Section 7: Spent Fuel Pool Integrity Evaluation

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 prior to Step 5 in Figure 1-1.

This section provides guidance that may be employed in addressing this consideration for plant-specific evaluations.

7.1 Scope of the Seismic Evaluation for the SFP

The focus of the evaluation process described in this report is on elements of the SFP that might fail due to a seismic event such that draining of the SFP could result. This approach is intended to ensure that efforts to gain an understanding of potential seismic risks needed to respond to the 50.54(f) letter make the best possible use of available resources.

In developing guidance for the walkdowns associated with NTTF Recommendation 2.3 [46], the emphasis was on SFP connections whose failure could result in "rapid drain-down." The definition of "rapid drain-down" encompassesed failures that could lead to uncovering of irradiated fuel stored in the SFP within 72 hours of the earthquake [46]. This criterion is used for the evaluations under NTTF Recommendation 2.1 as well; that is, the evaluations consider possible failures that could lead to uncovering fuel stored in the SFP within 72 hours. Note that 72 hours is suggested as an upper bound of the time to be considered for this evaluation. The evaluation may be further limited to address only those failures that could drain the SFP in a shorter time if it can be shown that adequate measures are in place to provide SFP inventory makeup sooner. This could be justified if, for example, there is adequate instrumentation to provide indication of the status of the SFP, procedures exist to guide response by the operators, and makeup resources are available and are seismically rugged.

Failures that could conceivably lead to uncovering of irradiated fuel stored in the SFP would include the following:

Comment [AK1]: Plants for which the GMPE exceeds the SSE, but that screened from a risk-evaluation due to IPEEE did not demonstrate that their SFPs do not need further evaluation.

Comment [AK2]:
WE NEED TO DISCUSS ADDING A SENTENCE ABOUT HUMAN ACTIONS

[Section 7.1 provides guidance about how licensees can demonstrate that makeup systems have adequate seismic capacity. This guidance is high-level, and does not specifically point out the importance of discussing operator actions that may be required to provide SFP makeup. When crediting operator actions to provide SFP makeup, licensees should discuss relevant procedures and training, accessibility to plant areas needed to implement the actions, and coordination of the SFP-related actions with other potential operator actions involving the reactors.]

Comment [AK3]: This sentence does not give the right impression. The public could read this as money being more important than safety.

Comment [AK4]: Confusing sentance

- A significant failure of the steel-lined, reinforced concrete structure of the SFP, causing inventory in 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 the absence of adequate makeup) evaporation and boil-off could cause fuel to be uncovered within 72 hours.
- Extensive sloshing such that sufficient water could be lost from the pool and, as in the previous item, lead to uncovering of the 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.
- Tearing of the steel liner due to movement of fuel assemblies as a result of the earthquake.
- Failures that could lead to draining of SFP inventory when the pool and reactor are configured for refueling operations.

With regard to these possibilities, the evaluation may generally be focused on connected structures and systems that penetrate the SFP structure, rather than the basic structure of the SFP itself. The rationale for focusing the scope of the evaluation in this manner accounts for the following:

- Detailed assessments have been made of SFP structural integrity, including by the NRC on several structures, and these have found SFP structures to be reasonably rugged; and
- Even if the SFP were to experience a structural failure that led to draining of its inventory, there should still be an ability to provide makeup to the SFP at a sufficient rate to prevent sustained uncovering of the fuel.

Previous evaluations documented in NUREG-1353 [57], NUREG-1738 [47] and NUREG/CR-5176 [48] characterized the generally robust nature of the design of SFPs currently in use. NUREG-1738 further identified a checklist that could be used to conclude that a SFP would achieve a high very HCLPF. Evaluations reported in NUREG/CR-5176 [48] for two older plants concluded that "…seismic risk contribution from spent fuel pool structural failures is negligibly small." In addition, previous screening criteria for civil structures in EPRI NP-6041 [39] (e.g. Table 2-3) provide principles that would be helpful in evaluating the ruggedness of SFP structures. Either the checklist in NUREG-1738 should be used to demonstrate that the structure is sufficiently robust or another approach can be used if sufficiently justified.

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 [49]. If the

Comment [AK5]: This continues to give the impression that there have been more studies than actually occurred.

