Fire Risks of Loviisa NPP During Shutdown States

Sami Sirén[a*], Ilkka Paavola[a], Kalle Jänkälä[a]
[a] Fortum Power And Heat Oy, Espoo, Finland

Abstract:

Fire PRA for all 15 shutdown states of Loviisa NPP has been performed. The fire PRA for power operation and the internal event PRA for shutdown have been used as a basis for the analysis, reducing the time needed for investigating cable routing and potential of fire-induced initiating events. The hot states are mostly modeled using applicable power operation fire scenarios. For the cold states, 342 fire scenarios have been created and integrated with the PRA model. Fire frequencies have been estimated with an empirical Bayesian method using both plant data and international data. The importance of moving from conservative modeling towards best estimate is underlined in the shutdown fire PRA. The real availability of systems instead of the minimum requirements in Technical Specifications has been taken into account to decrease the conservatism related to maintenance activities. Fires inside the control building during cold states dominate the risk. (The shutdown fire risk is relatively small,) but it would be hundredfold without the backup RHR system.

Keywords: Fire PRA, Shutdown PRA.

---

1. INTRODUCTION

Loviisa nuclear power plant in southern Finland consists of two almost identical VVER units, commissioned in 1977 and 1980. Unit 1 (PRA was started in 1985 and the) internal event PRA for power operation was completed in 1989. Since then the PRA has been continuously updated and expanded to cover new initiating event groups, such as severe weather and flooding events. The fire PRA for power operation was first completed in 1997. It was and still is a major contributor to the overall core damage risk. As the PRA was developed, fires during shutdown became the last missing part of the level 1 PRA that already included internal events, floods, severe weather and seismic events for both power operation and shutdown and fire events for power operation.

Even though both shutdown risks and power operation fire risks contribute very significantly to the overall plant risk, fires during shutdown had been estimated to be much less important. However, to achieve completeness of the level 1 PRA and thus improve the accuracy of PRA applications such as the risk informed inspection of Technical Specifications, it was decided to develop a fire PRA for shutdown states. The focus was on getting a best estimate quantification result while making use of the already finished parts of Loviisa PRA as much as possible to reduce the amount of work needed and to keep the risk model simple and manageable. The starting point for the shutdown fire PRA is described in Chapter 2. Chapters 3 and 4 include the description of the shutdown fire PRA development and the results. Conclusions can be found in Chapter 5.

2. LOVIISA PRA MODEL

The basis for the shutdown fire PRA model is in the internal event PRA for shutdown and in the fire PRA for power operation. Both are very significant contributors to the annual core damage frequency of Loviisa NPP.

---

[*] sami.siren@fortum.com

2.1 Internal Events Shutdown PRA

The shutdown PRA model of Loviisa NPP consists of 15 plant operating states (POSs), as shown in Table 1. Each POS represents a distinct phase in an average refueling shutdown. Initiating events, success criteria, reliability data etc. are separate for each POS. Currently, internal initiating events during shutdown contribute 29 % of the annual core damage frequency (CDF). The shutdown fire PRA was not considered very significant because most of the core damage frequency in shutdown states is caused by events that are unlikely to be caused by fires, e.g. drops of heavy loads.

Table 1: Plant Operating States in Loviisa Shutdown PRA

POS	Description	Avg. duration (h)
B	Low power and sub-criticality	2.1
C	Hot standby	8.6
D	Hot shutdown	7.7
E	Hot shutdown, residual heat removal system is water solid	14.3
F	Cold shutdown	8.8
G	Cold shutdown, primary circuit open	38.4
H	Refueling shutdown, procedures before refueling	39.9
I	Refueling shutdown	106.5
J	Refueling shutdown, procedures after refueling	74.1
K	Cold shutdown, assembly of the reactor	65.9
L	Cold shutdown, pressurization of the primary circuit	76.0
M	Hot shutdown	61.7
N	Hot standby	40.2
O	Startup	13.4
Q	Power operation, power increase and turbine startup	6.9

2.2 Power Operation Fire PRA

Fire PRA for Loviisa NPP unit 1 power operation was developed in the late 1980s and 1990s. Fire PRA analysis methods used for other NPPs at the time were varied, but little detailed information on the methodology was available. Furthermore, many methods concentrated on systems thought to be the most critical to safety and did not consider cabling systematically. Therefore, a method was developed for Loviisa fire PRA.

