimated, that a release of 100 % of noble gases core inventory during power operation results in maximum doses of about 3 Sv in average weather conditions at distance of 1 km from the NPP. Release of 1 % of iodine results in maximum doses of about the same level.

In Finnish Regulatory Guides on nuclear safety and security (YVL) C.5 it is required, that:
"Even in the severest radiation hazard, the objective is that, after the implementation of protective actions, radiation dose does not exceed the maximum radiation exposure level of 20 mSv during the first year."
Considering this, if the release during the first 5 hours does not exceed 10 mSv, it can be stated with confidence, that the total doses should remain below 20 mSv after the protective measures are taken into account. To transform that into release fraction of Loviisa core inventory, if the release during the first 5 hours does not exceed 0.1 % of noble gases or 0.001 % of iodine of total core inventory during power operation the maximum doses for people are estimated at around 6 mSv and there is some margin left for the rest of the easily volatile fission products.

3.2 Accident scenarios leading to ERRPA

All the accident scenarios covered in level 2 PSA are also covered in evaluation of ERRPA. For purposes of level 2 PSA of Loviisa NPP, releases as a function of time are analyzed with SaTu tool. [10] The SaTu tool uses a relatively simple approach to calculate a quick estimate of the release of an accident scenario. Releases have been analyzed in over 99 % of core damage frequency (CDF). Also many such scenarios are analyzed, which have been significant in the past but no longer present a substantial share of the CDF. For study of ERRPA all such accident scenarios were considered, in which core is damaged within 5 hours since initiating event.

Based on accident scenarios created in SaTu tool, releases may occur within 5 hours from initiating event in the accident scenarios leading to core melt bins (CMB) which are presented in Table 1. Containment sequences include loss of coolant accidents (LOCA) larger than 5 cm^2 with injection failure. In case of large LOCA also early recirculation failure may lead to core damage within 5 hours from initiating event. By-pass sequences include large LOCAs, in which steam blow is not directed to the ice-condenser leading to containment breach (BLR, BLU), primary secondary leaks and LOCAs outside the containment (VLOCA). X-sequences include extreme events and such scenarios, in which the outcome differs significantly from other cases leading to core damage. Typically SAM systems are not able to mitigate these accidents and they are evaluated using a single multiplier as CDF-to-LRF/ERRPAF-ratio instead of event trees.

Table 1: Core melt bins potentially leading to ERRPA.

Containment sequences	
NII	Small-medium LOCA (SMLOCA, 5-42 cm^2), injection failure
NLE	Large LOCA (LLOCA, >140 cm^2), early recirculation failure
NLI	Large LOCA (LLOCA, >140 cm^2), injection failure
NMI	Medium LOCA (MLOCA, 5-140 cm^2), injection failure
By-pass sequences	
BLR	Large LOCA in reactor coolant pump room (LRLOCA)
BLU	Upper containment LOCA (UCLOCA)
BMI	Multiple steam generator tube rupture or steam generator collector cover break (MSGTR, LSGTR), injection failure
BVB	Leak via auxiliary systems (VLOCA) to the basement of the reactor building
X-sequences	
XAT	Anticipated transient without scram
XND	Fall of the ventilation stack on the reactor building
XRE	Reactivity accident
XTS	Pressurized thermal shock, PTS

Table 2 presents the accident progression categories (APC), which may lead to ERRPA in CMBs presented above. In APCs 05-08, 11-12 and 18 containment isolation fails at various degrees and in APCs 13-17 other parts of the SAM strategy fail. When considering LRF, the in-containment spray system makes a major difference in the APCs with only small leak to the containment (05-12), because it is possible to use the spray system to wash fission products as aerosols from the air volume of the containment into the sump water. However, in case of early releases noble gases make the effect negligible.

Table 2 : Accident proggression categories potentially leading to ERRPA in fast propagating core melt bins.

