ELECTRIC POWER RESEARCH INSTITUTE

Seismic Evaluation Guidance

Spent Fuel Pool Integrity Evaluation

2016 TECHNICAL UPDATE

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Product Description

Following the accident at the Fukushima Daiichi nuclear power plant (NPP) resulting from the March 11, 2011, Great Tohoku Earthquake and subsequent tsunami, reviews were conducted, including examinations of the seismic safety of NPPs. In the United States, the Nuclear Regulatory Commission (NRC) established a Near-Term Task Force (NTTF) to 1) conduct a systematic review of NRC processes and regulations and 2) determine whether the agency should make additional improvements to its regulatory system.

Background

From time to time, new assessments of seismic hazard are performed for NPPs around the world. In some cases, updated information has led to an assessment that the seismic hazard is, in some ways, higher than had been previously understood. When a new catalog of seismic sources was compiled for plants in the central and eastern portion of the United States, this catalog was used to develop updated estimates of seismic hazard. At about the same time that this reassessment of seismic hazard was completed, the NTTF developed a set of recommendations intended to clarify and strengthen the regulatory framework for protection against natural phenomena in light of the Great Tohoku Earthquake and the resulting tsunamis. Subsequently, the NRC issued a letter that requested information to ensure that all U.S. NPP licensees address these recommendations.

EPRI report 1025287 provides guidance for conducting seismic evaluations, including those requested in the NRC's letter, which asks that licensees reevaluate the seismic hazards at their sites against present-day NRC requirements and guidance. Section 7 of EPRI report 1025287 provides guidance for performing an evaluation of the spent fuel pool (SFP) that considers all seismically induced failures that can lead to draining of the SFP.

Objectives

- To provide evaluation guidance for the effects of seismic ground motions on SFPs that supplements the SFP evaluation guidance provided in EPRI report 1025287
- To provide alternate guidance for performing the structural evaluation and generic implementation guidance for performing the nonstructural evaluations

Approach

This report provides simplified evaluation guidance for plants in which the ground motion response spectrum (GMRS) peak spectral acceleration is less than 0.8g, which represents 75% of the plants performing SFP seismic evaluations. Additional evaluation guidance will be provided for the remaining plants in an update to the report.

Seismic evaluation criteria in EPRI report NP-6041 are applied to address seismic adequacy of the SFP structure up to 0.8g spectral acceleration. Generic seismic assessments are also provided for SFP piping penetrations, refueling gates, and potential siphoning conditions. Finally, evaluations are provided for SFP seismic-induced sloshing losses and boil-off losses using site-specific parameters to evaluate the ability of SFPs to retain adequate water inventory for 72 hours.

Results and Findings

The evaluations provided in this report show that SFPs can retain adequate water inventory for 72 hours provided the plant meets a limited set of parameters. The key application parameter for this report is that the GMRS peak spectral acceleration is limited to 0.8g. A key conclusion of the report is that the seismic-induced SFP inventory losses are modest and that the majority of inventory losses over 72 hours are a result of evaporation and boil-off.

Evaluation guidance will be provided for plants with GMRS peak spectral acceleration more than 0.8g in an update to this report.

Applications, Value, and Use

The criteria presented in this report support the SFP seismic evaluations as identified in EPRI report 1025287 and licensee responses to the NRC 50.54(f) letter. These criteria can also be applied at any plant performing an SFP seismic evaluation with ground motions up to 0.8g peak spectral acceleration.

Keywords

Earthquakes
Fukushima
Seismic evaluation
Spent fuel pool

Acronyms and Abbreviations

ACI	American Concrete Institute
Btu	British thermal unit
BWR	boiling water reactor
CEUS	central and eastern United States
CFR	Code of Federal Regulations
cm	centimeter
EPRI	Electric Power Research Institute
°F	degrees Fahrenheit
ft	feet
g	acceleration due to gravity
GMRS	ground motion response spectrum
HCLPF	high confidence of low probability of failure
hr	hour(s)
Hz	Hertz
in	inches
ksi	kilopound per square inch
lb	pound
m	meter
MPa	megapascal
MW	megawatts
MWt	megawatts thermal
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NTTF	Near Term Task Force
PGA	peak ground acceleration
psi	pound per square inch
PWR	pressurized water reactor
RG	Regulatory Guide
RLE	review level earthquake
RPV	reactor pressure vessel
Sa	spectral acceleration
SFP	spent fuel pool
SPID	Screening, Prioritization, and Implementation Details
SPRA	seismic probabilistic risk assessment
SRSS	square root sum of the squares
SSC	structures, systems, and components
SSE	Safe Shutdown Earthquake
UHS	uniform hazard spectra

Table of Contents

List of Figures

List of Tables

Section 1: Introduction and Purpose

Many plants in the United States are performing seismic evaluations of spent fuel pools (SFP) in response to the Nuclear Regulatory Commission's (NRC) 50.54(f) letter [1] requesting that plants perform a number of seismic evaluations using updated site-specific seismic hazards. The primary guidance for performing those evaluations is provided in EPRI 1025287 [2].

The 50.54(f) letter requested that, in conjunction with the response to Near Term Task Force (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." This report provides evaluation guidance for the effects of seismic ground motions on SFPs that supplements the SFP evaluation criteria provided in EPRI 1025287.

Although the guidance in this document is specifically directed at supporting responses to the 50.54(f) letter, the evaluation guidance is applicable to any SFP seismic evaluation.

1.1 NRC Near Term Task Force Recommendations

Following the accident at the Fukushima Daiichi Nuclear Power Plant (NPP) resulting from the March 11, 2011 Great Tohoku Earthquake and subsequent tsunami, the U.S. NRC established the (NTTF) in response to Commission direction. The NTTF issued a report with a series of recommendations, some of which were to be acted upon "without unnecessary delay," concerned with the capability of NPPs to deal with extreme events. NTTF Recommendation 2.1 instructed NRC staff to issue requests for licensees to re-evaluate the seismic hazards at their sites, using present-day NRC requirements and guidance, and to identify and address any site-specific vulnerabilities associated with the updated seismic hazards. Subsequently in 2012, the NRC issued a 50.54(f) letter [1] that requested information to ensure that these recommendations were addressed by all operating U.S. NPPs.

The NRC requested that each licensee provide information about the updated hazard on an accelerated schedule and proposed a progressive screening/evaluation approach to evaluate the potential risk posed by future seismic events. While the full seismic hazard studies were requested, the measure of the re-evaluated seismic hazard for a given site was provided by a new horizontal ground motion response spectrum (GMRS) developed using updated uniform hazard spectra (UHS) [1]. Depending on the comparison between the

GMRS and the current design basis spectrum, the plants either were screened-out from further evaluation or were screened-in to perform a seismic risk assessment using the updated seismic hazard.

1.2 Industry Response

EPRI 1025287, *Seismic Evaluation Guidance, Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic* [2] provided screening, prioritization, and implementation details to the U.S. nuclear utility industry for the resolution of NTTF Recommendation 2.1: Seismic. This report was developed with NRC participation and was subsequently endorsed by the NRC. The SPID [2] provided screening guidance for the comparison of site-specific horizontal GMRS, developed from the new seismic hazard evaluations, with the site safe-shutdown earthquake (SSE).

The NRC 50.54(f) letter [1] requested that seismic evaluations be performed for SFPs to consider all seismically induced failures that could lead to draining of the SFP. Section 7 of the SPID [2] describes an approach for performing the requested SFP drain-down evaluations.

The approach outlined in the SPID focuses on those plants that have GMRS exceedances of the SSE in the frequency range of structural significance (i.e., 1 to 10 Hz). For those plants where the GMRS exceeds the SSE in the 1 to 10 Hz frequency range, spent fuel pool evaluations are required. The SPID [2] provides guidance on how to consider possible failures that could lead to a rapid drain-down uncovering more than 1/3 the height of fuel stored in the SFP within 72 hours. Such failures that could conceivably lead to SFP rapid drain-down events would include the following:

- A significant failure of the steel-lined, reinforced concrete structure of the SFP, causing inventory of the pool to drain out.
- Failure of a connection penetrating the SFP structure (drain line, cooling water line, etc.) below the top of the stored fuel.
- Failure of a connection penetrating the SFP structure above the fuel sufficient to drain significant inventory from the pool such that (in absence of adequate makeup) evaporation and boil-off would cause fuel to be uncovered within 72 hours.
- Extensive sloshing such that sufficient water could be lost from the pool and lead to uncovering of fuel within 72 hours.
- Failure of a cooling-water line or other connection that could siphon water out of the pool sufficient to lead to uncovering of the fuel within 72 hours.

With regard to the above scenarios, the SPID [2] notes that the SFP structure can be evaluated using a checklist described in NUREG-1738 [4], or another approach can be used if sufficiently justified. The SPID also provides additional criteria for selecting and evaluating SFP penetrations, estimating sloshing losses, and estimating boil-off losses using a method in EPRI 1025295 [17].

As part of the rapid drain-down evaluations, licensees may consider the ability to make up inventory losses to ensure that the spent fuel remains adequately covered. SFP inventory makeup strategies can be credited provided; makeup resources, including any necessary instrumentation, are seismically rugged and available; procedures exist to guide the response by the operator; and there is sufficient time for operators to recognize the need for makeup and take action. Credited operator actions should be reviewed to account for habitability and accessibility limitations.

In addition to the SFP evaluation guidance in the SPID [2], seismic walkdowns were performed of plant equipment, including SFP equipment, in accordance with EPRI 1025286 [5] to address NTTF Recommendation 2.3. These walkdowns were performed to verify that the current plant SFP configuration is consistent with the design basis, identify degraded, nonconforming, or unanalyzed conditions, and verify the adequacy of licensee monitoring and maintenance programs. The walkdown criteria in EPRI 1025286 [5] address equipment anchorage, 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.

The SFP seismic walkdowns also focused on SFP connections whose failure could result in a rapid drain-down. The rapid drain-down event was defined as a failure that could lead to uncovering of spent fuel assemblies stored in the SFP within 72 hours of the earthquake.

1.3 Purpose of Report

The purpose of this report is to provide supplemental guidance for performing the SFP evaluations identified in the SPID [2]. The report describes the technical basis supporting the evaluation of plants with low-to-moderate seismic ground motions, or peak spectral accelerations less than 0.8g. Plants with peak spectral accelerations greater than 0.8g, will be addressed in a future revision to this report.

Section 2 of this report provides an overall description of SFP general arrangements and systems functions. Distinctions are made between Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) (Mark I, II, and III) SFP designs. This section also provides a brief description of the seismic classification of SFP structures, systems, and components (SSC).

Section 3 of this report provides evaluation criteria for SFPs at sites with GMRS peak spectral accelerations less than 0.8g. An approach is described for evaluating the SFP structure that can be used as an alternate to the NUREG-1738 checklist identified in the SPID [2]. This section also provides criteria for evaluating the non-structural aspects of the SFP, such as piping connections, fuel gates, and anti-siphoning devices, as well as an evaluation of SFP sloshing and an approach for assessing the heat up and boil-off of SFP water inventory. The results are based on industry survey results, site-specific GMRS demands, conservative estimates of sloshing losses, and realistic SFP heat loads. Finally, Section 3 of this report provides screening criteria, which will enable licensees to confirm that their site-specific parameters are within the bounds of the criteria considered in this report.

Appendices provide a summary of a survey of SFP characteristics and an example SFP heat up and boil-off calculation of a representative pool.

Section 2: Characteristics of Spent Fuel Pools

2.1 Spent Fuel Pool Characteristics

Spent fuel pools (SFPs) are generally rectangular in cross section and approximately 40 feet (12 m) deep. Both BWR and PWR reactor SFPs typically range from 30 to 60 feet (9 to 18 m) in length and 20 to 40 feet (6 to 12 m) in width. For multi-unit sites there may be a shared SFP, two SFPs that may or may not be connected, or a separate SFP which stores used nuclear fuel for multiple units. Fuel assemblies are placed vertically in storage racks which maintain an adequate spacing to prevent criticality and to promote natural convective cooling in water medium. The pools themselves are constructed of reinforced concrete with sufficient thickness to meet radiation shielding and structural requirements, and are lined with stainless steel plates of approximately ¼ inch (0.64cm) thickness to ensure a leak-tight system.

Because of design features of the reactor pressure vessel (RPV) and containments, there are characteristic differences between BWR and PWR SFP locations. For example, BWR reactor vessels are taller than PWR vessels. A typical BWR RPV may be over 66 ft (20 m) in height, while a PWR RPV may be 44 ft (13.4 m) in height (see Figure 3-1). PWRs operate the reactor using borated water as one reactivity control measure; BWRs do not. PWRs do not typically have a Reactor Building surrounding the containment [6, 7].

PWRs typically have a spent fuel storage pool which is located in the Fuel Building or Auxiliary Building (not the Reactor Building) and is either embedded partially below ground or is significantly closer to ground level than the BWR Mark I and II plants. Some PWR SFPs are positioned such that their used nuclear fuel is below grade.

Mark I and II boiling water reactors are designed with the SFP within the secondary containment (reactor building), with the fuel pool adjacent to the RPV cavity. The bottom of the pool is usually elevated approximately 50 ft (15m) above ground level, which places the top of the pool at the level of the refueling floor. Mark III BWRs have their SFP outside of secondary containment in the fuel handling building, with the bottom of the pool at ground level. During

BWR Mark I and II refueling operations, the spent fuel is moved directly from the RPV to the SFP through a narrow refueling cavity. Under normal operations, the cavity is sealed with removable steel gates. Removable concrete blocks are also installed for radiation shielding purposes.

