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# International Agreement Report

# Simulation with RELAP5/MOD3.3 of an Integral-Effect Test on Loop-Seal Clearing in the Upper Plenum Test Facility During Test A5


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# ABSTRACT

The RELAP5/MOD 3.3 computer code has been used to simulate an experiment on loop-seal clearing conducted in the Upper Plenum Test Facility. An assessment of this code version was performed by comparing the calculated results to the measured data from the experimental facility.

Loop-seal clearing in a pressurized-water reactor during an intermediate-break loss-of-coolant accident was investigated in the UPTF-TRAM experimental facility during a series of experiments designated Test A5. The phenomenon of loop-seal clearing was studied at 15 bar(a) during an integral-effects test designated ITRun2a.

This report presents assessments that demonstrate the suitability of the code for analyzing loop-seal clearing transients.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# EXECUTIVE SUMMARY


During a postulated break in the cold leg of a pressurized-water reactor, break sizes in a certain range lead to a reduction in the volume of primary-side water but not a complete emptying of the primary side. If water remains in the loop seal, then that water is not available for core cooling. The water in the loop seal is eventually displaced into the cold leg when the difference between steam pressure in the downward pipe of the loop seal and the pressure at the outlet of the reactor coolant pump (RCP) is less than the hydrostatic pressure difference for a water column in the upward pipe and RCP. When the pressure difference is sufficient to displace the water in the loop seal into the cold leg, the displacement is called loop-seal clearing.

Numerous phenomena occur during loop-seal clearing, such as sinking collapsed level of water in the downcomer, water displacement from the downward pipe of the loop seal into the upward pipe, entrainment of water by the steam flowing in the horizontal pipe of the loop seal, and water displacement and entrainment by steam in the upward pipe of the loop seal. These phenomena depend on parameters such as the break size, system pressure, core decay heat

A RELAP5 simulation of these phenomena was performed for a four-loop pressurized-water reactor with pressure-scaled break size of 490 $cm^2$ at an initial pressure of 15 bar(a) and a pressure-scaled decay heat of 3%. The results of the simulation were compared with experimental data from the Upper Plenum Test Facility, which simulated a 1300 MWe pressurized-water reactor with four loops and a geometric scaling factor of one-to-one. Integral-effect test ITRun2a was carried out using initial and boundary conditions that match those in the RELAP5 simulation.

The results of the RELAP5 simulation were compared with the experimental data. The time during the transient simulation at which the collapsed water level in the downward pipe of the loop seal sank to the top of the horizontal pipe of the loop seal was approximately 90 s after the break opening. The corresponding time during the experiment was within a few seconds of the simulated time. This defined the start of loop-seal clearing, because steam could then flow through the horizontal pipe to the upward pipe of the loop seal. The flow of steam displaced some of the water in the upward pipe.

At approximately 125 s after the break opening in the RELAP5 simulation, nearly all of the water in the upward pipe of the loop seal was removed, and the collapsed level of water in the bottom of the horizontal pipe reached a steady-state value of (24% of the pipe diameter). The steady-state conditions during the experiment were reached at approximately 140 s after the break opening. After steady-state conditions were reached, the collapsed level of water at the end of the horizontal pipe had the same value in the experiments as in the results from RELAP5. The general observation is that RELAP5 successfully simulated the transient that occurred during the integral-effect test ITRun2a in UPTF-TRAM Test A5.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| DC | downcomer |
| LOCA | loss-of-coolant accidents |
| PWR | pressurized-water reactor |
| RCP | reactor coolant pump |
| RPV | reactor pressure vessel |
| TRAM | Transient and Accident Management |
| UP | upper plenum |
| UPTF | Upper Plenum Test Facility |

# 1 INTRODUCTION

A break in the cold leg of a pressurized-water reactor (PWR) reduces the volume of primary-side water if the flow of water out of the break exceeds the flow of replacement water injected into the primary side. A sufficiently large reduction in the volume of water causes the water level in the reactor pressure vessel (RPV) to sink below the top of the core, which can lead to inadequate cooling and increased temperatures of the fuel assemblies. A sufficiently large reduction of the volume of primary-side water also leads to reduced pressure and steam production in the core. If the size of the break is not so large that the primary-side pressure sinks below the pressure on the secondary side, steam is condensed in the steam generators. Break sizes that are between these two boundaries, referred to in this report as intermediate-size breaks, lead to core temperatures that depend not only on the total volume of primary-side water but also on the distribution of that water in the primary side and, in particular, on the volume of water in the loop seal.

An example of unfavorable water distribution is shown schematically in Figure 1-1, which is taken from Liebert and Emmerling [1]. The water level in upper plenum (UP) of the RPV has sunk below the level of the hot leg, and steam produced in the core flows from the UP to the steam generators. Steam also flows from the UP through the gap between the hot leg nozzle and the core barrel (the UP/DC bypass) into the downcomer (DC). Because the pressure-loss coefficient for the UP/DC bypass is large, the pressure in the DC is less than the pressure in the UP, and this causes the water level in the DC to be above the level in the UP. The large pressure-loss coefficient for the UP/DC bypass also has the potential to cause the pressure at the outlet of the steam generator to be greater than the pressure in the DC. This is the case shown in Figure 1-1, as indicated by the low water level in the downward pipe of the loop seal, i.e. below the outlet of the steam generator, compared to the higher water level in the upward pipe of the loop seal, i.e. below the reactor coolant pump (RCP).

