Evaluation of Maximum Allowable Temperature for the RHR Suction Piping System When Aligned to the ECCS

Jaehyok Lim, Ph. D., Principal Nuclear Engineer, Plant Services, Fauske & Associates, LLC

1.0 Introduction

In 1993, Westinghouse issued NSAL-93-004 (Ref. [1]). This Nuclear Safety Advisory Letter (NSAL) identified a potential concern associated with steam flashing of hot water in the Residual Heat Removal (RHR) system suction piping during the transition from mode 3 to mode 4 when the RHR system is aligned to the Reactor Coolant System (RCS). In mode 3 (hot standby mode), the reactor is subcritical with an average reactor coolant temperature equal to or greater than 350 °F and in mode 4 (hot shutdown mode), the temperature is between 200 °F and 350 °F (Ref. [3]). During mode 4, one train of ECCS is required to be operable in order to provide core cooling in the event of a Loss-of-Coolant Accident (LOCA). If the LOCA occurs, the RHR system provides an Emergency Core Cooling System (ECCS) function with the lower pressure Refueling Water Storage Tank (RWST) aligned as the water source. Additionally, in 2009, Westinghouse issued NSAL-09-8 (Ref. [2]). This NSAL clarified the previous guidance provided in NSAL-93-004 to take into account the significantly reduced elevation head present when the RHR system water source is transferred from the RWST to the containment recirculation sump.

According to the issue raised in NSAL-93-004 and NSAL-09-8, the transient response of the RHR pump suction fluid has been evaluated for the LOCA postulated to occur shortly after transition from the shutdown cooling mode to the standby ECCS injection mode of RHR system.

Figure 1-1 shows the schematic diagram of the Westinghouse three-loop Pressurized Water Reactor (PWR) RHR system. The RHR pumps are normally fed from the RWST, until ECCS suction swap-over to recirculation is initiated based on the RWST water level. The RWST injection line is a 16” diameter and reduced to a 14” diameter. Each pump suction line is fed by a 14” header through an isolation valve and a check valve. The other normal supply path for the pump is from the containment recirculation sump. Each RHR pump has a suction header leading from a sump compartment through the isolation valves with or without a check valve. This header is a 14” diameter and continues down to the pump suction inlet. A 12” diameter hot leg suction line is connected to this header downstream of the isolation valves of the RWST and the sump to provide the shutdown cooling suction path. A 3” dimeter mini-flow return line is connected to the hot leg suction line above this header.

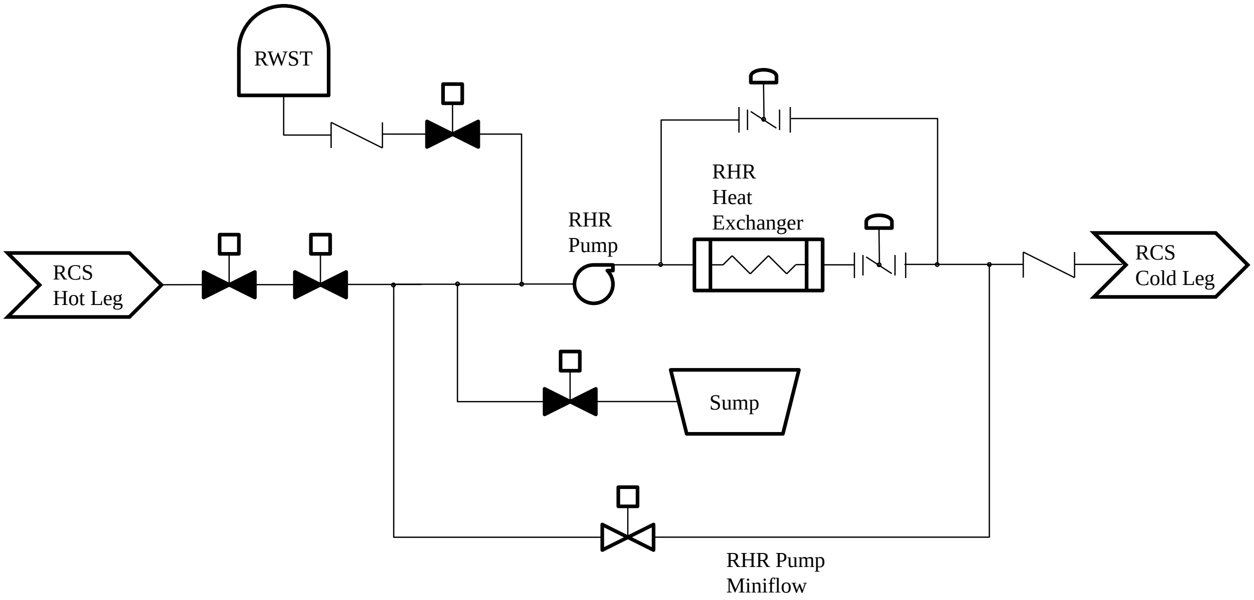

Figure 1-1 Westinghouse Three-Loop Pressurized Water Reactor Residual Heat Removal System

2.0 Phenomena of Concern and Screening Evaluation

2.1 Phenomena of Concern

The issues associated with trapped fluid at an elevated temperature in the RHR hot leg suction line when a postulated ECCS injection occurs are:

1) The fluid can flash and a steam-water mixture will preferentially feed the pump suction as long as the saturation pressure remains above the source pressures from the RWST or the containment recirculation sump. This condition can lead to steam binding and postulated failure of the RHR pump.
2) If voiding occurs and the pressure drops below that needed to open the check valve from the RWST as well as during switchover to the sump recirculation mode, conditions favorable to condensation induced water hammer may be created that can challenge the piping and supports.
3) If drainage in the RHR pump discharge line is occurred during the manual swap-over to recirculation, a liquid column separation and rejoining water hammer may be expected in the RHR pump discharge line including the RHR Heat Exchanger (HX) tubes when the RHR pump is restarted.