Both BWR and PWR SFPs are designed such that failure of any SFP cooling line penetrating the pool will not permit the water level to drop below approximately 10 ft (3 m) above the top of the spent fuel racks. All lines that penetrate the SFP are provided with isolation valves located as close as possible to the penetration.

Piping design is such that it is not possible to siphon the SFP water level down as the result of a failed pipe or component to a water level below approximately 10 ft (3 m) above the top of the spent fuel rack. This level provides adequate shielding and cooling of the spent fuel while system repair is completed.

2.2 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 2-1 and 2-2). 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 [8].

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 [8].

The spent fuel assemblies are stored in stainless steel racks and submerged with approximately 23 feet (7.01 m) of water above the top of the stored fuel [8]. 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 (1.52-3.05 m) of water above the fuel assemblies provides adequate shielding [8].

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 3.2.3 of this report.

2.3 Seismic Classification

Buildings that house the SFPs, as well as the pool structure itself, are required to be Seismic Category I and designed to the SSE [9]. However, due to the distribution of U.S. NPP vintage, 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) [9] 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.

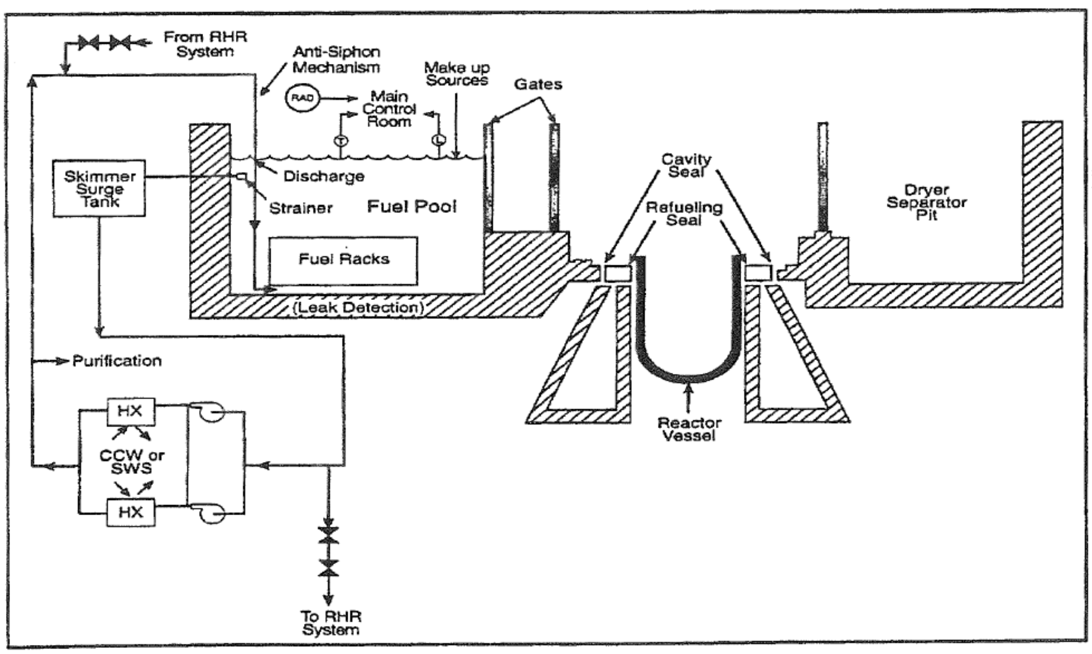

Figure 2-1
Typical BWR SFP Cooling System (Source: NUREG-1275)

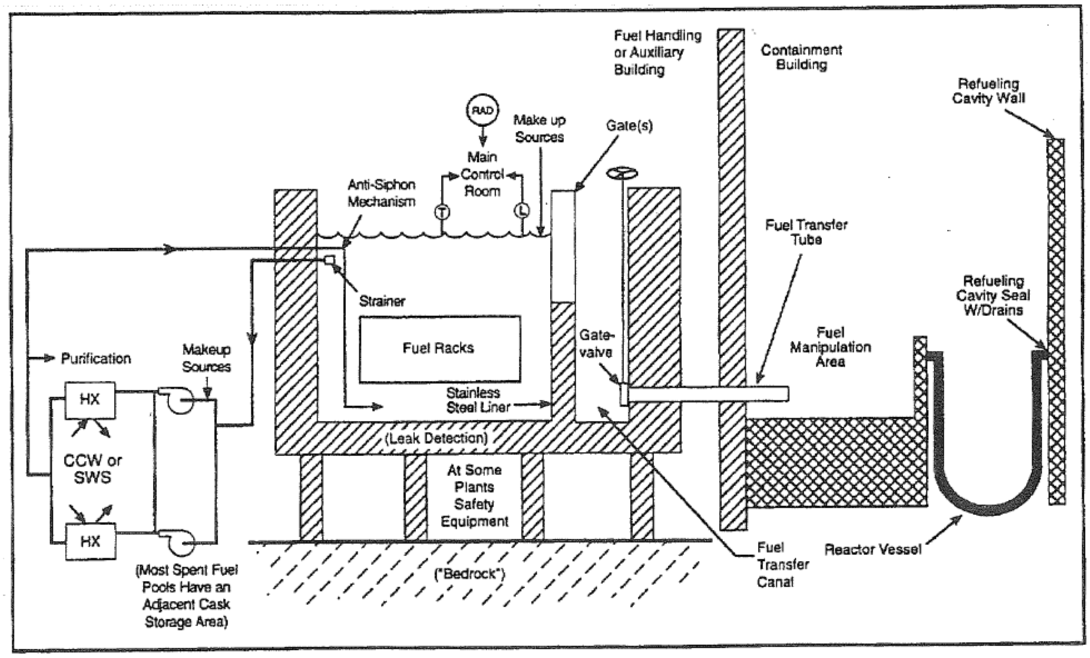

Figure 2-2
Typical PWR SFP Cooling System (Source: NUREG-1275)

Section 3: Seismic Review of Spent Fuel Pools at Low GMRS Sites

Spent fuel pool evaluation criteria are provided in this section for plants with GMRS peak spectral accelerations (Sa) less than 0.8g. The criteria address SFP structural elements (e.g., floors, walls, and supports), non-structural elements (e.g., penetrations), seismic-induced SFP sloshing, and loses due to heat-up and boil-off.

3.1 Spent Fuel Pool Structural Evaluation

Section 7 of the SPID [2] identifies a checklist in NUREG-1738 [4] as an acceptable way of demonstrating that an SFP structure is sufficiently robust. The SPID [2] also allows for an alternate approach if it is sufficiently justified. This section describes an alternate SFP structural evaluation approach for plants with GMRS peak spectral accelerations (Sa) less than 0.8g, using an accepted method of assessing seismic capacity of nuclear power plant SSCs in EPRI NP-6041 [10].

3.1.1 Background on Spent Fuel Pool 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 SFP structures at NPPs 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 SFPs, industry surveys were conducted to identify the structural characteristics of the SFPs and their supporting structures for the fleet of U.S. operating nuclear plants. The key elements from that survey are summarized in Table 3-1 below. Additional summaries are presented in Appendix A.

The fundamental structural configurations of the SFPs 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 SFPs are constructed of reinforced concrete shear walls with stainless steel liners attached to the floors and walls. The SFPs are rectilinear with adjoining compartments next to the fuel storage pool for various operations, such as 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 included structural characteristics such as wall spans, thicknesses, concrete strength, and percentage of steel reinforcing.

Table 3-1
Summary of Key Spent Fuel Pool Dimensional and Strength Parameters

Parameter	Minimum	Maximum	Average
Wall span	30 ft (9.1 m)	120 ft (36.6 m)	52 ft (15.9 m)
Wall thickness	42 in (to 106.7 cm)	96 in (243.8 cm)	64 in (162.6 cm)
Concrete strength	3 ksi (20.7 MPa)	5 ksi (34.5 MPa)	3.6 ksi (24.8 MPa)
Reinforcing ratio	0.1%	0.9%	0.3%
Reinforcing strength	24 ksi (165 MPa)	60 ksi (414 MPa)	52 ksi (359 MPa)
Liner thickness	1/8 in (0.32 cm)	3/8 in (0.95 cm)	1/4 in (0.64 cm)

The characteristics of the structures supporting/housing the SFPs were also part of the industry SFP surveys. The SFPs are part of 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) with Mark I and Mark II containment designs typically have different designs of the structures housing the SFPs than both the Pressurized Water Reactors (PWR) and the BWR Mark III designs. The spent fuel storage pools at BWR Mark I & II 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 3-1 depicts one of the early BWR plant configurations with the SFP elevated in the reactor building. 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.

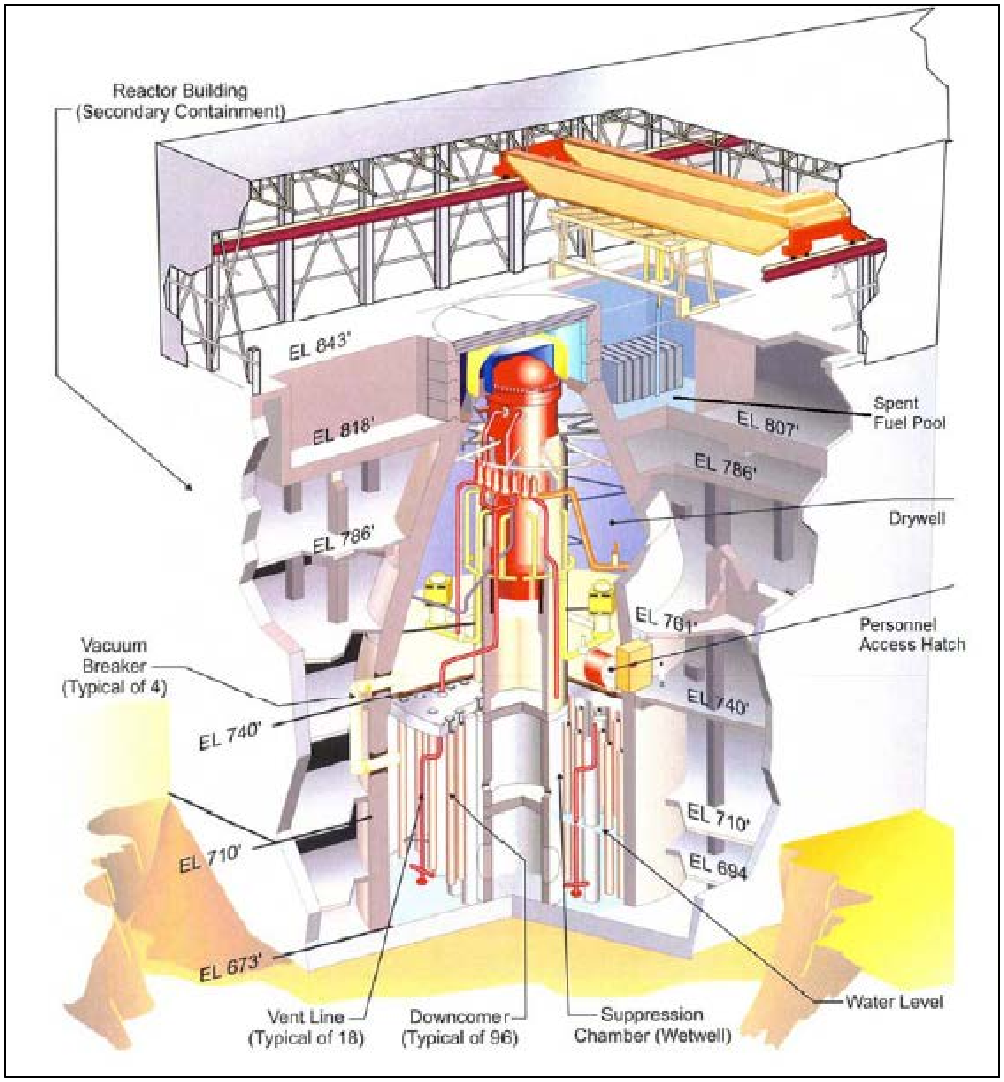

Figure 3-1
Schematic for Typical Boiling Water Reactor Configuration with Elevated Spent Fuel Storage Pool

At PWR and BWR Mark III 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 3-2 depicts a typical PWR plant configuration including the location of the SFP. The structures housing the SFP 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 SFP structural load paths include reinforced concrete frame members and/or structural steel frame members.

