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Original Article

# Development of risk assessment framework and the case study for a spent fuel pool of a nuclear power plant

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ABSTRACT

A Spent Fuel Pool (SFP) is designed to store spent fuel assemblies in the pool. And, a SFP cooling and cleanup system cools the SFP coolant through a heat exchanger which exchanges heat with component cooling water. If the cooling system fails or interfacing pipe (e.g., suction or discharge pipe) breaks, the cooling function may be lost, probably leading to fuel damage. In order to prevent such an incident, it is required to properly cool the spent fuel assemblies in the SFP by either recovering the cooling system or injecting water into the SFP. Probabilistic safety assessment (PSA) is a good tool to assess the SFP risk when an initiating event for the SFP occurs. Since PSA has been focused on reactor-side so far, it is required to study on the framework of PSA approach for SFP and identify the key factors in terms of fuel damage frequency (FDF) through a case study. In this study, therefore, a case study of SFP-PSA on the basis of design information of APR-1400 has been conducted quantitatively, and several sensitivity analyses have been conducted to understand the impact of the key factors on FDF.



## 1. Introduction

A SFP is designed to store spent fuel assemblies within the pool. In APR-1400, the SFP is housed in the auxiliary building, which also contains essential SFP equipment, such as the SFP cooling and cleanup system. The SFP cooling and cleanup system consists of pumps, heat exchangers, and valves. The pumps circulate the SFP coolant in closed loop to cool spent fuel assemblies, and the SFP coolant is cooled by a heat exchanger which exchanges heat with component cooling water. If the cooling function is lost by any reason (e.g., failure of pumps or failure of heat exchangers or break of interfacing pipes), the SFP coolant's temperature becomes higher and the SFP coolant would eventually be evaporated resulting in decrease of the SFP coolant level. Therefore, to prevent fuel damage, it is required to properly cool the SFP coolant by either recovering the cooling system or injecting water into the SFP.

Probabilistic safety assessment (PSA) is a good tool to assess the SFP risk. There have been several studies of SFP-PSA. NUREG-1738 describes the evaluation result of the potential accident risk in a spent fuel pool at decommissioning plants in the Unites States [1]. NUREG-1738 explains the overall information of SFP-PSA for a decommissioning plant. Therefore, the overall information in NUREG-1738 is mostly limited to decommissioning plants.

EPRI report develops a generic framework and methodology for conducting a PWR SFP-Reactor PSA reflecting the interrelationship with reactor accidents and to demonstrate its use for a typical PWR [2]. The generic framework includes the potential impact of SFP by reactor-SFP interaction. The SFP-PSA in the EPRI report basically starts with a reactor PSA model, and expand the end-states to SFP-PSA model.

This paper introduces the framework for SFP-PSA as shown in Fig. 1. The detailed approach for the each step in Fig. 1 is introduced in the following sections. Also, a case study incorporating the framework is conducted to obtain the insights of SFP risk. For the case study, plant specific information for APR-1400 is applied. In contrast to the framework in EPRI report, the interrelationship with reactor is not incorporated into the framework. However, the potential impact by the interrelationship is consulted with respect to the physical characteristic of SFP, containment failure phenomena/modes and their frequencies (see section 8).

## 2. Operating cycle phase (OCP) development

The term, OCP, is used to represent the various operating states of the spent fuel pool. The objective of OCP development is to make

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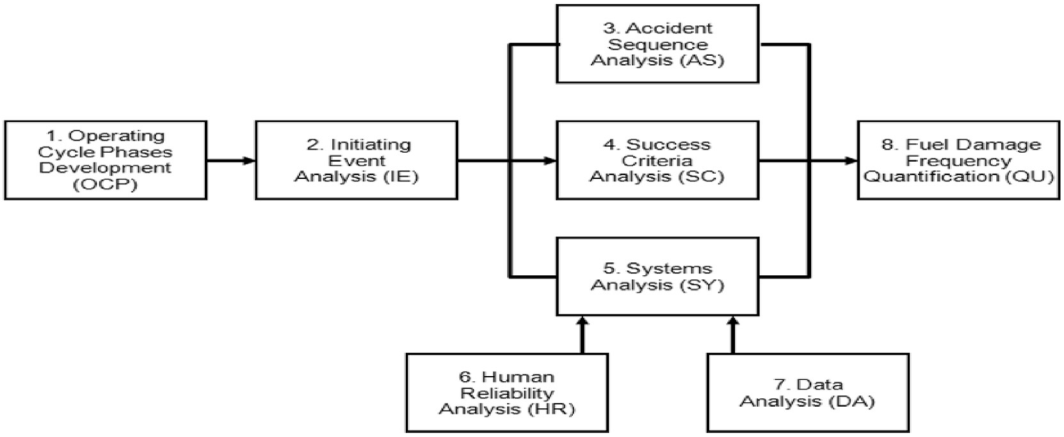