Therefore, it becomes important to identify a primary system temperature at which the RHR system can be isolated and avoid these issues. It is desirable to maximize this temperature for the following reasons:

1) During startup, it is desirable to establish pressure in the steam generators to allow steam dump operations in order to control primary system heat up prior to isolating the RHR system.

2) The RHR system needs to remain in operation to support Low Temperature Overpressure Protection (LTOP) pressure relief until a bubble is drawn in the pressurizer.

2.2 Screening Evaluation

The first step in addressing this issue was to establish the geometry of the system and understand the effects of this geometry. Westinghouse three-loop PWR piping isometric drawings (units 1 and 2, trains A and B) were reviewed in detail and key features of the RHR suction systems include:

1) A review of the operating procedures indicates that the RHR pumps would be shut down before the switchover from the RWST injection to sump recirculation. The RHR HXs are horizontally located at approximately 20’ below the sump water surface and the highpoint of the pump discharge line is about 10’ below the sump water surface. Therefore, there should be no drainage in the pump discharge line during the manual swap-over to recirculation. In a result, a liquid column separation and rejoining water hammer is not expected in the pump discharge line including RHR HX tubes when the RHR pump is restarted.
2) The mini-flow return is relatively close to the pump suction downcomer, near where the RWST supply header ties in. This means that forced circulation cooling of the RHR system will not provide cooling of the bulk of the hot leg suction piping.

The pressures available at the hot leg suction highpoint under supply via the RWST or containment recirculation sump following the ECCS suction swap-over to recirculation were calculated. The RWST water level is the nominal value with no instrument uncertainty or additional margin and the sump water level is based on a large break LOCA but a minimal sump water temperature of 120 °F was used to yield a minimum containment pressure as a conservatively low estimate. The static pressures and their corresponding saturation temperatures define the maximum temperature that could be supported without steam voiding occurring in the hot leg suction line. Note that these were calculated including the effects of the pressure drop through RWST supply and containment recirculation sump suction lines. In particular, total sump suction line losses were calculated by adding the sump suction pipe losses and the strainer head loss as calculated from Net Positive Suction Head (NPSH) calculation notes.

Based on these results, the following conclusions can be drawn:

1) Comparison of the both units with the review of the piping layouts suggests that the most limiting void generation and transport will be observed from train B of unit 2 and train A of unit 1.
2) The limit that would result based on the hot leg suction highpoint pressures available after swap-over to recirculation is 196 °F (train A)/188 °F (train B) for unit 2 and 183 °F (train A)/191 °F (train B) for unit 1 to positively prevent any void formation.

However, the maximum temperature based limit for zero voiding would be too restrictive for plant startup operations during the transition from mode 5 to mode 4. In mode 5 (cold shutdown mode), the average reactor coolant temperature is less than or equal to 200 °F and in mode 4 (hot shutdown mode), the temperature is between 200 °F and 350 °F (Ref. [3]). As a result, a transient analysis was initiated to provide dynamically based thermal limits.

3.0 RELAP5 Analysis

RELAP (Reactor Excursion and Leakage Analysis Program) is a light water reactor transient analysis code developed for the U.S.NRC for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of steam, water, non-condensable and solute under single phase and two phase conditions (Ref. [4]). The RELAP5 computer code has capability to analyze void generation and transport as well as void collapse. This code is also capable of characterizing water hammer events, provided appropriate attention is given to time step selection and model nodalization.

3.1 Description of Model

The RELAP5 hydraulic nodalization of the unit 2 RHR system is shown in Figure 3-1 for train A and Figure 3-2 for train B, respectively. The unit 1 and unit 2 are virtually identical with the review of the piping isometrics and the effect of geometric differences between two units has been investigated in the Section 4.2.2.

The sources and destinations of the external flows, including the RWST, containment recirculation sump and two of the RCS cold legs were modeled as Time Dependent Volumes (TDVs) which enable easy specifications of the desired boundary conditions on the RHR system including a time history of pressure and temperature.

The RELAP5 Mod 3.3 (Patch 03) code was executed for a sufficient interval of 10 seconds to reach a steady state that is representative of the pressure and temperature distribution in the RHR system when the postulated transient starts. The following list represents the key features and assumptions made in the RELAP5 model:

1) It is important to properly select the calculation time step and node size. The pipes were nodalized such that the node length was approximately equal to its diameter (L/D ~ 1) in the hot leg suction line to accurately track the void generation and propagation as well as to support computation of wave loads should quantification of water hammer loading conditions become necessary. Since water hammer events are essentially wave propagation at acoustic velocities, use of time steps and plotting frequencies capable of resolving the acoustic behavior is mandatory.

2) The mini-flow isolation valve was closed when the RHR pump discharge flow increases to greater than 2200 gpm based on operating procedures. The mini-flow isolation valve (RELAP5 valve V135) stroke time was set to 5.52 (train A)/5.5 (train B) seconds. There was no or very minimal effect of the stroke time on the results.

3) The RHR HX was not modeled since the details of RHR HX are not of first order importance as noted in Section 2.2. Hence, the RHR pump discharge line and the mini-flow line were not explicitly modeled. During the swap-over to recirculation, the mini-flow isolation valve was kept closed once it is closed to prevent steam bypass to the pump discharge line as discussed in Section 4.2.