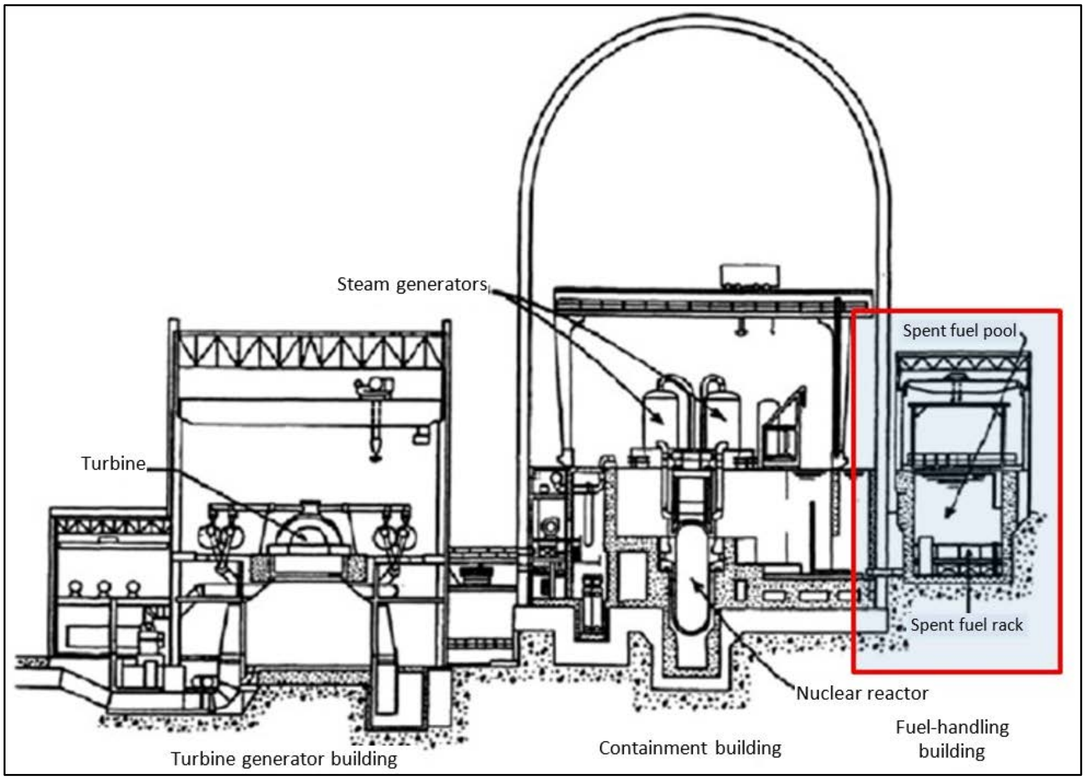

Figure 3-2
Schematic for Typical Pressurized Water Reactor Configuration with Spent Fuel Storage Pool

3.1.2 Treatment of Spent Fuel Pool Structures within NTTF 2.1 Seismic

The 50.54(f) letter [1] 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 [2].

Previous evaluations in NUREG-1353 [11], NUREG-1738 [4] and NUREG/CR-5176 [12] 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 high confidence of a low probability of failure (HCLPF) of at least 1.2g spectral acceleration. Evaluations reported in NUREG/CR-5176 [12] for two older plants concluded that "…seismic risk contribution from SFP 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 [11]. The SPID [2] states that either the checklist in NUREG-1738 [4] 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 the seismic adequacy justification for SFP structures at nuclear power plant sites with a relatively low GMRS.

As noted in the SPID [2], the screening criteria for civil structures in EPRI NP-6041 [10] provide principles that are 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 Table 2-3 assessment criteria. As noted earlier in Section 3.1.1, SFP structures have 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 SFPs and their supporting structures all fall within four rows of the NP-6041 Table 2.3 [10] addressing these four structural configurations. Table 3-2 shows an excerpt of the NP-6041 Table 2-3 structural screening criteria.

The first capacity column in Table 3-2 presents the requirements for the assessment of different types of structures to a 5% damped ground motion peak spectral acceleration of 0.8g. The SFP structures for all NPPs fall within the first, fourth, sixth and seventh rows of Table 3-2. 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 0.8g peak spectral acceleration level and can be screened from further consideration based solely on demonstration of meeting the "<0.8g" spectral acceleration criteria in the first capacity column. For the "<0.8g" of Table 3-2, the footnote requirements for the other three structural configurations (shear wall structures, concrete frame structures and steel frame structures) considered in this SFP study are limited to the single footnote "e", which states:

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

All spent fuel pool structures are, by necessity, Category 1 structures since they contain spent fuel and are designed to the site SSE. All U.S. nuclear plants have design basis SSEs (or the equivalent Design Basis Earthquakes) at or exceeding the 0.1g threshold. Thus, all operating U.S. nuclear plant SFP structures meet the EPRI NP-6041 [10] criteria that demonstrates that they have a high confidence of exceeding the 0.8g spectral acceleration capacity in the free field. The criteria associated with EPRI NP-6041 stipulates that the 0.8g screening level would apply to sites where the peak spectral acceleration of their review level earthquake (RLE) is less than or equal to this 0.8g spectral acceleration. For purposes of the SFP structure review, the GMRS is used as the RLE.

Table 3-2
Excerpted Table 2-3 from EPRI NP-6041

EPRI NP-6041 Table 2-3 Summary Of Civil Structures Criteria For Seismic Margin Evaluation (Page 1 of 2)				
Row	**Type of Structure**	**< 0.8g**	**0.8 - 1.2g**	**> 1.2g**
1	Concrete containment (post-tensioned and reinforced)	no	(a)*	(b)
2	Freestanding steel containment	(c)(d)	(c)(d)	yes
3	Containment internal structures	(e)	(f)	yes
4	Shear walls, footings and containment shield walls	(e)	(f)	yes
5	Diaphragms	(e)	(g)	yes
6	Category I concrete frame structures	(e)	(f)	yes
7	Category I steel frame structures	(e)	(h)	yes
8	Masonry walls	yes	yes	yes
9	Control room ceilings	(i)	(i)	yes
10	Impact between structures	no	(j)	yes
11	Category II structures with safety-related equipment or with potential to fail Category I structures	(k)	yes	yes

3.1.3 Structural Evaluation Criteria for Plants with GMRS Sa Less Than 0.8g

All U.S. operating nuclear plants have submitted GMRS values to the NRC. Based on the review of the industry GMRS submittals and the NRC responses [13], 21 plants screen out of having to conduct a review of the SFPs. Of the remaining 41 plants, 31 plants have GMRS peak spectral acceleration (5% damping) values are below the 0.8g peak spectral acceleration threshold value (Figure 3-3).

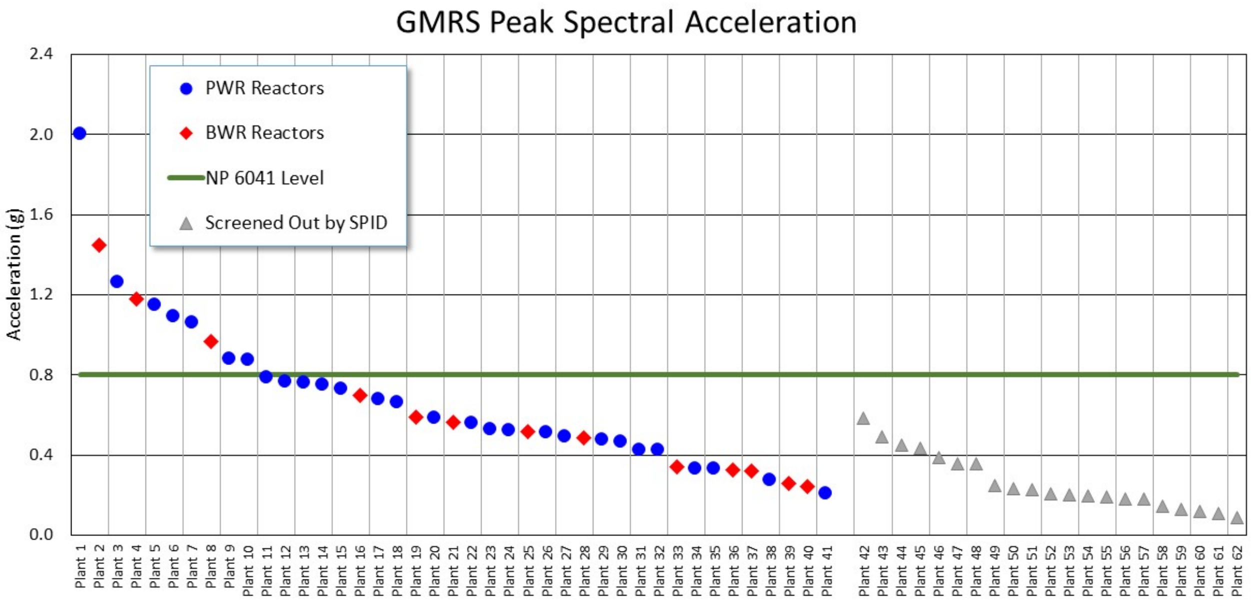

Figure 3-3
GMRS Peak Spectral Acceleration Comparisons to 0.8g Ground Spectral Acceleration Threshold for U.S. Plants

Thus, based on the criteria in Table 3-2, 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 by verifying that:

- The GMRS is less than or equal to the 0.8g spectral acceleration capacity level from column 1 of Table 3-2
- The structure housing the SFP was designed to an SSE of at least 0.1g
- The structure load path to the SFP consists of some combination of reinforced concrete shear wall elements, reinforced concrete frame elements, post-tensioned concrete elements and/or structural steel frame elements
- The SFP structure is included in the Civil inspection program in accordance with the NRC Maintenance Rule (10 CFR 50.65) [14]

While not required by the checks in EPRI NP-6041 [10] for the low ground motion site reviews (column 1 of Table 3-2), a review of the potential for out-of-plane response was conducted. Three previous studies on the seismic capacities of SFPs were reviewed to determine the lowest HCLPF values associated with the out-of-plane response of the SFP walls and floors. The results of those studies indicate relatively high HCLPF values compared to the 0.8g peak spectral acceleration (PSA) value (or approximately 0.3g PGA) associated with the first column of Table 3-2:

- NRC SFP Scoping Study [15] results indicate HCLPF (for out-of-plane response) of 0.5g PGA
- NUREG 5176 [12] documents HCLPFs (for out-of-plane response) of 0.65g PGA and 0.5g PGA for Robinson and Vermont Yankee, respectively.

3.2 Spent Fuel Pool Non-Structural Evaluation

The focus of SPF evaluations in Section 7.0 of the SPID [2] 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 more than 1/3 of the spent fuel height within 72 hours. The non-structural considerations that could affect the ability of SFPs to maintain SFP inventory for 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) boil-off losses. This section also provides evaluation criteria for demonstrating that there will not be an uncovering of SFP inventory within 72 hours.

3.2.1 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 [12], focused on the seismic response of a BWR and PWR SFP. For the systems analyzed 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 boil-off 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, and perhaps as much as 7 days before fuel uncovering would occur [12]. 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 [12, Section 6.1].

Further, a 1989 NRC study (NUREG-1353) [11] 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 SFPs 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) [4], states that for 60 days after reactor shutdown for boil-off 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 4, Table 2-1, indicates the estimated time to heat up and boil-off SFP inventory down to 3 feet above top of fuel is 100 hours for PWR and 145 hours for a BWR.

More recently, a SFP Scoping study [15] was performed by NRC to continue its examination of the risks and consequences of postulated SFP accidents initiated by a low likelihood seismic event. The seismic event considered in the study was based on a central and eastern United States (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 U.S. plants with peak spectral accelerations (Sa) less than 0.8g (Figure 3-4).

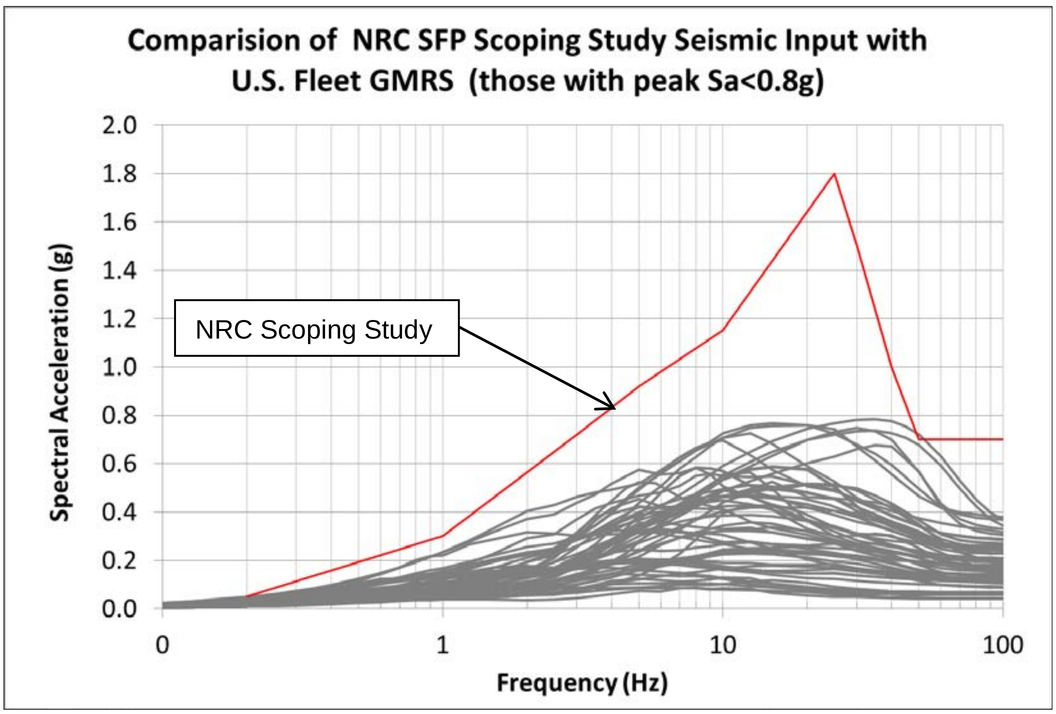

Figure 3-4
Comparison of NRC Scoping Study Seismic Input (red) with U.S. Fleet GMRS (Those with Peak Sa < 0.8g)

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 [15]. Based on detailed analyses, the maximum amplitude of SFP sloshing was found to be 20 inches (51 cm). 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 [15]. The refueling cavity gate and piping attached to the SFP were evaluated and found to be sufficiently strong and flexible enough to resist ground motion without leakage [15].

