NRR-PMDAPEm Resource

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Subject: [External_Sender] SFP Evaluation Criteria for Sa<0.8g
Attachments: Seismic Screening of SFP Structures - 08-31-2015.docx

Mohamed/Nick,

In preparation for our public meeting on Thursday, attached is a white paper to support spent fuel pool evaluations for plants with an Sa

Thanks,
Andrew

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NTTF 2.1 SEISMIC REVIEW OF SPENT FUEL POOLSAT LOW GMRS SITES

1. NTTF 2.1 Scope of Seismic Evaluation for Spent Fuel Pools

Seismic evaluations of Spent Fuel Pool (SFP) integrity described in EPRI 1025287 [7] focuses on elements of the SFP that might fail due to a seismic event such that rapid drain-down of the SFP could result.EPRI 1025287 Section 7 includes the following.

> Maintaining the SFP water level above about two-thirds of the height of the fuel assemblies in the pool should prevent overheating the fuel [8]. Therefore, the ability to maintain SFP inventory at a level of about two-thirds of the height of the fuel assemblies would be considered acceptable.

EPRI 1025287 focuses on SFP elements that could contribute to SFP inventory losses. Those elements are:

- SFP structure,
- SFP penetrations above the top of fuel,
- SFP penetrations below the top of fuel,
- Potential siphoning through cooling systems,
- Sloshing losses, and
- Evaporative losses.

If the above elements lead to losses that uncover more than one third of the fuel, the makeup systems can be credited provided:

1. makeup resources (including any necessary instrumentation) are seismically rugged and available
2. procedures exist to guide response by the operator; and
3. there is sufficient time for operators to recognize the need for makeup and take action.

Credited operator actions would also need to be reviewed to account for habitability and accessibility limitations.

Evaluation criteria for each element for plants with low GMRS (peak spectral accelerations less than 0.8g) is provided in the following sections.

2. SFP Structural Evaluation

2.1 Background on SFP Structures

Spent Fuel Pool structures are typically constructed as part of the reactor building or as part of a separate structure to support the fuel handling operations at the reactor. The spent fuel pool structures at nuclear power plants currently operating in the U.S. are configured differently

depending on the reactor design vintages, site-specific design requirements and also to the design preferences of the engineering and construction companies involved in the design of the facility. To support the NTTF 2.1 seismic assessment of the spent fuel pools, industry surveys were conducted to identify the structural characteristics of the SFP and their supporting structures for the fleet of US operating nuclear plants. The key elements resulting from that survey are summarized in the sections below as they relate to the seismic capacity verifications of the SFP structures.

The fundamental structural configurations of the spent fuel pools themselves have similar characteristics due to functional design requirements (including radioactive shielding considerations) and due to structural design loading requirements (seismic, dead weight, etc.). The spent fuel pools are constructed of reinforced concrete shear walls with stainless steel liners attached to the floors and walls. The spent fuel pools are rectilinear with adjoining compartments next to the fuel storage pool for various operations, such a station for loading and unloading fuel, and a canal for transferring the fuel assemblies into and out of the reactor. The industry SFP survey results demonstrated that the SPF walls span from 30 ft to 120 ft with an average span of 52 feet. The wall thickness ranged from 42 inches to 78 inches with an average of 64 inches. The steel rebar reinforcement ratio ranged from 0.1% to 0.9% with an average ratio of 0.3%. The concrete strength ranged from 3 ksi to 5 ksi with an average strength of 3.6 ksi and the steel reinforcing strength ranged from 24 ksi to 60 ksi with an average steel reinforcing strength of 52 ksi. The liner thickness ranged from 1/8 inch to 3/8 inch with an average thickness of 1/4 inch.

The characteristics of the structures supporting/housing the spent fuel pools were also part of the industry survey of the SFPs. The spent fuel pools are part of the three different nuclear structures depending on the site design:

- Auxiliary Building – 33% of the plants
- Fuel Building – 38% of the plants
- Reactor/Containment Buildings – 29% of the plants

The Boiling Water Reactors (BWR)and the Pressurized Water Reactors (PWR) typically have different designs of the structures housing the SFPs. The spent fuel storage pools at BWR sites are typically located within the BWR reactor building at an elevation above grade, which allows alignment of the top of the pool with the operating deck used for re-fueling the reactor. Figure 1 depicts a typical BWR plant configuration including the location of the spent fuel pool. The BWR structures housing the SFPs are typically designed with reinforced concrete shear walls providing the primary structural load path. In a few cases, the primary load path also contains reinforced concrete moment frame elements or structural steel frame members. In one case, the structural load path included post-tensioned concrete walls associated with the containment structure.