4) Pipe walls were modeled using the RELAP5 heat structure components assuming that they are perfectly insulated with respect to heat transfer to the environment.

5) The forced cooling procedure was assumed to be implemented and the temperature was assumed as 150 °F between the mini-flow line and the pump.

6) The RWST water temperature was assumed as 100 °F and the containment sump water temperature was assumed as 120 °F.

7) The RHR pump was modeled using the built in homologous curves for the Bingham pump. Rated head and flow are applied to normalize these curves to represent the RHR pump curves. The pump ramp-up time was assumed as 2.5 seconds.

8) The RCS cold leg was represented by the TDV whose pressure is determined such that the injection flow rate is about 4500 gpm which is the pump runout flow rate.

9) The RWST and the containment recirculation sump were also represented as TDVs.

10) The pressure in the injection intake of the RWST at 157.5’ is 30.88 psia when the borated water level is high (full level), 16.49 psia when the water level reaches the LO-LO-1 set point for swap-over to recirculation, and 15.31 psia when the water level reaches the vortex suppression minimum level.

11) Containment conditions were assumed as 0 psig with 120 °F. The elevations of the sump water and the finished floor are 110’ and 105.5’, respectively. The pressure at the bottom of the containment recirculation sump was taken to be 18.32 psia with a minimal containment overpressure.

12) The containment recirculation sump isolation valve (RELAP5 valve V355) and the RWST isolation valve (RELAP5 valve V378) were modeled as motor operated valves with stroke times of 12.68 (train A)/13.77 (train B) for the sump and 17 seconds for the RWST, respectively. There was no or very minimal effect of the stroke time on the results.

13) The pipe lines from the pump suction header to the RWST and the containment recirculation sump were modeled in detail since the inertial behavior of these lines was shown to be of importance in earlier sensitivity cases.

14) In addition to the detail of the sump suction piping, the pressure drop through the sump screens at full flow was included in the evaluation of the pressure losses in the sump piping.

