The Reliability Research and Risk Analysis of Spent Fuel Pool under Internal Fire

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Abstract. The Fukushima nuclear disaster has raised the focus on the reliability and risk evaluation of the spent fuel pool (SFP), especially the fire risk. From a safety point of view, the low decay heat of the spent fuel assemblies and large water inventory may make the accident progress very slow, but a large number of fuel assemblies stored inside the pool and without containment above the SFP building might bring greater risk. For pressurized water reactor HPR1000 nuclear power plant, the reliability and risk of spent fuel pool under internal fire is assessed. The fire probabilistic safety analysis method is used to assess the reliability and risk of spent fuel pool under internal fire. Through quantitative analysis, we can know more about which aspects play a leading role in the internal fire risk contribution.

1. Introduction
The first reliability and safety research about spent fuel pool (SFP) in nuclear power plant is provided in WASH1400[1], which studied the risk evaluation result of SFP. Because the coolant in SFP is not pressurized, the spent fuel is subcritical, the decay heat level is relatively low, and there is a large amount of water in the SFP to submerge these spent fuels and carry out the decay heat, the risk of the SFP is several orders of magnitude lower than the risk of the reactor core.

After the 9/11 attacks in the US in 2001, SFP safety researches have focused more on (a) assessing the effectiveness of mitigation measures on SFP; (b) improving the analysis of fuel coolability and heat up; (c) improving the fuel configuration within the pool to achieve a substantially greater passive cooling capability through natural convection; and (d) further understanding and validating the analytical modeling about relevant experiments. The Bulletin 2011-01 “Mitigating Strategies” is published by NRC [2], in which it is required that the plant operator should consider and prepare the mitigation strategies in case of explosion and fire. The Fukushima nuclear disaster has stimulated the need for comprehensive research on SFP safety and the related regulation requirements. A series of improvement measures have been applied to the design of SFP, such as diverse sources of water make up and electricity supply, application of instrument of the water level and water temperature. Nowadays, the reliability and safety level of SFP has been better than the evaluation result of SFP provided in NUREG-1738 report [3], which is focused on the SFP at decommissioning NPP in 2001.

The internal fire is an important risk contributor to the generic SFP, the consequence of internal fire accidents in different areas of the SFP building will cause different initiating events that can affect the safety function or equipments, and finally affect the reliability and safety of the spent fuel pool, if the mitigation measures fail, the worst situation is that the decay heat of the spent fuel can’t be removed within a long time, the temperature will continue rising until the fuel cladding is damaged. Although the accident phenomena and progress in SFP are somewhat different from the reactor,
including the primary pressure, temperature, and configuration of the fuels, the analysis method, framework and technical element of SFP PSA is similar to PSA about the reactor core, namely the Level 1 PSA.

2. System Description
The HPR1000 NPP is selected as the reference plant for the present SFP risk study, which is a three-loop pressurized water reactor. The SFP is located adjacent to the primary containment. The design of spent fuel pool is to provide enough shielding water and cooling water to keep the spent fuels submerged. The large amount of borated water is used for neutron absorption and can supply enough sub-critical margin. The water also act as the coolant to remove the decay heat from the fuel assemblies stored in the SFP. The most important system of SFP is the spent fuel cooling system, PTR system. The cooling function of the PTR is performed by three cooling trains arranged in the fuel building. The penetrations in the PTR should ensure the integrity of the containment to accomplish the confinement of radioactive substance. Furthermore, the PTR provides other functions, such as water purification, filling/discharge for the reactor building pools and so on. The schematic diagram of the PTR is shown in Fig. 1.

3. Methodology of Internal Fire PSA about SFP
This paper focuses on the research of reliability and risk of the SFP under internal fire. Internal fire event in SFP is a fire that occurs in the SFP area, which may cause an initiating event that will affect the safety of the spent fuel or affect the safety function of the SFP. The internal fire PSA method and process[4-7] that will be applied to SFP risk analysis is shown in Figure 2.