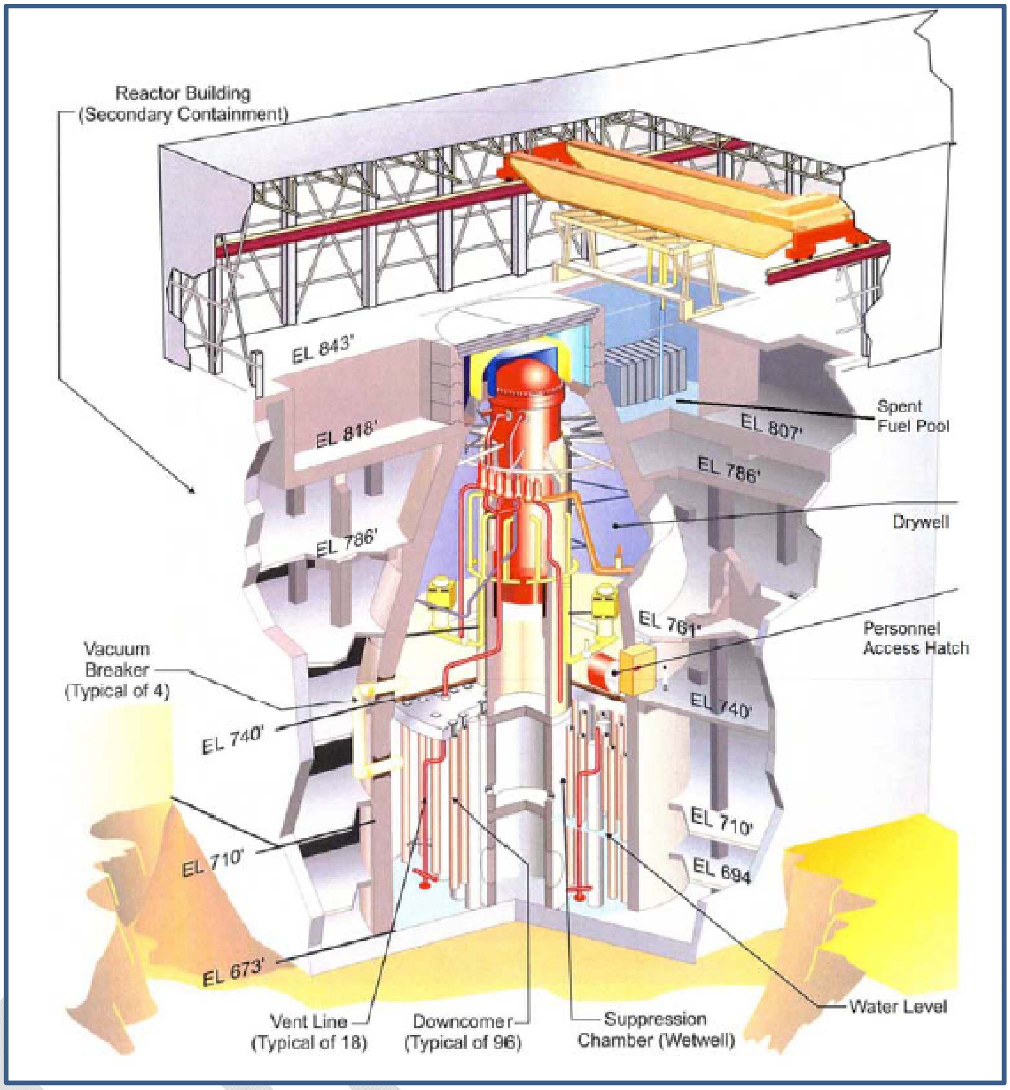

Figure 1: Schematic for Typical BWR Configuration with Spent Fuel Storage Pool

At PWR sites, the floor (bottom) of the pool is generally on or even partially below grade with the pool floor constructed as part of a thick foundation. Figure 2 depicts a typical PWR plant configuration including the location of the spent fuel pool. The structures housing the spent fuel pool typically have load paths with reinforced concrete shear walls with the pool bottom typically supported directly on the building foundation. As with the BWR structures, there are a few PWRs where the spent fuel pool structural load paths include reinforced concrete frame members and/or structural steel frame members.

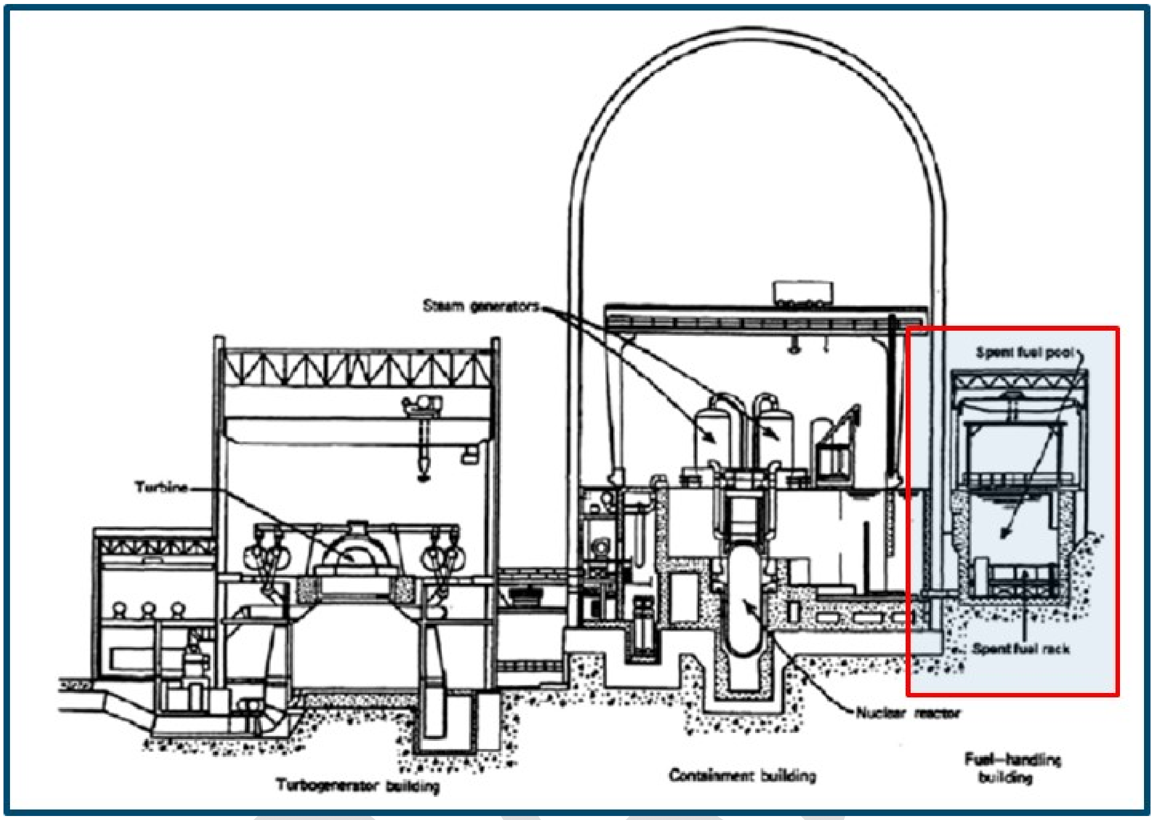

Figure 2: Schematic for TypicalPWR Configuration with Spent Fuel Storage Pool

2.2 Treatment of Spent Fuel Pool Structures within NTTF 2.1 Seismic

The 50.54(f) letter requested that, in conjunction with the response to NTTF Recommendation 2.1, a seismic evaluation be made of the SFP. More specifically, plants were asked to consider "…all seismically induced failures that can lead to draining of the SFP." Such an evaluation would be needed for any plants that are not screened from further assessment based on the screening process documented in the SPID [7].

Previous evaluations in NUREG-1353 [1], NUREG-1738 [2] and NUREG/CR-5176 [3] characterized the generally robust nature of the design of SFPs currently in use. NUREG-1738 further identified a checklist that could be used to demonstrate that a SFP would achieve a very high HCLPF. Evaluations reported in NUREG/CR-5176 [3] for two older plants concluded that "…seismic risk contribution from spent fuel pool structural failures is negligibly small." Tearing of the stainless-steel liner due to overall structural failure of the fuel pool structure would be precluded by the successful completion of the EPRI NP-6041 structural evaluations. Tearing of the stainless-steel liner due to sliding or other movement of the fuel assemblies in the pool is considered to be very unlikely [1]. The SPID defines that either the checklist in NUREG-1738 can be used to demonstrate that the structure is sufficiently robust or another approach can be used if sufficiently justified. The purpose of this section is to present theseismic adequacy

justification for SFP structures at nuclear power plant sites with a relatively low GMRS being robust.

As noted in the SPID, the screening criteria for civil structures in EPRI NP-6041 [4] provide principles that would be helpful in evaluating the seismic capacity of SFP structures. The approach used for the screening of the lower GMRS sites is the EPRI NP-6041 assessment criteria presented in Table 2-3. As noted in the background section of this paper, the spent fuel pool structureshave structural load paths consisting of one or more of the following structural configurations:

- Reinforced concrete shear walls
- Reinforced concrete moment frames
- Structural steel frames
- Post-tensioned containments

As such, the spent fuel pools and their supporting structures all fall within fourrows of the NP-6041 Table 2.3 addressing these four structural configurations. Figure 3 shows the Table 2-3 structural screening criteria.