**Fig. 1.** Overall step of SFP-PSA framework for internal event.

discretization of the operating cycle of a nuclear power plant. This is to reflect the configuration change of supporting systems, and physical characteristics over the plant operating cycle. Major concerns in development of OCP are as follows:

1) The overall operating cycle of a nuclear power plant is covered by the defined set of OCPs.
2) The configuration of the structures, systems, and components (SSCs) relevant to SFP safety (e.g., status of fuel transfer tube, fuel pool gate, diesel generator) and associated physical characteristics (e.g., hydraulic coupling of the SFP, the fuel transfer canal, and the RPV refueling cavity) are clearly identified and characterized for each OCP.
3) The defined OCPs allow sufficient resolution of fuel handling operations and changes in decay heat.
4) The major risk contributors of the SFP operation can be adequately found by performing the SFP-PSA for each OCP separately.

The OCP development is performed using a grouping method. This method is to take advantage of output (plant operating states, POS) of low power and shutdown (LPSD) PSA since the POS includes the information of systems relevant to SFP operation and configuration changes of interface between RCS and SFP. This method is conducted by grouping plant operating states (output of LPSD PSA for APR-1400) in terms of characteristics of SFP operation. The OCP development is a lot easier and simpler with this method without losing important information of SFP operation.

Table 1 shows the result of OCP development. The maintenance schedule of emergency diesel generator, component cooling water system, essential service water system and refueling schedule are considered for OCP development. The systems above are considered due to their use as supporting system for SFP cooling pump. Refueling schedule is considered due to hydraulic coupling of SFP, fuel transfer canal, and RPV refueling cavity. Four OCPs are defined for the SFP-PSA, along with the corresponding POSs, the percentage of the duration with respect to the refueling cycle period of 18 months. The duration ratio for OCP is determined in consideration of the duration of the corresponding POSs which are used in the LPSD PSA for APR-1400. The total plant operating states of POS 0 to 15 correspond to the four OCPs. The four OCPs cover the whole operation cycle, power operation and low and power shutdown operation.

The information of duration ratio and system availability for each OCP needs to be incorporated into SFP-PSA model.

## 3. Initiating event analysis

In SFP-PSA, the term, initiating events, refers to those which challenge fuel integrity in the spent fuel pool and require successful mitigation to prevent damage to the fuel assemblies stored in the pool. The concerns for initiating event analysis are as follows:

1) Include all the events that challenge fuel integrity and need safety features to prevent fuel damage.
2) Group the events that are expected to need the same safety features to prevent fuel damage.

If an initiating event occurs, it is required to either recovering cooling function or injecting water into SFP to prevent fuel damage. There are two major categories for initiating events. One is “Loss of SFP Inventory” while the other is “Loss of SFP Cooling”.

1) Loss of SFP Inventory
2) Loss of SFP Cooling

### 3.1. Initiating events for APR-1400

Loss of SFP cooling occurs if cooling function for SFP is lost by any reason (e.g., electricity failure, spurious close of valve, random failure of cooling pumps). Loss of SFP Inventory occurs if any of interfacing pipes breaks. In case of Loss of SFP Inventory, the break size and break location are important factors to be considered because the amount of flow or potential outflow level of coolant depend on the factors.

The systematic review and FMEA (Failure Modes and Effects Analysis) of the SFP for APR-1400 are performed to determine if there are any plant-specific initiating events resulting from individual systems or train failures. In addition, generic initiating events introduced in NRC reports [1,3] are reviewed.

The initiating events from the review are presented in Table 2. All the initiating events in Table 2 are referred from the NRC reports since the reports introduce a broad range of initiating events, covering the initiating event of SFP from the FMEA for APR-1400. For each of the initiating events, the impact analysis on the SFP for APR-1400 in the Republic of Korea is performed. Plant specific design information for APR-1400 is utilized for the initiating event analysis.

