Internal Events Level 1 PSA study of Armenian NPP Spent Fuel Pools

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Abstract: The spent fuel pools (SFPs) of WWER 440 are located in the reactor hall, which is not leak-tight, and, therefore the fuel damage can lead to significant releases with very severe consequences. As well as insights from Fukushima, accident underlined the importance of safety of the SFP. The paper presents a probabilistic analysis for Armenian nuclear power plant (ANPP) SFPs performed in the frame of lifetime extension, which covers consideration of internal events for spent fuel pool at full power operation. The internal events analysis will allow understanding the risk profile of spent fuel pool and will give a platform for further analysis of the influence of the different types of hazards (internal and external) on spent fuel pool safety operation, as well as to conduct level 2 PSA for SFPs. The main steps to conduct the internal events Level 1 PSA for SFPs are presented. It is shown that the mean values of fuel damage (FD) frequency of SFPs in the case when ANPP Unit 2 is in full power mode are 5.74E-7 [1/y] for Unit 1 SFP and 5.78E-7 [1/y] for Unit 2 SFP. Based on quantification results main insights are discussed in the paper.

Keywords: PSA, SFP PSA, Spent Fuel Pool, WWER, Internal Initiating events.

1. INTRODUCTION

The accidents at the Fukushima nuclear power plants (NPPs) on 11th March 2011 highlighted the importance of the safety of spent fuel pool (SFP) [1-3]. After this accident many utilities initiated SFP PSAs to show that the SFP safety is at appropriate level and reveal possible weak points and areas that could be improved.

This paper is intended to present the approaches, results and conclusions of the internal event Level 1 PSA performed for WWER-440 SFP of ANPP. The internal events analysis will allow understanding the risk profile of the spent fuel pool and will give a platform for further analysis of the influence of the different types of hazards (internal and external) on spent fuel pool safety operation, as well as to conduct level 2 PSA for SFPs.

1. WORKFLOW

The internal event Level 1 PSA performed for SFP of ANPP consists of technical activities presented in Figure 1.

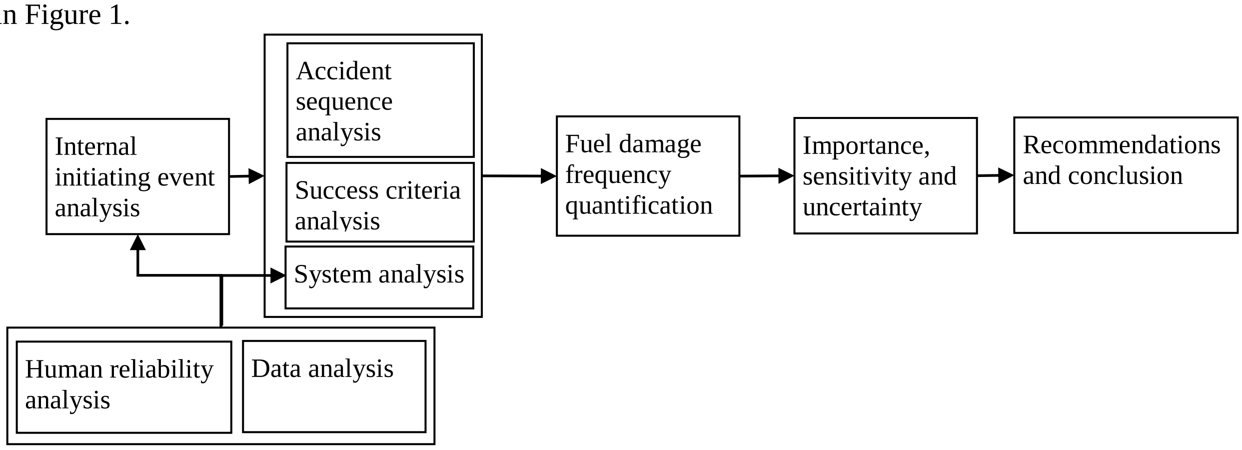

Figure 1. Main technical tasks of Armenian NPP SFP PSA

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These activities are the ones that must be implemented during any PSA study independently of hazard source. More detailed information on each implemented task are presented in the further sections of the paper.

