The Study of Spent Fuel Pool Risk at Decommissioning Nuclear Power Plant in Taiwan

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Abstract: In Taiwan there are three nuclear power plants in operation, but their operation licenses are going to expire in recent years. According to the current Nuclear-Free- Homeland policy of the government, the existing plants are not allowed to extend their operations. Therefore, the plants will be shutdown permanently as long as their licenses are expired, and the process of decommissioning the plants will be implemented.

Removing spent fuel of the last fuel cycle from the reactor is usually the first step of decommissioning, followed by the transfer of all spent fuel assemblies to an interim storage facility. In the practical situation of Taiwan, the interim storage facilities could not come into use in time; therefore, it means that the spent fuel in the plants is very likely to remain stored in the spent fuel pools for a long time. This would make the licensing process of decommissioning much more complicated.

This paper attempts to demonstrate the risk of a decommissioning plant that would store its fuel in the spent fuel pool for an indefinite period. The initiating events under study includes loss of coolant inventory, loss of offsite power, loss of cooling, internal fire, internal flood, seismic events, high wind events and aircraft crashes. According to the results of the study, the total risk in terms of spent fuel uncovery frequency is about one order less than the CDF of the power operation.

Evaluating the risk of the spent fuel pool may assist to modify the original pool into an independent spent fuel storage installation. It is found that keeping an emergency diesel generator available will significantly lower the risk of spent fuel uncovery. It also demonstrates that the risk is quite low during the nuclear power plant decommissioning.

Keywords: PRA, Risk of Spent Fuel Pool, Risk of Decommissioning Nuclear Power Plant.

1. INTRODUCTION

Kuosheng Nuclear Power Plant (KSNPP), at which there are two BWR units, has been in operation for about 37 years; therefore, the forty-year-operation license of the first unit is going to expire. Because of Nuclear-Free-Homeland policy in Taiwan, Taiwanese government has a tendency to not extend the expiration of licenses; additionally, the Electricity Act claims that in 2025 all nuclear power units will be shutdown.

Generally speaking, the first step of decommissioning nuclear power plant is to remove nuclear fuel assemblies from a reactor vessel and a spent fuel pool; however, KSNPP will not remove the assemblies from the spent fuel pool until dry storage facilities are installed. It means that the licensee must take the extended operation of the spent fuel pool into consideration during decommissioning the plant.

The purpose of this paper is to find out the potential hazard of the spent fuel pool in KSNPP during decommissioning the plant and to evaluate the initiating events which are likely to have a significant impact on the spent fuel assemblies. The result could help licensee modify the spent fuel pools safer.

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2. SYSTEMS OF SFP DURING KSNPP DECOMMISSIONED

The main system about a spent fuel pool is a cooling system which removes the decay heat of spent fuel from the pool. In addition, there are other systems supporting the cooling system such as electricity systems, compressed air system and cooling water system which is the heat sink of the spent fuel pool cooling system.

The normal spent fuel cooling system in the plant is the spent fuel cooling and purification system (SFPCPS) whose functions are to maintain the coolant quality in the pool and to remove the decay heat from spent fuel pool. The SFPCPS has two 100-percent capacity cooling loops and each cooling loop has a pump, a heat exchanger and related pipes and valves. Furthermore, there is a drain tank for both loops. The water in the spent fuel pool overflows down the drain tank from which the pump takes water through a pipe. The pumping loop circulates water through the heat exchanger and the filter-demineralizer and returns the flow to the spent fuel pool

The tube side of the heat exchanger is the pool water, and its shell side is the fluid of the nuclear component closed cooling water system (NCCCWS). During the power operation, the NCCCWS provide some plant systems with cooling water, included the heat exchanger of the spent fuel pool. The NCCCWS also has its own pumps, exchangers, pipes and valves. Its heat sink was provided by the external circulating water system which is the subsystem of circulating water system providing cooling water for the removal of heat from the main condensers.

When reactor shutdown, reducing the cost of operating and maintaining spent fuel pool will be expected. The NCCCWS and circulating water system are large systems; therefore, the SPFCPS and its supporting systems should be changed during the plant decommissioning. The ultimate heat sink of the original design is sea water which be provided by external circulating water system. The licensee consider that changing ultimate heat sink from water cool to air cool would be more reliable and simpler. Hence, the fluid of the shell side of the heat exchanger will be replaced with new system which has cooling towers and the NCCCWS and circulating water system will no longer serve the SFPCPS when finishing the design change.

