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3.0 Risk Assessment of Spent Fuel Pools at Decommissioning Plants

As discussed in Section 1 of this paper, the scenarios leading to significant off-site consequences at a decommissioning plant are very different from an operating plant. Once fuel is permanently removed from the reactor vessel, the primary public risk in a decommissioning facility is associated with the spent fuel pool. The spent fuel assemblies are retained in the storage pool, and are submerged in water to provide cooling of the fuel's remaining decay heat as well as to provide shielding for the radioactive assemblies. The most severe accidents postulated for SFPs are associated with the loss of water (either through boil-off or draining) from the pool.

Depending on the time since reactor shutdown, fuel burnup, and on fuel rack configurations, there may be sufficient decay heat to cause the fuel clad to heat up over time, swell, and burst in the event of loss of pool water. The breach in the clad would result in the release of radioactive gases present in the gap between the fuel and clad, called "a gap release" (See Appendix 1). If the fuel continues to heat up, the temperature of the zirconium clad will reach the point of rapid oxidation in air. This reaction of zirconium and air, or zirconium and steam is exothermic. The energy released from the reaction combined with the fuel's decay energy can cause the reaction to become self-sustaining and lead to the ignition of the zirconium, or a "zirconium fire." The increase in heat from the oxidation reaction could also raise the temperature in adjacent fuel assemblies and cause the propagation of the oxidation reaction. This zirconium fire would result in a significant release of the fission products contained in the spent fuel, which would be dispersed from the reactor site due to the thermal plume from the zirconium fire. Consequence assessments (Appendix 4) have shown that such a zirconium fire could have significant latent health effects (cancers) as well as the possibility of a number of early fatalities. Gap releases for fuel from a reactor that has been shut down more than a year release only moderately small quantities of radionuclides, in the absence of a zirconium fire, and would only be of concern for on-site effects.

Based upon the preceding insights, the staff conducted its risk evaluation to estimate the likelihood of credible accident scenarios that could result in loss of pool water and fuel heat up to the point of rapid oxidation. In addition to developing an order-of-magnitude assessment of the level of risk associated with SFPs at decommissioning plants, the objective of this risk assessment included the identification of potential vulnerabilities and the design and operational characteristics that would minimize these vulnerabilities. If a decay period exists beyond which no zirconium fire could occur if the fuel were uncovered (a deterministic calculation), no significant risk would remain from fuel stored that length of time. The staff attempted to identify on a generic basis a decay period that precludes fuel heat up to zirconium fire conditions. Staff calculations (see Appendix 1) show this time will vary depending on fuel burn up, SFP storage configuration, loading pattern of the assemblies, and assumptions regarding the air flow to the fuel bundles. The staff has been unable to identify a definite period after which a zirconium fire is no longer possible. [1]

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[1] Even so, from a probabilistic stand point, the longer the period available for recovery, the lower the risk. Thermal-hydraulic heat up analyses indicate that for decay periods of five years or longer, the time from fuel uncovery to the beginning of a zirconium fire is on the order of 24 hours or more for BWRs with a burnup of 60 gigawatt days per metric ton or less and on the order of 17 or more hours for PWRs with a burnup of 60 GWd/MT or less.

In order to support the risk evaluation, the staff conducted a thermal-hydraulic assessment of the SFP for various scenarios such as loss of pool cooling and loss of inventory. These calculations provided information on heat up and boil off rates for the pool, as well as heat up rates for the uncovered fuel assemblies and timing to initiation of a zirconium fire for a number of scenarios and sequences (see Table **YYY**, Section **XXXX**). The results of these calculations provided fundamental information on the timing of accident sequences and provided insights on the time available to recover from events and time available to initiate off-site measures, if necessary. This information was then used in the risk assessment to support the human reliability analysis that assessed the likelihood of recovering level or cooling before a zirconium fire occurs.

For these calculations, the end state assumed for the accident sequences was when the water level reached three feet from the top of the spent fuel, rather than calculating the temperature response of the fuel as the level gradually drops. This simplification was used because of the complex heat transfer mechanisms and chemical reactions occurring in the fuel assemblies that are slowly being uncovered. This analytical approach understates the time that is available for possible fuel handler recovery of SFP events prior to initiation of a zirconium fire. However, since the recoverable events such as small loss of inventory or loss of power/pool cooling are very slowly evolving events, many days are generally available for recovery whether the end point of the analysis is uncovery of the top of the fuel or complete fuel uncovery. The extra time available (estimated to be in the tens of hours) as the water level boils down the assemblies, would not impact the very high probabilities of fuel handler recovery from these events given the industry commitments and additional staff assumptions. The staff notes that the assumption that no recovery is possible once the water level reaches 3 feet above the fuel tends to obscure the effect of partial drain down events on event timing, which is addressed in Section **ZZZZZ**. The details of the staff thermal hydraulic assessment are provided in Appendix 1.

3.1 Basis and Findings of SFP Risk Assessment

In order to follow the framework for the regulatory decision-making process described in Section 2, a comprehensive assessment of SFP risk was necessary. To gather information on SFP design and operational characteristics for the preliminary risk assessment done for the June 1999 draft report, the staff conducted site visits to four decommissioning plants to ascertain what would be an appropriate model for decommissioning spent fuel pools. The site visits confirmed that the as-operated spent fuel pool cooling systems were different from those in operation when the plants were in power operation. The operating plant pool cooling and make-up systems generally have been removed and replaced with portable, skid-mounted pumps and heat exchangers. While in some cases there are redundant pumps, in most cases physical separation, barrier protection, and emergency on-site power sources are no longer maintained. Modeling information for the PRA analysis was determined from system walk-downs as well as limited discussions with the decommissioning plant staff. Since limited information was collected for the preliminary assessment on procedural and recovery activities as well as what the minimum configuration a decommissioning plant might have, a number of assumptions and bounding conditions were assumed for the June 1999 preliminary study. These preliminary results have been refined in this assessment after obtaining more detailed information from industry on SFP design and operating characteristics for a decommissioning plant, as well as a number of industry commitments that contribute to achieving low risk findings

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The staff identified the following nine initiating event categories to investigate as part of the quantitative assessment on SFP risk:

1. Loss of Off-site Power from plant centered and grid related events
2. Loss of Off-site Power from events initiated by severe weather
3. Internal Fire
4. Loss of Pool Cooling
5. Loss of Coolant Inventory
6. Seismic Event
7. Cask Drop
8. Aircraft Impact
9. Tornado Missile

In addition, a qualitative risk perspective was developed for inadvertent criticality in the SFP. The risk model, as developed by the staff and supplemented through a quality review from Idaho National Engineering & Environmental Laboratory (INEEL), is provided in Appendix 2. Appendix 2 also includes the modeling details for the heavy load drop, aircraft impacts, seismic, and tornado missile assessments. Input and comments from stakeholders were also utilized in updating the June 1999 and February 2000 models to the present model.

3.2 Characteristics of SFP Design and Operations for a Decommissioning Plant

Based on information gathered from the site visits and interactions with NEI and other stakeholders, the staff modeled the spent fuel pool cooling system (SFPC) (see Figure 3.1) as being located in the SFP area and consisting of motor-driven pumps, a heat exchanger, an ultimate heat sink, a make-up tank, a filtration system and isolation valves. Suction is taken from the spent fuel pool via one of the two pumps and is passed through the heat exchanger and returned back to the pool. One of the two pumps on the secondary side of the heat exchanger rejects the heat to the ultimate heat sink. A small amount of water is diverted to the filtration process and is returned back into the discharge line. A manually operated make-up system (with a limited volumetric flow rate) supplements the small losses due to evaporation. In the case of prolonged loss of SFPC system or loss of inventory events, the inventory in the pool can be made up using the firewater system, if needed. There are two firewater pumps, one motor-driven (electric) and one diesel-driven, which provide firewater in the SFP area. A firewater hose station is provided in the SFP area. The firewater pumps are located in a separate structure.