Comment [AK6]: What is this based on? This assertion is not supported by what has been provided.

Comment [AMK7]: **NEED TO DISCUSS.** It is not clear where this comes from or how it is justified.

liner were to fail, leakage rates would typically be limited to systems provided to accommodate water between the liner and the concrete SFP structure.

~~While some sloshing has been observed during, for example, the 2007 earthquake at Kashiwazaki-Kariwa in Japan, it did not result in significant loss of inventory.~~ Guidance related to ~~this aspect of the earthquake response~~the potential for inventory loss due to sloshing is provided in Section 7.3.2.

Comment [AMK8]: Kashiwazaki experienced a near-field earthquake. Close earthquakes generally have higher frequency motions. IAEA cameras have recorded sloshing of SFPs on many occasions. What do we know about Fukushima? I don't think one anecdotal case should be added.

Beyond the impact of possible failures on the cooling of the fuel stored in the SFP, for some plants the loss of inventory from the pool could cause flooding that could affect other systems. The assessment of flooding will be evaluated separately, as part of the response to a NTTF Tier 3 recommendation.

The remainder of this section outlines a process for identifying and evaluating features that could lead to draining of the SFP.

7.2 Evaluation Process for the SFP

The process for evaluating the SFP begins with the identification of any penetrations that should be considered. All penetrations should be identified and placed into one of the following three categories:

1. Those that are above the level of the fuel in the SFP;

2. Those that are at a level below the top of the fuel in the SFP; and

3. Those that may have the potential to siphon water from the SFP (most typically, the discharge line from the SFP cooling system).

The sections that follow provide guidance for addressing each of these categories. Figure 7-1 shows the general process for evaluating SFP penetrations.

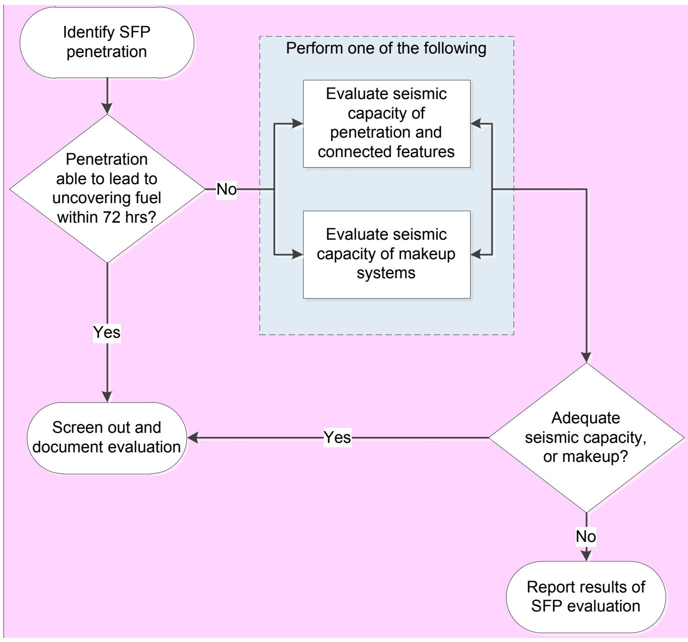

Figure 7-1
Basic Process for Evaluation of Potential Failures for SFP Penetrations

7.2.1 Evaluation of Penetrations above Top of Fuel

In most cases, penetrations in the SFP will be located above the top of the irradiated fuel. Assessment of these penetrations does not need to account for the potential that a failure would, in and of itself, result in draining the pool level below the fuel. Failures of these penetrations could, however, still affect SFP inventory. If the level in the pool could be lowered sufficiently due to a failure associated with a connection via such a penetration, the volume of water in the pool serving as a heat sink for the residual decay heat in the fuel assemblies could be reduced.

In this case, the evaluation should determine whether the potential failure could lead to uncovering the fuel within 72 hours. It is acceptable to evaluate either the seismic adequacy of the penetrations or the makeup capabilities to demonstrate overall SFP adequacy. Plants can choose which of these to address first (that is, the seismic capacity of the penetration or the availability of makeup adequacy). The evaluation should include the following.

- The criteria in NP-6041 [39] can be used to evaluate the seismic adequacy of SFP features.