The analysis contained identification of the fire-induced initiating events (IEs), estimation of different fire frequencies and estimation of conditional core damage (CD) probabilities for the fire events. IE fault trees were used to identify possible fire-induced IEs in rooms or groups of adjacent rooms. [1]

In the first phase of the analysis, all cabling and equipment inside the ignition room was assumed to fail due to the fire. Internal event PRA models were used to calculate the conditional core damage frequency. The possibility of the fire spreading to adjacent rooms through doors and openings was estimated based on the fire load and its location. Automatic extinguishing systems were taken into account in the fire spreading scenarios, but not when considering the fire damage in the ignition room.

In the second phase, the most significant fire scenarios were examined more closely to remove conservatism. The total fire frequency of a room was allocated to separate ignition sources and more detailed fire scenarios were created to consider their respective damage potential based on the location of fire loads and critical equipment. Extinguishing systems were taken into account also in the ignition room in case of equipment located outside the flame area. Various fire simulation codes were used when needed. Less important fire scenarios were left as is.

As a result of the fire PRA, weaknesses were identified and several plant modifications were made to address them. Fire protection covers were installed for critical cabling, sprinkler system was extended and high pressure hydraulic oil pipelines were covered to prevent jet fires. A new backup residual heat removal (RHR) system, shared by both units, was installed to mitigate the impact of large turbine hall oil fires.

After its completion the power operation fire PRA has been continuously updated due to plant and risk model modifications. It currently consists of 241 ignition rooms and 718 analysis cases, some of which include more than one fire scenario, and contributes 29 % of the annual core damage frequency.

3. SHUTDOWN FIRE PRA DEVELOPMENT

The objective in the shutdown fire PRA development was to combine the methodology and fire data from the power operation fire PRA and the plant response models and reliability data from the existing shutdown PRA. By fully integrating the shutdown fire model into the existing living PRA model makes it easier to keep it up to date.

3.1 Identification of Initiating Events

The fire PRA is based on the initiating events identified in the internal event PRA. The principles of the method include:

- Multiple simultaneous initiating events of the internal event PRA were considered possible due to fire
- Outside the control building the IEs are modeled with fault trees taking into account possible equipment and cable failures due to fire
- Inside the control building the analysis is more coarse and based on conservative assumptions about cable routes and potential fire damage

The principles used in the fire PRA for power operation were applied also in the shutdown fire PRA. In addition, the initiating events included in the shutdown fire PRA were screened using several criteria, such as:

- Only IEs applicable for the POS in question are considered
- If an IE cannot be caused by fire alone, it is excluded
- If fire as the cause of the initiating event does not have any effect on the consequences and the IE is more likely to happen due to other reasons, it is excluded

Most of the IEs are the same as during power operation, but some are only relevant in shutdown states (e.g. loss of residual heat removal system) or triggered differently than during power operation (e.g. loss of off-site power during the maintenance of main transformers). The identified initiating events for shutdown fire PRA in each POS are shown in Table 2.

In the hot POSs B-D, M-O and Q, the remaining initiating events after the screening are all included in the fire PRA for power operation. Also, the plant response is similar to power operation and the fire risk was expected to be small due to the short time spent in these POSs. Therefore, the fire scenarios for these POSs were adopted from power operation fire PRA, only making minor POS-specific adjustments.

