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PROBABILISTIC SAFETY ASSESSMENT OF KOEBERG SPENT FUEL POOL

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Abstract. The effective management of spent fuel pool (SFP) safety has been raised as one of the emerging issues to further enhance nuclear installation safety after the Fukushima accident on March 11, 2011. SFP safety-related issues have been mainly focused on (a) controlling the configuration of the fuel assemblies in the pool with no loss of pool coolants, and (b) ensuring adequate pool storage space to prevent fuel criticality owing to chain reactions of the fission products and the ability for neutron absorption to keep the fuel cool. In support of regulatory functions, the Centre for Nuclear Safety and Security (CNSS) seeks to perform confirmatory analysis for all potential accident scenarios that may occur in the Koeberg nuclear power plant SFP. Probabilistic safety assessment (PSA) was done using the Systems Analysis Program for Hands-On Integrated Reliability Evaluations (SAPHIRE) computer code. We present preliminary PSA results of initiating events that lead to boiling and cause fuel uncovering, resulting in possible fuel damage in the Koeberg nuclear power plant SFP.

Keywords: Computer code, fuel assemblies, probabilistic safety assessment, spent fuel pool.

1. Introduction

Highly radioactive spent fuel assemblies that are unloaded from the nuclear reactor core are typically stored for a certain period in cooling water pools called spent fuel pools (SFP). The safe storage of these spent fuel assemblies in the SFP is very vital since many radioactive fission products could potentially be released into the environment if a severe accident occurred in the SFP [1]. The Fukushima Daiichi nuclear accident has proven that it is crucial to investigate potential severe accidents and corresponding mitigation measures for the SFP of a nuclear power plant (NPP) [2, 3]. The necessary mitigation measures, the effects of recovering the SFP cooling system and makeup water in SFP as the accident progresses have also been investigated respectively based on the events of pool water boiling and spent fuel uncovery [3–5].

To use risk insights in the decision-making processes in an adequate manner, it is very important to establish a systematic approach that integrates in a sound, transparent and justifiable manner all the elements required as stated in IAEA TECDOC 1436 [6].

Requirement 21 Paragraph 4.71 of the IAEA general safety requirements part 4; states that the regulatory body should carry out a separate independent verification to satisfy itself that the safety assessment is acceptable and to determine whether it provides an adequate demonstration of whether the legal and regulatory requirements are being met [7]. This work looks at all internal possible initiating events that may cause severe accidents in the Koeberg nuclear power plant SFP. However, external events such as seismic activity and aircraft crash were not considered for this study.

A list of abbreviations is provided in Appendix A.

2. Probabistic analysis

The Systems Analysis Programs for Integrated Reliability Evaluations (SAPHIRE) code was used as the modelling tool. This work was carried out by (1) Identifying initiating events and scenarios, (2) Accident sequence modelling, (3) Quantification of top events and (4) Analysis of results.

The main modelling assumptions for the SFP PSA model are listed below:

- The SFP water is at initial level of 19.65m.
- The initial pool water temperature is at 50°C. The SFP cooling loop is designed to provide a 50°C bulk SFP temperature with the maximum component cooling system (RRI) temperature and a maximum heat load of 2.88 MW during normal and outage operation.
- The model is done for the normal operating mode which is 94.2 % of an 18-month fuel cycle.
- No gate seal failure during SFP boiling.
- Make up from the reactor cavity and SFP cooling system is not considered because of limited capacity.
- The Demineralised Water Distribution System (SED), Fire Fighting Water Supply (JPP) and the Mobile Fire Fighting System (JPS) are the considered make up systems. Make up from the reactor cavity and SFP cooling system (PTR) is not considered because of limited capacity

