Thermal-Hydraulic Analyses in Spent Fuel Pool Probabilistic Safety Assessment

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Abstract: Simplified thermal-hydraulic analyses are typically performed to support the human reliability analysis and development of the accident sequence models in the spent fuel pool (SFP) probabilistic safety assessment. The rate of coolant loss due to the siphoning effect in a loss-of-coolant inventory event as well as the operator action time windows for the loss-of-cooling and loss-of-coolant inventory scenarios can be determined using first-principle energy and mass balance calculations. Following a complete loss of the SFP cooling, the decay heat generated from the spent fuel will initially cause the SFP water temperature to increase. Once the boiling temperature is reached, the SFP water level will start decreasing due to boiloff. Rupture of a pipe section in the SFP cooling system with no anti-siphoning design could potentially lead to a large coolant loss due to the siphoning effect. If the piping component friction losses are conservatively neglected, the maximum, initial rate of coolant loss estimated due to the siphoning effect could be substantially greater than the realistic flow rate of coolant loss with the consideration of piping component friction losses. Following a loss of SFP inventory event, the SFP water level will decrease continuously. When it drops to below the cooling system suction strainer, the SFP heat removal function will be lost, and the water temperature will start increasing. For a small leak, the rate of SFP level decrease is smaller and there is more time for water temperature increase before the water level dropping to the top of active spent fuel and termination of the leak when the SFP level drops to below the opening of the SFP cooling return line distribution header. For a large leak, the SFP water level could drop rapidly to the top of active spent fuel or leak termination level before the SFP water boils.

1. INTRODUCTION

To support the human reliability analysis (HRA) and development of the event sequence models in the spent fuel pool (SFP) probabilistic safety assessment (PSA), thermal-hydraulic analyses of selected, representative event scenarios must be performed. To evaluate such model parameters as the break flow rate of a SFP loss of inventory initiating event, the time available for specific operator actions, or the number of mitigation equipment trains required to perform a safety-related function, these analyses can be performed based only on first principle energy and mass balance considerations, which are adequate to determine the broad event characteristics required to perform the HRA and develop the event sequence models with the needed accuracy. The results are considered reasonable approximations intended to reveal overall SFP response behavior and insights.

This paper describes the plant and SFP design input information used in the analyses, the derivation of the SFP heat load and the various heat load cases considered, the estimate of the break flow rate of the loss of SFP inventory initiating event, the analysis of the thermal-hydraulic time windows for the loss of SFP cooling events, and the analysis of the thermal-hydraulic time windows for the loss of SFP inventory events.

2. PLANT AND SFP DESIGN INPUT INFORMATION

The design and other relevant information used in the thermal-hydraulic analyses performed to support the SFP risk assessment may include the following:

- SFP and core
  - SFP volume
  - Number of fuel assemblies
  - Number of fuel rods in each fuel assembly
  - Fuel rod outside diameter
  - Fuel assembly length
  - Active fuel length
  - Weight of all fuel assemblies
  - Volumes of 1 fuel assembly, 1 core, 1+1/3 cores, fuel rack (assume 20% of core), all fuel assemblies and storage racks
- SFP water, temperature, and level
  - Total SFP net water volume
  - Cross section of SFP
  - Water volume below SFP cooling loop suction strainer
  - SFP normal water level
  - SFP low level alarm setpoints
  - SFP suction strainer level
  - Minimum SFP level, 3 feet above top of active spent fuel, top of active spent fuel
  - Lowest elevation of pipe with break for siphoning
  - Siphoning stop level, maximum possible siphoning depth
  - Initial SFP temperature
  - SFP high temperature alarm setpoints
- Initial power level
- Assumed SFP heat loads
  - SFP with freshly discharged full core (constant heat load)
  - Full core discharge with 150 hours of decay
  - SFP with freshly discharged full core (decreasing heat load)

The volume occupied by the fuel elements and fuel racks listed above are necessary for the estimate of the SFP water level.

3. SFP HEAT LOAD

At an example plant, the decay heat after plant shutdown was monitored for an equilibrium fuel cycle having been operated for 12 months at full power and having been shut down for 2 months for replacing one-third of the fuel elements in each refueling outage. The upper bound decay heat power fractions for the period between 1.04 days and 11.57 days after the plant shutdown was best fitted using the following expression [1]:

$$Q/Q_0 = 0.00661\ t^{-0.321} \qquad (1)$$

where Q_0 is the initial power level and t is the time after shutdown in days.