It is identified that six initiating events (noted as SFP initiating event in Table 2) need to be considered as initiating events for the

**Table 1**
OCP development for SFP-PSA.

| POS | POS Description | OCP (Duration Ratio) |
|---|---|---|
| 0 | Power operation | OCP1 (95.1%) |
| 1 | Reactor trip and Subcritical operation | |
| 2 | Cooldown with Steam Generators | |
| 3A | Cooldown with Shutdown Cooling System (hot-standby) | |
| 3B | Cooldown with Shutdown Cooling System (cold-shutdown) | OCP2 (1.0%) |
| 4A | Reactor Coolant System drain down (pressurizer manway closed) | |
| 4B | Reactor Coolant System Drain-down (Pressurizer manway Open) | |
| 5 | Reduced Inventory operation and nozzle dam installation | |
| 6 | Fill for refueling | |
| 7 | Off-load | OCP3 (2.0%) |
| 8 | Defueled | |
| 9 | On-load | |
| 10 | Reactor Coolant System drain down to Reduced Inventory after refueling | OCP4 (1.9%) |
| 11 | Reduced Inventory operation with steam generator manway closure | |
| 12A | Refill Reactor Coolant System (pressurizer manway open) | |
| 12B | Refill Reactor Coolant System (pressurizer manway closed) | |
| 13 | Reactor Coolant System heat up with Shutdown Cooling System isolation | |
| 14 | Reactor Coolant System heat up with steam generators | |
| 15 | Reactor startup | |

**Table 2**
Initiating analysis with list of generic SFP initiating events.

| No. | List of Generic SFP Initiating Events | Initiating Events Analysis for APR-1400 |
|---|---|---|
| 1 | Loss of offsite power | SFP Initiating Event |
| 2 | Internal fire/flood | SFP Initiating Event |
| 3 | Loss of pool cooling | SFP Initiating Event |
| 4 | Loss of coolant inventory | SFP Initiating Event |
| 5 | Seismic event | SFP Initiating Event |
| 6 | Cask drop | This event can only be caused by structural failure of an overhead crane (falling into the pool), either with or without a heavy load in place. However, the crane is not supposed to be directly over the pool in design of APR-1400. This event can be screened out. |
| 7 | Aircraft impact | This event can be screened out based on the hazard analysis of aircraft impact. |
| 8 | Tornado missile | This event can be screened out based on the fact that strong tornado is rarely possible to occur in Republic of Korea due to the domestic weather characteristic. |
| 9 | Gate Seal Failure | A calculation indicates that even if the SFP gate or seals completely fail, such an event will not result in a loss of SFP cooling because the amount of outflow is limited due to the volume of the fuel transfer canal. |
| 10 | Configuration Control Failure (through connected system) | SFP Initiating Event |
| 11 | Criticality in SFP | This event can be screened out based on the design characteristics of SFP for APR-1400<br>- Criticality Control by Borated water or boral plate<br>- Administrative controls (fuel location, refueling method) |

SFP of APR-1400.

In this paper, however, Loss of offsite power (LOOP) is selected as an initiating event for the case study incorporating the framework. It is reasonable because LOOP should be a major risk contributor to SFP considering the frequency and availability of safety system (e.g., emergency diesel generator).

## 4. Accident sequence analysis

Accident sequence analysis is a logical process to identify the accident sequence progression as well as the combination of accident sequences. To do so, it is required to define safety functions, related systems and operator actions to prevent fuel damage. The general safety functions for SFP are SFP cooling and SFP make-up. The accident sequence model needs to include the safety functions as the top heading. Either of SFP cooling or SFP make-up needs to be successful to be OKed in the end state. In this aspect.

An event tree is developed incorporating the required mitigation functions of 1) AC power recovery, 2) Off-site power recovery, 3) SFP cooling recovery, 4) On-site SFP make-up 5) External SFP make-up.

Fig. 2 shows the event tree for the initiating event, LOOP. Each heading in the event tree represents the required mitigation function, and is described in Table 3.