The first column in Table 2-3 presents the requirements for the assessment of different types of structures to a peak spectral (5% damped) ground peak spectral acceleration of 0.8 g's. The SFP structures for all NPPs fall within the first, fourth, sixth and seventh rows of Table 2-3. Row #1 addresses concrete containments designed using post-tensioning and reinforcement. These post-tensioned containment structures have been shown to be rugged up to the 0.8 g peak spectral acceleration level and can be screened from further consideration based solely on demonstration of meeting the "0.8 g spectral acceleration" first column. For the first column of Table 2-3 of EPRI NP-6041, the footnote requirements for the other three structural configurations (shear wall structures, concrete frame structures and steel frame structures) being reviewed for this SFP study are defined within the single footnote "e". Footnote e is defined below.

e. Evaluation not required for Category I structures if design was for a SSE of 0.1 g or greater.

All spent fuel pool structures are, by necessity, Category 1 structures since they contain spent fuel and they all are designed to an SSE. All US nuclear plants have design basis SSEs (or the equivalent DBEs) at or exceeding the 0.1 g threshold. Thus, all operating US nuclear plant SFP structures meet the EPRI NP-6041 criteria that demonstrates that they have a high confidence of exceeding the 0.8 g spectral acceleration capacity in the free field. The criteria associated with EPRI NP-6041 stipulates that the 0.8 g screening level would apply to sites where the peak spectral acceleration of their review level earthquake (RLE) is less than or equal to this 0.8 g spectral acceleration. For purposes of the spent fuel pool structure review, the GMRS is used as the RLE.

Figure 3: Table 2-3 Section from EPRI NP-6041

Table 2-3

SUMMARY OF CIVIL STRUCTURES SCREENING CRITERIA FOR SEISMIC MARGIN EVALUATION
(Page 1 of 2)

Type of Structure	5 Percent-Damped Peak Spectral Acceleration		
	<0.8g	0.8 - 1.2g	>1.2g
Concrete containment (post-tensioned and reinforced)	no	(a)*	(b)
Freestanding steel containment	(c)(d)	(c)(d)	yes
Containment internal structures	(e)	(f)	yes
Shear walls, footings and containment shield walls	(e)	(f)	yes
Diaphragms	(e)	(g)	yes
Category I concrete frame structures	(e)	(f)	yes
Category I steel frame structures	(e)	(h)	yes
Masonry walls	yes	yes	yes
Control room ceilings	(i)	(i)	yes

2.3 Plants with GMRS less than 0.8 g Spectral Acceleration

All US operating nuclear plants have now submitted GMRS values to the NRC. Based on the review of the industry GMRS submittals and the NRC responses, 21 plants screen out of having to conduct a review of the spent fuel pools. Of the remaining 42 plants, 31 plants have GMRS peak spectral acceleration (5% damping) values are below the 0.8 g threshold value (Figure 4). Thus, based on the NP-6041 Table 2-3 criteria, these 31 plants can demonstrate seismic adequacy of the SFP structure to the GMRS level. As such they can demonstrate that they have adequate seismic capacity to withstand the new seismic hazard at their sites based on verifying that:

a) the GMRS is less than or equal to the 0.8 g spectral acceleration capacity level from column 1 of Table 2-3 of EPRI NP-6041,

b) the structure housing the SFP was designed to an SSE of at least 0.1 g, and

c) the structure load path to the spent fuel pool consists of some combination of reinforced concrete shear wall elements, reinforced concrete frame elements, post-tensioned concrete elements and/or structural steel frame elements

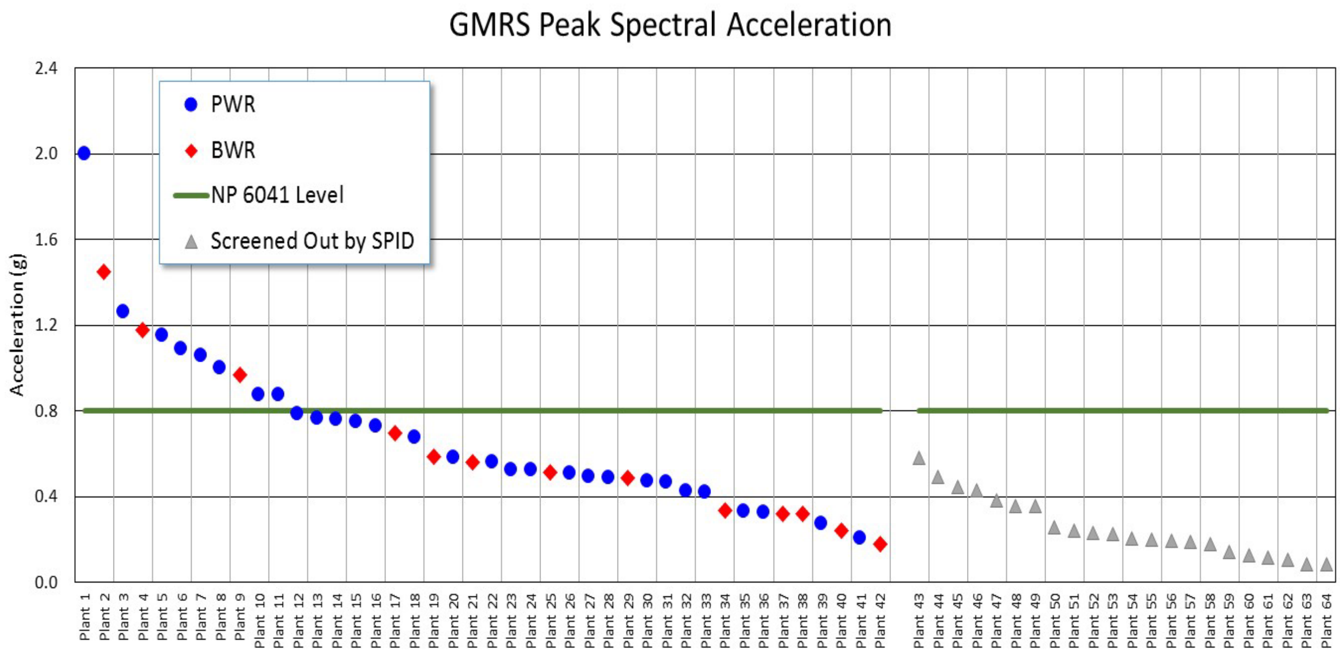

Figure 4: GMRS Peak Spectral Acceleration Comparisons to 0.8 g Ground Spectral Acceleration Threshold for US Plants

3. SFP Non-Structural Evaluation

Section 7.0 of the SPID [7] describes that the focus of the SFP evaluation is on the elements of the SFP that might fail due to a seismic event such that a rapid draining could result. This rapid draining (or "drain-down") is defined as failure of a pool's Structures, Systems, and Components (SSCs) such that there is an uncovering of spent fuel within 72 hours. The following non-structural considerations that could affect the ability of SFPs to maintain SFP inventory 72 hours are (1) penetrations that could lead to uncovering the fuel, (2) SFP cooling functional failures that could lead to siphoning inventory from the pool, (3) sloshing losses, and (4) evaporative losses.