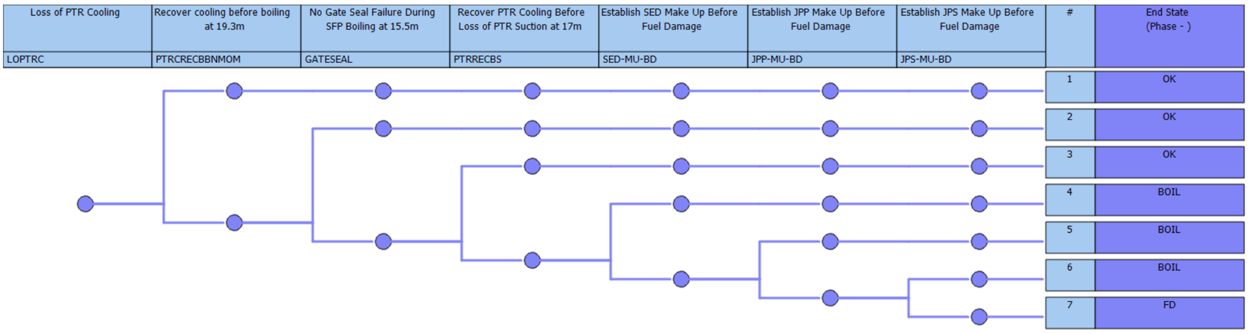

Figure 1. Loss of SFP Cooling Event Tree.

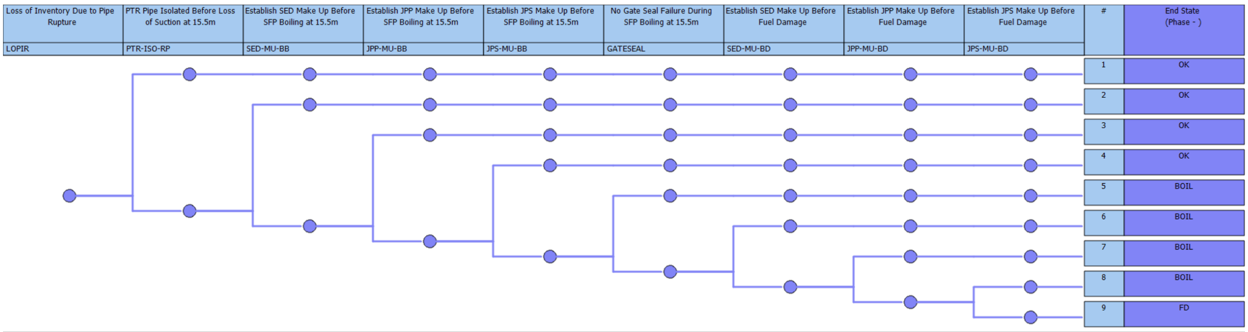

Figure 2. Event tree model of the Loss of Inventory due to Pipe Rupture.

3. Results and discussions

Event tree models were developed for the identified initiating events; this was done to better understand accident progression in the SFP resulting from the initiating events. The Loss of SFP Cooling, Loss of SFP Inventory due to Pipe Rupture, Loss of SFP Inventory due to Flow Diversion, Loss of Offsite Power and Station Blackout are the initiating events that were modelled in this study. These initiating events either lead to a loss of SFP cooling, a loss of SFP inventory or both. The success criteria for a loss of cooling or inventory is generally to recover PTR cooling before boiling or before a loss of PTR suction. It also entails making up inventory before PTR suction uncovery and making up inventory prior to fuel uncovery.

3.1. Event sequence modelling

The loss of SFP cooling initiating event results from a failure of the reactor cavity and spent fuel pool cooling system (PTR) whereby all trains are unavailable for SFP cooling. The Loss of SFP Cooling event tree is shown in Figure 1.

Following a loss of SFP cooling it will be ideal to recover cooling before boiling occurs (PTRCRECBBNMOM). Although boiling occurs when the pool heats up to a temperature of 100°C, it is crucial to maintain the pool level at a safe level, in this case 15,5m. The pumps take suction from the fuel pool at an inlet located below the pool water level (~ 15.5 m), transfer the pool water through a heat exchanger and return it back into the pool through an outlet typically located below the cooling system inlet and some large distance from it. Recovering PTR cooling before the loss of suction at the 17 m level would be ideal in this case (PTRRECBS).