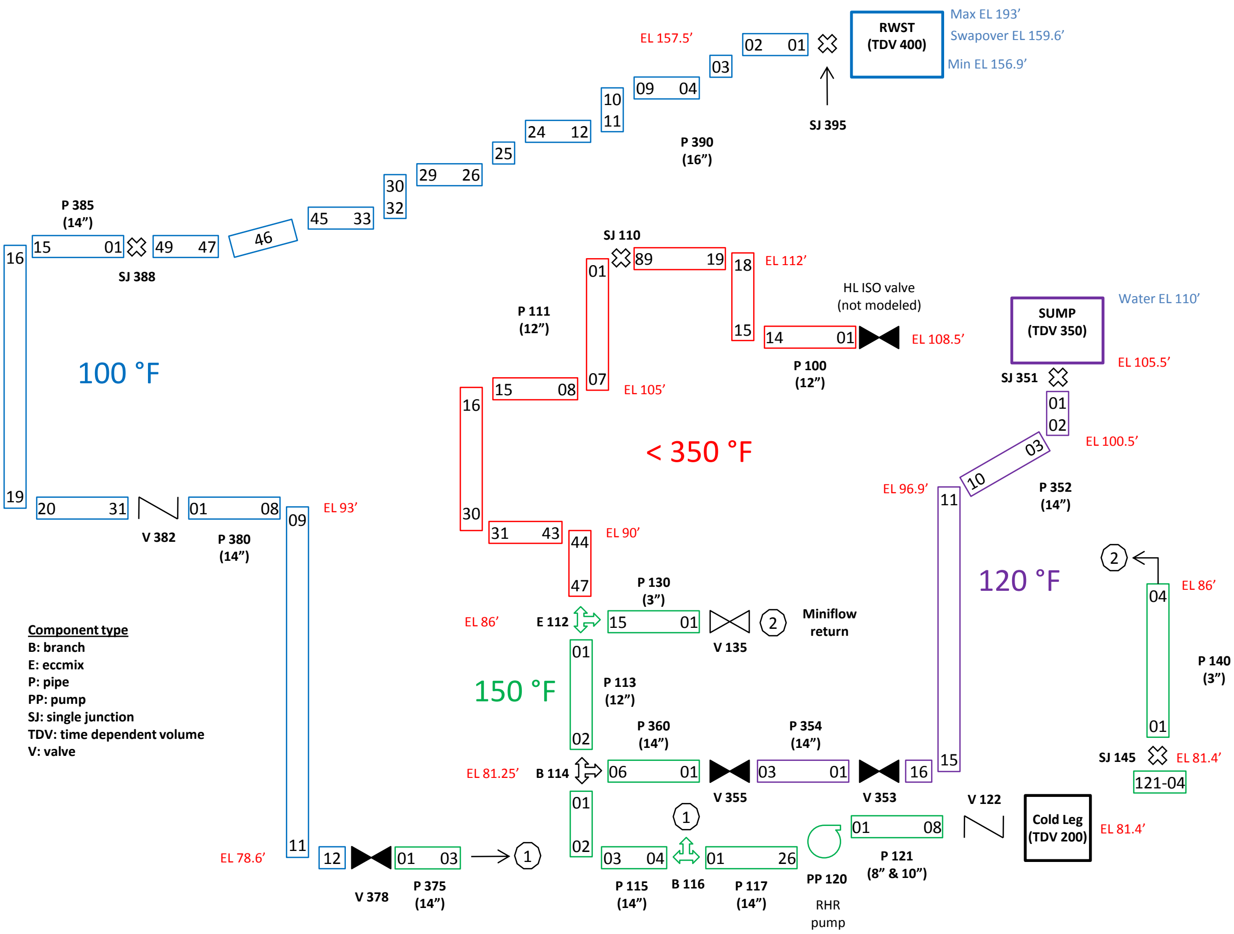

Figure 3-1 RELAP5 Model Diagram of Unit 2 Train A Residual Heat Removal System

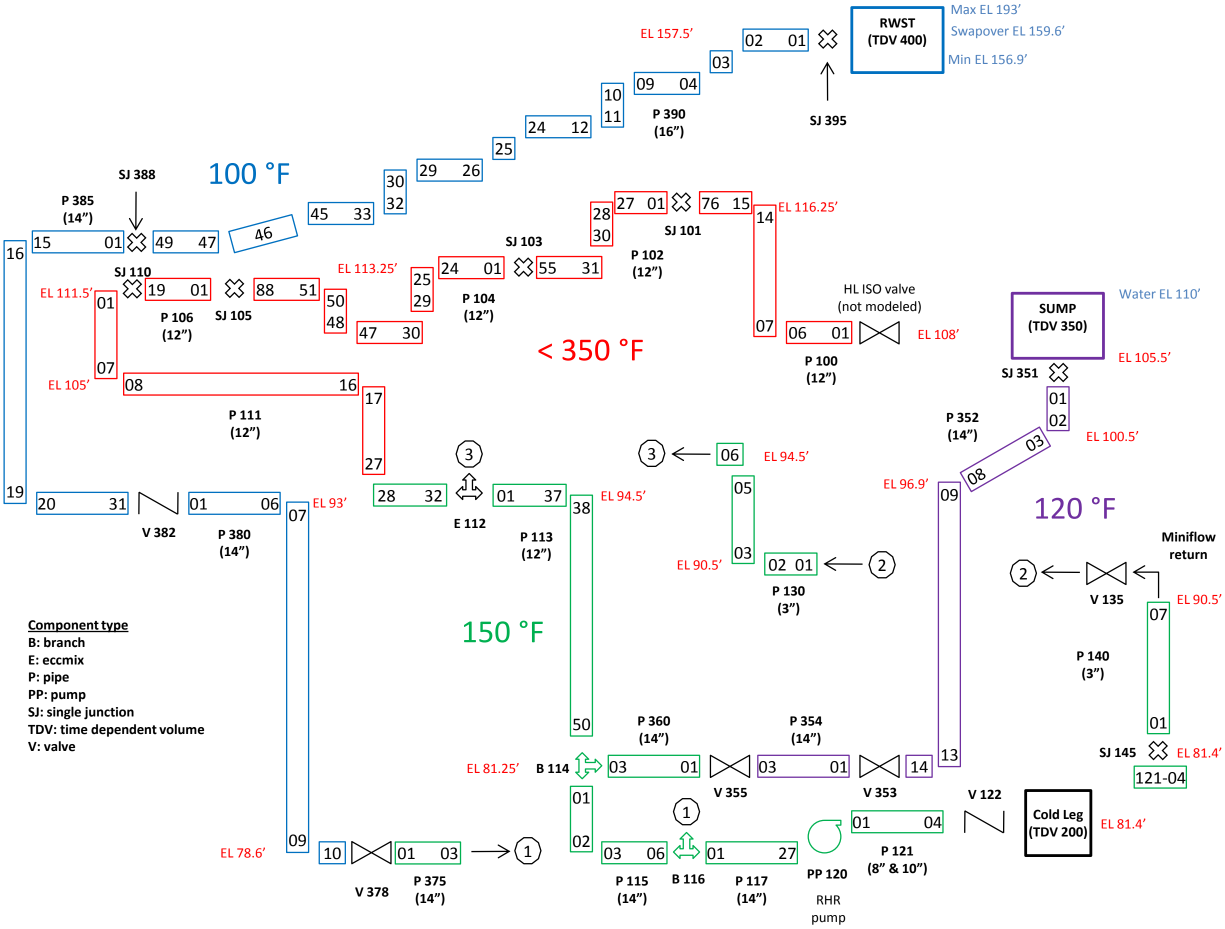

Figure 3-2 RELAP5 Model Diagram of Unit 2 Train B Residual Heat Removal System

3.2 Description of Cases Analyzed

The following two cases were considered to potentially lead to either water hammer events or to steam suction into the pump and were therefore of interest in assessing the performance of the RHR trains under design basis events.

3.2.1 Injection from RWST

By closing the RHR isolation valve, the hot water at a maximum pressure of 402.5 psig with a temperature of 350 °F could be trapped in the hot leg suction pipe. An isolation of the RHR system is achieved by additionally closing the discharge valve to the cold leg. A forced cooling procedure is then implemented whereby the RHR pump is operating with a minimum discharge flow rate through the mini-flow line. This is assumed to be implemented over a sufficient time interval that the entire piping run to the pump is cooled to a low temperature in the range of 150 °F.

At this time, a LOCA can be postulated to occur. It is assumed that the pump start occurs with the water in the suction piping at the specified temperature. The analysis of interest is the RHR pump start with flow proceeding to maximum (runout) values. By design, the water source for the RHR pump is the

RWST and this would be the case as long as this represents the highest pressure source connected to the pump. In addition, the mini-flow isolation valve would be shut if the resulting pump discharge flow rate exceeds 2200 gpm when the valve enabling injection into the cold leg is opened.

