Experiences from Developing and Implementing Shutdown Fire PRA at Forsmark NPP

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Abstract: The cold shutdown mode has earlier been considered as a safe mode without a significant risk for a major accident. However during the last few decades knowledge has improved regarding risks during shutdown mode. Many activities are on-going during this period and the risk of fire occurrence may be affected. Due to an increased number of plant activities the integrity of the fire compartments may not be intact and this could lead to more extensive fire spreading. At the same time important barriers may be unavailable due to maintenance and a fire event could become critical. Time available for recoveries before fuel is exposed in the reactor pressure vessel after an initiating event i.e. fire event, which results in loss of residual heat removal, is in many cases significantly longer than 24 hours.

Area event analyses for shutdown mode generally tend to produce quite conservative results, which is why efforts have been made to increase realism in the analyses by using of improved methods. In order to increase realism dependencies between plant risk and maintenance activities, i.e. different combinations of safety system alignments, during the shutdown period have been studied in detail. This has had an impact on the estimation of both fire ignition frequencies and probabilities for fire spreading between different compartments.

This paper will discuss the methodology applied to the fire PRA at Forsmark NPP during the cold shutdown period, with focus on fire frequency analysis and fire scenario analysis. The implementation of fire analysis in the PRA and lessons learned from this will also be addressed.

Keywords: PRA, PSA, shutdown mode, Fire PRA, Fire PSA

1. INTRODUCTION

This paper will discuss the methodology applied to the fire Probabilistic Risk Assessment (PRA) at Forsmark NPP during the cold shutdown period, with focus on fire frequency analysis and fire scenario analysis. The paper will also address the implementation of the fire analysis in the PRA and lessons learned from this.

The cold shutdown period has earlier been considered as a safe mode without a significant risk for a major accident. However during the last few decades knowledge has improved regarding risks during shutdown mode. Many plant activities are ongoing during this period and the risk of fire occurrence may be affected. Due to the increased number of plant activities the integrity of fire compartments may not be intact and this could lead to a more extensive fire spreading. At the same time important barriers may be unavailable due to maintenance and a fire event could become critical.

Fire event analyses for the shutdown period generally tend to produce quite conservative results, which is why efforts have been made to increase realism in the analyses by using improved methods. In order to increase realism in the analyses dependencies between plant risk and maintenance activities, i.e. different combinations of safety system alignments, during the shutdown period has been studied in detail. This has had an impact on both fire ignition frequencies and probabilities for fire spreading between different compartments.

The conditions during the shutdown period at Forsmark NPP must be known in order to enable the analysis. In order to perform the analysis it is relevant to know for example conditions during the different phases of the cold shutdown and also what initiating event that should be analysed.

1.1 Initiating Event

The definition of an initiating event, at Forsmark NPP, is a disturbance in the nuclear power plant that requires one or more automatic or human initiated actions to bring the nuclear plant to a "safe" and "stable" mode. Loss of manual or automatic action can cause risk of a continuing process that may lead to release of radioactive materials to the environment.

During the cold shut down mode the initiating event is defined as an event that causes loss of residual heat removal. The different ways in which residual heat removal is maintained during the different phases is described in the section below.

1.2 The phases of during cold shut down mode

At Forsmark NPP the analysis has been divided into six phases. The systems operating for residual heat removal differs depending on phase and this affects how a fire event should be analysed. In phase 1-3 the residual heat removal in the reactor pressure vessel, RPV, is performed by residual heat removal system (321).

These are the different phases during the cold shutdown mode:

- In phase 1 the reactor lid is mounted but the filling of the RPV has not started.
- In phase 2 the reactor lid is still mounted and the process for filling the RPV has started. At the end of this phase the reactor lid has been dismounted.
- In phase 3 the reactor lid is dismounted and the filling process of the pool above the RPV has begun.
- In phase 4 the pools in the reactor service room are filled with water. In this phase it is assumed that the majority of all maintenance is ongoing. During this phase the residual heat removal is performed by the residual heat removal system (321) and the fuel pit cooling and cleaning system (324), combined.
- Phase 5 see phase 2, the only difference is that the draining process of the RPV has begun.
- Phase 6 see phase 1.

The safety systems are divided into four independent trains A-D. During cold shut down mode it is assumed that two trains is unavailable for maintenance. In Forsmark 1 and 2 it is only possible for the combination of A and C or B and D to be unavailable at the same time. In Forsmark 3 all combinations of two trains can be unavailable at the same time.