3.1 Risk Assessment Acceptance Criterion
The design criteria of SFP is to prevent the spent fuel returning to criticality, to keep the spent fuel always covered by the water, and to ensure that the decay heat can be removed, so the integrity of spent fuel can be maintained. The risk of SFP is mainly from the following two aspects: one is the fuel thermal damage (FD-T), which refers to fuel damage due to loss of decay heat removal associated with loss of SFP cooling or loss of SFP water inventory. The other is fuel mechanical damage (FD-M), which refers to fuel damage accidents associated with fuel cask drops, fuel assembly or components drops during fuel route operation. This paper mainly focuses on the study of thermal damage risk induced by internal fire in SFP area. The fuel damage frequency is used to represent the risk of SFP,
and the criteria of fuel damage is conservatively set as that once the top of fuel stored in SFP is uncovered, the fuel is assumed damaged.

Figure 2. Overview of Internal Fire PSA Process

3.2 Internal Fire Induced Initiating Events Analysis

The internal fire induced initiating events (IEs) can be identified as any internal events that caused by fire that occurred in the SFP area, if the plant mitigation systems or operators can’t response correctly, these events may lead to fuel damage.

The key steps related to internal fire IEs identifying and frequencies calculation are as follows:

- SFP boundary definition and partitioning.
- Fire PSA components and cables selection.
- Qualitative screening.
- Fire-induced initiating events definition.
- Fire ignition frequencies calculation.

Table 1 provide the internal fire induced initiating events list for HPR1000 SFP.

| Table 1. Internal Fire-induced Initiating Events for SFP |
|--------------------------------------------------------|
| No | Event Code | Event Name and Description | SFP State                      |
|----|------------|----------------------------|--------------------------------|
| 1  | F-LOOP     | Fire Induced Loss of Power | Non-Refuelling & Refuelling    |
| 2  | F-LOPTR    | Fire Induced Loss of PTR Operation Trains | Non-Refuelling |
| 3  | F-LOCC     | Fire Induced Loss of RRI/SEC | Non-Refuelling                 |
| 4  | F-LOAC     | Fire Induced Loss of AC Power | Non-Refuelling                 |

3.3 Fire Ignition Frequencies Analysis

The fire ignition frequency analysis is to estimate the fire ignition frequencies associated with fire ignition sources in the SFP area. There are two kinds of ignition sources, fixed ignition sources and transient ignition sources, totally 39 bins of fire ignition sources need to be considered in this analysis, such as battery, motors, and transformers, which may have the possibility to cause fire.

And the fire ignition frequency \( \lambda_{IS,J} \) is estimated by the following equation:

\[
\lambda_{IS,J} = \lambda_{IS} W_{\alpha,J} W_i
\]
Where:

\( \lambda_{IS} \)  
- Plant-level generic fire frequency associated with ignition source (IS) (1/(ry)).

\( W_{IS, J, L} \)  
- Ignition source weighting factor, which is the fraction of ignition source that is present in compartment J of location L.

\( W_L \)  
- Location weighting factor.

3.4 Event Sequence Analysis Due to Internal Fire

In the event sequence analysis, since the accident progress may develop very slowly, the mission time used in this analysis may be longer than 24 hours, which is used in the level 1 PSA for reactor core. To consider the time influence on the risk of spent fuel pool, two methods are applied:

- Actual available time for diagnosis and operation is used in the HRA analysis.
- Sensitivity Analysis is carried out for the longer mission time.

Four types of events in Table 1, together with the non-refuelling and refuelling state of the SFP are analysed in detail in this research.

3.4.1 Loss of PTR Cooling Operating Train(s) at Non-refuelling State by internal fire.

At non-refuelling state, loss of PTR operating train A leads to the interruption of SFP cooling and the increase of SFP temperature. According to the abnormal temperature alarm signals, operators need to start up the standby trains for recovering the cooling function before SFP water level drops to certain height due to water boiling and evaporation. If operators fail to start and run the standby trains, PTR cooling is unavailable, and the residual heat of fuel assemblies will be removed by the pool water heat capacity and water evaporation. As the temperature continues rising, SFP water boils and vapors, thus SFP water level decreases. Operators need to make up water for the SFP before the water level drops to the top of the fuel assemblies. If any water make-up measures can be performed successfully, the consequence can be mitigated. If failed, the FD-T will be considered.