In addition to the aforementioned risk and consequence analyses, earthquake experience contributes to an understanding of 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 U.S. The previously mentioned 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 [15]. 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 [15], which is generally higher than the U.S. fleet GMRS PGAs in Figure 3-4. For the 20 BWR SFPs, there was no reported leakage of water, other than from seismic-induced sloshing. Sloshing effects are discussed in Section 3.2.3, below.

3.2.2 Treatment Within Near Term Task Force 2.1 Seismic

Section 7 of the SPID [2] 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.

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 [5]. In response to the NTTF Recommendation 2.3, licensees performed seismic walkdowns of the SFP to verify that the current plant configuration was 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 also addressed 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.

3.2.3 Non-Structural Evaluation Criteria for Plants with GMRS Sa Less Than 0.8g

Penetrations and Piping Connections

Section 7.2.1 of the SPID [2] 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.

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 (or elastomeric seals) that are not susceptible to large leak rates [8]. The refueling gate openings have narrow widths (short spans) and the gate structures themselves are comprised of stiffened steel plates.

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 hydrostatic pressure and thermal loads. As such, the designs of these gates have an inherently high seismic margin to failure and have a negligible seismic risk contribution. This is particularly true for the plants within the scope of this section where the peak Sa is less than 0.8g.

As a specific example of this ruggedness, the NRC Spent Fuel Pool Scoping Study [15] evaluated the fuel transfer gate for the referenced BWR Mark I design at Peach Bottom. 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 assumed high seismic event. 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 representative of the high seismic capacity of SFP gates.

As previously mentioned, refueling gates have seals for ensuring water-tight integrity. As a defense-in-depth measure, many plants have design features that help to limit the loss of pool inventory in the event of a gate failure. For most SFP designs, it is expected that a catastrophic seal failure will result in only limited water level loss due to either (1) limited volume of the adjacent cavity (e.g., refueling cavity), (2) redundant steel refueling gates, or (3) having a weir opening that has a bottom 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 the 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" [16]. 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 U.S. 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 3-3). 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). This finding supports the earlier statement that SFP refueling gate designs are dominated by hydrostatic pressure rather than seismic-induced pressures.

For SFP gate designs that make use of pneumatic seals (mostly PWR designs [8]), 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 psi, which is significantly higher than the maximum SRSS pressure of 8.1 psi in Table 3-3.

Table 3-3
Comparison of Spent Fuel Pool Wall Pressures at Mid-Height (Median Values for all U.S. Spent Fuel Pools 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	4.0	0.3	4.5	5.9
BWR SFPs	8.5	5.3	0.3	6.2	8.1

On the basis that (1) refueling gates (including seals) are inherently rugged components typically comprised of stiffened steel plates and (2) the observation that refueling gate design is dominated by hydrostatic demands rather than seismic, it is judged that typical SFP refueling gates will remain functional in cases where the GMRS peak Sa is less than 0.8g.

Piping

Piping connections to the SFP are required for the SFP cooling system discharge and suction lines. Most piping penetrations are well above the elevation of the fuel assemblies in the SFP. However, there are limited cases where SFPs have piping connections below about 10 feet above the top of the fuel assemblies. An industry survey of the U.S. plants screened-in to perform SFP confirmations, substantiated 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 [5].

SFP cooling and makeup piping systems are considered to be seismically rugged. Seismically designed (or seismically evaluated) piping is inherently rugged and has been shown in past seismic margin and seismic risk 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 [12], which exceeds the GMRS PGAs for each of the plants within the scope of this section (Figure 3-4). As a check at higher seismic acceleration levels, the NRC Scoping Study [15] evaluated piping connections for the SFP at Peach Bottom (peak Sa of 1.8g) and found that due to the very small resulting displacements / 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 [12], (2) the 2.3 seismic walkdowns included SFP piping systems, and (3) the detailed NRC SFP Scoping Study analysis, which found small relative displacements for an elevated SFP, there is high confidence that the SFP piping and penetrations will remain functional for plants with GMRS peak Sa less than 0.8g.

Siphoning of Spent Fuel Pool Inventory

Section 7.2.3 of the SPID [2] 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 [10], Table 2-4, identifies that passive valves are assumed to be rugged for peak spectral accelerations less than 0.8g. The NP-6041 criteria also require the evaluation of extremely large extended operators on valves attached to 2 inch (5.1 cm) or smaller piping. The NP-6041 screening criteria are applicable to the SFP cooling system.

Therefore, siphoning of SFP inventory is not a significant risk provided anti-siphoning devices exist in applicable piping systems and any extremely large extended operators on valves attached to 2 inch (5.1 cm) or smaller piping are evaluated.

Sloshing

Horizontal seismic demands on the SFP can induce vertical fluid motion, or sloshing. SFP sloshing is addressed in SPID Section 7.3.2 [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 of all of the U.S. NPP fleet screened in to perform SFP evaluations 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 SSE 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 [2] equations, the median slosh height is calculated to be 3.7 feet (1.1 m). Assuming a minimum free-board of 1 foot (0.3 m), this corresponds to a conservative estimate of 2.7 feet (0.8 m) 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 (12.2 m).

SPID Section 7.3.2 [2] acknowledges the conservatism in the slosh height analysis. As the GMRS of most U.S. 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, to estimate the approximate degree of conservatism, sloshing results were calculated (using the SPID equations) for the plant in the NRC Spent Fuel Pool Scoping Study [15]. While the SPID methodology yields sloshing frequencies that are comparable to those calculated in the detailed Scoping Study, the SPID-based sloshing heights are well above the Scoping Study sloshing heights. For the reference SFP, the SPID methodology predicts a sloshing height of 10 feet (3.0 m). However, the NRC Scoping Study, which used a more refined sloshing analysis based on finite element modeling, predicted a maximum sloshing height of approximately 2 feet (0.6 m). 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 by 32.4 feet (12.2 m by 9.9 m) and a depth of 38.7 feet (11.8 m) and has fundamental sloshing frequencies of 0.25 Hz and 0.28 Hz (each horizontal direction). The ground motion in this frequency (0.2-0.3 Hz) is comparable to the NRC Scoping Study (peak Sa of 0.1g) (Figure 3-5). Using the Fukushima-Daiichi Unit 2 parameters, the SPID [2] equation predicts a sloshing height of 10 feet (3.0 m); however, the estimates of actual sloshing amplitudes for Fukushima-Daiichi Unit 2 were approximately 2.6 feet (0.8 m) [15]. In the case of Fukushima-Daiichi Unit 2, the SPID equation estimates sloshing heights that are approximately 3.8 times higher than those observed. Despite the apparent conservatism in the SPID methodology, this method is used in this report for estimating SFP sloshing losses.

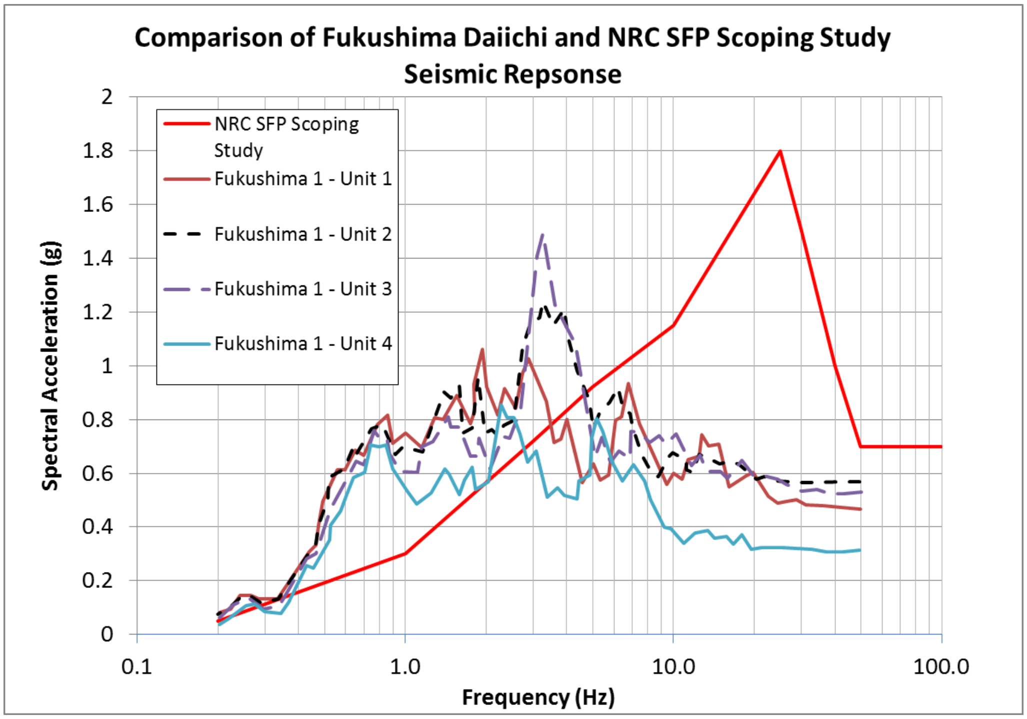

Figure 3-5
Horizontal Response Spectra (5% Damping): Fukushima Daiichi Units 1-4 (Foundation) and NRC Spent Fuel Pool Study (Free-Field) (Source: NRC Spent Fuel Pool Scoping Study)

Estimates of sloshing for plants with peak spectral accelerations less than 0.8g were computed using the industry SFP survey results, site-specific GMRS demands, and SPID [2] sloshing equations. These results, shown in Figure 3-6, indicate the distribution of sloshing losses and remaining water inventory. Despite losses due to sloshing, the remaining water inventory above the top elevation of fuel assemblies ranged from 16.8 ft to 29.2 ft (mean = 22.4 ft) for the plants analyzed. Accounting for allowed inventory losses down to 1/3rd the height of the fuel assemblies in accordance with SPID [2], the increased inventory height ranges from 21.8 ft to 34.2 ft (mean = 27.4 ft). The remaining water inventory after accounting for sloshing losses is used as the initial condition for boil-off losses which are discussed in the next section of this report.

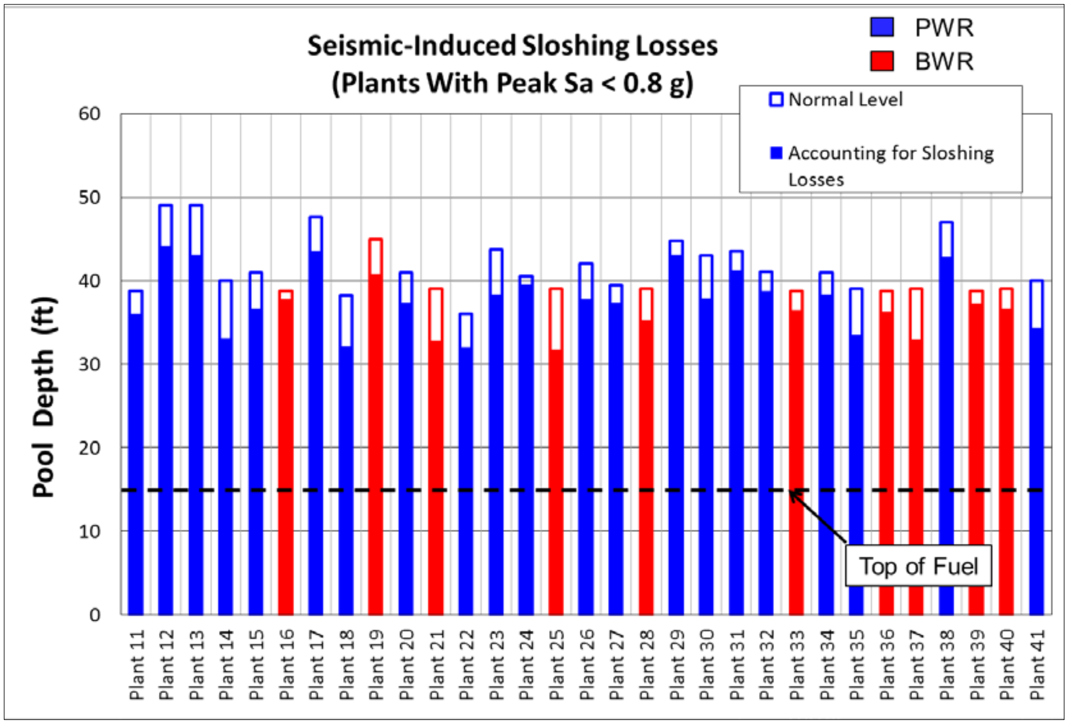

Figure 3-6
Seismic-Induced Sloshing Losses and Remaining Spent Fuel Pool Inventory for Plants with Peak Sa < 0.8g

Boil-Off Losses

The SPID [2] criteria includes an assessment of SFP boil-off inventory losses using equations in Appendix EE of EPRI 1025295, "Update of the Technical Bases for Severe Accident Management Guidance" [17]. These equations can be used to determine the length of time necessary to uncover more than 1/3rd of the height of the spent fuel.

Site-specific estimates of heat up and drain down times for plants with peak spectral accelerations less than 0.8g were computed using the industry SFP survey results, site-specific sloshing results, and Appendix EE of [17].

