Section 7: Spent Fuel Pool Integrity Evaluation

The 50.54(f) letter ~~also~~ 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~~, and the measures available to respond to such failures~~. 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" encompassed 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:

- 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 ~~and interrupt SFP cooling,~~ 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 ~~to interrupt SFP cooling~~ 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 integrity, including by the NRC, 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~~systems (including those associated with the FLEX capability) should be able to prevent serious damage to the stored fuel~~.

P~~With regard to p~~revious evaluations documented~~,~~ in NUREG-1353 [57], NUREG-1738 [47] and NUREG/CR-5176 [48] characterized the robust nature of the design of SFPs currently in use. NUREG-1738 ~~, and~~ identified a checklist~~inspection criteria~~ that could be used to conclude that ~~evaluate whether~~ a SFP would achieve a high very HCLPF~~should be expected to retain its integrity to a peak spectral acceleration of at least 1.2g~~. E~~Moreover, e~~valuations 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.

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 liner were to fail, leakage rates would typically be limited to systems provided to accommodate water between the liner and the concrete SFP structure. ~~<This aspect is still being investigated>~~

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~~may be necessary to evaluate sloshing for larger earthquakes~~. Guidance related to this aspect of the earthquake response is provided in Section 7.3.2.

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;

~~1.~~2. Those that are at a level below the top of the fuel in the SFP; and

~~2. Those that are above the level 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.

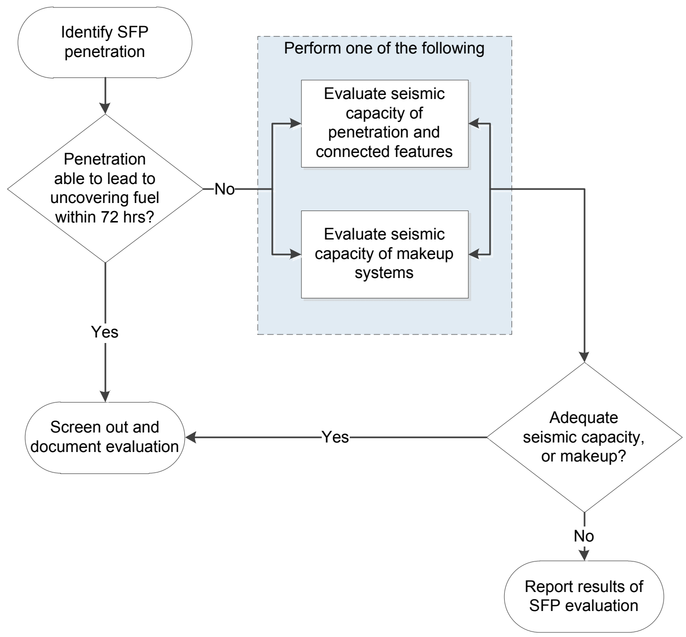

Figure 7-1
Basic Process for Evaluation of Potential Failures for SFP Penetrations

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.

- 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~~1~~ 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. ~~Moreover, while the transfer gates opened when moving fuel into and out of the SFP typically extend down to relatively near the top of the stored fuel, t~~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~~ if there were inadequate~~

~~makeup flow to the pool. A process for evaluating connections to the SFP with penetrations below the top of the fuel is outlined in Figure 7-1~~.

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. ~~The first step is to determine whether a failure of system connected through the penetration in question could drain water from the pool at a rate sufficient to lead to uncovering of the fuel within 72 hours. Note that, for a typical SFP, even an opening with an effective diameter of 1 in. at or near the bottom of the SFP could result in a drainage flow rate, at least initially, on the order of 100 gpm. For a nominal SFP containing approximately 400,000 gal, such a flow rate would be sufficient to lower level to below the top of the fuel within about 50 hours. Therefore, only very small penetrations could be eliminated based solely on the length of time it would take to lower the level in the pool below the top of the fuel.~~