Based upon information obtained during the site visits and discussions with the decommissioning plant personnel during those visits, the staff also made the following assumptions that are believed to be representative of a typical decommissioning facility:

- The make-up capacity (with respect to volumetric flow) is assumed to be as follows:

Make-up pump:	20 - 30 gpm
Firewater pump:	100 - 200 gpm

Fire engine: 100 - 250 gpm [depending on hose size: 1-½" (100 gpm) or 2-½" (250 gpm)]

The staff also assumed that for the larger loss-of-coolant inventory accidents, water addition through the make-up pumps does not successfully mitigate the loss of inventory event unless the location of inventory loss is isolated.

- The SFP fuel handlers perform walk-downs of the SFP area once per shift (8 to 12 hour shifts). A different crew member is assumed for the next shift. The staff also assumed that the SFP water is clear and pool level is observable via a measuring stick in the pool that can alert fuel handlers to level changes.

- Plants do not have drain paths in their spent fuel pools that could lower the pool level (by draining, suction, or pumping) more that 15 feet below the normal pool operating level.

Based upon the results of the June 1999 preliminary risk analysis and its associated sensitivity cases, it became clear that many of the risk sequences were quite sensitive to the performance of the SFP operating staff in identifying and responding to off-normal conditions. This is due to the fact that the remaining systems of the SFP are relatively simple, with manual rather than automatic initiation of backups or realignments. Therefore, if scenarios such as loss of cooling or inventory loss to the pool occur, fuel handler response to diagnose the failures and bring on-site and off-site resources to bear are instrumental for ensuring that the fuel assemblies remain cooled and a zirconium fire is prevented.

As part of its technical evaluations, the staff assembled a small panel of experts[2] who identified the attributes necessary to achieving very high levels of human reliability for responding to potential accident scenarios in a decommissioning plant SFP. (A discussion of these attributes and the HRA methodology used is provided in Section 3.2 of Appendix 2a.)

Upon consideration of the sensitivities identified in the staff's preliminary study and to reflect actual operating practices at many decommissioning facilities, the nuclear industry, through NEI, made important commitments (reproduced in Appendix 6), which were reflected in the staff's updated risk assessment. The revisions to the risk assessment generally reflect changes of assumptions in the areas shown below. The applicability of the specific industry decommissioning commitments (IDCs) with respect to the risk analysis results are discussed

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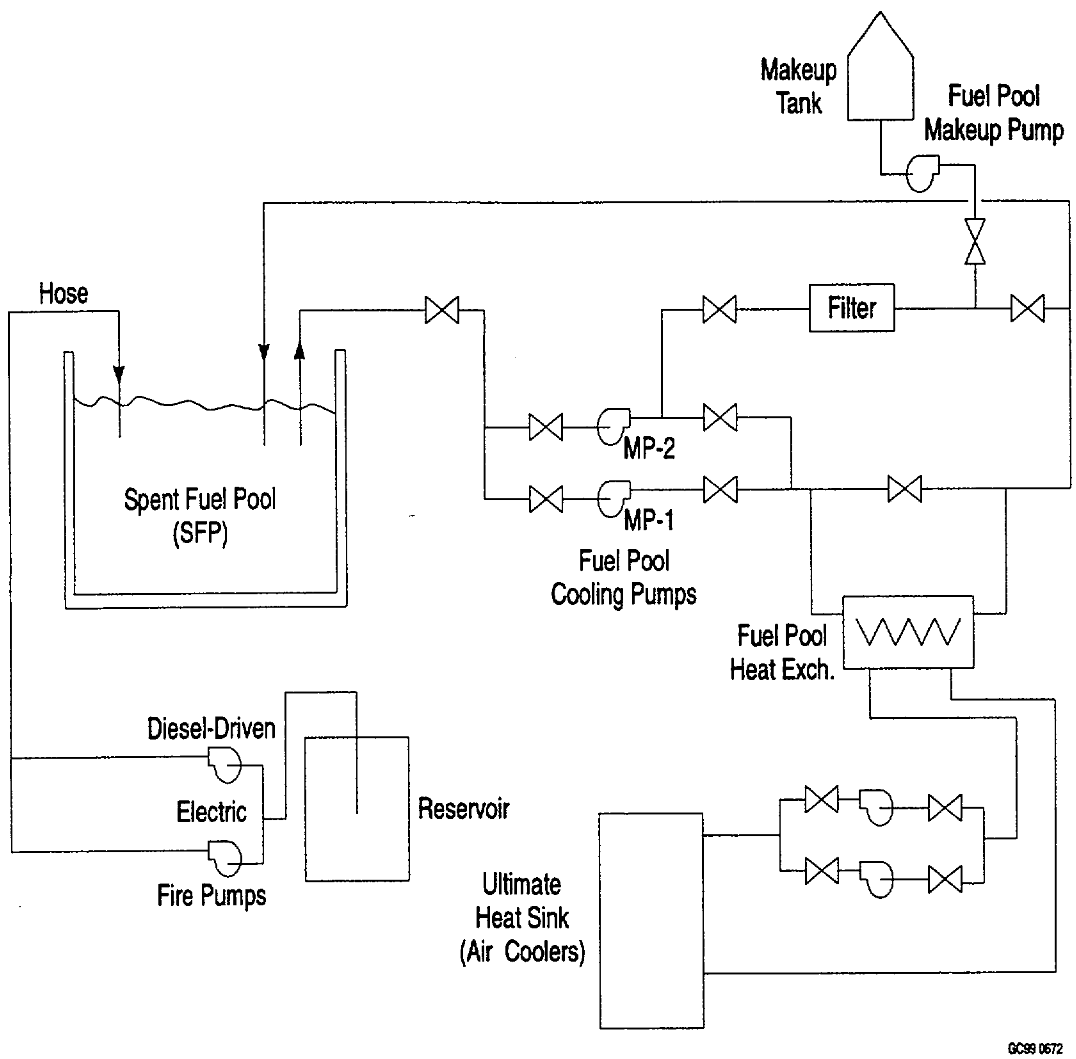
[2]Panel composed of Gareth Parry, U.S. NRC; Harold Blackman, INEEL; and Dennis Bley, Buttonwood Consulting

Figure 3.1 Assumed Spent Fuel Pool Cooling System



later in this section. How the commitments relate to specific risk conclusions and safety principles is also discussed in Section 4. Any future rulemaking or other regulatory activity would determine how these commitments are implemented.

Where additional operational and design considerations (beyond industry commitments) had to be assumed to ensure that the low risk estimates presented in this study are achieved, the staff identified additional staff decommissioning assumptions (SDAs), which are detailed in later sections of this report. As with the industry commitments, staff assumptions on SFP design and operational features, which were necessary to achieve the low SFP risk findings of this report, will be identified and implemented as appropriate in future regulatory activities.

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 will be implemented).

IDC #2 — Procedures and training of personnel will be in place to ensure that on-site and off-site resources can be brought to bear during an event.

IDC #3 — Procedures will be in place to establish communication between on-site and off-site organizations during severe weather and seismic events.

IDC #4 — An off-site resource plan will be developed which will include access to portable pumps and emergency power to supplement on-site resources. The plan would principally identify organizations or suppliers where off-site resources could be obtained in a timely manner.