3.4.2 Loss of RRI / SEC Train(s) caused by Internal Fire.

At non-refuelling state, loss of RRI/SEC train A, leads to the interruption of SFP cooling and the increase of SFP temperature, which triggers alarm signals of abnormal SFP temperature. According to these signals, operators need to recover the cooling. Operator need to start up the standby trains of PTR for SFP cooling. If operators fail to start and run the standby trains, the extra cooling system would be started to recover the cooling of heat exchanger of PTR train A and train B. If extra cooling system is unavailable, operators need to make up water for SFP. If any water make-up measure can be performed and run successfully, loss of water inventory could be mitigated. If failed, the FD-T will be considered.

3.4.3 LOOP caused by Internal Fire.

At non-refuelling state, LOOP can cause shutdown of PTR operating cooling pump, resulting in the interruption of SFP cooling. If the emergency diesel engineers (EDGs) can be successfully started, the PTR cooling pump are required to restart by the operator to establish the SFP cooling before the SFP water level drops to certain height due to water boiling and evaporation. If all EDGs fail, the accident will turn to a station black out (SBO) accident. SBO DGs have to be started to provide power supply for PTR train A and train B. In this case, the PTR cooling pumps should also be restarted by the operators, where the human reliability and the available operation time should be considered together. If EDGs or SBO DGs fail to start or the PTR cooling pump can’t be recovered, the operation of make-up water for SFP will be triggered by the water level alert to compensate the SFP water inventory. If all these operation fails, the fuel will be exposed and the FD-T will be considered. At refuelling state, fuel transfer tube is opened and SFP is connected to reactor pool. If a LOOP occurs when the fuel operation is being performed, the fuel assembly will be stopped at the operating position, emergency manual devices will be operated to ensure that the fuel assembly be placed at specified position.
3.4.4 Loss of AC/DC Power caused by Internal Fire. At non-refuelling state, loss of AC/DC power for PTR operating train(s) for SFP cooling due to internal fire can lead to the interruption of SFP cooling and the increase of SFP temperature. Accident process and system response of loss of AC/DC power for PTR operating train(s) due to internal fire are similar to the loss of PTR operating train(s) at the corresponding state.

Figure 3. Event Tree Case of LOOP

3.5 SFP Fault Tree Analysis

The fault tree method is used to assess the system reliability of SFP under internal fire. The fault tree models of the front systems, which is to perform the cooling and water makeup function, and the related supporting systems including the RRI/SEC system, AC/DC Power system, emergency diesel engines and the I&C system, which is to provide the heat sink, electrical power and I&C signals, are built in the Risk-Spectrum software, which is a widely used PSA software.

3.6 Analysis Result

The quantification of the reliability and risk analysis of SFP under internal fire, including the event sequence analysis and consequence analysis, is performed by combine the above fault tree models and event tree models. The analysis result shows that, in all stages, including non-refuelling stage and refuelling stage, the internal fire induced spent fuel damage frequency is 5.01E-11/ry, which means that the risk caused by the internal fire in SFP is at a relatively low level, accounting about few percent of the total SFP risk, which is of the same order of risk magnitude as that of the passive pressurized reactor SFP risk [8]. The requirement that the contribution of SFP accidents should be a few percent of the overall CDF target of 1.0E-04/ry is met.

Figure 4. FDF Contribution of Fire-induced IEs Figure 5. FDF Contribution of SFP States

4. Summary and Conclusion

To obtain the reliability insight and risk insight of the HPR1000 SFP under the internal fire, a systematic and as far as possible comprehensive PSA model is developed to include all the possible fire-induced internal events and possible states of the SFP which must be analysed in detail. For this purpose, the list of fire-induced initiating events, the relevant process and consequence are derived in a systematic way. The research shows that the risk of HPR1000 SFP under internal fire is at a relatively low level, because of large water inventory and relative low decay heat level. A lot of new design features are adopted for the SFP after the Fukushima accident, such as more reliable designs, multi
water make-up sources, mobile electrical supply, more reliable and sensitive water level sensors, which have further enhanced the reliability and safety level of the SFP.

To obtain more insight into the SFP risk, future study should be more focused on investing the following:

- Fuel degradation inside the SFP.
- More detailed model of fuel assemblies in case of uncovered.
- The accident mitigation strategies.
- More realistic PSA model removing unnecessary uncertainties.

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