The condensate transfer system is the original design which severs the pool for making up water inventory. During the plant decommissioned, this system is to conduct normal and emergency water make-up for ensuring fuel covered by water and the SFPCPS runs exactly. Therefore, this system is deemed a mitigation system in this study.

The power supply of the SFPCPS is connected to non-safety related buses, which means that the components of the SFPCPS will not run during losing offsite power. Although the decay heat generation rate of fuel assemblies would be quite low, changing its power supply should be conducted in view of the philosophy of defense in depth. The 5th diesel generator is the backup diesel generator of division I and division II diesel generator. During the plant decommissioned, the safety related systems of division I and division II will be dismantled, and the backup AC power will be the 5th diesel generator which serves SFPCPS during losing offsite power. Furthermore, the licensee will prepare another extra mobile diesel generator as the backup of the 5th diesel generator.

There will be other design change for making spent fuel pool become an independent spent fuel storage installation as able as possible. At least, the operation of the spent fuel pools could not have negative effects on the decommissioning work

3. INITIATING EVENTS

3.1. Screening Internal Initiating Events

The internal initiating events for a spent fuel pool are very limited. First, the pool stores many nuclear fuel assemblies, so the criticality has to take into consideration. In this part, the Final Safety Analysis [1] of KSNPP has related analysis and multiplication has to ensure less than 1; therefore, the criticality event in the spent fuel pool can be screened.

Second, when fuel assemblies in the spent fuel pool are covered by pool water, the integrity of them will not be challenged. The loss of coolant is another important initiating event. According the result of Structure Integrity Evaluation of Spent Fuel Pool for Kuosheng Nuclear Power Plant [2], the integrity of the spent fuel pool has been analyzed and it demonstrates that the loss of coolant is very limited and the fuel could have been covered by water for 72 hours after any event happens. Therefore, the loss of coolant can be screened.

Third, in regard to the storage of spent fuel assemblies, removing their decay heat is another significant issue in a facility. Therefore, loss of cooling event cannot be screened and its frequency should be evaluated for the following risk assessment. The method of evaluating its frequency is to prepare the SFPCS of the system fault tree and to change it to initiating event fault tree which calculate the frequency of loss of cooling.

At last, the power systems, included the 4.16kV system and the 480V system, provide the SPFCPS with electricity power, so the power source will have direct effect on the operation of cooling system. When losing offsite power, SPFCPS will be stop running until recover the AC power and restart the system. Therefore, loss of offsite should take into consideration and evaluate its frequency. The frequency comes from the data which use the data of the plant to modify the generic data which from NUREG/CR-6928 [3].

3.2. Screening External Initiating Events

External events always play an important role on the safety of nuclear reactors operating, and they will also happen to the spent fuel pool. In order to gain the entire events concerned by the industry, the list of external events was collected from the NUREG-1407[4], NUREG/CR-2300[5] and ASME/ANS RA-S-2009[6], and then 43 events was gotten. In addition, there are two extra events to be taken into discussion. They are the formation of dammed lakes and stranded ships, the events which were happened in Taiwan.

When the external initiating events were collected as much as possible, screening the events is the following the screening criteria, EXT-B1 and EXT-B2, on ASME/ANS RA-S-2009[6].

EXT-B1 has five screening criteria providing as acceptable bases for initially preliminarily screening out an external hazard. EXT-B2 is a criterion of the second preliminary screening, which is to meet the criteria in the U.S. Nuclear Regulatory Commission 1975 Standard Review Plan [7]. If an external hazard meets the criteria in the above Standard Review Plan, the contribution to core damage frequency (CDF) is less than 1E-6/year, or the frequency of an event is less than 1E-5/year and conditional core damage probability is less than 0.1 when the event occurred. However, above conditions are for the power operation. If EXT-B2 is repurposed on screening out external hazards of a spent fuel pool, its criteria will be changed for spent fuel pool during nuclear power decommissioning; otherwise, the result of screening will be over optimistic and not conservative due to the risk of spent fuel pools is less than the one of core. The risk indicator of this report is the fuel uncovery frequency of spent fuel pools. Therefore, compared with CDF, the screening-out value of fuel uncovery frequency (FUF) is adjusted to reducing a magnitude, i.e. a contributor to FUF is less than 1E-7/year. On the other hand, compared power operation, the occurrence frequency of events is adjusted to lessening a magnitude, i.e. the screening-out value of occurrence frequency is less than 1E-6/year.