Table 1 Phase classification during cold shutdown

	Reactor lid	Water Level in RPV / Reactor pool	Operational system for residual heat removal system
Phase 1	Mounted	Normal	The residual heat removal system (321) is cooling RPV
Phase 2	Mounted	Top filling/water level above steamlines.	The residual heat removal system (321) is cooling RPV
Phase 3	Dismounted	Reactor pool is empty	The residual heat removal system (321) is cooling RPV
Phase 4	Dismounted	Reactor hall pools are met	The residual heat removal system (321) and the fuel pit cooling and cleaning system (324) is cooling RPV and reactor halls pool together.
Phase 5	Dismounted	Reactor pool is empty	The residual heat removal system (321) is cooling RPV
Phase 6	Mounted	Normal	The residual heat removal system (321) is cooling RPV

The environment in the containment is assumed not to be inert during the whole shut down period and fires inside the containment can therefore occur.

3. METHOD

This chapter aims to give a short introduction and background to the method chosen for the analysis at Forsmark NPP. The standard method for the cold shutdown period at Forsmark is retrieved from reference [1]. The method used in this analysis is partly based on reference [2]. But due to limited resources the method could not be used completely.

3.1 Identify critical equipment

Critical components are those components that directly or indirectly are included in the safety related systems and also are included in the PRA model. When the critical components have been identified the failure mode in case of fire needs to be determined. Only active equipment which need power supply is assumed to be affected by the fire. Passive objects such as a heat exchanger can be assumed to be unaffected by a fire.

3.2 Mapping of the electrical system

Mapping of the electrical system is a very important step in the fire analysis. The electrical systems are built with circuits that form networks and branches with cables, loads, cabinets and breaking points. The electrical networks are widespread throughout the building and therefore sensitive to area events such as fire.

The power supply to various consumers is hierarchical. From an overhead power input the electrical system branches out to supply voltage to different loads over switches, fuses and cables.The cable routes can be identified when the electrical system for all objects included in the PRA model is completely mapped. Cable routs can be described by listing all the rooms which cables go through. Cable paths should be mapped for each fuse and breaker and room dependencies are set. It is important that all of the cables, as fire can causes blown fuses, can be identified. In general cables are placed in open cable trays, but cables can also be placed in fireproof boxes. However this is not taken into account in the fire analysis. The objects need different kind of power supply like for example control voltage and power supply. All these voltages should be mapped. Hot shorts are not required to be mapped in this analysis and this could be non-conservative.

3.4 Identify fire events

Fire can be assumed to occur in all rooms in the power plant. Rooms containing objects included in the PRA model are analysed. Fire spreading from other rooms into these rooms must be taken into account.

3.3 Screening

A screening of fires in fire compartments or fire cells which implies an initiating event, the screening criterion, i.e. fires that causes loss of residual heat removal, should be done. A fire should be assumed to destroy all the electrical system in the fire compartment or fire cell. This approach can be sensitive to errors in electrical mapping which is fundamental to the screening process. This approach does not consider if a fire event causes a degraded barrier, only events that lead to an initiating event will be taken into account.

3.4 Data analysis

Frequency for fire occurrence should be calculated for each room included in the fire compartments or fire cells that have been screened out. The frequency depends on the type of room and is calculated from fire statistics from the Swedish and Finnish NPPs countries. The statistics are based on fires during shut down periods. In the statistics there is information about whether the fire occurred due to on-going work in the room. The risk for fire during on-going work could be much higher, in order of twice the risk.
For example assume that power supply train A is unavailable because of maintenance. This means that the all rooms that contain at least some equipment for train A the room gets a higher fire frequency, this is relevant in the PSA-model because the room could also contain equipment from train B. In rooms that only contain equipment from train B, which is not shut down for maintenance, it is assumed that no work is in progress and the lower frequency should be applied.

If the fire compartment or fire cell contains equipment from the train which is unavailable for maintenance the frequency for on-going work should be applied. So depending on what train combination that are unavailable for maintenance the frequency varies. The frequency should be allocated to the different phases in proportion to its length.

3.4.1 Fire extinguishing

Manual and automatic extinguishing is not modeled explicitly in the PRA model. However successful firefighting efforts could be considered when calculating fire occurrence frequencies.