APC05	Isolation failure, 2 cm^2 leak from the containment, in-containment spray successful
APC06	Isolation failure, 2 cm^2 leak from the containment, in-containment spray fails
APC07	Isolation failure, 20 cm^2 leak from the containment, in-containment spray successful
APC08	Isolation failure, 20 cm^2 leak from the containment, in-containment spray fails
APC11	Isolation failure, 20 cm^2 leak from the containment, in-containment spray successful, long term pressure control of containment fails
APC12	Isolation failure, 20 cm^2 leak from the containment, in-containment spray fails, long term pressure control of containment fails
APC13	In-vessel retention fails
APC14	In-vessel steam explosion
APC15	Hydrogen explosion
APC16	Opening of the ice-condenser doors fails leading to hydrogen explosion and/or failure of in-vessel retention
APC17	Depressurization of primary circuit fails
APC18	Containment isolation fails (large openings)
XAPC	Uncategorized failure in X-sequences

The combinations of CMBs and APCs leading to ERRPA are following:

- In containment sequences APCs 14-18, additionally APCs 05-08, 11-12 in NLE and APCs 05-08, 11-13 in NLI

- In by-pass sequences all APCs
- In X-sequences all scenarios leading to XAPC except only half of the cases related to XND

3.3 Accident scenarios outside the scope of this study

During shutdown states leaks from the primary circuit and loss of residual heat removal systems propagate too slowly to result in ERRPA. At fastest large leak from the primary circuit to drain the reactor pit to the level of cold leg is estimated to lead to releases in about 6 hours since initiating event. Also the accidents leading to large release due to loss of spent fuel pool cooling are propagating slowly and the emergency personnel is assumed to have enough time for necessary actions to protect people living close to the power plant.

A special feature of VVER-440 type reactors is that during annual refueling shutdown several very heavy lifts like reactor vessel head and internals and biological shield weighing 180-260 metric tons have to be completed. Therefore a drop of heavy load is a significant factor considering large releases at Loviisa NPP. Based on structural analysis the containment survives the drops and the release will be result of e.g. failing of in-vessel retention at the later stage of the accident. Therefore drop of heavy load has not been considered in ERRPA.

For Loviisa NPP no such scenarios have been detected, in which large release would occur without core damage. However, in case of ERRPA the release of gas gap activity of several fuel bundles may be enough to exceed 10 mSv limit. Drop of the fuel pool lid into the fuel pool after refueling shutdown has been detected as a potential scenario for such a release. The scenario has not been included in the results, but its significance is discussed Chapter 4.2.

4 RESULTS

4.1 ERRPA due to core damage

Frequencies of core damage, large release and ERRPA for each unit at Loviisa are presented in Table 3. ERRPAF for each unit is $2.4 \cdot 10^{-7}$ /a. This is about 2 % of CDF and about 3 % of LRF. Despite the difference in CDF, the units are very similar in terms of accidents leading to ERRPA. The division of ERRPAF between initiating event groups is presented in Figure 2. 56 % of the early release risk originates from power operation and 44 % from shutdown states. Internal events dominate the risk.

Table 3: Frequencies of core damage, large release and early release requiring protective actions at Loviisa.

	Loviisa 1			Loviisa 2		
	Power	**Shutdown**	**Total**	**Power**	**Shutdown**	**Total**
CDF (/a)	$4.5 \cdot 10^{-6}$	$7.8 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$6.0 \cdot 10^{-6}$	$7.4 \cdot 10^{-6}$	$1.3 \cdot 10^{-5}$
LRF (/a)	$2.0 \cdot 10^{-6}$	$5.9 \cdot 10^{-6}$	$7.8 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$5.4 \cdot 10^{-6}$	$7.4 \cdot 10^{-6}$
ERRPAF (/a)	$1.4 \cdot 10^{-7}$	$1.1 \cdot 10^{-7}$	$2.4 \cdot 10^{-7}$	$1.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-7}$	$2.4 \cdot 10^{-7}$