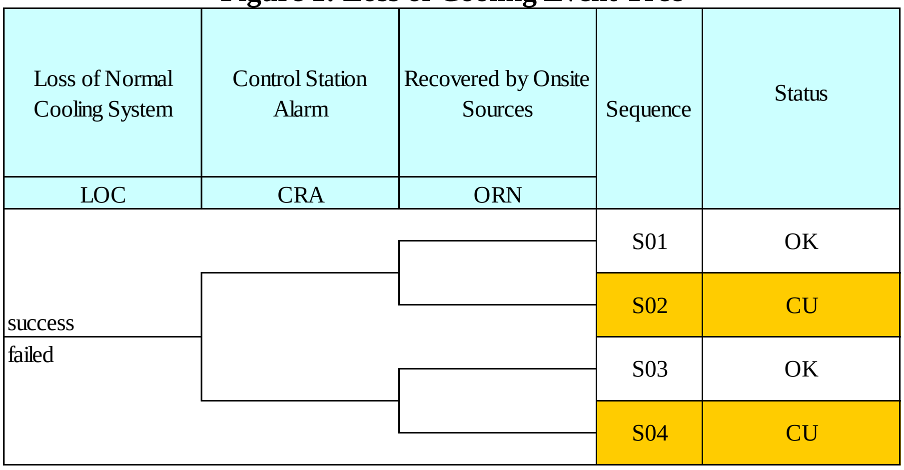
Eventually, five events were left behind after screening the external hazards. They are aircraft impact, high wind events, fire, internal flooding and seismic activities, those events which have to be analyzed in detail.

4. EVALUATING RISK
4.1. Internal Initiating Event Trees

The previous contents show that two internal events should be taken into account on the risk assessment, so developing event trees is the next step for quantifying. With regard to the loss of cooling event, alarm in a spent fuel pool control station and recovery using onsite source are important. The operators will be noticed what happened on a spent fuel pool and take action in time; otherwise, operator will be blind to status of the pool until crew members discover transient events when performing their walk-down of spent fuel pool area. Therefore, the alarms could decide available time for responses and influence human error probabilities. The other heading is recovery by onsite source. During loss of normal cooling, which means both loops are failed, the next strategy is to make up the coolant inventory of the pool for preventing fuel assemblies from uncovering by coolant. Fuel uncovery will be occurred when cooling system and makeup system are failed. The event tree of loss of cooling system is shown in Figure 1.

Every heading has its corresponding fault tree. The frequency of loss of cooling is from an IE-fault tree which is modified from cooling system fault tree. The corresponding fault tree of CRA heading takes temperature instruments of SFP and alarms in the control station and the fault tree of ORN heading is about condensate transfer system. When SFPCPS and condensate transfer system are failed, fuel will be not covered by water. There are some assumptions to make the conclusion. The cooling time of the last batch fuel assemblies is 7 days, and then the decay heat of the fuel assemblies will boil water inventory boil in 9.7 hours and cause water level to descend to above 3 meters of top of fuel assemblies in 47 hours. Therefore, when losing the cooling system, there is a little time for prepare makeup water system. Once the normal makeup water system failed, there is not enough time to mitigate the event.