## 5. Success criteria analysis

Success criteria define the number of trains (or components) to succeed for preventing fuel damage and the timing for successful operator action. In SFP-PSA, success criteria are primarily dependent upon the type of initiating events and OCP group. As explained, OCPs are characterized by the plant configuration (e.g., status of systems and physical characteristics) and decay power. Decay power level is the highest during OCP3 because full core is offloaded into the SFP. Decay power level for other OCPs is expected to be much lower than that of OCP3.

Thermal-Hydraulic analysis using RELAP5 or MAAP5 can be implemented for success criteria analysis incorporating SFP design information. However, a simple approach of using maximum evaporation rate and SFP area is introduced in this study. The maximum decrease rate of SFP water level can be calculated by dividing the maximum evaporation rate with SFP area. Then, the times to important set-points can be calculated by dividing a set-point level with the maximum decrease rate.

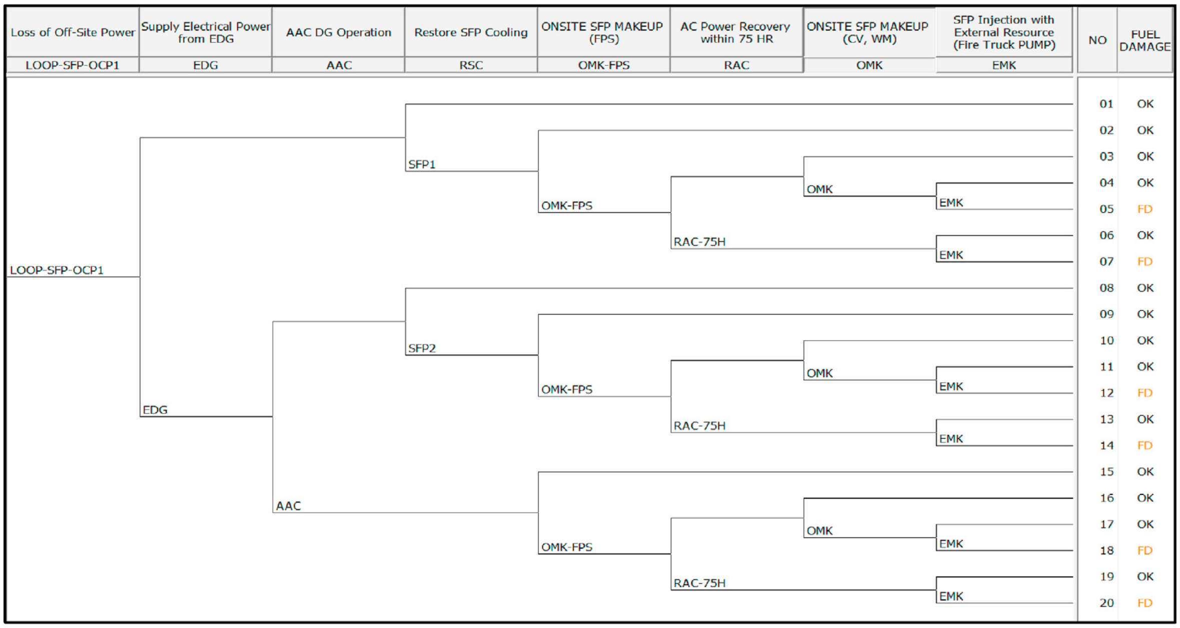


**Fig. 2.** Event tree for loss of offsite power.

**Table 3**
Headings in LOOP event tree.

| Heading Name | Description |
|---|---|
| EDG | Emergency diesel generators provide power to Class 1E 4.16 kV AC buses |
| AAC | AAC power source provides power to Class 1E 4.16 kV AC buses |
| RSC | Restore SFP Cooling Function |
| OMK-FPS | SFP make-up by on-site Fire Protection System |
| RAC | Off-site Power Recovery |
| OMK | SFP make-up by Chemical and Volume Control System or Demi-Water System |
| EMK | SFP make-up by External Resource (Fire Truck Pump) |

$$Decrease\ Rate_{\max} = \frac{Evaporation\ Rate_{\max}}{SFP\ Area}\left(\frac{ft}{hr}\right) \tag{1}$$

$$Time_{Set\cdot point\ Level} = \frac{Set\cdot point\ Level}{Decrease\ Rate_{\max}}(hr) \tag{2}$$

Maximum evaporation rate can be referred to plant-specific SFP design document. It should be careful that maximum evaporation rate is different depending on situation of SFP operation (Normal operation or Refueling operation). Analysts should use the proper maximum evaporation rate for each OCP. This simple approach is to be conservative because it assumes the evaporation rate as the maximum constant value.