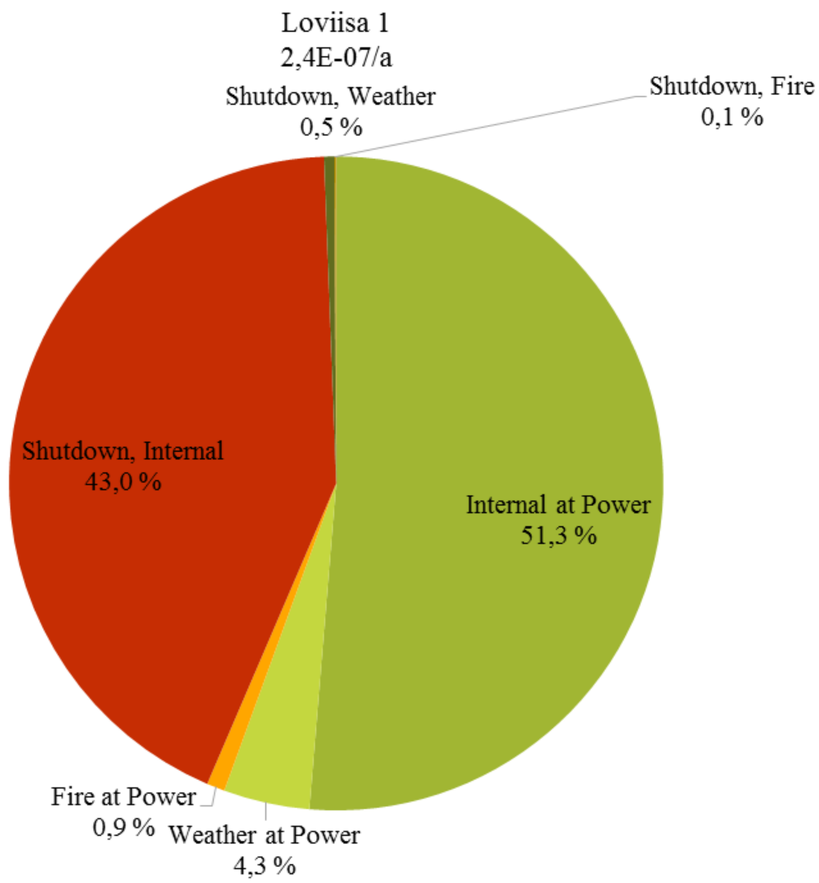

Figure 2: Division of ERRPAF between initiating event groups during power and shutdown states.

The most important CMBs leading to ERRPA are presented in Figure 3 and division between plant operating states (POS) in Figure 4. The plant operating states are as follows:

- B-E: hot shutdown states during cooling down
- F-G: cold shutdown states during the cooling down
- H-J: refuelling
- K-L: cold shutdown states during warming up
- M-Q: hot shutdown states during the warming and starting up
- P: power operation

The dominating CMBs leading to ERRPA are reactivity accidents (XRE) and large LOCA in RCP room (BLR). The shutdown risk originates almost completely from reactivity accidents, while half of the risk during power operation is due to LLOCA in RCP room. Other large contributors to ERRPAF during power operation are LLOCA and VLOCA.