Table 2: Applicable Initiating Events in Each Plant Operating State

Initating event		**Relevancy by plant operating state**														
Acronym	**Description**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**Q**
LDCP	Loss of DC Power	x	x	x	x	x	x	x	x	x	x					x
LIRV	Loss of Instrumentation Room Ventilation	x	x	x	x	x	x	x	x	x	x					x
LMFW	Loss of Main Feed Water	x	x													x
LOOP	Loss Of Offsite Power	x	x	x	x	x	x	x	x	x	x					x
MLOCA	Medium Loss Of Coolant Accident	x	x	x	x								x	x	x	x
PLOCA	Pressurizer Loss Of Coolant Accident	x	x											x	x	x
PLRR	Partial Loss of RR (residual heat removal)				x	x	x	x		x	x					
PLSW	Partial Loss of Service Water				x	x	x	x	x	x	x					
RT	Reactor Trip	x														x
TLFW	Total Loss of Feed Water	x	x	x												x
TLRR	Total Loss of RR (residual heat removal)				x	x	x	x		x	x					
TLSW	Total Loss of Service Water	x	x	x	x	x	x	x	x	x	x					x
XSLOCA	Very Small Loss Of Coolant Accident	x	x	x	x											x

For the cold POSs F-L, new fire scenarios were developed. Criteria for triggering the applicable IEs were, where needed, redefined to match the plant configuration, e.g. Loss Of Offsite Power was redefined because during the shutdown states, the offsite power is supplied from the 110 kV grid instead of the 400 kV grid. Equipment and cable failure combinations leading to the IEs were then identified.

The hot shutdown state E has some properties of both the hot and cold POSs. Loss of coolant accident is still considered possible due to loss of primary coolant pump sealing water, but loss of RHR system can also be a problem. Therefore, it was modeled using the hot POS procedure, but adding the fire scenarios related to IEs PLRR, PLSW and TLRR from the cold POS analysis.

3.2 Cable Routing and Plant Walk Downs

After identifying the systems and cabling related to triggering each IE, the IEs were linked to individual rooms and areas by carrying out plant walk downs. Individual cable routes were investigated on a room-level accuracy and all the rooms containing those systems or cables were assessed for relevant characteristics, such as fire loads, fire propagation and suppression possibilities. The same was done with safety systems needed to prevent core damage after the IE. Normally this would be very time consuming, but for the shutdown fire PRA, most of the needed data was already available as part of the extensive work carried out earlier for power operation fire PRA. For the cold POSs, only five new ignition rooms were identified that were not part of the power operation fire PRA.

3.3 Fire Frequency Estimation

Shutdown fire events from the plant and international fire databases [2,3] were used for the fire frequency estimation. The fire events were first distributed among 'hot POSs before refueling', 'cold POSs' and 'hot POSs after refueling' and then among 17 room types, e.g. 'process rooms' or 'cable spreading rooms'. A screening was then done using the criteria in the fire PRA for power operation with two exceptions:

- Only fires during a refueling shutdown were included
- Fires related to maintenance activities were excluded, except in areas where the fire could affect systems in the other redundancy, e.g. in the turbine hall

Fire frequencies were estimated using an empirical Bayesian method [4]. No fire events were allocated for 'hot POSs before refueling' so fire frequencies for power operation were used instead. For fires during 'hot POSs after refueling', there were six fire events and the overall fire frequency was about 3.5 times that of power operation. However, to get a more realistic distribution among different types of rooms, power operation frequencies for each room type multiplied by 3.5 were used instead. For the 'cold POSs', there was sufficient data and the fire frequencies for each room type were estimated normally. The overall fire frequencies used in the analysis are presented in Table 3.

Table 3: Overall Fire Frequencies in Each Plant Operating State

POSs	Description	Fire Events	Overall Fire Freq. (1/h)
P	Power operation	344	7.1E-06
B…E	Hot POSs before refueling	0	7.1E-06
F…L	Cold POSs	66	2.1E-05
M…O, Q	Hot POSs after refueling	6	2.5E-05

The fire frequencies for room types were then distributed among individual rooms using various weighting methods, including the Berry model [5]. Even though the activities in certain plant areas may vary significantly during the plant shutdown, in absence of good data the fire frequencies were distributed among individual rooms using the same parameters as in power operation fire PRA.