In this case, however, the higher pressure hot water and steam in the hot leg suction highpoint would be the source for the pump suction and would be pulled into the pump suction header. Simultaneously, the imposed higher pressure would also close the RWST check valve (RELAP5 valve V382) thereby preventing water flow from the RWST to the suction header. The objective of the analysis of this case was to determine whether a large volume of steam could be ingested into the pump, thereby leading to severe degradation of the pump operation and potentially even to pump damage.

To examine this accident sequence, scenario was set up in the following manner to examine the response of the train that is secured from the RCS heat removal.

1) RHR pump operation: start at 10 seconds with 2.5 seconds of ramp-up time.
2) Sump isolation valve (RELAP5 valve V355): closed all the time.
3) RWST isolation valve (RELAP5 valve V378): open at 10 seconds with 17 seconds of a stroke time.
4) Mini-flow isolation valve (RELAP5 valve V135): close within 5.52 seconds (train A)/ 5 seconds (train B) when the flow rate is larger than 2200 gpm.
5) Cold leg pressure (primary system): 50 psia.
6) Initial temperature: see Figure 3-1 and Figure 3-2.

3.2.2 Switchover from RWST Injection to Sump Recirculation

This situation could occur when the RWST water level reaches the LO-LO-1 set point or in a number of possible break scenarios following depletion of the RWST. A review of the containment flooding calculations suggests a minimal sump temperature from these conditions on swap-over would be 120 °F. Upon switchover of the suction water source from the RWST to the containment recirculation sump, which is accompanied by the operator action of closing of the RWST isolation, the pressure in the suction header would be reduced. There could be additional flashing of the water in the hot leg suction highpoint and the expansion of any existing steam volume. This could result in an additional steam intrusion into the RHR pump that could be sufficient to degrade its performance. It is to be noted that the swap-over to recirculation is followed by the restart of the RHR pump regardless of whether the accident is a small, medium or large break LOCA.

By the operating procedure, the RHR pump is shut down and the RWST is isolated before the sump isolation valve is open. The steam generated by flashing in the highpoint of the hot leg suction pipe would be flushed into the containment through the sump suction line with no check valve. The RHR pump is then started and allowed to inject to a primary system depressurized to 50 psia to maximize flow demand, ensuring a large flow rate. As the void expands and the void pressure drops, flow could commence from the sump. The analysis performed was intended to determine the maximum void propagation in the system as well as the maximum temperature limiting the water hammer conditions. Key acceptance criteria for this analysis are that:

1) No void fraction exceeding 2% reaches the inlet of the pump suction header.
2) Water hammer loads need to be minimal. This is considered to be the case when piping segment loads are comparable to the flooded weight of the pipe segment, which is the summation of the pipe weight and the weight of water within the pipe.

4.0 Results and Analyses

The RELAP5 models of train A and train B of the unit 2 were set up and exercised with different initial temperatures of hot fluid trapped in the hot leg suction line. A 10-second steady state initialization was allowed with the pump start occurring at 10 seconds. The following analyses are for unit 2 and the application to unit 1 will be discussed later in Section 4.2.2.

4.1 Results of Injection from RWST

This case, as designed, principally deals with the potential to transport steam to the pump suction. Therefore, the RHR pump runout flow rates and the minimum RWST water level assumptions will tend to be the most bounding, since the steam generation and transport are maximized. The criterion applied for "success" with respect to steam transport was that an average void fraction less than 2% must be achieved for 20 seconds in the pump suction header adjacent to the tee where the RWST supply line ties in (RELAP5 pipe P117 nodal volume 01).

4.1.1 Results with Nominal RWST Water Level

This case was performed with nominal (maximum) RWST water level (193' – 0 ¼") to identify the RHR isolation temperature where minimal steam ingestion would be expected. For this RWST water level, it was shown that the initial temperature of 285 °F (train A) and 290 °F (train B) yielded minimal steam intrusion to the pump suction header. The higher temperature is allowed for train B and it is discussed in Section 4.1.2.

The initial pressure in the hot leg suction is not important since as soon as a steam bubble is formed the pressure in this piping will be equal to the saturation pressure corresponding to the temperature of water. At 10 seconds following the pump start, the pressure rapidly falls to the saturation pressure of 53 psia which corresponds to the 285 °F. The steam bubble is condensed or collapsed by the RWST cold water and through the wall heat transfer in the pump suction header. Note that no steam ingestion is occurred at the inlet of the pump (RELAP5 pipe P117 nodal volume 26 for train A and nodal volume 27 for train B, respectively) if the void fraction is limited to 2% at the inlet of suction header (RELAP5 pipe P117 nodal volume 01).

4.1.2 Results with Minimum RWST Water Level

Additional cases were run assuming a minimum RWST water level as the vortex suppression minimum level (156' – 10 ¼") instead of the LO-LO-1 level with a small conservatism in the calculated behavior. Additional cases were run which determined that void propagation less than 2 % at the pump suction header would occur for an initial trapped water temperature of 265 °F for train A and 270 °F for train B, respectively. Both of these initial conditions would result in an acceptable amount of steam intrusion to the pump suction header. The higher temperature is allowed for train B due to the different location of the mini-flow junction connection on the hot leg suction line. As shown in Table 4-5, hot fluid piping length for train B of unit 2 is two times longer than that of the train A but the longer cold piping length of train B initialized with the temperature of 150 °F was able to condense more steam bubbles.