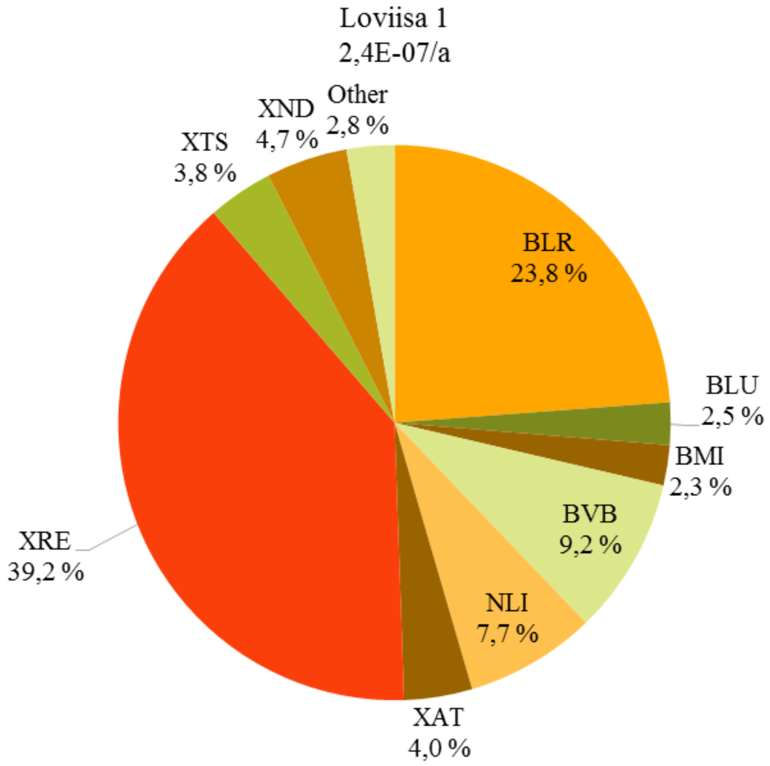

Figure 3: ERRPAF divided to core melt bins (see Table 1).

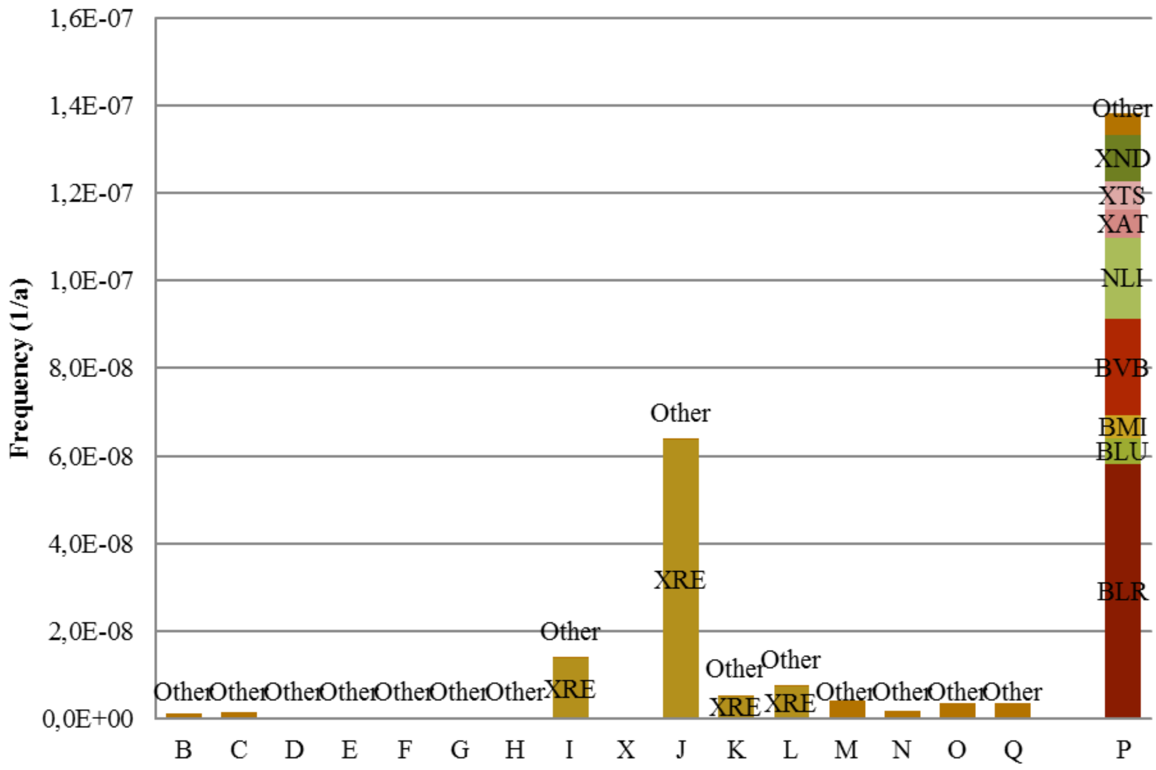

Figure 4:ERRPAF divided to core melt bins (see Table 1) in each plant operating state.

Division of ERRPAF to accident progression categories in each POS is presented in Figure 5. Most important core melt bins leading to

- XAPC is reactivity accidents (XRE)
- APC18 is LLOCA to RCP room (BLR)

- APC13 are LLOCA with injection failure (NLI), VLOCA (BVB) and LSGTR with injection failure (BMI). In case of VLOCA and LSGTR the in-vessel retention has not yet failed at 5 h since initiating event, but the release is due to existing leak from the containment and the accident scenario is assumed to always lead to failure of in-vessel retention in long term due to lack of water in the reactor cavity.