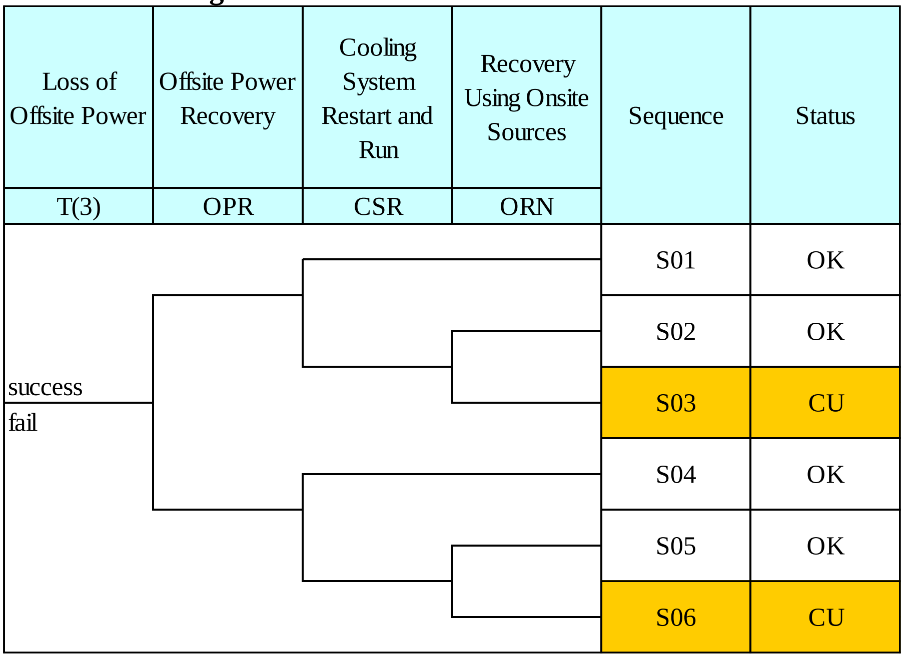
Figure 1: Loss of Cooling Event Tree



The loss of offsite power is the other internal event and the event tree of losing offsite power is shown in Figure 2. When it happens, recovering offsite power is the first concern. The third heading is the recovery of cooling system. Because this system fault tree includes an emergency diesel generator, recovery of offsite power is not necessary. The statuses of spent fuel pool will be OK if cooling system is restored. Otherwise, recovery using onsite sources has to take in the response strategy for this internal event. There is no difference in the assumptions of the fuel assemblies' decay heat between the two internal events. Therefore, once cooling system and condensate transfer system failed, the fuel uncover will take place.

A conditional fuel uncovery probability (CFUP) is a target to find out. When the frequency of initiating events is determined, frequency multiplies by CFUP is fuel uncovery frequency which is the main risk indicator to be discussed in this study.

Figure 2: Loss of Offsite Power Event Tree



4.2. Evaluating External Initiating Events

The methodology of frequency of aircraft impact is the Aircraft Crash Analysis Methodology (ACRAM) from DOE-STD-3014-2006[8], and information of aircrafts route map near the plant site was collected for calculating the frequency. Considering the geographic location of KSNPP, some directions of crash will hardly influence on the spent fuel pool. As a result, these directions will be excluded for avoiding overestimating. Categories of aircraft crash includes take-off, landing and in-flight crashes. The total aircraft crash rate which includes commercial and military aviation is 4.28E-08/year.

Evaluating internal fire and assessing internal flood are similar. The first step is to find out areas at where there is equipment relating to SFP. In order to evaluate the fire frequency, it is necessary to count up how much equipment is in the area. On the other hand, evaluating frequency of internal has to measure total water pipe lengths and their diameter. According to the previous information, the frequency of initiating events can be quantified, but also the scenarios of fire and flood events can be determined. Further information can gain from Table 1.

High wind event and seismic event are the same methodology to assess the risks. The process of analysing seismic events or high wind events has three parts. The first part is the seismic hazard analysis and the second part is the seismic fragility evaluation. The report of Development of Seismic PRA model for Kuosheng Nuclear Power Plants Following Fukushima Accident [9] has the latest data for this study. In addition, analysing high wind need wind hazard analysis and wind fragility evaluation. Those information can be found on the report of External Events PRA Models Standard Compliance and Application for the Operating NPPs [10]. The last part of analysing high wind event and seismic event is to develop sequences during the event. Figure 3 and Figure 4 demonstrate the event front end trees which are used to define sequences and also identify the plant statuses. Depending on the sequences and the statuses, suitable initiating event and the malfunctioning systems or components under certain sequence which be given feedback on the quantification model. Afterward, calculating frequency of sequences is the result of combination of hazard curves, fragility curves of equipment, and the successes and failures in a sequence, and the outcome is shown in Table 1.

