A Human Reliability Analysis of the Safety of the Spent Fuel in the Spent Fuel Pool of Decommissioning Nuclear Plants

- Task 1 Report for the User Need NSIR-2015-001
"Request to Perform Applied Research to Inform Decommissioning Plant Rulemaking"

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ABSTRACT

This report fulfills Task 1 of the User Need NSIR-2015-001 request to perform applied research to inform decommissioning plant rulemaking. Task 1 of the user need requests the performance of a task analysis of mitigation actions. Specifically, RES agreed to perform two task analyses, one for a boiling water reactor (BWR) and one for a pressurized water reactor (PWR), to (i) determine the time the representative licensee’s on-shift decommissioning organization would take to implement procedures to mitigate a spent fuel pool drain down event, and (ii) estimate the likelihood of successful deployment of the mitigation measures to prevent fuel overheating. The report uses the Vermont Yankee Nuclear Power Station (VY) and the San Onofre Nuclear Generation Station (SONGS) as the BWR and PWR reference plants respectively to perform the task analyses. The task analyses are based on the various NRC-conducted or -sponsored studies related to the safety of the spent fuel in the spent fuel pools and plant-specific information collected before, during, and after the two plant visits conducted for the study.

The task analyses were performed against the nine initiating events identified in NUREG-1738 “Technical study of SFP Accident Risk at Decommissioning Nuclear Power Plants” for a decommissioning plant probabilistic risk assessment. The results show that the plant staff and offsite support can reliably implement the mitigation strategies to prevent spent fuel heat-up damage. This study identified that only the events (extreme earthquake and large aircraft impact) causing a rapid SFP water draindown would challenge the successful mitigation of fuel heat-up.

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1 Introduction

This report documents a human reliability analysis (HRA) performed to support a rulemaking on the emergency plan regulatory requirements for decommissioning nuclear power plants (NPPs). For decommissioning NPPs, because the reactor no longer contains fuel, the spent fuel in spent fuel pools (SFPs) and in dry casks are the main radioactivity sources. It is generally understood that decommissioning plants have significantly lower risk compared to operating plants. Nevertheless, during normal plant operation, automated systems are in place to protect reactor safety. There is no system automation to protect SFP safety. SFP protection relies on manual action.

Staffing, instrumentation, procedures, training, event mitigation equipment and administrative controls, etc. are in place to ensure the safety of SFP fuel until all fuel is loaded into dry casks. In this study, two activities provided the study's foundation: (1) a literature review and (2) visits to two decommissioning sites, Vermont Yankee nuclear power station (VY) and the San Onofre Nuclear Generating Station (SONGS), in which project staff walked down the mitigation equipment and talked to the plant staff familiar with SFP operations and mitigation strategies.

The staff selected VY and SONGS to represent the designs of boiling water reactors (BWRs) and pressurized water reactors (PWRs). VY, owned by Entergy, is a single unit BWR. It has an SFP located on the upper section of the reactor building. The top of VY's SFP is about 93 feet above grade level. VY permanently ceased reactor operation on December 29, 2014. On March 14, 2014, Entergy requested the Nuclear Regulatory Commission (NRC) to approve the elimination of the portions of the requirements for the licensee to maintain formal offsite radiological emergency plans, and reduce some of the onsite emergency plan (EP) activities, based on the reduced risks associated with the plant being permanently shutdown and defueled [1]. The NRC approved Entergy's request, effective on April 15, 2016 [2]. After the effective date, VY no longer needs to maintain the emergency planning zone identified in its license. The plant will maintain an onsite emergency plan and response capabilities, including the continued notification of state and local government officials for an emergency declaration. Based on the decommissioning schedule, all of VY's spent fuel is scheduled to be in dry casks by the end of December, 2020.

SONGS, owned by Southern California Edison (SCE), has two PWRs (Units 2 and 3). It has two SFPs located separately within the two SFP buildings adjacent to Unit 2 and Unit 3. Each unit has its own SFP cooling system and the SFP normal makeup system. About half of each SFP is below grade level. SCE formally notified the NRC on June 12, 2013, that it had permanently ceased operation of Units 2 and 3 on June 7, 2013. The shutdown of the two units occurred much earlier than the notification to the NRC. Unit 2 was shutdown in early January 2012, and Unit 3 was shutdown on January 31, 2012. The NRC approved SCE's EP exemption request for SONGS and it took effect on June 4, 2015 [3]. With the EP exemption, SONGS is no longer required to maintain a 10-mile emergency planning zone identified in its license. SONGS will maintain an onsite emergency plan and response capabilities, including the continued notification of state and local government officials for an emergency declaration [4]. Based on the SONGS' decommissioning plan, the Unit 2 and Unit 3 spent fuel will be in dry casks by June 2018. The key dates for both plants are shown in Table 1.

In summary, assuming the decommissioning activities are performed as scheduled, VY will have been shutdown for 16.5 months when the EP requirements exemption takes effect, and 72 months (6 years) from shutdown to having all spent fuel in dry casks; and SONGS Unit 2 will have been shutdown for 41 months (40 months for Unit 3) when the EP requirements exemption takes effect, and 84 months (7 years) from shutdown to having all spent fuel in dry casks (Table 2)

Table 1 Key decommissioning dates of VY and SONGS

Plant	Shutdown	EP Requirements Exempted	All Spent Fuel in Dry Casks*
VY	12/29/2014	4/15/2016	12/2020
SONGS Unit 2	1/9/2012	6/4/2015	6/2018
SONGS Unit 3	1/31/2012	6/4/2015	6/2018

*Based on the planned schedule of the plants.

Table 2 Duration of decommissioning phases.

Plant	From shutdown to EP requirements exempted	From shutdown to All spent fuel in dry casks
VY	16.5 months	72 months
SONGS Unit 2	41 months	79 months
SONGS Unit 3	40 months	78 months

Section 2 provides a literature review that establishes the foundation for this HRA. Section 3 discusses the site specific information of the two study plants. Section 4 documents the HRA. The HRA is intended to be general, but, because design differences could have significant effects on human reliability, PWRs and BWRs are discussed separately. Section 5 provides a summary and conclusions of the analytical results.

2 Summary of literature Review

2.1 Overview of Literature Review

The literature review focuses on NRC's publications related to SFP safety:

NUREG/CR-6451 "A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plant" [5]

> This report raises awareness on performing regulatory assessments for the permanently shutdown (PSD) or decommissioned NPPs. As stated in NUREG/CR-6451 [5]:
>
> > The long-term availability of less expensive power and the increasing plant modification and maintenance costs have caused some utilities to re-examine the economics of nuclear power. As a result, several utilities have opted to permanently shutdown their plants. Each licensee of these permanently shutdown (PSD) plants has submitted plant-specific exemption requests for those regulations that they believe are no longer applicable to their facility. The preparation and subsequent review of these exemption requests represents a large level of effort for both the licensees and the NRC staff. This experience has indicated the need for an explicit regulatory treatment of PSD nuclear power plants. This report presents a regulatory assessment for generic BWR and PWR

plants that have permanently ceased operation in support of NRC rulemaking activities in this area.

The NUREG/CR-6451 technical assessment results are largely superseded by later NRC studies.

NUREG-1738, "Technical study of SFP Accident Risk at Decommissioning Nuclear Power Plants" [6]

NUREG-1738 [6] documents a multiple-discipline evaluation of the potential accident risk of spent fuel pools at decommissioning plants in the United States. The principle disciplines in the NUREG-1738 study include thermal-hydraulic analyses evaluating the behavior of spent fuel in the SFPs of decommissioning plants; risk assessment of SFP accidents including probabilistic risk assessment (PRA) and human reliability analysis (HRA); consequence calculations; and a sensitivity study and implications for decommissioning regulatory requirements. Because NUREG-1738 aims to provide a technical basis for rulemaking for all decommissioning plants, the content is generally applicable to all NPPs. The HRA in the current study uses a substantial amount of the information documented in NUREG-1738. The information used is identified in section 2.2.

NUREG-1774 "A Survey of Crane Operating Experience at U.S. Nuclear Power Plants from 1968 through 2002" [7]

Dropping a dry cask and damaging the SFP is one of the initiating events identified in NUREG-1738 [6]. NUREG-1774 [7] describes the results of a detailed review of crane operating experience at U.S. NPPs from 1968 through 2002. Among the data reviewed, NUREG-1774 identifies three events involving very heavy load drops among an estimated 54,000 lifts. This results in an estimated probability of very heavy load drops of 5.6E-5 per lift. The three very heavy load drop events did not occur near any safety related areas, and none resulted in radiation releases or risks to licensee personnel or the public. The dry cask drop events affecting SFP risk occur only when the drop is near or above the SFP. NUREG-1738 estimated that heavy loads travel near or over the pool approximately 13 percent of the total path lift length (the path lift length is the distance from where the load is lifted to where it is placed on the pool floor), and the critical path (the fraction of total path the load is lifted high enough above the pool to damage the structure in a drop) is approximately 16 percent. This results in a probability of 1.2×10^{-6} per very heavy load lift that may affect SFP safety.

NUREG-2161, "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor" [8]

NUREG-2161 [8] documents a consequence study of an hypothetical SFP accident initiated by a low likelihood seismic event at the study plant with the extreme earthquake frequency of once every 60,000 years. The study compares high-density and low-density spent fuel loading conditions. An HRA was performed in NUREG-2161[8] to analyze the reliability of post 9/11 mitigation measures. Even though NUREG-2161[8] only studied the offload of one third of the reactor fuel into the SFP, instead of a full core offload, which would be expected for decommissioning plants, NUREG-2161 [8] provides the following useful information for the current study:

- The post -9/11 mitigation measures: NUREG-2161 [8] HRA section discusses the strategies presented in NEI 06-12 [9] to mitigate a large-scale site area event. The mitigation strategies rely on installed, portable, and offsite available resources to provide SFP makeup or spray or both; to scrub down radioactivity from being released to the offsite environment; and to reduce leakage flow when SFP integrity is compromised. Both VY and SONGS mitigation strategies are consistent with NEI 06-12 [9].
- In using the portable diesel-driven pump or portable gas-driven pump (referred to as the B5b pump in this document) to makeup or spray the SFP, a limiting factor is the adverse environmental work conditions in the refueling floor area because the portable monitors to makeup or spray the SFP have to be manually setup on the refueling floor. NUREG-2161 [8] uses two conditions to represent the threshold for environmental conditions: (1) the radiation levels when the SFP water level reaches to the top of fuel rack; and (2) when the refueling floor air temperature reaches 140 °F. The second threshold is replaced in this study by the point in time at which the SFP starts to boil, because after the SFP starts to boil, the refueling floor air temperature increases rapidly (discussed further in section 2.2).
- While the fuel is submerged in water, it cannot reach a temperature that causes fuel damage. Therefore, as long as the operator can keep the water level above the fuel, fuel damage by overheating can be prevented.
- In a high density loading configuration, about 12 days after the fuel is offloaded to the SFP (represented by the 2nd operation cycle phase in NUREG-2161 [8]), 200 gpm of flow evenly sprayed into the SFP is sufficient to prevent fuel heat-up. The B5b pump is required, by regulation, to have a minimum capacity of delivering 500 gpm of makeup flow or 250 gpm of spray flow to the SFP. Therefore, fuel damage can be prevented if the operator can deliver the spray flow before fuel damage occurs.
- In a high density loading configuration, 107 days after fuel offload to the SFP (represented by the 4th operation cycle phase in NUREG-2161 [8]), and the SFP is fully draindown, natural air circulation can prevent fuel heat-up.

Regulatory analysis of COMSECY-13-0030 "Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel" [10]

The regulatory analysis of COMSECY-13-0030 [10] evaluated whether additional study of expedited transfer of spent fuel from spent fuel pools (SFPs) to dry cask storage (i.e., expedited transfer) might be warranted. The analysis results suggest that expediting movement of spent fuel to casks for the reference plant would provide only a minor or limited safety benefit, and that this benefit would be outweighed by the expected implementation costs. The COMSECY-13-0030 regulatory analysis [10] describes initiating events that challenge spent fuel safety:

> There are a variety of postulated events or conditions that can challenge the ability of a SFP to provide adequate cooling to spent fuel assemblies. A loss of heat removal from the SFP, which could be caused by a loss of electrical power, produces a slowly evolving event that could be mitigated with a high probability of success by plant staff and available equipment. Potentially more significant events involve coolant inventory loss resulting from a loss of pool integrity. These

events could result from low likelihood initiators such as a large earthquake producing ground accelerations well above those considered in the design of the facility. Past and recent studies have shown that these types of events could potentially lead to large radiological releases.

Sandia National Laboratories (SNL) letter report "Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents and Extension of Reference Plant Analyses to Other Spent Fuel Pool" [11]

NUREG-2161 [8] identified a small time and event window, within eight days after spent fuel offloaded to the SFP and a moderate SFP leak event, the 200 gpm spray flow rate, a minimum flow requirement of NEI 06-12, is not sufficient to cool the spent fuel. This SNL report [11] documents MELCOR for better understanding of the SFP spent fuel configuration and fuel age that can be cooled by the 200 gpm spray flow. The SNL results are expected to be more realistic and less conservative than NUREG-1738's estimates. The following are information in the SNL report most relevant to this HRA study:

- "It was known that some of the assumptions in the accident progression in NUREG-1738 [6] were conservative, especially the estimation of the fuel damage."
- "If the leak can be repaired prior to the water level dropping below ~60% of the active fuel height, or is located above the midplane of the assemblies, a modest make-up flow (~25 gpm) is required to remove decay heat from the reference BWR or PWR at 30 days following shutdown." In other words, as long as the water level can be maintained at the level of above 40% height of the active fuel, it is sufficient to cool the spent fuel that has been offloaded to the SFP for more than 30 days.

Plant submitted documents

The plant-submitted documents (including the VY and SONGS replies to the NRC's requests for additional information) for emergency plan exemption provides plant-specific information for this study.

2.2 NUREG-1738 and NUREG-2161 Information

NUREG-1738's [6] study was based on the assumption that decommissioning plants comply with the Maintenance Rule, the Industry Decommissioning Commitments (IDCs), and the Staff Decommissioning Assumptions (SDAs). Both VY and SONGS commit to comply with the IDCs and SDAs. Ten IDCs and seven SDAs are identified in NUREG-1738 [6]. This study assumes plants comply with IDCs and SDAs listed below:

<u>Industry Decommissioning Commitments</u>

IDC 1. Cask drop analyses will be performed or single failure-proof cranes will be used for handling heavy loads (i.e., phase II of NUREG-0612 [12] will be implemented).

IDC 2. Procedures and training of personnel will be in place to ensure that onsite and offsite resources can be brought to bear during an event.

IDC 3. Procedures will be in place to establish communications between onsite and offsite organizations during severe weather and seismic events.

IDC 4. An offsite resource plan will be developed which will include access to portable pumps and emergency power to supplement onsite resources. The plant would principally identify organizations or suppliers where offsite resources could be obtained in a timely manner.

IDC 5. SFP instrumentation will include readouts and alarms in the control room (or where personnel are stationed) for SFP temperature, water level, and area radiation levels.

IDC 6. SFP seals that could cause leakage leading to fuel uncovery in the event of seal failure shall be self-limiting to leakage or otherwise engineered so that drainage cannot occur.

IDC 7. Procedures or administrative controls to reduce the likelihood of rapid draindown events will include (1) prohibitions on the use of pumps that lack adequate siphon protection or (2) controls for pump suction and discharge points. The functionality of anti-siphon devices will be periodically verified.

IDC 8. An onsite restoration plan will be in place to provide repair of the SFP cooling systems or to provide access for makeup water to the SFP. The plan will provide for remote alignment of the makeup source to the SFP without requiring entry to the refuel floor.

IDC 9. Control of SFP operations that have the potential to rapidly decrease SFP inventory. These administrative controls may require additional operations or management review, management physical presence for designated operations or administrative limitations such as restrictions on heavy load movements.

IDC 10. Routine testing of the alternative fuel pool makeup system components will be performed and administrative controls for equipment out of service will be implemented to provide added assurance that the components would be available, if needed.

Staff Decommissioning Assumptions

SDA 1. Licensee's SFP cooling design will be at least as capable as that assumed in the risk assessment, including instrumentation. Licensees will have at least one motor-driven and one diesel-driven fire pump capable of delivering inventory to the SFP.

SDA 2. Walk-downs of SFP systems will be performed at least once per shift by the operators. Procedures will be developed for and employed by the operators to provide guidance on the capability and availability of onsite and offsite inventory makeup sources and time available to initiate these sources for various loss of cooling or inventory events.

SDA 3. Control room instrumentation that monitors SFP temperature and water level will directly measure the parameters involved. Level instrumentation will provide alarms at levels associated with calling in offsite resources and with declaring an emergency.

SDA 4. Licensee determines that there are no drain paths in the SFP that could lower the pool level (by draining, suctioning, or pumping) more than 15 feet below the normal pool operating level and that the licensee initiates recovery using offsite sources.

SDA 5. Load drop consequence analysis will be performed for facilities with non-single-failure-proof systems. The analyses and any mitigative actions necessary to preclude catastrophic damage to the SFP that would lead to a rapid pool draining would be sufficient to demonstrate that there is high enough confidence in the facilities' ability to withstand a heavy load drop.

SDA 6. Each decommissioning plant will successfully complete the seismic checklist provided in Appendix 2B of NUREG-1738 [6]. If the checklist cannot be successfully completed, the decommissioning plant will perform a plant-specific seismic risk assessment of the SFP and demonstrate that the risk of SFP seismically induced structural failure and rapid loss of inventory is less than the generic bounding estimates provided in this study ($1x10^{-5}$ per year including non-seismic events).

SDA 7. Licensees will maintain a program to provide surveillance and monitoring of Boraflex in high-density spent fuel racks until such time as spent fuel is no longer stored in these high-density racks.

Performance Limiting Factors

A typical BWR pool is 40 feet deep, 26 feet wide, and 39 feet long, and a typical PWR pool is 43 feet deep, 22 feet wide, and 40 feet long. The depth of water above the fuel is normally between 23 to 25 feet [6]. The minimum allowable water level, based on technical specifications, is approximately 2 feet lower than the normal water level. This large amount of water provides a huge heat capacity to absorb the heat generated by the fuel. In a normal situation, the heat is transmitted to the outside environment by the SFP cooling system. In a loss of SFP cooling event, the SFP water temperature will gradually rise to the boiling point and the SFP water level will gradually decrease by evaporation. Because part of the SFP makeup strategies with the use of the fire system or the B5b pump require that the personnel manually set up the monitors (portable spray nozzle) close to the SFP, an adverse work environment could make the action infeasible. NUREG-2161 [8] identifies two limiting conditions that affect the refueling floor accessibility:

- High air temperature in the refueling floor area
  Soon after the SFP starts to boil, the temperature of the refueling floor area will increase rapidly. Figures 1 to 3 show the rapid air temperature increase after the SFP starts to boil at 37 days, 107 days, and 383 days after a full core offload. Figure 4 shows the decay heat of fuel. These figures indicate that the air temperature increases rapidly after the SFP starts to boil.