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

IDC #6 — Spent fuel pool 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 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.

IDC #8 — An on-site restoration plan will be in place to provide repair of the spent fuel pool cooling systems or to provide access for make-up water to the spent fuel pool. The plan will provide for remote alignment of the make-up source to the spent fuel pool without requiring entry to the refuel floor.

IDC #9 — Procedures will be in place to control spent fuel pool operations that have the potential to rapidly decrease spent fuel pool 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 make-up 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.

3.3 Estimated Frequencies of Spent Fuel Uncovery and Assumptions That Influence the Results

Based upon the above design and operational features, industry commitments, technical comments from stakeholders, and the input from the INEEL technical review, the staff's SFP risk model was updated. The updates have improved the estimated frequency calculations, but have not changed the need for the industry commitments or staff decommissioning assumptions. Absolute values of some sequences have decreased, but the overall insights from the risk assessment remain.

3.3.1 Internal and External Initiator Frequency of Spent Fuel Pool Uncovery

The results for the initiators that were assessed quantitatively are shown in Table 3.1. This table summarizes the fuel uncovery frequency for each accident initiator. The frequencies are point estimates, based on the use of point estimates for the input parameters. For the most part, these input parameter values would be used as the mean values of the probability distributions that would be used in a calculation to propagate parameter uncertainty. Because the systems are very simple with little support needs, the point estimates therefore reasonably correlate to the mean values that would be obtained from a full propagation of parameter uncertainty. Due to the large margin between the loss of cooling and inventory sequence frequencies and the pool performance guideline, this propagation was judged to be unnecessary (See Section 5 of Appendix 2a for further discussion of uncertainties).

The results in Table 3.1 show that the estimated generic frequency for a zirconium fire for fuel that has decay time of one year ranges from less than $2x10^{-6}$ per year to less than $5X10^{-6}$ per year (depending on the seismic hazard curves used), with the dominant contribution being from a severe seismic event. Plant-specific frequency estimates in some cases would be as much as an order of magnitude lower because of a much lower seismic hazard at the plant site. A more detailed characterization of the seismic risk is discussed in Section 3.5.1 and Appendix 2b. In Section 3.4.7 the staff discusses the expected fuel uncovery frequencies for fuel that has been decayed for 2 years, 5 years, and 10 years.

In conjunction with the frequency of the uncovery of the spent fuel, it is important to know the time it takes to heat up the fuel once it has been uncovered fully or partially. Table VVV in Section JJJ lists the times to heat up the fuel from 30 °C to 800 °C (the temperature at which zirconium oxidation is postulated to become runaway oxidation and at which Ruthenium is expected to be expelled from the fuel and cladding) with no oxidation heat source based on heatups assuming either a turnover of the air to the spent fuel pool of two building volumes per hour or almost no turnover of air volume.

The staff realizes that the volumetric rate of air that a fuel bundle receives during a loss of cooling event significantly influences the heat-up of the bundle. Based on engineering judgement, we have partitioned the frequency of each sequence into parts that will be treated as if the spent fuel pool area turns over two building volumes per hour (high air flow) and as if the bundle receives little or no air flow (low air flow). For the low air flow case in order to simplify and bound a very complex calculation that is highly dependent on plant-specific fuel and bundle design, the staff has performed the heat up calculations assuming adiabatic heat transfer (See Appendix 1). Table 3.2 provides this partition.

Table 3.1 Spent Fuel Pool Cooling Risk Analysis Frequency of Fuel Uncovery (per year)

INITIATING EVENT	**Frequency of Fuel Uncovery (EPRI hazard) at 1 year**	**Frequency of Fuel Uncovery (LLNL hazard) at 1 year**
Seismic Event [3]	less than $1.9X10^{-06}$	less than $4.5X10^{-06}$
Cask Drop [4]	$2.0X10^{-07}$	same
Loss of Off-site Power - Initiated by severe weather	$1.1X10^{-07}$	same
Loss of Off-site Power - Plant centered and grid related events	$2.9X10^{-08}$	same
Internal Fire	$2.3X10^{-08}$	same
Loss of Pool Cooling	$1.4X10^{-08}$	same
Loss of Coolant Inventory	$3.0X10^{-09}$	same
Aircraft Impact	$2.9X10^{-09}$	same
Tornado Missile	$<1.0X10^{-09}$	same
Total	$<2.3X10^{-06}$	$<4.9X10^{-06}$

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[3]This contribution applies to SFPs that satisfy the seismic checklist and includes seismically induced catastrophic failure of the pool (which dominates the results) and a small contribution from seismically induced failure of pool support systems.

Both the EPRI and Lawrence Livermore National Laboratory (LLNL) hazard curves for reactor sites are considered reasonable by the NRC. The frequency of $5x10^{-6}$ per year (based on the use of Lawrence Livermore National Laboratory hazard curves) for seismic events bounds all but seven sites (Diablo Canyon, San Onofre, WPPS, Robinson, Pilgrim, Maine Yankee, and Vogtle). About half of the potential decommissioning sites have return periods less than $1x10^{-6}$ per year. Excluding the seven sites, the rest are clustered in the range of $1x10^{-6}$ per year to $4.5x10^{-6}$ per year. See Appendix 2b for details of the seismic analysis. If EPRI hazard curves were used, all sites east of the Rocky Mountains have return frequencies less than $1.9x10^{-6}$ per year with only one site identified as being greater than $1x10^{-6}$ per year. For the EPRI curves, most frequencies are clustered around $5x10^{-7}$ per year.

[4]For a single failure proof system without a load drop analysis. The staff assumed that facilities that chose the option in NUREG-0612 to have a non-single failure proof system performed and implemented their load drop analysis including taking mitigative actions to the extent that there would be high confidence that the risk of catastrophic failure was less than or equivalent to that of a single failure proof system.

NEI said this # was incorrect should be Zero.

Table 3.2 Spent Fuel Pool Cooling Risk Analysis Frequency Partition (per year) at One Year Decay Time Assuming LLNL Hazard Curves

SEQUENCES	TOTAL FREQ (PER YEAR)	% HIGH AIR FLOW	% LOW AIR FLOW (ADIABATIC)	FREQ W/ HIGH AIR FLOW	FREQ W/ LOW AIR FLOW
Seismic	$<4.5\times10^{-6}$	30%	70%	$<1.4\times10^{-6}$	$<3.1\times10^{-6}$
Heavy Load Drop	2.0×10^{-7}	50%	50%	1.0×10^{-7}	1.0×10^{-7}
Loss of Off-site Power, Severe Weather	1.1×10^{-7}	90%	10%	1.0×10^{-7}	1.1×10^{-8}
Loss of Off-site Power, Plant/Grid Centered	2.9×10^{-8}	90%	10%	2.6×10^{-8}	2.9×10^{-9}
Internal Fire	2.3×10^{-8}	90%	10%	2.1×10^{-8}	2.3×10^{-9}
Loss of Pool Cooling	1.4×10^{-8}	90%	10%	1.3×10^{-8}	1.4×10^{-9}
Loss of Coolant Inventory	3.0×10^{-9}	90%	10%	2.7×10^{-9}	3.0×10^{-10}
Aircraft Impact	2.9×10^{-9}	50%	50%	1.5×10^{-9}	1.5×10^{-9}
Tornado Missile	$<1.0\times10^{-9}$	50%	50%	$<5\times10^{-10}$	$<5\times10^{-10}$
TOTALS	$<4.9\times10^{-6}$	-	-	$<1.7\times10^{-6}$	$<3.2\times10^{-6}$

In Table 3.2 for seismic sequences, we have assumed that 30 percent of the time the building will turn over two building volumes of air per hour (high air flow case) and 70 percent of the time the individual bundle of concern will receive little or no air turnover. These percentages are based on discussions with staff structural engineers who believe that at accelerations in excess of 1.2 g spectral acceleration (which is greater than three times the SSE for many reactor sites east of the Rocky Mountains) there is a high likelihood that there will be building damage that leads to blockage of some spent fuel bundles. For heavy load drop sequences, the staff assumed a 50 percent partition to the high air flow case. This is based on consideration for both damage to fuel bundles due to a heavy load drop that renders bundles uncoolable and to the alternative possibility that the drop damaged the building structure in such a manner that some spent fuel bundles are blocked. For loss of off-site power events caused by severe weather, the staff assumed a 90 percent partition to the high airflow case. This is based on a staff assumption that openings in the building containing the spent fuel pool (e.g., doors and roof hatches) are sized such that, if forced circulation is lost, natural circulation cooling will provide at least two building volume turnovers per hour to the spent fuel pool. Such an assumption may need to be confirmed on a plant-specific basis.