The SFP heat loads assumed in the analysis were based on realistic values obtained from several plants (Figure 3-7). A distribution of BWR and PWR units, ranging in core thermal power from 1,800 MW_t to 4,000 MW_t, were surveyed for representative SFP heat loads and outage durations. Results indicated (1) a strong correlation of SFP heat load with core thermal power, (2) plants only retain 30-40% of the core in the SFP after the outage, and (3) the typical outage periods last from 20-30 days. This data was used to estimate site-specific SFP heat loads corresponding to 20 days following shutdown, which corresponds to the shortest estimated outage duration. Additional information about the process used to estimate the heat loads is provided in Appendix B.

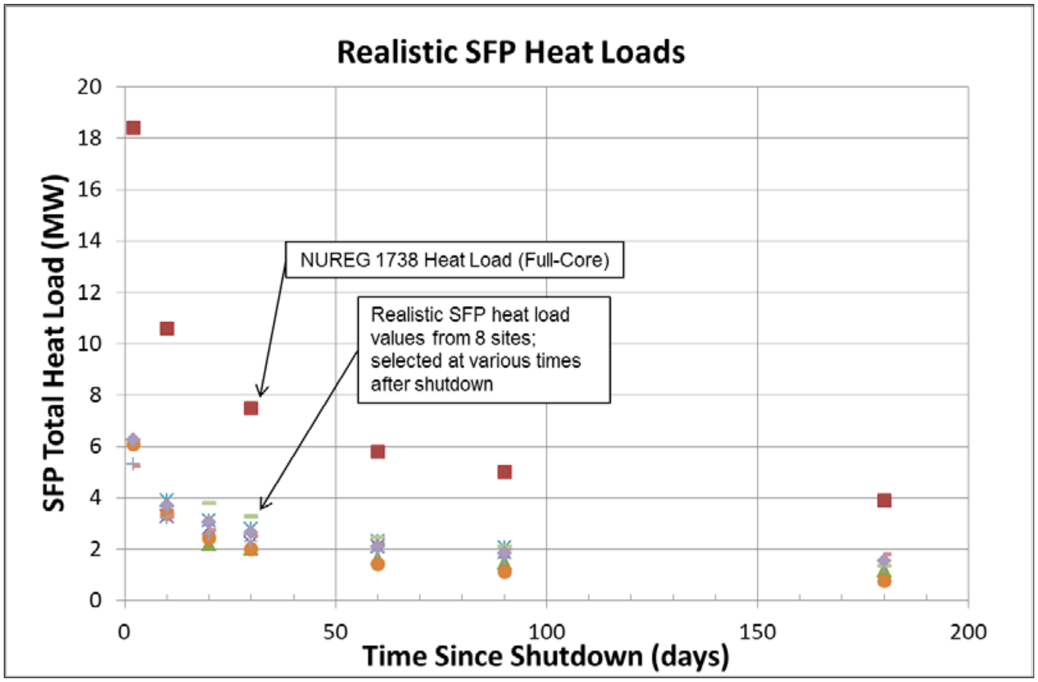

Figure 3-7
Comparison of Realistic and Full-Core Spent Fuel Pool Heat Loads

The boil-off analysis results indicate that all plants have significantly more than 72 hours before uncovering fuel. These results, shown in Figure 3-8, indicate the distribution of drain-down times to uncover the upper 1/3rd height of the fuel assemblies.

Site-specific results indicate that plants have a minimum of 149 hours and a maximum of 711 hours (mean=279 hours) before drain-down to the upper 1/3rd fuel assembly height (Figure 3-8).

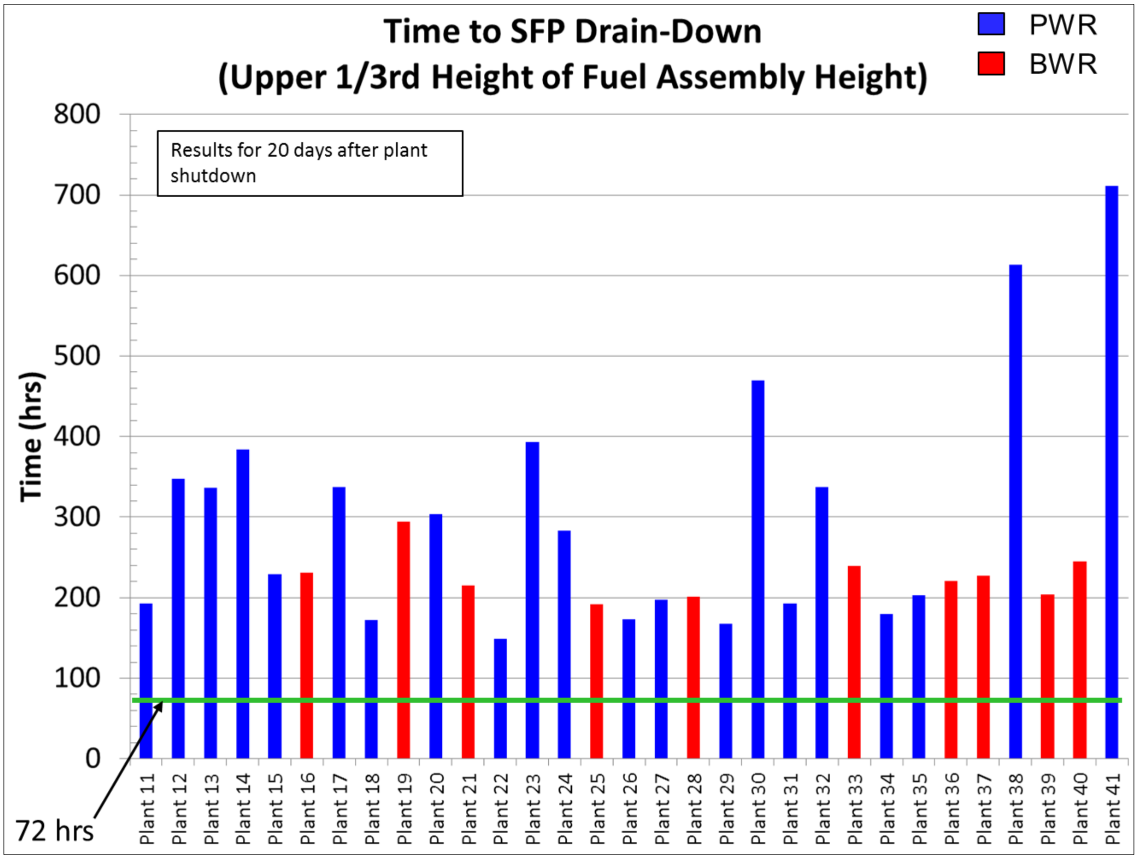

Figure 3-8
Spent Fuel Pool Drain-Down Results for Plants with Peak Sa < 0.8g

3.2.4 Summary of Non-Structural Evaluation Criteria

Table 3-4 provides a summary of the SFP non-structural evaluation criteria derived in Section 3.2

Table 3-4
Spent Fuel Pool Non-Structural Drain-Down Criteria

Potential Rapid Drain-Down Mechanism	Evaluation	Applicability Criteria
Scope of Evaluation	Evaluations in Section 3.2 are applicable to plants with GMRS peak Sa < 0.8g.	• Site-specific GMRS has a peak Sa < 0.8g.
Piping Connections	Past risk evaluations have found SFP piping, evaluated to SSE demands, to be rugged.	• Attached piping up to the first valve designed (or evaluated) to the SSE.
Fuel Transfer Gate	Gates and seals have rugged designs with adequate capacity for GMRS with peak Sa < 0.8g.	• No additional criteria.
Siphoning	Anti-siphoning devices are rugged and not a significant contributor to rapid drain-down. In accordance with NP-6041 Table 2-4 [10], in cases where active anti-siphoning valves are used, confirmation that extremely large extended operators (attached to 2-inch or smaller piping) be walked down to confirm lateral support.	• Anti-siphoning devices exist in applicable piping systems. • In cases where active anti-siphoning devices are attached to 2-inch or smaller piping and have extremely large extended operators, the valves should be walked down to confirm adequate lateral support.
Sloshing	Site-specific sloshing analyses show that inventory losses are minor. 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).	• Maximum pool dimension (length or width) is less than 125 ft. • SFP pool depth greater than 36 ft. • GMRS peak Sa < 0.1g at 0.3 Hz.
Evaporative Losses	Estimated time to heat up and boil-off and uncover more than 1/3 of the SFP fuel assemblies is more than 72 hours.	• SFP surface area greater than 500 ft^2. • Licensed core thermal power less than 4,000 MWt/unit.

3.3 Site-Specific Spent Fuel Pool Criteria for Low GMRS Sites

Sections 3.1 and 3.2 provide evaluation criteria that can be applied at sites where the GMRS peak spectral acceleration (Sa) is less than 0.8g. The following parameters should be verified on a site-specific basis to confirm that the evaluation criteria applies to the site.

Site Parameters

1. The site-specific GMRS peak spectral acceleration at any frequency should be less than or equal to 0.8g.

Structural Parameters

1. The structure housing the SFP should be designed using an SSE with a peak ground acceleration (PGA) of at least 0.1g.
2. The structural load path to the SFP should consist of some combination of reinforced concrete shear wall elements, reinforced concrete frame elements, post-tensioned concrete elements and/or structural steel frame elements.
3. The SFP structure should be included in the Civil Inspection Program performed in accordance with Maintenance Rule [14].

Non-Structural Parameters (the criteria below assumes the site and structural criteria above (items 1-4) are satisfied)

1. To confirm applicability of the piping evaluation in Section 3.2, piping attached to the SFP up to the first valve should have been evaluated for the SSE.
2. Anti-siphoning devices should be installed on any piping that could lead to siphoning water from the SFP. In addition, for any cases where active anti-siphoning devices are attached to 2-inch or smaller piping and have extremely large extended operators, the valves should be walked down to confirm adequate lateral support.
3. To confirm applicability of the sloshing evaluation in Section 3.2, the maximum SFP horizontal dimension (length or width) should be less than 125 ft, the SFP depth should be greater than 36 ft, and the GMRS peak Sa should be <0.1g at frequencies equal to or less than 0.3 Hz.
4. To confirm applicability of the evaporation loss evaluation in Section 3.2, the SFP surface area should be greater than 500 ft^2 and the licensed reactor core thermal power should be less than 4,000 MWt per unit.

Section 4: Conclusions

The NRC 50.54(f) letter [1] requested that a seismic evaluation be performed on the SFP to consider all seismically induced failures that could lead to rapid draining. The evaluation described in Section 3 addresses this requirement for plants with low-to-moderate seismic ground motions (peak spectral accelerations less than 0.8g).

The evaluation addresses both structural and non-structural aspects in accordance with the SPID [2]. Structural failure modes are evaluated using criteria in EPRI NP-6041 [10] as an alternate to the checklist provided in NUREG-1738 [4]. The non-structural failure modes that were considered were those that could affect the ability of SFPs to maintain SFP inventory for 72 hours. These included: (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.

A survey of industry plants was performed to gain an understanding of the ranges of important SFP parameters, such as wall and floor spans, thicknesses, reinforcement, support configuration, elevation above grade, depth, representative heat loads, etc.

Spent fuel pool structures are constructed with thick reinforced concrete walls which contribute to the seismic robustness. Past risk studies, including the NRC's Spent Fuel Pool Scoping Study, have demonstrated low seismically-induced failure frequencies and HCLPF values greater than 0.5g PGA. Earthquake experience from Japan has also provided examples of robust pool structures. 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, which is generally higher than the U.S. fleet GMRS PGAs. For these plants, there was no reported leakage of SFP water, other than from seismic-induced sloshing.

Structures supporting or housing SFPs are typically constructed with reinforced concrete shear walls, moment frames, steel frames, and post-tensioned girders. For plants with peak spectral accelerations less than 0.8g, these structures can be screened using criteria described in EPRI NP-6041 [10]. Piping systems connected to the SFP are seismically rugged as are fuel transfer gates, which are constructed with stiffened steel plates.

Site-specific calculations, based on GMRS demands, conservative estimates of sloshing losses, and realistic SFP heat loads, were performed. The estimated time to drain-down to the upper 1/3rd fuel assembly height ranged from 149 hours to over 700 hours. These estimates provide reasonable assurance that there will not be a rapid drain-down of the SFP leading to uncovering more than 1/3rd of the fuel in 72 hours and that additional make-up capabilities are not required to be credited.

This report provides screening criteria, which will enable plants to confirm that their plant parameters are enveloped by those considered in this evaluation.

SFP evaluation criteria for sites having peak spectral accelerations greater than 0.8g will be provided in a future revision to this report.

Section 5: References

1. NRC (E Leeds and M Johnson) Letter to All Power Reactor Licensees et al., Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) Requesting Recommendations 2.1, 2.3, and 9.3 of the Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident. March 12, 2012.
2. *Screening Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic*. EPRI, Palo Alto, CA: 2013. 1025287.
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4. NRC NUREG-1738, *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, February 2001.
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6. *PWR Spent Fuel Pool Risk Assessment Integration Framework and Pilot Plant Application*. EPRI, Palo Alto, CA: 2014. 3002002691.
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8. NUREG-1275, Vol. 12, *Operating Experience Feedback Report, Assessment of Spent Fuel Pool Cooling*, February 1997.
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10. *A Methodology for Assessment of Nuclear Plant Seismic Margin, Revision 1*. EPRI, Palo Alto, CA: 1991. NP-6041-SL.
11. NRC NUREG-1353, *Regulatory Analysis for the Resolution of Generic Issue 82, Beyond Design Basis Accidents in Spent Fuel Pools*, April 1989.
12. NRC NUREG/CR-5176, *Seismic Failure and Cask Drop Analyses of the Spent Fuel Pools at Two Representative Nuclear Power Plants*, January 1989.