3.4 Plant Response Model

Most of the important fire compartments in shutdown fire PRA were also important in power operation fire PRA. Because of this, detailed analyses of fire impact on plant equipment were available for easy implementation in the shutdown fire PRA, even though the plant response and some parameters might differ from the power operation. No new fire simulations were made. However, after the initial assessment, some further refinements were done to remove conservatism related to shutdown PRA.

In Loviisa NPP, most safety related systems are divided into two redundancies, both with two 100 % capacity safety trains. The Technical Specifications state that one redundancy can be taken out of service for maintenance activities in the cold plant operation states. However, usually the maintenance activities are restricted to one safety train at a time and systems, the maintenance of which is not on the critical path, can even be fully operable at any given time. In the internal event PRA this is not very significant, since the difference in risk is small between two and three or four available safety trains. However, the power and instrumentation cabling of both safety trains of one redundancy often follow the same routes, and are therefore vulnerable to fires. In these cases the number of available safety trains after the fire can vary from zero (both safety trains under maintenance) to two (no safety trains under maintenance). Therefore, to remove excessive conservatism, maintenance unavailability was modeled according to plant maintenance schedules.

Further assumptions made to reduce work load and/or conservatism include:

- Manual operation of motor operated valves was assumed successful in case of cable failures
- Recovery of one 400 kV transformer was assumed possible in case of 110 kV grid failure
- Main feed water and emergency feed water systems were assumed inoperable due to lack of knowledge of cable routes and small risk impact
- Operation of residual heat removal systems from the switchgear rooms was assumed possible in case of automation failures

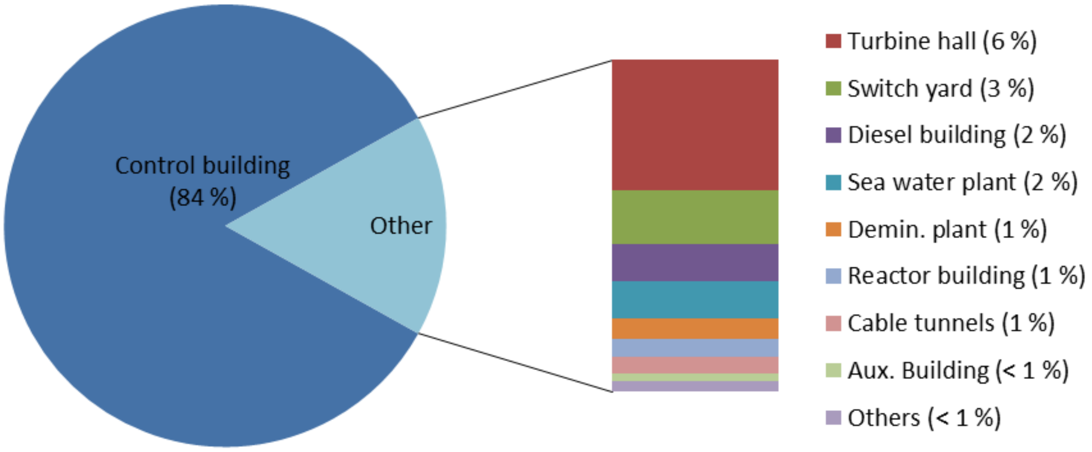
Although the hot POSs were modeled using power operation fire PRA analysis cases, 342 new analysis cases, each including 1 to 5 fire scenarios, were created for the shutdown fire PRA. Most of them are applicable to all cold POSs, and some also for the POS E.

4. RESULTS

The CDF due to shutdown fire is 4.2E-07/yr. which is about 3 % of the total shutdown CDF and under 2 % of the total CDF. The result is roughly as expected and similar results have been reported by other VVERs [6].