NUREG-2161 [8] specifies when the refueling floor air temperature is above 140 °F (60 °C) then it is assumed that performing manual actions is not feasible in the refueling floor area. Table 1 shows the time to SFP boiling calculations of NUREG-1738 [6] and a MELCOR calculation performed to support this study. This study relaxes the conservativism by specifying that the high air temperature is a limiting factor when workers are not using personal protective equipment (special hat, mask, cloth, glove, and breathing system, etc.) to insulate the individual from the environmental heat. If the workers have the appropriate personal protective equipment, then the high temperature is not a limiting factor.

- High radiation in the refueling floor area
  After the SFP starts to boil, the SFP water level gradually decreases. The water on the top of the spent fuel is a good shield to the radiation from the spent fuel. A decrease in SFP water level would reduce the effectiveness of radiation shielding. NUREG-2161 [8] specifies that when the SFP water level is decreased to the top of the fuel assemblies, the radiation on the refueling floor becomes too high to work. Table 3 shows the NUREG-1738 [6] estimation of the time to boil-off (for an intact pool) to three feet above the top of fuel assemblies at various times after reactor shutdown. Table 4 shows that 60 days after shutdown, in the event of a loss of SFP cooling, the time to boil-off of the SFP water level to the top of the fuel assemblies takes more than four days.[1]

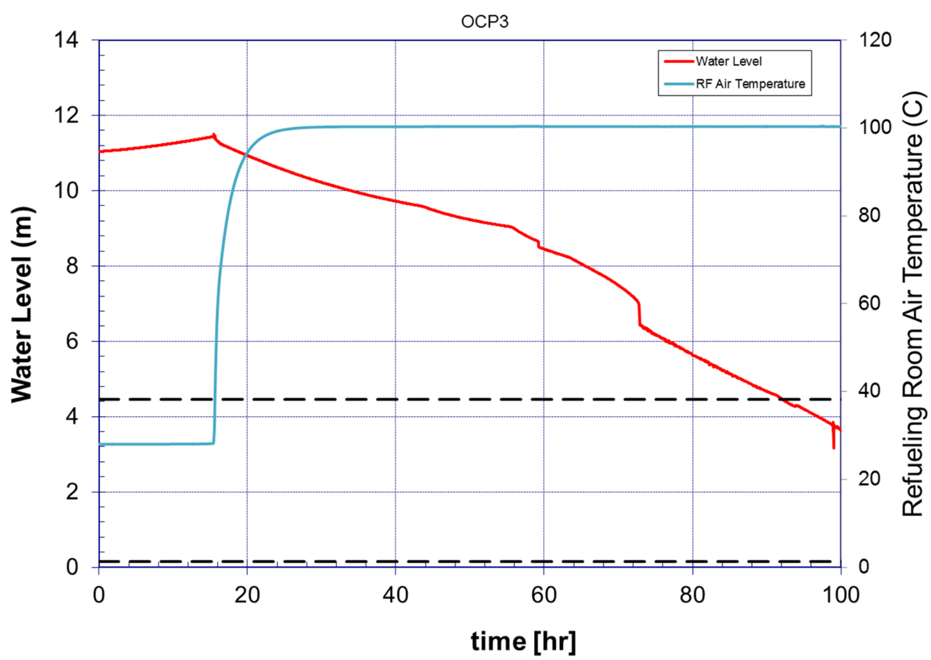

Figure 1 Refueling floor air temperature and the SFP water level after a loss of SFP cooling event occurred at 37 days after full core offload of a generic SFP.

[1] At the time of the project team's site visit to SONGS, the licensee was modifying the external SFP spray piping. The modification was scheduled to be completed in February 2016. This modification provides seismically robust piping to spray SFP using the normal makeup system or external sources (B5b pumps) without the need of entering into the refueling floor area to protect the operator from potential high radiation and high air temperature in the refueling floor area.

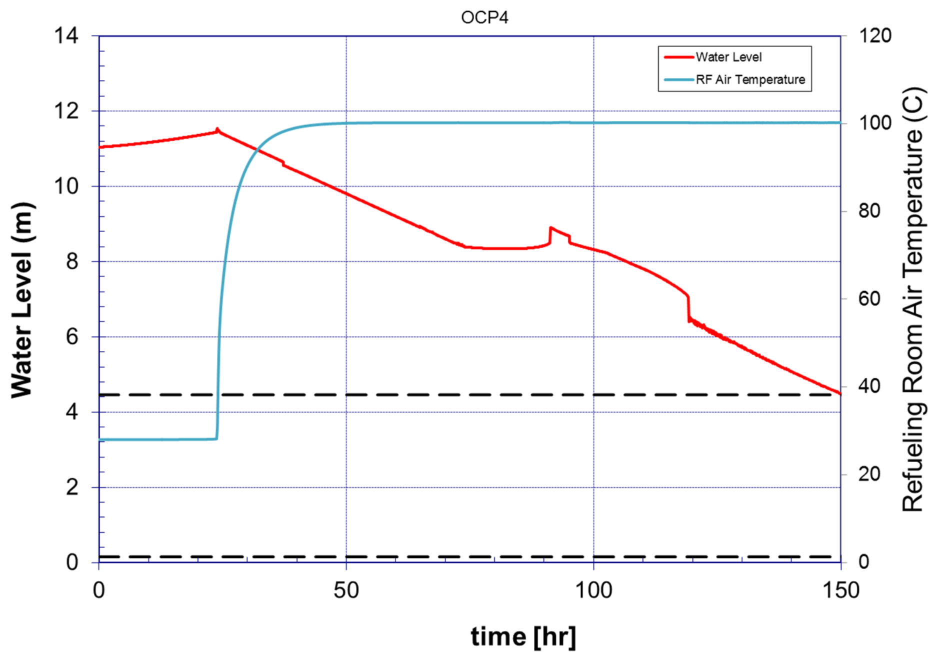

Figure 2 Refueling floor air temperature and the SFP water level after a loss of SFP cooling event occurred at 107 days after full core offload of a generic SFP

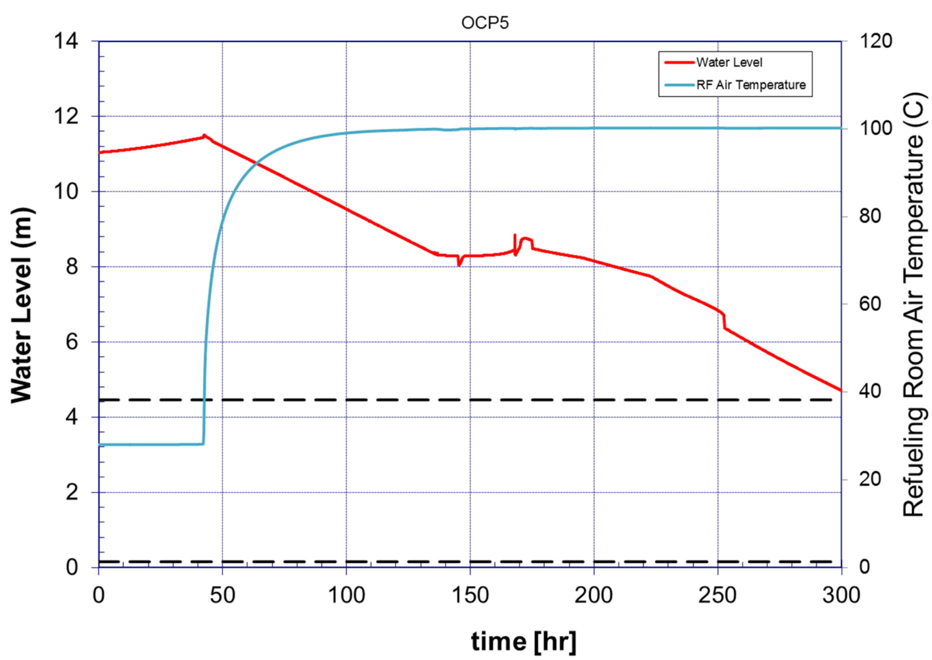

Figure 3 Refueling floor air temperature and the SFP water level after a loss of SFP cooling event occurred at 383 days after full core offload of a generic SFP

Table 3. Calculations of the time to SFP boiling after the loss of spent fuel cooling with a full core offload.

Days After Shutdown	NUREG-1738 (Hour)
30	14
60	18
90	21
180	27
365	33

Table 4 The time to boil-off spent fuel pool water to three feet above the fuel assemblies after the loss of spent fuel cooling.

Time After Shutdown	NUREG-1738 PWR	NUREG-1738 BWR
60 days	100 hours (>4 days)	145 hours (>6 days)
1 year	195 hours (>8 days)	253 hours (>10 days)
2 years	272 hours (>11 days)	337 hours (>14 days)
5 years	400 hours (>16 days)	459 hours (>19 days)
10 years	476 hours (>19 days)	532 hours (>22 days)

Initiating Events

NUREG-1738 [6] considered the following nine initiating event categories to assess SFP risk:

- Loss of offsite power from plant-centered and grid-related events
- Loss of offsite power from events initiated by severe weather
- Internal fire
- Loss of pool cooling
- Loss of coolant inventory
- Seismic event
- Cask drop
- Aircraft impact
- Tornado missile

The Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage Board on Radiative Waste Management of the National Research Council [13] states that an SFP drain down event resulting from damage from a collapse of the SFP could have more severe consequences than the boil-off events. The National Research Council's report [13] focuses on the following three types of terrorist attacks:

- Attacks with large civilian aircraft
- Attacks with high-energy weapons
- Attacks with explosive charges

The events caused by sabotage of an adversary is not within the scope of this HRA study. Therefore, the last two bullets above are not analyzed in this report. The aircraft impact events are identified in NUREG-1738 [6] and is analyzed in this report.

2.3 The Ten Hour Heat Up Time Frame for Taking Mitigative Actions

In 1981, NRC proposed rules on emergency planning and preparedness for production and utilization facilities in the Federal Register [14]. In the statement of the proposed rules, the Commission provides three justifications for why a determination of the state of or adequacy of offsite emergency preparedness was not necessary for issuing a low power license, authorizing only fuel loading and low power operation (up to 5% of the rated power). The three reasons are that the low power licensees have the following characteristics compared to full power licensees:

- Having much less fission product inventory.
- Requiring less system capacities to mitigate an abnormal event.
- Having much longer time available to mitigate an event. This is defined as the operators having at least 10 hours for a postulated low likelihood sequence, which eventually results in release of the fission products accumulated at low power into the containment. This amount of time would allow adequate precautionary actions to be taken to protect the public near the site.

SECY-99-168 [15] states, "In a recent plant-specific EP exemption, the staff determined that 10 hours was sufficient time to take mitigative actions and, if necessary, offsite protective measures without preplanning."

The 10 hours mentioned in the third bullet of the above FRN [14] and SECY-99-168 [15] was used in SECY 2014-0118 [16], which states:

> The underlying technical basis for the approval of the Zion facility exemptions was based on demonstrating that the radiological consequences of design-basis accidents (DBAs) would not exceed the limits of the U.S. Environmental Protection Agency's (EPA's) Protective Action Guides (PAGs) at the exclusion area boundary and that the spent fuel stored in the spent fuel pool (SFP) would not reach the zirconium ignition temperature in fewer than 10 hours based on analysis that assumes no water or air cooling of the fuel. The staff concluded that if 10 hours was available to initiate mitigative actions or, if needed, offsite protective actions using a comprehensive emergency management plan (CEMP) formal offsite radiological emergency plans are not necessary for permanently defueled nuclear power reactor licensees. [16]
>
> Exemptions from offsite EP requirements have previously been approved when the site-specific analyses show that at least 10 hours is available from a partial drain-down event where cooling of the spent fuel is not effective until the hottest fuel assembly reaches 900°C. [16]

The 10 hour heat-up time has been an NRC consideration for granting EP exemptions. Regarding the decay time required to meet the 10-hour criterion, SECY-99-168 [15] states, "The working group's preliminary generic results indicate that, at 2 years of decay time for a boiling-water reactor and 2.5 years for a pressurized-water reactor, about 10 hours will be available from fuel uncovery before onset of zirconium ignition." The NUREG-1738 calculation is shown in Figure 4. It shows that the BWRs and PWRs require about 18 months and 27 months respectively, post shutdown to have a 10-hour heat up time of the fuel to 900 °C for drain down events with air cooling. Figure 5 shows the NUREG-1738 estimations of PWR spent fuel heat up times with and without natural air circulation. It shows that, for PWRs, roughly within three years of shutdown, the time to heat the fuel to 900 °C is longer without natural air circulation (adiabatic heat-up) scenarios than with natural air circulation scenarios. For example, to have a 10-hour heat up time to 900 °C for natural air circulation scenarios, it requires the plant to have been shutdown for roughly 22 months. Without natural air circulation, this time occurs at about 27 months after shutdown.

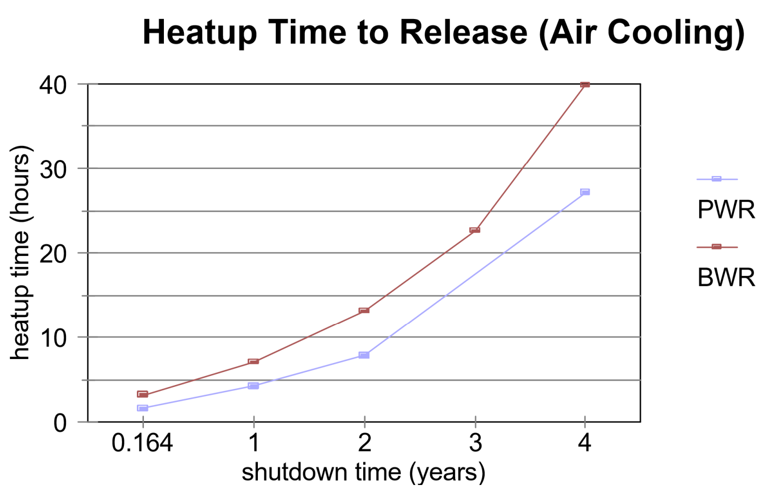

Figure 4 Heat-up time from 30 °C to 900 °C [6]

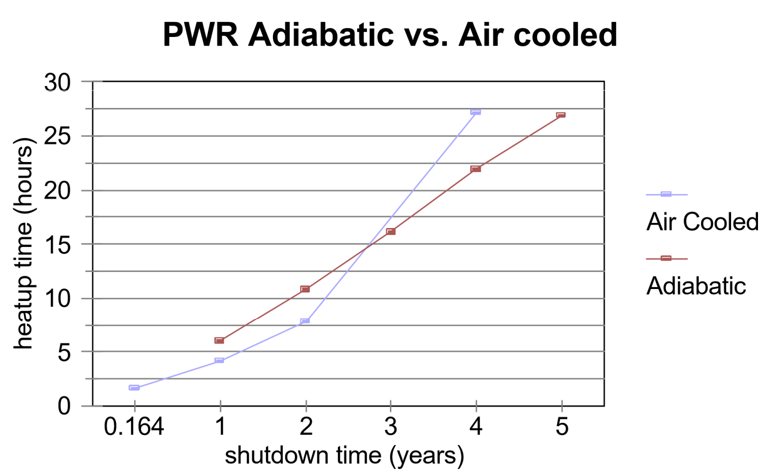

Figure 5 PWR heat-up times for air cooling and adiabatic heat-up [6].

Table 5 shows the SECY-99-168 [15] and NUREG-1738 [6] estimates of when the heat up to 900 °C at 10 hours is reached for PWRs and BWRs. Table 5 shows that the NUREG-1738 estimations are less conservative than those in SECY-99-168 [15] even though NUREG-1738 [6] was a generic study for BWRs and PWRs whose results were considered to be conservative. VY's site-specific calculation shows that the 10-hour heat up time is reached before 16.5

months post reactor shutdown. This explains why, in Table 5, the EP exemption for VY will be in effect earlier than 18 months.

Table 5 The estimated decay times required (in months) for the spent fuel to adiabatically heat up to 900 °C at 10 hours in the condition of loss of SFP water inventory and a full core offload.

Month	SECY-99-168	NUREG-1738	EP Exemption Granted
PWR	30	27	40 (SONGS)
BWR	24	18	16.5 (VY)

In this HRA study, the limiting factors for performing mitigation strategies are scenario dependent. The limiting factors and the time limits are discussed in Section 4.

3 Site-Specific Information

3.1 Onsite Staffing and Training

Both of the VY and SONGS emergency response organizations (EROs) list three on-shift staff excluding security as the minimum staffing level. The minimum staffing ERO positions include:

- Shift manager or certified fuel handler: The individual is a former senior reactor operator (SRO) or reactor operator (RO). The shift manager is the emergency director.
- Certified operator: This is a former reactor operator in SONGS. In VY, this individual is a Non-Certified Operator (equipment operator).
- Shift radiation protection (RP) technician.

The shift manger and the certified operator's principal work location is the main control room (MCR). But the certified operator may be on site depending on the tasks required. There is at least one individual who will be physically close to or within the MCR. The RP's principal work location is on site.

To meet the fire protection requirements, SONGS has three staff in the fire brigade. They are certified operators on shift.   VY has two staff in the fire brigade for each shift. The fire brigade are additional personnel to the three minimum staffing EROs of the two plants. Therefore, in every shift, SONGS has six individuals, and VT has five individuals. During day shifts, it is expected that additional plant staff will be on site and likely contractors. Both VY and SONGS use contractors for decommissioning tasks including loading spent fuel into dry casks.

After the emergency director declares an unusual event or an alert, both plants have two augmented staff who are expected to arrive to the site within two hours. The two augmented staff positions are: technical coordinator and radiation coordinator. The augmented staff coordinate technical expertise to assist the emergency director.

Both VY and SONGS commit to maintain the above-mentioned staffing level until all spent fuel is in dry casks.

Operator training related to the SFP tasks and safety are summarized as the following:

- SFP related tasks are contained in the training matrix of the shift manager and the certified operator.

- SFP topic lessons are contained in the initial training and the continuing training programs for the shift manager and the certified operator.
- Retraining periodicity is every 2 years.
- Retraining is planned and tracked via the Long Range Training Plan (4 year plan)
- Continuing training is provided for changes in plant configuration (plant modifications for decommissioning).
- Types of training include: classroom training, small group (shift crew), read and sign, and hands-on.
- SFP events are typical drill scenarios for all recent e-plan drills. These drills reinforce classroom training. Drills are performed every two years with voluntary participation of offsite organizations.

3.2 Command and Control Center

Both VY and SONGS use the MCR as the information center and command and control center. After permanently ceasing reactor operation, many MCR alarm tiles and indications are de-activated. These deactivated alarms and instruments are clearly marked. VY's MCR controls one unit. It is estimated that only 20% or less of the alarms are still active. For VY, the remaining active alarms are related to the following plant functions:

- Radiation monitoring
- Service water (the ultimate heat sink in VY)
- Radwaste and SFP
- Electric
- Service and instrument air
- Standby gas treatment

SONGS has a shared MCR for Units 2 and 3. During operation, each section of the shared MCR (controlling a unit) had about 1100 active annunciators. Additionally there were approximately 200 annunciators common to both units. At the time of the site visit, there were about 250 annunciators per unit and 75 common annunciators that remained active. SONGS is implementing a project to eventually transfer every indication needed for the operator to the Command Center Data Acquisition System (CDAS) and abandon all of the control board annunciators. The CDAS is a computer-based interaction system. Once the project is completed, the MCR operator can acquire all needed plant information from the CDAS without the need to walk to different locations.