The staff has partitioned the rest of the sequences in Table 3.2, but the partitions do not really matter in regulatory decision-making since their percentage of contribution to the overall zirconium fire frequency is so low and their absolute value is so low. Regarding their absolute value, the staff notes that these estimated frequencies are so low that most individuals have little understanding of what the frequencies really mean. At such low frequencies, scenarios not modeled (e.g., meteor strikes and volcanic eruptions) probably would have a higher contribution to the overall risk. We merely note that our analysis shows on a relative and absolute basis their contribution is very low.

In addition in general, consideration of whether or not a spent fuel bundle would receive high air flow or low air flow following fuel uncovery does not change our insights into the risk associated with operation of spent fuel pools. The partition results are driven by how one partitions seismic events.

3.3.2 Important Assumptions

As discussed in more detail in Appendix 2, the results of the risk analysis depend on assumptions on the design and operational characteristics of the SFP facility. The inputs that have the potential to significantly influence the results are summarized below.

- The modeled system configuration is described in Section 3.2. The assumed availability of a diesel-driven fire pump is an important element in the conclusion that fuel uncovery frequency is low for the loss of off-site power initiating events and the internal fire initiating event. The assumption of the availability of a redundant fuel pool cooling pump is not as important since the modeling of the recovery of the failed system includes repair of the failed pump, not just the startup of the redundant pump. Finally, multiple sources of make-up water are assumed for the fire pumps. This lessens the concern for possible dependencies between initiating events (e.g., severe weather events, high wind events, or seismic events) and the availability of make-up water supply (e.g., fragility of the fire water supply tank).

- Plants do not have drain paths in their spent fuel pools that could lower the pool level (by draining, suction, or pumping) more that 15 feet below the normal pool operating level.

- Openings in the building containing the spent fuel pool (e.g., doors and roof hatches) are sized such that, if forced circulation is lost, natural circulation cooling will provide at least two building volume turnovers per hour to the spent fuel pool.

- Credit is taken for industry/NEI commitments as described in Section 3.2. Without this credit, the risk is estimated to be more than an order of magnitude higher. Specifically,

  - IDC #1 is credited for lowering the risk from cask drop accidents.

  - IDCs # 2, 3, 4, and 8 are credited for the high probability of recovery of loss of cooling (including events initiated by loss of power or fire) and loss of inventory scenarios. In order to take full credit for these commitments, additional assumptions concerning how these commitments will be implemented have been made. These include: procedures and training are explicit in giving guidance on the capability of the fuel pool make-up system, and when it becomes essential to supplement with alternate higher volume sources; procedures and training are sufficiently clear in giving guidance on early preparation for using the alternate make-up sources; and walk-downs are performed on a regular (once per shift) basis and the fuel handlers document the observations in a log. The later is important to compensate for potential failures to the instrumentation monitoring the status of the pool.

  - IDC # 5 is credited for the high probability of early identification and diagnosis (from the control room) of the loss of cooling or loss of inventory.

  - IDCs # 6, 7, and 9 are credited with lowering the initiating event frequency for the loss of inventory event from its historical levels. In addition, these commitments were used to justify the assumption that a large non-catastrophic leak rate is limited to approximately 60 gpm, and the assumption that the leak is self limiting after a drop in level of 15 feet. These assumptions may be non-conservative on a plant-specific basis depending on SFP configuration and specific commitments on configuration control.

  - IDC # 10 is credited for the equipment availabilities and reliabilities used in the analysis. In addition, if there are specific administrative procedures to control the out of service duration for the diesel fire pump, the relatively high unavailability for this pump (of 0.18) could be lowered.

- Initiating event frequencies for the loss of cooling, loss of inventory, and loss of off-site power are based on generic data. In addition, the probability of power recovery is also based on generic information. Site-specific differences would proportionately affect the risk from these initiating events.

The various initiating event categories are discussed below. The staff's qualitative risk insights on the potential for SFP criticality are discussed in Section 3.5.4.

3.4 Internal Event Scenarios Leading to Fuel Uncovery

The following summary is a description of the accident associated with each internal event initiator. Details of the assessment are provided in Appendix 2.

3.4.1 Loss of Cooling

The loss of cooling initiating event may be caused by the loss of coolant system flow from 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). While it may not be directly applicable due to design differences in a decommissioning plant, operational data from NUREG-1275, Volume 12 [Ref. 3] shows that the frequency of loss of spent fuel pool cooling events in which a temperature increase of more than 20°F occurred can be estimated to be on the order of two to three events per 1000 reactor years. The data also showed that for the majority of events the duration of the loss of cooling was less than one hour. Only three events exceeded 24 hours, with the maximum duration being 32 hours. There were four events where the temperature increase exceeded 20°F, with the maximum increase being 50°F.

The calculated fuel uncovery frequency for this initiating event is 1.4×10^{-8} per year. Indications of a loss of pool cooling that are available to fuel handlers include control room alarms and indicators, local temperature measurements, and eventually increasing area temperature and humidity and low pool water level from boil-off. To have fuel uncovery, the plant fuel handlers would have to fail to recover the cooling system (either fails to notice the loss of cooling indications, or fails to repair or restore the cooling system). In addition, the fuel handlers would have to fail to provide make-up cooling using other on-site sources (e.g., fire pumps) or off-site sources (e.g., use of a fire brigade). For these recovery actions, there is a lot of time available. In the case of 1-year-old fuel (i.e., fuel that was in the reactor when it was shutdown one year previously), approximately 195 hours is available for a PWR and 253 hours for a BWR until the water level is within 3 feet of the spent fuel. These heat up and boil-off times are about double those reported by the staff previously due to an error in the staff's heat load assumptions. For 2-year-old, 5 year-old, and 10-year-old fuel, much longer periods are available (See Table 3.3). Because the uncovery frequency is already very low (on the order of 1 in a 100,000,000 per year) in absolute and relative terms among initiators, and because the quantification of human reliability analysis values for such extended periods of recovery is beyond the state-of-the-art, the staff did not attempt to recalculate the expected uncovery frequency.

A careful and thorough adherence to IDCs 2, 5, 8, and 10 is crucial to establishing and maintaining the low frequency. In addition, however, the assumption that walk-downs are performed on a regular (once per shift) basis is important to compensate for potential failures of the instrumentation monitoring the status of the pool. The analysis has also assumed that the procedures and/or training are explicit in giving guidance on the capability of the fuel pool make-up system, and when it becomes essential to supplement with alternative higher volume sources. The analysis also assumed that the procedures and training are sufficiently clear in giving guidance on early preparation for using the alternative make-up sources.