Comment [AK9]: The first set of yes and no are reversed.
The arrows go both ways between the "perform one of the following" box and the "adequate seismic capacity" diamond. The arrows going into the box should be removed.

Comment [AK10]: TO BE DISCUSSED AT MEETING

The use of the GMRS as the main screening element for the seismic evaluations of the SFP in Section 7 seems to suggest that the GMRS also would be the load to compare to the seismic HCLPFs of SFP features (in case the makeup water provided would not be sufficient to maintain a threshold water level). Section 7.2.1 and Section 7.2.2 state that the criteria in NP-6041 [39] can be used to evaluate the seismic adequacy of SFP features. Section 7.2.3 says "The capacity of the anti-siphon feature can be assessed and the resulting HCLPF compared to the GMRS." Is it implicit in Section 7.2.1 and 7.2.2 that the seismic adequacy of the SFP features should be assessed by comparing their HCLPF to the GRMS or some other criteria in NP-6041 [39] are invoked in those two sections? **If the former applies should it be stated explicitly but if the latter applies, should these criteria be defined more precisely?**

Comment [AK11]: TO BE DISCUSSED AT MEETING

WHAT ABOUT MULTIPLE PENETRATION FAILURES DUE TO COMMON CAUSE?

In case of more than one penetration failure (either above or below the level of the irradiated fuel) are multiple penetration failures considered as well as correlation between failures (common cause failures) especially when estimating drainage rates and assessing the related capabilities to provide makeup water?
In case of a gate failure should the water level in the SFP be related to the volume of the cavity into which water from the SFP would flow (this might lead to a water level in the SFP above the level of the bottom of the gate under certain circumstances)?

- For a relatively large potential failure (such as that of the fuel transfer gate), the analysis should begin with an assumption that the level in the SFP drops to the bottom of the penetration at essentially the same time as when the failure occurred. For smaller failures, the time required to lower pool level to the bottom of the penetration may be significant (refer to Section 7.3.1 for guidance).
- The amount of water lost due to sloshing (refer to Section 7.3.2 for guidance) should be taken into account.

For a failure associated with a penetration above the top of the fuel, the loss of inventory through the break will be limited to the level of the penetration. Therefore, the makeup requirements are only those associated with matching decay heat. If it is necessary to consider makeup capabilities, the evaluation should confirm that the makeup systems have adequate seismic capacity to address the needs for restoring and maintaining SFP inventory.

Maintaining the SFP water level above about two-thirds of the height of the fuel assemblies in the pool should prevent overheating the fuel [49]. 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.

The makeup required to match decay heat if the SFP does not have fuel assemblies freshly removed from the reactor may be as low as 20 to 30 gpm. For an SFP that contains freshly offloaded fuel, the decay heat load may be significantly higher. Plants routinely maintain information needed to calculate the heat load in the SFP. Guidance for calculating the required makeup rates can be found in Appendix EE of the report documenting the technical bases for severe accident management guidance (SAMG) [49].

The evaluation should document the assessment of the penetrations, including the provisions for makeup to prevent uncovering the stored fuel. If limitations are identified with respect to the capability of makeup systems, these results should be reported as part of the SFP seismic evaluation.

7.2.2 Evaluation of Penetrations below Top of Fuel

The SFPs for plants operating in the United States are generally configured so that they do not have penetrations below the top of the stored fuel. The absence of penetrations lower in the pool inherently limits the potential to drain inventory sufficiently to begin uncovering fuel. It is possible; however, that some SFPs may have penetrations (e.g., drain lines) below the top of the stored fuel assemblies. There may also be some SFPs for which the bottom of the transfer gates is below the top of the fuel. A failure associated with such a penetration could drain the pool level below the top of the fuel.

The evaluation should include the following.

- The criteria in NP-6041 [39] can be used to evaluate the seismic adequacy of SFP features.
- For a relatively large potential failure (such as that of the fuel transfer gate), the analysis should begin with an assumption that the level in the SFP drops to the bottom of the penetration at essentially the same time as when the failure occurred. For smaller failures, the time required to lower pool level to the bottom of the penetration may be significant (refer to Section 7.3.1 for guidance).
- The amount of water lost due to sloshing (refer to Section 7.3.2 for guidance) should be taken into account.