In the analysis of the thermal-hydraulic event time windows, the following three separate SFP heat load cases were postulated:

1. Case 1. This heat load case is assumed conservatively based on the heat load from a freshly discharged core after about 5 days following the reactor shutdown plus the decay heat from the spent fuel assemblies from previous fuel cycles that are still stored in the SFP. It is further assumed that this heat load remains constant for the entire event duration from the onset of initiating event.

   This is the most conservative heat load value because the earliest time all the fuel assemblies can be moved to the SFP is about 150 hours after the reactor shutdown. Also, by the time the plant is restarted and reaches the power operation configuration in which the SFP is isolated from the containment refueling cavity, the decay heat load in the SFP should be significantly less since more than 25 days may have elapsed after the reactor shutdown and the end of the previous fuel cycle. As such, of the three heat load cases, a constant heat load is a conservative representation of the SFP heat load.

2. Case 2. This heat load case is calculated from Equation (1) using a "t" value of 6.25 days (i.e., 150 hours) after reactor shutdown. Similar to Case 1, it is also conservatively assumed that this heat load remains constant for the entire event duration from the onset of initiating event.

   This heat load case is slightly optimistic at the beginning of the period immediately after the plant shutdown since it does not address the legacy fuel assemblies discharged into the SFP from the previous fuel cycles. However, this heat load is assumed to be constant; i.e., it does not decrease with time. Therefore, of the three heat load cases, this case is the lower bound at the beginning, but becomes the middle value for the longer-term period.

3. Case 3. The starting heat load value in this case is the same as that for Case 1. However, in this case, the heat load value is assumed to continue to decrease following the same decay function as Equation (1). Although this heat load is still slightly conservative, it is the most realistic heat load of the three cases.

4. BREAK FLOW RATE OF LOSS OF SFP INVENTORY EVENT

Due to the robustness of the SFP walls and slab, the analysis of the loss of inventory events typically focuses on failures of the systems interfacing with the SFP. As such, the loss of SFP inventory initiating event (i.e., loss of SFP inventory from leaks, breaks, or failures of piping or gates/seals) includes loss of SFP inventory events such as those resulting from configuration control errors, siphoning, piping failures, and gate or seals failures. Catastrophic structural failure of the SFP boundary that could result from seismic events, tornado-generated missiles, aircraft crash, heavy load drops, etc., is usually evaluated separately for their effects on the SFP. Identification of the system segments/equipment whose failure may cause a loss of inventory event should be performed systematically for possible scenarios of ruptures of pipes connected to the SFP leading to loss of inventory. This could occur, in particular, in pipe segments with no anti-siphoning protection.

At an example plant with a high level of protection against a large loss of coolant from the SFP, only one pipe segment was identified with no anti-siphoning protection. Rupture of this pipe section can only rely on closure of the associated check valves to prevent inventory loss. All other pipes interfacing with the SFP are designed with small boreholes in the pipes providing the anti-siphoning protection. As such, the only pipe sections with the potential for a large coolant loss from a pipe failure are the SFP cooling water return lines with their branch to the mixed bed ion exchange filter. The lowest elevation of the pipe section that has the potential to cause a large coolant loss is about 15 meters below the normal SFP water level. If a pipe rupture occurs at the lowest point in the section of the SFP cooling system return lines with no anti-siphoning design, the maximum water level decrease in the SFP due to the siphoning effect is actually less than 10 meters (i.e., decrease from the normal SFP water level to the opening in the distribution header for the SFP cooling loop return line), even though the lowest elevation inside the SFP is about 11 meters below the normal SFP water level. However, the elevation head for this coolant loss flow path is about 15 meters; i.e., the difference between the normal (or the actual) water surface and the elevation at the break location (at the lowest elevation point).

The maximum, initial siphoning flow rate through this leak path can be estimated in the following calculation:

$$P_1 + \frac{1}{2} \rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho g h_2 \quad (2)$$

Where

"1" denotes the elevation/location at the normal water level; i.e., water surface of the SFP.
"2" denotes the break elevation/location.