This report provides evaluation criteria (Table 1) for demonstrating that there will not be an uncovering of SFP inventory within 72 hours. The supporting technical basis is provided in references sections of this report.

Table 1: SFP Non-Structural Drain-down Criteria

Potential Rapid Drain-Down Mechanism	Criteria	Evaluation	Notes
Piping Connections	(1) Site-specific GMRS has a peak Sa less than 0.8g	Past risk evaluations have found SFP piping to be rugged.	Basis: Report Section 3.3.1.2
Fuel Transfer Gate	(1) Site-specific GMRS has a peak Sa less than 0.8g	Rugged design of gate and seals	Basis: Report Section 3.3.1.1
Siphoning	(1) Site-specific GMRS has a peak Sa less than 0.8g	Anti-siphoning devices are assumed to be rugged and not a significant contributor to rapid drain-down. However, in cases where active anti-siphoning valves are used, NP-6041 (Table 2-4) requiresconfirmation that extremely large extended operators (attached to 2-inch or smaller piping) be walked down to confirm lateral support.	Basis: Report Section 3.3.2
Sloshing	(1) Site-specific GMRS has a peak Sa less than 0.8g	Minor inventory losses expected. For plants with peak Sa less than 0.8g, a conservative estimate of SFP inventory lost to sloshing is 3 feet. This lost inventory is accounted for in estimating evaporative losses (below)	Basis: Report Section 3.3.3
Evaporative Losses	(1) Site-specific GMRS has a peak Sa less than 0.8g (2) Anti-siphoning valves are found to be rugged (Section 3.3.2)	Time to heat up and boiloff and uncover more than 1/3 of the SFP fuel assemblies is expected to be more than 72 hours.	Basis: Report Section 3.3.4

Brief Systems Description

A typical SFP cooling system consists of circulating pumps, heat exchangers, filter-demineralizers, a makeup tank, piping, valves, instrumentation and their structural supports (Figures 5&6). The pumps circulate the pool water in a closed loop, taking suction from the pool, circulating the water through heat exchangers and filters, and discharging through diffusers at or near the bottom of the pool. The SFP system takes suction from the SFP through a skimmer (or strainer) at an elevation that is typically higher in the SFP (e.g., more than ten feet above the

top of the fuel assemblies. The SFP cooling return lines either discharge near the top of the SFP or extend deeper into the pool to distribute coolant to the bottom of the fuel. For systems where the SFP coolant lines extend deep into the pool, anti-siphon devices (e.g., drilled holes or valves) are used to prevent loss of inventory should there be a break in the piping system [13].

Each plant has a source of high purity water to provide makeup to the SFP. The typical sources are the refueling water storage tank (borated water) for PWRs and the condensate storage tank (demineralized) for BWRs. Plants will also typically have alternate sources of makeup if normal makeup is unavailable, and may include the service water system and the fire protection system [13].

The spent fuel assemblies are stored in stainless steel racks and submerged with approximately 23 feet of water above the top of the stored fuel [13]. In addition to cooling, the SFP water inventory provides radiological shielding for personnel in the fuel pool area and adjacent areas. Many plants assume that a minimum of 5-10 feet of water above the fuel assemblies provides adequate shielding [13].

During refueling operations, the refueling cavity above the reactor is filled with water equal to the water level in the SFP. Fuel is moved from the reactor to the SFP via transfer canals in BWRs or transfer tubes in PWRs. Removable gates, or refueling gates, are used in both PWR and BWR applications to isolate the SFP during normal operations. These gates are further discussed in Section 4.3.1 of this report.

Seismic Classification

Although the building housing the SFP, as well as the pool structure itself, are required to be Seismic Category I and designed to the Safe Shutdown Earthquake (SSE) [11], there is variability in the classification of the SFP cooling and makeup systems. For the design of SFPs, Regulatory Guide (RG) 1.13, "Spent Fuel Storage Facility Design Basis," (Rev 1, 1975) requires that drains, permanently connected mechanical or hydraulic systems, and other features that by maloperation or failure could cause loss of coolant resulting in uncovering the fuel should not be installed or included in design. Systems for maintaining water quality and quantity should be designed so that any maloperation or failure of such systems (including failures resulting from the SSE) will not cause fuel to be uncovered. RG 1.13 states that these systems are not otherwise required to meet Seismic Category I requirements.

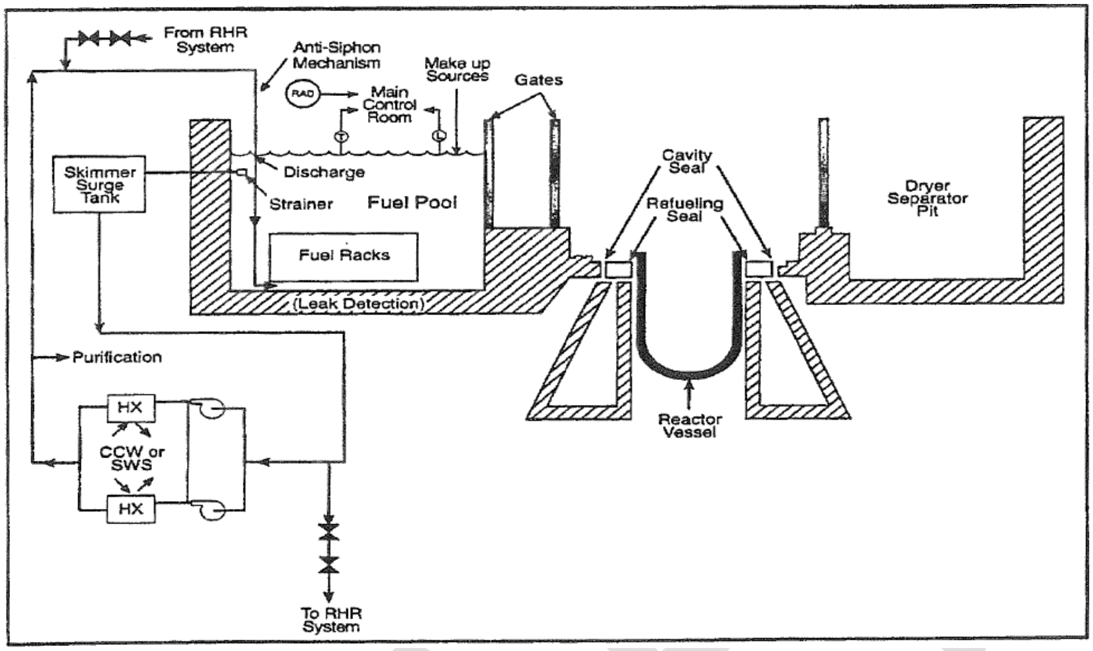

Figure 5: Typical BWR SFP Cooling System (Source: NUREG-1275)