3.3 Mitigation Strategies and Equipment

3.3.1 NEI 06-12 Mitigation Strategies

Both VY's and SONGS' mitigation strategies are consistent with NEI 06-12 [9] and provide three mitigation strategies:

- Internal strategy: This strategy uses the plant installed equipment, e.g., fire suppression system and normal makeup system, to provide more than 500 gpm makeup flow to the SFP. Even though the fire hose and fire water is readily available on the refueling floor area, the fire hoses are typically 1.5 inch in diameter. The internal strategies referred to in this report do not use the 1.5 inch fire hose to connect to the fire hydrant. Instead, the internal strategy refers to setting up the monitor(s)[2] on the refueling floor area and connecting the monitor(s) to the fire hydrant on the refueling floor with a 2.5 inch diameter fire hose. The fire water is injected or sprayed into the SFP through the monitors. The monitors are stored in tool boxes close to the refueling floor.

- External strategy: The external strategy uses the B5b pump to makeup or spray the SFP. NEI 06-12 [9] sub-divides the strategy into the following two sub-strategies:
    - Local makeup and spray: This strategy is to set up the monitors on the refueling floor to makeup SFP with more than 500 gpm flow or spray more than 250 gpm toward the SFP. NUREG-2161 [8] assumes only 200 out of 250 gpm of the spray flow is sprayed into the SFP.
    - External spray: This strategy is used when the refueling floor is not accessible. Monitors are to be set up outside of the reactor/SFP building to water down the released radioactivity. To implement the external spray, both VT and SONGS rely on offsite laddered fire trucks.
- Leakage control strategy: This strategy is to use any materials that can block the SFP leak flow to reduce the leak rate. During the plant visits for this study, both VT and SONGS referred to obtaining the material from offsite organizations (fire station). There is no material staged onsite for the leakage control strategy. Procuring the leak control material takes time. Because small leaks can be mitigated by the makeup and spray strategies, and large leak events have a short time available to perform mitigation strategies, the leak control strategy is considered to have marginal effects and is not discussed further.

In summary, the onsite mitigation strategies for both plants are the internal strategy and the external strategy with local makeup and spray. In addition, the external spray strategy requires offsite support (fire engines).

3.3.2 VY's Mitigation Strategies and Equipment

The credible VY makeup and spray mitigation strategies are the following:

A. SFP makeup water system: The makeup water system's water resource is a demineralized (demin) water tank with a 50,000 gallon capacity. At the time of the plant visit for this study, VY was modifying the plant to use the torus water for makeup. The torus contains more than 500,000 gallons of water. The torus is a seismically robust structure and is protected by the containment. The normal makeup flow capacity is 50 gpm with demin cleaning and 250 gpm without demin cleaning. The system is not seismically robust. The makeup system can be operated from the MCR.

   Note: NUREG-1738 assumes the makeup flow capacity is 20 – 30 gpm.

B. Fire protection system: The fire protection system includes one electric motor-driven and one diesel-driven fire pump. Each pump has a capacity of 2,500 gpm at 125 psi discharge pressure. To use the fire protection system for SFP makeup or spray, the operator needs to run fire hose(s) to connect the fire hydrant on the refueling floor area

[2] The portable monitors are the spray nozzles that connect to fire hoses to eject water commonly used for firefighting. The monitors have tri-pot to stable itself on the ground to eject water without human to hold it. The typical maximum flowrate is 500 gpm per monitor. The flow pattern (from inject to spray) can be adjusted by manually screw the monitor's flow control cap. Adjusting the flow pattern will affect the flow rate. Most of the monitors are able to automatically swing the nozzle head horizontally 40 degrees (20 left and 20 right) for the spray water to cover a wide area.

and the monitor setup on the refueling floor to makeup or spray into the SFP. The operator has to set up the monitor(s). SFP makeup requires running two 2½-inch fire hoses from the two fire stations located at the refueling floor area to two makeup monitors. To makeup SFP, the operator would remove the spray nozzle heads of the two makeup monitors then open the fire stations' valves. The two makeup monitors provide greater than 500 gpm makeup flow or greater than 250 gpm of spray flow.

Note: NUREG-1738 assumes the makeup flow using the fire protection system is 100 gpm for 1½-inch fire hose, and 250 gpm for 2½-inch fire hose.

C. B5b portable pump: This strategy uses a portable pump to pump water from a deep basin to the SFP. The portable pump has installed piping to take suction from a nearby deep basin and discharge it to a nearby fire hydrant (FH-1). Two primary options for pumping the deep basin water to the SFP depend on the integrity of the underground fire system piping (as shown in Figure 6).

   C1. When the underground fire piping is intact: There is another fire hydrant (FH-2 in Figure 6) close to a 4" storz penetration of the reactor building wall at grade level (elevation 252'). Because FH-1 and FH-2 are connected by the underground fire protection system pipes, outside the reactor building, the operator uses a fire hose to connect FH-2 and the 4" storz. Inside the reactor building, the operator lays a hose from the refueling floor (elevation 345') to another 4" stortz inside the reactor building wall of the same penetration (elevation 252'). A wye adaptor is needed to connect the 4" fire hose to two 2.5" fire hoses that in turn connect to the monitors.

   C2. When the underground fire piping is damaged: The operator would need to connect the B5b pump discharge to the 4" storz connection at the reactor building penetration. This connection requires about 500 feet of 4" fire hoses. The 500 feet of hose is established by connecting a number of hoses. Typically each hose is 50 or 100 feet in length. Establishing a 500 foot hose to connect the B5b pump and the reactor building penetration takes about 70 minutes for a team of two operators with good coordination. The time estimation is based on a VY verification report of conducting the same task before the reactor building wall penetration was modified from a double flange design [17] to the double 4" storz design. This design change is estimated to save about 30 minutes of implementation time for this mitigation strategy.

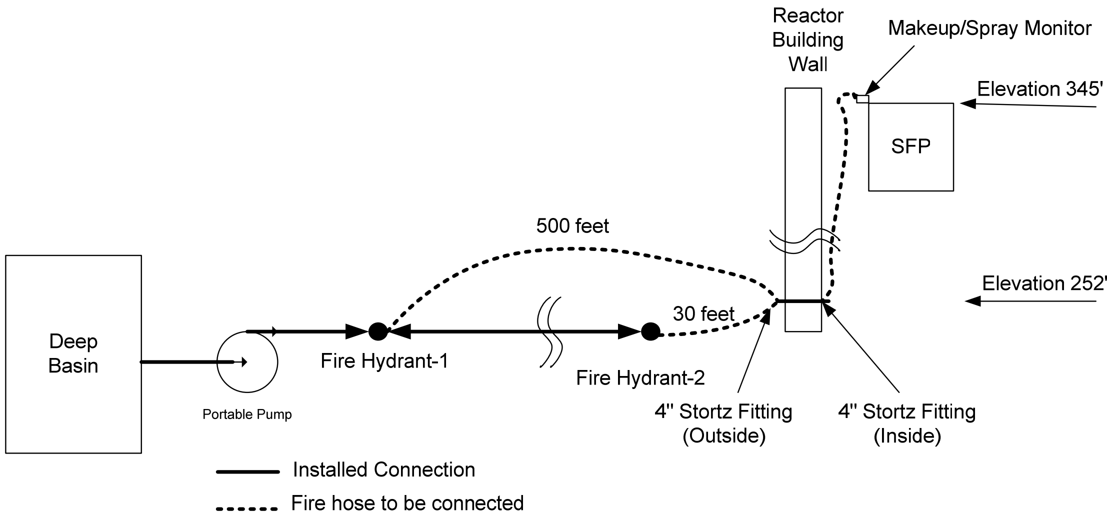

Figure 6 The portable pump connections to makeup the spent fuel pool.

Note: NRC inspected all plants to ensure they are able to deliver at least 500 gpm makeup or 250 gpm spray flow to the SFP.

D. Service Water System makeup: VY has a service water system (SWS) cross-tie that can be connected to the SFP cooling system piping to makeup SFP. This requires manually re-positioning a spectacle flange. The SWS is a seismically robust system but the portion of the piping to support this mitigation strategy is not seismically robust. If this mitigation strategy is available, it allows using Connecticut River water to makeup the SFP.

E. Offsite support: In an augmented response, the offsite fire stations and Entergy fleet could provide needed mitigation equipment. NUREG-1738 [6] assumes fire engine flow capacity is 100 - 250 gpm.

Backup ac Power

In a loss of offsite power situation, VY has three options to provide backup ac power. The first option is to use the onsite diesel generator. The second option is to use a tie-line to connect to the downstream Vernon Hydro station. Both options require manual actions (to start the diesel generator and to connect to the hydro station, respectively). Either option can provide all electricity needed to operate the SFP cooling system, the SFP normal makeup system, the motor-driven fire pump, and the SW makeup. The third option is offsite support to provide portable generators.

3.3.3 SONGS Mitigation Strategies and Equipment

The credible SONGS' makeup and spray mitigation strategies are the following:

- Fire protection system: The fire protection system includes two motor-driven pumps and one diesel-driven pump. The maximum capacity of each motor-driven pump is 1,500 gpm and the maximum capacity of the diesel driven pump is 2,500 gpm. The fire system takes suction water from two fire water storage tanks. Its pipe connects to the fire hydrant on the refueling floor. On the refueling floor, the operator needs to run a fire hose(s) to connect the fire hydrant and a monitor setup on the refueling floor to makeup or spray into the SFP. The operator has to set up the monitor(s). The fire pumps automatically start when the fire protection system's pressure is below the set points. The fire system is not seismically robust.

- SFP Normal Makeup system: The normal makeup system contains an SFP makeup water storage tank (300,000 gallons capacity), two low flow electric-driven pumps (40 gpm each), and one large flow electric-driven pump (500 gpm). The system can provide makeup and spray flow into the SFP. Two spray nozzles permanently mounted on the SFP room wall with pipe connection to the makeup system can spray the water from the SFP normal makeup system into the SFP. The system is seismically robust except for the electricity required to drive the makeup pumps. The actions to operate the SFP normal makeup are performed from the MCR.
- B5b pumps: SONGS has two portable B5b pumps: one gasoline-driven and another diesel-driven. The gasoline pump's capacity is 500 gpm. The diesel pump's capacity is 2500 gpm. The two pumps are staged at different locations with one close to an SFP building (Unit 2 and Unit 3 each has a SFP). Both B5b pumps are staged in open areas that are unlikely to be damaged by falling objects. SONGS has seismically robust pipes (riser piping), one for each SFP, with one end at the grade level of the radwaste building and the other end at the SFP work deck level (refueling floor). The strategy is to connect a portable pump's discharge to the two riser pipes at grade level in the radwaste building, one for each unit, then connect a fire hose between the raiser pipe at the SFP work deck and a makeup/spray monitor. On the refueling deck, fire hoses are available to connect the SFP deck end of the riser pipe to monitors to makeup or spray the SFP. The specifications of the two B5b pumps' makeup strategies are:
    - Gasoline pump: The pump takes suction from three demineralized water tanks. Each tank has 535,000 gallons capacity. The three demineralized water tanks are not seismically robust structures. The following is a summary of the human actions:
        - Use 4" harden hoses to connect the pump suction to a nearby 4" storz that provides a water source from the three demineralized water tanks
        - Travel to the demineralized water tanks' locations to open the isolation valves. These tanks are located on a hill that takes about 20 minutes on foot or a few minutes by vehicle to reach.
        - Lay hoses from the pump discharge to the riser pipes for the Units 2 and 3 SFPs.
        - At the SFP deck elevation, connect the riser pipes to two spray monitors for each Unit with fire hoses. The fire hoses are 2.5" hoses.
        - Start the B5b pump to provide flow. The pump is started by pushing the pump start button.

      A SONGS' document shows that a team of three operators were timed while performing the above procedure to use the B5b pump to makeup the SFPs of Unit 2 and Unit 3. The above procedure was divided into three separate tasks. Each task was performed either by one or two operators. Each task was timed differently. Then the times used to complete the three tasks were added. This resulted in 106 minutes. If performed by a crew of three operators, the tasks of opening the tank isolation valve and laying hoses to Unit 2 and Unit 3 can be performed in parallel. This could shorten the time of implementing the mitigation strategy.

- o Diesel pump: The procedure to use the diesel-driven B5b pump to makeup the SFPs is similar to using the gasoline-driven B5b pump, except that the diesel pump's suction is from a nearby seismically robust water tank (another demineralize water tank). The water tank has 150,000 gallons capacity and is about 30 feet from the diesel pump suction point. The hardened hoses for suction are staged with the pump.

As mentioned earlier SONGS was modifying the SFP piping to spray the SFP using the SFP normal makeup system or the B5b pumps or the fire system. After the modification, the seismically robust piping connecting the makeup system, fire system, and B5b system are established. To use a B5b pump to spray the SFPs, the operators connect the pump discharge to the 4" storz outside of the fuel handling building then manually operate six manual valves, for each unit, to direct the flow to the SFP spray path. Actions on these valves includes:

- Open two valves to connect the pump injection flow to the piping
- Close two valves to isolate the flow from being injected to the SFP makeup path.
- Open two valves to direct the flow to the spray nozzles.

The modification is expected to reduce the time required to makeup or spray SFP with use of external water sources.

<u>Backup ac Power</u>

At the time of the site visit, SONGS maintained two emergency diesel generators (EDGs) that were used during reactor operations to provide backup ac power. One EDG provides electricity to one unit. SONGS was in a transition to use a newly procured diesel generator to replace the two EDGs. The new diesel generator provides electricity for the SFP cooling system and the SFP normal makeup system. Unlike VY, the SONGS diesel generator does not power the motor-driven fire pump. The diesel generator needs to be manually started either from the MCR or locally.

3.4 Dry Cask Plan

At the time of this study's site visits, SONGS had 51 loaded dry casks on the storage pad. The SONGS site has three units. Unit 1 was permanently shutdown in 1992. An estimate of 91 additional dry casks are needed for the Unit 2 and Unit 3 highly radioactive material. Based on the planning schedule, all of the spent fuel for Units 2 and 3 will be in dry casks by the end of June, 2018. VY, on the other hand, had 13 loaded dry casks on the storage pad. An estimate of an additional 45 dry casks are needed to store all highly radioactive material. All of VY's spent fuel is scheduled to be in dry casks by the end of December, 2020.

Both plants use contractors, who are experienced in dry cask loading, to load the spent fuel into dry casks. When performing dry cask loading, the plant certified operator will be at the site to monitor the activities. Both VY and SONGS plan to use the campaign approach to have all spent fuel loaded into dry casks as a continuous effort instead of breaking it into several time segments. NPPs have a strong financial incentive to place all spent fuel into dry cask storage as soon as possible because after all spent fuel is removed from the SFP, the plant's staffing level can be significantly reduced.

3.5 Commitment to the Industry Decommissioning Commitments

VY and SONGS commit to align with the IDCs. Table 6 summarizes their commitments [18, 19].

Table 6 Highlights of VY and SONGS commitments to the Industry Decommissioning Commitments

IDC 1: Cask drop analyses will be performed or single failure-proof cranes will be in use for handling of heavy loads (i.e., phase II of NUREG-0612 [12] will be implemented). • Both plants use the single-failure-proof crane to handle heavy loads. • The SONGS' dry cask cannot fall into the SFP. The dry casks are placed in the cask loading pit adjacent to the SFP with a water gate in between. The bottom of the water gate is 2 feet 5 inches above the top of the spent fuel. This is to ensure that an inadvertent drain-down or leakage via a spent fuel gate opening cannot uncover the fuel. • Both plants implemented administrative controls on dry cask move paths to minimize the dry cask drop risk.
IDC 2: Procedures and training of personnel will be in place to ensure that onsite and offsite resources can be brought to bear during an event. • Both plants have corresponding procedures and training.
IDC 3: Procedures will be in place to establish communication between onsite and offsite organizations during severe weather and seismic events. • Both plants have procedures for communication protocols and practices.
IDC 4: An offsite resource plan will be developed which will include access to portable pumps and emergency power to supplement onsite resources. The plan would principally identify organizations or suppliers where offsite resources could be obtained in a timely manner. • Both plants' offsite resource plans include a list of offsite resources, providers, and contact information, • Both plants conduct emergency drills with participation of offsite organizations. • Both plants maintain letters of agreement (LOA) and memoranda of understanding (MOU) with offsite agencies to ensure additional resources are available if needed.
IDC 5: SFP instrumentation will include readouts and alarms in the control room (or where personnel are stationed) for SFP temperature, water level, and area radiation levels. • Both plants have indications of SFP water level, water temperature, and refueling floor area radiation inside the MCRs. Alarms include high/low water level, high temperature, and high radiation.
IDC 6: SFP seals that could cause leakage leading to fuel uncovery in the event of seal failure shall be self-limiting to leakage or otherwise engineered so that drainage cannot occur. • Both plants have high reliability seals so that a catastrophic seal failure is unlikely. The VY SFP gate seal is located about two inches above the top of fuel assemblies. The SONGS' gate seal is about two feet above the top of fuel assemblies.
IDC 7: Procedures or administrative controls to reduce the likelihood of rapid drain down events will include (1) prohibitions on the use of pumps that lack adequate siphon protection or (2) controls for pump suction and discharge points. The functionality of anti-siphon devices will be periodically verified. • Both plants have procedures and administrative controls in place. • VY does not use an anti-siphon device. The VY's lowest credible drain down path is the SFP cooling system suction which is about 15 feet 3 inches above the top of the fuel assemblies.

• SONGS has a pipe that reaches to the bottom of SFP for SFP cooling system discharge. This pipe has an anti-siphon device installed. The lowest pipe location within the SFP without an anti-siphon device is 20 feet 9 inches above the top of fuel assemblies[3].
IDC 8: An onsite restoration plan will be in place to provide repair of the SFP cooling systems or to provide access for makeup water to the SFP. The plan will provide for remote alignment of the makeup source to the SFP without requiring entry to the refueling floor. • Both plants have plans and procedures in place. • Both plants' SFP normal makeup system can be controlled from the MCR.
IDC 9: Procedures will be in place to control SFP operations that have the potential to rapidly decrease SFP inventory. These administrative controls may require additional operations, management review, or management physical presence for designated operations or administrative limitations such as restrictions on heavy load movements. • Both plants have procedures and administrative controls in place to prevent and mitigate rapid SFP draindown events.
IDC 10: Routine testing of the alternative fuel pool makeup system components will be performed and administrative controls for equipment out of service will be implemented to provide added assurance that the components would be available, if needed. • Both plants have administrative controls in place for periodic functional tests of the multiple methods to makeup SFP.

3.6 Commitments to the Staff Decommissioning Assumptions

VY and SONGS commit to align with the SDAs specified in the NUREG-1738 [6] IDCs. Highlights of the implementation are listed in Table 7 [18, 19].

Table 7 The Staff Decommissioning Assumptions of NUREG-1738 and the VY and SONGS compliance with the Staff Decommissioning Assumptions.