At location "1", the pressure (P1) is at the atmospheric pressure and flow velocity v1 is very close to 0. At the break location (location "2"), P2 is also at the atmospheric pressure. As such, the above equation reduces to:

$\rho g(h_1 - h_2) = \frac{1}{2} \rho v_2^2$, or $g(h_1 - h_2) = \frac{1}{2} v_2^2$
$h_1 - h_2$ = normal level – lowest elevation of the pipe segment with the break
Flow rate $Q = v_2 * A \cong 92$ l/s

The above calculation ignores the piping component friction losses (including losses at elbows/bends/turns, etc.) and the velocity at the water surface. So, it is the maximum, initial break flow rate that could possibly attain due to the siphoning effect. As the SFP water level decreases, the siphoning flow rate will also reduce due to the decreasing elevation head. A more detailed and rigorous evaluation of the siphoning flow rate with the consideration of piping component friction losses will likely show that the realistic coolant loss flow rate is much lower. However, for conservatism, the siphoning flow rate estimated in this manner can be used as the initial coolant loss flow rate in the scenario.

In summary, due to the lack of anti-siphoning device in the SFP cooling return line, a rupture at the lowest point in that pipe section can lead to a scenario of loss of SFP coolant from the SFP cooling return line due to the siphoning effect and result in a conservatively evaluated maximum, initial coolant loss flow rate of approximately 92 l/s. Without operator intervention, the SFP water level will decrease until the opening for the SFP cooling loop return distribution header is uncovered, which is even lower than the top of active spent fuel.

5. THERMAL-HYDRAULIC TIME WINDOWS FOR LOSS OF SFP COOLING EVENT

5.1. SFP Temperature Increase to Boiling

Following a complete loss of the SFP cooling event, the decay heat generated from the spent fuel assemblies stored in the SFP will cause the SFP water temperature to increase. Until boiling occurs in the SFP, the relationship between the decay heat generation and SFP water temperature increase can be described as follows:

$$\int_0^t Q(t)dt = V_0 \cdot \rho_l \cdot C_P \cdot [T(t) - T_0] \quad (3)$$

Where

$Q(t)$ = decay heat generation rate
$\int_0^t Q(t)dt$ = cumulative decay heat generated from time = 0 to time = t

V_0 = initial total volume of SFP water being heated up
ρ_l = density of water in the liquid phase
C_P = specific heat of water
T_0 = initial SFP water temperature
$T(t)$ = SFP water temperature at time = t

The left side of the above equation represents the cumulative decay heat generated from time 0 to time = t. The right side of Equation (3) represents the total energy required to heat up the pool of water with an initial volume of V_o at an initial temperature of T_0 to an elevated temperature of T. Equation (3) can be used to estimate the time to main control room (MCR) high temperature alarm, time to emergency control room (ECR) high temperature alarm, and time to boiling.

5.2. SFP Level Decrease

Once the SFP temperature has reached the boiling temperature, the SFP water level will start decreasing due to boiloff. Following the onset of boiling in the SFP, the relationship between the decay heat generation and the SFP water level decrease can be expressed as follows:

$$\int_{t_b}^{t} Q(t)dt = A_C \cdot [h_0 - h(t)] \cdot \rho_s \cdot H_v \quad (4)$$

Where

$Q(t)$ = decay heat generation rate at time = t
$\int_{t_b}^{t} Q(t)dt$ = cumulative decay heat generated from time of boiling (t_b) to time = t
A_C = SFP cross sectional area
h_0 = initial SFP level
$h(t)$ = SFP level at time = t
ρ_s = density of water at saturation under the STP condition (212°F)
H_v = water heat of vaporization

The left side of the above equation represents the cumulative decay heat generated from the time of boiling (t_b) to time = t. The right side of Equation (4) represents the total heat required to boil off the SFP water so that the SFP level will drop from the initial level of h_0 to the level at time = t; i.e., h(t). Equation (4) can be used to estimate the time to MCR low level alarm, time to ECR low level alarm, time to SFP cooling system suction strainer level, time to 3 feet above the top of the active spent fuel, and time to top of the active spent fuel.