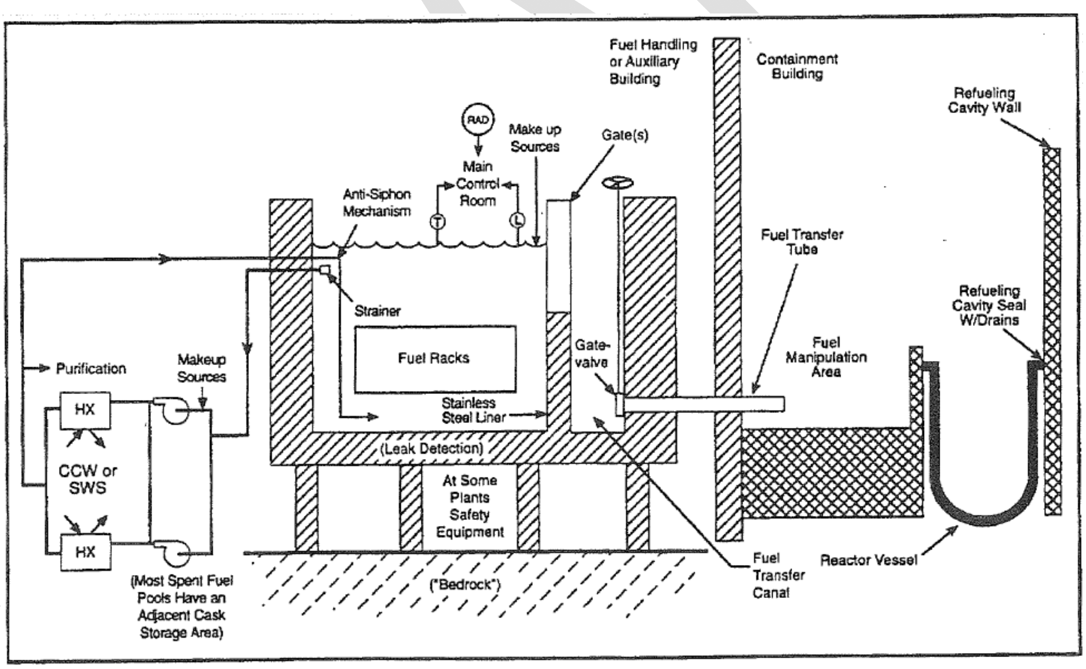

Figure 6: Typical PWR SFP Cooling System (Source: NUREG-1275)

3.1 Background on Non Structural Considerations

Earlier seismic risk studies have included SFP cooling and makeup systems in the analysis and have demonstrated that rapid drain-down events for SFPs are not likely. One such study, NUREG/CR-5176 (1989) [3], focused on the seismic response of a BWR and PWR SFP. For thesystems analyses in this study, SFP failure was defined as loss of water inventory leading to spent fuel rupture or degradation and possible radioactive material release. Loss of pool inventory was assumed to occur due to water boiloff following the failures of the pool cooling system and the systems that provide water makeup. The scope of the systems analysis included only those front-line systems that perform the primary functions of pool cooling and inventory makeup and the immediate systems or components that supported these systems.

These analyses showed that failure of cooling and make-up systems would not result in immediate uncovering of fuel rods. It was concluded, for the plants evaluated, that there is a response time of at least 3 days, maybe as much as 7 days before fuel uncovering would occur [3]. This study also demonstrated that SFP failure attributed to these systems are not directly comparable to SFP failures caused by structural degradation leading to sudden loss of water in the pool [3, Section 6.1].

Further, a 1989 NRC study (NUREG-1353) [1] found that the risk from the storage of spent fuel in the SFP at light water reactors is dominated by the beyond design basis earthquake scenario. The report concluded that the seismic capacities, or fragility, of two older spent fuel pools indicate that the high confidence of the low probability of failure (HCLPF) is about three times the SSE design level. The HCLPF values for SFPs were estimated to be in the 0.5g to 0.65g range.

A later study, NUREG-1738 (2001) [2], states that for 60 days after reactor shutdown for boiloff type events, there is considerable time (>100 hours) to take action to preclude a fission product release or zirconium fire before uncovering the top of fuel. Reference 2, Table 2.1, indicates the estimated the time to heatup and boiloff SFP inventory down to 3 feet above top of fuel is 100 hours for PWR and 145 hours for a BWR.

More recently, an SFP Scoping study [9] was performed by NRC to continue its examination of the risks and consequences of postulated spent fuel pool accidents initiated by a low likelihood seismic event. The seismic event considered in the study was based on a CEUS location (Peach Bottom) and an extremely rare recurrence interval (frequency of 1/60,000 years). The resulting free-field ground motion had a peak spectral acceleration of 1.8g and peak ground acceleration of 0.7g. The ground motion assumed in the NRC SFP Scoping Study envelopes all the US plants with peak Spectral Accelerations (Sa) less than 0.8g (Figure 7).

At the assumed seismic ground motion level, 0.7g PGA, radiological release from the reference BWR SFP was predicted to not occur within at least the first 3 days of the event [9]. Based on detailed analyses, the maximum amplitude of SFP sloshing was found to be 20 inches. The reference SFP has no connections that would allow water to drain below the bottom elevation of the refueling gate or below 10 feet above the top of active fuel [9]. The refueling cavity gate and

piping attached to the SFP were analyzed and found to be sufficiently strong and flexible enough to resist ground motion without leakage [9].

In addition to aforementioned risk and consequence analyses, earthquake experience plays an important role in understanding how SFPs behave under extreme seismic events. The Japanese earthquake experience is relevant, as the SFP designs (in the case of BWRs) are similar to those designed in the US. The previouslymentioned NRC Scoping Study reference plant is a BWR 4 with a Mark I containment, as was Fukushima Daiichi Units 2-5. Five Japanese nuclear power plant sites with a combined total of 20 reactors (all BWR designs) and 20 SFPs were subjected to severe ground motions from two major earthquakes in recent years [9]. In the case of the six units at Fukushima Daiichi, the measured horizontal peak ground accelerations from the 2011 Tohoku Earthquake ranged from 0.29g to 0.56g [9], which is generally higher than the US fleet GMRS PGAs in Figure 7. For the 20 BWR SFPs, there was no reported leakage of water, other than from seismic-induced sloshing. Sloshing effects are discussed in Section 3.3.3, below.