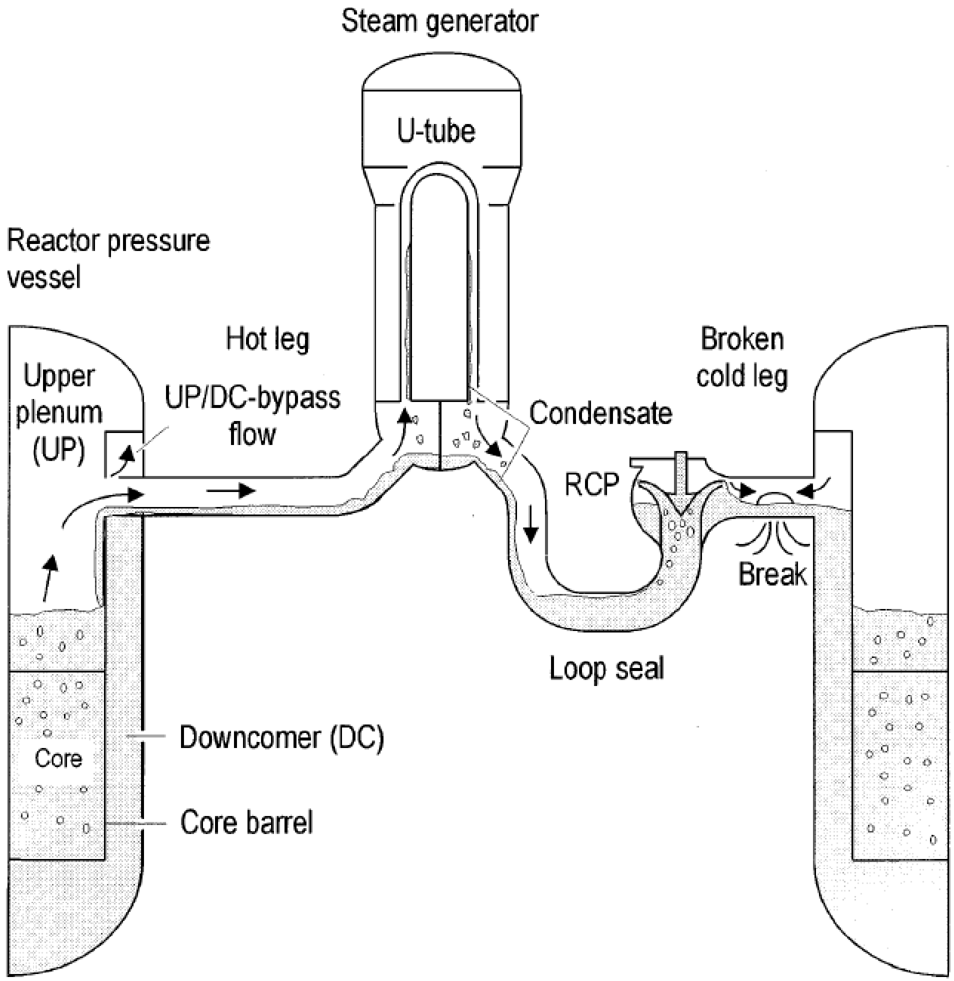


**Figure 1-1 Elevation View of Steam Flow in the Primary System of a PWR During Loop-Seal Clearing with a Break in the Cold Leg**

When the difference between steam pressure in the downward pipe and the pressure at the outlet of the RCP is less than the hydrostatic pressure difference for a water column in the upward pipe and RCP, the water level in the downward pipe is above the top of the horizontal pipe in the loop seal. In this case, the water distribution is unfavorable to cooling the core, because a volume of water remains in the horizontal and upward pipes of the loop seal instead of in the core. When the pressure difference across the loop seal is greater than the hydrostatic pressure difference for a water column in the upward pipe and RCP, the water level in the downward pipe sinks below the top of the horizontal pipe in the loop seal. The low water level provides a passage for steam in the downward pipe to flow through the horizontal and upward pipes. The steam flow also entrains water with it, and the volume of water in the upward pipe is reduced. This is referred to as loop-seal clearing, and it is favorable to core cooling. Loop-seal clearing causes water from the loop seal to flow to the downcomer, which increases the water level in the core. Loop-seal clearing also causes the pressure difference between the UP and the DC to be subsequently reduced, which also increases the water level in the core.

A schematic of flow paths for steam between the UP and the break is shown in Figure 1-2, which is adapted from Liebert and Emmerling [1]. Figure 1-2 shows the UP and DC of the RPV along with four loops, with a cold-leg break in Loop 4. Before loop-seal clearing, the flow path of steam from the UP through the loop seal to the cold-leg break is blocked by the column of water in the upward pipe of the loop seal. The only path for steam from the UP is through the UP/DC bypass and through the cold leg. After loop-seal clearing, the steam has the additional path shown in Loop 4 from the UP through the hot leg, the SG, and the loop seal to the cold leg.

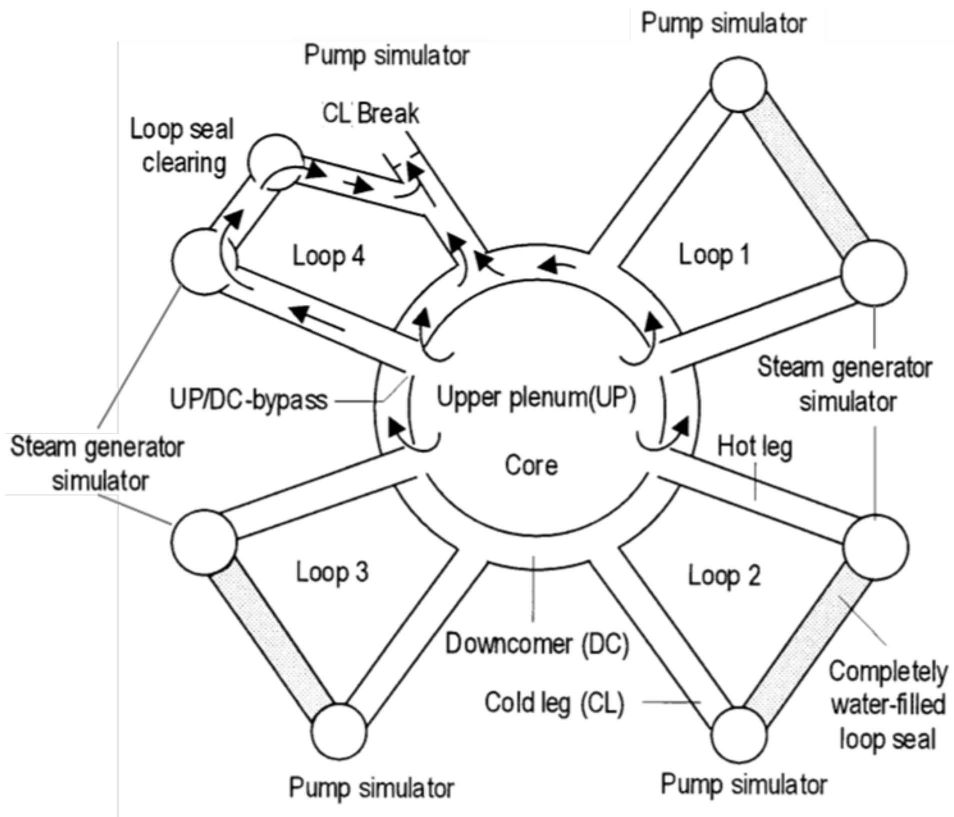


**Figure 1-2 Plan View of Steam Flow in the Primary System of o PWR During Loop-Seal Clearing with a Break in the Cold Leg of Loop 4**

Correct modeling of the loop seal behavior by thermal-hydraulic system-analysis computer codes such as RELAP5/MOD3.3 is important for accurately calculating core temperatures during loss-of-coolant accidents (LOCAs) with intermediate-size breaks. Geometrical and pressure scaling effects may cause difficulties when applying experimental results obtained from scaled-down test facilities to full-size reactor systems. Therefore, the ability of RELAP5/MOD3.3 to simulate loop-seal clearing was investigated by comparing the results of RELAP5/MOD3.3 with experimental data obtained in the Upper Plenum Test Facility (UPTF) during the Transient and Accident Management (TRAM) program. UPTF was geometrically scaled one-to-one for a 1300-MW PWR of the type common in Germany. The goal of the UPTF-TRAM Test A5 series of experiments was to investigate the water distribution during loop-seal clearing. The integral-effect test ITRun2a was chosen for comparisons between RELAP5/MOD3.3 and experimental data.