SDA 1: Licensee's SFP cooling design will be at least as capable as that assumed in the risk assessment, including instrumentation. Licensees will have at least one motor-driven and one diesel-driven fire pump capable of delivering inventory to the SFP. • The plants' capabilities in SFP makeup and spray are discussed in sections 3.3.2 and 3.3.3 of this report. Both plants' fire protection system met the SDA 1's specification.
SDA 2: Walk-downs of SFP systems will be performed at least once per shift by the operators. Procedures will be developed for and employed by the operators to provide guidance on the capability and availability of onsite and offsite inventory makeup sources and time available to initiate these sources for various loss of cooling or inventory events. • The SFP system walk-downs with walking to the refueling floor area is performed once a day at both sites. An SFP system walk-down in the MCR without walking to the refueling floor area is performed every shift. Both plants use 12-hour shifts.
SDA 3: Control room instrumentation that monitors SFP temperature and water level will directly measure the parameters involved. Level instrumentation will provide alarms at levels associated with calling in offsite resources and with declaring an emergency. • Indications and alarms of SFP water level, temperature, and refueling floor high radiation are available to the MCR at both plants. • Both plants have emergency action level declaration procedures to declare an emergency and call for offsite support.
SDA 4: Licensee determines that there are no drain paths in the SFP that could lower the pool level (by draining, suctioning, or pumping) more than 15 feet below the normal pool operating level and that licensee must initiate recovery using offsite sources.

[3] The normal SFP water level is between 23 feet and 25 feet above the top of the spent fuel assemblies. The SDA #4 states, "…no drain paths in the SFP that could lower the pool level (by draining, suctioning, or pumping) more than 15 feet below the normal pool operating level" (Table 7) that is only 8 feet above the top of the fuel assemblies. This is conservative comparing to the 15'3" at VY and 20'9" at SONGS.

• The SONGS' lowest pipe location within the SFP without an anti-siphon device is 20 feet 9 inches above the top of fuel assemblies (i.e., less than 5 feet below the normal water level). The normal SFP water level is between 23 feet and 25 feet above the top of spent fuel assemblies. • VY has a 3" drain line between the inboard and outboard SFP gates. Drain down through this pipe would results in lowest water level of 1.5 feet below the top of fuel assemblies. A drain down from this pipe requires a gross structural failure of the inboard gate sealing gasket and the 3" pipe. This is not considered as a credible failure mechanism. The VY's lowest credible drain down path the SFP cooling system suction which is about 15 feet 3 inches above the top of the fuel assemblies. This is less than 10 feet below the SFP normal water level.
SDA 5: Load drop consequence analysis will be performed for facilities with non-single failure-proof systems. The analyses and any mitigative actions necessary to preclude catastrophic damage to the SFP that would lead to a rapid pool draining would be sufficient to demonstrate that there is high enough confidence in the facilities' ability to withstand a heavy load drop. • Both plants use single-failure-proof cranes to move dry casks in the refueling floor area. • SONGS' cask drop analysis is documented in its Updated Final Safety Analysis Report (UFSAR) section 15.7.3.5. Cask drop into the SFP is not credible because the cask is loaded in the cask loading pit adjacent to the SFP. A drop was postulated when the cask is placed on the upper shelf (i.e., step) of the cask loading pit when performing a yoke-lift change-out, prior to the transfer cask being welded close. The bounding spent fuel cask drop accident is from the upper shelf in the cask loading pit back into the lower portion of the cask loading pit. During this evolution, the transfer cask is not restrained and could fall back into the lower portion of the cask pool if an earthquake occurs. The fuel rods from all 32 fuel assemblies present in a transfer cask are conservatively assumed to rupture on impact with the bottom of the cask pool [20]. The drop is not expected to breach the SFP integrity. • VY's cask drop event was analyzed in NUREG/CR-5176 [21]. The analysis results indicate that the SFP walls would suffer severe damage as a result of a cask drop. NUREG/CR-5176 does not estimate the probability of a cask drop event. NUREG-1738 [6] states, "a (heavy load) drop would seriously damage the SFP (either the bottom or walls of the pool) to the extent that the pool would drain very rapidly and it would not be possible to refill it using onsite or offsite resources." VY stated that the drop of a fuel cask is not a credible event [22].
SDA 6: Each decommissioning plant will successfully complete the seismic checklist provided in Appendix 2B of NUREG-1738 [6]. If the checklist cannot be successfully completed, the decommissioning plant will perform a plant specific seismic risk assessment of the SFP and demonstrate that the SFP seismically induced structural failure and rapid loss of inventory is less than the generic bounding estimates provided in this study ($1x10^{-5}$ per year including non-seismic events). • VY's seismic risk assessment is documented in Attachment 2 to Appendix 2B of NUREG-1738 [6]. The estimated seismic-induced SFP failure is 8.9×10^{-7} per year. • Neither VY nor SONGS performed a seismic checklist. Based on the thermal hydraulic calculation, at the time of the requested emergency plan exemption, it would take more than 10 hours to heat up the hottest spent fuel assembly adiabatically to 900 °C.
SDA 7: Licensees will maintain a program to provide surveillance and monitoring of Boraflex in high density spent fuel racks until such time as spent fuel is no longer stored in these high-density racks. • The VY aging management program is in place to manage loss of material and reduction of neutron absorption capacity of Boral neutron absorption panels in the spent fuel racks. • The VY spent fuel racks utilize Boral, rather than Boraflex, as the neutron absorbing material. • The SONGS spent fuel racks utilize soluble boron concentration, rather than Boraflex, as the neutron absorbing material.

4 Human Reliability Analysis

4.1 Analysis Approach

This section applies the General IDHEAS (IDHEAS-G) HRA methodology's guidance to analyze each of the following nine initiating events identified in NUREG-1738 [6] for SFP safety:

- Loss of offsite power from plant-centered and grid-related events
- Loss of offsite power from events initiated by severe weather
- Internal fire
- Loss of pool cooling
- Loss of coolant inventory
- Seismic event
- Cask drop
- Aircraft impact
- Tornado missile

For each of the above nine initiating events, the analysis includes a description of the initiating event and its impact on the plant (with emphasis on spent fuel safety), a crew response diagram, the cognitive task analysis, time analysis, and HEP estimates. The analyses of these initiating events are discussed in sections 4.2 to 4.10.

4.1.1 Initiating Event and Crew Responses

The description of the initiating event and its impact on SFP safety set the situation for operator response. The crew's main responses to the event are represented by the crew response diagram (CRD), which is a graphic representation of how to document the operators' responses to the situation. This graphic is intended to provide a high-level understanding of the sequences of the key operator tasks and the credible human error recovery opportunities in case the key human tasks are not successfully performed. The estimated times that the key human tasks are completed are specified in the CRD. The information provides a structure for the cognitive task analysis and time analysis.

4.1.2 Cognitive Task Analysis

The cognitive task analysis is based on the draft general methodology of the Integrated Human Event Analysis System (IDHEAS-G) which uses the following four macrocognitive functions to estimate human reliability:

- **Detecting**: The Detecting macrocognitive function in this context is to detect the occurrence of an abnormal event. The shift manager (SM) in the MCR detects what the event could be by MCR alarms and indications (e.g., loss of offsite power events), via communications with others (e.g., weather-related events), and human sensors (e.g., earthquake and aircraft impact), etc.
- **Understanding**: After detecting the occurrence of an event, the Understanding macrocognitive function is to collect more information to assess plant status with the primary focus of supporting decision-making to maintain safety margin, i.e., maintaining key parameters within their safety ranges. Understanding the root cause of the problem is not an immediate priority. Information such as the statuses of personnel availability, key SFP parameters, available equipment and event mitigation strategies, etc. are the SM's primary interest. If the MCR instrumentation is available, the following SFP information is readily available in the MCR: water level, water temperature, and radiation level, and the statuses of SFP cooling pumps and SFP makeup pumps, etc. During the site visit, SONGS was adding a computer display that also can show the trends of the

selected plant parameters. Weather information and the regional electricity network status (related to the prospect of restoring offsite power) are available by phone. For a cask drop event, the workers on the refueling floor would radio the SM about the event. For a severe earthquake or tornado, the SM would dispatch personnel, when available, to perform a plant walkdown to gather information about earthquake damage.

- **Deciding**: Based on the understanding, the Deciding macrocognitive function is to decide how to respond to protect SFP fuel safety. Procedures are available to respond to various events. Operators are trained to implement the procedures. Assuming the SFP cooling system is not available, the operator's decision on maintaining SFP fuel safety is to makeup or spray SFP following NEI 06-12 [9] guidelines. The implementation sequence in order of preference is:
    - Internal makeup strategies: This includes the SFP normal makeup and the fire protection system.
    - External makeup and spray strategies: This is to use the B5b pump(s) to makeup or spray the spent fuel. Based on procedure, the operator would use the monitors' makeup mode first. If the SFP water level cannot be maintained, the operator is instructed to switch to the spray mode. Switching from the makeup mode to the spray mode is simply performed by hand screwing the monitor head to adjust the flow pattern.
    - Offsite strategies: This refers to requests for offsite support including the suppliers and contractors listed in the emergency plan, e.g., local fire stations, the other plants of the same company, and the regional response centers.

  The criterion for choosing among these mitigation strategies is to use the most convenient and quick strategy available to make up the SFP. If the SFP water level cannot be maintained, then use the fire pump or B5b pump to spray into the SFP. When performing one strategy, the operator would try to get another mitigation strategy ready in case the strategy being implemented fails.

  Procedures are available for the SM to declare the emergency action level. After an unusual event or an alert is declared, each plant has two augmented staff who will be notified and are expected to arrive at the site within two hours. The two augmented staff positions are: technical coordinator and radiation coordinator. The augmented staff access and coordinate technical expertise to assist the emergency director. Depending on the situation's urgency, offsite support (local fire station or other plants of the same company) may be requested before or after the arrival of the augmented staff.

  For an earthquake that caused damage to the SFP, the same earthquake is expected to cause severe damage to the area near the site. Site accessibility in a large earthquake event would significantly different for different nuclear power stations. Because this study is to inform rulemaking for all commercial nuclear reactors, site-specific accessibility is not analyzed. Instead, this study uses NEI 12-06's assumption that the augmented staff will not be available until six hours after the initiating event, and the local fire truck and other offsite equipment will not be available until 24 hours after the initiating event. Based on the perceived event damage and other communication means, it is assumed that the SM would have appropriate expectations regarding the likelihood that offsite support would take longer than usual to be available.

- **Action**: The Action macrocognitive is to implement the selected mitigation strategy or strategies. The normal makeup system can be controlled from the MCR. The fire protection system and the B5b pump require working on the refueling floor area. When using the fire protection system to makeup the SFP, the workers only need to travel within the building. The action is not affected by adverse weather events (e.g., tornado) if the system is available. The B5b pump option requires working outside of the building. Human performance can be affected by severe weather conditions (e.g., strong winds, intense precipitation). The offsite support option would be used when the onsite options are not available, not sufficient, or not reliable to mitigate the event.

4.1.3 Time Analysis

The timing analysis described in the NUREG-1921 [23] is used in this report with a small modification. For convenience, Figure 7 reproduces NUREG-1921's timeline diagram with the only difference on the T_{SW} definition. T_{SW} is the system time window that is defined in NUREG-1921 [23] as the time when the mitigation action is no longer beneficial to the scenario. In this study, it is represented by when the spent fuel temperature reaches to 900 °C. However, severe adverse environmental conditions (e.g., high air temperature and high radiation) could occur that prevent mitigating actions before reaching the 900 °C threshold. In these situations, performing the mitigation actions is still beneficial to the scenarios but, because of the adverse environment, the actions cannot be performed. Therefore, this study modifies the T_{SW} definition to mean that either the mitigation action is no longer beneficial to the scenario or the mitigation action is no longer feasible.

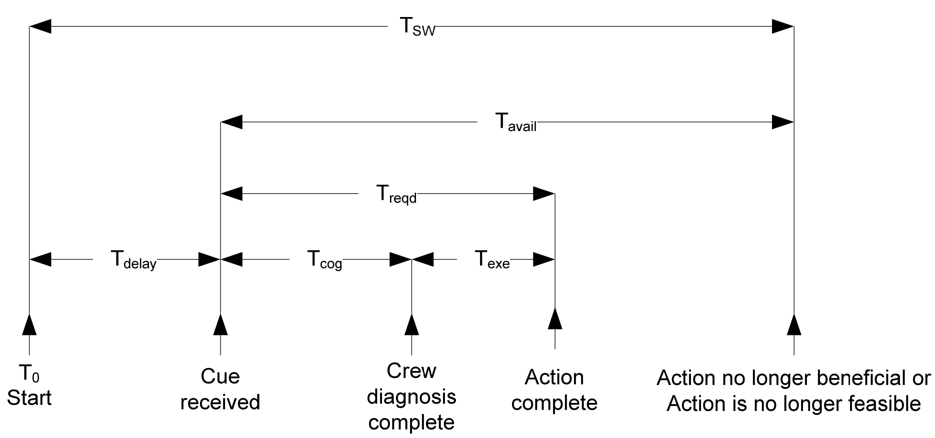

Figure 7 Timeline illustration diagram [NUREG-1921]

The terms associated with each timing element are defined as below:
T_0 = start time = start of the event
T_{delay} = time delay = duration of time it takes for an operator to acknowledge the cue
T_{sw} = system time window, which is the earliest time of either when the action is no longer beneficial or the action is no longer feasible
T_{avail} = time available = time available for action = (T_{sw} - T_{delay})
T_{cog} = cognition time consisting of detection, diagnosis, and decision making
T_{exe} = execution time including travel, collection of tools, donning of PPE, and manipulation of relevant equipment
T_{reqd} = time required = response time to accomplish the action = (T_{cog} + T_{exe})

NUREG-1921 defines time margin (TM) as shown in equation 1.

$$Time\ Margin\ (TM)\ =\ \frac{T_{avail} - T_{reqd}}{T_{reqd}} \times 100\% \quad \textit{(Equation 1)}$$

The time margin (TM) is an indication of the human error recovery availability based on the relative time availability. This is under the assumption that the individuals know what need to be accomplished and are working on to achieve the objectives. The time taken to achieve the objectives varies. The TM is a time margin indication relative to the nominally required time. If the time available (T_{avail}) equals the time required (T_{reqd}), the time margin (TM) is zero. This means that if the operator(s) fails to perform the first attempt of the task there is no time for a second attempt. If the T_{avail} is twice as much as T_{reqd} (i.e., TM is one), it implies that if the first attempt fails, there is still sufficient time for a second attempt to succeed. The larger the TM, the more time available for error recovery.

In this study, the available mitigation strategies and their characteristics (e.g., equipment and staff requirements and performance time, etc.) are familiar to the emergency director. The spent fuel in the SFP is the main focus of the plant staff. It is expected that determining a working strategy for event mitigation would follow the established procedure. The decision variability is limited. Therefore, in the situation that the chosen strategy is not working but the emergency director insists continue to try the non-working strategy (a fixation[4] human error). This caused an appropriate mitigation strategy is not implemented in time to mitigate the event. This fixation error is determined negligible in this study because the reasons stated above.

The following describes the general implementation of the time parameters in this study.

<u>T_{Delay} Implementation</u>

T_{delay} is the time taken for the operator to be aware that any of the nine initiating events identified in NUREG1738 [6] has occurred (cue perceived). This triggers the operator's cognitive processes to understand what has happened and determine how to respond. Because all of the NUREG-1738 initiating events generate vivid cues that are immediately available to the operator, T_{Delay} is assumed to be negligible.

<u>T_{SW} Implementation</u>

T_{SW} is the earliest time at which the mitigation actions are no longer beneficial to the scenario or the mitigation actions are no longer feasible to be performed. The following are the T_{SW} implemented in this study:

- The spent fuel temperature reaches to 900 ^{o}C for all mitigation actions.
- The SFP starts to boil for mitigation actions that must be performed on the refueling floor and without personnel protective equipment. As discussed in section 2.2, after the SFP starts to boil, the air temperature in the refueling floor area increases rapidly. Without

[4] Fixation error refers to that the emergency director insists in using a non-working strategy to mitigate the events even though the available information clearly indicates that the chosen strategy is not working or not applicable. The insistence caused the applicable strategy is not implemented in time or event mitigation.

personal protective equipment, setting up the SFP makeup monitors on the refueling floor area is assumed to be not feasible.

- The SFP water level decreases to the top of fuel assemblies for the mitigation actions that must be performed on the refueling floor regardless of personal protective equipment availability. This is limiting because the water above the spent fuel assemblies is a radiation shield. NUREG-2161 shows high radiation in the refuel floor area when the SFP water decreases to the top of the fuel assemblies. The personal protective equipment for firefighting cannot shield personnel from the radiation. After the SFP water decreases to the top of the fuel assembly level, setting up the SFP makeup monitors on the refueling floor area is assumed to be not feasible.
- The event causes structural damage or generates hazardous environmental conditions so that the work location cannot be accessed.

In the situation of a loss of SFP cooling, no SFP makeup, and with an intact SFP with full core offload, NUREG-1738 [6] estimates that for spent fuel of six months and one year of age, it would take about 27 hours and 33 hours, respectively, to reach the high temperature threshold and about 140 hours and 195 hours, respectively, to reach to the high radiation threshold for PWRs. The high radiation threshold for BWR SFPs after six months and one year after full core offload are about 188 hours and 253 hours, respectively. Because the high air temperature can be overcome by wearing appropriate personal protective equipment for firefighting (protective clothing and breathing gear), without appropriate personal protective equipment, both the high air temperature and high radiation are limiting factors. With appropriate personnel protective equipment, high radiation is the limiting factor. Table 8 shows the time limitations for mitigation actions to be performed in the MCR and the refueling floor with the assumptions of an intact SFP, loss of SFP cooling, no makeup and a full core offload.

Table 8 The time requirements for performing mitigation actions (based on NUREG-1738) in the condition of the SFP is intact.

Time After Full Core Offload	MCR Actions (Hours)[1]	Refueling Floor Actions		
		Without Personal Protected Equipment (Hours)[2]	With Personal Protective Equipment (Hour)[3]	
			PWR	BWR
6 months	> 140 (PWR) > 188 (BWR)	27	140	188
1 year	> 195 (PWR) > 253 (BWR)	33	195	253

[1]The time that the hottest spent fuel assembly adiabatically heats up to 900 °C.
[2] The time that the SFP starts to boil.
[3] The time that the SFP water level decreases to the top of the fuel assemblies.

T_{cog} Implementation

T_{cog} includes the time spent surveying the MCR indications and MCR computer displays, dispatching operators to perform plant walkdowns, and communicating to understand the situation (the event damage and the available equipment and personnel, etc.) and to decide how to respond to the situation. If the MCR indications or information are immediately available to understand the situation (e.g., a LOOP event and a dry cask drop event) and to confidently make the mitigation decision, 5 minutes is applied to T_{cog}. If the event requires sending operators to walkdown the plant to collect information to support situational understanding, 30 minutes is applied to T_{cog}.

In a loss of all plant indications event (e.g., loss of ac and dc power), 40 minutes is applied to T_{cog}. This is because the operators will need walk to the SFP area to understand the SFP status to decide upon a response strategy. The readily available mitigation equipment includes the diesel-driven fire pump and the B5b pump. Availability of the fire protection system can be checked on the refueling floor area by opening the fire hydrant valve. If the fire protection system is not available, an additional 30 minutes is added to assess the B5b pump availability.