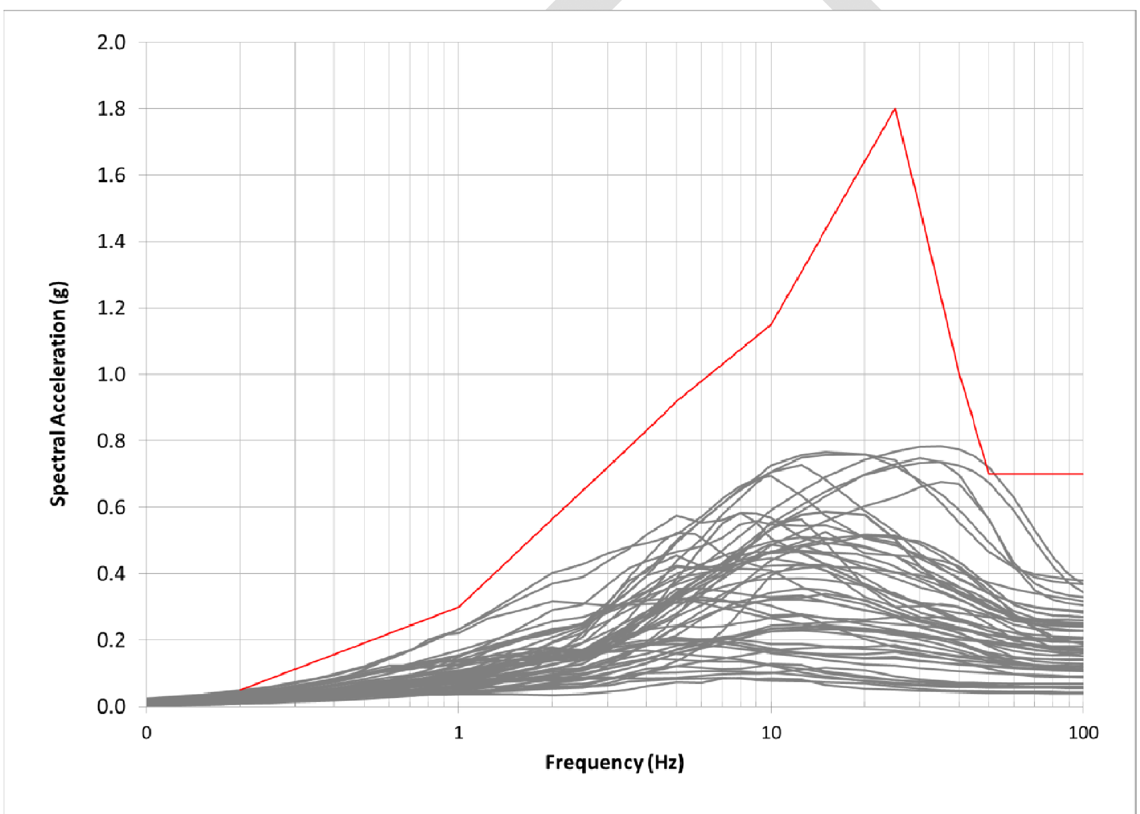

Figure 7. Comparison of NRC Scoping Study Seismic Input (red) with U.S. Fleet GMRS (those with peak Sa < 0.8g)

3.2 Treatment Within NTTF 2.1 Seismic

Section 7 of the SPID [7] provides guidance for evaluating potential drain-down of the SFP due to a seismic event, with emphasis on those failure modes that could lead to uncovering the spent fuel within 72 hours. Guidance is provided to evaluate penetrations (both above and below top

of fuel), potential for siphoning inventory, potential for sloshing, and drain-down and evaporative losses. An additional aspect of the SFP evaluation is plant-specific walk-downs of the SFP cooling and makeup systems.

Consideration of SFP connections (penetrations) whose failure could result in rapid drain-down was included in the scope of the NTTF Recommendation 2.3 seismic walkdowns [10]. In response to the NTTF Recommendation 2.3, utilities performed seismic walkdowns of the spent fuel pool to verify that the current plant configuration is consistent with the design basis, verify the adequacy of current strategies, monitoring, and maintenance programs, and identify degraded, nonconforming, or unanalyzed conditions. The SFP walkdowns were performed in accordance with NRC endorsed guidance (EPRI 1025286 [10]), which addresses adverse anchorage conditions, seismic spatial interactions, and adverse seismic conditions. Any potentially degraded, non-conforming, or unanalyzed conditions identified during the seismic walkdown program were to be assessed in accordance with the plant corrective action program.

3.3 Plants with GMRS Peak Spectral Accelerations (Sa) Less Than 0.8g

3.3.1 Penetrations and Piping Connections

SPID, Section 7.2.1 requires an evaluation of whether fuel could be uncovered in the event of a failure of an interconnection at a level above the fuel. This section allows for the demonstration of seismic adequacy of any connections or penetrations. Typical SFP penetrations are those associated with refueling gates and piping connections.

3.3.1.1 Refueling Gates

Spent fuel pools are typically configured with refueling gates, which are removed for refueling operations, and allow for the transfer of fuel assemblies in and out of the SFP. These removable gates have seals that are pneumatic or mechanical by design. Some plants (mostly PWRs) use inflatable seals and others (mostly BWRs) make use of permanent spring bellows that are not susceptible to large leak rates [13]. The refueling gate openings have narrow widths (or short spans) and the gate structures themselves are comprised of stiffened steel plates or monolithic concrete blocks.

Refueling gates have been shown to have high seismic capacities in the past due to their inherent ruggedness. Their designs have high ductility and seismic loads do not dominate the design. Rather, the design is typically dominated by pressure loads and thermal loads. As such, the designs of these gates have an inherently high seismic margin to failure and would be expected to have a negligible seismic risk contribution. This is particularly true for the plants within the scope of this paper where the peak Sa is less than 0.8 g.

As a specific check of this ruggedness, the NRC Spent Fuel Pool Scoping Study [9] analyzed the fuel transfer gate for the referenced BWR Mark I design at Peach Bottom. This Peach Bottom assessment was for a seismic input level where the peak spectral acceleration was over twice the level considered in this assessment. The Peach Bottom seismic assessment considered a peak Sa of 1.8 g (the peak ground acceleration was 0.7 g) and the NRC analysis concluded that the

refueling gate would not fail for the seismic event and will continue to maintain its intended function during the accident progression. In particular, the evaluation found that there was redundancy in the design (e.g., use of two back-to-back gates), use of polymeric seal around the perimeter that is compressed against the concrete by mechanical means which is not expected to be lost during the seismic event, and tolerances around the seals that are sufficient to accommodate the already small distortions of the SFP concrete wall. These results are typical and consistent with our expectations related to the high seismic capacity of gates.

As previously mentioned, refueling gates have seals for ensuring water-tight integrity. It is expected that a catastrophic failure of an inflatable seal will result in only limited water level loss due to limited volume of the adjacent cavity (e.g., refueling cavity) [13]. In addition, failure of the gate (or seal) will not lead to a full pool drain-down, as the weir elevation of these gates is typically at an elevation that is above the top of the fuel assemblies.