It should be noted that there were two recent events involving a loss of cooling at SFPs. The first, occurring in December 1998 at Browns Ferry Unit 3, involved a temperature increase of approximately 25°F over a two day period. This incident, caused by the short cycling of cooling water through a stuck-open check valve, was not detected by the control room indicators due to a design flaw in the indicators. In the second event, occurring in January 2000, the SFP temperature increased by approximately 40° to 50° F at the Duane Arnold Unit 1 plant. The incident, which was undetected for approximately two and a half days, was caused by operator failure to restore the SFP cooling system heat sink following maintenance activities. At this plant, there was no alarm for high fuel pool temperature, although temperature indicators are available in the control room. Since the conditional probability of fuel uncovery is low given a loss of cooling initiating event, the addition of these two recent events to the database will not affect the conclusion that the risk from these events is low. However, the recent events further illustrate the importance of industry commitments, particularly IDC # 5 that requires temperature instrumentation and alarms in the control room. In addition, the staff assumptions that walk-downs are performed on a regular (once per shift) basis, with the fuel handler documenting the observations in a log, and the assumption that control room instrumentation that monitors spent fuel pool temperature and water level will directly measure the parameters involved are important elements to keep the risk low, since the walk-downs compensate for potential failures of the control room instrumentation and direct measurement would preclude failures such as occurred at Browns Ferry.

Even with the above referenced industry commitments, the additional need for walk-downs to be performed at least once per shift and the specific need for direct indication of level and temperature had to be assumed in order to arrive at the low accident frequency calculated for this scenario. These additional assumptions are identified by the staff as staff decommissioning assumptions number 1 (SDA #1) and SDA #2. SDA #1 includes the assumed presence of explicit procedures and fuel handler training, which provide guidance on the capability and availability of inventory make-up sources and the time available to initiate these sources.

SDA #1 — Walk-downs of SFP systems will be performed at least once per shift by the fuel handlers. Procedures will be developed for and employed by the fuel handlers to provide guidance on the capability and availability of on-site and off-site inventory make-up sources and time available to initiate these sources for various loss of cooling or inventory events.

SDA #2 — Control room instrumentation that monitors spent fuel pool temperature and water level will directly measure the parameters involved.

3.4.2 Loss of Coolant Inventory

This initiator includes loss of coolant inventory from events such as those resulting from configuration control errors, siphoning, piping failures, and gate and seal failures. Operational data provided in NUREG-1275, Volume 12 show that the frequency of loss of inventory events in which a level decrease of more than one foot occurred can be estimated to be less than one event per 100 reactor years. Most of these events are as a result of fuel handler error and are recoverable. Many of the events are not applicable in a decommissioning facility. NUREG-1275 shows that, except for one event that lasted for 72 hours, there were no events that lasted more than 24 hours. Eight events resulted in a level decrease of between one and five feet, and another two events resulted in an inventory loss of between five and ten feet.

Using the information from NUREG-1275, it can be estimated that 6% of the loss of inventory events will be large enough and/or occur for a duration that is long enough so that isolation of the loss is required if the only system available for make-up is the spent fuel pool make-up system. For the other 94% of the cases, operation of the make-up pump is sufficient to prevent fuel uncovery.

The calculated fuel uncovery frequency for loss of inventory events is 3.0×10^{-9} per year. Fuel uncovery occurs if plant fuel handlers fail to initiate inventory make-up either by use of on-site sources such as the fire pumps or off-site sources such as the local fire department. In the case of a large leak, isolation of the leak would also be necessary if the make-up pumps were used. The time available for fuel handler action is considerable, and even in the case of a large leak, it is estimated that 40 hours will be available. Fuel handlers will be alerted to a loss of inventory condition by control room alarms and indicators, visibly decreasing water level in the pool, accumulation of water in unexpected locations, and local alarms (radiation alarms, building sump high level alarms, etc.).

As in the case for the loss of pool cooling, the frequency of fuel uncovery is calculated to be very low. Again a careful and thorough adherence to IDCs 2, 5, 8, and 10 is crucial to establishing the low frequency. In addition, the assumption that walk-downs (see SDA #1 above) are performed on a regular (once per shift) basis is important to compensate for potential failures of the instrumentation monitoring the status of the pool, the assumption that the procedures and/or training are explicit in giving guidance on the capability of the fuel pool make-up system lowers the expected probability of fuel handler human errors, and the assumption that fuel handlers will supplement spent fuel pool makeup at appropriate times from alternative higher volume sources lowers the estimated frequency of failure of the fuel handler to mitigate the loss of coolant inventory. Also, IDCs 6, 7, and 9 have been credited with lowering the initiating event frequency.

3.4.3 Loss of Off-Site Power from Plant-Centered and Grid Related Events

A loss of off-site power 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 of these. Grid-related events are those in which problems in the off-site power grid cause the loss of off-site power. With off-site power lost (and therefore on-site power is lost too, since the staff assumes there is no diesel generator available to pick up the necessary electrical loads), there is no effective heat removal process for the spent fuel pool. If power were not restored in time, the pool would heat up and boil off inventory until the fuel is uncovered. The diesel-driven fire pump would be available to provide inventory make-up. If the diesel-driven pump fails, and if off-site power were not recovered in a timely manner, recovery using off-site fire engines is a possibility. With 1-year-old fuel (i.e., the newest fuel in the fuel pool was shutdown in the reactor one year ago), approximately 195 hours for a PWR or 253 hours for a BWR are available for this recovery action. These heat up and boil-off times are about double those reported by the staff previously due to an error in the staff's heat load assumptions. For 2-year-old, 5 year-old, and 10-year-old fuel, much longer periods are available (See Table 3.3).

Even given recovery of off-site power, the fuel handlers have to restart the fuel pool cooling pumps. Failure to do this or failure of the equipment to restart will necessitate other fuel handler recovery actions. Again, considerable time is available.

The calculated fuel uncovery frequency for this sequence of events is 2.9×10^{-8} per year. This frequency is very low, and similar to the cases for the loss of pool cooling and loss of inventory, is based on adherence to IDCs 2, 5, 8, and 10. In addition, the performance of regular plant walk-downs and the availability of clear and explicit procedures and fuel handler training are assumed as documented in SDA #1 above.

3.4.4 Loss of Off-Site Power from Severe Weather Events

This event represents the loss of SFP cooling due to a loss of off-site power from severe weather-related events. This includes contributions from hurricanes, snow and wind, ice, wind and salt, wind, and one tornado event. Because of their potential for severe localized damage, tornadoes and their direct impact to the site were analyzed separately in Appendix 2e and summarized in Section 3.5.3 of this report.

Until off-site power is recovered, the electrical pumps would be unavailable and the diesel-driven fire pump would be available to only provide make-up. When compared to the loss of off-site power events from grid-related and plant-centered causes, recovery of off-site power in this case is assumed to be less probable. In addition, given the conditions, it would be more difficult for off-site help to assist the fuel handlers at the site than for an ordinary loss of off-site power event.

The calculated fuel uncovery frequency for this event is 1.1×10^{-7} per year. As in the previous cases, this estimate was based on IDCs 2, 5, 8, 10 and on assumptions documented in SDA #1. In addition, IDC 3, related to having procedures in place for communication between on-site and off-site organizations during severe weather, is also important in the analysis for increasing the likelihood of off-site resources being able to respond effectively.