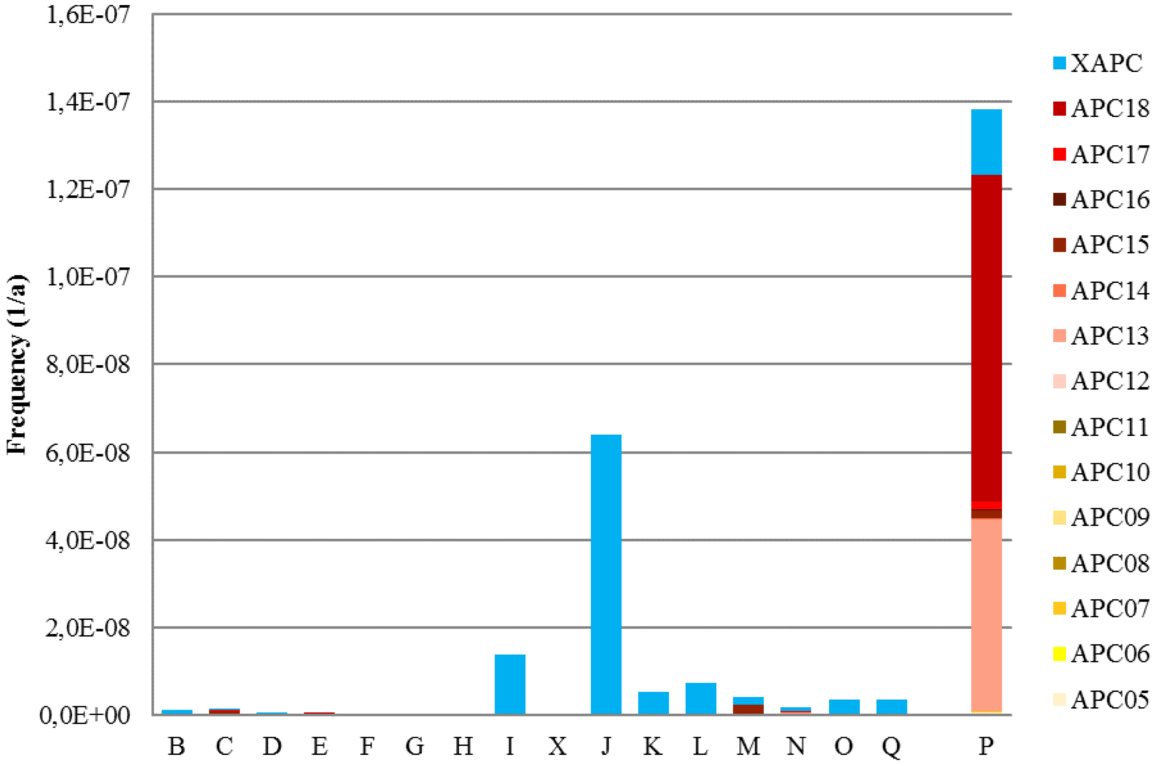

Figure 5: ERRPAF divided to accident progression categories (see Table 2) in each plant operating state.

4.2 Drop of spent fuel pool lid

Drop of a spent fuel pool lid may lead to mechanical breaking of several fuel bundles. In such a scenario, the gas gap activity of the fuel bundles will be released into the water of the spent fuel pool inside containment. The procedures in 2017 allowed removal of the lids without requirements for the containment.

When the lids are being removed, the gas gap activity of 1-2 year old fuel bundles is already low and risk of exceeding 10 mSv doses in short term in the environment is negligible. However after the refueling the fuel bundles have had only 1-2 weeks to cool down and large amount of radioactivity is still present in the gas gap. If the gas gap activity of a fuel bundle is released into the water, from the water on to the open containment and finally filters of the ventilation systems are not successfully turned on, short term maximum doses for the residents in the environment are estimated to be 1 mSv per completely broken fuel bundle.