2. SCOPE OF THE STUDY

Armenian NPP consists of 2 units. Although the Unit 1 is in the permanent shutdown condition, its SFP is in operation for storing the spent fuel with relatively low decay heat from the Unit 2. Current study considers not only full power plant operational state (OS), but also fuel transportation SFP OS, which was not covered in low power shutdown (LPSD) PSA study. The fuel transportation can have significant impact on risk associated with fuel integrity and impact on the fuel damage frequency, despite the fact that in such accidents the releases will be significantly low.

The OSs which were considered in Unit 1 SFP and Unit 2 SFP PSA are presented in the Table 1 and Table 2 correspondingly.

Table 1. OSs of Unit 1 SFP

ID	Description	Duration [hour]	Probability of SFP OS
SFP OS 1	In SFP the coolant level is in the range of 4.6÷4.9 m, transportation is not permitted	8725.06	9.960E-1
SFP OS 2	In SFP the coolant level is in the range of 10.2÷10.5 m, transportation of spent fuel is not practiced	34.316	3.92E-3
SFP OS 3	In SFP the coolant level is in the range of 10.2÷10.5 m, transportation of spent fuel	0.6251	7.14E-5

Table 2. OSs of Unit 2 SFP

ID	Description	Duration [hour]	Probability of SFP OS
SFP OS 1	In SFP the coolant level is in the range of 4.6÷4.9 m, transportation is not permitted	8241.23	9.41E-1
SFP OS 2	In SFP the coolant level is in the range of 10.2÷10.5 m, transportation of spent fuel is not practiced	177.0551	2.02E-2
SFP OS 3	In SFP the coolant level is in the range of 10.2÷10.5 m, transportation of spent fuel	27.965	3.19E-3

During plant operation, depending on the plant operational state (POS), two possible coolant levels can be found in the Unit 2 SFP.

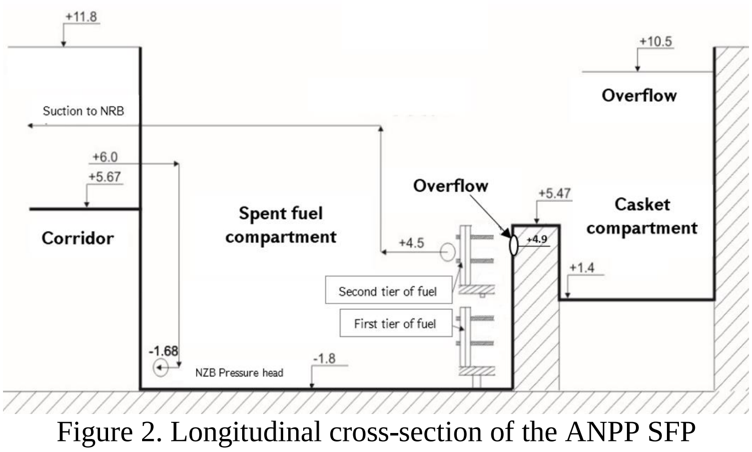

Figure 2. Longitudinal cross-section of the ANPP SFP

During the POS at which transportation of fuel is allowed, coolant levels can be 10.5 m, in cases when the fuel is transported it must be 10.5 m, in all other cases the coolant levels should be at least in the range of 4.6 ÷ 4.9 m [4]. The elevations are shown in Figure 2.

3. INITIATING EVENT ANALYSIS

The list of initiating events (IEs) for the probabilistic safety analysis of Units 1 and 2 SFPs was selected based on international practices. During IE selection, the following was considered:

- Generalized lists of IEs;
- Operational experience;
- List of IEs for the low power and shutdown ANPP study;
- Investigation of SFP related systems;
- Analysis with master logic diagram (MLD).

The list of IEs was revised to reveal the IEs that could be screened out. After the final applicable IEs were identified and grouped (see Table 3).