~~If the failure of interest is that of a fuel transfer gate, the time it would take to drain down to the top of the fuel could be substantially less than 72 hours.~~

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~~Figure 7-1~~
~~Basic Process for Evaluation of Potential Failures for Penetrations below Top of Irradiated Fuel~~

~~Thus, the first step may be irrelevant for all but the smallest potential penetration failures. These very small penetrations should be screened from further analysis on the basis of the very long time it would take to drain the SFP to the top of the irradiated fuel. The evaluation of the penetrations should be documented for future reference.~~

~~If the penetration cannot be screened out, the next step is to determine whether provisions to make up to the SFP following an earthquake are sufficient to keep the fuel cooled. Two primary elements need to be considered together in performing this part of the evaluation:~~

- ~~The location of the penetration relative to the top of the fuel, and~~
- ~~The potential size of the failure.~~

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.

~~Makeup capabilities that might be considered would include normal plant systems (if they are seismically rugged) and capabilities installed as part of the FLEX initiative (which are required to be available for earthquake ground motions that exceed the design basis of the plant). Current requirements for FLEX capabilities call for being able to make up at a rate of at least 100 gpm, or to spray the fuel at a rate of at least 200 gpm for larger failures [50].~~

~~Lowering the level in the pool will also interrupt normal SFP cooling (even if the SFP cooling system itself is not affected by the earthquake). Therefore, makeup sufficient to match boil-off from the SFP must be provided. 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 three times as high. Plants routinely maintain information needed to calculate the heat load in the SFP. Straightforward 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].~~

~~Finally, timing comes into consideration. Actions to restore level and ensure continued cooling of the fuel need to be accomplished before level decreases to two-thirds of the height of the fuel assembly. If actions need to be taken in the vicinity of the SFP, however, the time may be much shorter. As the level in the SFP decreases, the shielding normally provided by the water also decreases. The time available before the SFP area would no longer be habitable may be much shorter than the time it would take to uncover the fuel.~~

~~Therefore, this portion of the analysis requires evaluating the following:~~

- ~~The rate at which makeup is needed to prevent draining water below the acceptable level (about two-thirds of the height of the fuel assemblies) and to match boil-off due to decay heat in the pool;~~
- ~~The capacity of makeup systems that would remain available following the earthquake;~~

- ~~The ability of the FLEX spray function to prevent damage to the fuel if level cannot be maintained;~~
- ~~The time available to effect these makeup provisions[1]; and~~
- ~~The feasibility of performing any manual actions required for establishing makeup, including the time available and the implications of reduced shielding in the SFP area.~~

~~If the evaluation of these aspects of responding to a failure concludes that makeup may not be sufficient or that it may not be possible to implement it in time, an assessment of the seismic capacity of the feature potentially subject to failure is needed. This assessment should establish the HCLPF value for the affected portion of the system and should compare the estimated HCLPF to the GMRS.~~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 c~~w~~ould ~~essentially~~ be similar~~equivalent~~ to a break below the top of the fuel, as addressed in Section 7.2.2~~1~~. T~~hus, t~~he 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~~made~~ 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 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