4.2 Results of Switchover from RWST Injection to Sump Recirculation

This scenario is an extension of the injection from RWST case with the accident scenario decreasing the RWST water level from nominal level to minimum level which would be available when the recirculation is accomplished. The swap-over process begins when the RWST water level reaches the LO-LO-1 signal and this case examines the potential to result in steam ingestion during the manual swap-over process that transfers the pump suction source to the containment recirculation sump water. As mentioned earlier, the RHR pump is assumed to be running and injecting to the RCS at a volumetric flow rate that is close to the runout condition, i.e. which approaches 4500 gpm for the prescribed low RCS pressure of 50 psia. With respect to steam intrusion to the RHR pump, a flow rate that approaches runout is conservative and this flow rate is also well above the mini-flow isolation set point. The following conditions were assumed for this case:

1) RWST water level
    - 0 second to 100 seconds: 193’ – 0 ¼” (30.88 psia).
    - 100 seconds to 195 seconds: decreased from 193’ – 0 ¼” (30.88 psia) to 159’ – 7 ¼” (16.49 psia).
    - 195 seconds to 200 seconds: decreased from 159’ – 7 ¼” (16.49 psia) to 156’ – 10 ¼” (15.31 psia).
2) Pump operation
    - Start at 10 seconds with a ramp-up time of 2.5 seconds.
    - Stop at 195 seconds within 5 seconds.
    - Restart after sump isolation valve opens.
3) Sump isolation valve (RELAP5 valve V355): open at 220 seconds with a stroke time of 12.68 seconds (train A)/ 13.77 seconds (train B).
4) RWST isolation valve (RELAP5 valve V378)
    - Open at 10 seconds with a stroke time of 17 seconds.
    - Close at 195 seconds with a stroke time of 17 seconds.
5) Mini-flow isolation valve (RELAP5 valve V135): close within 5.52 seconds (train A)/ 5.5 seconds (train B) when pump discharge flow rate is larger than 2200 gpm.
6) Cold leg pressure (RELAP5 TDV200): 50 psia.
7) Initial temp: see Figure 3-1 and Figure 3-2.

Step 1 through step 5 above document how the code was operated to simulate the plant conditions of interest. The first step starts the flow through the pump suction piping and this continues for 190 seconds before the containment recirculation sump valve begins to open. This 190 second interval is sufficient for the code to develop the transition that would be developed during the RWST injection, which includes the closing of the mini-flow isolation valve.

RWST water level decreased to the vortex suppression level conservatively relative to what would be expected. The nominal LO-LO-1 level of 159' – 7 ¼" would be 158' – 0 ¼" if the instrument uncertainty and additional margins are considered. However, the use of nominal level will not change the fundamental results assuming the minimum RWST water level as the vortex suppression level in this accident scenario.

Once the swap-over level is reached, the transient is initiated by closing the RWST isolation valve following the pump shutdown and by opening the sump isolation valve. It is also noted that the suction flow from the containment recirculation sump includes the acceleration and frictional pressure losses in the line as well as the design pressure drop through the sump strainer at the maximum sump flow rate.

In step 5, the mini-flow isolation valve was kept closed to prevent steam bypass to the pump discharge line through this valve when the sump isolation valve was open. This nonrealistic steam bypass was due to the lack of modeling the RHR HX and mini-flow line. By closing the mini-flow isolation valve, more steam was added to the pump suction downcomer but this was eventually flushed into the sump when the pump was idle.

For the train B, the void propagation less than 2% at the pump suction header would occur for an initial trapped water temperature of 273 °F with the restart of the pump at least 30 seconds after opening the sump isolation valve. The flow through the sump isolation valve is shown in Figure 4-1. The flow from the sump is in the positive direction. For the purpose of observing the entire void transient period, the pump did not restart and a quasi-steady state was established as illustrated in the figure. It was observed that steam bubble with a void fraction larger than 2% flows to the pump if the pump restarts when the steam is flushed into the sump between 220 seconds and 250 seconds.