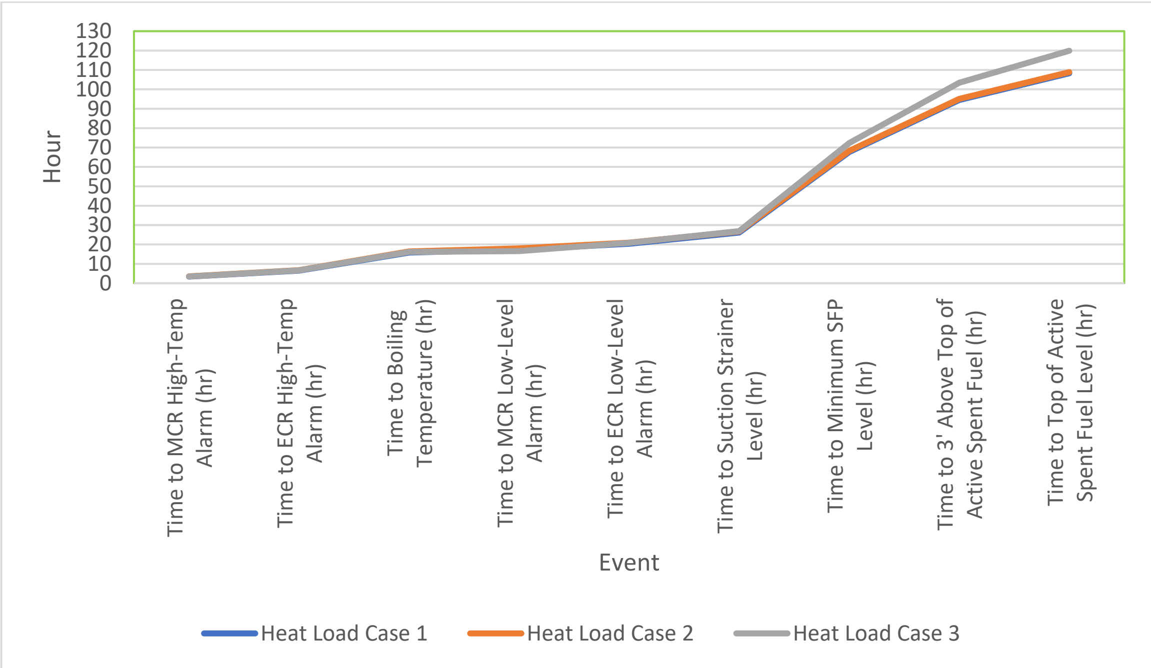
Table 1 and Figure 1 show the thermal-hydraulic time windows calculated for the loss of SFP cooling event scenario for the example plant. This timing information is used to determine the time windows available for the operators to perform the various recovery actions (e.g., recover the SFP heat removal function, provide makeup water to the SFP) following a complete loss of the SFP heat removal event. The actual times are longer than shown in Table 1 because the energy absorbed into the pool walls, the fuel assemblies, and the fuel racks has not been considered in this simplified calculation.

Table 1: Conservative Time Windows Following a Complete Loss of SFP Cooling

	Heat Load Case 1	Heat Load Case 2	Heat Load Case 3
Time to MCR High-Temp Alarm (hr)	3.42	3.54	3.45
Time to ECR High-Temp Alarm (hr)	6.53	6.76	6.63
Time to Boiling Temperature (hr)	15.85	16.43	16.12
Time to MCR Low Level Alarm (hr)	17.36	17.94	16.56

	Heat Load Case 1	Heat Load Case 2	Heat Load Case 3
Time to ECR Low Level Alarm (hr)	20.38	20.96	20.82
Time to Suction Strainer Level (hr)	26.12	26.70	26.84
Time to Minimum SFP Level (hr)	67.66	68.24	72.32
Time to 3’ above Top of Active Spent Fuel (hr)	94.48	95.06	103.41
Time to Top of Active Spent Fuel Level (hr)	108.29	108.87	119.92