During seismic events, the water in the SFP will impart increased pressures on the fuel transfer gates and seals. The water in upper part of the pool (typically the upper 20%) will undergo convective motion (or sloshing) and the remaining water will impart impulsive pressure demands on the SFP. Guidance for estimating seismic-induced wall pressures on rectangular-shaped liquid storage tanks, which are representative of SFPs, is provided in ACI-350.3-01, "Seismic Design of Liquid-Containing Concrete Structures and Commentary [14]. Using site-specific SFP geometry (based on survey results), reevaluated GMRS, and ACI-350.3 provisions (for pressure distribution), a comparison of the relative magnitudes of hydrostatic, impulsive, convective, and vertical impulsive pressures was made for current US plants with peak Sa less than 0.8g. The results indicate that at the mid-height of the pool (approximately the bottom elevation of the refueling gate), the median convective pressures are small compared to median hydrostatic, impulsive, and vertical pressures (Table 1). When combined using the Square-Root-Sum-of-the-Squares methodology, (SRSS), the median seismic pressures for both BWR and PWR SFPs are generally less than the hydrostatic pressure (at pool mid-height). For SFP gate designs that make use of pneumatic seals (mostly PWR designs [13]), seal pressures are typically greater than the seismic-induced pressures, and will therefore not be damaging. For example, in a few observed PWR applications, the refueling gate seal pressures were found to be 30 psig, which is significantly higher than the maximum SRSS pressure of 7.9 psi (Table 2).

Table 2. Comparison of SFP Wall Pressures at Mid-Height (Median values for all US SFPs with peak Sa<0.8g)

	Hydrostatic Pressure (psi)	Horizontal Impulsive Pressure (psi)	Horizontal Convective Pressure (psi)	Vertical Pressure (psi)	Combined Pressure SRSS(psi)
PWR SFPs	8.9	3.8	0.3	4.4	5.8
BWR SFPs	8.5	5.0	0.3	6.1	7.9

On the basis that (1) refueling gates (including seals) are inherently rugged components typically comprised of stiffened steel plate or monolithic concrete blocks and (2) detailed NRC analysis found that a BWR Mark I SFP refueling gate under high seismic demands (peak Sa ~ 1.8g)

remains functional, it is judged that typical SFP refueling gates will remain functional in cases where the GMRS peak Sa is less than 0.8g.

The following criteria for SFP refueling gates are recommended:

> *In cases where the site-specific GMRS has a peak Sa less than 0.8g, PWR and BWR SFP refueling gates (and seals) are determined to be adequately rugged and to not be source of rapid drain-down.*

3.3.1.2 Piping

Piping connections to the spent fuel pool are required for the SFP cooling system discharge and suction lines. There are limited cases were spent fuel pools have piping connections below about 10 feet above the top the fuel assemblies. An industry survey, based on over 95 percent of the US plants required to perform SFP confirmations, substantiates this assumption. The SFP cooling systems were included in the scope of the NTTF 2.3 seismic walkdowns, where seismic interactions, corrosion, and degraded conditions were assessed [10].

SFP cooling and makeup piping systems are considered to be seismically rugged. Seismically designed piping is inherently rugged and has been shown in past SPRAs and margin studies not to contribute appreciably to the seismic risk. Past SFP risk assessments concluded that HCLPF capacities of piping systems are estimated to be in excess of 0.5g PGA [3], which exceeds the PGA of the GMRS for each of the plants within the scope of this paper. As a check at even higher acceleration levels, the NRC Scoping Study [9] evaluated piping connections for the spent fuel pool at Peach Bottom (peak Sa of 1.8 g) and found that due to the very small resultingdisplacements/distortions, the piping would remain functional and leak tight.

On the basis that (1) SFP piping systems are typically designed for seismic loading and considered to be rugged [3], (2) the 2.3 seismic walkdowns included SFP piping systems, and (3) NRC SFP Scoping Study for an elevated BWR found small relative displacements, it is judged that there exists high confidence that the SFP piping and penetrations will remain functional for plants with GMRS peak spectral accelerations less than 0.8g PGA.

The following criteria for SFP piping connections are recommended:

> *In cases where the site-specific GMRS has a peak Sa less than 0.8g, PWR and BWR SFP piping connections are determined to be adequately rugged and to not be source of rapid drain-down.*

3.3.2 Siphoning of SFP inventory

SPID Section 7.2.3 provides guidance for assessing SFP cooling functional failures that could lead to siphoning inventory from the pool. As SFP suction lines are typically connected near the top of the pool, these lines are not susceptible to siphoning significant amounts of inventory in an event leading to siphoning. However, SFP discharge lines can extend to near the bottom elevation of the SFP. These lines typically have anti-siphoning devices (holes or valves) that prevent drain-down of the SFP. Anti-siphoning valves are typically passive mechanical devices that permit flow in one direction.

EPRI NP-6041, Table 2-4, identifies that passive valves are assumed to be rugged for peak spectral accelerations less than 0.8g PGA. The NP-6041 screening criteria are applicable to the SFP cooling system.

The following criteria for SFP anti-siphoning valves are recommended:

> *In cases where the site-specific GMRS has a peak Sa less than 0.8g, passive anti-siphoning valves are assumed to be rugged and not be a source of rapid drain-down.*
>
> *However, in cases where active anti-siphoning valves are used, NP-6041 (Table 2-4) requires confirmation that extremely large extended operators (attached to 2-inch or smaller piping) be walked down to confirm lateral support.*

3.3.3 Sloshing

Horizontal seismic demands on the SFP can induce vertical fluid motion, or sloshing. Spent fuel pool sloshing is addressed in SPID, Section 7.3.2. This section provides guidance for estimating the fundamental sloshing frequencies (one in each direction of the pool) and for estimating the slosh height. Industry SFP survey results, which represent over 90 percent of the US NPP fleet, confirm that sloshing frequencies are in the low frequency range (< 0.5 Hz). For plants with peak Sa less than 0.8g, it is observed that most GMRS are enveloped by the GMRS in the low frequency range. In the few cases where site-specific GMRS exceeds the SSE in the low frequency range, these exceedances have low spectral amplitude (<0.1g) and are generally no more than 20 percent above the SSE. The sloshing heights, resulting from these exceedances, are estimated to be several feet, not accounting for pool free-board. Using the conservative SPID equations, the median slosh height is 3.7 feet. Assuming a minimum free-board of 1 foot, this results a conservative estimate of 2.7 feet of SFP water inventory lost due to sloshing. This loss of inventory is judged to not be significant given the typical SFP depth of 40 feet.

SPID Section 7.3.2 acknowledges the conservatism in the slosh height analysis. As the GMRS of most US plants are enveloped by the SSE in the low frequency range, the level of conservatism in the SPID equations is not a significant consideration, however, in some cases, it may be beneficial to estimate the approximate degree of conservatism. For this purpose, sloshing results were calculated (using the SPID equations) for the NRC Spent Fuel Pool Scoping Study. The SPID methodology yields sloshing frequencies that are comparable to those calculated in the detailed Scoping Study. For the reference SFP, the SPID methodology predicts a combined (SRSS) slosh height of 10 feet. However, the NRC Scoping Study, which utilized a more refined sloshing analysis based on finite element modeling, predicted a maximum slosh height of approximately 2 feet. In this case, the conservative SPID equation yields results that are approximately five times higher than the detailed analysis.