3.4.2 Fire spreading

It is possible for the fire to spread inside the fire compartment or fire cell. A probability for the fire to spread to the next room can be applied.

3.4.3 Impact of manual operation

Fire could have an impact on manual operations, Post-incident actions (Category C), it could for example affect the place where local maneuvers are performed or the information at the main control room could be affected. Therefore the probability for failure of manual operations should be re-estimated during an on-going fire.

3.5 Detailed analysis

If needed a more detailed analysis can be done, focusing on analyzing the compartments that give high core damage frequency.

4. ANALYSIS

In this chapter the fire analysis performed at Forsmark NNP is described. An extensive work of mapping of the electrical system, according to the described method, has been performed and applied in the full power PRA model. Figure 1, below, illustrates the entire analysis process. This chapter will explain and describe the different parts of the process.

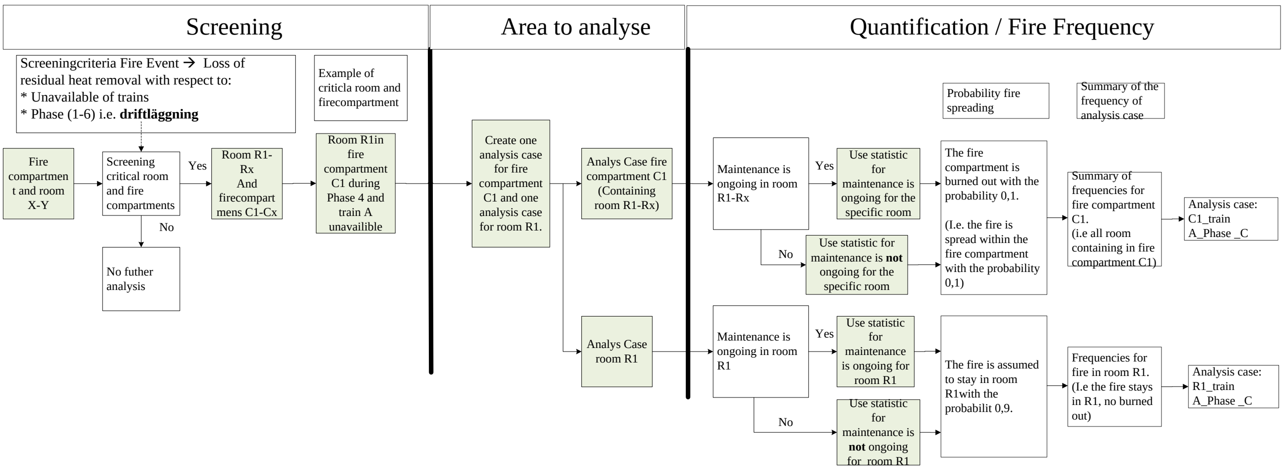

Figure 1: Fire analysis process

4.1 Screening process

A screening was done for fire in fire compartment and fire in room that leads to initiating event, i.e. loss off residual heat removal, see figure 2. To be considered a critical compartment a fire need to cause loss of residual heat removal if the whole compartment is burnt out and to be a critical room fire needs to cause loss of residual heat removal if the whole room is burnt out. One critical compartment could consist of several critical rooms.

Since there are different conditions, depending on phase during the cold shutdown and what train combination is unavailable, the screening was done for each train combination unavailable during every phase. When a list of fire compartments and rooms needed to be analysed further was done the analysis cases was created and described in the next section.