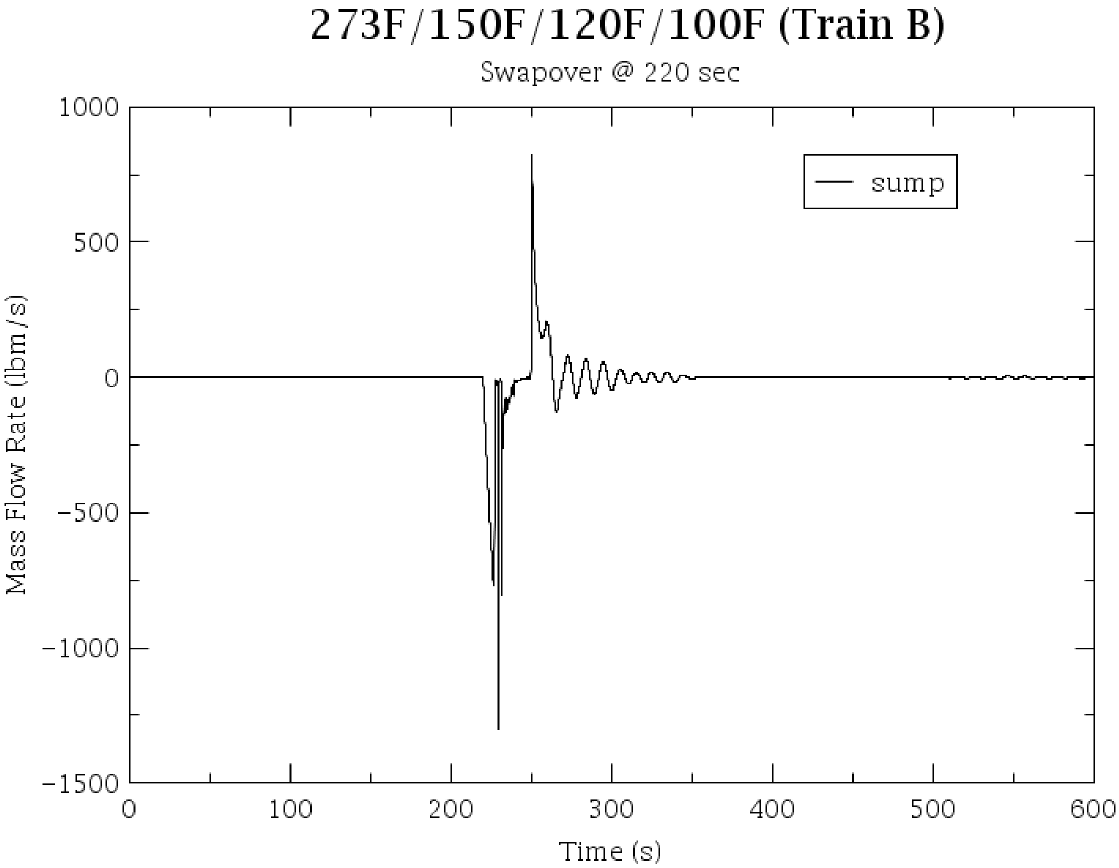

Figure 4-1 Unit 2 Train B Containment Recirculation Sump Flow Rate

In addition to an evaluation of void behavior, a sensitivity study was performed to consider condensation induced water hammer condition. A heat loss was considered on the hot leg suction line (RELAP5 pipe components 100, 102, 104, and 106). From 0 to 400 seconds, a heat transfer coefficient was assumed as 2.777e-4 Btu/s-ft^2-F (1 Btu/hr-ft^2-F) which is a typical natural convection heat transfer coefficient. From 400 to 450 seconds, it increased linearly to 2.777e-2 Btu/s-ft^2-F (100 Btu/hr-ft^2-F) and then it was constant. This non-mechanistic increase acts to increase the steam condensation in the pipe and reduce the steam pressure in the voided region, thereby enabling the cold water to flow towards the end of the hot leg suction line. In this case, the RHR pump restarted at 370 seconds.

The pipe reaction force was computed via post-processing command files operating within the framework of the AptPlot graphics support package. The development of the transient force time history information for application to structural analysis models was based on the general force equations for a container (Ref. [5]). The generalized force equation in one-dimensional form can be resolved for a piping segment bounded by two elbows as:

$$F = -\frac{1}{g}\frac{d}{dt}\int \rho A V dx$$

This is the unsteady reaction force caused by the rate of fluid momentum change within the control volume represented by the pipe segment (so-called wave load) and the wave load approaches zero when the flow approaches the steady state condition. RELAP5 employs a two fluid treatment, and with consideration of the vapor components of the flow, this equation becomes:

$$F = -\frac{1}{g}\frac{d}{dt}\int (\rho_f A V_f \alpha_f + \rho_g A V_g \alpha_g) dx$$, (Mixture mass flux: $\rho V = \alpha_g \rho_g V_g + \alpha_f \rho_f V_f$)

Where, ρ = density, A = flow area, V = velocity, α = void fraction, x = distance along piping axis, g = gravitational constant (used for English units calculation), and subscripts f and g refer to liquid and gas phases. Note that the sign convention applied in all calculations is that force is positive in the nominal direction of the flow in the physical system, unless otherwise noted.

A result with non-mechanistic increase in the heat loss shows that the condensation induced water hammer does not occur and the calculated force is well below the flooded weight of 813 lb_f. The hot water trapped in the hot suction line could prevent the cold water to contact the trapped steam void and collapse it. Subsequently, the cold water temperature increases to a level where rapid condensation cannot be sustained.

The next step was finding the temperature condition that can be unconditionally acceptable regardless of the pump restart time. As a result, the initial temperature of 236 °F can limit the maximum void fraction less than 2% at the inlet of pump suction header as presented in Table 4-1 and Table 4-2 for unit 2, train A and train B. In this sump recirculation mode with a lower pressure, the higher temperature is not observed for train B unlike the RWST injection mode as shown in Section 4.1.1 and Section 4.1.2.

Table 4-1 Unit 2 Train B Void Fraction at the Inlet of the Pump Suction Header (RELAP5 Pipe 117 Nodal Volume 01) with Hot Leg Water Temperature of 236 °F

Sump isolation valve opening time (sec)	Sump water level (ft)	Hot leg water temperature (°F)	Pump restart time (sec)	Void fraction (%)
220	110	236	220	< 0.010
			225	< 0.023
			230	< 0.214
			235	< 0.818
			240	< 1.414
			250	< 0.154
			265	< 0.278
			285	< 0.664
			300	< 1.423
			340	< 0.111
			370	< 0.043

Table 4-2 Unit 2 Train A Void Fraction at the Inlet of the Pump Suction Header (RELAP5 Pipe 117 Nodal Volume 01) with Hot Leg Water Temperature of 236 °F

Sump isolation valve opening time (sec)	Sump water level (ft)	Hot leg water temperature (°F)	Pump restart time (sec)	Void fraction (%)
220	110	236	220	< 0.197
			225	< 1.944
			230	< 1.848
			235	< 0.080
			240	< 0.480
			250	< 0.449
			265	< 0.506
			285	< 0.369
			300	< 0.314
			340	< 0.278
			370	< 0.336

4.2.1 Effect of Sump Water Level

The analysis has been performed with an elevation of 110’ of the containment recirculation sump water level for the large break LOCA. However, different sump water levels are possible for the small break LOCA. Review of the sump water levels for small break LOCA indicates that the lowest sump water level is 108’. Sensitivity studies were conducted with this value and the maximum hot leg suction water temperature was limited to 233 °F for the train B of the unit 2 as provided in Table 4-3. Table 4-4 shows that this temperature can be increased to 234 °F for the train A of the unit 2.