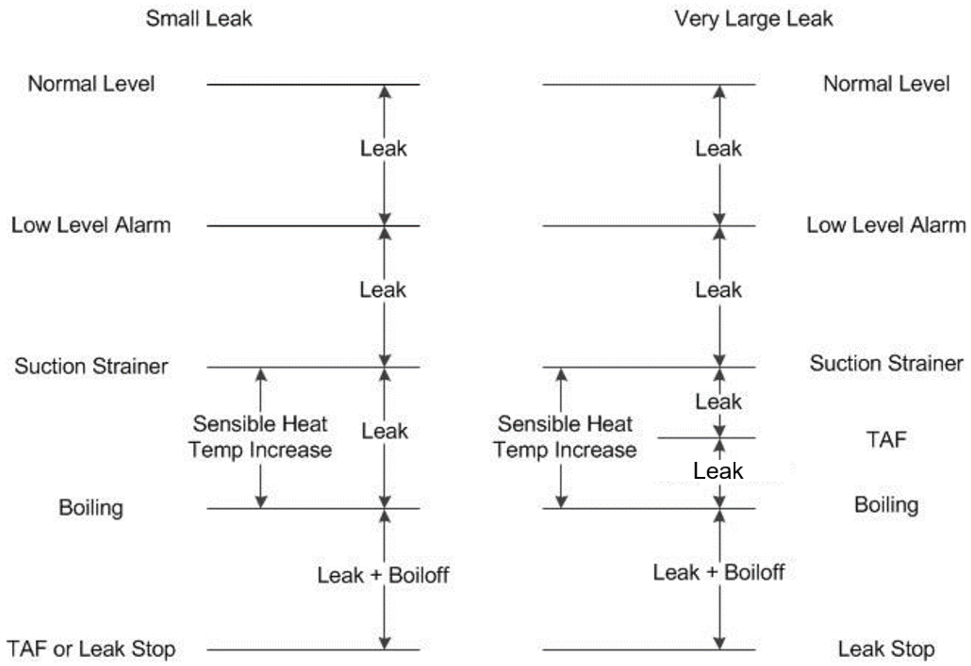
Figure 1: SFP Loss of Cooling Event Time Windows



6. THERMAL-HYDRAULIC TIME WINDOWS FOR LOSS OF SFP INVENTORY EVENT

Following a loss of SFP inventory event, the SFP water level will continue to decrease. When the SFP water level drops to below the SFP cooling system suction strainer, the SFP heat removal function will be lost, at which point the SFP water temperature will start increasing. Depending on the size of the SFP leak, the order of the timing for the subsequent events, including boiling, reaching top of active spent fuel, and termination of leak, may be different. For a small leak, the rate of SFP level decrease is smaller and as such there is more time for water temperature increase before the water level dropping to the top of active spent fuel and the termination of the leak when the SFP level drops to below the opening of the SFP cooling return line distribution header. For a large leak, the SFP water level could drop rapidly (due to the large leak rate) to the top of active spent fuel or leak termination level before the SFP water boils (see Figure 2). In one example plant, the rate of loss of SFP inventory could potentially as high as 92 l/s. As a result, the SFP level drops to the top of active spent fuel first. Also, at this example plant, the lowest point in the pipe section considered for large loss of SFP inventory event is even lower than the inside bottom of the SFP. The leak termination level is at the level of the SFP cooling line return distribution header, which is very close to the inside bottom of the SFP.

Figure 2: Leakage and Boiloff for Small Leak versus Large Leak



6.1. SFP Level Decrease (Reaching Top of Active Spent Fuel First)

Prior to the SFP level decreases to the SFP cooling system suction strainer level, the SFP inventory loss is only through the break due to the siphoning effect. Once the SFP level drops to below the SFP cooling system suction strainer level, SFP heat removal function will be lost and the SFP water temperature will start increasing. After the SFP water temperature reaches the boiling temperature, the SFP coolant loss will also result from boiloff; i.e., SFP water will be lost due to both break flow and boiloff.