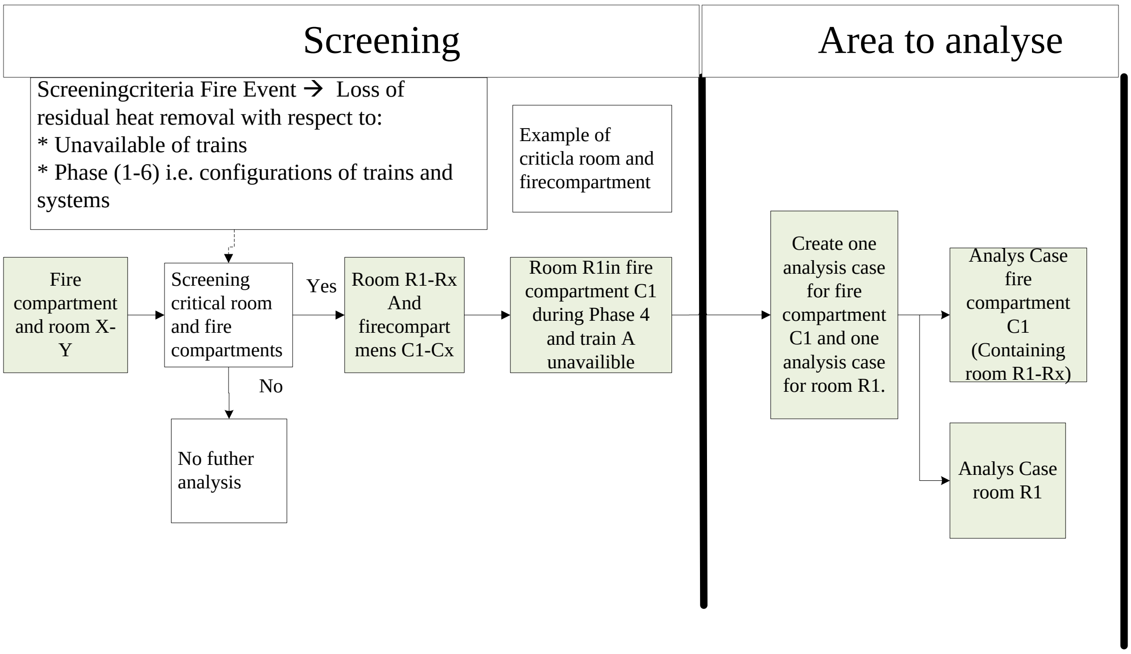

Figure 2: Screening process

4.1 Analysis cases and frequency for fire occurrence

For each critical room or compartment analysis cases was created for the critical conditions i.e. phase and unavailable train combinations.

The frequency for fire occurrence in each room or fire compartment is calculated depending on several parameters described in the method. The process is described in figure 3.