The evaluation should confirm that the makeup systems have adequate seismic capacity to address the needs for restoring and maintaining SFP inventory. One consideration is that a significant failure low in the pool has the potential to drain water from the pool at a rate in excess of readily available makeup provisions. If the penetration is above about two-thirds of the height of the fuel assemblies in the pool, however, maintaining the water level at that point should prevent overheating the fuel [49]. So, for example, if the transfer gate extends down to 2 ft below the top of the fuel, its failure may be acceptable, even though it may not be possible to restore water level to above the top of the fuel.

The evaluation should document the assessment of the penetrations, including the provisions for makeup to prevent uncovering the stored fuel. If limitations are identified with respect to the capability of makeup systems, these results should be reported as part of the SFP seismic evaluation.

7.2.3 Evaluation of Potential for Siphoning Inventory

Although designs differ from plant to plant, for some SFPs the discharge line from the SFP cooling system extends down into the pool. Cool water is introduced low in the pool, and the suction line takes warm water from closer to the top of the pool. If the SFP cooling system were to experience a failure, it is possible that water could be siphoned back through the discharge line and out the break. To prevent such an occurrence, SFP cooling systems with this configuration are typically equipped with anti-siphon devices. If the anti-siphon device were to function improperly, the effect could be similar to a break below the top of the fuel, as addressed in Section 7.2.2. The process for evaluating failures in the SFP cooling system that might lead to siphoning inventory from the pool is outlined in Figure 7-3.

The anti-siphon devices are expected to be relatively rugged; for purposes of this evaluation, an evaluation should be performed to confirm that, if such a feature is needed to prevent siphoning water from the pool. If there are questions about the ruggedness of the feature, the evaluation may follow one of three paths, depending on what information is most readily available:

- The seismic capacity of the anti-siphon feature can be assessed and the resulting HCLPF compared to the GMRS;
- The SFP cooling system can be examined to determine if there are effective isolation features that could be used to terminate the loss of inventory; or
- An evaluation of makeup capabilities could be made, as for other breaks below the level of the fuel.

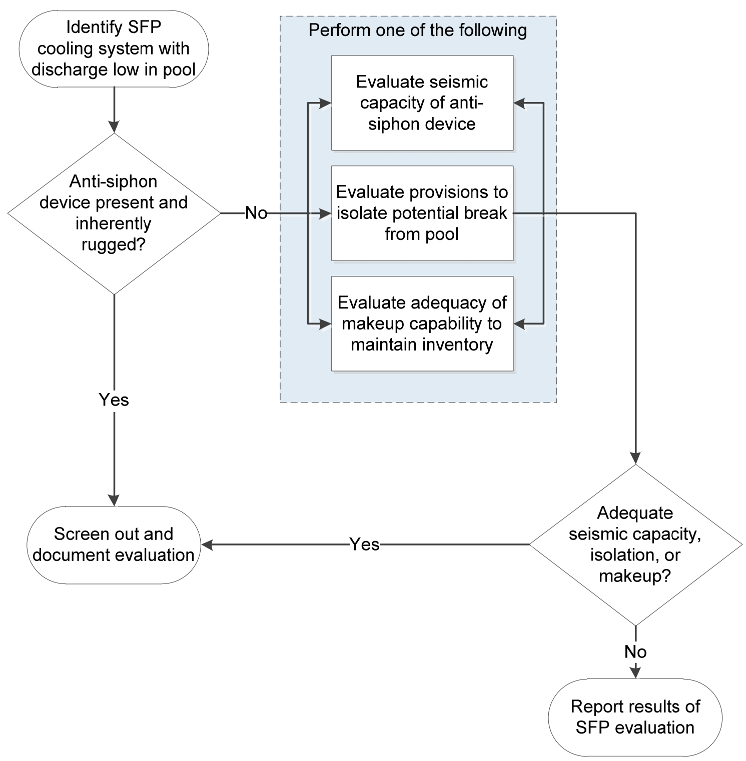

Figure 7-2
Basic Process for Evaluation of Potential Siphoning of SFP Inventory

In the very unlikely event that none of these options is viable, an evaluation can be made of the seismic capacity of the SFP system (analogous to the assessment called for in Section 7.2.2 for penetrations below the top of the stored fuel).