# 2 FACILITY AND TEST DESCRIPTION

The UPTF was constructed for participation in the international 2D/3D Program that was carried out by Germany, Japan and the United States to investigate the thermal-hydraulics of a PWR during a LOCA. A schematic of UPTF is shown in Figure 2-1, which is adapted from Damerell and Simons [2].

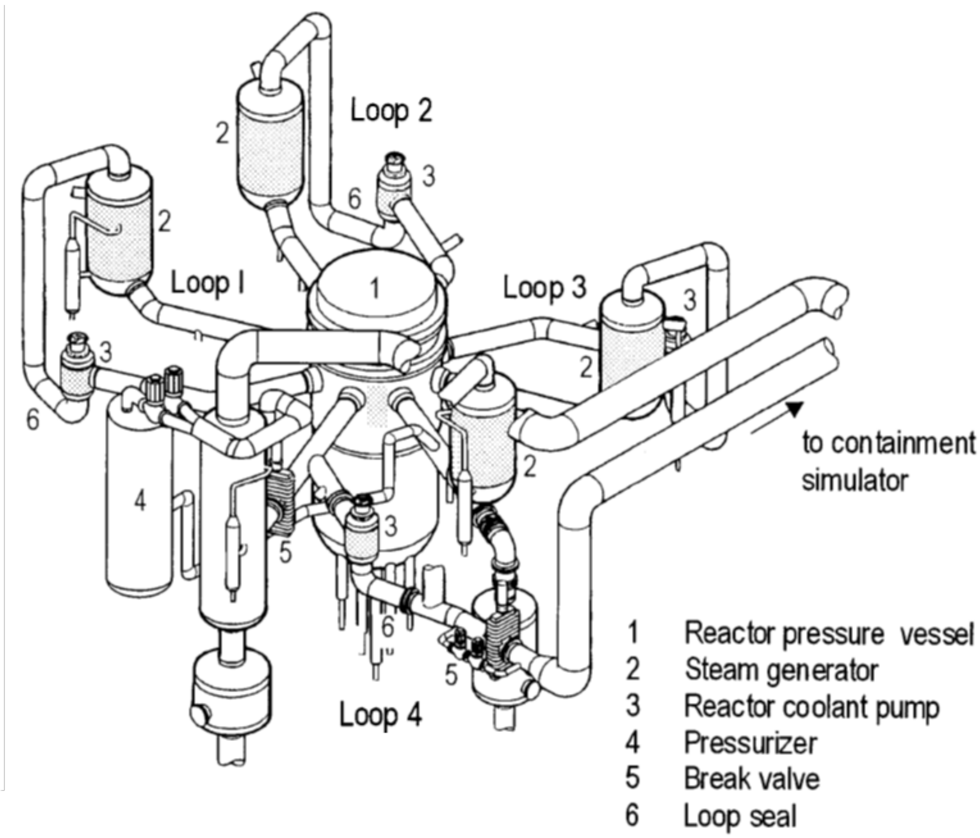


**Figure 2-1 Schematic of UPTF Indicating Primary-Side Components**

After the 2D/3D program, UPTF was modified for the TRAM test program by the addition of instrumentation at various locations. All four loop seals were instrumented with differential and absolute pressure transducers as well as thermocouples for fluid temperature measurement. The water levels were calculated from measured differential pressures. The steam flow through the loop seal was measured with an orifice.

## 2.1 Boundary Conditions

Prior to the start of the experiment, the UPTF was heated to the saturation temperature corresponding to 15 bar(a). The water in the test vessel and the four loops was also at the saturation temperature. The loop seals were filled with colder water at approximately 100°C for simulating condensate from the steam generators.

The experiment was initiated by opening the cold-leg break valve (in Loop 4) and starting the steam injection into the core simulator at an initial system pressure of 15 bar(a). The boundary and initial conditions are shown in Table 2-1.

**Table 2-1 Boundary and Initial Conditions for ITRun2a**

| | |
|---|---|
| Initial system pressure, bar(a) | 15 |
| Break size, $cm^2$ | 490 |
| Break location | cold leg of Loop 4 |
| Flow resistance of each pump* $(\Delta p \; 2 \; \rho \; A^2)/\dot{m}^2$ | 18 (simulation of a stationary pump) |
| Initial water level in the test vessel and loops | above hot legs |
| Initial water inventory in the loop seals | filled |

* relative to the cross-sectional flow area of the cold leg

After the start of the experiment, the system pressure was initially maintained at 15 bar(a) by increasing flow of steam, in order to compensate for the decreasing volume of water and the flow of steam through the leak. The pressure in the upper head is shown Figure 2-2 as the blue line labeled JAA01CP001H. After the steam flow reached a value corresponding to a decay heat of 3% at 80 bar(a), which occurred at a time of 251 s, the steam flow was held constant, and the pressure decreased as a result. The pressure reduction caused saturated water to flash to steam.