Table 3: List of IEs groups

#	Groups of IEs	IEs
1.	Loss of SFP cooling system of Unit 2 SFP	Loss of SFP cooling system of Unit 2 SFP
2.	Partial loss of the essential service water system	Partial loss of the essential service water system
3.	Loss of the essential service water system	Loss of the essential service water system
4.	Loss of site power	Loss of site power
5.	Loss of coolant from SFP to confinement, compensable with one NBO for SFP OS 1 and OS 2	Loss of coolant from SFP to confinement, compensable with one NBO for SFP OS 1 and OS 2
6.	Loss of coolant from SFP out of confinement, compensable with one NBO for SFP OS 1 and OS 2	Loss of coolant from SFP out of confinement, compensable with one NBO for SFP OS 1 and OS 2
7.	Loss of coolant from SFP to casket compartment of SFP, compensable with one NBO for SFP OS 1 and OS 2	Loss of coolant from SFP to casket compartment of SFP, compensable with one NBO for SFP OS 1 and OS 2
8.	Inadvertent draining of the Unit 2 SFP	Inadvertent draining of the SFP
9.	Mechanical damage of fuel	Heavy load drop into SFP
		Fuel damage during transportation

The frequencies were estimated for each group of IEs.

4. ACCIDENT SEQUENCE ANALYSIS

Accident sequence modeling during PSA implementation was an interactive process and was conducted in parallel with another task. An accident/event sequence model provides sequences of the events that follow the IE and are aimed to mitigate it. These sequences of the events lead either to the successful state or to the undesirable end state. Modeling of accident sequences was performed using event tree (ET) method. The considered end states are:

OK: successful final condition of the accident sequence specified by the stable parameters (the parameters are maintainable at least for mission time upon stabilization) of SFP.

FD1: Unit 1 SFP – unsuccessful final condition of the accident sequence is identified by FD, which, in its turn, is specified by achievement of the following conditions:

- uncovery of Unit 1 SFP fuel,
- mechanical damage of Unit 1 SFP fuel.

FD2: Unit 2 SFP – unsuccessful final condition of the accident sequence is identified by FD, which, in its turn, is specified by achievement of the following conditions:

- uncovery of Unit 2 SFP fuel,
- mechanical damage of Unit 2 SFP fuel.

The assumed final conditions were deterministically obtained using the models of ANPP Unit 1 SFP and Unit 2 SFP developed with RELAP5/Mod3.3 code. Calculations were performed applying basic event (BE) approach.

5. SYSTEM ANALYSIS

The system analysis is aimed at development of logic model that would correctly reflect the system's functioning depending on:

- Condition of system components;
- Operation of support systems;
- Human activities;
- Other factors.

System analysis was performed applying fault tree (FT) method. RiskSpectrum code was used to develop the system logical model. Based on the success criteria specified for IEs, the systems that are necessary to mitigate IEs were identified. The cooling and refilling systems were analyzed. In performed analysis, supporting systems of cooling and refilling systems were not modelled anew, IIE PSA model was used to reflect essential service water system (ESWS) and power supply systems.

Below we present the assumptions made during model development, these assumptions are based on principles, which are outlined in [4]:

- Conservatively 72-hour mission time was used for the entire model, despite the fact that based on thermal-hydraulic analysis results for loss of cooling accidents 8-hour mission time can be used.
- Taking into account that in case of the loss of cooling accidents the operator has sufficient time, it was considered that in case of failure of all cooling means of Unit 2 SFP the operator uses the means of Unit 1 SFP to cool Unit 2 SFP fuel.
- The boron solution purification station is separated from the cooling and refilling system. The U4-1 valve is closed and should remain closed. It is not considered in the current model, since it consists of passive components only.
- In case when two valves are in-line and both are closed, only one valve is considered.
- The cooling and refilling system conditionally was divided into 2 systems - cooling system and refilling system.

6. HUMAN RELIABILITY ANALYSIS

To reflect the human errors in the Unit 1 and Unit 2 SFP models, the following human error categories were considered:

Category A – actions that cause equipment or systems to be unavailable, when required, post-fault.

Category B – actions that either by themselves or in combination with equipment failures lead directly to the initiating events/faults.

Category C – actions occurring post-fault. These can either occur in the performance of safety actions or can be actions that aggravate the fault sequence.

For any type of human error, incorporation of HRA into PSA is separated into seven basic tasks: definition, screening, qualitative analysis, representation, model integration, quantification and documentation. The data presented in technique for human error rate prediction (THERP) were used to quantify the human failure probabilities for different actions and conditions. Table of failed actions was developed for the selected human errors. Based on this table, FTs were constructed to quantify the BE values [5].