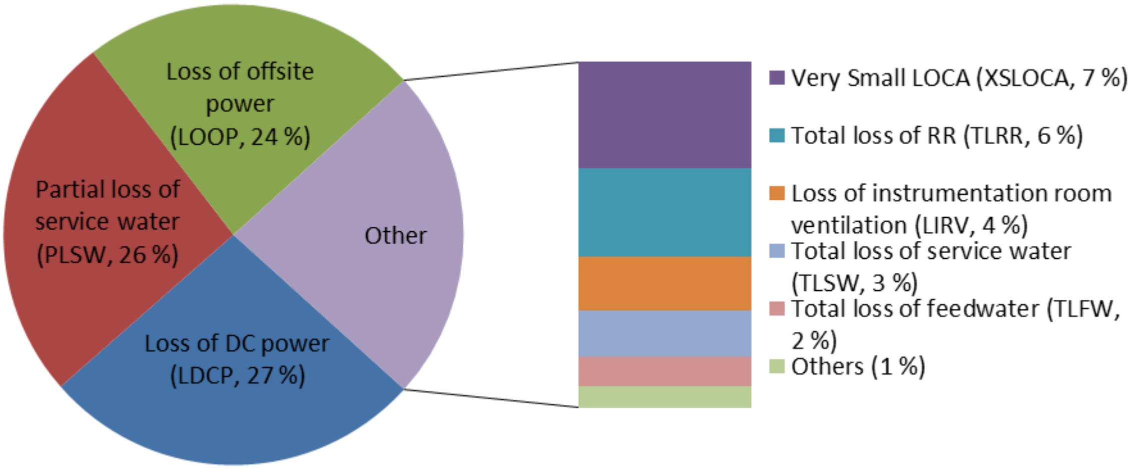
As shown in Fig. 1, fires inside the control building dominate the risk. Switchgear rooms and cable spreading rooms below them are the biggest contributors. I&C system cabinets and related cable spreading rooms are also significant. Fires inside the reactor building only amount to 1 % of the total shutdown fire risk.

Figure 1: CDF Contributions of Plant Areas



Contributions of individual IEs to the shutdown fire CDF is shown in Fig. 2. Most of the risk is related to IEs that cause loss of AC or DC power. In addition to LDCP and LOOP, many of the fire scenarios modeled as partial loss of service water are in fact caused by loss of AC supply to one or two trains.

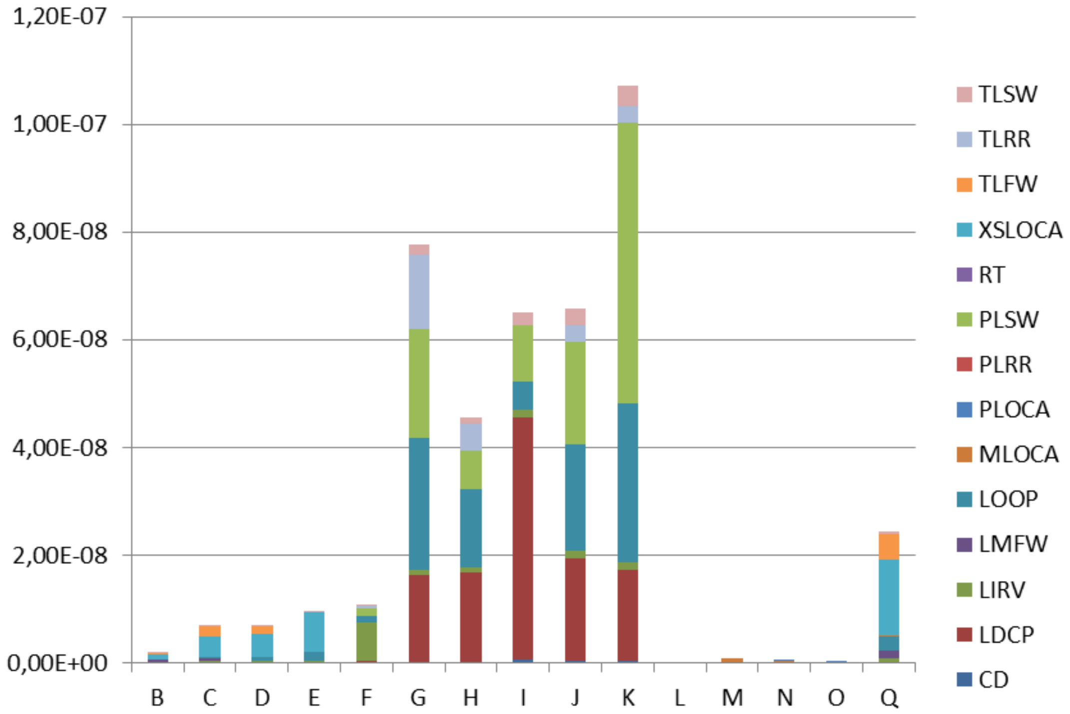
Figure 2: CDF Contributions of Initiating Events