If make-up cannot be established and PTR cooling is not restored the SFP level will drop from the 17 m level to the point where it is assumed that fuel damage occurs i.e. at the 9,85m level. The success criterion will be to establish SED make up before fuel damage (SED-MU-BD). In the event where SED is unavailable for make up to the SFP, an operator will be instructed to use the JPP system (JPP-MU-BD). As a last resort, if make up cannot be established through the SED and JPP systems, an operator will have to start the mobile fire pump (JPS-MU-BD).

This end state indicates that fuel damage has not occurred, the pool is boiling as illustrated by the BOIL in the event trees. The OK end state indicates that the accident has been successfully mitigated. This state comprises of all states where spent fuel damage has not occurred and either cooling has been re-established or make up to the SFP has been established.

The Loss of SFP Inventory due to a Pipe Rupture, this initiating event considers the loss of SFP inventory due to pipe breaks in the PTR system. After a pipe rupture event the operator action required is to isolate the break before the loss of the PTR pump suction (PTR-ISO-RP). A similar action is required in the case of loss of inventory due to flow diversion, with the operator being required to isolate the PTR flow diversion before the loss of suction (PTRFDISO).

The loss of SFP Inventory due to a Flow Diversion, this event is defined as a loss of SFP inventory due to diversion through an interfacing system valve failing

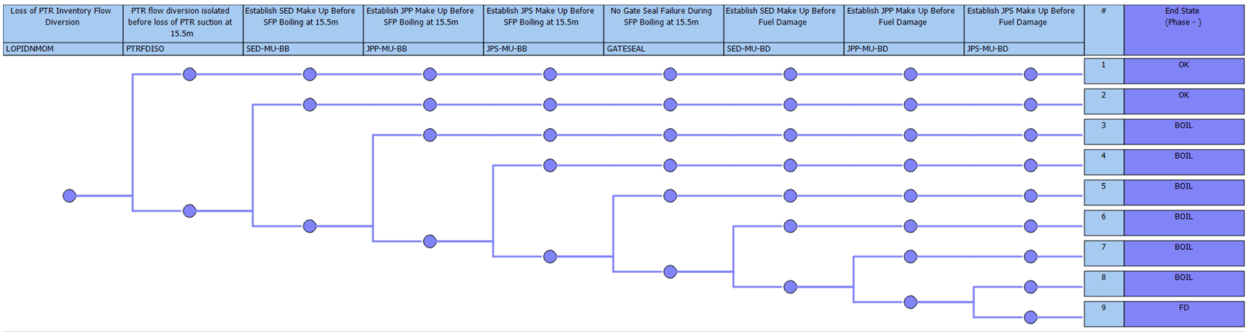

FIGURE 3. Event tree model of the Loss of Inventory due to Flow Diversion.

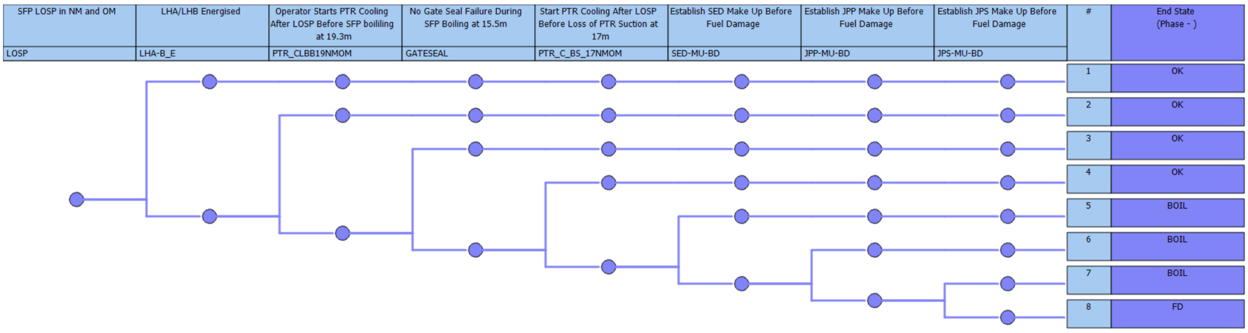

FIGURE 4. Event tree model of LOSP.