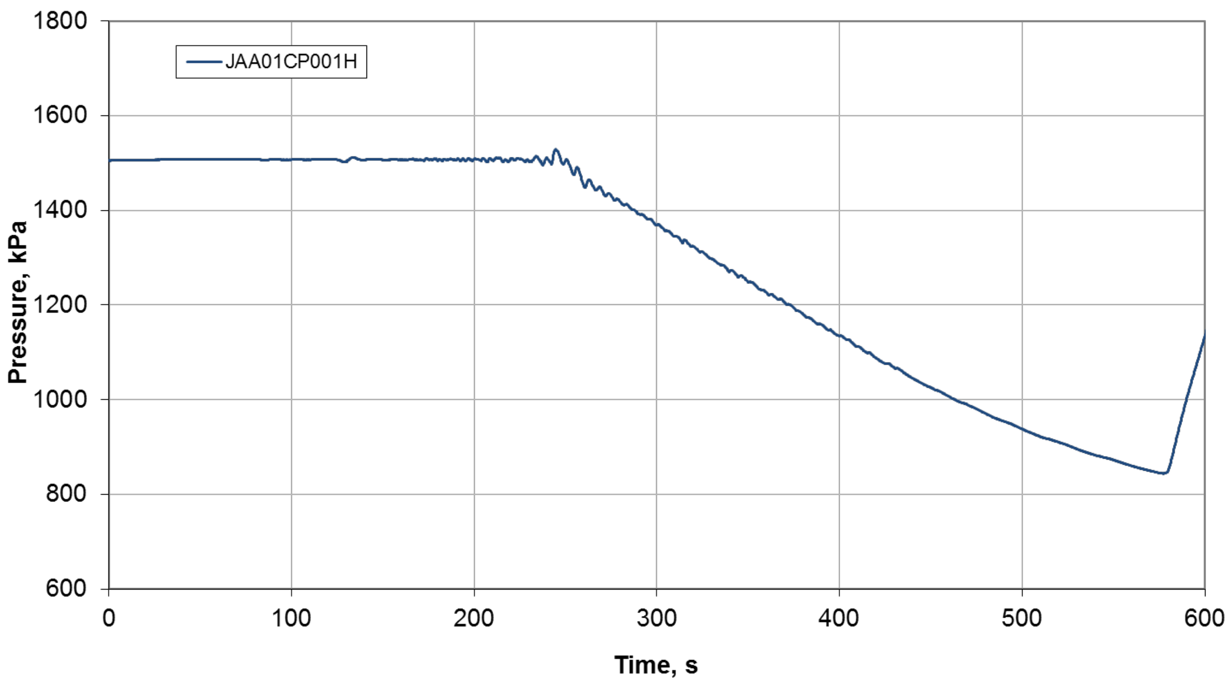


**Figure 2-2 UPTF-TRAM Test A5 ITRun2a: Steam Injection Rate and System Response**

## 2.2 Experimental Results

Immediately after the break valve opened, water flowed from the UP through the UP/DC bypass to the broken cold leg. Due to the large pressure-loss coefficient across the small gap that forms the UP/DC bypass, the pressure drop across the UP/DC bypass is correspondingly large. The pressure in the DC sinks below the pressure in the UP. Therefore, the water level UP sinks below the water level in the DC. These two water levels are shown in Figure 2-3. The water level in the downcomer is the blue curve labeled CJAA01CL003B. Also shown are horizontal lines labeled “top of HL” and “bottom of HL”, which are not experimental data. The line “top of HL” indicates the elevation at the top of the hot leg, which is also the elevation at the top of the cold leg. When the water level sinks to the top of the cold leg, a path for steam to flow from the downcomer to the leak is formed. The line “bottom of HL” indicates the elevation at the bottom of the hot leg, which is also the elevation at the bottom of the cold leg. The difference in elevation for these two lines is 0.75 m, which is the diameter of the cold leg. These lines are for reference only.

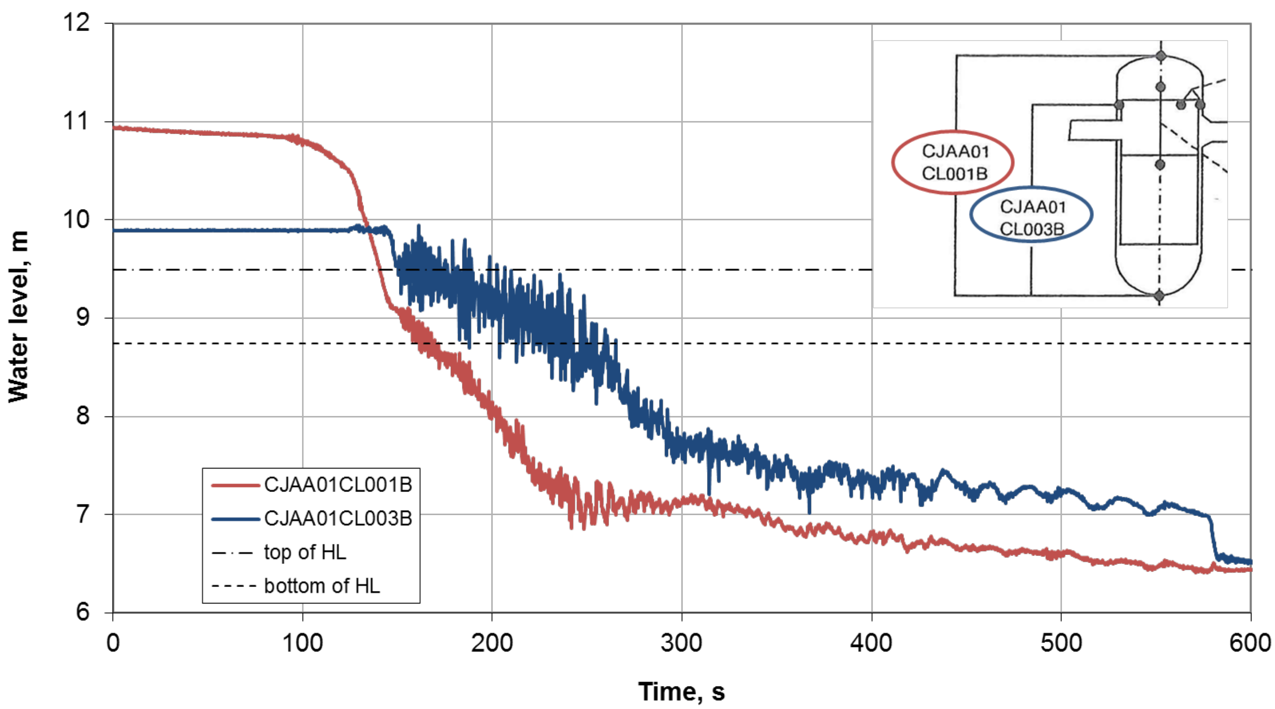


**Figure 2-3 Experimentally Derived Water Level in the Downcomer**

The water level in the UP sank below the top of the hot legs at 140 s. Steam injected into the core could flow from the UP through the UP/DC bypass into the downcomer. At 150 s, the water level in the downcomer sank below cold legs. The steam could flow from the downcomer through the cold leg, and two-phase flow through the break was possible.

After the break valve opened, water was discharged through the leak, and the pressure in the cold leg of the broken loop decreased. However, the pressure in the UP was held approximately constant by the injection of steam in the core. Consequently, the pressure in the downward pipe of the loop seal also remained approximately constant. The reduced pressure in the cold leg caused the water level in the downward pipe of the loop seal to decrease. A plot of the experimentally derived water level (as calculated from a measured pressure difference) in the downward pipe as a function of time is shown in Figure 2-4, and the decreasing water level is indicated by the red curve labeled CJEC04CL004. The location of the pressure taps where the pressure difference was measure is shown schematically in the inset in the figure.