As discussed previously, at the example plant, the SFP level decreases to the top of active spent fuel before the SFP water temperature increase to the boiling temperature. Before the SFP level decreases to the SFP cooling system suction strainer level, the relationship between decay heat generation and SFP water level decrease can be described in the following equation:

$$\int_{t_0}^{t} L(t)dt = A_C \cdot [h_0 - h(t)] \tag{5}$$

$$L(t) = \sqrt{2g[h(t) - h_b]} \cdot \frac{1}{4}\pi d^2 \tag{6}$$

Where

t_0	=	time 0 when the loss of inventory event occurs
$L(t)$	=	leak rate as a function of time, which decreases as the elevation head decreases
$\int_{t_0}^{t} L(t)dt$	=	total water volume leaked out from t_0 to time = t
A_C	=	SFP cross sectional area
h_0	=	initial SFP level
$h(t)$	=	SFP level at time = t
h_b	=	break elevation
g	=	gravitational acceleration constant
d	=	inside diameter of pipe section that ruptures

As can be seen from Equation (6), the leak rate resulting from the siphoning effect decreases as the SFP level and the associated elevation head (i.e., $h - h_b$) decrease. Using Equation (5), time to MCR low level alarm, time to ECR low level alarm, and time to SFP cooling system suction strainer level can be determined. Since the SFP level decreases to the top of active spent fuel before the SFP water boiling occurs, Equation (5) can also be used to determine the time to reach top of active spent fuel; i.e., Equation (5) is used to determine the SFP level decrease to both the SFP cooling system suction strainer level and the top of active fuel.

Table 2 lists the thermal-hydraulic event time windows estimated for the loss of SFP inventory event (with a leak rate of 92 l/s). Figures 3 and 4 show the SFP LOCA thermal-hydraulic event time windows as a function of the leak rate based on Heat Load Cases 1 and 3, respectively.

Table 2: Conservative Time Windows Following a Large Loss of SFP Inventory (with Initial Leak Rate of 92 l/s and Decreases as SFP Level Decreases)

	Heat Load Case 1	Heat Load Case 2	Heat Load Case 3
Time to MCR Low Level Alarm (hr)	0.03	0.03	0.03
Time to ECR Low Level Alarm (hr)	0.10	0.10	0.10
Time to Suction Strainer Level (hr)	0.22	0.22	0.22
Time to Minimum SFP Level (hr)	1.12	1.12	1.19
Time to 3' above Top of Active Spent Fuel (hr)	1.70	1.70	1.88
Time to Top of Active Spent Fuel Level (hr)	2.00	2.00	2.26

Figure 3: SFP LOCA Event Time Windows as a Function of Leak Rate – Heat Load Case 1