The first quantification results were analyzed to identify the MCSs which contain more than one human error BEs. For these BEs the dependencies were revealed and considered based on THERP methodology.

7. DATA ANALYSIS

Performed data analysis provided us with quantitative information necessary to assess occurrence of accident sequences. In particular, this task included assessment of the following:

- Parameters of equipment reliability (i.e., intensity of component failures and probability of their request failures);
- Unavailability of components due to testing and maintenance;
- Parameters of component CCFs;
- IE frequency.

The required information was derived from two main sources [6]:

- Armenian NPP specific data (starting from 1996);
- Generic data.

This information was used to perform Bayesian modification.

In analysis of IE frequencies, it was postulated that IE frequency does not depend on time and it is a constant value. For system failure IEs the frequencies were specified based on the relevant system FT analysis.

To perform CCF analysis, the components were grouped based on their similarities and possible failure types. In order to specify CCFs, the MGL model was used.

8. FUEL DAMAGE FREQUENCY QUANTIFICATION RESULTS

Quantification shows that the mean values of FD frequency when the ANPP Unit 2 is in full power mode are 5.74E-7 [1/y] for Unit 1 SFP and 5.78E-7 [1/y] for Unit 2 SFP. Quantification results are presented.

The mean values of the total FD frequencies (due to fuel uncovery) of the Unit 1 SFP and Unit 2 SFP for extended project scope (including fuel transportation SFPOS) are 5.74E-7[1/y] and 7.71E-5[1/y] correspondingly. In addition, it was found that the mechanical damage of fuel can be observed with the frequency 6.93E-5[1/y]. Calculation results are presented in the Table 4.

Table 4: Results of SFP PSA model quantification - mechanical FD and FD due to uncovery for extended project scope

	Mechanical fuel damage[1] [1/y]			**Fuel damage due to uncovery [1/y]**		
	5th percentile	**Mean**	**95th percentile**	**5th percentile**	**Mean**	**95th percentile**
Unit 1 SFP	1.37E-6	3.26E-5	1.19E-4	3.73E-8	5.74E-7	1.80E-6
Unit 2 SFP	1.36E-6	3.67E-5	1.61E-4	2.16E-5	7.71E-5	1.95E-4
Unit 1 SFP and Unit 2 SFP	6.89E-6	6.93E-5	2.31E-4	2.16E-5	7.77E-5	1.72E-4

Dominant risk contributors, risk importance and sensitivity analyses were performed.

Based on the analysis of dominant risk contributors it could be concluded that:

- The importance of mechanical damage is high, this is conditioned by the fact that for the fuel of Unit 1 SFP and Unit 2 SFP any mechanical damage is considered as an undesirable event;
- Though the human induced LOCA is possible only in case of Unit 2 SFP fuel transportation inside the pool, its importance is extremely high. This is conditioned by the fact that no means were considered to mitigate this accident. Since during transportation inside the pool the coolant layer above the fuel is decreased, the mitigation actions were not considered.

Analysis showed that the following items are risk important:

[1]In case of mechanical damage of fuel, there is a procedure to isolate the damaged fuel in casket which is not reflected in the estimated value.

- Human actions aimed at configuring feeding lines for refilling Unit 1 SFP and Unit 2 SFP, and cooling Unit 2 SFP;
- 1NBO[2]-1, 1NZB[3] and 2NZB pumps;
- 2NBO-1 and 2NBO-2 pumps;
- Sump clogging.

Sensitivity analysis showed that the results are sensitive to the following assumptions and data:

- Human error probabilities (all front-line systems of Unit 1 SFP and Unit 2 SFP are operated manually);
- Assumption related to the mission time for loss of cooling accidents (72 hours);
- Crediting possibility to perform "supply and overflow the coolant" procedure of Unit 2 SFP using Unit 1 SFP systems.

9. CONCLUSION

The paper presents the process of the implementation of the SFP level 1 study for internal events of Armenian NPP. The PSA model was developed for SFP taking into consideration the specificity of ANPP and fuel damage frequency was quantified. Based on quantification results significant risk contributors for SFP internal events were identified. The risk important items were determined, the assumptions and data to which the results are sensitive were revealed by sensitivity analysis.

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