3.4.5 Internal Fire

This event tree models the loss of SFP cooling caused by internal fires. The staff assumed that there is no automatic fire suppression system for the SFP cooling area. The fuel handler may initially attempt to manually suppress the fire given that they respond to the control room or local area alarms. If the fuel handler fails to respond to the alarm, or is unsuccessful in extinguishing the fire within the first 20 minutes, the staff assumed that the SFP cooling system will be significantly damaged and cannot be repaired. 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 make-up, either using the site firewater system or by calling upon off-site resources. It was assumed that fire damages the plant power supply system such that the power to the electrical firewater pump is lost and would not be available.

The calculated fuel uncovery frequency for this event is 2.3×10^{-8} per year. As in the previous cases, this estimate was based on IDCs 2, 5, 8, and 10 and on the staff assumptions in SDA #1 and SDA #2. In addition, IDC 3, related to having procedures in place for communication between on-site and off-site organizations during severe weather, is also important in the analysis for increasing the likelihood of off-site resources being able to respond effectively to this fire event by increasing the likelihood for recovery using off-site resources.

3.4.6 Heavy Load Drops

The staff investigated the frequency of dropping a heavy load in or near the spent fuel pool, and investigated potential damage to the pool from such a drop. The previous assessment done for resolution of Generic Issue 82 (in NUREG/CR-4982 (Ref 4)) only considered the possibility of a heavy load drop falling on the pool wall. The assessment conducted for this study identified other failure modes, such as the pool floor, as also being credible for some sites. Details of the heavy load evaluation can be found in Appendix 2c. The analysis exclusively considered drops that were severe enough to catastrophically damage the spent fuel pool such that pool inventory would be lost rapidly and it would be impossible to refill the pool using on-site or off-site resources. In essence there is no possibility for mitigation in such circumstances, only prevention. In particular the staff has not attempted to partition the initiator into events where there is full rapid drain down and events where there is rapid, but partial drain down. The staff assumes a catastrophic heavy load drop (that caused a large leakage path in the pool) would lead directly to a zirconium fire. The time from the load drop until a fire would vary depending on fuel age, burn up, and configuration. The dose rates in the pool area prior to any zirconium fire would be on the order of tens of thousands of rem per hour, making any potential recovery actions such as temporary large inventory addition systems very difficult.

Based on discussions with staff structural engineers, it was assumed that only spent fuel casks had sufficient weight to catastrophically damage the pool if dropped. The staff assumed there is a very low likelihood that other heavy loads would be moved over the spent fuel pool, and in addition, if there were a drop of one of these lighter loads over the spent fuel pool, there would be a very low likelihood that it would cause catastrophic damage to the pool.

For a non-single failure proof load handling system, the likelihood of a heavy load drop (i.e., the drop frequency) was estimated, based on NUREG-0612 information, to have a mean value of 3.4×10^{-4} per year. The number of heavy load lifts was based on the NEI estimate of 100 spent fuel shipping cask lifts per year, which probably is an overestimate. For plants with a single failure proof load handling system or a plant conforming to the NUREG-0612 guidelines, the plant is estimated to have a drop frequency mean value of 9.6×10^{-6} per year, again for 100 heavy load lifts per year but using data from U.S. Navy crane experience. Once the load is dropped, the analysis must then consider whether the drop would do significant damage to the spent fuel pool.

When estimating the failure frequency of the pool floor and pool wall, the staff assumed that heavy loads physically travel near or over the pool approximately 13% of the total path lift length (the path lift length is the distance from the lift of the load to the placement of the load on the pool floor). The staff also assumed that the critical path length (the fraction of total path the load is lifted high enough above the pool that a drop could cause damage to the structure) is approximately 16% of the time the load is near or over the pool. The staff estimated the catastrophic failure rate from heavy load drops to have a mean value of 2.1×10^{-5} per year for a non-single failure proof system where reliance is placed on electrical interlocks, fuel handling system reliability, and safe load path procedures. The staff estimated the catastrophic failure rate from heavy load drops to have a mean value of 2×10^{-7} per year for a single failure proof system. The staff assumed that licensees that chose the non-single failure proof system option in NUREG-0612 performed appropriate analyses and took mitigative actions to reduce the expected frequency of catastrophic damage to the same range as that of facilities with a single failure proof system.

NEI has made a commitment (IDC #1) for the nuclear industry that future decommissioning plants will comply with Phases I and II to the NUREG-0612 guidelines. Consistent with this industry commitment, the additional assurance of a well performed and implemented load drop analysis, including mitigative actions, was assumed in order to arrive at a low accident frequency for non-single failure proof systems that is comparable to single failure proof systems.

SDA #3 Load Drop consequence analyses will be performed for facilities with non-single failure proof systems. The analyses and any mitigative actions necessary to preclude catastrophic damage to the spent fuel pool that would lead to a rapid pool draining should be performed with sufficient rigor to demonstrate that there is high confidence in the facility's ability to withstand a heavy load drop.

While the focus of this report is the risk associated with wet storage of spent fuel during decommissioning, the staff was alert to any implications on the storage of spent fuel during power operation. With regard to power operation, the resolution of Generic Issue (GI) 82, "Beyond Design Basis Accidents in Spent Fuel Pools," and other studies of operating reactor spent fuel pools concluded that existing requirements for operating reactor spent fuel pools are sufficient. During this study, the staff evaluated one additional issue concerning the drop of a cask on the spent fuel pool floor. As noted above, due to the industry's commitment to Phase II of NUREG-0612, "Control of Heavy Loads at Nuclear Power Plants, Resolution of Generic Technical Activity A-36," this is not a concern for decommissioning reactors.

Operating reactors are not required to implement Phase II of NUREG-0612. The risk for spent fuel pools at operating plants is limited by the lower expected frequency of heavy load lifts as compared to decommissioning plants. Nonetheless, this issue will be further examined as part of the Office of Nuclear Regulatory Research's prioritization of Generic Safety Issue 186, "Potential Risk and Consequences of Heavy Load Drops in Nuclear Power Plants," which was accepted in May 1999.

3.4.7 Spent Fuel Pool Uncovery Frequency at 2, 5, and 10 Years After Shutdown

The staff has considered how the increased recovery time available to fuel handlers at 2, 5, and 10 years after shutdown (See Table XYZ) would change the insights or bottom line numerical results from the risk assessment . The increased recovery times primarily affect the human reliability analysis (HRA) results and insights. Even without the increased recovery time, the HRA estimates are very small and are dominated by institutional factors (e.g., training, quality of procedures, staffing.) The increased recovery time lowers the uncertainty that these HRA estimates really are very small, but the increased time has not translated into significant changes in the bottom line numerical estimates because quantification of the effect on organizational problems is beyond the state-of-the-art.

3.5 Beyond Design Basis Spent Fuel Pool Accident Scenarios (External Events)

The following is a description of how each of the external event initiators was modeled, a discussion of the frequency of fuel uncovery associated with the initiator, and a description of the most important insights regarding risk reduction strategies for each initiator.

3.5.1 Seismic Events

The staff performed a simplified bounding seismic risk analysis in its June 1999 preliminary draft risk assessment to gain initial insights on seismic contribution to SFP risk. The analysis indicated that seismic events could not be dismissed on the basis of a simplified bounding approach. The additional efforts by the staff to evaluate the seismic risk to spent fuel pools are addressed here and in Appendix 2b.

