Analysis of the Presence of Vapor in Residual Heat Removal System in Modes 3/4 Loss-of-Coolant Accident Conditions using RELAP5

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Related topic: Nuclear Safety

ABSTRACT
The Westinghouse Nuclear Safety Advisory Letter NSAL-09-8 investigated the possibility of presence of vapor in Residual Heat Removal (RHR) System in Modes 3/4 Loss-of-Coolant Accident (LOCA) Conditions. This concerns the Westinghouse standard 3-loops plant for which the RHR is the low pressure part of the Safety Injection (SI). In some cases one or both RHR trains may become inoperable for Safety Injection (SI) function. As a response to this letter, Westinghouse Electric Belgium is providing RELAP5 analyzes for Westinghouse Nuclear Steam Supply System (NSSS) European plants to assess the thermal hydraulic behavior of the RHR suction piping system for Emergency Core Cooling System (ECCS) initiation events postulated to occur during startup/shutdown operations. Several concerns including condensation induced water hammer and voiding at the RHR pump have been investigated. As a conclusion, the analysis allowed to define the bounding Hot Leg temperature conditions under which both RHR Trains remain safely operable. These bounding conditions are then implemented by the customer in their Operating Procedures (OPs) to achieve safe operations and successful accident management.

1 INTRODUCTION
According to the Nuclear Safety Advisory Letter NSAL-09-8 (Ref 1), when the RHR system (Figure 1) is secured from shutdown cooling operation and placed in stand-by for ECCS function, water at the prevailing reactor coolant system (RCS) temperature becomes trapped in the RHR system piping. This trapped fluid may be well in excess of 100°C. In the event of a postulated shutdown LOCA (Modes 3/4), the trapped fluid in the ECCS suction lines might flash if the system is called upon to deliver flow in the safety injection mode because it would suddenly be exposed to lower pressure. This pressure can be much lower than the saturation pressure corresponding to the temperature of the fluid previously trapped
in the RHR system piping. Vapor formation in this piping has the potential to degrade pump performance and may cause component damage. There is also a potential for condensation induced water hammer (CIWH) in these lines, should water flowing from the refueling water storage tank (RWST) or from the containment sump come in contact with vapor present in the RHR pump suction line. In addition, the issue may not be only limited to the suction side of the RHR pumps. Depending on the lay-out of the RHR system with regard to check valve presence, location, and system elevation relative to the containment sump, the RHR Heat Exchanger and portions of the discharge piping could also be vulnerable to CIWH if the design and alignment permit the fluid in the primary side of the RHR HX to drain (backflow) into the sump during the switchover from injection to recirculation during a LOCA. This would pertain to some plants for postulated small break (SB) LOCA scenarios when the RHR pumps are turned off and not restarted until after alignment to the ECCS sump for recirculation.

As a response to this issue, Westinghouse Electric Belgium is providing RELAP5 analysis to investigate the thermal hydraulic behavior of the RHR suction piping system for ECCS initiation events postulated to occur during startup/shutdown operations. These behaviors include the potential for steam intrusion into the RHR pump as well as to create conditions conducive to condensation induced water hammer, both on initiation of Refueling Water Storage Tank (RWST) injection as well as during switchover to the sump recirculation mode. This NSAL applies to Westinghouse NSSS in which the RHR system serves as part of the ECCS.

The first part of the project characterizes the RHR system and the conditions in which it is operated. The second part deals with the modelization of the RHR system with RELAP5/mod3, including the initial, boundary and time transient conditions of the cases studied. The third and final part is the thermal hydraulic analysis of the RELAP5 model, in which sensitivity studies based on RHR initial temperature are performed to define the limiting temperature at which void transportation to the RHR pump and water hammer wave load magnitude remain under the acceptance criteria, to be defined with the plant engineering staff.

**2 OBJECTIVES**

The first objective of the project is to represent the RHR system within its current plant specific conditions to assess whether it is operable or not regarding given safety criteria.

