Challenges and Lessons Learned from a PSA on a Spent Fuel Pool Facility

Frida Olofsson and Anders Olsson[a]
[a]Vysus Group, Landsvägen 50A, Sundbyberg, Sweden,
e-mail: frida.olofsson@vysusgroup.com, anders.olsson@vysusgroup.com

Abstract: Performing a PSA on a spent fuel pool storage facility provides new challenges but also new insights. Even though the nuclear fuel is the common subject for the risk to be evaluated, the differences compared to a traditional PSA for a nuclear power plant are several.

In this spent fuel pool facility, the risk is evaluated both regarding the process of the transport containers and fuel elements handling, as well as for the long-term storage in spent fuel pools. The studied end-states and sequences depend on where in the facility the spent fuel is situated.

Most methodologies used in this spent fuel pool PSA are developed with respect to nuclear power plants and related equipment, time windows and prevailing circumstances etc. Challenges are encountered in applying methodologies commonly used for nuclear power plants in areas such as HRA and area event analysis. The methods have in some cases been modified to adapt them for this purpose.

One important difference from a traditional PSA is the long time windows in the analysis due to the fact that many events in the facility develop slowly. In many cases there are several days between an initiating event and an adverse consequence. This issue pervades for example in the analysis of manual actions as well as when modelling mission times for systems and components. The facility has a low grade of automatization and, therefore, the importance of human actions is even more prominent. The system mission times originates from deterministic acceptance criteria. This assumption has proven to have an important impact on the analysis.

The PSA has contributed with important insights about risk at the facility which has led to some plant modifications and other significant improvements in equipment, procedures and training.

1. INTRODUCTION

This paper will briefly introduce the PSA of a spent fuel pool (SFP) facility (chapter 2). Some main differences in the specific SFP PSA compared to a traditional PSA for a nuclear power plant (NPP) will be discussed (chapter 3). After that a few selected challenges (chapter 4) that were encountered through the development of the PSA regarding the following topics will be described:

- Long time windows
    - Long mission times
    - Modelling repair
- Using methodology for nuclear power plants
    - Fire analysis

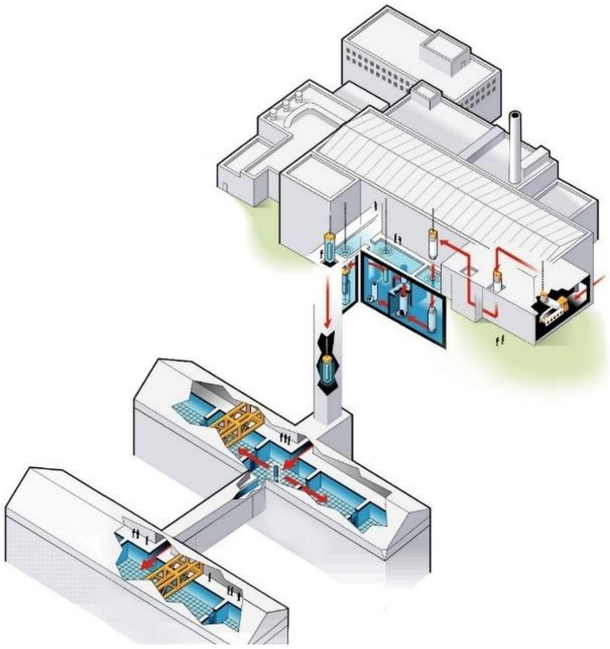
Lastly, some of the lessons learned and how the SFP PSA has contributed so far with insights to other parts of the organization will be discussed (chapter 5).

2. DESCRIPTION OF THE FACILITY

The studied facility is an interim storage facility which has the purpose of keeping the spent fuel coming from different NPPs in storage pools before disposal in the final repository. The fuel is handled in two separate processes. Firstly, the spent nuclear fuel arrives and is properly prepared to be placed in the interim storage pool. Secondly, the interim storage pool itself where the spent fuel is kept cooled and under observation waiting for the final repository.

When the transport container with the spent fuel arrives at the facility it must first be cooled down. The transport container is placed in a cooling cell where water cooling systems are connected to the container. Next the transport container is transported via a bridge crane into a pool in which the process of unloading the fuel elements and placing them in a storage canister takes place. The storage canister is transported underground to the long-term storage pools. The fuel is then kept in these pools about 30 meters below ground and covered with eight meters of water. An overview of the fuel handling process through its way in the facility is shown in figure 1.

Figure 1: Overview of the fuel transportation process.



3. GENERAL OVERVIEW OF THE PSA

The PSA evaluates the risk both related to the process of the containers´ transport and fuel elements handling, as well as the long-term storage in spent fuel pools.