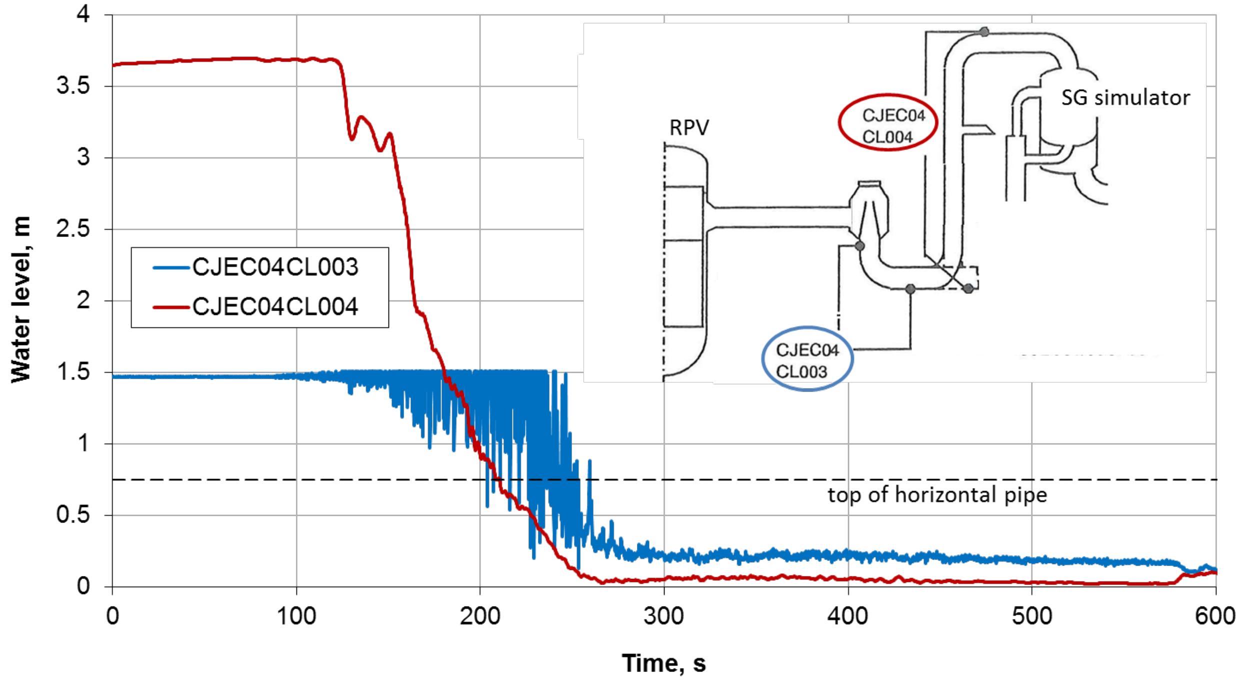


**Figure 2-4 Experimentally Derived Water Level in the Loop Seal**

Figure 2-4 also shows the experimentally derived water level in the upward pipe as a function of time, which is indicated by the blue curve labeled CJEC04CL003. The range of the measured pressure difference was limited to a corresponding water level of less than 1.5 m, even though the water level at the beginning of the experiment was higher. Also shown in Figure 2-4 is a horizontal line labeled “top of horizontal pipe”, which is not experimental data. The line is at a water level of 0.75 m, which is the diameter of the horizontal pipe. This line is for reference only.

Figure 2-4 shows that the water level in the downward pipe of the loop seal reaches the top of the horizontal pipe at a time of 207 s. This is the start of loop-seal clearing, because steam is able to flow from the downward pipe to the upward pipe of the loop seal. The steam entrains water in the upward leg, and the entrainment results in a decreasing water level. This decrease in the water level in the upward pipe is also seen in Figure 2-4. The fluctuation in the water level in the upward pipe is the result of unstable nature of the entrainment phenomenon.

The experimentally derived water level in the upward pipe reached a steady-state value of 0.25 m at approximately 262 s. This is also the time point at which the collapsed level in the downcomer sank below the bottom of the cold leg.

**Table 2-2 Sequence of Events for ITRun2a**

| Event | Time, s |
|---|---|
| Start of data-collection system | 0 |
| Opening of cold-leg break valve | 124 |
| Start steam injection by the core simulator | 124 |
| Single-phase water flow from the break valve began | 124 |
| Reduction of water level began in the upper plenum | 124 |
| Reduction of water level began in Cold Leg 4 | 124 |
| Water level sank to top of hot leg | 140 |
| Reduction of water level began in broken Cold Leg 4 | 148 |
| Two-phase flow in began in break valve | 148 |
| Water level in the downcomer sank to the top of the cold legs | 150 |
| Displacement of water from loop seal of Cold Leg 4 | 150 |
| Water level in the upper plenum sank to the bottom of the hot legs | 180 |
| Water level in the downward leg of the loop seal in broken Cold Leg 4 sank below the top of the horizontal section. **Start of loop-seal clearing**. Continues until 262 s | **207** |
| Water level in the downcomer occasionally sank below the bottom of the cold legs | 232 |
| Water level in the downcomer remained below the bottom of the cold legs | 241 |
| Water level in the *upward* leg of the loop seal in broken Cold Leg 4 sank below the top of the horizontal section. | 241 |
| Completion of loop-seal clearing in Loop 4 | 262 |
| End of experiment | 572 |

# 3 RELAP5/MOD3.3 CALCULATIONS

The experiment UPTF-TRAM Test A5 ITRun2a was simulated with RELAP5/MOD3.3. A nodalization for UPTF was created for the RPV and the cold legs and hot legs. The boundary conditions were taken from the experimental data. The results for loop-seal clearing from RELAP5/MOD3.3 were compared with experimental data.

All simulations were performed in two calculations: a steady-state calculation in order to stabilize the computational process before the opening of the break valve, and a subsequent transient calculation for times after the opening of the break-valve.

## 3.1 Model of UPTF-TRAM Test A5 ITRun2a

The nodalization applied in the simulations by RELAP5/Mod 3.3 is shown in Figure 3-1. The nodalization includes the downcomer, lower head, core, upper plenum, and upper head of the RPV. Also included are the cold legs of the four loops and the hot leg of the broken loop. The remaining three hot legs were combined into a single nodalization.