The distribution of CDF by POSs is shown in Fig. 3. The majority of the CDF is concentrated in the cold POSs, when a lot of systems are unavailable due to maintenance. This is where the importance of moving from conservative modeling towards best estimate is underlined. A considerable decrease in CDF has been achieved by taking into account that systems can be - and more likely than not are - available also when not required by the Technical Specifications. Although already normal plant practice, this verifies the importance of taking PRA information into account when planning the maintenance schedules.

Systems that are shared by both units and powered by either one also proved to be very important. This is due to many fire scenarios involving loss of power from one or both redundancies in one unit. E.g. the backup RHR system, originally built to mitigate the turbine building fire risk, is essential when coping with various loss of power events and the shutdown fire CDF would be about a hundred times higher without it. Operator performance in using the available and non-damaged systems is also important.

Figure 3: CDF Contributions of Plant Operating States



As the shutdown fire risk is relatively small compared to other shutdown risks, no new plant modification needs were identified.

The biggest uncertainties related to shutdown fire risk are related to the extent of fire and smoke damage, operation of the backup RHR system and the possibility of restoring systems under maintenance. Some uncertainty is also related to the quantification of the fire scenarios, as some scenarios are screened out by the cut-off limit.

During a forced repair shutdown, the relative contribution of fire risks is much higher. This is because many of the risks of a refueling and maintenance shutdown are absent. This can have a major effect on the allowed outage time optimization, when comparing the risk impact of continued power operation and a shutdown to repair failed safety equipment.

5. CONCLUSIONS

The shutdown fire risk is relatively small compared to other shutdown risks. However, the value of some modifications already implemented against fire risks and many good plant practices has been found to be even higher than expected.

With the completion of the shutdown fire PRA, the level 1 PRA model for Loviisa 1 is now comprehensive, including internal, weather and man-made external, seismic, flooding and fire events. This allows for greater confidence when using the PRA results for various applications, such as risk informed inspection of Technical Specifications and analyses of plant modifications.

References

[1] M. Lehto et al. “*Fire risk analysis for Loviisa 1 during power operation*”, Proc. PSA’96, Park City, Utah, Sept. 29–Oct. 3, 1996.

[2] DUKE Power Company. “*Fire Data for Loviisa 1 Fire-PSA*”, (1995).

[3] “*OECD FIRE Database*”, Fire Incident Record Exchange project operated under OECD/NEA, (2008).

[4] J. K. Vaurio and K. E. Jänkälä. “*Evaluation and comparison of estimation methods for failure rates and probabilities*”, Reliability Engineering and System Safety, 91, pp. 209–221, (2006)

[5] D. L. Berry and E. E. Minor. “*Nuclear Power Plant Fire Protection - Fire Hazard Analysis (Subsystems Study Task 4)* (*NUREG/CR-0654)*”, U.S. NRC, 1979, Washington DC.

[6] V. Vladimirova et al. “*Fire Risk Analysis of NPP "Kozloduy" Units 3&4*”, Proc. PSA2008, Knoxville, Tennessee, Sept. 7-11, 2008.