Another comparison case is the Fukushima-Daiichi Unit 2 SFP, which was subjected to severe seismic ground motion during the March 11, 2011 Tohoku earthquake. The Unit 2 reactor is a BWR 4 Mark I with similar characteristics as the NRC Scoping Study reference plant (BWR 4 Mark I). The Unit 2 SFP has dimensions of 40 feet x 32.4 feet and a depth of 38.7 feet and has fundamental sloshing frequencies of 0.25 Hz and 0.28 Hz (each direction). The ground motion in this frequency (0.2-0.3 Hz) is similar to the NRC Scoping Study (peak Sa of 0.1g) (Figure 8).

Using the Fukushima-Daiichi Unit 2 parameters, the SPID equation predicts a sloshing height of 10 feet; however, the estimates of actual sloshing amplitudes for Unit 2 were approximately 2.6 feet [9]. In the case of Fukushima-Daiichi Unit 2, the SPID equation estimates slosh heights that are approximately 3.8 times higher than those observed. However, despite the apparent conservatism in the SPID methodology (Section 7.3.2), it is relied upon for estimating SFP sloshing losses.

The following criteria for SFP sloshing are recommended:

> *In cases where the site-specific GMRS Sa is less than 0.8g, the conservatively calculated losses are small (less than 3 ft). When sloshing losses are accounted for, the time to uncover the SFP is expected to exceed 72 hours.*

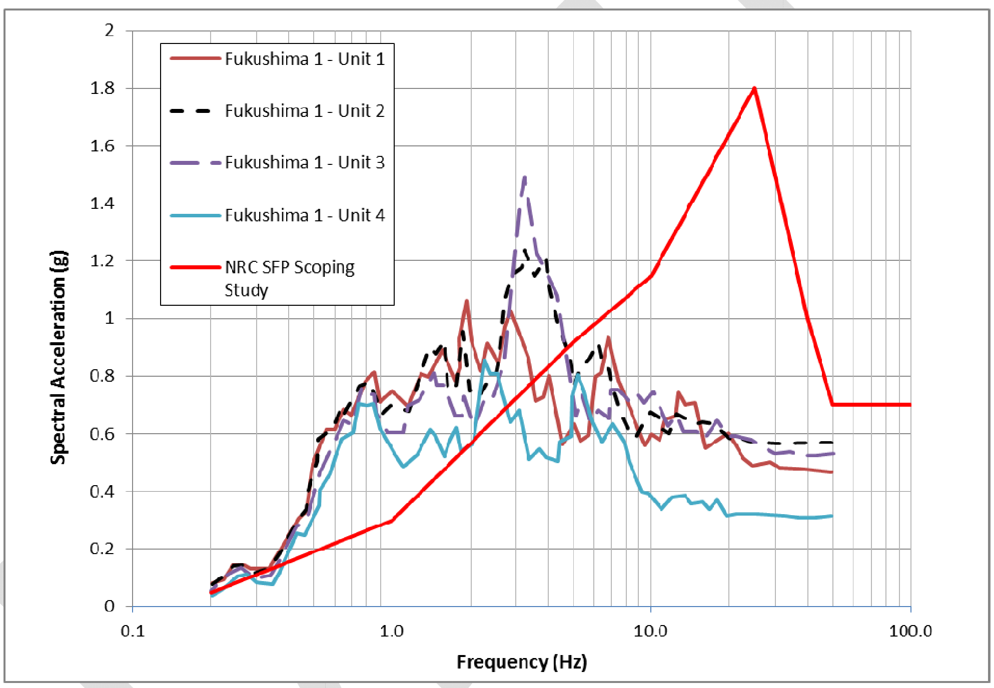

Figure 8. Horizontal response spectra (5% Damping): Fukushima Daiichi Units 1-4 (foundation) and NRC SFP study (free-field) (Source: NRC Spent Fuel Pool Scoping Study)

3.3.4 Evaporative Losses

The SPID requires an assessment of evaporative losses of inventory from the SFP. The SPID references a method to calculate the additional loss of inventory that occurs up to 72 hours in absence of makeup flow. This rate of boil off loss can be determined using the correlations provided in Appendix EE of EPRI 1025295, “Update of the Technical Bases for Severe AccidentManagement Guidance” [8]. These correlations can be used to determine whether the top of the fuel could begin to be uncovered within 72 hours.

NUREG-1738, Appendix 2A [2] also provides a simplified approach for calculating SFP heat up and boil off times. For an SFP, the depth of water above the fuel is typically 23-25 feet [2]. By reducing water inventory height by 3 feet to conservatively account for sloshing (refer to Section 3.3.3), and applying the SPID criteria allowing up to 1/3 of the fuel to be uncovered, it is estimated that approximately 25 feet of water will have to boil off to prevent overheating the fuel. Using Table 3 (below), and assuming 60 days after discharge (representative of non-outage period decay power) [9, Table 16], the total time available before fuel starts to be uncovered is shown below:

Total Time = 18 hrs + (25 ft)/0.33 ft/hr) = 93.7 hours

A survey of US SFPs indicate that the median pool surface area is approximately 1,300 ft^2 rather than the 1,000 ft^2, assumed in [2]. The increased pool surface area will slightly decrease the pool level decrease rate. Using the same boil off rate of 41 gpm, the pool level decrease rate changes to approximately 0.24 ft/hr. Based on this more representative level decrease rate, the total time before fuel uncovers increases to approximately 122 hours.

Based on the above sections, the following criteria for SFP evaporation effects are recommended:

In cases where the where the GMRS peak Sa is less than 0.8g, and the SFP anti-siphoning valves are assessed to be rugged (Section 3.3.2), the time to heat up,boil off, and uncover more than 1/3 of the SFP fuel assemblies is expected to be more than 72 hours.

Table 3: NUREG-1738, Appendix 2A, Table 3.1, "Time to Bulk Boiling, and Boil off Rates"

Time after discharge (days)	Decay power from last core (MW)	Total heat load (MW)	Time to bulk boiling (hr)	Boil-off rate (gpm)	Level decrease (ft/hr)[1]
2	16.4	18.4	5.6	130	1.0
10	8.6	10.6	9.8	74	0.6
30	5.5	7.5	14	52	0.42
60	3.8	5.8	18	41	0.33
90	3.0	5.0	21	35	0.28
180	1.9	3.9	27	27	0.22
365	1.1	3.1	33	22	0.18 = 0.2

Notes: (1) using typical pool sizes, it is estimated that for BWRs, we have 1040 ft^3/ft depth, and for PWRs, we have 957 ft^3/ft depth. Assume ~ 1000 ft^3/ft depth for level decreases resulting from boil-off.

4. References

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