7.3 Guidance for Additional Evaluations

To accomplish the tasks outlined in the preceding section, additional evaluations may be required. This section provides guidance for the assessment of the timing of uncovering fuel and for addressing the effects of sloshing.

7.3.1 Drain-down and Evaporative Losses

The evaluation of whether fuel could be uncovered in the event of a failure of an interconnection at a level above the fuel can be accomplished in a relatively straightforward manner.

For failures of piping systems connected above the top of the fuel, a flow rate can be approximated using standard correlations, and assuming a driving head equivalent to the initial height of water above the top of the connection. This flow rate can be used to bound the time it would take lower level to that of the connection.

For larger connections (such as the gate used for transferring fuel during refueling), the level can be assumed to drop to the bottom of the connection nearly instantaneously.

Once level drops to the connection, a calculation can be made to determine the time it would take to boil off inventory sufficient to begin uncovering fuel in the absence of makeup flow. This time can be determined using the correlations provided in Appendix EE of the report documenting the technical bases for severe accident management guidance [49].

These times can then be used to determine (a) whether the top of the fuel could begin to be uncovered within 72 hours, and (b) if so, how much time would be available for the operators to effect adequate makeup to the SFP.

7.3.2 Assessment of the Potential for Sloshing

To support the assessments described in Section 7.2, an estimate is needed of the amount of water lost from the SFP due to sloshing. An initial, bounding assessment can be made using the approach described in this section.

The natural frequency (f_{c1}) for the fundamental convective (sloshing) mode of vertical oscillation of the water surface in a rectangular pool due to shaking input in either horizontal direction can be expressed as follows:

$$f_{c1} = (1/(2\pi)[3.16g / L) \tanh(3.16h / L)]^{0.5} \qquad \text{Equation 7-1}$$

where: L = pool length in the direction of shaking
h = water depth
g = gravity

Next, the slosh height (h_{s1}) for the fundamental convective mode can be estimated from:

$$h_{s1} = \tfrac{1}{2}L(SA_{c1} / g) \qquad \text{Equation 7-2}$$

where: SA_{c1} = ½% damped horizontal spectral acceleration at the top of the pool wall at the frequency f_{c1} in the direction of motion

In order to account for higher convective modes of sloshing and nonlinear sloshing effects (more upward splash than downward movement) observed during stronger shaking, the theoretical slosh height predicted by Equation 7-2 may be increased by 20%. Thus, the total estimated slosh height becomes:

$$h_s = 0.6L(SA_{c1} / g) \qquad \text{Equation 7-3}$$

For a rectangular pool of length a in the x-direction, and width b in the y-direction, the slosh height due to x-direction shaking, and y-direction shaking can be computed independently by substituting a and b, respectively, into Equations 7-1 and 7-3. Next, the total slosh height (h_{st}) can be estimated from:

$$h_{st} = [h_{sx}^2 + h_{sy}^2]^{0.5} \qquad \text{Equation 7-4}$$

where: h_{sx} = slosh height due to x shaking
h_{sy} = slosh height due to y shaking

An upper bound estimate of the total volume V of water that might splash out of the pool can be estimated from:

$$V = (h_{st} - h_f)ab \qquad \text{Equation 7-5}$$

where: h_f = freeboard height of the wall above the top of the water

Note that this approach reflects that sloshing in a pool is a very low frequency phenomenon governed by either the peak ground displacement or the peak ground velocity of the ground motion. It is independent of the PGA of the ground motion.

While this approach is expected to produce a reasonable estimate of the slosh height, it is expected to produce a very conservative estimate of the volume of water displaced from the pool. It effectively assumes that a solid mass of water equivalent to the product of the splash height above the side of the pool and the pool area is lost from the pool.

This relatively simple calculation is adequate for purposes of estimating the loss of SFP inventory due to sloshing. For most scenarios, it is judged that this conservative estimate of the inventory lost due to sloshing will not have a significant effect on the estimate of SFP drain-down. If the inventory lost due to sloshing has a significant impact on SFP drain-down time, a more careful calculation may be required. Such a calculation would need to account for the time histories of a range of earthquakes, and is likely to require significant resources and a peer review.