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I. Spasov, G. Gerova, K. Filipov, Al. Grigorov, and N. P. Kolev

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# Simulation and Integrated Uncertainty Analysis of the OECD/ NEA V1000CT2 Vessel Mixing Problem with RELAP/ SCDAPSIM mod3.5

I. Spasov[1,2,a)], G. Gerova[1,b)], K. Filipov[1,c)], Al. Grigorov[1,d)] and N. P. Kolev[2,e)]

*[1]Technical University of Sofia*
*Faculty of Power Engineering and Power Machines*
*Department of Thermal and Nuclear Power Engineering*
*8, Kl.Ohridski Blvd., 1000 Sofia, Bulgaria*

*[2]Institute for Nuclear Research and Nuclear Energy*
*Bulgarian Academy of Sciences,*
*72 Tzarigradsko Shosse Blvd., 1000 Sofia, Bulgaria*

[a)] Corresponding author: spasov@tu-sofia.bg, spasov@inrne.bas.bg
[b)] ggg@tu-sofia.bg
[c)] filipov@tu-sofia.bg
[d)] grigorov@tu-sofia.bg
[e)] npkolev@inrne.bas.bg

**Abstract.** The paper presents validation results for multi-1D thermal-hydraulic models with RELAP/SCDAPSIM mod3.5 used for pseudo-3D reactor vessel simulation. The main objective is to test the capabilities and limitations of such calculation models to represent the vessel mixing phenomena in a VVER-1000. The test case is from Phase 2 of the OECD/NEA VVER-1000 coolant transient benchmark (V1000CT-2) and includes the calculation of an asymmetric vessel thermal-hydraulic transient caused by a steam generator isolation leading to heat-up of the disturbed loop. The considered 3D thermal-hydraulic transient in the reactor vessel is relevant to the initial part of VVER-1000 main steam line break scenarios from hot full power. The task is to solve a reactor vessel boundary condition problem with given initial and boundary thermal-hydraulic conditions and to calculate the fuel assembly inlet temperatures in the final state, the formation of the disturbed sector at the core inlet, the angular shift of the loop flows in the final state and the reactor vessel outlet parameters during the transient. Plant data from flow mixing experiments conducted during the commissioning of Kozloduy-6 are available for comparison. Two calculation models with different detail of vessel discretization and cross-flow junctions were tested: a 12-azimuth sector vessel model without radial discretization and a 24-sector model with radial discretization. The predicted integral parameters are in generally good agreement with the reference plant data. The preliminary results from the 24-sector model show some improvement in the predicted peripheral azimuthal and radial transition zones of the disturbed core inlet sector compared to the 12-sector ones but indicate a need for further mesh refinement studies. An integrated uncertainty analysis for input parameters used as vessel boundary conditions was carried out with RELAP/SCDAPSIM for the 12-sector model simulation. The benchmark calculation results illustrate the applicability of such models to asymmetric vessel transients involving thermal mixing and azimuthal flow rotation.

## INTRODUCTION

The realistic modeling of the coolant mixing in the reactor pressure vessel is of special importance for the accuracy of the reactor safety analysis involving 3D vessel thermal hydraulics or coupled neutronic-thermal

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hydraulic calculations. It is of practical interest to test the applicability and limitations of widely used coarse-mesh system thermal-hydraulic codes in simulations involving such phenomena. The objectives of this work are to:

- Develop a multi-1D thermal-hydraulic (T-H) calculation model of a VVER-1000 reactor pressure vessel with a recent version of the RELAP/SCDAPSIM mod3.5 code [1]
- Test and validate the calculation model on the VVER-1000 vessel mixing benchmark [2] which is part of Phase 2 of the OECD/NEA VVER-1000 coolant transient benchmark (V1000CT-2)
- Perform an integrated uncertainty analysis of the V1000CT-2 vessel mixing simulation with RELAP/SCDAPSIM mod3.5.

Phase 2 of the OECD VVER-1000 coolant transient benchmark (V1000CT-2) [2], [3] was defined because previous studies had identified the vessel mixing as an unresolved issue in the simulation of complex reactivity transients. The V1000CT-2 benchmark consists of two parts: the calculation of a vessel mixing (thermal-hydraulic) problem [2] and a coupled 3D neutronic-thermal hydraulic simulation of a main steam line break (MSLB) transient [3] using improved vessel T-H models.

The vessel mixing thermal-hydraulic problem is based on a Kozloduy-6 startup experiment [2], [4] with isolation of one steam generator at low reactor power which causes heat-up of the disturbed coolant loop. The loop heat-up triggers a 3D thermal-hydraulic transient in the reactor vessel which is relevant to the initial part of VVER-1000 main steam line break (MSLB) scenarios from hot full power. The purpose of this T-H benchmark is to test the capability of computational fluid dynamics codes (CFD) and coarse-mesh system codes to represent the in-vessel thermal hydraulics, and to analyze the coolant mixing in the down-comer and the lower plenum of the reactor pressure vessel (RPV).