14. NRC (Dean, W.), Final Determination Of Licensee Seismic Probabilistic Risk Assessments Under The Request For Information Pursuant To Title 10 Of The Code Of Federal Regulations 50.54(f) Regarding Recommendation 2.1 “Seismic” Of The Near-Term Task Force Review of Insights From The Fukushima Dai-ichi Accident, Letter to all Power Reactor Licensees et al., Washington, D.C., October 27, 2015.
15. The Maintenance Rule, 10 CFR 50.65, Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants. 56 FR 31324, July 10, 1991 (as amended).
16. *Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor [Spent Fuel Pool Scoping Study]*, June, 2013 (ML13133A132).
17. ACI-350.3-01, Seismic Design of Liquid-Containing Concrete Structures and Commentary.
18. *Update of the Technical Bases for Severe Accident Management Guidance*. EPRI, Palo Alto, CA: 2012. 1025295.

Appendix A: Spent Fuel Pool Data

In April 2015, the industry conducted a survey of key SFP parameters. The parameters considered were those relating to physical configuration of the pool (size, elevation above grade, and supporting structure) and structural characteristics (reinforcement percentage, steel and concrete strength, etc.). Understanding the range of these parameters is helpful in comparing to generic seismic capacity criteria (e.g., EPRI NP-6041 [10]) and in drawing conclusions from earlier studies regarding the robustness of SFP structures. The range of core thermal power was also assessed, as it is an important parameter in evaluating SFP heat loads.

The SFP survey requested design information from those plants that screened in for an SFP evaluation under NTTF 2.1. However, on the basis that the SFP survey collected detailed design information from over 60-percent of the SFPs across the U.S. NPP fleet (e.g., PWR and BWR Mark I, II, III), it is believed that the survey results are also representative of the those plants that did not screen in for an SFP evaluation.

The data presented in this appendix are presented in histogram format in order to easily visualize the distribution in results.