Table 1: Risk of Spent Fuel Pool

Initiating Event	Scenario	Frequency	Condition Fuel Uncovery Probability
Loss of Cooling	SFPCPS failed	5.74E-03	2.44E-08
Loss of Offsite Power	Electrical grid failed	5.48E-02	6.26E-08
	Electrical equipment failed	1.49E-03	1.03E-07
	Switchyard failed	4.04E-03	1.04E-07
	Weather phenomenon induce	2.71E-03	6.49E-08
Aircraft Impact	Aircraft Impact	4.28E-08	1.00E+00
Internal Flood	Room 261A (Spray)	1.18E-04	2.44E-07
	Room 261A (Flood)	3.64E-05	2.44E-07
	Room 261A (Major Flood)	3.82E-05	2.44E-07
	Cooling tower Area	1.14E-06	2.44E-07
Internal Fire	Fire of Room 261A damaging SFPCPS pump A and B	2.12E-04	2.44E-07
	Fire of Room 266 damaging A train electrical power supply system	2.22E-05	1.25E-04
	Fire of Room 218 damaging B train electrical power supply system	2.22E-05	3.24E-07
	Fire of Cooling tower area	6.67E-04	2.44E-07
High Wind	Sequence S02	9.20E-05	2.44E-07
	Sequence S04	1.81E-05	2.97E-06
	Sequence S05	2.42E-06	4.39E-05
	Sequence S06	1.97E-06	5.40E-05
	Sequence S07	1.44E-04	6.66E-06
	Sequence S08	3.17E-05	9.11E-05
Seismic Event	Sequence S02	1.59E-03	4.39E-07
	Sequence S03	5.28E-08	1.45E-05
	Sequence S04	1.45E-05	3.03E-04
	Sequence S05	2.67E-07	1.00E-02
	Sequence S06	3.22E-06	7.68E-06
	Sequence S07	4.80E-08	2.53E-04
	Sequence S08	3.63E-06	3.33E-04
	Sequence S09	5.03E-07	1.00E-02
	Sequence S10	1.61E-06	1.00E-02
	Sequence S11	4.84E-07	1.00E-02
	Sequence S12	8.14E-08	1.00E-01
	Sequence S13	6.42E-08	1.00E+00