As stated above, in this study, the method of the simple approach is used for success criteria analysis. The SFP volume and maximum evaporation rate of normal and refueling states for APR-1400 are incorporated to calculate the time when the level of SFP reaches a certain set-point. Table 4 shows the major level set-points of the SFP.

## 6. System analysis

The front line and related supporting systems for mitigating SFP accidents are identified as follows:

- Emergency Diesel Generator
- Alternative AC Diesel Generator
- SFP cooling and cleanup system
- Fire Protection System
- Chemical and Volume Control System
- Demi-Water System
- Fire Truck Pump (External Water Resource)
- Supporting System (HVAC, Power, Control Equipment)

FMEA for the components in the systems is conducted to identify the required components for their safety function. Fault Tree(s) for systems are developed and incorporated with the event tree.

## 7. Data analysis

### 7.1. Frequency of initiating event

The frequency of the initiating event, LOOP, is evaluated based on the generic industry data of NUREG/CR-6928 as is typically done in the reactor PSA. The duration ratio for each OCP is incorporated into SFP-PSA model to adjust the frequency along with the OCP ratio as shown in Fig. 3.

### 7.2. Component reliability/unavailability

The component reliability and unavailability for general components such as pumps, valves or heat exchangers are evaluated based on the generic industry data of NUREG/CR-6928 [4] as is typically done in most reactor PSA. In case of a fire truck pump, it

**Table 4**
Major Level set-points of SFP.

| Major Level Set-points |
|---|
| Normal Level |
| Lo Alarm |
| Lo-Lo Alarm |
| SFP cooling pump automatically stop |
| Suction Line |
| Discharge Line (Siphone Success) |
| Discharge Line (Siphone Failure) |
| Required shielding level |
| Top of the fuel |

may need further analysis considering its working environment because it is a mobile equipment. However, the reliability data for a fire truck pump in this study is referred to the reliability data for diesel engine pump in NUREG/CR-6928 considering that a fire truck pump is driven by diesel-driven engine.

### 7.3. Common cause failure

Common cause failure (CCF) analysis for the SFP-PSA is performed using the alpha factor method. The CCF parameters in the NRC report entitled "CCF Parameter Estimations, 2015 Update [5]" are used in this study.

### 7.4. Offsite power recovery

The probability of offsite power recovery is evaluated based on the lognormal distribution introduced in NUREG/CR-6890 [6].

### 7.5. Human error probability

Human Reliability Analysis (HRA) for the SFP-PSA is carried out to evaluate the human failure events (HFEs) associated with mitigation systems operation. The HFEs are identified as part of the event sequence development process, and the human error probabilities (HEPs) for the HFEs are evaluated using the EPRI HRA Calculator (Version 5.1) [7]. In this study, Human Cognitive Reliability/Operator Reactor Experiments (HCR/ORE), Cause-Based Decision Tree Method (CBDTM) [8], and Techniques for Human Error Rate Prediction (THERP) [9] are used to evaluate the HFEs modeled in the SFP-PSA model. The maximum value between the two methodologies, HCR/ORE and CBDTM, is used for cognitive error. The value by the methodology of THERP is used for action error. The HRA procedure for SFP-PSA in this study follows the general procedure used for Reactor PSA. However, as stated in section 5, the timings for successful operator actions change along with the OCP group. Therefore, analysts should be careful of applying the accurate timings for HFEs in each OCP group. Dependency analysis for HFEs is also conducted, and the result is incorporated in model quantification.

## 8. Potential interaction between reactor and SFP

Potential interaction between reactor and SFP is highlighted in the EPRI report [2]. Impact of the potential interaction between reactor and SFP for APR-1400 is consulted with the review of Level 2 PS A result for APR-1400.

Since the containment and SFP are physically separated in APR-1400, potential interaction may occur when containment building is dynamically damaged, assuming that the fragments of containment building may strike the safety systems or the structure for SFP.