Spent fuel pool structures at nuclear power plants should be seismically robust. They are constructed with thick reinforced concrete walls and slabs lined with stainless steel liners 1/8 to 1/4 inch thick[5]. Pool walls are about 5 feet thick and the pool floor slabs are around 4 feet thick. The overall pool dimensions are typically about 50 feet long by 40 feet wide and 55 to 60 feet high. In boiling water reactor (BWR) plants, the pool structures are located in the reactor building at an elevation several stories above the ground. In pressurized water reactor (PWR) plants, the spent fuel pool structures are located outside the containment structure supported on the ground or partially embedded in the ground. The location and supporting arrangement of the pool structures largely determine their capacity to withstand seismic ground motion beyond their design basis. The dimensions of the pool structure are generally derived from radiation shielding considerations rather than seismic demand needs. Spent fuel structures at nuclear power plants are able to withstand loads substantially beyond those for which they were designed.

To evaluate the risk from a seismic event at a spent fuel pool, one needs to know both the likelihood of seismic ground motion at various g-levels (i.e., seismic hazard curves) and the conditional probability that a structure, system, or component (SSC) will fail at a given acceleration level (i.e., the fragility of the SSC). These curves are convoluted mathematically to arrive at the likelihood that the spent fuel pool will fail due to a seismic event. In evaluating the effect of seismic events on spent fuel pools, it became apparent that although information was available on seismic hazard curves for nuclear power plant sites, the staff did not have fragility analyses of the pools, nor generally did licensees. The staff recognized that many of the spent fuel pools and the buildings housing them were designed by different architect engineers. Some buildings and pools were built to the Uniform Building Code and others were built to different standards.

To overcome lack of knowledge of the capacity of the spent fuel pools, the staff and NEI developed a seismic check list and used generic fragility analyses (one for PWRs and one for BWRs) corresponding to the capacity of the spent fuel pool assured by the seismic checklist. During stakeholder interactions, the staff proposed the use of a seismic checklist, and in a letter dated August 18, 1999, NEI proposed a checklist that could be used to show a spent fuel pool would retain its structural integrity at a peak spectral acceleration of about 1.2 g. This value (1.2 g peak spectral acceleration) was chosen in part due to existing databases that could be used in the checklist but that only went up to 1.2 g peak spectral acceleration. The checklist was reviewed and enhanced by the staff (See Appendix 2b). The checklist includes elements to assure there are no weaknesses in the design or construction nor any service induced

[5]Except at Dresden Unit 1 and Indian Point Unit 1, these two plants do not have any liner plates. They were permanently shutdown more than 20 years ago and no safety significant degradation of the concrete pool structure has been reported.

degradation of the pools that would make them vulnerable to failure under earthquake ground motions that exceed their design basis ground motion, but are less than the 1.2 g peak spectral acceleration. The staff has concluded that plants that satisfy the revised seismic checklist can demonstrate with reasonable assurance a high-confidence low-probability of failure (HCLPF)[6] at a ground motion that has a very small likelihood of exceedence. Convolution of the site-specific seismic hazard curves with the generic fragility curves results in annual probabilities of a zirconium fire from seismic events ranging from less than 1x10^{-7} per year to over 1x10^{-5} per year, depending on the site and the hazard curves used.

Since our evaluation is intended to apply to all potential decommissioning sites, the generic values for seismic risk will tend to be bounding. Individual sites may have hazard curves that are much lower than the sites with the highest hazard curves. Figures 3.2 and 3.3 show the estimated annual probabilities of a zirconium fire from a seismic event with the probabilities put in order from lowest to highest. Figure 3.2 shows the results of convoluting the site-specific Lawrence Livermore National Laboratory seismic hazard curves (ref. ZZZ) with the generic spent fuel pool fragility analysis, and Figure 3.3 shows the results convoluting the EPRI site-specific seismic hazard curves (ref. YYYY) in a similar manner[7]. These figures show that for the zirconium fire frequencies using the LLNL curves, the annual probabilities cluster for most sites just above 1x10^{-6} per year and for EPRI just below 1x10^{-6} per year. Note that the order of the sites differs somewhat between the EPRI and LLNL curves. Given that a utility performs and passes the checklist, the staff finds that the frequency of a zirconium fire from a seismic event will be less than 5x10^{-6} per year using the LLNL curves or slightly less than 1x10^{-6} per year using the EPRI curves if the below mentioned plants are excluded and perform plant-specific analyses. In looking at these two different sets of hazard curves, the NRC has previously found that both sets are reasonable and equally valid.

In passing the checklist, the staff believes that a spent fuel pool will be assured a HCLPF of at least 1.2 g spectral acceleration. For many sites (particularly PWRs because their SFPs are closer to ground level and receive less amplification), the plant-specific HCLPF may be considerably higher. The only two plant-specific spent fuel pool fragility analyses that the staff is aware of were used in this analysis.

All decommissioning plants that seek to take advantage of exemptions or rule changes with respect to EP, indemnification, or safeguards would need to perform and pass the checklist. In addition to passing the checklist, some decommissioning plant sites that have hazard curves with particularly high relative return periods at a given acceleration would need to perform a plant-specific seismic assessment of their spent fuel pool risk if they wish to gain exemptions from EP, security, or indemnification. Such sites include Robinson, Vogtle, Maine Yankee, and Pilgrim east of the Rocky Mountains and San Onofre, Diablo Canyon, and WPPS west of the Rocky Mountains. These same plants generally are the outliers if one uses either Lawrence

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[6] The HCLPF value is defined as the peak seismic acceleration at which there is 95% confidence that less than 5% of the time the structure, system, or component will fail.

[7] At higher accelerations, especially for plant sites east of the Rocky Mountains, there is great modeling uncertainty about the ground motions, return periods, and the possibility of cutoff. There is virtually no data at these acceleration levels, and there is no chance that we will be able to gather such data in the near future (next 100 years).

Livermore National Laboratory hazard curves or those by EPRI. The staff proposes that these sites would need to show that their frequency of catastrophic failure of the spent fuel pool due to seismic events was less than $5x10^{-6}$ per year using LLNL hazard curves or staff approved site-specific hazard curves, if they wished to take advantage of EP, security , or indemnification exemptions or the rulemaking. The staff finds $5X10^{-6}$ per year to be a reasonable acceptance criterion for seismic return period for earthquake ground motions that could fail the spent fuel pools since it is a factor of 2 less than the $1x10^{-5}$ per year PPG and the estimated frequency of zirconium cladding fires from other initiators is about an order of magnitude lower. Such a margin is warranted due to the uncertainties of the seismic hazard and spent fuel pool fragilities at each site, and to the small margin between seismic risk results and the Quantitative Health Objectives (QHOs) of the NRC.

3.5.2 Aircraft Crashes

The staff evaluated the likelihood of an aircraft crashing into a nuclear power plant site and seriously damaging the spent fuel pool or its support systems (details are in Appendix 2d). The generic data provided in DOE-STD-3014-96 [Ref. 6] were used to assess the likelihood of an aircraft crash into or near a decommissioning spent fuel pool. Aircraft damage can affect the structural integrity of the spent fuel pool or affect the availability of nearby support systems, such as power supplies, heat exchangers, or water makeup sources, and may also affect recovery actions. ~~There are~~ two approaches ~~that can be~~ taken to evaluate the likelihood of an aircraft crash into a structure. The first is called the point target model, which uses the area (length times width) of the target to determine the likelihood that an aircraft will strike the target. The aircraft itself does not have real dimensions when using this model. In the second approach, the DOE model modifies the point target approach to account for the wing span and the skidding of the aircraft after it hits the ground by including the additional area the aircraft could cover. Further, that model takes into account the plane's glide path by introducing the height of the structure into the equation, which effectively increase the area of the target (see Appendix 2d).