Figure 3: The Front End Tree of High Wind Event

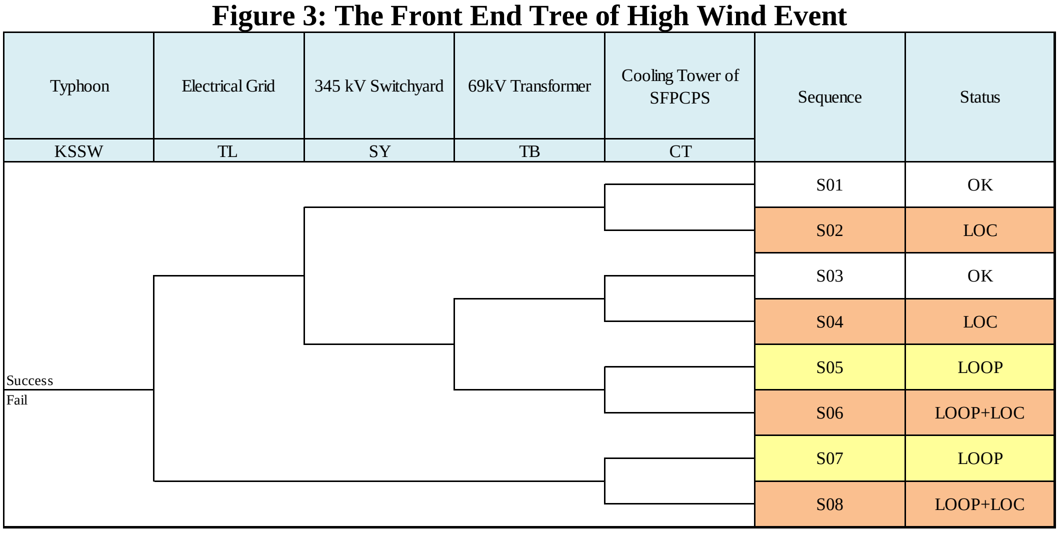
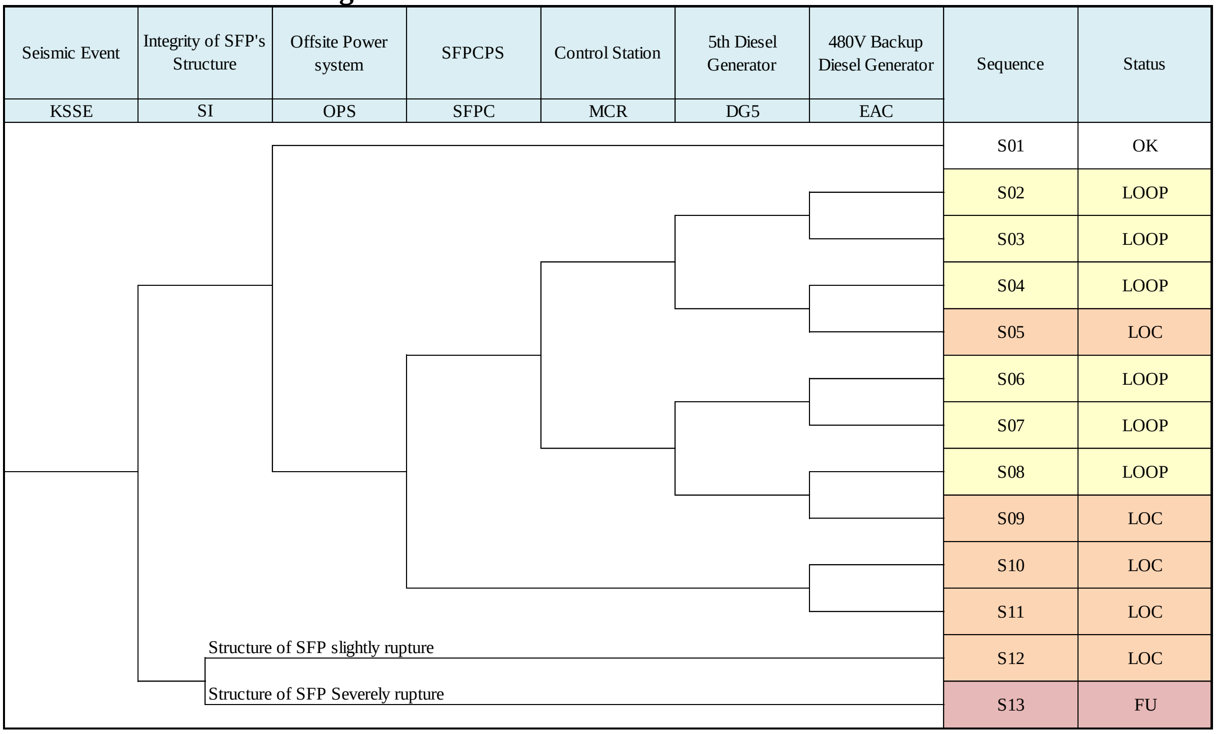


Figure 4: The Front End Tree of Seismic Event



4.3. Determining Probabilities of Offsite Resources Recovering

Except onsite resources, offsite resources can be taken into account and provide important strategy to mitigate accidents. However, the probabilities of offsite resources recovering are not easy to be identified. Hence, depending on the condition of system from the respective statuses, the reasonable probabilities of failing to recover by offsite resources are given. There are three distinctive conditions from slight failure to severe one, conditions which mean the damaging severity of the plant statuses. These conditions are given the probabilities from 1.00E-03 to 1.00E-1. The slightest condition means single system fail, so the shift crew members hardly fail to mitigate accidents by offsite resources. The second condition tells that situations are more complex and operators need more time to fix problems and have less strategy to recover systems. The last condition means that the plant encounters harsh disasters, such as beyond design basis earthquakes, ruin infrastructures on site or out of the site, which will make rescue actions more difficult. The scenarios from Table 1 are be categorized into the three conditions. Besides, the CFUPs in Table 1 have multiplied by the probabilities of failing to recovery by offsite resources.