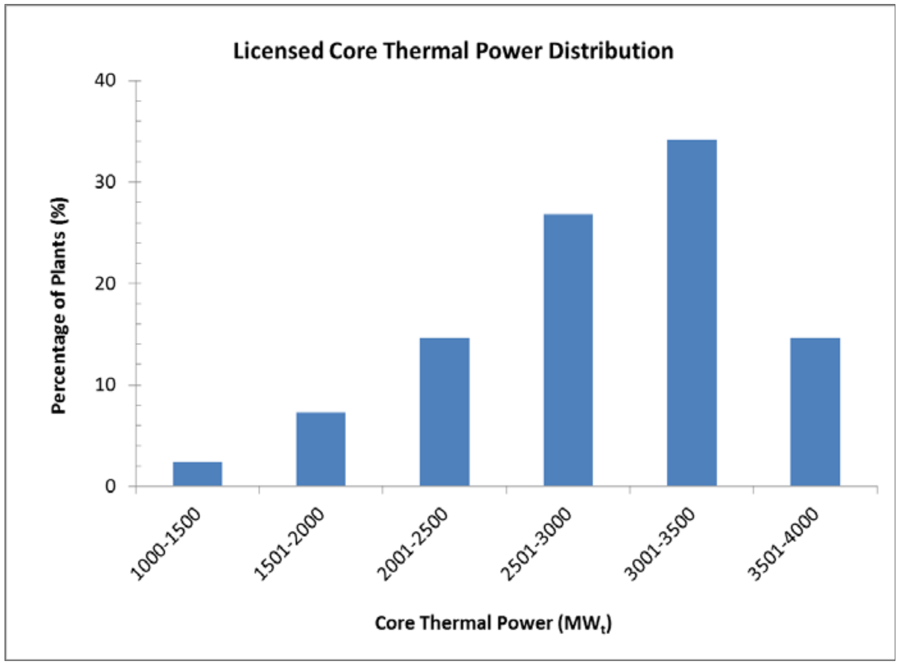

Figure A-1
Plant Licensed Core Thermal Power Distribution

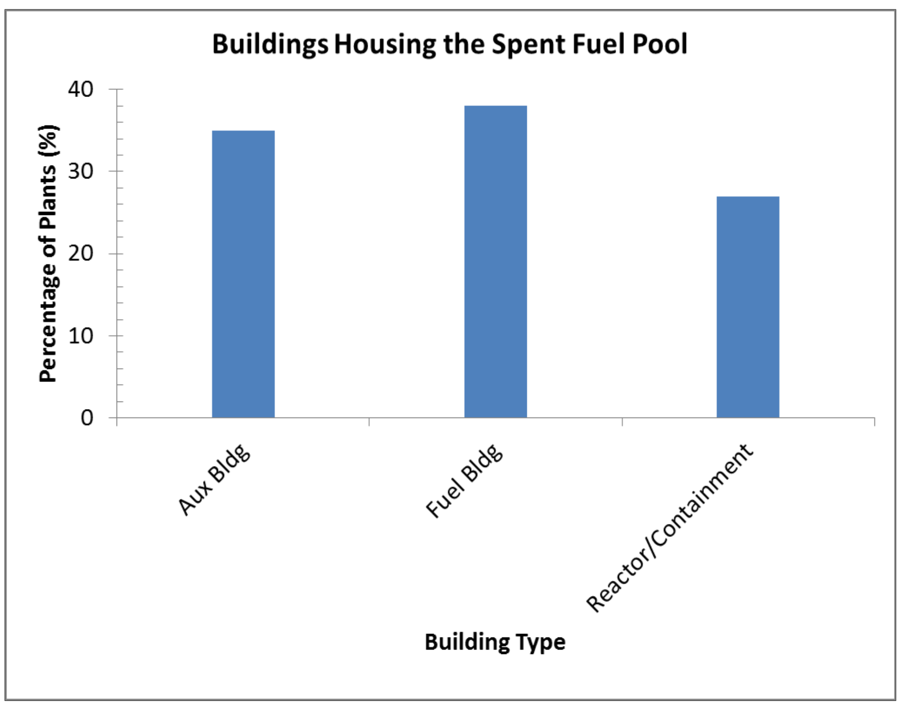

Figure A-2
Buildings Housing the Spent Fuel Pool

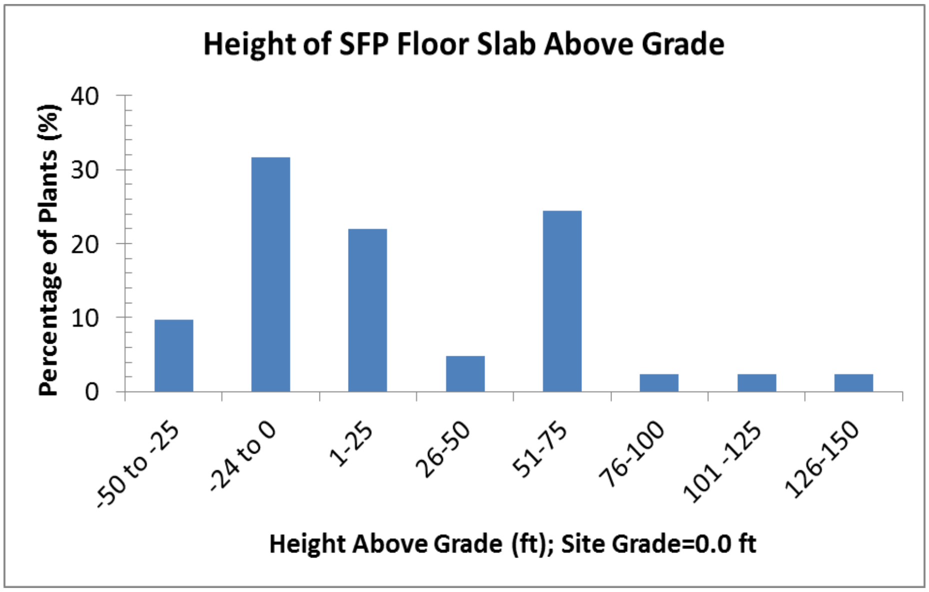

Figure A-3
Distribution of Height of SFP Floor Slab Above Grade Elevation

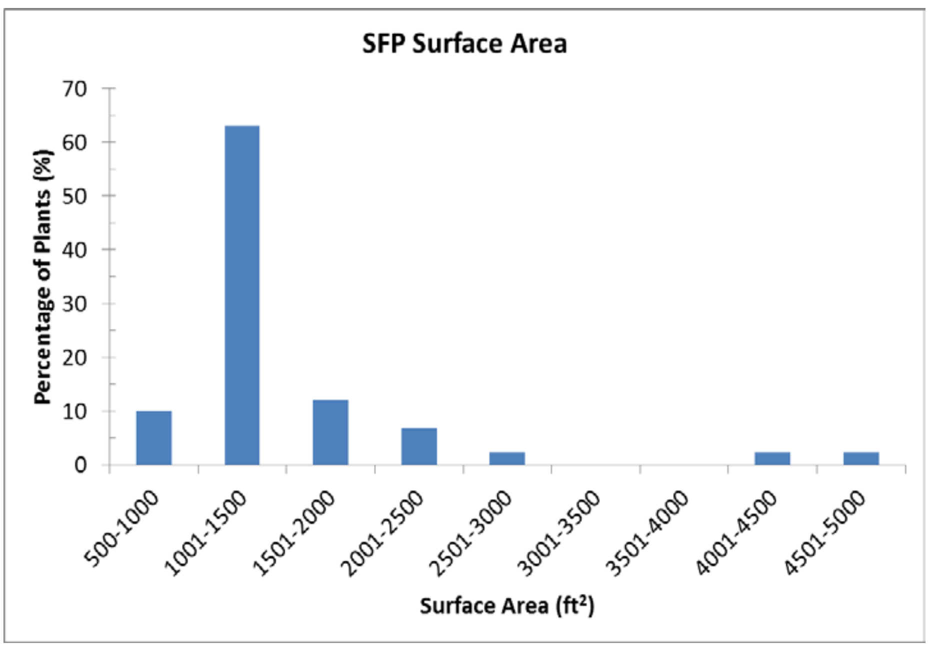

Figure A-4
Spent Fuel Pool Surface Area Distribution

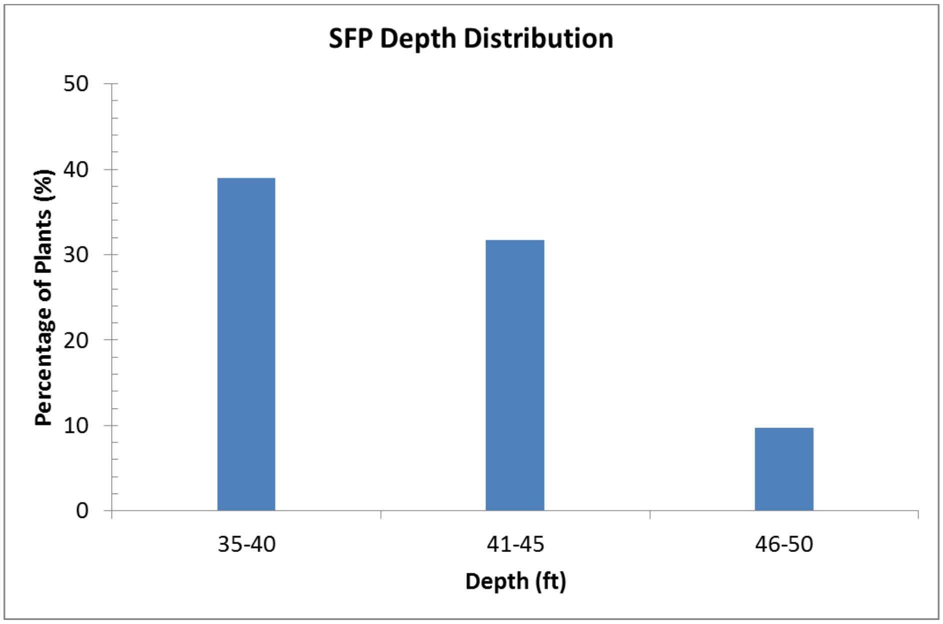

Figure A-5
Spent Fuel Pool Depth Distribution

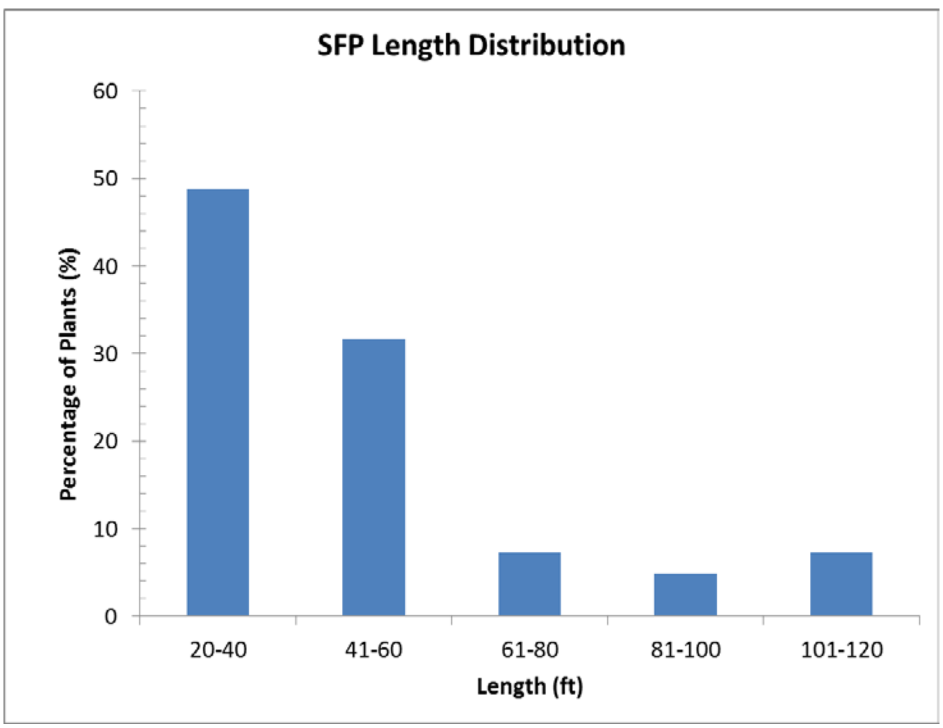

Figure A-6
Spent Fuel Pool Length Distribution

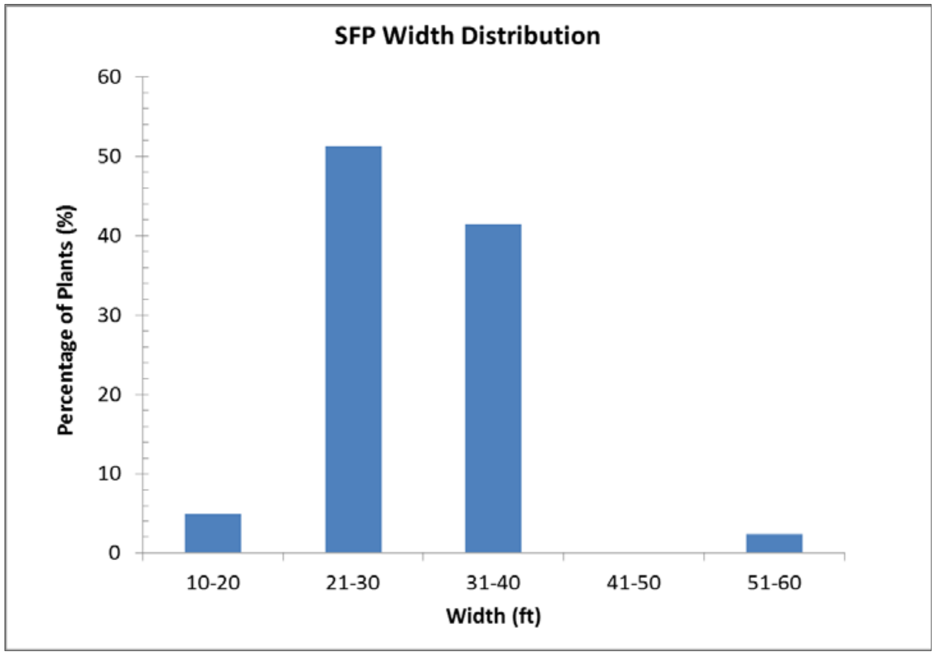

Figure A-7
Spent Fuel Pool Width Distribution

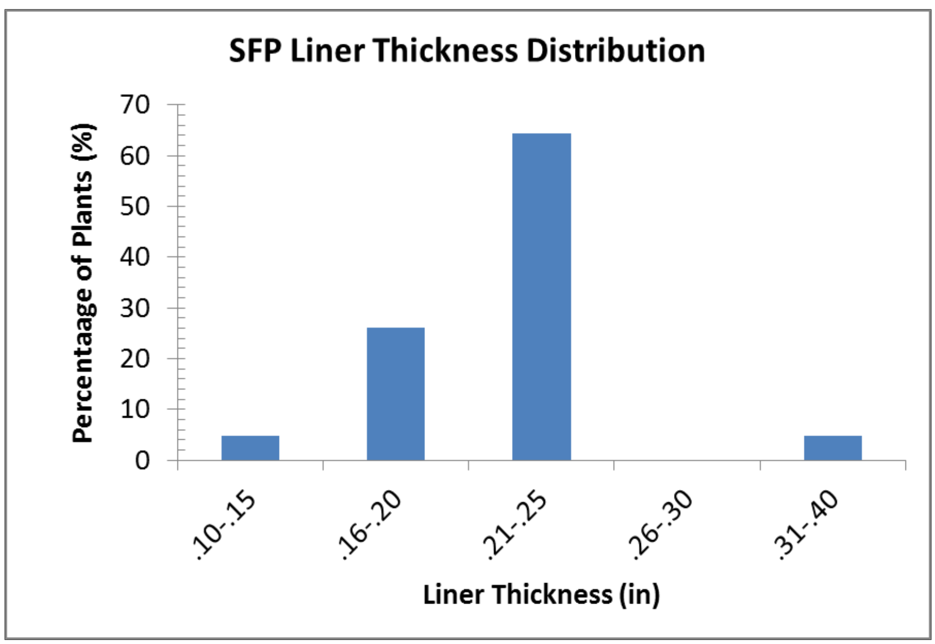

Figure A-8
Spent Fuel Pool Liner Thickness Distribution

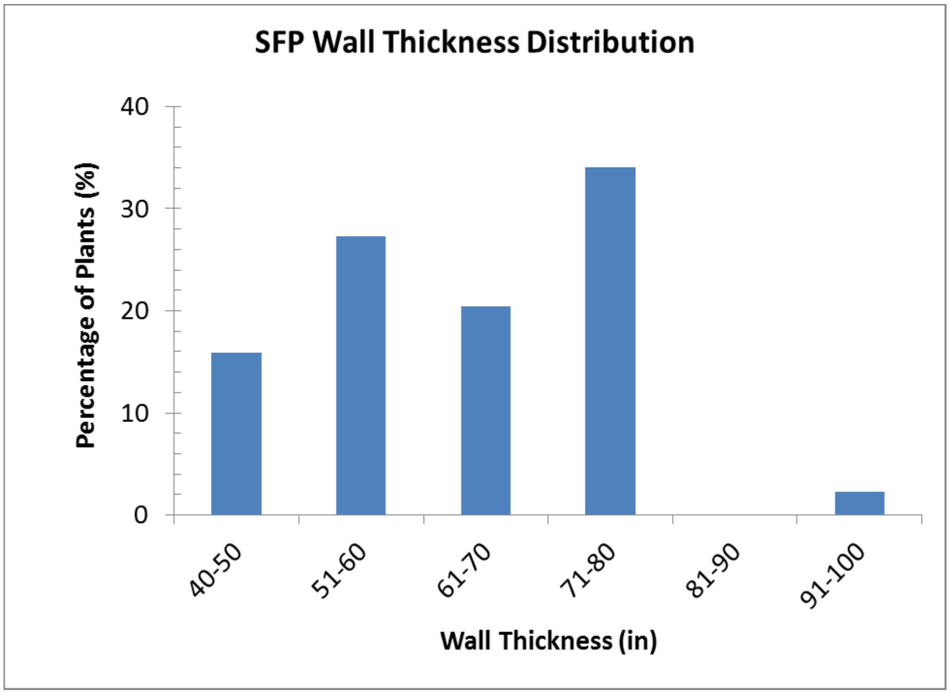

Figure A-9
Spent Fuel Pool Wall Thickness Distribution

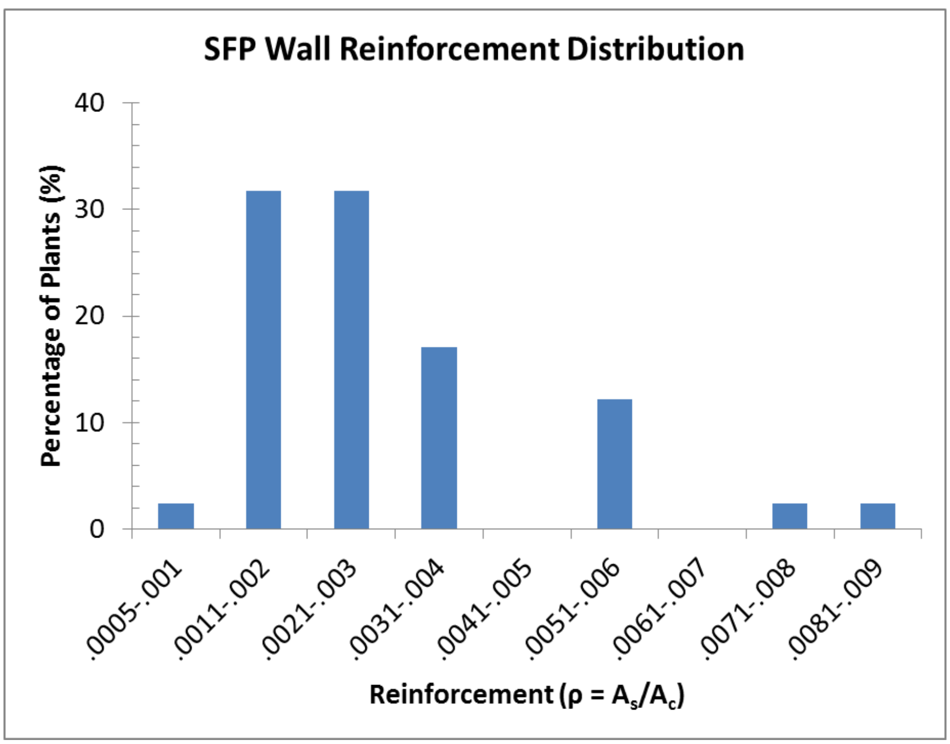

Figure A-10
Spent Fuel Pool Wall Reinforcement Ratio Distribution

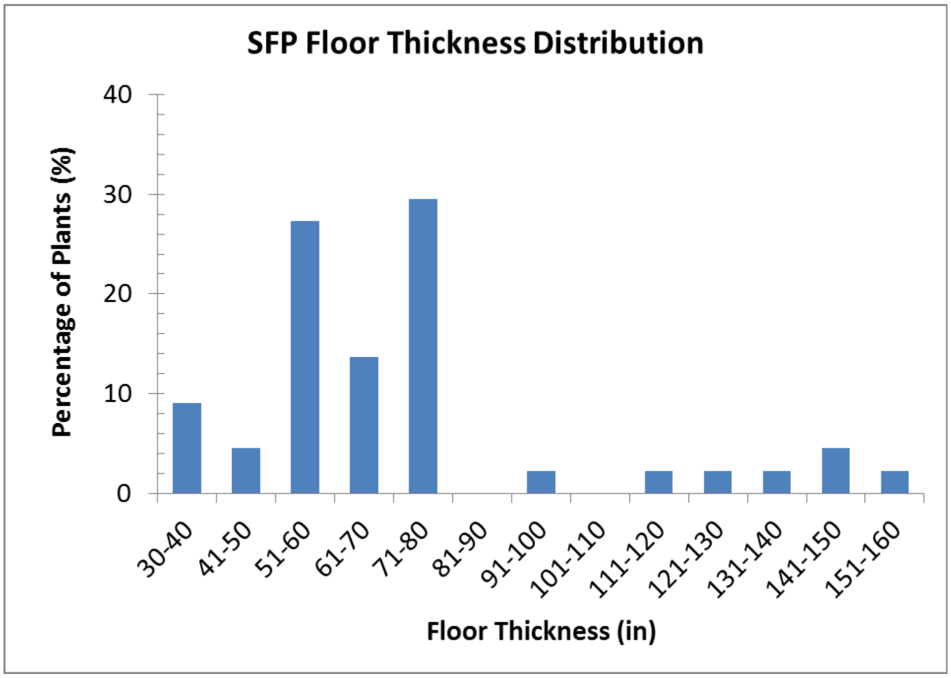

Figure A-11
Spent Fuel Pool Floor Thickness Distribution

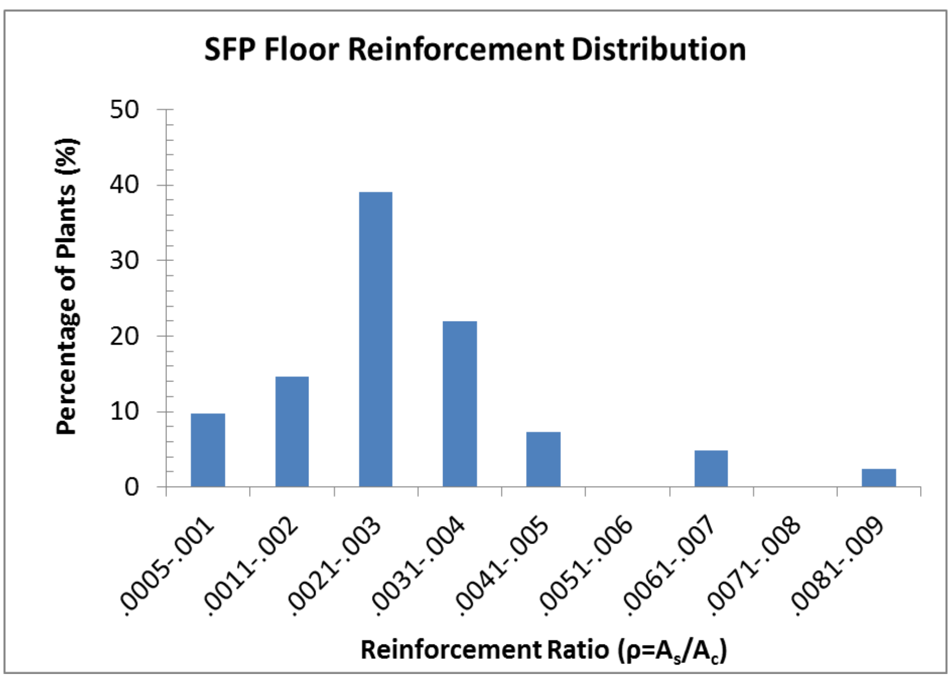

Figure A-12
Spent Fuel Pool Floor Reinforcement Distribution

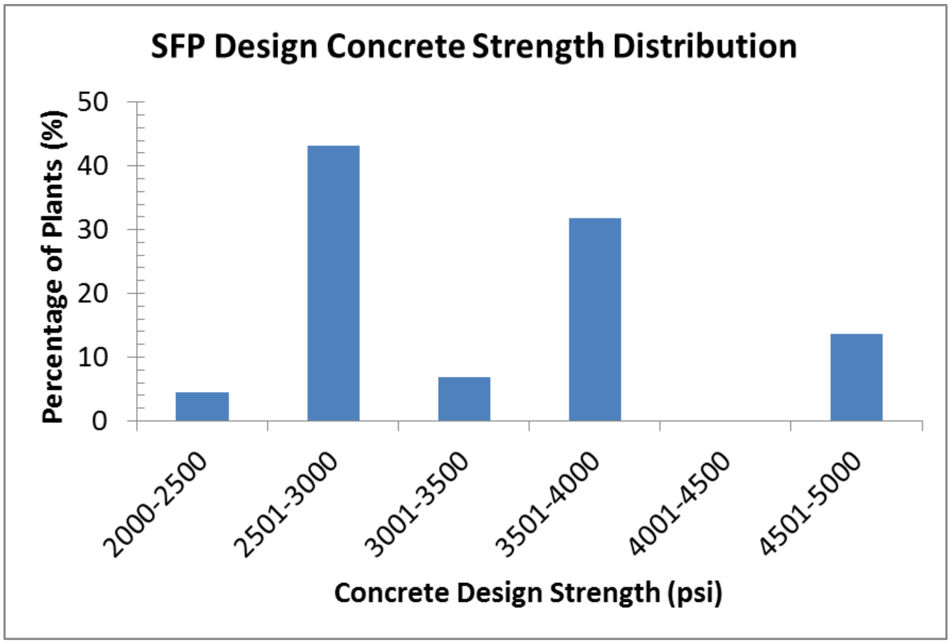

Figure A-13
Spent Fuel Pool Design Concrete Strength Distribution

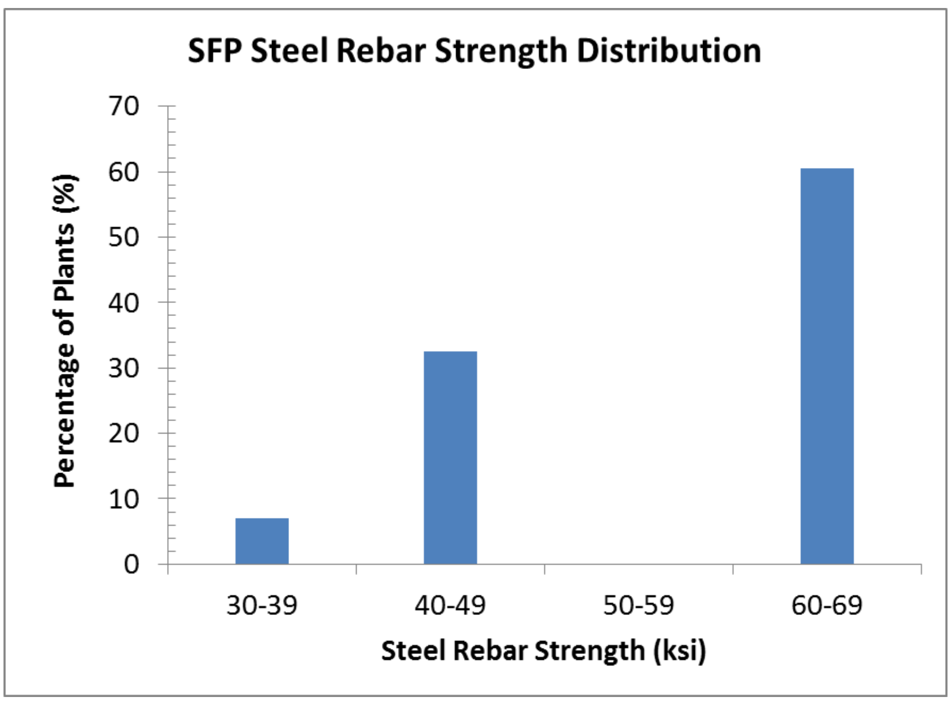

Figure A-14
Spent Fuel Pool Steel Rebar Strength Distribution

Appendix B: Sample Spent Fuel Pool Heat Up and Boil-Off Calculation

B.1 Purpose

The purpose of this example calculation is to illustrate the approach used to estimate site-specific SFP boil-off times in the event that (1) cooling and makeup systems are rendered in-operable and (2) water inventory is lost due to seismic-induced sloshing. The approach for estimating heat-up and boil-off times is consistent with Appendix EE to EPRI TR 1025295, "Severe Accident Management Guidance Technical Basis Report," [17] which is referenced as an acceptable method in the SPID [2] (Section 7.3.1). While representative, the selected SFP geometry (35 ft x 45 ft x by 40 ft) does not relate to a particular plant (Figure B-1). Site-specific calculations (Figures 3-6 and 3-8) make use of realistic SFP heat loads (based on survey results from several plants) and site-specific seismic demands based on respective GMRS motions.

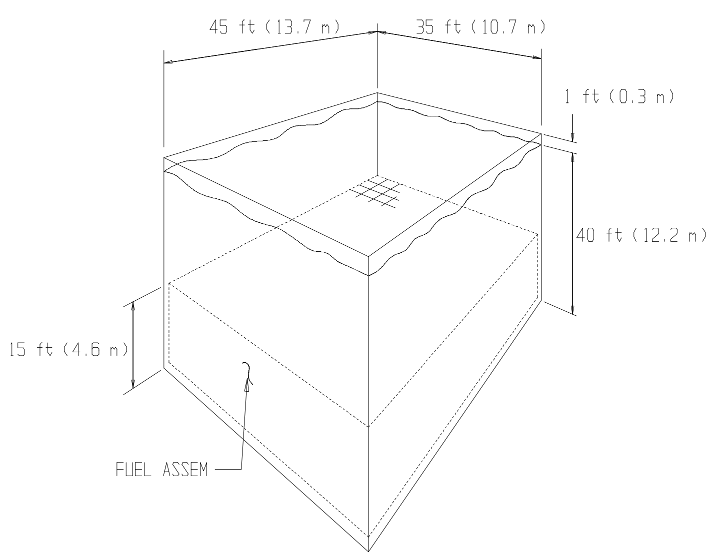

Figure B-1
Example Spent Fuel Pool Geometry

B.2 Assumptions

The following assumptions are used in this example calculation:

- Licensed reactor core power = 3,000 MWt
- Pool depth = 40.0 ft
- Pool freeboard = 1 ft
- Pool width = 35 ft
- Pool length = 45 ft
- Seismic-induced sloshing height = 4.0 ft (SRSS sloshing height in accordance with SPID [2])
- Fuel assembly and rack height = 15 ft
- Spent fuel volume = 1,779 ft^3 (EPRI 1025295 [17])
- Water specific heat (std value) = 1 BTU/lb/°F
- Initial pool temp = 100°F
- Boil temp = 212°F
- Water heat of vaporization, h_{fg} , = 970.3 Btu/lbm (at 212°F, P=1atm)
- Specific volume of water at 100°F (1 atm) = 62.04 lb/ft^3
- Specific volume of water at 212°F (1 atm) = 60.29 lb/ft^3

B.3 Sample Calculation

1. Estimate SFP heat load at 20 days after shutdown, Q, based linear interpolation of realistic heat load data.