- Type of room
- On-going work/no work on-going
- Length of the phase

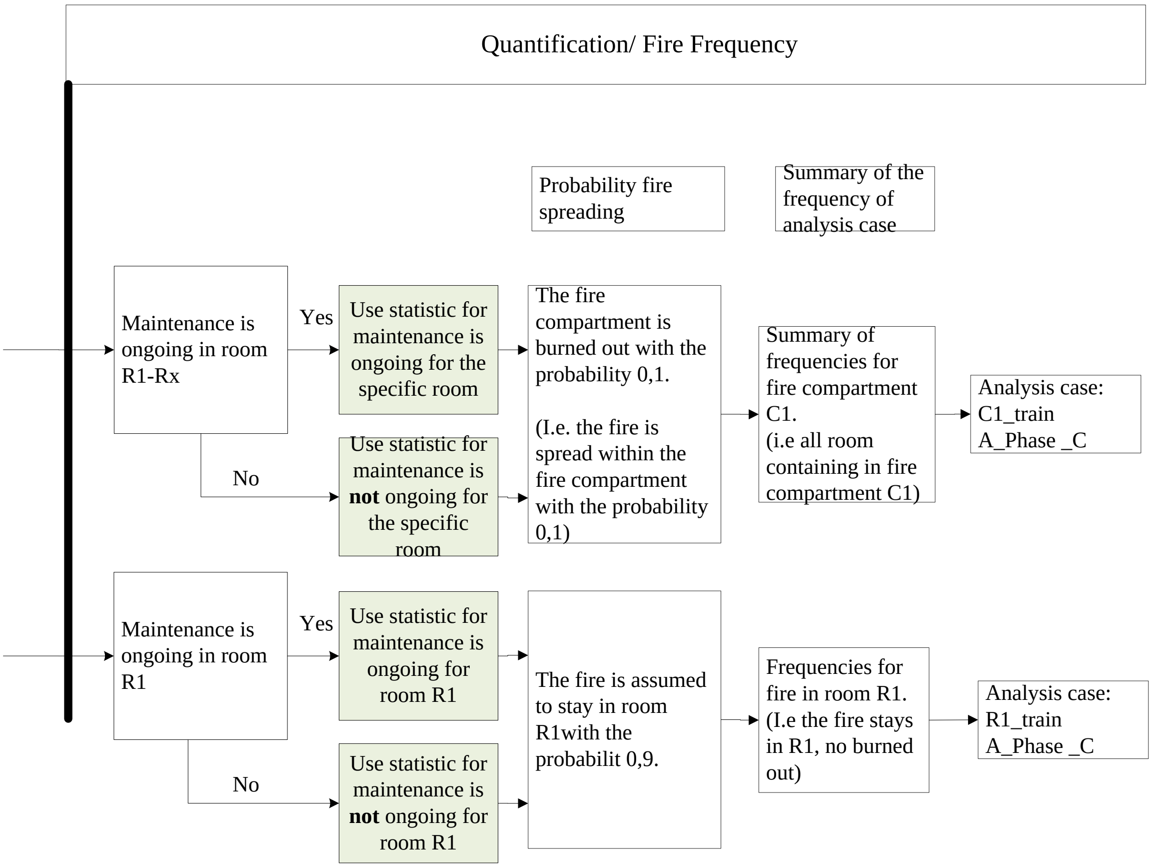

Figure 3: Quantification / Fire Frequency

4.1.1 Fire spreading

Fire in fire compartment was assumed to burn out the whole compartment with a probability of 0.1 and with a probability of 0.9 the fire was assumed to only burn out the room.

4.2 Walk downs

Walk downs have been performed with purpose to find deficiencies in the mapping of fire compartments. The main reason for the deficiencies in the mapping of compartment is that the layout in some cases does not correspond to reality.

5. RESULTS

In order to increase realism, dependencies between plant risk and maintenance activities, i.e. different combinations of safety system alignments, during the shutdown mode have been studied in detail. This has had an impact on both fire occurrence frequencies.

Fire during the cold shutdown period leading to loss off residual heat removal gives a core damage frequency in the magnitude of 1E-6 and is 4,5% of the total core damage frequency for Forsmark 3. Fire during power operation gives a core damage frequency in the magnitude of 1E-7 and is 3% of the total core damage frequency for Forsmark 3. Fire is not a dominating initiating event. But the risk of getting a critical fire is greater during cold shutdown mode than during power operation.

The risk for fire during cold shutdown period is much higher that during power operation. The reason for that is the risk increase because of on-going maintenance.

6. CONCLUSION

The results of our analysis indicate that the most critical phases with respect to a fire event are the phases when upper head (reactor vessel lid) still is mounted. If a fire event occurs during any of these phases it leads to loss of residual heat removal and the time of recovery is quite short.

Due to an increased number of plant activities during the cold shutdown period the integrity of fire compartments may not be intact and this could lead to an even more extensive fire spreading. At the same time important barriers may be unavailable due to maintenance and a fire event could become critical. The risk for a fire to occur and to be critical is more probable during cold shutdown than during power operation. Therefore it is very important to analyse this and implement this in the PRA studies. Available time for recoveries before fuel is uncovered in the reactor pressure vessel after an initiating event, i.e. fire event that result in loss of residual heat removal, is in many cases significantly longer than 24 hours. The reason for this is that during phase 4 when most of the maintenance is ongoing all pools are filled with water and a large water volume must be boiled off before fuel is uncovered. This means that other aspects related to fire events during the cold shutdown period might be more relevant. For example consequences originating from the spent fuel pool after a fire event or combinations of fire event that could cause a leakage from RPV. It seems that the only phases a fire event could lead to exposed fuel within 24 hours are during phase 1, 2 and 3.

The frequency of fire occurrence differs significantly between the rooms where maintenance is on-going and rooms where maintenance is not on-going. On the other hand the probability of successfully fire extinguishing is significantly higher in rooms where work is in progress. Fire frequencies are generally higher during the cold shutdown mode compared to operating mode.

During our work with fire analysis the points below with possible further development were found.

- More detailed analysis of how human error is affected by a fire.
- Secondary events caused by fire leading to combined events, for example LOCA caused by a fire.
- Secondary fire event caused by the initiating event.
- Fire when all fuel is unloaded from reactor pressure vessel and put into the spent fuel pool.
- A more detailed analysis of how human error is affected by a fire.

Reference

[1] Probabilistic Safety Assessments of Nuclear Power Plants for Low Power and Shutdown Modes, IAEA, Vienna, 2000 IAEA-TECDOC-1144, ISSN 1011-4289

[2] Fire PRA Methodology for Nuclear Power Facilities, EPRI/NRC-RES, vol 2 detailed methodology, EPRI 1011989, NUREG/CR-6850