In this work, a multi-1D T-H calculation model of the Kozloduy-6 VVER-1000 reactor pressure vessel was developed with RELAP/SCDAPSIM mod3.5 and tested on the V1000CT-2 vessel mixing benchmark vs. plant measured data and in code-to-code comparisons. After the model validation a built-in module in RELAP [5] was used for integrated uncertainty analysis, based on the Wilks' formula. Uncertainty analysis was carried out only for the measurement uncertainties of integral parameters used as boundary conditions. Uncertainties related to models and correlations, spatial discretization, numerical schemes, modeling options, material properties and user effects are not considered. A probabilistic approach to the propagation of input uncertainties was applied.

In the sequel, Section 2 gives a schematic of the VVER-1000 reactor pressure vessel. Section 3 summarizes the main features of the vessel mixing experiment and the corresponding standard problem. Details of the benchmark specifications can be found in ref. [2]. Section 4 presents the RELAP modeling assumptions and the simulation results. Section 5 describes the methodology and the results of the uncertainty analysis.

## THE VVER-1000 REACTOR

The reactor vessel of the four-loop VVER-1000 V320 is schematically illustrated in Figure 1. The detailed description of the reactor vessel and internals can be found in refs. [2] and [6].

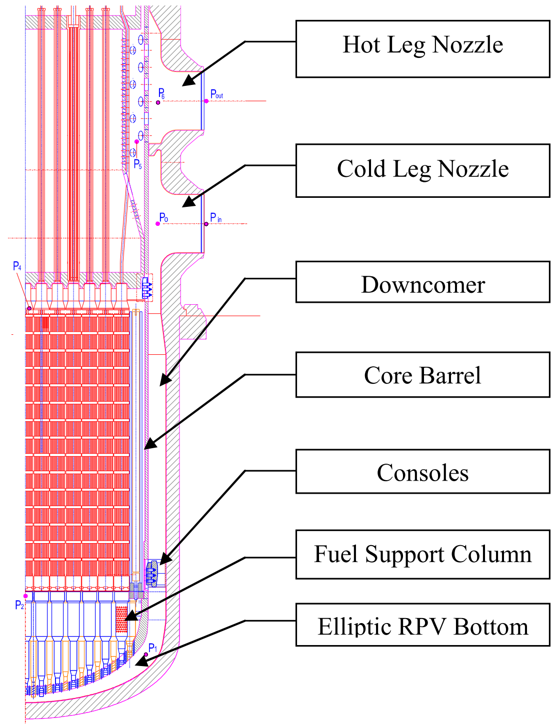


**FIGURE 1.** Reactor vessel and internals of Kozloduy-6

## THE VVER-1000 VESSEL MIXING BENCHMARK

### The Kozloduy-6 Vessel Mixing Experiments

Coolant mixing in a VVER-1000 V320 reactor has been investigated in plant experiments [2], [4] during the commissioning of units 5 and 6 of the Kozloduy nuclear power plant (NPP). Starting from a nearly symmetric initial hydraulic state at low reactor power (9.36% of the rated nominal power), thermal asymmetric loop operation was caused by disturbing the steam flow of one of the four steam generators (SG). The control rod positions were fixed and the moderator temperature feedback was negligible at high boron concentration. Thus the resulting 3D RPV transient can be considered as a nearly pure thermal-hydraulic test case because of the approximately constant relative power distribution during the transient.

For the vessel mixing experiment, the primary circuit was stabilized at 270ºC. All main coolant pumps were in operation and the steam generators were operated by feed water and steam. In order to heat up a certain loop, the pressure in the corresponding SG was first increased by closing the steam isolation valve and by isolating the SG from feed water. Then the pressure was stabilized by steam dump to the condenser. Non-uniform and asymmetric loop flow mixing in the RPV was observed in the event of such thermally asymmetric loop operation. For certain flow conditions a swirl was formed in the down-comer and the lower plenum causing an azimuthal shift of the main loop flows with respect to the cold leg axes. During the TH transient the measured integral parameters were documented for a time interval of 1800 s. For the initial and final stabilized states the plant data include integral parameters, the assembly-wise core outlet temperatures and the estimated assembly temperature rises.

**Initial State:** The reactor is at the beginning of Cycle 1 and the power is 9.36% of the nominal. All four main coolant pumps and four SGs are in operation. The pressure above the core is 15.59 MPa, the coolant temperature at the reactor inlet is 268.6ºC and the boron acid concentration is 7.2 g/kg (the coolant temperature reactivity coefficient is zero near 7.5 g/kg). For this initial state, the relative fuel assembly temperature rise $\delta T_{k,rel}$ (k=1,95) in 95 instrumented assemblies was calculated from measured cold leg and assembly outlet temperatures. The measured data and the 60-degree rotational symmetry of the fresh fuel core were used to estimate the heat up for assemblies without temperature control, so that the full core temperature rise distribution was obtained.