The frequency of ERRPA due to drop of spent fuel pool lid is estimated at $2.6 \cdot 10^{-8}$ /a. This is about 10 % of the total ERRPAF presented in chapter 4.2. This risk can be reduced very significantly by relatively simple measures. The ventilation system can be used in filter mode for the time of the lifting of the lids, or the requirement for leak-tightness of the containment may be continued from refueling stage until the lids have been lifted back on the spent fuel pool.

5 DISCUSSION

In case of Loviisa large share of the cases leading to ERRPA would lead also to large early release. Accident scenarios leading to ERRPA, but not leading to large early release are:

- All VLOCA scenarios (core melt bin BVB), 9.2 % of the total risk of ERRPA
- LRLOCA and UCLOCA scenarios (BLR and BLU), 26.3 % of the total risk of ERRPA
- All accident scenarios leading to APCs 05-08, 0.3 % of the total risk of ERRPA
- LLOCA & injection failure leading to APC13 (92 % of NLI scenarios leading to ERRPA), 7.0 % of the total risk of ERRPA
- Drop of a spent fuel pool lid (not included in ERRPAF presented in this paper)

We can conclude, that for Loviisa LERF is about 57 % of ERRPAF.

To get more confidence in the results, the effect of chosen time delay or maximum acceptable doses (i.e. release fraction of the fission products) was analyzed. In Figure 6 frequency of exceeding the 10 mSv dose limit is presented as a function of time measured from the initiating event. It is evident, that until 6 hours the effect of time is small. In Loviisa VVER-440 reactors it takes over 8 hours for the core to be uncovered in case of SBO and if small LOCA is included, the time delay is still over 6 hours. Therefore only after 6 hours the risk begins to increase significantly. Another important finding is, that the frequency for a release leading to 10 mSv release and 10 times greater release have practically same frequency. Although the limit for LER is not exceeded in about 44 % of the cases, maximum doses in case of ERRPA would most likely be over 100 mSv.