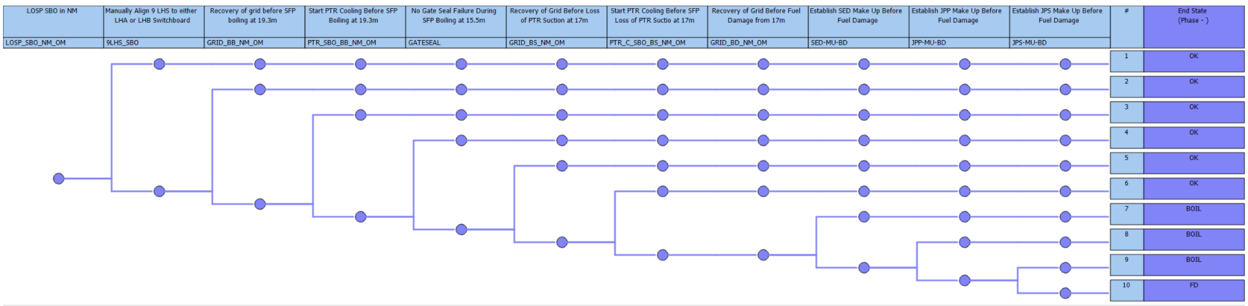

FIGURE 5. Event tree model of SBO.

open or having been left open during PTR operation. The event tree models for the loss of inventory due to pipe rupture and flow diversion are shown in Figure 2 and 3 respectively.

At the 15.5 m level, PTR pump suction is lost. This means PTR cannot be recovered and make-up via SED, JPP or JPS is the only remaining options. This event considers maintaining the SFP water level so that PTR repairs can still be undertaken even after boiling has started. Success for this function event is defined as the establishment of SED make-up to the SFP before SFP boiling (SED-MU-BB). Should the SED be unavailable for make up to the SFP, an operator will be instructed to use the JPP system (JPP-MU-BB). As a last resort, if make up cannot be established through the SED and JPP systems, an operator will have to start the mobile fire pump (JPS-MU-BB).

The Loss of Offsite Power is defined as the failure of off-site power supplies. Both units are tripped and the emergency diesel generators (EDGs) and Acacia power station supply are started. Off-site power restoration is attempted as soon as possible. EDGs will automatically actuate and supply power to the emergency AC buses (LHA-B_E).

If the EDGs start and run, and the operator starts a PTR pump, SFP cooling can be re-established (PTR_CLBB19NMOM). The PTR pumps must not be restarted with a level of less than 17.0 m in the SFP. The suction of the PTR pumps located at the 15.5 m level in the SFP. Below this level PTR cooling cannot be restarted (PTR_C_BS17NMOM), therefore make-up is the only remaining option (SED-MU-BD, JPP-MU-BD and JPS-MU-BD).

The SBO initiating event is the failure of the off-site power supplies, including emergency off-site power from Acacia. Both units are tripped, the EDGs fail to start or run for 24 hours and offsite sources are not recovered.

Following a SBO, it is desirable to recover power before SFP boiling. This can be done in one of two ways: either the recovery of the grid or by aligning

Initiating Event Frequencies			
Initiator	Time Factor	Conditional Initiating Frequency (IEC)	Initiating Event Frequency (IEF)
Loss of SFP Cooling (NM)	9,42E-01	9,52E-04	8,97E-04
Loss of SFP Inventory due to Flow Diversion (NM)	9,42E-01	3,57E-02	3,36E-02
Loss of SFP Inventory due to PTR Pipe Rupture	9,42E-01	1,37E-08	1,22E-08
Loss of Offsite Power (NM)	9,42E-01	4,50E-01	4,24E-01

Table 1. Summary of Initiating Event Frequencies.