   A distribution of BWR and PWR units, ranging in core thermal power from 1,800 MWt to 4,000 MWt, were surveyed for representative SFP heat loads and outage durations. Results indicated (1) a strong correlation of SFP heat load with core thermal power, (2) plants only retain 30-40% of the core in the SFP after the outage, and (3) the typical outage period lasts from 20-30 days. The SFP heat load is compared with the rated thermal power in Figure B-2. A linear curve fit was applied to that data, and an 84th percentile was used conservatively estimate the SFP heat load for any plant that was not specifically surveyed using the following equations.

   Q = 5.77E-4 (x) + 1.29 [Blue line in Figure B-2 below]

   x = 3,000 MWt (assumed rated core power for this example)

   Q = 5.77E-4 (3,000) +1.29 (MW)

   Q = 3.02 MW (10.31E6 Btu/hr)

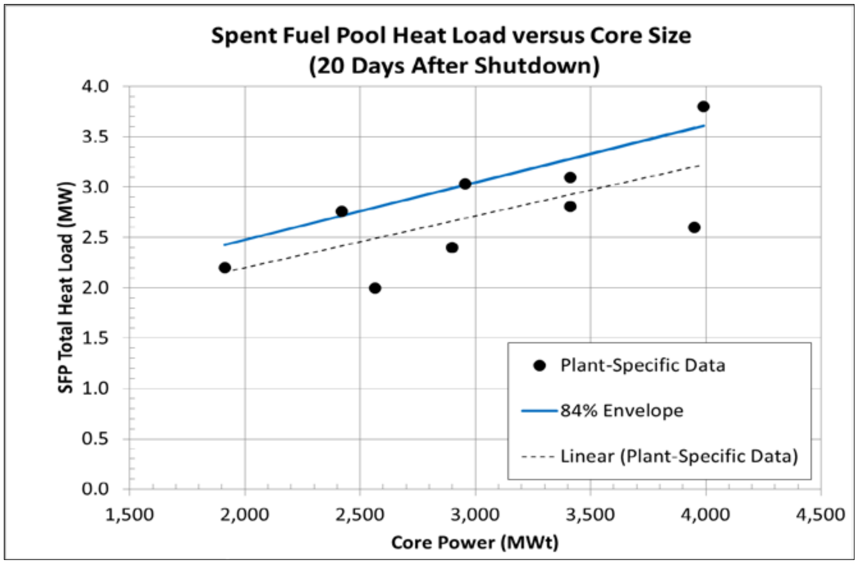

Figure B-2
Survey Results for Licensed Core Power Versus Spent Fuel Pool Heat Load

2. Estimate SFP water depth accounting for seismic-induced losses. Sloshing amplitudes are estimated in in accordance with SPID criteria. For this example, the sloshing amplitude is assumed to be 4.0 ft.

   SFP water depth (post-sloshing) = 40.0 ft - 4.0 ft (sloshing) + 1 ft (freeboard) = 37.0 ft

3. Estimate time to heat pool water to boiling, t

   Neglecting losses due to heat conduction and heat convection (conservative):

   $Q = \frac{mC_p\Delta T}{t}\ (Btu/hr)$; Ref EPRI TR1025295, Equation EE-6 [17]

   $t = \frac{mC_p\Delta T}{Q}\ (hr)$

   Where:

   t = time to boil (hr)

   Q = heat input (Btu/hr)

   m = mass of pool water (lbm)

   C_p = specific heat of water = 1 BTU/lb/°F

   ΔT = temperature rise (°F)

SFP water volume = (pool length • pool width • water depth) - spent fuel volume

SFP water volume = (45.0 ft • 35.0 ft • 37.0 ft) - 1,779 ft^3 = 56,496 ft^3

m = 56,496 ft^3 • 62.04 lb/ft^3 = 3.505E6 lb

ΔT = boil temp - initial temp = 212°F - 100°F = 112°F

t = (3.505E6 lb)(1 BTU/lb/°F)(112°F)/(10.31E6 Btu/hr)

t = 38.08 hr (time to boil)

4. Estimate boil-off rate, H

   H = Q /(ρ_w • A_{sfp} • h_{fg}) ; Ref EPRI TR1025295, Equation EE-7

   Where:

   A_{sfp} = 35 ft • 45 ft = 1,575 ft^2

   ρ_w= 60.29 lb/ft^3 (@212°F)

   h_{fg} = heat of vaporization; 970.3 Btu/lbm (at 212°F, P=1atm)

   Q = 10.31E6 Btu/hr

   H = (10.31E6 Btu/hr)/(60.29 lb/ft^3 • 1,575 ft^3 • 970.40 Btu/lb)

   H = 0.112 ft/hr

5. Estimate time to boil-off to top of fuel assemblies:

   Depth above spent fuel = 37.0 ft - 15.0 ft = 22.0 ft

   T_{top} = 38.08 hr (heat up) + (22.0 ft)/(0.112 ft/hr) = 234.5 hrs

6. Estimate time to boil-off to upper 1/3rd of fuel assembly height in accordance with SPID Section 7:

   Depth above upper 1/3rd height = 37.0 ft - 10.0 ft = 27.0 ft

   $T_{upper\text{-}third}$ = 38.08 hr (heat up) + (27.0 ft)/(0.112 ft/hr) = 279.2 hrs

7. Conclusion

   This sample calculation, based on realistic SFP geometry, conservative seismic-induced sloshing losses, and realistic SFP heat loads indicated that there is significantly more than 72 hours before uncovering of spent fuel. For this example, the estimated time to drain-down to the top of the fuel assemblies is 234 hours. Similarly, the estimated time to drain-down to the upper 1/3rd fuel assembly height is 279 hours. The significant margin beyond 72 hours helps to provide confidence that there is adequate time to employ operator actions and mitigation strategies to maintain SFP cooling under extreme seismic events.

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