T_{EXE} Implementation

T_{EXE} is the time required to perform the selected mitigation strategy. This includes the time to travel (on foot or by vehicle) to the work location and the time to complete the action. When there are no severe adverse environmental conditions present, the following are the T_{EXE} values:

- Normal makeup: one minute. The action is performed from the MCR.
- Manually start the diesel generator: one minute. This action is performed from the MCR.
- Fire protection system: 30 minutes without wearing personal protection equipment (PPE). This includes dispatching an operator to the refueling floor to open the fire hydrant valve and using a fire hose to make up the SFP.
- In using the onsite fire protection system or B5b pump to make up the SFP, if personal protective equipment is required to perform the task, an hour is added to account for obtaining the personal protective equipment and performing the actions needed on the refueling floor area.
- B5b pump: Two hours is used for normal conditions on the assumption that no significant adverse environmental conditions would affect human performance. The NEI 06-12 [9] specifies that the B5b system should be capable of being deployed within two hours from the time plant personnel diagnose that external SFP makeup is required. This time window includes dispatching operators to set up the makeup/spray monitor on the refueling floor and lay fire hoses to use the B5b pump to make up or spray the SFP.
- Local fire fighter: 3 hours. This includes the time for the firetruck to arrive at the site and using the fire engine in place of a B5b pump.

When the event causes a severe adverse environmental condition, T_{EXE} is discussed in each initiating event discussion (sections 4.2 – 4.10).

Offsite Support

The following additional time assumptions are applied to this study:

- Without severe adverse environmental conditions, the augmented emergency response staff (two staff per plant) arrive two hours after the initiating event. Local fire fighters arrive 30 minutes after they are notified.
- When the event causes wide area damage (large earthquake), the NEI 12-06 [24] site accessibility guidelines apply. This mean that the augmented response staff arrive at the site six hours after the initiating event. Offsite fire trucks and mitigation equipment from offsite will not arrive at the site until 24 hours after the initiating event. As mentioned earlier, this study is to inform rulemaking for all commercial nuclear power

stations and the site-specific site accessibility analysis is not performed, the 24 hours is more likely a conservative estimate for a randomly selected site.

4.2 Loss of offsite power from plant centered and grid-related events

4.2.1 Initiating Event and Crew Responses

A loss of offsite power (LOOP) from plant-centered events typically involves hardware failures, design deficiencies, human errors (in maintenance and switching), localized weather-induced faults (e.g., lightning), or combinations. Grid-related offsite power events are caused by problems in the offsite power grid. These events cause the loss of ac power to the SFP cooling system, the makeup system, and normal lighting.

Unlike the emergency diesel generators of an operating plant that start automatically in a LOOP event, the diesel generators at VY and SONGS have to be manually started. The diesel generator can be started from the MCR or locally. Once the diesel generator is started, it provides electric power to the SFP cooling system and the SFP normal makeup system. The operators' short-term focus is to maintain the diesel generator running, to prepare for the backup alternatives (fire system and B5b makeup), and to restore offsite power. VY's diesel generator also powers the motor-driven fire pump but the SONGS' diesel generator does not power the SONGS' motor-driven fire pumps.

A LOOP could develop into a station blackout (SBO) event if the diesel generator failed to start. A SBO event disables the SFP cooling system, the normal makeup system, and the motor-driven fire pumps. Operator(s) will be dispatched to the refueling floor to use the fire system to maintain SFP water level. The diesel-driven fire pump would automatically start to maintain the fire protection system hydraulic pressure. The operators' short term focus is to maintain the SFP water level using the fire protection system, to restore the onsite and offsite power, and to prepare B5b makeup (in case the diesel-drive fire pump fails).

Figure 8 shows a crew response diagram (CRD) for a LOOP event. The horizontal lines in the CRD represent success paths. The downward lines represent failure paths. The prioritized sequence of mitigation strategies to implement is the following:

1. Start the diesel generator manually to restore the normal SFP cooling system and the SFP normal makeup system
2. Use the fire protection system (diesel-driven fire pump) to make up the SFP
3. Use the B5b pump to make up the SFP
4. Use the offsite portable generators to power the SFP normal makeup system, SFP normal makeup pumps, motor driven fire pumps, and the offsite portable pumps to makeup the SFP

Once offsite power is restored and the SFP normal cooling system is running, the mitigation strategy can be exited. Note that some plants (e.g., VY) have separate lines to connect to nearby hydraulic power plants to provide an alternative source of offsite power. This is not shown in figure 8.

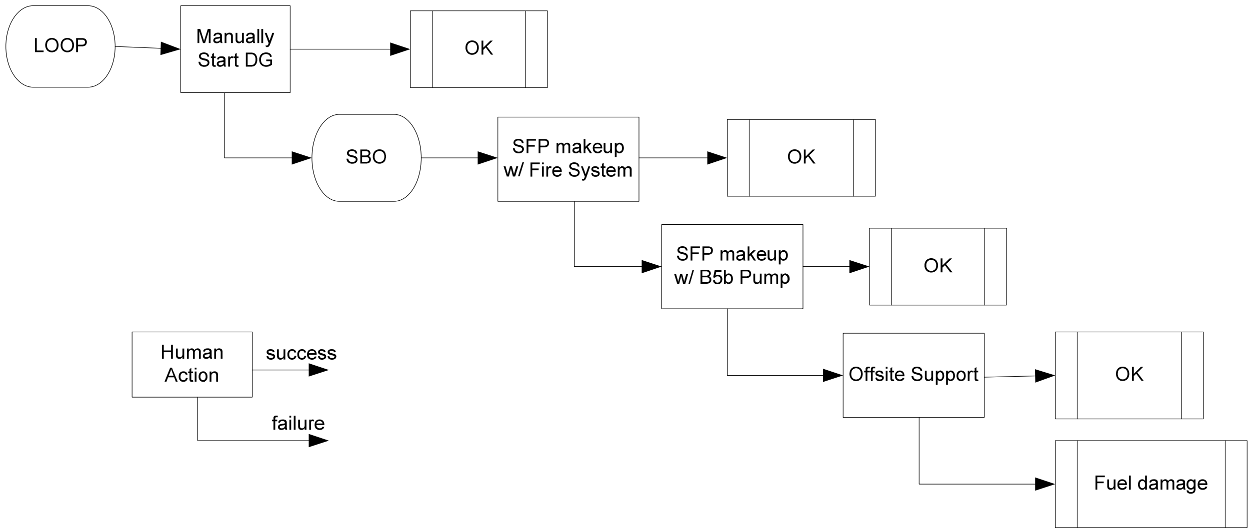

Figure 8 The crew response diagram for a LOOP event

4.2.2 Cognitive Task Analysis

Detecting

The LOOP symptoms are apparent to the operator (e.g., switching to emergency lighting in the MCR and the indication lights of all running pumps changing color).

Understanding

The perceived symptoms directly point to a LOOP. The operator's first response is to confirm that offsite power is lost by the indications in the MCR then manually start the diesel generator. The diesel generator can provide power to the SFP normal cooling system and normal makeup system to maintain spent fuel safety. If the diesel generator cannot be started it is clear to the operator that an SBO event is occurring. The status of the diesel generator is indicated in the MCR. Because the MCR indications show that all key SFP parameters are within their safety range and there are no signs of a rapid change (there is no high radiation, nor rapid SFP water level decrease, with no significant increase in SFP water temperature), the SM knows that the spent fuel is not at immediate risk.

Deciding

The rules to make the mitigation strategy decision are clear. The following is the priority of implementation:

1. Start the diesel generator and maintain the diesel generator running for the use of the SFP normal cooling system and the normal makeup system
2. Use the diesel-driven fire pump to make up the SFP
3. Use the B5b pump to make up the SFP
4. Ask for offsite support

If alternative offsite power sources are available, the mitigation strategy will also include powering the plant systems by connecting to the alternative offsite power. Once the situation is under control, the operator would try to restore normal offsite power. Once the offsite power is restored, the mitigation strategies can be exited.

Action

All actions are straightforward and operators are trained to perform these actions. Staffing is not an issue in this event. All onsite mitigation strategies require only one person to perform them except for the B5b make up, which requires a team of two. There are no severe adverse environmental conditions to affect the human action, unless it is necessary to use the fire system or B5b pump to make up the SFP. Some of the actions need to be performed on the refueling floor. In most situations, the operators initially perform the actions without wearing personal protective equipment. If the actions cannot be completed before SFP boiling, the high air temperature in the refueling floor area is assumed to make the action not feasible. The operators would have to retreat to equip with personal protective equipment to complete the actions before the high radiation threshold is reached. Figure 9 shows a CRD of the mitigation actions that need to be performed on the refueling floor.

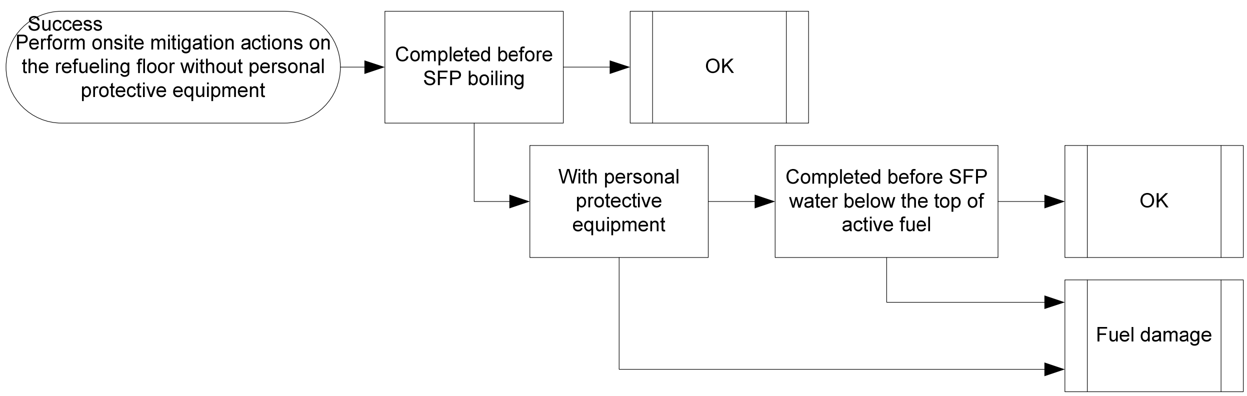

Figure 9 The CRD for using the fire protection system or B5b pump to makeup the SFP

4.2.3 Time Analysis

The following is the time analysis. The T_{SW} is based on a decay time of 12 months. It is conservatively assumed that the mitigation strategies are performed in sequence. After a mitigation action cannot be performed, ten minutes is assumed for the operator to decide to give up the current strategy and to perform the next strategy. The ten minutes is represented by T_{cog}. In addition, after the first attempt of a strategy, if the strategy fails, there is no recovery action for the same strategy. For example, if the MCR manual action fails to start the diesel generator, even though it is likely that an operator will be dispatched to try to locally start the diesel generator, the local action is not modeled. These assumptions are made to simplify the discussion. Not crediting this type of recovery action has little effect on the risk analysis. Tables 9 and 10 are the time analysis results for PWRs and BWRs, respectively.

Table 9 The mitigation strategy time analysis of PWRs.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{req} (min)	T_{avail} (min.)	T_{SW} (min.)	TM
Start the diesel generator[1]	0	1	1	2	> 11700	> 11700	> 5849
Fire system makeup without PPE[2]	2	10	30	40	1978	1980	48
Fire system makeup with PPE[3]	42	10	60	70	11658	11700	166
B5b makeup without PPE[2]	172	10	120	130	1808	1980	13
B5b makeup with PPE[3]	302	10	60	70	11398	11700	162
Offsite[3]	372	10	180	190	11328	11700	59

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 195 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)
[3]The limiting factor is the water level decreasing to the top of the fuel assemblies (195 hours, table 2)

Table 10 The mitigation strategy time analysis for BWRs.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW} (min)	TM
Start the diesel generator[1]	0	1	1	2	> 15180	> 15180	> 7589
Fire system makeup without PPE[2]	2	10	30	40	1978	1980	48
Fire system makeup with PPE[3]	42	10	60	70	15138	15180	215
B5b makeup without PPE[2]	172	10	120	130	1808	1980	13
B5b makeup with PPE[3]	302	10	60	70	14878	15180	212
Offsite[3]	372	10	180	190	14808	15180	77

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 253 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)
[3]The limiting factor is the water level decreasing to the top of the fuel assemblies. (253 hours, table 2)

4.2.4 Discussion

Tables 9 and 10 show large time margins for the multiple mitigation strategies. With the equipment available, the human failure probability to maintain spent fuel safety is negligible. The hardware failure reliability is failure of all the diesel generators, the diesel-driven fire pump, the B5b pump, and offsite equipment. The combined failure probability of human and hardware is negligible. Therefore, the plant-centered LOOP event has a negligible risk contribution to the spent fuel safety.

4.3 Loss of offsite power from events initiated by severe weather

4.3.1 Initiating Event and Crew Response

This initiating event represents the loss of SFP cooling because of a loss of offsite power from severe weather-related events (hurricanes, snow and wind, ice, wind and salt, wind, and one tornado event). Because of the potential for severe localized damage, tornadoes are analyzed separately. The operator's response strategies are similar to the plant-centered LOOP event (discussed in section 4.2) except the severe weather condition could block or delay some of the actions especially the actions locations are not protected from the severe weather (outdoors). The mitigative strategies not affected by severe weather include:

- Manually starting the diesel generator (a MCR action): this enables the SFP normal cooling system, the SFP normal makeup system, and the motor-driven fire pump(s) of some plants.
- The fire protection system: If the fire protection system is available, all work and travel routes are inside buildings.

- The use of B5b pump and offsite support could be limited or delayed by the severe weather.

This analysis assumes that the extreme cold weather caused the loss of the offsite power, and the diesel generator and the diesel and gasoline pumps are assumed not able to be started. The onsite and offsite roads are either covered by heavy snow or icy that delayed onsite works and the offsite support is not available until 24 hours after the loss of offsite power.

After the loss of offsite power and the operators failed to manually start the diesel generator from the MCR, operators will be dispatched to try to start the diesel generator locally. This is assumed not working based on this event assumptions. Learning that the station is in a station blackout condition, the emergency director is expected to declare an unusual event (UE). The plants' emergency action level (EAL) declaration follows NEI 99-01 guidance [25]. An unusual event is likely declared for the above severe weather induced station blackout based on either NEI 99-01 [25] PD-SU1 "unplanned SFP temperature rise" or PD-HU3 "other conditions exist which in the judgment of the Emergency Director warrant declaration of a notification of unusual event." As the event progress, the emergency director could declare an Alert emergency. NEI 99-01 states:

- The source terms and release motive forces associated with a permanently defueled plant would not be sufficient to require declaration of a Site Area Emergency or General Emergency
- The Unusual Event initiating conditions provide for an increased awareness of abnormal conditions while the Alert initiating conditions are specific to actual or potential impacts to spent fuel.
- The Emergency Director should declare the Unusual Event promptly upon determining that 60 minutes has been exceeded, or will likely be exceeded.

Declaring an unusual event may mobilize the augmented emergency response personnel and request for offsite support. The CRD of this extremely cold weather event is shown in figure 10.

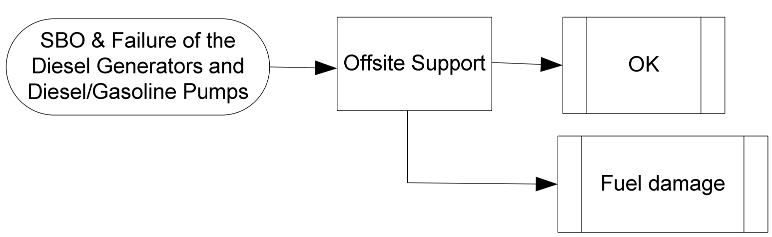

Figure 10 The crew response diagram of the station blackout event with failures of all onsite diesel generators and the diesel and gasoline pumps

4.3.2 Cognitive Task Analysis

Detecting

The LOOP symptom would be detected immediately.

Understanding

The operator needs component availability information locally to understand that the unavailable of the diesel generator, the diesel pumps, and gasoline pumps are not available.

Deciding

After having a good understanding of the plant status, the emergency director declares an Unusual Event and calls for offsite support. This is assumed to occur one hour after the LOOP event.

Action

This event is an extreme external event. Based on NEI 12-06 guidelines, the offsite support is assumed not available until 24 hours after the initiating event. The action time is assumed doubled to 4 hours because the effects of severe weather. Before the arrival of offsite support, the onsite operators are expected to open the SFP building doors to left outside cold air to cool the SFP. High air temperature in the SFP floor area is unlikely. Therefore, the T_{SW} is determined the time that the water reaches to the top of fuel assemblies.

4.3.3 Time Analysis

The T_{SW} is time that the SFP water level reaches to the top of fuel assemblies. This for PWRs is 195 hours and 253 hours for BWRs. Table 11 show the time analysis for PWRs and BWRs assuming that the offsite support not arrive at the site until 24 hours after the initiating event, and the setup for the SFP makeup takes four hours.

Table 11 The mitigation strategy time analysis of PWRs.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min.)	T_{SW} (min.)	TM
Offsite – PWRs	1440	0	240	240	10260	11700	42
Offsite - BWRs	1440	0	240	240	13740	15180	56

4.3.4 Discussion

Table 11 shows that the long available time to perform the mitigation actions strongly benefits spent fuel safety. Even though all onsite mitigation equipment failed and offsite support is delayed, the available time (T_{avail}) and time margin (TM) are large for both PWRs and BWRs. This long available time provides a large buffer for the mitigation actions to be performed to prevent fuel heat-up. The failure probability is determined to be negligible.

4.4 Internal fire

4.4.1 Initiating Event and Crew Responses

This analysis makes the following assumptions:

- An internal fire causes the loss of the SFP cooling system.
- There is no automatic fire suppression system in the SFP cooling system area.
- No personnel were in the refueling floor area to extinguish the fire when the fire occurred. The fire caused significant damage to the SFP cooling system and cannot be repaired.

NUREG-1738 [6] assumes that an SFP drain down event occurred through the damaged SFP cooling system piping. NUREG-1738 [6] states, “Once the inventory level drops below the SFP cooling system suction level, the fuel handlers have about 85 hours to provide some sort of alternative makeup." Figure 11 shows the CRD of the internal fire event.

There are many opportunities to detect the plant abnormality. The operators noticing the plant abnormality is likely by perceiving the fire alarms or the indication of the SFP cooling pump trip. If the information is missed (annunciator or indicator failure), the high SFP water temperature alarm and low water level alarms will be triggered. The SFP system walkdown, performed every shift, and the SFP area walkdown, performed every 24 hours, will also support problem detection. After perceiving fire alarms, the fire brigade will be dispatched to extinguish the fire and assess the fire damage. At the same time, the key SFP parameters will be monitored closely, principally by the SM to ensure spent fuel safety. Because of the draindown, the SFP normal makeup system will be used to restore SFP water. The leakage is expected to be detected and sealed by the local inspection crew.