The operation is divided into different modes depending on where the fuel is situated:

- *Storage* – No handling of fuel is in progress, but all fuel is situated in the long-term underground storage pool.
- *Temporary storage* – No handling of fuel is in operation, but fuel is situated in the intermediate pools in the above ground part of the facility.
- *Operation* – Handling of fuel in any of the process steps.

Relevant initiating events are dependent on where in the facility the fuel is situated. The analysis is divided into eight process steps following the fuel on its way through the process. In each step of the process the specific relevant initiating events are identified. Internal events, area events and external events are covered.

The studied end-states and sequences are also dependent on which process step the fuel is in. The main consequences studied in the model are mechanical damage to fuel, overheating of fuel or uncovering of fuel. These events could potentially lead to radioactive releases. In addition, boiling in the storage pool is studied as an undesired consequence.

Due to the low grade of automatization and redundancies, the human actions are an important part of the PSA. Available time for recoveries and repairs is, generally, long in many of the studied sequences. HRA are performed with ASEP (NUREG/CR-4772) [2] for category A and B actions and SPAR-H (NUREG/CR-6883) [4] for category C actions.

4. CHALLENGES

Performing a PSA for a spent fuel pool facility provides several different aspects and challenges even for the experienced NPP PSA analyst. Some main differences compared to an NPP PSA are

- Different initiating events
- Different end-states
- Division into Level 1 and Level 2 PSA is not applicable
- Lower grade of automatization
- Lower grade of redundancy/diversity
- Longer available time
- Repair plays a more important role

A few specific challenges encountered along the road developing the spent fuel pool PSA for this specific facility are discussed in this chapter. The challenges are mainly regarding to ensure that the study has an acceptable level of realism and detail for its intended applications. The main topics for these are challenges related to:

- Long Time Windows (chapter 4.1)
- Fire Analysis (chapter 4.2)

4.1 Challenges Related to Long Time Windows

In a traditional NPP PSA the most common time frames considered are 24 hours for PSA level 1 and 48 hours for PSA level 2. Modelling sequences that expand over a longer time frame brings several new aspects of the modelling that will play a more important role compared to the NPP PSA. A few of these issues are discussed in the following chapters.

4.1.1 Mission Time

The mission time used for most system functions, 30 days, is derived from deterministic criteria. For certain system functions shorter mission times are assumed.

It has been identified through sensitivity analysis that such a long mission time becomes one of the main driving factors of the results. A summary of the impact on the results for consequence boiling is presented in table 1.

Table 1: The impact on the result for consequence boiling in the spent fuel pool from varying the 720-hour mission time parameter.

Normal	Sensitivity Analysis	Difference in frequency for boiling
720 hours	72 hours	-77 %
720 hours	360 hours	-42 %
720 hours	1440 hours	+85 %

As of now, managing and improving the model regarding this issue is ongoing. Different solutions are evaluated and results from the NPSAG (Nordic PSA Group) research projects PROSAFE (Prolonged Available Time and Safe States) [6] and DIOR (Deeper Investigation of Repairability) [7] are going to provide input to further model development.

4.1.2 Modelling of repair

Crediting repair is not common practice in traditional NPP PSAs. In this study repairs are considered for a few components, as without crediting repair for some components the result would be greatly conservative. Sensitivity analysis indicates that crediting repair and calculated repair probabilities are of great importance to the result.

Repairs are only considered in sequences leading to consequence *boiling of the underground spent fuel pool*. Repair is also considered for some initiating events.

Repairs are modelled explicitly in the fault trees and event trees with a probability of failure to repair. Calculations for repair probabilities are based on availability of spare parts and expert judgements on the repair time. Following are a couple of examples on how repair failure probabilities have been estimated.

Many important components in the different systems in the spent fuel pool cooling function, such as pumps, heat exchangers etc, have been analysed with regards to which type of repairs that will require the longest time. The repair that was evaluated to require the longest time was still well within the margin before any undesired consequences would occur. Almost double the required time is available. The probability to fail to perform such a repair is assumed to be 0.01. As a second input, historical failure records for the components are studied as well as what spare parts are available on-site. Here it was noted that one failure of the historical failure events meant that one particular spare part had to be sent away for repair. Also a few specific parts do not have spare parts on-site. Based on this information it is estimated that 0.05 of the failures are such that no spare parts are available or that the component has to be sent away for repair. The total probability of failure to repair the component can then be calculated:

$$0.05 * 1 + 0.95 * 0.01 = 0.06 \qquad (1)$$

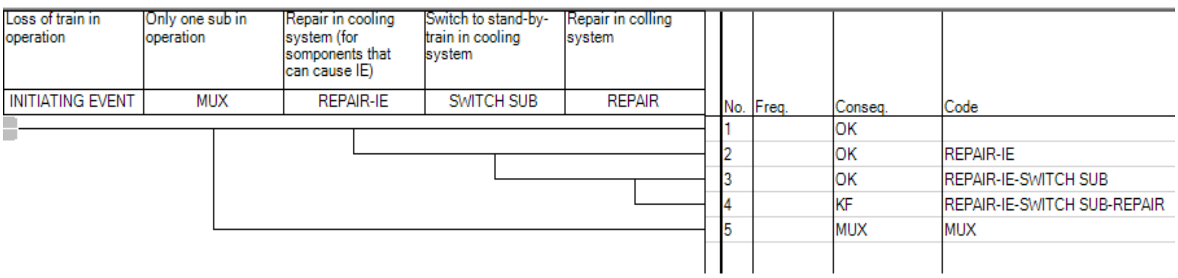
For some of the pumps one spare pump is available in the next room prepared to replace a failed pump. Based on data for when the spare pump has been unavailable due to maintenance, the probability that the spare pump is not available is 0.07. The probability that the switchover to the spare pump fails is estimated to be negligible. It is also possible to repair the failed pump. This has conservatively been estimated to 0.5 and the probability of failure to repair for the two pumps are calculated as:

$$Pump\ in\ operation: 0.07 * 0.5 = 0.035 \qquad (2)$$

$$Pump\ in\ standby: 0.5 \qquad (3)$$

The main cooling systems for the spent fuel pool always have one pump in operation. If none of the trains are functioning the available time for recovery is several days before boiling occurs in the spent fuel pool. The event loss off cooling of the spent fuel pool is modelled in the event tree presented in figure 2. The sequence is initiated by failure of the operating pump train. The function event MUX is basically a technicality used to exclude unwanted combinations of events as only one sub can be in operation at a time. If the failure is caused by failure of one component where repair is credited, the possibility to repair the initiating event, i.e. the component failure is modelled in function event REPAIR-IE. The function events INITIATING EVENT and REPAIR-IE do in principle have the same

Figure 2: The event tree modelling loss of cooling for the spent fuel pool. Repair is credited for some initiating events, as well as for failures of components in the stand-by train.



input fault tree. The possibility to allow repair in REPAIR-IE is controlled with house events in the fault tree that are set to TRUE in the function event. The input to function events SWITCH SUB and REPAIR are in an analogous manner using the same input fault tree. Crediting repair in the function event REPAIR is managed through activating house events.

4.2 Challenges Related to Fire Analysis

4.2.1 Fire Ignition Frequencies

The compilation of fire ignition frequencies is performed to a great degree in accordance to NUREG/CR-6850 [3]. This methodology is developed to apply to nuclear power plants, and consequently some modifications in the analysis steps have been adopted in this study. This chapter highlights some of the challenges with utilizing this method for a spent fuel pool facility as well as some of the modifications introduced to adapt the method for this purpose.

In Task 6 of NUREG/CR-6850, *fire ignition frequencies*, as step 1 potential plant fire sources are divided into categories also denoted *bins*. Each bin constitutes one generic equipment type that can be an ignition source. A total fire ignition frequency is given for each bin. This frequency is to be distributed among the fire compartments in the facility based on a fire ignition source count for each compartment. Updated fire ignition frequencies are presented in NUREG-2169 [1] which incorporates fire event experience through the year 2009.

Another complementary document to NUREG/CR-6850 is NUREG/CR-7114 [5] that estimates frequencies for shutdown. In NUREG/CR-7114 frequencies are presented for bins that differs depending on operation mode.

The total fire ignition frequency for one plant is 2.1E-1 per year at full power and 2.8E-1 (BWR) or 2.7E-1 (PWR) per year at shutdown.

In total 37 bins are defined in NUREG/CR-6850. Some of these bins are relevant to the studied facility, yet others are specific for nuclear power plants and thus not applicable. The second type of bins has then been excluded from the analysis, as these types of components are not found in the studied facility. These include to a large extent bins regarding components typically situated in the containment and the turbine building. Altogether, the following bins have been considered:

Bin 1 – Batteries
Bin 9 – Air Compressors
Bin 12 – Cable Run
Bin 14 – Electric Motors
Bin 15 – Electrical Cabinets
Bin 18 – Junction Boxes
Bin 21 – Pumps
Bin 23 – Transformers
Bin 25 – Transients (Plant-Wide Components)
Bin 26 – Ventilation Subsystems

Shutdown is the mode considered to be the most representative for the conditions in the analyzed facility. For this reason, shutdown frequencies according to NUREG/CR-7114 are used for bins where it is applicable. Out of the considered bins listed above, the frequency for bin 25 is dependent on operational mode. Hence, the shutdown frequency has been used for this bin.