For such a potential interaction with SFP, containment failure mode should be dynamic. Even though containment fails dynamically, this is very unlikely due to the uncertainty of the direction and the energy of fragments. For reviewing the potential interaction impact, it is assumed that all the dynamic containment failures cause an initiating event on SFP. The dynamic containment failures are known to be caused by the phenomena of reactor vessel explosion, hydrogen explosion, steam explosion, containment high pressure, and high pressure melt ejection. In APR-1400 Level 2 PS A, the dynamic containment failures by the phenomena above are contributors to early containment failure (ECF), late containment failure (LCF), and containment failure before vessel breach (CFBRB) among the containment failure groups (see Table 5).

For the review, the frequency for the dynamic containment failures is calculated by summing the frequency of ECF, LCF, and CFBRB. This is quite conservative approach in the fact that the containment failure groups contain a leak containment failure mode which is not expected to have the potential interaction. From the result of APR-1400 Level 2 PS A, the frequency is mid of E−08/yr. The frequency itself is low enough to be screened out following ASME/ANS PRA standard [10]. Therefore, the SFP risk by dynamic containment failure should be negligible.

## 9. Quantification

The event tree and fault tree model developed for the SFP Level 1 internal events PSA is quantified using SAREX computer code [11] to identify potential accident scenarios for fuel damage. The total

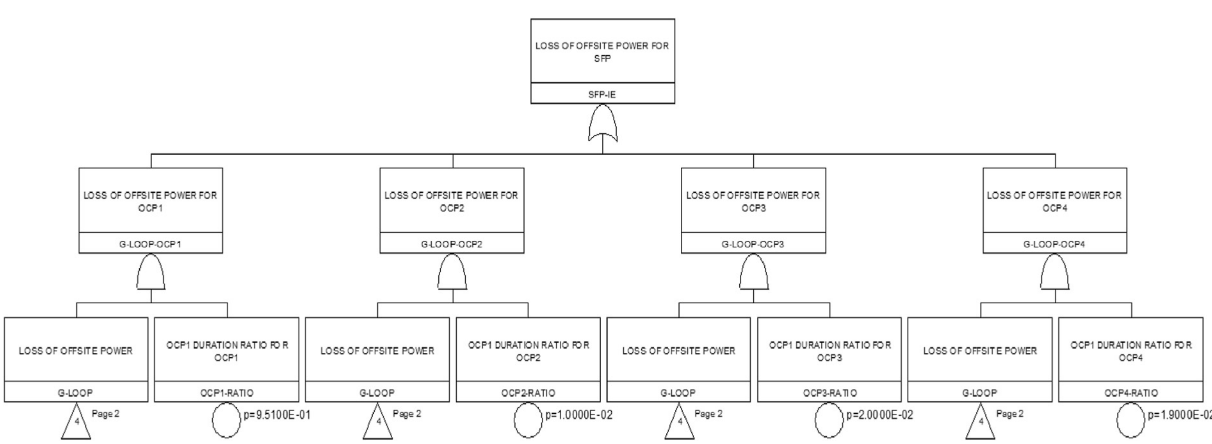


**Fig. 3.** Fault tree modelling for incorporating each OCP ratio.

**Table 5**
Containment failure modes in APR-1400 level 2 PS A

| Containment Failure Mode | Description |
|---|---|
| NOCF | No Containment Failure |
| ECF | Early Containment Failure |
| LCF | Late Containment Failure |
| BMT | Base-mat Melt Through |
| CFBRB | Containment Failure Before Vessel Breach |
| NOTISO | Containment Isolation Failure |
| BYPASS | Containment Bypass |

fuel damage frequency (FDF) is evaluated to be the mid-range of 1E-9/yr. Table 6 shows contribution of each OCP to FDF. The result shows that risk contribution of OCP1 is the highest while that of OCP4 is the lowest.

Decay power level changes along with the OCP group, and it affects the timings for reaching major level set-points. Especially, as stated in section 5, OCP3 has the highest decay power meaning that there is relatively shorter time available for successful operator actions. As well as decay power, system configuration changes along with the OCP group. For instance, in OCP3, one of two EDGs is unavailable due to scheduled maintenance. Even if the condition of OCP3 for the accident mitigation is worst among the OCPs, its contribution to SFP risk is estimated to be the second highest. This is due to the much shorter duration ratio of OCP3 (2.0%) than that of OCP1 (95.1%) which has the highest contribution to SFP risk.