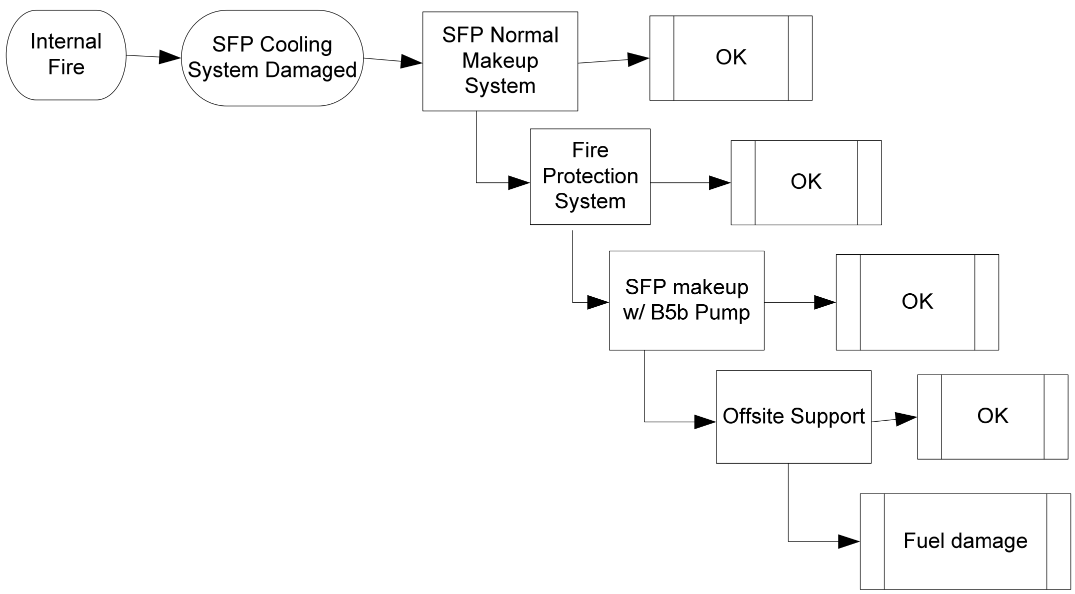

Figure 11 The CRD of an internal fire event

4.4.2 Cognitive Task Analysis

<u>Detecting</u>

There are many means to detect the plant abnormality because of the fire. The following are some of the likely means:

- The fire and smoke would trigger the fire alarms in the MCR and local area.
- Inside the MCR, the SFP cooling pumps' status indications changed color to indicate the pumps are not running, the low SFP water alarm actuates, and the high SFP water temperature alarm may also actuate to alert the operator.
- The key plant parameters are logged at least every shift (12 hours). This would identify the unusually low SFP water level.
- An SFP area walkdown is conducted every 24 hours. This would provide an opportunity for direct visual detection of an unusually low SFP water level and the fire damage. Assuming the SFP cooling system suction is 15 feet below the normal water level

(between 23 and 25 feet above the top of fuel assemblies), based on the SFP dimensions used in NUREG-1738 [6] (22 feet by 40 feet for PWRs, and 26 feet by 39 feet for BWRs), the leakage rates would have to be greater than 68 gpm (PWR) or 79 gpm (BWR) to drain down the SFP water level to 15 feet below the normal water level within 24 hours. This leak flow rate is large and abnormal enough that it is expected to be detected when performing an SFP system walkdown.

Understanding

The fire brigade will be dispatched to extinguish the fire and assess the fire damage after receiving the fire alarm. The MCR indications are available to monitor SFP parameters. The SM is expected to know that the system damage is caused by the fire. The other SFP systems are functional. The decrease in SFP water level and the gradual increase in SFP water temperature would lead to suspicion of a concurrent drain down event.

Deciding

The priority is to extinguish the fire, to maintain key SFP parameters within their safety ranges, and to assess the fire damage. The available options to provide spent fuel cooling include the SFP normal makeup system, the fire protection system, the B5b makeup strategy, and offsite support. The SM selects the appropriate mitigation strategy based on the situation. In this event, the SFP leakage is assumed to be occurring through the fire-damaged SFP cooling system. Once local operators identify the leak, the leak will be sealed.

Action

The firefighting equipment and fire brigade are readily available. As mentioned earlier, SONGS has three staff in the fire brigade and the VY has two staff in the fire brigade for each shift. The firefighting equipment includes personal protective equipment.

4.4.3 Time Analysis

Assuming the fire alarms were not triggered until 30 minutes after the initial fire (T_{delay}). A diagnosis time of 5 minutes is assumed (T_{cog}) to check the key SFP parameters in the MCR. The SFP normal makeup is actuated from the MCR. The SFP water level is expected to be restored and maintained by the SFP normal makeup system. The leakage could be sealed later. It does not affect system capability to maintain the SFP water level. Tables 12 and 13 show the time analysis of PWRs and BWRs, respectively, for internal fire events. The tables assume that the operators did not detect the fire until 30 minutes after the initiating event.

Table 12 The mitigation strategy time analysis of PWRs for internal fire events.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min.)	T_{SW} (min.)	TM
SFP normal makeup[1]	30	5	1	6	11670	11700	1944
Fire system makeup without PPE[2]	36	10	30	40	1944	1980	48
Fire system makeup with PPE[3]	76	10	60	70	11624	11700	165
B5b makeup without PPE[2]	146	10	120	130	1834	1980	13
B5b makeup with PPE[3]	276	10	60	70	11424	11700	162
Offsite[3]	346	10	180	190	11354	11700	59

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 195 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)

[3]The limiting factor is the water level decreasing to the top of the fuel assemblies. (195 hours, table 2)

Table 13 The mitigation strategy time analysis of BWRs for internal fire events.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW} (min)	TM
SFP normal makeup[1]	30	5	1	6	15150	15180	2524
Fire system makeup without PPE[2]	36	10	30	40	1944	1980	48
Fire system makeup with PPE[3]	76	10	60	70	15104	15180	215
B5b makeup without PPE[2]	146	10	120	130	1834	1980	13
B5b makeup with PPE[3]	276	10	60	70	14904	15180	212
Offsite[3]	346	10	180	190	14834	15180	77

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 253 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)
[3]The limiting factor is the water level decreasing to the top of the fuel assemblies. (253 hours, table 2)

4.4.4 Discussion

Tables 12 and 13 show large time margins for the multiple mitigation strategies available for this event. With the equipment available, the human failure probability to maintain spent fuel safety is negligible. The hardware reliability requires failures of the SFP normal makeup system, the fire protection system, the B5b makeup system, and offsite support. The combination failure probability is negligible. Therefore, internal fire events have a negligible risk contribution to spent fuel safety.

4.5 Loss of pool cooling

4.5.1 Initiating Event and Crew Response

NUREG-1738 states:

> The loss of cooling initiating event may be caused by the failure of pumps or valves, by piping failures, by an ineffective heat sink (e.g., loss of heat exchangers), or by a local loss of power (e.g., electrical connections). Although it may not be directly applicable because of design differences in decommissioning plants, operational data from NUREG-1275, Volume 12 [26], show that the frequency of loss of SFP cooling events in which temperature increases more than 20 °F is on the order of two to three events per 1000 reactor years. The data also show that most of the loss of cooling events lasted less than one hour. Only three events exceeded 24 hours. The longest was 32 hours[5]. In four events the temperature increase exceeded 20 °F. The largest increase being 50 °F.

NUREG-1275 Volume 12 [26] states:

> The dominant cause of the actual loss of SFP cooling events was loss of electrical power to the SFP cooling pumps…For these losses of electrical power, the time for which cooling was not available ranged from a few minutes with no accompanying temperature increase to 8 hours with an associated temperature rise of 20 °F. The

[5] NUREG-1275 Volume 12 does not provide details of the event with 32 hours of loss of SFP cooling.

primary causes appeared to be human error and administrative problems in 22 of the 39 events.

NUREG-1275 Volume 12 [26] also reports that:

- Five events involved failure of one SFP cooling pump while the second pump remained operable. During these events, the second SFP cooling pump was adequate to cool the SFP.
- Several conditions were reported in which full core off-loads were performed with insufficient evaluation of the heat loads or SFP cooling system during the offload. Errors in the calculated heat load and non-conservative ultimate heat sink temperature assumptions also occurred. This issue surfaced at Millstone Unit 1. The licensee determined that, during prior refueling outages, the SFP cooling system would not have been capable, by itself, of maintaining pool temperature below the 150 °F design limit under certain postulated conditions, including a single active equipment failure.

The operator's response to the loss of SFP cooling event is, after becoming aware of the event, to use the normal makeup system to restore the SFP water level. The backup SFP makeup strategies include the fire protection system, B5b makeup system, and offsite support.

4.5.2 Cognitive Task Analysis

<u>Detecting</u>

The loss of SFP cooling pumps is most likely to be detected quickly by the MCR operator based on the pump status indications. Otherwise, the following means could allow for the detection of the abnormality:

- The loss of the SFP cooling system would increase SFP water temperature and eventually trigger the high water temperature alarm to warn the operator.
- Every shift (every 12 hours) requires logging the key plant parameters. This check would identify the abnormal increase of SFP water temperature.
- The plant walkdown performed every 24 hours identifies the unusually warm SFP temperature.

<u>Understanding</u>

The SFP cooling system status is the first system to check when an abnormally high SFP water temperature is perceived. This would lead to identification of the loss of SFP normal cooling system.

<u>Deciding</u>

Restoring the SFP cooling system and using the SFP normal makeup strategies to maintain the SFP water level are the priorities.

<u>Action</u>

The SFP normal makeup system can be operated from the MCR. The needed system indications and controls are available in the MCR to maintain the SFP water temperature and level.

4.5.3 Time Analysis

Assuming a complete loss of the SFP cooling system was not detected until 32 hours after the initial loss of the cooling system, Tables 14 and 15 show the time analysis for PWRs and BWRs, respectively.

Table 14 The mitigation strategy time analysis of PWRs for the loss of SFP cooling events.

Action	T_{delay}[4] (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min.)	T_{SW} (min.)	TM
SFP normal makeup[1]	1920	5	1	6	9780	11700	1629
Fire system makeup without PPE[2]	1926	10	30	40	54	1980	0
Fire system makeup with PPE[3]	1966	10	60	70	9734	11700	138
B5b makeup without PPE[2]	2036	10	120	130	-56	1980	-1
B5b makeup with PPE[3]	2166	10	60	70	9534	11700	135
Offsite[3]	2236	10	180	190	9464	11700	49

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 195 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)
[3]The limiting factor is the water level decreasing to the top of the fuel assemblies. (195 hours, table 2)
[4]Assume the problem was not detected for 32 hours.

Table 15 The mitigation strategy time analysis of BWRs for the loss of SFP cooling events.

Action	T_{delay}[4] (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW} (min)	TM
SFP normal makeup[1]	1920	5	1	6	13260	15180	2209
Fire system makeup without PPE[2]	1926	10	30	40	54	1980	0
Fire system makeup with PPE[3]	1966	10	60	70	13214	15180	188
B5b makeup without PPE[2]	2036	10	120	130	-56	1980	-1
B5b makeup with PPE[3]	2166	10	60	70	13014	15180	185
Offsite[3]	2236	10	180	190	12944	15180	67

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 253 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)
[3]The limiting factor is the water level decreasing to the top of the fuel assemblies. (253 hours, table 2)
[4]Assume the problem was not detected for 32 hours.

4.5.4 Discussion

It takes more than 8 days to boil off SFP water to the top of the fuel assembly level after the pool starts to boil regardless of whether or not it is in a BWR or PWR. Tables 15 and 16 show that there are large time margins to perform multiple SFP makeup strategies. The probability of failing to maintain spent fuel safety in a loss of SFP cooling event is determined to be negligible.

It is unlikely that a complete loss of SFP cooling event would not be detected by operator much earlier than the 32 hours assumed in this time analysis. Multiple ways are available to detect the abnormality including indications of the cooling pump operating status, alarms (high water temperature), the SFP system walkdown performed every 12 hours, and the SFP area walkdown performed every 24 hours walkdown, etc. Tables 14 and 15 show that even though with 32 hours delay, the operator still have multiple options to prevent a spent fuel heat-up event.

4.6 Loss of coolant inventory

4.6.1 Initiating Event and Crew Response

NUREG-1738 [6] describes the event as the following:

> This initiator includes loss of coolant inventory resulting from configuration control errors, siphoning, piping failures, and gate and seal failures. Operational data in NUREG-1275, Volume 12, shows that the frequency of loss of inventory events in which a level decrease of more than 1 foot occurred is less than one event per 100 reactor years. Most of these events are as a result of fuel handler errors and are recoverable. Many of the events are not applicable in a decommissioning facility.
>
> NUREG-1275 Volume 12 [26] shows that, except for one event that lasted 72 hours, no events lasted more than 24 hours. Eight events resulted in a level decrease of between 1 and 5 feet, and another two events resulted in an inventory loss of between 5 and 10 feet.
>
> Using the information from NUREG-1275, it can be estimated that 6 percent of the loss of inventory events will be large enough and/or long enough to require isolating the loss if the only system available for makeup is the SFP makeup system. For the other 94 percent of the cases, operation of the makeup pump is sufficient to prevent fuel uncovery.

NUREG-1275 Volume 12 [26] classifies the primary pathways for the loss of SFP coolant inventory into the following three classes:

- Loss through connected systems
- Leakage through movable gates or seals
- Leakage through or failure of the fuel pool or the fuel liner

NUREG-1275 Volume 12 [26] states an event that resulted in estimated loss of the most SFP inventory of between five and ten feet of the SFP water level was due to siphoning effects. A siphoning drain down event is unlikely for decommissioning plants because of industry decommissioning commitment #7, which states, “Procedures or administrative controls to reduce the likelihood of rapid draindown events include: (1) prohibitions on the use of pumps that lack adequate siphon protection or (2) controls for pump suction and discharge points. The functionality of anti-siphon devices will be periodically verified.” Nevertheless, this HRA assumed a drain down event occurred that drained the SFP water down to 15 feet below the normal water level or 8 feet above the top of the fuel assembly.

The operator’s primary response will be using the SFP normal makeup to maintain SFP water level. A backup SFP makeup option will be prepared when the situation requires. This includes the fire protection system, B5b makeup strategy, and offsite assistance. In addition, manually isolating or sealing the leak flow will be performed to prevent further leakage.

4.6.2 Cognitive Analysis

<u>Detecting</u>

A quick drain down event is likely to be observed by the decrease of SFP water level, a parameter available in the MCR. Low SFP water level will trigger an MCR alarm to warn the operator about the abnormality. After the water level decreases to below the SFP cooling pump suction location, the SFP cooling system is lost. The SFP water temperature starts to rise slowly. A high SFP water temperature will trigger the high SFP water temperature alarm in the MCR. In addition, the plant parameters data log conducted every shift and the SFP area walkdown conducted every 24 hours are likely to detect the abnormality. If all of the above mechanisms fail to detect the abnormality, the MCR and local radiation alarms will be triggered when the SFP water level decreases to a certain level.

Understanding

After detecting the abnormality, the operator scanning the MCR control panels would identify low SFP water level.

Deciding

Immediate action to use the SFP normal makeup system to restore the SFP water level is the priority. In addition, operators will be dispatched to the SFP to identify the reason for the drain down and to isolate the drain down path from the SFP.

Action

The SFP normal makeup system can be operated from the MCR. Draindown isolation could involve manually isolating a valve or using material to seal the leakage.

4.6.3 Time Analysis

The time analysis below conservatively assumes a draindown event went unnoticed until the SFP water was drained down to 15 feet below the normal water level. The normal SFP water level is assumed to be 23 feet above the top of the fuel assembly. The time to boil and time to boil-off to the top of the active fuel are estimated as the following:

- Time to boil: NUREG-1738's estimate is 33 hours to boil with a normal SFP water level. This event assumes that 15 feet of water was drained out of the SFP. Only 8 feet of water remains on top of the fuel assembly. It is roughly estimated that the time to boil is 12 hours (about 33 × 8 ÷ 23).
- The PWR time to boil-off to the top of the fuel assemblies: 68 hours (about 195 × 8 ÷ 23, see the same reasoning in the first bullet above.)
- The BWR time to boil-off to the top of the fuel assemblies: 88 hours (about 253 × 8 ÷ 23, see the same reasoning in the first bullet above.)

Tables 16 and 17 show the time analysis data assuming the operator did not detect the SFP draindown event until the SFP water is 15 feet below the normal water level.

Table 16 The mitigation strategy time analysis of PWRs for the loss of inventory events.

Action	T_{delay}[4] (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min.)	T_{SW} (min.)	TM
SFP normal makeup[1]	0	5	1	6	4140	4140	689
Fire system makeup without PPE[2]	6	10	30	40	714	720	17
Fire system makeup with PPE[3]	46	10	60	70	4094	4140	57
B5b makeup without PPE[2]	116	10	120	130	604	720	4
B5b makeup with PPE[3]	246	10	60	70	3894	4140	55
Offsite[3]	316	10	180	190	3824	4140	19

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 195 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)
[3]The limiting factor is the water level decreasing to the top of the fuel assemblies. (195 hours, table 2)
[4]Assume the problem was not detected until after the drain down of 15 feet of SFP water.

Table 17 The mitigation strategy time analysis of BWRs for the loss of inventory events

Action	T_{delay}[4] (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW} (min)	TM
SFP normal makeup[1]	0	5	1	6	5280	5280	879
Fire system makeup without PPE[2]	6	10	30	40	714	720	17
Fire system makeup with PPE[3]	46	10	60	70	5234	5280	74
B5b makeup without PPE[2]	116	10	120	130	604	720	4
B5b makeup with PPE[3]	246	10	60	70	5034	5280	71
Offsite[3]	316	10	180	190	4964	5280	25

[1]The limiting factor (T_{SW}) is the spent fuel heat-up to 900 °C (> 253 hours, table 2)
[2]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)
[3]The limiting factor is the water level decreasing to the top of the fuel assemblies. (253 hours, table 2)
[4]Assume the problem was not detected until after the drain down of 15 feet of SFP water.

4.6.4 Discussion

Based on the large time margins and multiple mitigation strategies available to make up the SFP, the probability of the operators failing to protect the spent fuel from heat-up to 900 °C in a loss of SFP inventory event is determined to be negligible.

4.7 Seismic event

4.7.1 Initiating Event and Crew Response

Because NUREG-2161 [8] performed a more detailed analyses of seismic effects on the SFP than NUREG-1738 [6], the following descriptions are based on NUREG-2161 [8] for a plant-specific analysis of a BWR. The SFPs of BWRs (e.g., VY) are located on the upper level of the reactor building. The top of the SFP is about 100 feet above grade level. The depth of the SFP is about 40 feet. SONGS' SFP (a PWR) is partially underground. For SONGS, grade level is about three feet below the top of the fuel assemblies. Because of the lack of analytical data on seismic damage to PWR SFPs, this study uses NUREG-2161's analysis for this HRA.