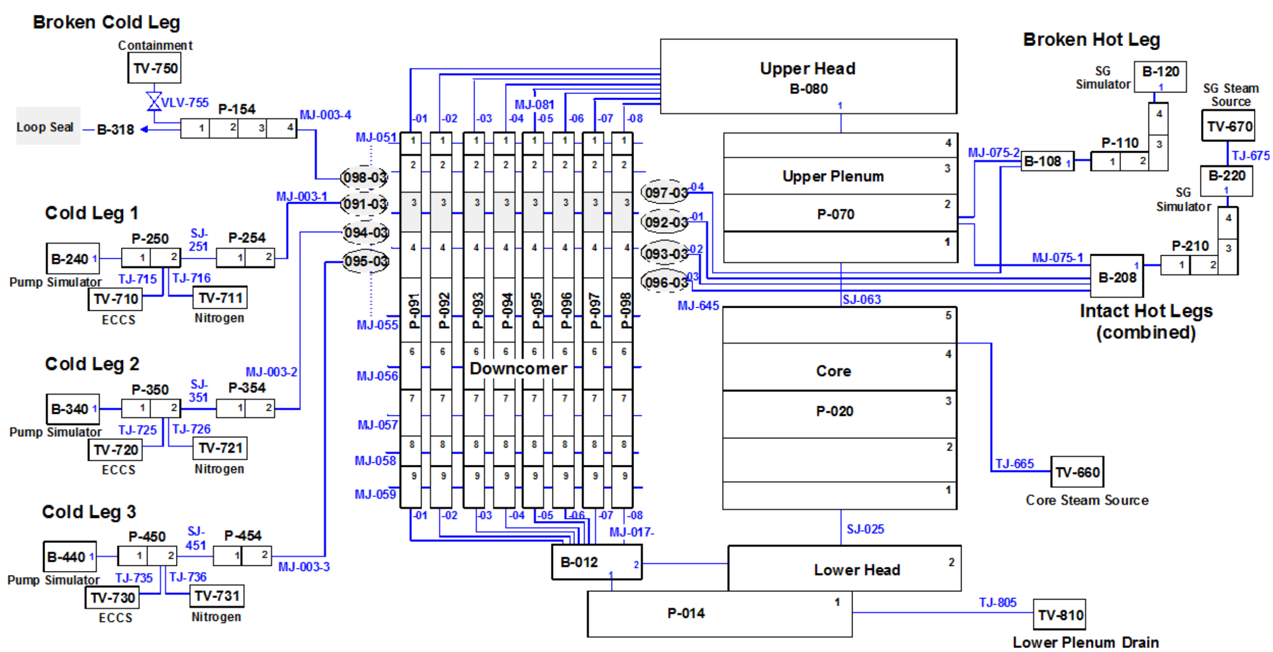


**Figure 3-1 RELAP5 Nodalization of UPTF-TRAM Test A5 ITRun2a**

The labels for the component types in Figure 3-1 have B for a branch, P for a pipe, TV for a time-dependent volume, TJ for a time-dependent junction, SJ for a single junction, MJ for a multiple junction, and VLV for a valve. The component numbers follow the letters for the component types.

The initial values for the pressures, temperatures, and water levels in the various components were taken from experimental data, such as those shown in Table 2-1. Some of these values were changed only slightly by RELAP5 during the steady-state calculation.

The nodalization of the cold leg in the broken loop, Loop 4, is shown in more detail in Figure 3-2. The break, pump, and the loop seal were included.

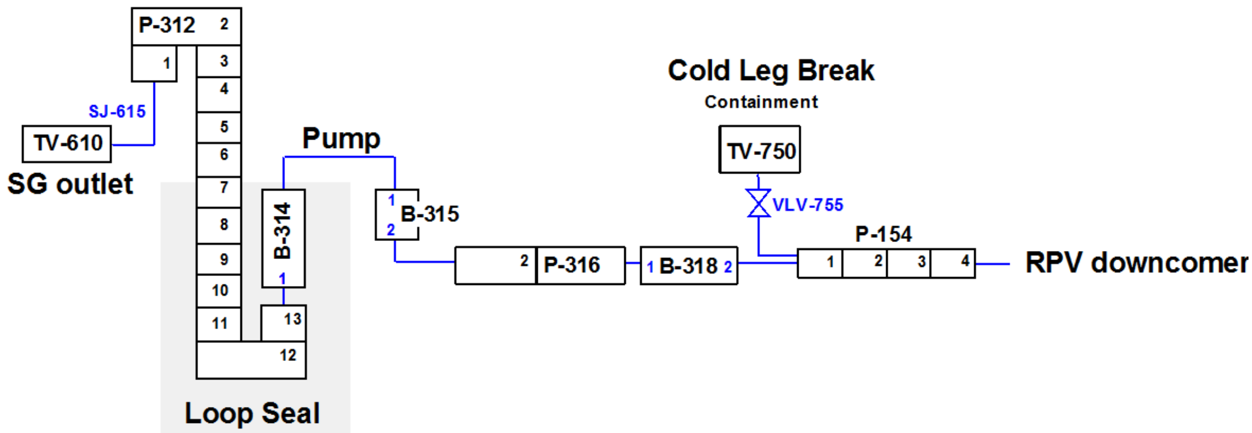


**Figure 3-2 RELAP5 Nodalization of the Loop Seal for UPTF-TRAM Test A5 ITRun2a**

The loop seal was simulated with a pipe component with the number 312 and having 13 volumes. At the outlet of the loop seal is the pump, which is simulated with two branches. One branch with a component number 314 is the inner passage of the pump extending to the pump weir, and the second branch with a component number 315 is the outer passage of the pump connecting the pump weir to the cold leg.

The boundary condition for the pressure in the UP, which was simulated by a branch with component number 80, was taken from the experimental data shown in Figure 2-2. These values from the transient calculation are shown in Figure 3-3 by the curve labeled PUH. Note that the experimental data indicated by the dashed line labeled JAA01CP001H are also shown for ease of comparison.

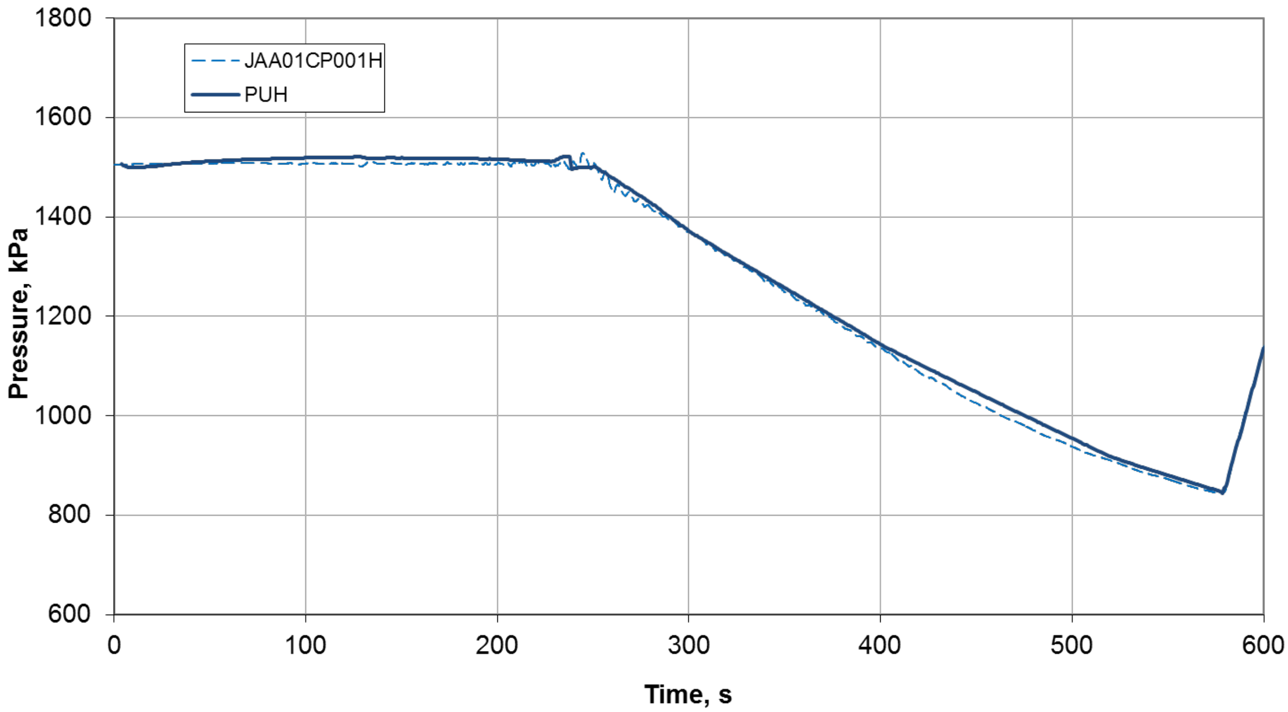


**Figure 3-3 RELAP5 Boundary Condition for Pressure in the Upper Head and SG**

The boundary condition for the pressure at the outlet of the SG, which was simulated with a time-dependent volume having a component number 610, was also input to the simulation, and the same values were used as for the UP. The pressure in the containment, which was simulated by a time-dependent volume having a component number 750, was set equal to the experimental value.