The result of importance analysis, Fussell-Vesely (FV), is presented in Table 7. Human actions, Emergency/Alternative AC Diesel Generator, SFP Cooling Pumps, and External Injection Pump are identified to be important.

## 10. Sensitivity analysis

As seen in the importance analysis, human actions are found to be important for SFP risk. Two sensitivity analyses are conducted to find out the impact of human-related action, repair of cooling train(s) and human actions. The results of the sensitivity analysis are presented in Table 8.

### *10.1. Consideration of repair*

Repair of cooling train(s) or injection train(s) could be possible

**Table 6**
Fuel damage frequency contribution for OCPs.

| OCP Classification | Contribution of each OCP to FDF (%) |
|---|---|
| 1 | 73.3 |
| 2 | 4.2 |
| 3 | 21.7 |
| 4 | 0.7 |
| Total | 100.0 |

**Table 7**
Result of importance analysis.

| Basic Event | Event Type | Fussell-Vesely (FV) |
|---|---|---|
| HR-MAKEUP-FPS | Human Action | 0.96 |
| HR-MAKEUP-EX | Human Action | 0.57 |
| EXDPR-S-PP | Equipment Failure | 0.42 |
| HR-MAKEUP-DWST | Human Action | 0.23 |
| DGDGR-A-DGA | Equipment Failure | 0.22 |
| HR-MAKEUP-BAST | Human Action | 0.21 |
| DADGR-S-AACDG | Equipment Failure | 0.16 |
| DGDGR-B-DGB | Equipment Failure | 0.15 |
| VFHVM-A-HV02A | Equipment Failure | 0.12 |
| FCMPS-A-PP01A | Equipment Failure | 0.11 |

**Table 8**
FDF change for sensitivity cases.

| Sensitivity Case | FDF Comparison (%) (Sensitivity/Base) |
|---|---|
| Consideration of Repair | −14.7 |
| Human Error Probability | 22.2 |

because the time available before fuel damage is considerably long. In this sensitivity study, the repair of SFP cooling pump is considered. The repair probability is estimated using an exponential distribution for the repair time following the approach taken in NUREG-1738:

$$P = \exp\left(-\left(\frac{1}{\mathrm{MTTR}}\right)^{*}t\right) \tag{3}$$

10 h for MTTR and 16 h for the arrangement of parts and technical support work are used in accordance with the assumption in NUREG-1738. This means that more than 16 h is required for repair work. Considering the minimum required time of 16 h, repairing of SFP cooling pump is applied except for refueling stage (OCP3) where the expected available time for repair is less than 16 h. Approach of cutsets recovery is used for the sensitivity analysis. The result shows 14.7% decrease compared with the base FDF.

### *10.2. Human error probability*

The SFP cooling and injection systems are not automated meaning that they need manual action for functioning. Therefore, HFE(s) are important contributors to SFP risk as it is noticed in the importance analysis. In the sensitivity analysis, all HEPs are assigned to be 2 times higher than that of the normal value. Approach of cutsets recovery is used for the sensitivity analysis. The result shows 22% increase compared with base FDF.

## 11. Conclusion

The Framework of SFP-PSA for APR-1400 is developed and a case study is conducted with the initiating event, LOOP. The result of the study shows relatively low FDF, and therefore, the SFP risk should be negligible. However, some meaningful insights are derived from the study as follows:

1) Human failure events are found to be most important factors for the SFP accident mitigation. Therefore, operator training and well-developed mitigation procedure should be effective for preventing the fuel damage. The procedure should have clear directions regarding to when, where, who, what, how, and why each mitigation system should be utilized.
2) Repairing action of cooling train or injection train is applicable because SFP accident progresses quite slowly. To do so, well-developed repairing procedure should be prepared. The procedure should clearly define control tower (communication hierarchy), maintenance training, the way for introduction of spare parts, inter-connection with mitigation procedure, communication method between operators and maintenance crew.
3) The containment failure-induced initiating event through potential interaction between reactor and SFP could occur. The impact of the potential initiating event for SFP is reviewed in terms of its frequency, and it is found to be low enough to be negligible.

The framework introduced here can be applicable to SFP-PSA for other plants with cautiously applying plant-specific information.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.09.011.

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