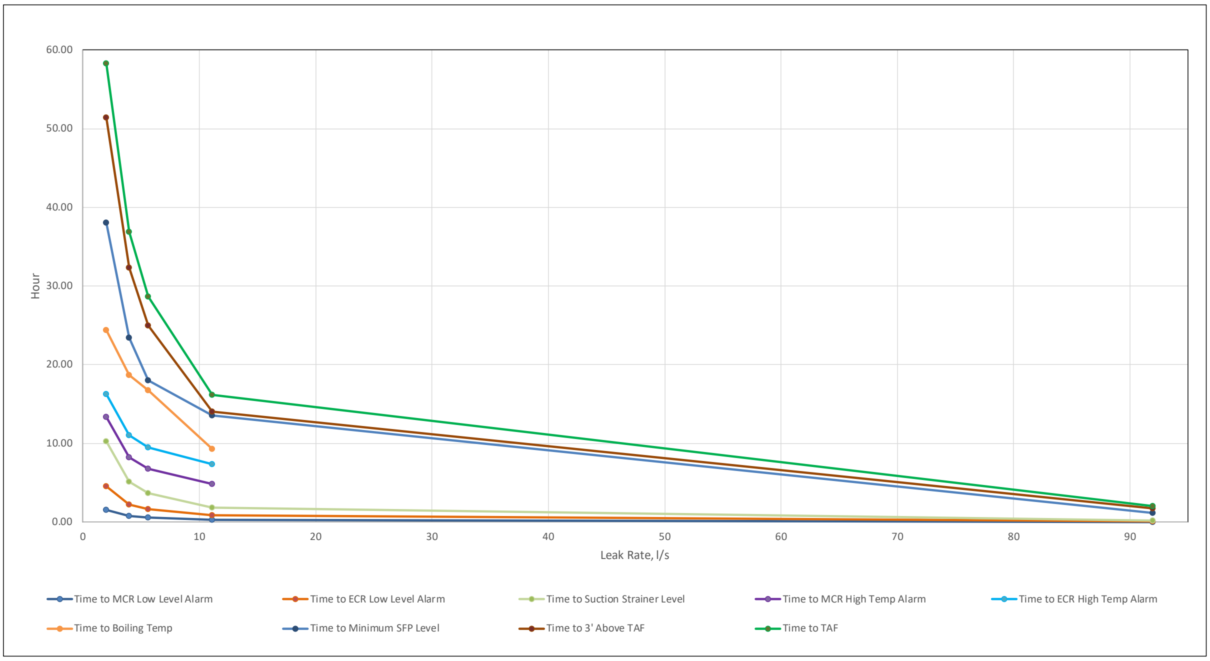
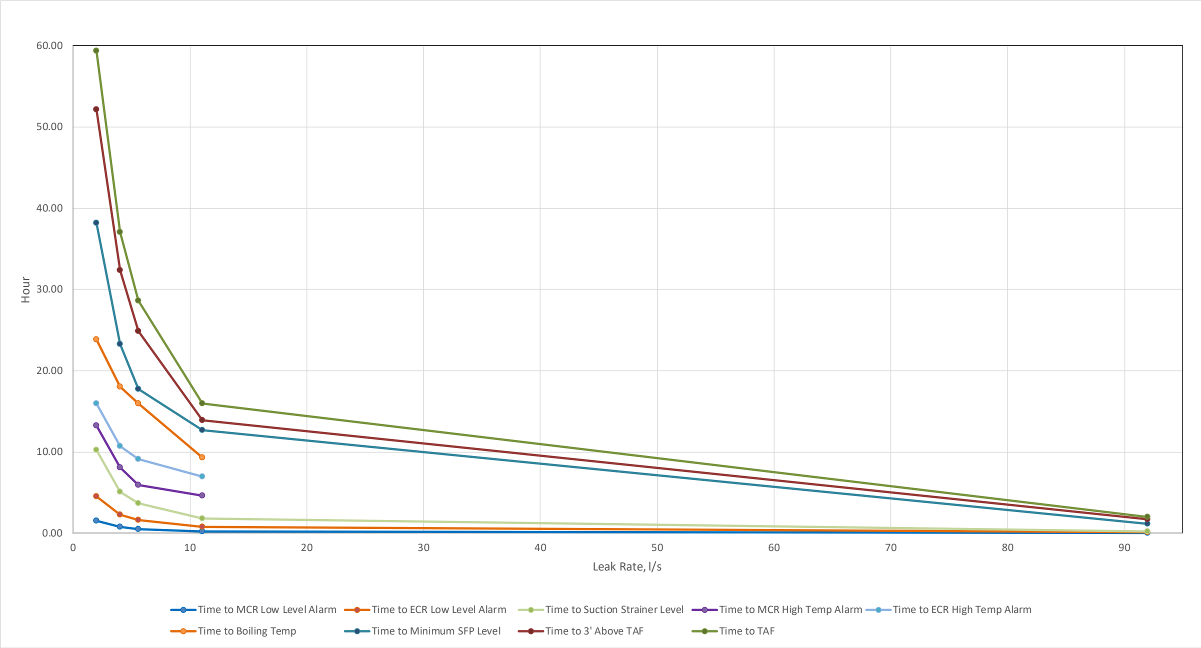


Figure 4: SFP LOCA Event Time Windows as a Function of Leak Rate – Heat Load Case 3



6.2. SFP Level Decrease (SFP Water Boiling First)

After the SFP level decreases to the SFP cooling system suction strainer level, the decay heat generated will heat up the SFP water. Therefore, from this point on, the water that leaks out of the SFP is also partially heated. Since, for a smaller leak, the SFP water will boil first, time to boiling must be determined first. In fact, time to MCR high temperature alarm, time to ECR high temperature alarm, and time to boiling can all be determined using the following relationship:

$$\int_{t_s}^{t} Q(t)dt = [V_0 - \int_{t_0}^{t} L(t)dt] \cdot \rho_l \cdot C_P \cdot [T(t) - T_0] + \int_{t_s}^{t} \{L(t) \cdot \rho_l \cdot C_P \cdot [T(t) - T_0]\} dt \quad (7)$$