The staff estimated the frequency of catastrophic PWR spent fuel pool damage (i.e., the pool is so damaged that it rapidly drains and cannot be refilled from either onsite or offsite resources) resulting from an aircraft crash based on the point target area model for a direct hit on a 100 x 50 foot spent fuel pool. Based on studies in NUREG/CR-5042, "Evaluation of External Hazards to Nuclear Power Plants in the United States," it was estimated that 1-of-2 aircraft are large enough to penetrate a 6-ft reinforced concrete wall. The conditional probability of a large aircraft crash resulting in penetration of a 6-ft of reinforced concrete wall was taken as 0.32 (from NUREG/CR-5042). It was further estimated that 1-of-2 crashes result in significant damage to the spent fuel pool resulting in uncovery of the stored fuel (for example, 50% 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 $9.6x10^{-12}$ to $4.3x10^{-8}$ per year. The mean value is estimated to be $2.9x10^{-9}$ 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 that for a PWR. Mark-I and Mark-II secondary containments generally do not appear to have any significant structures that might reduce the likelihood of aircraft penetration, although a crash into one of four sides of a BWR secondary containment may have a reduced likelihood of penetration due to other structures being in the way of the aircraft. Mark-III secondary containments may reduce the likelihood of penetration somewhat, as the spent fuel pool may be considered to be protected on one side by additional structures.

If instead of a direct hit, the aircraft skidded into the pool or a wing clipped the pool, catastrophic damage may not occur. The staff estimated that skidding aircraft will be negligible contributors to the frequency of fuel uncovery resulting from catastrophic failure of the pool as the impact velocity will likely be sufficiently reduced to preclude penetration of the wall. The estimated frequencies of aircraft-induced catastrophic spent fuel pool failure are bounded by other initiators.

The staff estimated the frequency of significant damage to spent fuel pool support systems (e.g., power supply, heat exchanger, or makeup water supply) for three different situations. The first case is based on the DOE model including the glide path and the wing and skid area for a 400 x 200 x 30 foot structure (i.e., the support systems are located inside a large building) with a conditional probability of 0.01 that one of these systems is hit (the critical system occupies a 30 x 30 x 30 foot cube within the large building). This model accounts for damage from the aircraft including, for example, being clipped by a wing. The estimated frequency range for significant damage to the support systems is 1.0×10^{-10} to 1.0×10^{-6} per year. The mean value is estimated to be 7.0×10^{-8} per year. The second case estimates the value for the loss of a support system (power supply, heat exchanger or makeup water supply) based on the DOE model including the glide path and the wing and skid area for a 10 x 10 x 10 foot structure (i.e., the support systems are housed in a small building). The estimated frequency of support system damage ranges from 1.1×10^{-9} to 1.1×10^{-5} per year, with the mean estimated to be 7.3×10^{-7} per year. The third case uses the point model for this 10x10 structure, and the estimated value range is 2.4×10^{-12} to 1.1×10^{-8} per year, with the mean estimated to be 7.4×10^{-10} per year. Depending on the model approach (selection of the target structure size; use of the point target model or the DOE model), the mean value for an aircraft damaging a support system is in the 7×10^{-7} per year, or less, range. This is not the estimated frequency of fuel uncovery or a zirconium fire caused by damage to the support systems, since the frequency estimate does not include recovery, either onsite or offsite. As an initiator to failure of a support system leading to fuel uncovery and a zirconium fire, an aircraft crash is bounded by other more probable events. Recovery of the support system will reduce the likelihood of spent fuel uncovery.

Overall, the likelihood of significant spent fuel pool damage from aircraft crashes is bounded by other more likely catastrophic spent fuel pool failure and loss of cooling modes.

3.5.3 Tornadoes and High Winds

The staff performed a risk evaluation of tornado threats to spent fuel pools (details are in Appendix 2e). It was 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 spent fuel pool. These tornados have wind speeds that result in damage characterized as devastating or incredible. The staff then looked at the frequency of such tornadoes occurring and the conditional probability that if such a tornado hit the site, it would seriously damage the spent fuel. To do this the staff examined the frequency and intensity of tornadoes in each of the continental United States using the methods described in NUREG/CR-2944 [Ref. 7]. The frequency of having an F4 to F5 tornado is estimated to be 5.6×10^{-7} per year for the central U.S., with a U.S. average value of 2.2×10^{-7} per year.

The staff then considered what level of damage an F4 or F5 tornado could do to a spent fuel pool. Based on the buildings housing the spent fuel pools and the thickness of the spent fuel pools themselves, the conditional probability of catastrophic failure given a tornado missile is very low. Hence, the overall frequency of catastrophic pool failure caused by a tornado is extremely low (i.e., the calculated frequency of such an event is less than $1x10^{-9}$ per year).

It was assumed that an F2 to F5 tornado would be required if significant damage were to occur to spent fuel pool support systems (e.g., power supply, cooling pumps, heat exchanger, or makeup water supply). These tornados have wind speeds that result in damage characterized as significant, severe, or worse. The frequency of having an F2 to F5 tornado is estimated to be $1.5x10^{-5}$ per year for the central U.S., with a U.S. average value of $6.1x10^{-6}$ per year. This is not the estimated frequency of fuel uncovery or a zirconium fire caused by damage to the support systems, since the frequency estimate does not include recovery, either on-site or off-site. As an initiator to failure of a support system leading to fuel uncovery and a zirconium fire, a tornado is bounded by other more probable events. Recovery of the support system(s) will reduce the likelihood of spent fuel uncovery.

Missiles generated by high winds (for example, straight winds or hurricanes) are not as powerful as those generated by tornados. Therefore high winds are estimated to have a neglible impact on the catastrophic failure of the spent fuel pool resulting in fuel uncovery. Long term loss of off-site power due to straight winds is evaluated in Section 3.4.4, Loss of Off-Site Power from Severe Weather Events.

The staff estimated the frequency of significant damage to spent fuel pool support systems from straight line winds to be very low. Damage was assumed to be caused by building collapse. Based on the construction requirements for secondary containments, the staff believes that the buildings containing BWR spent fuel pools are sufficiently robust that straight line winds will not challenge the integrity of the building. The staff assumes buildings covering PWR spent fuel pools have a concrete foundation that extends part way up the side of the building. The exterior of the rest of the building has a steel frame covered by corrugated steel siding. The PWR spent fuel buildings are assumed to be constructed to American National Standards Institute (ANSI) or American Society of Civil Engineers (ASCE) standards. Based on these assumptions, the staff believes that straight line winds will fail buildings housing PWR spent fuel pools at a frequency of $1x10^{-3}$ per year or less. This failure rate for support systems is subsumed in the initiating event frequency for loss of offsite power from severe weather events. The event tree for this initiator takes into account the time available for recovery of spent fuel pool cooling (approximately 195 hours for 1-year old PWR fuel and 253 hours for BWR fuel).

3.5.4 Criticality same as before

what fuel burnup

Table 3.3 Time to Heat Up and Boil Off SFP Inventory Down to Three Feet Above Top of Fuel

DECAY TIME	PWR	BWR
1 year	195 hours	253 hours
2 years	272 hours	337 hours
5 years	400 hours	459 hours
10 years	476 hours	532 hours

Figure 3.2 Frequency of Catastrophic Failure of Spent Fuel Pools Assuming Pools Have a HCLPF of 1.2 g Peak Spectral Acceleration
(LLNL seismic hazard curves, sites ranked lowest to highest frequency)

Figure 3.3 Frequency of Catastrophic Failure of Spent Fuel Pools Assuming Pools Have a HCLPF of 1.2 g Peak Spectral Acceleration
(EPRI seismic hazard curves, sites ranked lowest to highest frequency)