NUREG-2161 [8] classifies the following three SFP damage statuses for a 0.7g beyond design basis earthquake (representing the seismic class of between 0.5g and 1.0g), with an estimated event frequency of one out of 60,000 years for the study plant:

a. No leakage: A state with no leakage from the bottom of the pool. This state corresponds to concrete cracking at the base of the walls but without tearing of the liner. The liner is able to hold the SFP water. NUREG-2161 estimates 90% of the hypothetical earthquakes will result in no SFP damage.
b. Small leakage rate: A state with leakage from the bottom of the SFP, corresponding to through-wall concrete cracking at the bottom of the walls and tearing of the liner that remains localized to the where the floor liner is attached to the SFP floor near the walls. NUREG-2161 estimates the crack as, "The resulting crack width for a liner tear localized at the location of the backup bar is then estimated at 0.15x0.10 = 0.015 in (0.37 mm). The crack length at each location is taken to be equal to the width of a backup bar which is equal to 4.0 in (101.6 mm)." NUREG-2161 uses forty crack locations (backup bar). The estimated leakage flow when the SFP water level is about 16 feet above the SFP

floor is about 200 gallons per minute. This implies that the SFP water level can be maintained by the B5b makeup strategy if the makeup strategy is performed in time. NEI 06-12 requires greater than 500 gpm of B5b makeup flow. NUREG-2161 estimates 5% of the hypothetical earthquakes will result in a small leak.

c. Moderate leakage rate: A state with leakage from the bottom of the SFP, corresponding to through-wall concrete cracking at the bottom of the walls and tearing of the liner that propagates to an extent such that water leakage is controlled by the size of the cracks in the concrete. NUREG-2161 describes the crack as, "the crack areas estimated in this manner to estimate an average crack width of about 3.6 mm (about 0.14 inch) and an average crack length of about 33,000 mm (about 108 feet), with a non-smooth and non-uniform surface." Given the crack, the average flow rate for this condition to a height of about 16 feet above the SFP floor is about 1,500 gallons per minute. This indicates that the B5b makeup strategy cannot maintain the SFP water level. NUREG-2161 estimates 5% of the hypothetical earthquakes will result in moderate leakage damage.

After the SFP is isolated from the reactor cavity, NUREG-2161 estimates that:

- SFP with small leakage: the time to drain the SFP water to the top of the spent fuel pool is about 19 hours. Because of the drain down rate, the SFP starts to boil after the water level decreases to below the top of the fuel assemblies.
- SFP with moderate leakage: the time to drain the SFP water to the top of the fuel assemblies is about 2.5 hours.

It is assumed that the beyond design basis earthquake causes wide area damage. The non-seismically robust systems and structures are assumed not available, based on NEI 12-06 guidelines [24]. The only available SFP makeup systems are the B5b makeup strategy and offsite support. Because of the wide area damage, the offsite support is assumed not be available until 24 hours after the initiating event, based on NEI 12-06 [24]. The operator's immediate objective is to use the B5b pump(s) to make up or spray the spent fuel to maintain spent fuel safety. The B5b pump is required to have diesel fuel readily available to operate the pump continuously for 12 hours. Additional diesel fuel is available onsite to support longer operation. The equipment for the B5b makeup strategy (pump, fire hoses, and monitor) are either stored in light structures or seismically robust buildings. This equipment is assumed not to be damaged by the earthquake.

4.7.2 Cognitive Analysis

The operator is assumed not to respond to the earthquake until the main ground motion has ceased. Because the earthquake could potentially damage both ac and dc power, in this situation, all MCR indications will not be available. In this case, the state of the SFP has to be detected locally and communicated to the SM to support the selection of the appropriate mitigation strategy. This will delay the decision. For the moderate leak events, this delay significantly affects the time margin.

<u>Detecting</u>

The operators noticed the earthquake immediately because of the unusual, severe ground motion.

<u>Understanding</u>

If the MCR instrumentation is available, the operator will quickly know the SFP status (mainly the water level trend) and the available mitigation systems. Reports from local operators or operators dispatched to inspect the earthquake damage would inform the SM (the emergency director) about large, site-wide damage.

Deciding

The SONGS' B5b mitigation strategy entry conditions are:

- Loss of a large area of the plant due to fire, or explosion which creates the need for mitigation strategies beyond those given in existing procedures.
- Loss of all AC or all normal heat removal equipment by any means, including natural disasters.

The VY's B5b mitigation strategy entry condition is the loss of large areas of the plant due to fires or explosions.

Because of the loss of offsite power (due to the earthquake), the operator will manually start the diesel generator. In this event, the diesel generator is assumed not to be available. Unable to start the diesel generator from the MCR, the SM would dispatch an operator to start the diesel generator locally. In this event, the local start of the diesel generator is assumed to fail. In parallel to locally starting the diesel generator, soon the operator will notice the fire protection system is not available. (This study assumes the fire system piping is damaged by the earthquake). This leads to the decision to implement the only available onsite SFP mitigation strategy - the B5b makeup strategy.

Action

The earthquake damage is expected to affect the operators implementing the B5b makeup strategy. The mitigation strategy needs to be implemented before the water decreases to the top of the fuel assemblies.

4.7.3 Time Analysis

Table 18 shows the NUREG-2161's time estimates for operators to implement the B5b SFP makeup strategy for a beyond design basis earthquake. Appling the time data in Table 18 in this HRA, Tables 19 and 20 show the time analysis for PWRs and BWRs, respectively, when the SFP remains intact after the earthquake. Tables 21 and 22 show the time analyses of an SFP small leak scenario and moderate leak scenario, respectively.

Table 18 NUREG-2161's time estimates for operator to implement the B5b makeup strategy in an extreme earthquake.

	T_{delay}	T_{cog}	T_{EXE}	T_{reqd}
SBO	45 minutes	15 minutes	3 hours	3 hours 15 minutes
SBO without dc	60 minutes	15 minutes	3 hours	3 hours 15 minutes

Table 19 Time analysis of the SFP not damaged by the earthquake for PWRs.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW} (min)	TM
B5b makeup without PPE[1]	60	15	180	195	1920	1980	9
B5b makeup with PPE[2]	255	10	180	190	11445	11700	59
Offsite[3]	1440	10	180	190	10260	11700	53

[1]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)

[2]The limiting factor is the water level decreasing to the top of the fuel assemblies. (195 hours, table 2)

Table 20 Time analysis of the SFP not damaged by the earthquake for BWRs.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW} (min)	TM
B5b makeup without PPE[1]	60	15	180	195	1920	1980	9
B5b makeup with PPE[2]	255	10	180	190	14925	15180	78
Offsite[3]	1440	10	180	190	13740	15180	71

[1]The limiting factor is the spent fuel pool starting to boil (33 hours, table 1)

[2]The limiting factor is the water level decreasing to the top of the fuel assemblies. (253 hours, table 2)

Table 21 Time analysis of an SFP that has a small leak caused by the earthquake for BWRs.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW}[1] (min)	TM
B5b makeup	60	15	180	195	1080	1140	5
Offsite	1440	10	180	190	-300	1140	-3

[1]The limiting factor is the water level decreasing to the top of the fuel assemblies. (19 hours)

Table 22 Time analysis of the SFP has a moderate leak caused by the earthquake for BWRs.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW}[1] (min)	TM
B5b makeup	60	15	180	195	90	150	-1
Offsite	1440	10	180	190	-1290	150	-8

[1]The limiting factor is the water level decreasing to the top of fuel assemblies. (2.5 hours)

4.7.4 Discussion

If the SFP remains intact after the earthquake, Table 20 shows large time margins for performing B5b makeup or spray and obtaining offsite support. Offsite support is assumed not to arrive at the site until 24 hours after the event. If the needed equipment is available, the probability of failure to prevent the spent fuel heat-up is determined to be negligible. Table 21 shows a time margin of five for performing the B5b makeup strategy but negative T_{avail} for obtaining offsite support, based on the 24 hours of delay time specified in NEI 12-06 for extreme external events. This indicates that in a small leak event:

- Offsite support may not be deployed in time to prevent fuel heat-up based on NEI 12-06 assumptions on site accessibility.
- The B5b mitigations strategy is likely successful if the components are available. The failure probability is likely dominated by hardware reliability (failure of the B5b pump) instead of human reliability.

Table 23 indicates that in a moderate leak scenario, T_{avail} is less than the T_{reqd} for both the B5b and offsite support strategies. This means that none of the strategies would be expected to be implemented in time to prevent a fuel heat-up. This is the same conclusion as NUREG-2161 [8]. The short available time (2.5 hours) is based on the time that it will take for the SFP water level to lower to the top of the fuel assemblies. This results in a high radiation level in the refueling floor area so that setting up monitors for SFP spray cannot be performed.

If the SFP spray strategy can be performed without exposing the operators to the adverse environmental conditions on the SFP refueling floor, the time available for performing recovery actions could be significantly increased. This is because the system time window (T_{SW}) is moved from the SFP water reaches to the top of the fuel assemblies to the fuel heats up to 900 °C. The Sandia National Laboratories letter report "Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents and Extension of Reference Plant Analyses to Other Spent Fuel Pools "[11] calculated that for the one-year-old BWR spent fuel with the SFP breach at the 25% active fuel height level, it takes about 1.4 days to heat-up the spent fuel. NUREG-2161 estimated that for a one-year-old BWR spent fuel with SFP breach at the bottom of the SFP, the spent fuel will never heat-up. Because there is no calculation for PWR fuel, this study assumes 10 hours difference of the two T_{SW}s[6]. Table 23 shows the revised time analysis by assuming the B5b spray strategy can be performed without exposing the workers to the refueling floor high radiation. The time analysis indicates that the B5b spray strategy's time margin is three. It indicates the option has a fair chance of success if the needed equipment is available.

Table 23 Time analysis of the SFP that has a moderate leak caused by the earthquake for BWRs with the assumption that the workers do not need to enter the refueling floor to perform the B5b spray strategy.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW}[1] (min)	TM
B5b makeup	60	15	180	195	690	750	3
Offsite	1440	10	180	190	-690	750	-5

[1]The limiting factor is the water level decreasing to the top of the fuel assemblies. (2.5 hours)

4.8 Cask drop

4.8.1 Initiating Event and Crew Response

The cask drop events are that the SFP or the adjacent structure suffer damage from a cask drop incident resulting in an SFP drain down event. NUREG/CR-4982 [27] states, "Only horizontal movements of the cask above a structurally critical section of the pool would pose the threat of structural damage. As noted above, WASH-1400 [28] assumed that the sensitive section is the vertical wall at the pool edge." NUREG-1738 [6] states, "(NUREG/CR-4982 [27]) only considered the possibility of a heavy load drop on the pool wall. The assessment conducted for this study identifies other failure modes, such as the collapse of the pool floor, as also credible for some sites."

NUREG/CR-5176 [21] described finite element simulations of cask drop events on the SFP structure. Two calculations were performed with cask weights of 110 tons and 40 tons dropped from a height of six inches onto the SFP wall. The six inches height is the maximum height that the cask can be lifted, dictated by the operating criteria. The results indicated that "virtually the entire wall is subject to tensile cracking at some point. The pool has a thin metal liner which provides containment of the pool water. If the liner remains intact, the water will be contained despite concrete cracking." The 40 ton cask drop calculation showed that the SFP suffers significantly less impact than from the 110 ton cask. However, the calculation also showed that

[6] The bottom of PWR spent fuel pools are either under or on the grade level that are less likely to suffer an earthquake-induced rapid spent fuel uncover event than BWRs.

a through-wall concrete crack could potentially occur. NUREG-1738 states, “A (heavy load) drop would seriously damage the SFP (either the bottom or walls of the pool) to the extent that the pool would drain very rapidly and it would not be possible to refill it using onsite or offsite resources.”

Both SONGS and VY implement a single-failure-proof crane to move the dry casks in the refueling floor area. NUREG-1738 estimates the mean probability of a catastrophic heavy load drop is 2×10^{-9} per spent fuel cask lift for using a single-failure-proof system. Rigorous administrative controls are implemented to control the dry cask move path, moving height, moving speed, and descent rate, etc. to reduce the probability of a load drop and impacts. Figure 12 shows the VY’s administrative control of the dry cask move path to have minimum overlap with the SFP to reduce the heavy load drop risk. SONGS implemented similar administrative controls on its SFP move path. As mentioned earlier, SONGS’ dry casks are placed in the cask loading pit adjacent to the SFP with a water gate between the SFP and the cask loading pit. The bottom of the water gate is about two feet five inches above the top of fuel assemblies. In SONGS, it is geometrically infeasible for the crane to move the dry casks over the SFP. In addition, most of the fuel assemblies are located below grade level. These locations ensure that the worst cask drop event could only drain SFP water level to two feet five inches above the top of the SONGS fuel assembly. This increases the time available for operators to respond to a cask drop event. However, not all PWRs have cask loading pits. For these plants, dry cask loading will be performed in the SFP. Most PWRs have a portion of their SFPs below the grade level. This could reduce the leakage rate from a cask drop event.

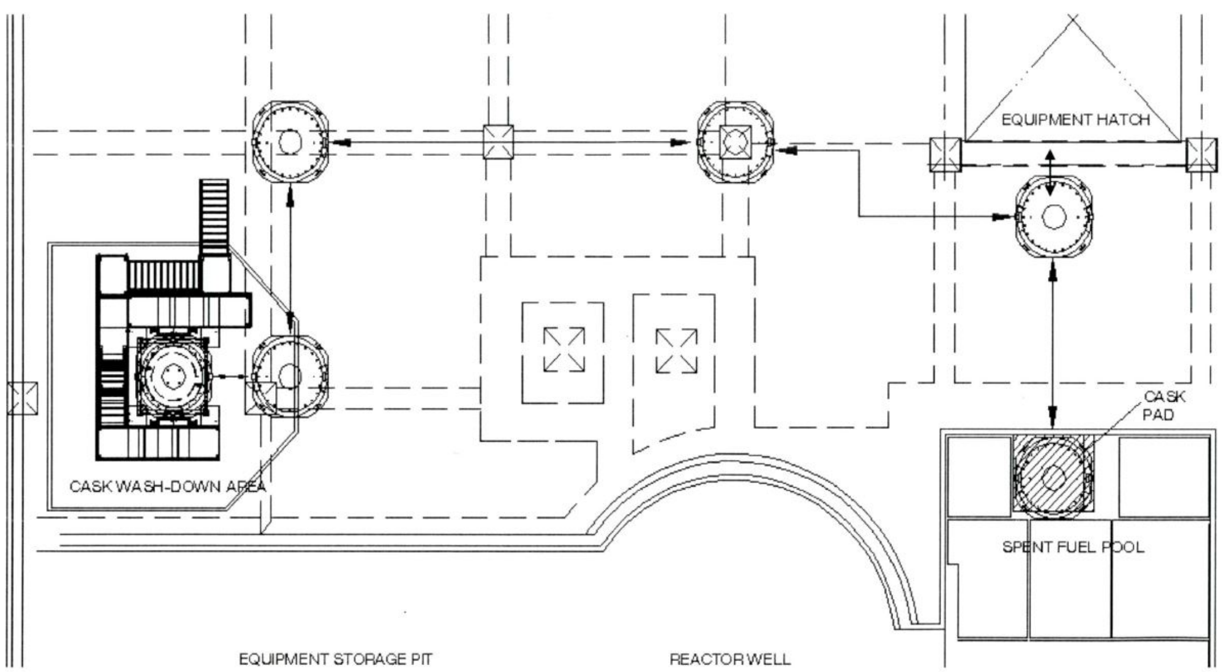

Figure 12 VY heavy load moving path on the refueling floor level (courtesy of VY)

Both VY and SONGS plan to use contractors to load the spent fuel into dry casks. The plant’s certified fuel handler will be in the refueling floor area to monitor the cask moving and fuel loading activities.

Even though it is not expected that a cask drop event would damage the SFP to the same extent as a 0.7g earthquake discussed section 4.7, this study assumes the cask drop caused the same damage to perform an HRA. The following two drain down rates are studied:

- Small leakage: The SFP drains to the top of the fuel assemblies within 19 hours. The water decrease rate is about 0.24 inch per minute. The leak flow rate is about 200 gpm when the water level is 16 feet above the SFP floor.
- Moderate leakage: The SFP drains to the top of the fuel assemblies within 2.5 hours. The water decrease rate is about 1.8 inches per minute. The leak flow rate is about 1,500 gpm when the water level is 16 feet above the SFP floor.

Immediately after a cask drop incident, the certified fuel operator on the refueling floor would radio the MCR operator to notify him/her of the incident. The SFP water level will be closely monitored in the MCR and locally. After detecting the unusual SFP water level decrease, the MCR operator will start the SFP normal makeup system. In addition, the operator on the refueling pool will set up monitors on the refuel floor to use the fire protection system to be ready to make up the SFP. If the combination of the SFP normal makeup and the fire water cannot maintain the SFP water level, the local operator will switch the monitor(s) to spray mode to spray water to cool the spent fuel.

NUREG-2161's analysis shows that within a few months after shutdown, heat up of the hottest fuel can be prevented by evenly spraying 200 gpm of water into the SFP. It is expected that the same spray flow rate will prevent fuel heat-up for one-year-old spent fuel regardless of whether it is in PWRs or BWRs.

4.8.2 Cognitive Analysis

<u>Detecting</u>

A cask drop event will be detected immediately locally. The MCR operator will be notified promptly.

<u>Understanding</u>

The SFP water level will be closely monitored locally and in the MCR. In addition, the cask drop damage to the spent fuel would be visually assessed locally.

<u>Deciding</u>

Assuming the cask drop caused an SFP drain down event, the MCR operator will actuate the SFP normal makeup system to make up the SFP. The maximum makeup flow rates are 250 gpm for VY and more than 500 gpm for the SONGS' SFP. The makeup flow is able to maintain the SFP water level above the top of the fuel assemblies for the small leakage scenario but the makeup flow rate is insufficient to maintain the SFP water level for the moderate leakage scenario. Therefore, the decisions are to use the makeup system to maintain the SFP water level. The local operator will deploy monitor(s) and connect the monitor(s) to the fire hydrant on the refueling floor with fire hose(s) as a redundant SFP makeup measure. If the makeup system cannot maintain the SFP water level, the SFP spray strategy will be used. The operator would need to protect the makeup water source from the internal flood damage and establish a long term cooling strategy (e.g., re-circulate sump water for the SFP makeup and applying materials to block and reduce the leak flow.).

Action

The SFP normal makeup system can be controlled from the MCR. The monitors and fire hoses are stored in equipment boxes located in the vicinity of the SFP refueling floor. Operators are trained to operate the monitors. The SFP water level can be observed from the MCR and locally to detect the effectiveness of the SFP makeup strategies.

4.8.3 Time Analysis

Because the operators are already at the refueling floor area, the time required to set up the monitor is estimated to be about 15 minutes. Tables 24 and 25 are the time analyses of small and moderate leakage events resulting from a cask drop.

The tables show that the operators have four mitigation strategies available to prevent fuel heat-up for the small leakage event. The operators have only one mitigation strategy (the fire protection system) available to prevent fuel heat-up for the moderate leakage event. The other strategies cannot be performed in time.

The 60 minutes of T_{cog} in the moderate leak event for applying the fire protection system, instead of 10 minutes, is to cover the time required for the operators to determine that the makeup flow cannot maintain the SFP water level. Based on the procedure instructions, the monitors will be switched to spray mode to spray water on the spent fuel.

The SFP normal makeup system listed in Table 25 (moderate leakage) is only applicable to SONGS. This is because SONGS has two spray nozzles mounted on the inside of the reactor building readily available to spray water into the SFP. The two spray nozzles are connected to the SFP normal makeup system. Therefore, SONGS can spray water into the SFP from the SFP normal makeup system. The spray flow can be controlled from the MCR, which prevents the need for working on the refueling floor area so that operator performance is not affected by the adverse environment in the refueling floor area. Therefore, the available time is the sum of the 2.5 hours it takes for the SFP water level to decrease to the top of fuel assemblies and the 10 hours it takes for the spent fuel to heat up to 900 °C.