Where

t_0 = time 0 when the loss of inventory event occurs
t_s = time when the SFP level drops to the SFP cooling system suction strainer level
$\int_{t_s}^{t} Q(t)dt$ = cumulative decay heat generated from time reaching the SFP cooling system suction strainer level (t_s) to time = t
V_0 = initial total volume of SFP water being heated up
$\int_{t_0}^{t} L(t)dt$ = total water volume leaked out from t_0 to time = t
ρ_l = density of water in the liquid phase
C_P = specific heat of water
T_0 = initial SFP water temperature
T(t) = SFP water temperature at time = t

The left-hand side of Equation (7) represents the total decay heat generated from the time when the SFP cooling system suction strainer level is reached to the time of interest; i.e., time of MCR high temperature alarm, time of ECR high temperature alarm, or time of boiling. The first term on the right-hand side of Equation (7) represents the amount of energy required to heat up the water volume that remains in the SFP at t; i.e., time reaching MCR high temperature alarm, ECR high temperature alarm, or boiling. The second term on the right-hand side of Equation (7) represents the amount of energy required to heat up the water that has leaked out of the SFP by time t.

After the SFP temperature reaches the boiling temperature, time to reaching the top of active spent fuel is determined by the following equation:

$$h(t) = h_0 - \frac{\int_{t_0}^{t_s} L(t)dt}{A_C} - \frac{\int_{t_s}^{t_b} L(t)dt}{A_C} - [\frac{\int_{t_b}^{t} L(t)dt}{A_C} + \frac{\int_{t_b}^{t} Q(t)dt}{A_C \cdot \rho_S \cdot C_P}] \quad (8)$$

Where

h(t)	=	SFP water level at time = t
h_0	=	initial SFP level
t_0	=	time 0 when the loss of inventory event occurs
t_s	=	time when the SFP level drops to the SFP cooling system suction strainer level
t_b	=	time of boiling
L(t)	=	leak rate as a function of time, which decreases as the elevation head decreases
Q(t)	=	decay heat generation rate at time = t
A_C	=	SFP cross sectional area
ρ_s	=	density of water at saturation under the STP condition (212°F)
C_P	=	specific heat of water

In the above equation, the second term on the right-hand side represents the level decrease due to leakage from t_0 to t_s. The third term represents the level decrease due to leakage from t_s to t_b. The last two terms in the bracket represent the level decrease due to leakage and boiloff. In Equation (8), time to top of active spent fuel (t) is determined when h(t) is set to be the level of the top of active spent fuel.

7. CONCLUSION

For the analysis of the thermal-hydraulic time windows for the loss of SFP cooling events, there are two time periods of event progression; i.e., SFP temperature increase to boiling and subsequent SFP level decrease after boiling. Following a complete loss of the SFP cooling event, the decay heat generated from the spent fuel assemblies stored in the SFP will initially cause the SFP water temperature to increase. Once the SFP temperature has reached the boiling temperature, the SFP water level will start decreasing due to boiloff. A number of time windows can be determined to support the HRA and the development of the event sequence models. These may include time to SFP high temperature alarm, time to SFP boiling temperature, time to SFP low level alarm, time to SFP cooling system suction strainer level, time to minimum SFP level, time to 3’ above top of active spent fuel, time to top of active spent fuel level, etc.

Rupture of a pipe section in the SFP cooling system with no anti-siphoning device could potentially lead to a large SFP coolant loss scenario due to the siphoning effect. If the piping component friction losses are conservatively neglected, the maximum, initial break flow rate that could possibly attain due to the siphoning effect could be substantially greater than the realistic coolant loss flow rate with the consideration of the piping component friction losses.

Following a loss of SFP inventory event, the SFP water level will continue to decrease. When the SFP water level drops to below the SFP cooling system suction strainer, the SFP heat removal function will be lost, at which point the SFP water temperature will start increasing. Depending on the size of the SFP leak, the order of the timing for the subsequent events, including boiling, reaching top of active spent fuel, and termination of leak, may be different. For a small leak, the rate of SFP level decrease is smaller and as such there is more time for water temperature increase before the water level dropping to the top of active spent fuel and termination of the leak when the SFP level drops to below the opening of the SFP cooling return line distribution header. For a large leak, the SFP water level could drop rapidly to the top of active spent fuel or leak termination level before the SFP water boils.

Reference

[1] ANSI/ANS-5.1-2005, Decay Heat Power in Light Water Reactors, American National Standard, American Nuclear Society (2005).