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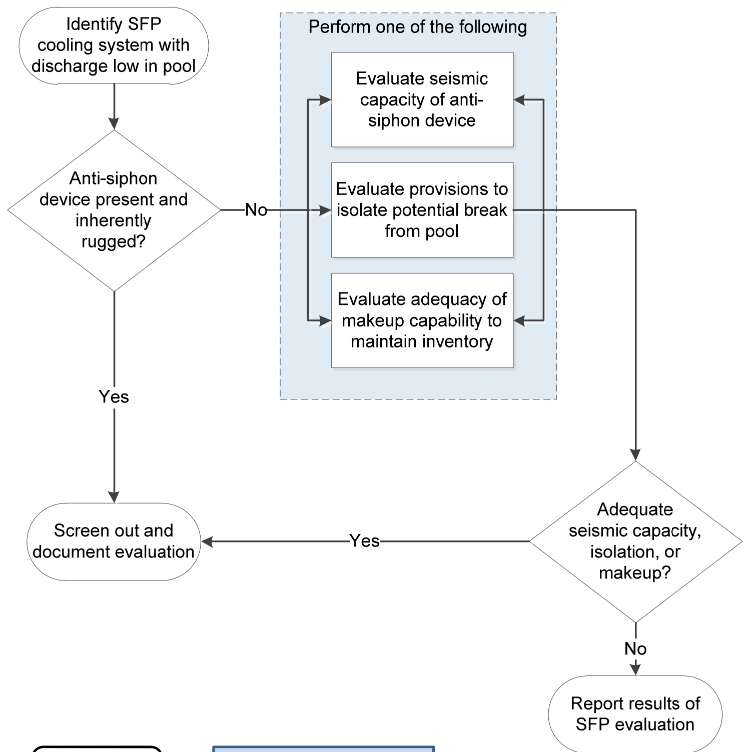
~~[1] Note that the estimation of time available should account for the possibility that a portion of the inventory in the SFP will be lost at the outset due to sloshing. This is addressed in Section 7.3.2.~~

- An evaluation of makeup capabilities could be made, as for other breaks below the level of the fuel.



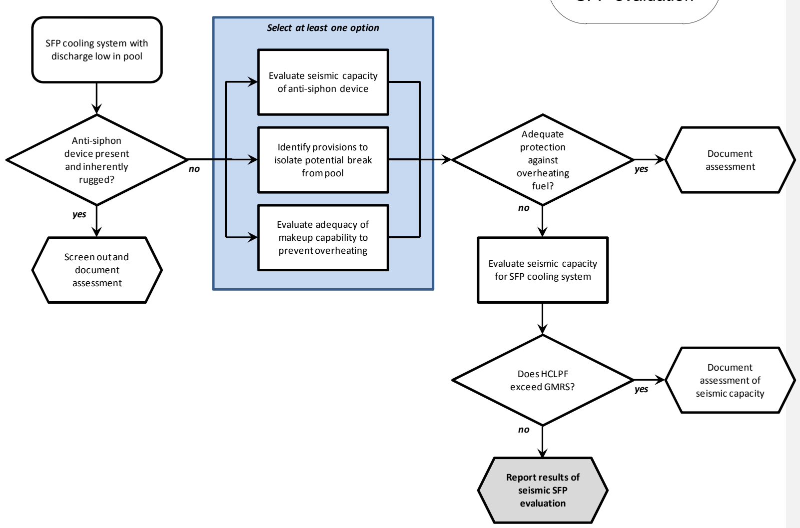


Figure 7-2
Basic Process for Evaluation of Potential Siphoning of SFP Inventory

~~Note that, even if the break in the SFP cooling system could stop the loss of inventory from the SFP, it would still be necessary eventually to establish makeup to the SFP because of the interruption of the cooling function.~~

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~~1~~ 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 ~~timing~~ 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:

$$h_{s1} = ½L(SA_{c1} / g) \qquad \text{Equation 7-2}$$

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~~may be~~ adequate for purposes of estimating the loss of SFP inventory~~the timing associated with pool draindown~~ due to sloshing. For most scenarios~~possible penetrations~~, it is judged that thise conservative estimate of the inventory~~volume~~ lost due to sloshing will not have a significant effect on the estimate of SFP drain-down~~the time it takes to drain the pool and to boil off inventory to the top of the stored fuel~~.

If ~~for a penetration into the SFP of a particular size and at a particular depth below~~ the inventory~~water the volume~~ lost due to sloshing has a significant impact on SFP drain-down time~~the timing of scenarios involving uncovering and overheating of stored fuel~~, 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. ~~These more extensive calculations may also be needed to support later evaluations of flooding induced by an earthquake. Such would be the case if differences in the volume of water lost due to sloshing could affect which equipment could be subjected to flooding.~~