The second objective is to lead an investigation on the initial thermal hydraulics conditions of the transient, more precisely the Hot Leg initial temperature, to provide the best conditions for which the RHR system can be operated safely and fulfill its purposes without any risk of damage during a LOCA accident in Mode 3/4.
3 THE RHR SYSTEM IN MODE 3/4 LOCA CONDITIONS

For Westinghouse NSSS power plants, there are up to 6 operating modes, representing different conditions for the plant. The modes to be considered in this analysis are:

- Mode 3, which is the Hot Standby, RCS average temperature $T_{avg} > 177^\circ$C
- Mode 4, which is the Hot Shutdown, where the RCS average temperature $T_{avg}$ satisfies $177^\circ$C > $T_{avg}$ > 93°C (these temperature may be reconsidered from one plant to another)

According to NSAL-09-8, the conditions to be considered are the transition from Mode 3 to Mode 4. In Mode 4, one or two trains may be connected to the RCS depending on the Operating Procedures. Water at the temperature of the RCS is flowing through the connected trains, and if Low Head Safety Injection (LHSI) would be required, this hot water would remain trapped in the RHR train as the realignment process is actuated. This defines the initial conditions for these analyzes.

If a LOCA occurs, the RHR System is used in ECCS modes to provide cooling of the RCS. In such conditions, the normal path of suction flow is from the RWST until swap over to the containment recirculation sump occurs on reaching the RWST low-low level set point. When the RWST level decreases to this value, the containment sump isolation valve is opened to line up suction from the containment sump and the RWST suction isolation valve is closed. Thereafter, RHR pump suction is taken from the containment sump. Pump discharge flow passes through the RHR Heat Exchanger and then into the RCS loops. Also, during low pump flow conditions, a minimum flow line returns a flow downstream of the Heat Exchanger to the suction header and vertical header from the containment sump/hot leg suction line.
4 RELAP5 MODEL OF RHR SYSTEM

The aim is to examine in details the RHR system of the NPP with respect to the NSAL-09-8 issues, i.e. the potential flashing of fluids at a high temperature trapped in the hot leg suction line following the isolation of the RHR system during startup/shutdown operations. A model of the RHR suction piping system is developed extending from the sump and RCS Hot Leg suction downstream Hot Leg isolation valves through the pump to a point downstream of the RHR Heat Exchanger. The model includes the minimum flow line as well to capture thermal feedback of cooler water as hot fluid travels toward the RHR pump in the suction piping.

A screening evaluation of the RHR system is first performed before building the RELAP5 model. This key step is an opportunity to discuss relevant assumptions that would fairly simplify the model. For example, modeling the Heat Exchanger could be avoided if the layout show it is mounted horizontal, and therefore that there is no risk to drain it by gravity if the RHR pump stops during the transient. After an accurate study of the plant specific layout and piping isometrics of the RHR system, the geometry of the RHR system is nodalized into RELAP5 hydrodynamic components (Figure 2), representing the hydraulic of the system, including pipes, elbows, tee branches, valves and heat structures.

Time and boundary conditions are then applied to the system in order to best represent the conditions in which this system is going to be used. Those conditions are mostly provided by the OPs and EOPS.

Based on the phenomena described above, the analytical approach needs to provide for the characterization of the following:

- Steam flashing and condensation.
- Heat transfer to/from piping structures
- Heat transfer to/from the Heat Exchanger.
- Ability to characterize inertial responses of piping systems.
- Pump model.
- Two phase flow.
- Water hammer response.
- Condensation phenomena occurring at the minimum flow return point.

The RELAP5 computer code has the ability to perform these characterizations. The numerical schemes of RELAP5 are selected regarding the phenomena of concern, and sensitivity studies are performed to evaluate the conservatism of the schemes used regarding specifically this analysis.
After the examination of the EOPs, two main parts can be defined in the transient. Simulating the first part of the computation can take in average 200 seconds in RELAP5. It includes the realignment process followed by the RWST injection phase. When the RHR train is realigned to LHSI mode, it takes suction from the RWST and cold water is injected into the RHR System. This first phase is mostly characterized by RHR pump start, the RWST isolation valve opening and the cold leg connection. Depending on how the RWST isolation valve is open, the start-up of the pump usually depressurizes the Hot Leg suction pipe, which creates void as it is where trapped hot water is located. It also creates void directly at the inlet of the pump, depending mostly on the start-up time of the RHR pump.

The second part of the computation is simulated to begin around 200 seconds after the start of the transient. It includes the switchover operation to containment sump recirculation. Once the RWST level reaches the low-low level setpoint, the injection path switches from the RWST line to the sump line. This swap over can be done with or without stopping the RHR pump, this actually depends on the plant specific EOPs. Steam located in the Hot Leg suction pipe is pulled back to the containment sump as a counter flow is created from the RWST to the containment sump. This steam pulled by this counter flow is condensed by cold water, which usually rises water hammer concerns.