## 3.2 Simulation Results

The results of the transient calculation were compared with corresponding experimental data. The water level in the downcomer was compared with the experimental data from Figure 2-3, and the results are shown in Figure 3-4. The water level reached the top of the cold leg at approximately 150 s, which is the same as for the experimental data. For times greater than 150 s, steam could flow from the downcomer through the cold leg, and the pressure difference between the downcomer and the break was reduced. There was a time span from 150 s until 290 s during which two-phase flow existed in the cold leg. This time span is longer than in the experimental data. A smaller two-phase flow rate through the break during choked flow calculations by RELAP5 would lead to a greater water volume in the cold leg than observed in the experiment. A comparison of the flow rates through the break between RELAP5 and the experimental values was not made, however. The measurements of the flow rate through the leak was difficult, because the cyclones that separated the liquid from the steam were flooded relatively quickly. This was observed in the measured water level in the separator that reached a maximum soon after the break opened and remained constant until loop-seal clearing was complete.

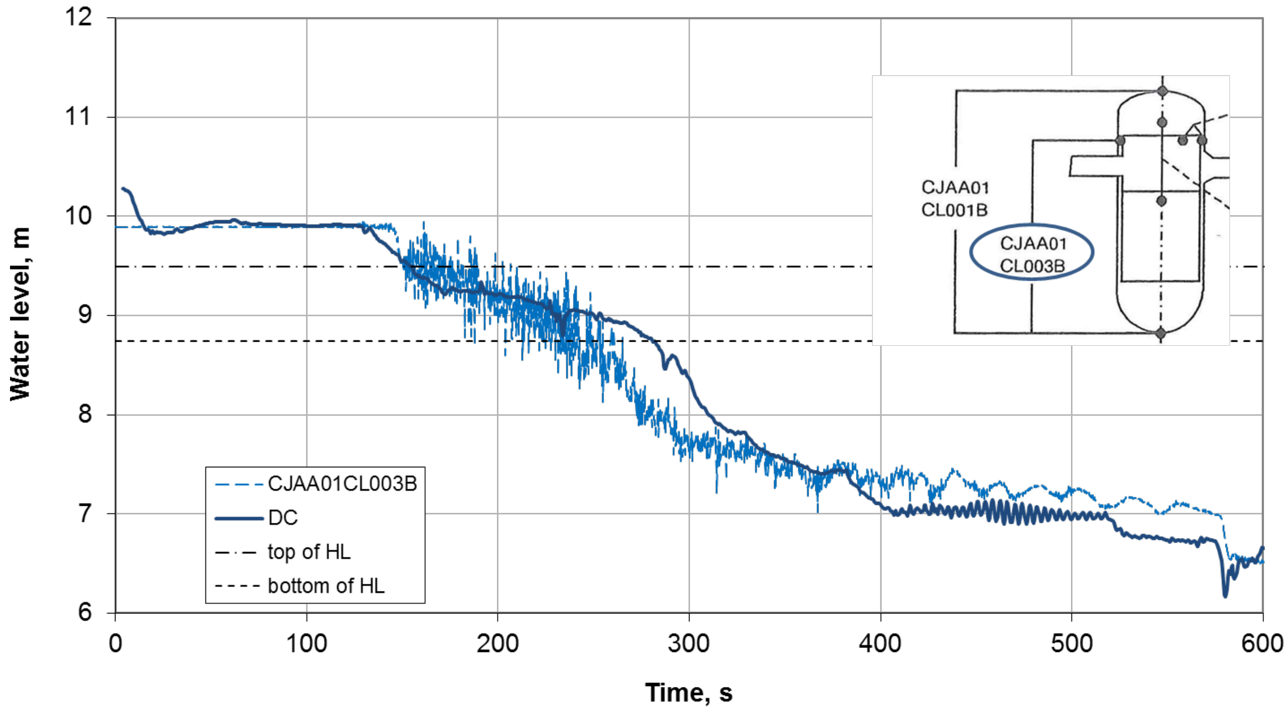


**Figure 3-4 RELAP5 Water Level in the Downcomer**

The water level in the downward pipe of the loop seal calculated by RELAP5 is shown in Figure 3-5 by the dark-red curve labeled “downward”. Also shown are the measured values from Figure 2-4 for ease of comparison. The steady-state level from RELAP5 starts to sink soon after the break opened, just as for the experimental value. The level in the downward pipe from RELAP5 sank more quickly than the experimental values, until the level equal to the bottom of the pump was reached. Thereafter, the water level in the downward pipe as calculated by RELAP5 sank more slowly than the measured level. The time at which loop-seal clearing started was 213 s for RELAP5, which is approximately the same as for the experiment.