Table 2: Probabilities of Offsite Resources Recovering

Condition	Scenario	Probability of failing to recover by offsite resource
General System Failure	Loss of cooling system, loss of offsite power, S02 in high wind event, S02 and S03 in seismic events	1.00E-03
Initiating events leading to systems severely damage	Internal fire, internal flood, S04, S05, S06, S07, S08, S09, S10 and S11 in seismic events	1.00E-02
Initiating events leading to infrastructure damage	S04, S05, S06, S07 and S08 in high wind events, S12 in seismic events	1.00E-01

4.4. The Risk of Spent Fuel Pool

The last accident which is not discussed in previous content is another existing issue. When relocating the fuel assemblies to interim storage facility, lifting cask has to implement; therefore, this risk should not be avoided. When transfer cask drop happens, the structure of the pool is ruined and rapid draindown occurs at the same time, that is, the fuel assemblies in the pool have to be uncovered. According NUREG-1738[11], the frequency rapid draindown due cask drop is 2.0E-7/year. Therefore, the fuel uncovery frequency is 2.0E-7/year.

After collating the data in Table 1, the fuel uncovery frequency, which is our risk indicator in our study, of SFP at KSNPP is shown as Table 3. The seismic event is a significant contributor in KSNPP. As Figure 4 shown, the scenario of seismic sequence S12 and seismic sequence S13 is that the pool structure damage. At first, the two sequences were not distinct; however, the frequency of the damage due to seismic events is 1.46E-7/year. As a result, the sequence separated into two independent sequences for presenting the risk more reasonable. The different between the two seismic sequences is that the sequence S12 can be mitigated by offsite resources but the sequence S13 cannot, and the probability of failing to recover by offsite resource is given by 0.1. Although this lessens the seismic risk, the pool, the pool rupture from beyond design basis earthquakes still accounts for 60% of the seismic risk, and it is too difficult to reduce this risk because of hardly reinforcing the pool structure.

Table 3: Risk of Spent Fuel Pool

Initiating Event	Fuel Uncovery Frequency(per year)	Percentage
Cask Drop	2.0E-07	55.35%
Loss of Cooling	1.40E-10	0.04%
Loss of Offsite Power	4.18E-09	1.16%
Aircraft impact	4.28E-08	11.85%
Internal Flood	4.73E-11	0.01%
Internal Fire	3.00E-09	0.83%
High Wind	4.14E-09	1.15%
Seismic Event	1.07E-07	29.61%
Total = 3.61E-07(per year)		

The aircraft impact is the second event for the risk. In this part, the most conservative scenario is that the cooling towers of SFPCPS, the condensate storage tank and the structure of pool are all damaged after aircraft crashes on the region of ISFSI, that is to say the CFUP equal to 1.00 in this condition. If the risk wants to be presented more realistic, influence of an aircraft impact is needed to study for further assessment.

4. CONCLUSION

The major risk is from the cask drop event and seismic event. The events have the same main cause which is the structure integrity of the pool is be challenged. Cask drop impacts the structure and leads to rapid draindown. The beyond design basis earthquake could ruin the integrity of structure and its liner, the failures which could cause rapid driandown as well. Both conditions are relating to the structure of the spent fuel pool, and it is difficult to reinforce the structure, i.e. the original design of the pool almost controls the result.

The risk from the pool during decommissioning is less two orders of magnitude than from the reactor during power operating. The offsite resources are taken into consideration as effective rescue actions, because the higher decay heat generation rate is adopted in this study. Predictably, while the cooling time of the last batch of the fuel is longer, the amount decay heat of the pool become lower. In other word, the risk will descend as time goes on. However, the major contributor is not relating to decay heat instead of the structure integrity. The effect of decay heat descending is limited.

Assessing the risk of spent fuel pool in KSNPP is a good way to identify the contributors and their importance. Because of some non-technical issues in Taiwan, interim storage facilities could not be built and operated in time to accommodate the spent fuel assemblies. For this reason, the assemblies are very likely to stay in the spent fuel pool during KSNPP decommissioning, and it will make decommissioning tasks more complicated. The result can provide the authority in Taiwan a clear the risk profile of the spent fuel pool during KSNPP decommissioning.

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