Trips are defined in RELAP5 to simulate those valve and pump manipulations, with the right delays and time sequence. Again, those parameters strongly depend on the plant specific EOPs.
5 VOID TRANSPORTATION AND WATERHAMMER CALCULATION

The following plots were created in several analyzes, and generally show the thermal hydraulic behavior of specific phenomena concerning the RHR trains when such a transient is computed.

At the start of the RHR pump (20s) the flow goes from the RWST to the RHR pump. The limiting parameter is usually the void fraction at the pump when it starts up, as it creates a depressurization in the suction line depending on the inertia of the RWST suction piping.

The switchover operation (230s) is usually the most limiting part of the analysis, as it makes the pressure of the Hot Leg suction line reach its lowest value during the transient. When the sump is connected to the RHR system, a counter flow can be created to the containment sump while the RWST isolation valve is closing. Then the flow goes from the containment sump to the RHR pump.

During this switchover operation, the Hot Leg is depressurized to the containment sump pressure; it tends to induce voiding into the RHR pump suction line, which is pulled into the RHR pump suction path. The void reaching the pump is the first limiting criterion. In addition, this void is condensed while traveling into the RHR pump suction path, which often leads to condensation induced water hammer. The water hammer wave load magnitude is the second limiting parameter.

Those limiting parameters are bound by physics criteria to be defined with the customer. For the void fraction criterion, a maximum void fraction value of 3% at the pump is recommended in pump handbooks, otherwise the pump performance is affected. For the water hammer magnitude wave load, a piping stress analysis can be realized afterwards, or a really conservative criterion could be preferred.
In any case, the limiting criteria are the void fraction at the pump and the water hammer magnitude wave load, so that the initial thermal hydraulics conditions of the problem have to be adjusted not to exceed the criteria.

Here is a table showing the impact of reducing the initial Hot Leg temperature of a RHR train on the void fraction encountered at the RHR pump, for a specific NPP.

<table>
<thead>
<tr>
<th>Hot Leg temperature (°C)</th>
<th>Maximum void fraction at the pump (%) during pump start up (shutdown mode)</th>
<th>Maximum void fraction at the pump (%) during pump start up (start up mode)</th>
<th>Maximum void fraction at the pump (%) during swap over operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
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<tr>
<td>115</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>&lt;24</td>
</tr>
<tr>
<td>120</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>&lt;25</td>
</tr>
</tbody>
</table>

Table-1 Sensitivity analysis on the initial Hot Leg temperature

The plot below shows that 120°C is not acceptable for the RHR train considered, as there is more than 20% of steam at the RHR pump. A reduction by 10 °C is required to reduce the void fraction under the criterion of 3 % maximum voiding at the pump.
The generalized force equation in one-dimensional form can be resolved for a piping segment bound by two elbows as:

\[
F_{tot} = -\frac{\partial}{\partial t} \int \rho A(z) V \cdot dz
\]

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:

\[
F_{tot} = -\frac{\partial}{\partial t} \int \left( \alpha_f \rho_f A_f (z)V_f + \alpha_g \rho_g A_g (z)V_g \right) \cdot dz
\]

Where, \( \rho \) = density, \( A \) = flow area, \( V \) = velocity, \( \alpha \) = void fraction, \( z \) = distance along piping axis and subscripts \( f \) and \( g \) refer to liquid and gas phases.

Adjusting the initial thermal hydraulic data mostly implies reducing the initial Hot Leg temperature to a value for which the results are acceptable regarding the chosen criteria. Other sensitivity studies are also performed, for example on the RWST water temperature, to make sure of the conservatism of the analysis. As shown below as an example, a 10 °C reduction significantly reduces the water hammer wave load encountered in a RHR piping during the switchover operation.
The wave load is greatly reduced when a lower Hot Leg initial temperature is used in the input deck.

6 SUMMARY AND CONCLUSION

The first objective was to describe the current conditions in which the RHR system would be operated if a LOCA would occur during Mode 3/4. This has been achieved by reviewing and analyzing the OPs/EOPs and RHR system layout, building a RELAP5 model to compute the transient evolution of the RHR system, and assess the potential damages encountered by the system within those conditions.

The second objective, given the potential damages encountered in the current operating conditions, was to provide bounding conditions for which the RHR system can be safely operated relatively to two protection criteria: limited void fraction at the RHR pump and limited water hammer wave load. It has been achieved by adjusting the initial Hot Leg suction line temperature of the trapped water. These new plant specific conditions are then implemented in the OPs/EOPs.

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REFERENCES