Excluding bins from the analysis thus means that the total fire ignition frequency for the whole facility will be lower than the generic fire ignition frequency for an NPP in NUREG/CR-6850. The summed frequency used in the study is 1.15E-1 per year. This is considered reasonable and even conservative considering the differences to this facility compared to an NPP.

One subtask within task 6 in NUREG/CR-6850 is also step 6, *fixed fire ignition source counts*. This task is to count the component types in each fire compartment to establish an ignition source weighing factor for each compartment. For each generic equipment type (bin) restrictions on the counting method is provided. An example of this is bin 21 - pumps, where only pumps above 5 hp are counted. As plant documentation and databases were not in line with the exact information needed according to NUREG/CR-6850 for this analysis step some modifications were introduced for the counting process.

One specific challenge related to step 6 was that a large amount of the available facility documentation was based on total fire load [MJ/m2] from different equipment types, rather than number of components. For some component groups it was judged that the total fire load per compartment provided a satisfactory input to estimate the ignition source weighing factor.

5. LESSONS LEARNED

The PSA has so far contributed with important insights about risk at the facility which have led to plant modifications and other significant improvements in equipment, procedures and training. A few examples of such insights from different areas of the PSA are discussed in the sections below.

5.1 Consideration of the whole risk profile

A general insight from the PSA is that even though the spent fuel does not reside very long time in certain positions during its transport, operations in such locations can still contribute with a significant risk. Factors that are important in this aspect are the initiating event frequency and the available barriers.

One such important example is when the transport container is transported using the bridge crane between the cooling cell and the fuel unloading pool. This phase does not take very long and the risk of the bridge crane failing and stopping for an extended time is not considered very high. However, in the event of a sudden stop in the bridge crane with the container hanging for several hours, the fuel needs cooling to prevent boiling inside the container. Previously, the only way to provide cooling for the container include moving it to another position with the bridge crane. The PSA showed that the risk from the event that the bridge crane cannot move indeed was significant compared to other risks. The solution was to install a new function which introduced a possibility for the operators to provide emergency cooling to the container while hanging in the bridge crane.

5.2 Insights from HRA

In the case of an initiating event, the operators are meant to follow the appropriate procedure. However, in case repair of components is required, this is performed by maintenance personnel and is not part of the procedures. From HRA performed as part of the PSA for repair actions, how procedures link to necessary maintenance actions such as repair or replacing components after an initiating event has been discussed among the personnel and the procedures were also clarified.

5.3 Findings in area events analysis

In the flooding analysis, the PSA pointed out a certain room to be sensitive to flooding. Thanks to that insight specific measures were introduced in this room. Hatches near the floor level were installed which can open in case of a flooding incident and thus limit the water levels in the room.

From the fire analysis the PSA can highlight if several important and/or redundant components can be affected by the same fire event and the risk contribution from such a fire event. Findings form the fire PSA has led to repositioning of certain components to other fire cells in order to reduce the risk from fire events.

4. CONCLUSION

This paper introduces the PSA of a spent fuel pool facility. Performing a PSA for a spent fuel pool facility is in many aspects different to a traditional NPP PSA.

Some specific challenges encountered during the work on this specific SFP PSA are discussed on the topics:

- Long available time
  - Long mission times
  - Modelling repair
- Using methodology for nuclear power plants
  - Fire analysis

For some of the identified challenges, tailor made modifications to commonly used methods that usually applies to NPP have been the resolution. For other challenges, reasonable and suitable solutions to further develop and improve the PSA study are still a work in progress.

References

[1] NUREG/CR-2169 (2015). Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability - Estimation Using the Updated Fire Events Database, United States Fire Event Experience Through 2009, Open resource.

[2] NUREG/CR-4772 (1987). Accident Sequence Evaluation Program, Open resource.

[3] NUREG/CR-6850 (2005). Fire PRA Methodology for Nuclear Power Facilities, Volume 1&2, Open resource.

[4] NUREG/CR-6883 (2005). The SPAR-H Human Reliability Analysis Method, Open resource.

[5] NUREG/CR-7114 (2013). A Framework for Low Power/Shutdown Fire PRA, Open resource.

[6] PROSAFE (2019-2020). Prolonged Available Time and Safe State, Nordic PSA Group, Research project.

[7] DIOR (2021). Deeper Investigation on Repairability, Nordic PSA Group, Research project.