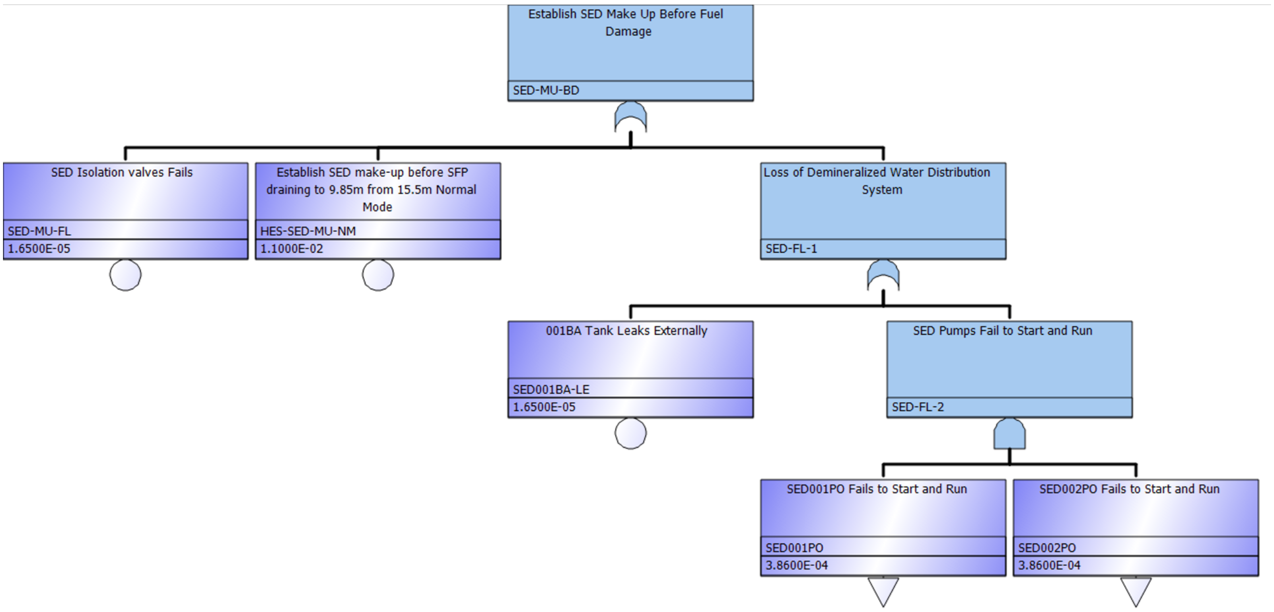

Figure 6. Failure Model of the SED System.

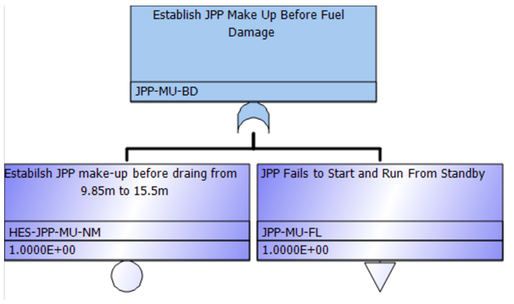

Figure 7. Failure Model of the JPP System.

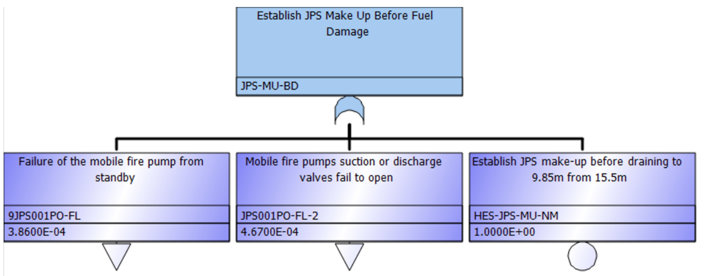

Figure 8. Failure Model of the JPS System.

the fifth diesel to either LHA or LHB (9LHS_SBO). It is also to recover the grid before SFP boiling

(GRID_BB_NM_OM) and to start PTR cooling before boiling (PTR_SBO_NM_OM). The loss of inventory due to boiling causes the SFP level to drop from the 19.3m level to the 17m level in 37.5 hours in Normal Mode. Success for this function event is defined as the recovery of the grid before the 17 m level is reached (GRID_BS_NM_OM). As already mentioned, the PTR pumps must not be restarted at a level less than 17m, PTR cooling must be started before loss of suction (PTR_C_SBO_BS_NM_OM). It is also desirable to recover the grid before fuel damage (GRID_BD_NM_OM). The available make up systems before fuel damage occurs are the SED, JPP and JPS systems (SED-MU-BD, JPP-MU-BD and JPS-MU-BD).