Table 24 Time analysis of the SFP with a small leak caused by a cask drop event.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW}[1] (min)	TM
SFP normal makeup	0	10	1	1	1140	1140	103
Fire protection system	0	10	30	45	1140	1140	28
B5b makeup/spray	40	10	120	130	1100	1140	7
Offsite	170	10	180	190	970	1140	4

[1]The limiting factor is the water level decreasing to the top of the fuel assemblies. (19 hours)

Table 25 Time analysis of the SFP has a moderate leak caused by a cask drop event.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW}[1] (min)	TM
Normal makeup system- spray[1]	0	10	1	11	750	750	67
Fire protection system – spray	0	60	30	90	150	150	2
B5b pump - spray	50	10	120	130	60	150	-1
Offsite	180	10	180	190	-70	150	-1

[1]SONGS design only. This cannot be generically applied to other plants.
[2]The limiting factor is the water level decreasing to the top of the fuel assemblies. (2.5 hours)

4.8.4 Discussion

For a small leak caused by a cask drop event, the SFP normal makeup system, the fire protection system, the B5b makeup, and offsite support are all available to provide SFP cooling to prevent fuel overheating in time. The risk of a spent fuel heat up is negligible.

Even though it is unlikely that a dry cask drop would damage the SFP to the same extent as the extreme earthquake discussed in section 4.7, this study performs time analysis to understand the operators' mitigation options. Table 25 shows that the operators have sufficient time to use the fire protection system to prevent fuel heat-up if the fire protection system is available. There is also sufficient time for error recovery when implementing the fire protection system mitigation strategy. If the fire protection system is not available, however, there will not be sufficient time to perform the B5b migration strategies nor to obtain offsite support because the T_{avail} is less than the T_{reqd}. This is because the high radiation in the refueling floor area prevents working on the refueling floor.

Table 25 shows the unique SONGS' design, in which two spray nozzles are mounted on the inside of the reactor building wall and are available to spray water into the SFP. The two spray nozzles are connected to the SFP normal makeup system that can be operated from the MCR. This becomes a significant advantage in large, rapid drain down events when the SFP water level cannot be maintained. The SFP normal makeup system does not provide a sufficient flow rate to maintain the SFP water level in a moderate leak event. An SFP spray strategy is needed to cool the spent fuel. With the SONGS' modification, the SFP normal makeup system becomes one of the optimal mitigation strategies to spray the SFP for the large, rapid drain down events.

It is anticipated after a few months of decay, the hottest spent fuel can be cooled by spray (200 gpm evenly sprayed into a SFP) based on the estimate in NUREG-2161 [8]. However, NUREG-2161's estimate was based on one third of the fuel being offloaded instead of a full-core offload. In addition, NUREG-2161 was based on a BWR. PWRs were not studied. The required spray flow rate depends on many factors such as decay heat of the hottest fuel, spent fuel assemblies configuration, and the coverage and pattern of water spray, etc. The SNL report "Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents and Extension of Reference Plant Analyses to Other Spent Fuel Pool"[11] provides useful information about the spent fuel coolability.

4.9 Aircraft impact

4.9.1 Initiating Event and Crew Responses

The Committee on the Safety and Security of Commercial Spent Fuel Nuclear Fuel Storage of National Research Council [13] concluded that there are some scenarios that could lead to partial failure of the SFP wall, thereby resulting in a partial or complete loss of pool coolant. A zirconium cladding fire could result if timely mitigation actions to cool the fuel were not taken.

The conclusion of [13] was made based on two aircraft impact studies performed by the Electric Power Research Institute (EPRI) and the SNL. The EPRI study used a Boeing 767-400 for analysis. The detailed analysis is classified information that is not available to this study. The

NEI described the EPRI results as, “State-of-the-art computer modeling techniques determined that typical nuclear power plant containment structures, used fuel storage pools, fuel storage containers, and used fuel transportation containers at U.S. nuclear power plants would withstand these impact forces despite some concrete crushing and bent steel” [29].

The Committee on the Safety and Security of Commercial Spent Fuel Nuclear Fuel Storage of the National Research Council [13] states, “…the consequences of such (aircraft) attacks are scenario- and plant- specific. It is not possible to make any general statements about spent fuel storage facility vulnerabilities to air attacks that would apply to all U.S. commercial nuclear power plants.” The discussion [13] implies that for an aircraft impact to challenge SFP safety, it requires a large civilian aircraft to hit at the SFP’s most vulnerable point.

Regarding aircraft impact frequency, NUREG-1738 [6] estimated:

> The conditional probability that a large aircraft crash will penetrate a 5-foot-thick reinforced concrete wall is taken as 0.45 (interpolated from NUREG/CR-5042 [30]). It is further estimated that 1 of 2 crashes damage the spent fuel pool enough to uncover the stored fuel (for example, 50 percent of the time the location of the damage is above the height of the stored fuel). The estimated range of catastrophic damage to the spent fuel pool resulting in uncovery of the spent fuel is 1.3×10^{-11} to 6.0×10^{-8}. The mean value is estimated to be 4.1×10^{-9} per year. The frequency of catastrophic BWR spent fuel pool damage resulting from a direct hit by a large aircraft is estimated to be the same as for a PWR.

Despite the low probability, the following describes the anticipated impacts of a large aircraft directly hitting a structure housing the SFP on event mitigation:

- For a large aircraft direct hit to the SFP, fatalities and injuries of local workers are likely. The MCR is not likely to be damaged but the MCR ventilation system may be damaged. An MCR evacuation may be needed.
- The building housing the SFP is not accessible.
- Because the monitors are stored within the building housing the SFP, the monitors are assumed to be damaged by the aircraft impact.
- The fire protection system piping is damaged by the aircraft impact. The fire pumps are actuated automatically so that they pump fire water out of the damaged pipes.
- The local fire station would be notified immediately. The fire engines are the main event mitigation equipment used, assuming the aircraft impact did not cause an immediate radiation release.

4.9.2 Cognitive Analysis

<u>Detecting</u>

The MCR operator immediately detects the event by the loud aircraft impact and swift changes of the key SFP parameters, indications, etc.

<u>Understanding</u>

The MCR soon would know that:

- A large fire event is ongoing,

- There is reduced staff availability due to fatalities and injuries,
- The SFP cooling system, the SFP normal makeup system, and the fire protection system are not available. The remaining option for SFP makeup is B5b makeup and offsite support.

Deciding

The decision would be to call for offsite (local fire station) support and to work with the available staff to use the available means for firefighting. The offsite fire trucks are expected to respond to the aircraft impact event immediately regardless of whether or not the SM called for offsite support.

Action

The B5b monitors are stored near the SFP and will not be available in this event. For BWRs, because of the high SFP elevation, local makeup is not feasible. BWRs will rely on ladder fire trucks to spray water from the penetration made by the aircraft. For PWRs, the SFPs are partially underground. Onsite fire water is likely available for firefighting if monitors are available. Offsite fire trucks are assumed to arrive on site within one hour after the event. The offsite fire trucks are the main resources to fight the fire and to spray the SFP. The water will be sprayed from the building penetration created by the aircraft impact to the SFP. Because of a lack of information of the spent fuel heat up time in a large aircraft impact event, T_{SW} is assumed to be 10 hours.

4.9.3 Time Analysis

The time window (T_{SW}) strongly depends on the damage to the spent fuel and SFP. Table 26 shows the time analysis. The time analysis is based on the following assumptions:

- Personnel and equipment are available to implement the B5b mitigation strategy. In a normal condition, implementing the B5b strategy requires two individuals for two hours. In this condition, four hours is assumed for T_{EXE} that includes the time needed to extinguish the fire and to makeup or spray water into the SFP.
- The B5b pump option is not available for BWRs because of the high SFP elevation and inaccessibility to the area close to the SFP.
- The B5b pump option is available to PWR SFPs.
- Offsite support includes the local firefighters. The first fire truck is assumed to arrive at the site one hour after the event. For BWRs, ladder fire trucks are needed to put water into the SFP through the reactor building penetration made by the aircraft impact.
- The SFP makeup or spray is performed from outside of the reactor building (BWRs) or within the SFP building (PWRs).
- The T_{EXE} to extinguish the fire and to makeup or spray into the SFP is assumed to be 4 hours.

Table 26 Time analysis of the SFP with a large aircraft impact.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW}[1] (min)	TM
B5b pump[2]	0	10	240	250	600	600	1
Offsite	60	10	240	250	540	600	1

[1]The system time is assumed to be 10 hours, an approximate time for the hottest spent fuel to heat up adiabatically to 900 °C.

[2]The B5b pump spray/makeup strategy is not available for BWRs' SFPs because of the high SFP elevation. Assume that spare monitors are available.

4.9.4 Discussion

The likelihood of a large commercial aircraft losing control, leading to a direct hit to the SFP of a nuclear plant is small. If the event did occur, the spent fuel is protected by a large amount of water in the SFP. There are about 570 tons of SFP water above the top of fuel assemblies for a BWR SFP and about 660 tons for a PWR SFP. The discussion in [13] suggests that an immediate zirconium fire is not expected. This allows for the mitigation actions to be performed near the SFP building and the time to extinguish the fire and provide SFP makeup or spray before a zirconium fire occurs. Because the SFP makeup or spray is performed from outside of the reactor building or SFP building, high radiation due to low SFP water level would not affect performance of the action. With the condition and time assumptions, the time analysis shows that there is sufficient time to mitigate the event to prevent a spent fuel heat-up.

4.10 Tornado missile

4.10.1 Initiating Event and Crew Response

Tornado damage from missiles has the potential to affect the SFP systems, such as power supplies, cooling pumps, heat exchangers, and makeup water sources, and may also affect recovery actions. NUREG-1738 states, "Department of Energy (DOE) studies indicate that the thickness of the SFP walls (greater than four feet of reinforced concrete) is more than sufficient protection from missiles that could be generated by the most powerful tornadoes ever recorded in the United States...Pool walls are about 5 feet thick and the pool floor slabs are around 4 feet thick…Based on the DOE-DOE-STD-1020-94 [31] information, it is very unlikely that a tornado missile would penetrate the SFP, even if it were hit by a missile generated by an F4 or F5 tornado."

NUREG-1738 assumed that very severe tornadoes (F4 to F5 tornadoes on the Fujita scale) would be required to cause catastrophic damage to a PWR or BWR SFP. These tornados have wind speeds that result in damage characterized as "devastating" or "incredible." The frequency of an F4 to F5 tornado is estimated to be 5.6×10^{-7} per year for the Central United States, with a U.S. average value of 2.2×10^{-7} per year. NUREG-1738 estimated that the frequency of catastrophic failure given a tornado missile is estimated less than 1×10^{-9} per year. This study assumed a powerful tornado caused the following site damage:

- Loss of offsite power
- Damaged the diesel generator, the B5b pump(s) and the fire pumps.

Because the tornado is a local event, the availability of offsite support is not constrained by the NEI 12-06 [24] assumption, i.e., not available until 24 hours after the event.

4.10.2 Cognitive Analysis

<u>Detection</u>

A short warning time is available for the operators to take shelter. The loss of offsite power is immediately detected by the MCR crew. The impacts to spent fuel safety include the loss of the SFP cooling system and the SFP normal makeup system.

Understanding
After the tornado has passed, site walk-downs are conducted to identify tornado damage and system availabilities. In this analysis, the fire pumps and the B5b pumps are assumed to be damaged by the tornado. The damage cannot be repaired. As a result, an SBO event is determined.

Deciding
Offsite support will be requested to provide portable pumps and generators because of the SBO event. At the same time, work will be performed to restore offsite power.

Action
The fire engine can use the fire protection system piping to makeup the SFP. Either offsite ac power is restored or a portable generator is available. The SFP cooling system and the SFP normal makeup system will return to service.

4.10.3 Time Analysis

The time analysis shown in Table 27 is based on the following assumptions:

- The tornado caused substantial structural damage to the B5b pumps, fire pumps, fire system piping, SFP cooling system, and SFP normal makeup system. This damage is not repairable.
- Offsite power is lost for an extensive amount of time.
- Because the offsite firefighters arrive with personal protective equipment, the T_{SW} is set to the time when the SFP boils off to the top of the fuel assemblies.
- It takes an hour for the offsite fire trucks to arrive at the site. The firefighters take three hours to set up for SFP makeup.

Table 27 Time analysis of an extreme tornado.

Action	T_{delay} (min)	T_{cog} (min)	T_{EXE} (min)	T_{reqd} (min)	T_{avail} (min)	T_{SW}[1] (min)	TM
Offsite (PWRs)	60	10	180	190	11640	11700	60
Offsite (BWRs)	60	10	180	190	15120	15180	79

[1]The time for the SFP water level to boil-off to the top of fuel assemblies.

4.10.4 Discussion

Even though with the conservative assumptions made in the time analysis to not credit any onsite systems, Table 27 shows that the time margin is large for the offsite fire trucks to provide SFP makeup. The failure probability of being unable to provide SFP makeup is determined as negligible.

5 Summary

This report documents an HRA on the SFPs of decommissioning nuclear plants by analyzing the risk of the nine initiating events identified in NUREG-1738. The analyses were performed to support NRC's rulemaking on decommissioning plants' emergency plan exemption requests. The key assumptions applied to this study include the industry decommissioning commitments and the staff decommissioning assumptions specified in the NUREG-1738. The analysis results can be summarized as the following:

- The overall risk from spent fuel in the SFPs is low, considering the low frequencies of the initiating events and the reliability of mitigation strategies that can be implemented in time to prevent spent fuel heat-up. This conclusion is consistent with NUREG-1738.
- The initiating events that do not damage SFP integrity have negligible risk. This risk is negligible mainly because of the clear indications of plant abnormalities, clarity of the plant status, clear rules to choose appropriate mitigation strategies, mostly skill-based actions with procedures available for reference, long time margins for performing the recovery actions, and multiple available recovery options. These initiating events include:
    - Loss of offsite power from plant-centered and grid-related events
    - Loss of offsite power from events initiated by severe weather
    - Internal fires
    - Loss of pool cooling
    - Tornado missiles
    - The earthquake or aircraft impact or cask drop events that do not breach the SFP integrity.
- The loss of coolant inventory initiating event reduces the time available for performing recovery actions. However, because of the IDC of controlling pump suction and discharge points to no more than 15 feet below the normal water level, the operators still have a large amount of time to perform recovery actions. The time reduction has little impact on human reliability. The risk of a loss of coolant inventory event is negligible.
- For the beyond design basis earthquake initiating event, NUREG-2161 analyzed two classes of SFP breaches: a small leak and a moderate leak. The HRA for these two breach classes is summarized as the following:
    - Small leak: The time available for performing the recovery actions is about 19 hours. Because offsite support is assumed to not be available until 24 hours after the initiating event, the only available mitigation option is to use the onsite B5b pump to makeup or spray the SFP. The reliability of the B5b pump may be a stronger risk contributor than human reliability, especially for sites with only one B5b pump. Individual nuclear stations may want to perform site accessibility analysis for a realistic determination of the availability of offsite support.
    - Moderate leak: The time available to perform recovery actions is 2.5 hours. Given the short time available and only one available onsite mitigation strategy (B5b spray), the action is determined to be not feasible. A note to the analysis is that the 2.5 hours available for performing the mitigation strategy is based on the time it takes for the SFP water level to drain down to the top of fuel assemblies. This results in a high radiation level in the refueling floor area that prevents setting up monitors for SFP spray. If the SFP spray can be performed remotely (without exposing operators to the adverse environmental conditions in the SFP refueling floor), the time available for performing the recovery action could be significantly increased. In this case, the system time window (T_{SW}) is determined by the time the fuel heats up to 900 °C instead of the time it takes for the SFP water level to decrease to the top of the fuel assemblies. For one-year-old spent fuel, the time available is estimated to be an additional 10 hours.
- For the cask drop initiating event, NUREG-1738 estimates the catastrophic failure rate from heavy load drops to have a mean value of 2×10^{-9} per spent fuel cask lift for using a single-failure-proof system. Therefore, the estimated probability of having a cask drop event before all spent fuel is in dry casks for VY is 9×10^{-8} (based on the 45 remaining dry casks to

be loaded) and for SONGS is 2×10^{-7} (based on the 91 remaining dry casks to be loaded for the two units). The probability of the event also needs to consider the conditional probability that a cask drop would damage the SFP and challenge SFP safety. The HRA analysis shows that, in a cask drop event with the same level of leakage as a large earthquake, because of the availability of the SFP normal makeup system and fire protection system, immediate detectability of the event, and ready availability of personnel on the refueling floor to communicate and implement mitigation strategies, the probability of successful event mitigation is high.

- For the aircraft impact initiating event, NUREG-1738 estimated the range of aircraft impact catastrophic damage to the SFP resulting in uncovery of the spent fuel is 1.3×10^{-11} to 6.0×10^{-8}. The mean value is estimated to be 4.1×10^{-9} per year. [13]'s discussion suggests that an immediate zirconium fire is not expected for a large aircraft impact on a SFP. There is still time available to perform mitigation strategies. It is assumed that the only available onsite mitigation strategy is B5b makeup. Two key uncertainties in implementing the B5b strategy are: (1) Personnel injury and fatality are likely. This reduces the available personnel to perform firefighting and SFP makeup; and (2) the monitors for SFP makeup are stored near the SFP refueling floor. They are likely not available in this event. Without available spare monitors, the B5b makeup strategy cannot be performed. Offsite support is expected to play an important role in event mitigation. Based on the assumption of having 10 hours of spent fuel heat-up time and a total of five hours for the offsite fire brigade to extinguish the fire and spray water into the SFP through the large building penetration caused by the aircraft impact, it is estimated as having a fair probability of successful event mitigation.

Based on the above analysis, the scenarios impose a non-negligible probability of failure to perform mitigation strategies including the following:

- An extreme earthquake caused an SFP moderate leak: The timing is the following:
    - The onsite mitigation strategies cannot be performed after 2.5 hours (based on NUREG-2161[8]) following the earthquake due to high radiation in the refueling floor area.
    - The estimated time to perform the B5b spray strategy is 4 hours 15 minutes.
    - The offsite support is not available until 24 hours after the earthquake based on NEI 12-06 assumptions.

  Conclusion:

    - The probability to perform SFP spray within 10 hours is 0 (zero).

- An extreme earthquake caused an SFP small leak: The timing is the following:
    - The onsite mitigation strategies cannot be performed after 19 hours (based on NUREG-2161[8]) following the earthquake due to high radiation in the refueling floor area.
    - The estimated time to perform the B5b makeup strategy is 4 hours 15 minutes.
    - The offsite support is not available until 24 hours after the earthquake based on NEI 12-06 assumptions.

Conclusion:

- Using a normal distribution with the mean of 4 hours 15 minutes and the standard deviation of 3 hours, there is 97% of probability that the mitigative actions will be performed within 10 hours, and more than 99.99% of probability that the action can be performed within 19 hours.
- For the plants that only have one B5b pump, the B5b pump reliability, a hardware reliability rather than human reliability, would dominate the risk of the small leak scenario.

- An aircraft impact resulting in an SFP moderate leak: The timing is the following:
  - Onsite mitigation will not be performed due to personnel fatality and injury and equipment damage caused by the event.
  - A mean of 5 hours 10 minutes and standard deviation of 3 hours for the offsite fire brigade to extinguish the fire and spray into the SFP is estimated

Conclusion:

- Using a normal distribution with the mean of 5 hours 10 minutes and the standard deviation of 3 hours (for the offsite fire brigade to extinguish the fire and spray to the SFP), there is 95% of probability that the actions will be performed within 10 hours.

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