Table 4-3 Unit 2 Train B Void Fraction at the Inlet of the Pump Suction Header (RELAP5 Pipe 117 Nodal Volume 01) with Sump Water Level of 108’

Sump isolation valve opening time (sec)	Sump water level (ft)	Hot leg water temperature (°F)	Pump restart time (sec)	Void fraction (%)
220	108	233	220	< 0.005
			225	< 0.008
			230	< 0.033
			235	< 0.461
			240	< 0.979
			250	< 0.032
			265	< 0.075
			285	< 0.118
			300	< 0.138
			340	< 0.188
			370	< 0.192

Table 4-4 Unit 2 Train A Void Fraction at the Inlet of the Pump Suction Header (RELAP5 Pipe 117 Nodal Volume 01) with Sump Water Level of 108'

Sump isolation valve opening time (sec)	Sump water level (ft)	Hot leg water temperature (°F)	Pump restart time (sec)	Void fraction (%)
220	108	234	220	< 0.192
			225	< 1.904
			230	< 1.788
			235	< 0.090
			240	< 0.479
			250	< 0.421
			265	< 0.439
			285	< 0.382
			300	< 0.312
			340	< 0.313
			370	< 0.351

4.2.2 Effect of Geometric Difference

A review of the piping isometrics for the RHR suction loops of unit 1 and unit 2 indicates that the loops are virtually identical except for 12" diameter pipe length for the hot leg suction line as summarized in Table 4-5.

Table 4-5 Length of Hot Leg Suction Line

Loop	Hot piping from hot leg isolation valve to the mini-flow return line tee (ft)	Cold piping from mini-flow return line tee to the sump header (ft)
Unit 1 Train A	301	3.1
Unit 1 Train B	118	50.3
Unit 2 Train A	134	4.8
Unit 2 Train B	269	53.5

These differences do not affect the static pressure based screening. A transient analysis for the train A of unit 1 was performed using the train B model of unit 2 with a longer hot piping length and a shorter cold piping length of hot leg suction line. The mini-flow line is isolated when the RHR loop flow increases to greater than 1500 gpm for unit 1 and 2200 gpm for unit 2. However, this difference has no or very minimal effect on the isolation valve closing time due to the RHR pump running with the runout flow rate of 4500 gpm for the prescribed low RCS pressure of 50 psia. As a result, the temperature was lowered to 232 °F as summarized in Table 4-6. This value is valid for both small and large break LOCAs. The temperature is also limited to 232 °F using the train A model of unit 2 with modifications applied to the train B model of unit 2.

Table 4-6 Unit 1 Train A Void Fraction at the Inlet of the Pump Suction Header (RELAP5 Pipe 117 Nodal Volume 01)

Sump isolation valve opening time (sec)	Sump water level (ft)	Hot leg water temperature (°F)	Pump restart time (sec)	Void fraction (%)
220	108	232	220	< 0.004
			225	< 0.005
			230	< 0.012
			235	< 0.226
			240	< 0.617
			250	< 0.017
			265	< 0.042
			285	< 0.076
			300	< 0.084
			340	< 0.119
			370	< 0.089

5.0 Conclusion

The Westinghouse three-loop PWR RHR system has been examined in detail with respect to the NSAL-93-004 and NSAL-09-8 issues regarding the potential flashing of the fluids at the elevated temperature trapped in the hot leg suction line following the isolation of the RHR system during startup and shutdown operations. The following items are salient:

1) Static pressure based evaluations directed at precluding any void formation was proved too conservative with respect to operational requirements.
2) Transient analysis of the system identified the threshold temperature for the isolation of the RHR system with no significant impact to be 232 °F limiting the void fraction less than 2% at the inlet of the pump suction header for units 1 & 2, both trains A and B. A period of “forced cooling” was included where the isolated RHR loop is run on the minimum flow through the RHR HX to cool the fluid and the piping until a pump discharge temperature of 150 °F. With respect to steam intrusion into the RHR pump, a flow rate that approaches runout is conservative and this flow rate is also well above the mini-flow isolation set point. The transient analysis has been performed conservatively limiting the void fraction less than 2% at the inlet of pump suction header instead of the inlet of the pump.
3) The condensation induced water hammer was not of concern due to the physical system design not creating conditions favorable to rapid condensation that could lead to a water hammer.
4) The liquid column separation and rejoining water hammer was not expected at the pump discharge line when the RHR pump restarts because there is no potential for the water to drain during the manual swap-over to recirculation.

Reference

1. Westinghouse, 1993, RHRS Operation as Part of the ECCS during Plant Startup, NSAL-93-004: Nuclear Safety Advisory Letter.
2. Westinghouse, 2009, Presence of Vapor in Emergency Core Cooling System/Residual Heat Removal System in Modes 3/4 Loss-of-Coolant Accident Conditions, NSAL-09-8: Nuclear Safety Advisory Letter.
3. United States Nuclear Regulatory Commission (U.S.NRC), 2012, Standard Technical Specifications Westinghouse Plants, NUREG-1431, Volume 1, Revision 4.0.
4. Information Systems Laboratories, Inc., 2006, RELAP5 MOD3.3 Code Manual: Prepared for NRC Office of Nuclear Regulatory Research.
5. Frederick J. Moody, 1990, Introduction to Unsteady Thermofluid Mechanics, John Wiley & Sons.