The worst-case scenario is a drop in the pool water level to an extent where the fuel assemblies will be uncovered, which is assumed to be at the 9.85m level. This will lead to the fuel being damaged as indicated by the end state FD in the event trees. Fuel damage will occur when all possible mitigating actions fail to be implemented. Several thermal hydraulic studies on the initiating events have also been performed. These studies are often used to support PSA because they reveal crucial information on SFP behaviour [8, 9].

3.2. Accident sequence quantification

To quantify accident sequences, fault tree models were used to quantify the function events in the event trees. Accident sequence quantification involves firstly the quantification of the initiating event frequencies. The conditional (IEC) and initiating event frequencies (IEF) were calculated for normal mode of operation (17 months) i.e., a time factor of 94.2 % of an 18-month fuel cycle was applied to the IEC to calculate the IEF. The IEC and the calculated IEF were obtained from Koeberg nuclear power plant documentation and are shown in Table 1.

The failure models of the make-up systems take into account human failure events, those function events which require human action were quantified following step by step standardized plant analysis risk-human reliability analysis (SPAR-H) methodology [10] for quantifying human failure events (HFE). A number of performance shaping factors (PSF) are taken in to consideration. These factors include available time, stress/stressor, complexity, experience/training, etc.

The failure model of the SED is modelled on the basis that the operator fails to start or align SED make up or the SED isolation valves fail or there is an overall loss of the SED. The loss of the SED results from two events, if the tank leaks externally or the pumps fail to start and run. The failure of the pumps was not modelled in detail and were treated as undeveloped transfers, in this case they are treated as basic events. SPAR models are generally not as detailed as those contained in licensee PRAs. The failure probabilities for valves, pumps and tanks were obtained from Koeberg internal documentation.

The failure model of the JPP system modelled JPP system fails to start and run from standby or Operator fails to start or align JPP make-up. The failure model of JPS because of the failure of the Mobile Fire Pump from standby or mobile fire pumps suction or discharge valves fail to open or operator ails to establish JPS make up. The failure models of the JPP and JPS are shown in Figure 7 and 8 respectively.

The other function events in the LOSP and the SBO event trees are operator actions such as "Operator Starts PTR Cooling After LOSP Before SFP boiling at 19.3m" (PTR_CLBB19NMOM) are operator actions and are currently being re-quantified using SAPHIRE HRA calculator.

4. Current and future work

The purpose of this work is to do an independent verification of the current Koeberg nuclear power plant spent fuel pool PSA model. Fuel Damage is the event consequence state of interest and is considered for quantification. System and failure probabilities were inputted into the model for quantification. Since the failure models of the make-up systems involve human or operator action, the function events which require human, or operator action will be re-quantified following a step-by-step standardized plant analysis risk-human reliability analysis (SPAR-H) methodology for quantifying human failure events (HFE).

5. Conclusions

This study entails the independent verification of the current Koeberg nuclear power plant SFP PSA model. Initiating events that lead to boiling and potential fuel uncovery were reviewed and investigated. The event tree models for the Loss of SFP cooling, Loss of SFP inventory, Loss of Offsite Power, Station Blackout were developed. The accident sequence modelling highlighted the importance of recovering SFP cooling and making up SFP inventory to prevent fuel uncovery. Operator or human action is a key component in always maintaining critical pool levels using the available make up systems. Through appropriate mitigation measures the increase in the fuel temperature could be stopped, limiting the release of fission products to the environment and preventing severe accident that could result in significant damage to the spent fuel assemblies in SFP.

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