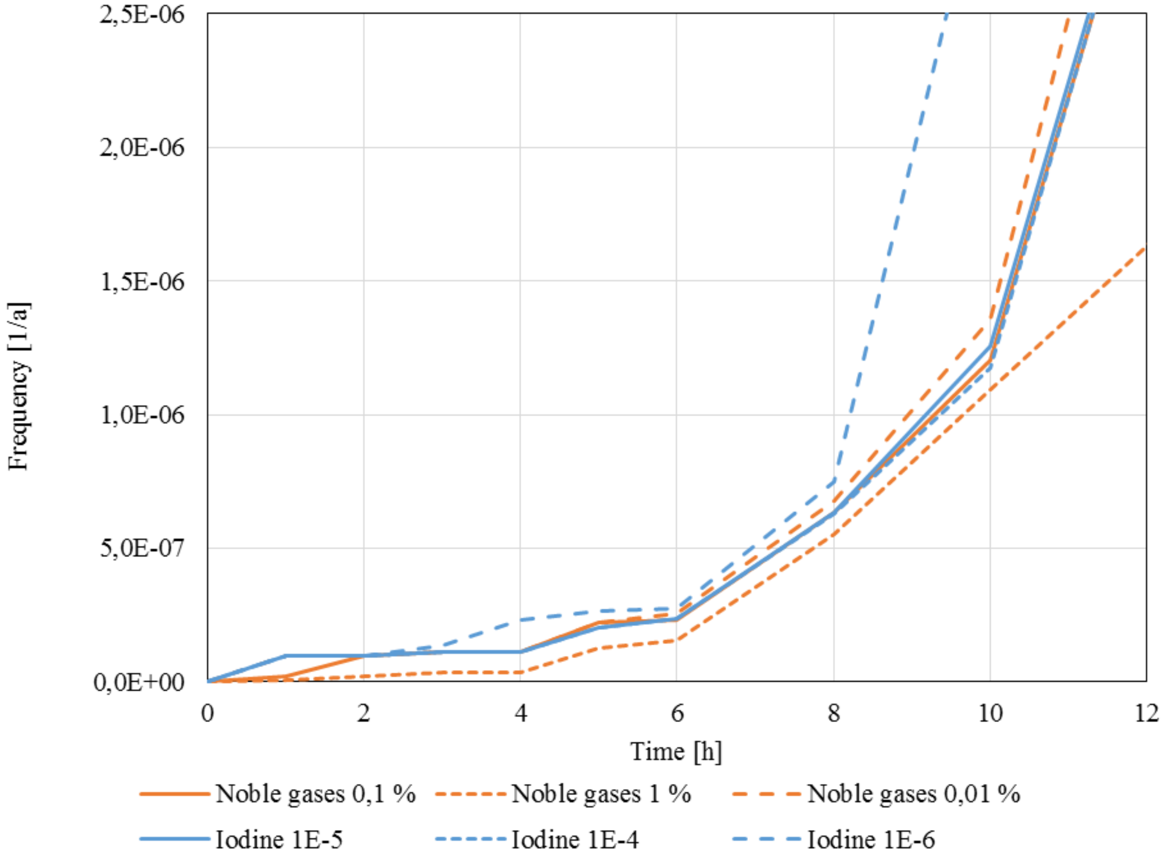

Figure 6: Frequency of exceeding dose limit of ERRPA as function of time (continuous line) and sensitivity curves (dashed lines).

VVER-440 type reactors are known to have large water volumes in primary and secondary circuit and low power density compared to many other reactor types. Therefore they respond slowly to many initiating events. The long response times are also highlighted by this study. The share of large releases leading to ERRPA is only about 3 % and to LER only 2 %, which are very low compared to other NPPs.

Comparison of LERF or ERRPAF to other power plants is challenging, as coverage of PRA models varies significantly and also time delay and definition of the release may vary between countries. For example in Switzerland time delay for a release to be considered as "early" is 10 hours since initiating event. Still at Leibstadt LERF is almost 80 % of LRF, while in Loviisa ERRPAF using 10 hours delay is $1.3 \cdot 10^{-6}$ /a, which is still less than 20 % of LRF. On the other hand it should be noted, that the absolute value for LRF at Leibstadt ($1.2 \cdot 10^{-6}$ /a) is lower than at Loviisa by a factor of 6. [11]

The contribution of reactivity accidents is 39 % of the ERRPA risk. During the plant life time several improvements have been made to reduce the risk of reactivity accidents. Also more detailed analysis of pumping of small amounts of unborated water into the reactor has reduced the risk significantly. By comparison in 2007 the calculated risk of a reactivity accident at Loviisa was 40 times higher. The remaining scenarios are such, that it has proven to be difficult to find improvements to reduce the risk further.

Along with improvements on reactivity accidents, also several other improvements have been made to reduce the risk of ERRPA, although ERRPA has not been calculated earlier. For example the risk of pressurized thermal shock accidents used to be about 80 times larger in 2007. Before this work many of the accident scenarios highlighted in ERRPA were considered such rare events, that conservative assumptions on these scenarios were justified. Significant further reductions of calculated risk may be possible by analyzing some of the accident scenarios in more detail. E.g. very preliminary results of analysis of LRLOCA and UCLOCA events suggest, that by using best-estimate approach the consequence estimates of the accident could be significantly reduced.

6 CONCLUSIONS

The risk of early release requiring protective actions at Loviisa NPP is very low considering its frequency ($2.4 \cdot 10^{-7}$ /a) or ratio to CDF (2 %) and LRF (3 %). Especially the low ERRPAF/LRF ratio suggests, that more gains on safety for the same amount of money could be available by reducing LRF in general.

The largest contributors to the risk are reactivity accidents and large LOCA in the reactor coolant pump room. There may be overly conservative assumptions in these accidents and more detailed analysis could reduce the calculated risk significantly.

Calculation of ERRPAF and analysis of accident scenarios leading to early releases gives important insights into plant behavior during accidents. Although most of the data was available and analyses were made already before this work as part of PRA model, now it is possible to treat the accident scenarios leading to the most severe consequences separate from less severe scenarios.

The calculation of ERRPAF was implemented into current PRA models in such a way, that the results are automatically updated every time a new model version is created. Therefore it is possible to follow the development of ERRPAF in the future and take actions if necessary.

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