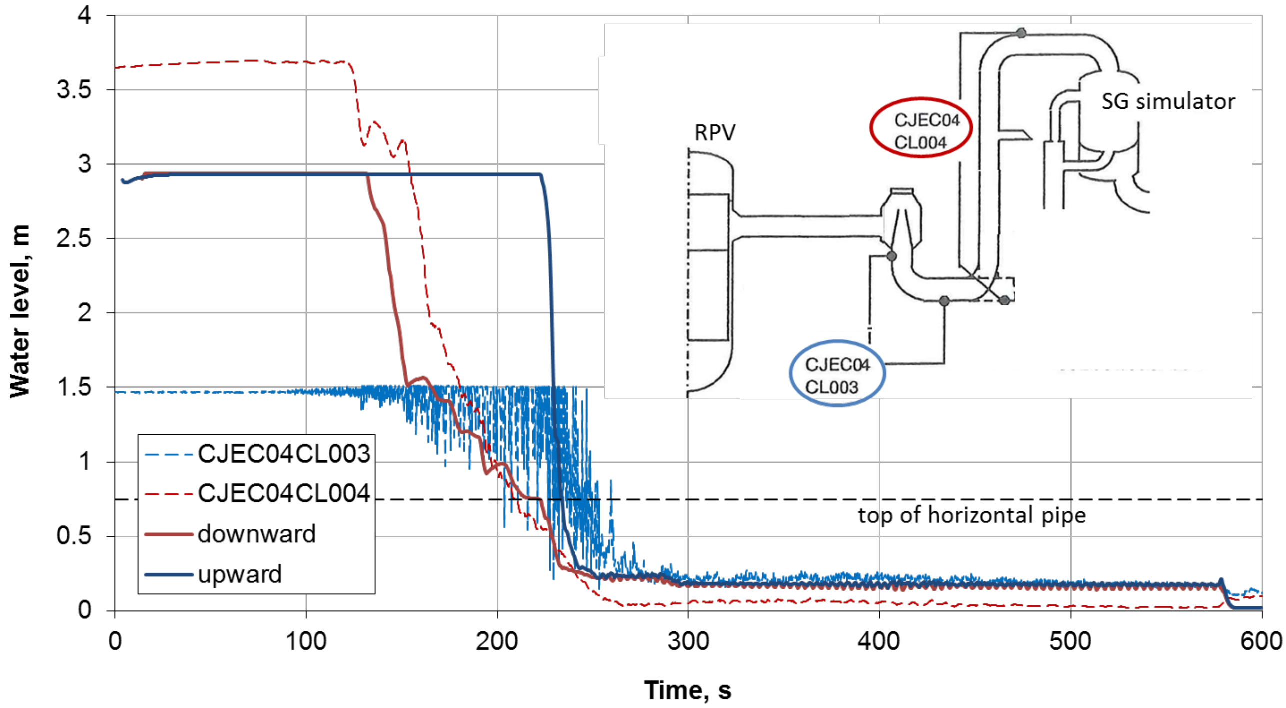


**Figure 3-5 RELAP5 Water Level in the Loop Seal**

Soon after the water level in the downward pipe sank below the top of the horizontal pipe, steam started to flow from the downward pipe to the upward pipe of the loop seal. The water displaced by steam in the upward leg caused the collapsed water level in the upward pipe to decrease. This decrease in the water level in the upward pipe from RELAP5 is shown in Figure 3-5 by the dark-blue curve labeled “upward”. Also shown are the measured values from Figure 2-4 for ease of comparison. At a time of approximately 230 s, the collapsed water level calculated by RELAP5 reached the maximum of the measurement range (1.5 m). This is consistent with an estimate of when the average of the fluctuations in the measured water level started to sink below 1.5 m. Therefore, the agreement between RELAP5 and the experimental data is acceptable.

After the collapsed water level in the upward pipe calculated by RELAP5 sank below 1.5 m, the rate of decrease exceeded the corresponding rate of decrease observed in the experimental data. Consequently, loop-seal clearing as calculated by RELAP5 was completed at approximately 250 s, which is slightly before the experimental data reached a steady-state value at 262 s. A smaller interfacial friction factor in RELAP5 would reduce the rate of decrease in the collapsed water level, and improve the agreement between RELAP5 and the experimental data. An adjustment in the default values for interfacial friction in RELAP5 was not investigated however, because the agreement was acceptable.

Although loop seal clearing as calculated by RELAP5 was completed slightly before the experimental data reached a steady-state value, the collapsed level in the upward pipe at the end of loop-seal clearing is equal to the experimentally derived level. This indicates that no adjustment to the interfacial friction is necessary for this phenomenon. The steady-state collapsed level of 0.18 m is 24% of the pipe diameter.

RELAP5 calculated no difference between the collapsed water level in the upward pipe and the downward pipe, indicating that the water level is uniform in the horizontal pipe of the loop seal. In contrast, the experimentally derived water levels for the upward pipe and downward pipe are not equal. The unequal water levels are depicted schematically in Figure 3-6. A large flow rate of steam or a large interfacial friction leads to a large pressure gradient in the horizontal direction that supports the difference in the hydrostatic head at the ends of the horizontal section. The absence of this difference in the calculations by RELAP5 could be corrected by a larger steam flow rate or a larger interfacial friction or both. These adjustments to the RELAP5 model were not made, however, due to the good agreement in the water level in the upward pipe between the RELAP5 value and the experimentally derived level at the end of loop-seal clearing.

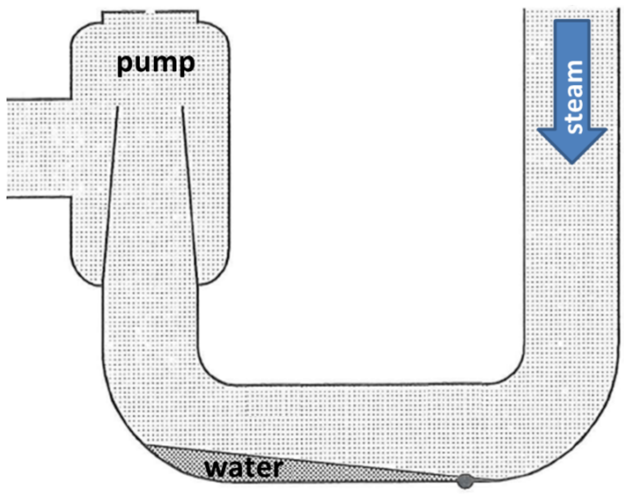


**Figure 3-6 Schematic of Water Remaining After Loop-Seal Clearing**

# 4 CONCLUSIONS

A RELAP5 simulation was performed of a four-loop PWR with a scaled break size of 490 $cm^2$ at an initial pressure of 15 bar(a). Numerous phenomena were simulated, such as the sinking of the collapsed level of water in the downcomer, the displacement of water from the downward pipe of the loop seal into the upward pipe, the entrainment of water by the steam flowing in the horizontal pipe of the loop seal, and the displacement and entrainment of water by steam in the upward pipe of the loop seal.

The results of the RELAP5 simulation were compared with data from experiment ITRun2a of UPTF-TRAM Test A5. The time during the transient simulation at which the collapsed water level in the downward pipe of the loop seal sank to the top of the horizontal pipe of the loop seal was approximately 90 s after the break opening. The corresponding time during the experiment was within a few seconds of the simulated time. This defined the start of loop-seal clearing, because steam could then flow through the horizontal pipe to the upward pipe of the loop seal. The flow of steam then displaced some of the water in the upward pipe.

At approximately 125 s after the break opening in the RELAP5 simulation, nearly all of the water in the upward pipe of the loop seal was removed, and the collapsed level of water in the bottom of the horizontal pipe reached a steady-state value of 0.18 m (24% of the pipe diameter). The steady-state conditions during the experiment were reached at approximately 140 s after the break opening. The experimentally derived collapsed level of water at the end of the horizontal pipe near the upward pipe had the same value as calculated by RELAP5. This indicates that the interfacial friction factor and the steam velocity or some combination of the two is the same in RELAP5 as in the experiment.

The agreement between the RELAP5 results and the experimental data shows that the unmodified models in RELAP5 are adequate for successfully reproducing the experimental data.

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K. Tien, Project Manager

11. ABSTRACT (200 words or less)

The RELAP5/MOD 3.3 computer code has been used to simulate an experiment on loop-seal clearing conducted in the Upper Plenum Test Facility. An assessment of this code version was performed by comparing the calculated results to the measured data from the experimental facility.
Loop-seal clearing in a pressurized-water reactor during an intermediate-break loss-of-coolant accident was investigated in the UPTF-TRAM experimental facility during a series of experiments designated Test A5. The phenomenon of loop-seal clearing was studied at 15 bar(a) during an integral-effects test designated ITRun2a.
This report presents assessments that demonstrate the suitability of the code for analyzing loop-seal clearing transients.

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