**Transient:** In the case considered here the transient was initiated by closing the steam isolation valve of SG-1 and isolating the SG-1 from feed water. The pressure in SG-1 started to increase and stabilized at 6.47 MPa in about 20 minutes. The main steam header pressure was maintained approximately constant during the transient by operating the steam dump to condenser in pressure control mode. The coolant temperature in the cold and hot legs of loop no. 1 rose by approximately 13.5ºC and the mass flow rate decreased by about 3.4%. The mass flow rate through the reactor decreased about 1%. At 90 seconds after the disturbance, the temperature of cold leg no. 1 exceeded that of the hot leg. The difference stabilized to 0.6–0.8ºC in about 20 minutes. The reactor power changed 0.16% as calculated from the primary circuit energy balance. The initially symmetric core power distribution did not change significantly.

**Final State:** For the analysis presented here, the stabilized state at 30 minutes after the separation of the SG-1 is considered as "final state." The core inlet temperatures were calculated from the measured core outlet temperatures and the estimated assembly by assembly temperature rise δTk, k=1,163 for the initial state, where k is the assembly number. The δTk,rel distribution was assumed constant during the transient due to the approximately constant normalized core power distribution.

The measurement errors are ±1.5ºC for temperatures, ± 110 kg/s for inlet mass flow rates, ± 0.3 MPa for the core outlet/reactor outlet pressure, and ± 60 MW for core power. In the initial and final stabilized states the values of the integral parameters were taken as the average of 10 readings.

## The VVER-1000 Vessel Mixing Test Problem

The test problem of the OECD/NEA VVER-1000 vessel mixing benchmark [2] is based on the above described Kozloduy-6 loop heat-up experiment. The benchmark provides a validation test of the vessel thermal hydraulics in case of loop temperature and flow disturbances with all main coolant pumps in operation.

The available plant data [2], [4] include:

- Core, vessel and plant integral parameters and time histories
- The pressure line in the vessel
- Initial and final state 2D distributions of the fuel assembly outlet temperatures in 95 out of 163 assemblies
- Core power distribution (assumed constant during the transient).

Part of the measured integral parameters such as the RPV inlet temperatures and mass flow rates, and the core outlet/reactor outlet pressure were used as vessel boundary conditions, assuming flat temperature and flow distributions over the vessel inlets.

Other plant data such as the assembly inlet temperatures, full core distributions and loop-to-assembly flow mixing coefficients have been derived from the direct measurements. The full core outlet temperatures (for 163 assemblies) were obtained by symmetry considerations and cross-interpolation from the 95 measured values. Note that at the beginning of life the core has 60 degrees rotational symmetry in the initial state.

In order to reduce the uncertainty associated with the modeling of local flow mixing and the quasi-stagnation zone in the assembly head, the assembly inlet temperatures Tin,k (k=1,163) were estimated from the outlet measurements and used for comparison with the calculations instead of the outlet temperatures. These temperatures were estimated under the following assumptions:

- Uniform assembly flows (the actual non-uniformity is max 1-1.5%)
- Constant assembly powers or temperature rise were during the transient (the actual local power changes during the transient were generally less than 2% according to self-powered neutron detector readings)
- No inter-assembly cross-flow.

The experimental mixing coefficients Cnk from cold leg # n to the outlet of FA # k are defined as the ratio of coolant flow from loop n into assembly k, to the total flow through assembly k (k=1,163). In general, the flow into assembly # k has contributions from all four loops and correspondingly there are four mixing coefficients C1k, C2k, C3k and C4k. These coefficients have been determined by means of the Least Squares Method from flow and temperature balance using the measured temperatures at the assembly outlets and integral parameters. In the case considered here the C1k coefficients are of specific interest.

The V1000CT2 vessel mixing benchmark is formulated as a reactor vessel boundary condition problem with given initial and boundary T-H conditions (core power, assembly-wise power distribution, RPV inlet coolant temperatures and mass flow rates, and core or reactor outlet pressure). The task is to calculate:

- The fuel assembly inlet temperatures in the final state

- The formation of the disturbed sector in the active core in the final state
- The angular shift (rotation) of the loop flows in the final state
- The reactor vessel outlet parameters during the transient.

## SIMULATION RESULTS

### The RELAP/SCDAPSIM code

The RELAP/SCDAPSIM [7], [8] is a best-estimate system thermal hydraulic code designed to predict nuclear reactor behavior during normal and accident conditions, including also the early phase of core damage progression during severe accidents. The code is being developed at the Idaho National Laboratory under the primary sponsorship of the U.S. Nuclear Regulatory Commission (NRC). It is a result of merging the RELAP5/MOD3 and SCDAP models. The RELAP5 code is based on a two-phase non-homogeneous non-equilibrium model which allows up to 6 non-condensing gases and uses a multi-1D approach with inter-channel cross-flow for pseudo-3D simulation of the reactor vessel thermal hydraulics.

### RELAP Modeling Assumptions

A multi-1D flow model with cross-flow was used for the reactor vessel. The cross-flow was modeled through horizontal junctions of cross-flow type and is governed by local pressure drops. No user specified pressure loss coefficients in the horizontal junctions were applied up to the first axial layer of the upper plenum. A value of 0.25 was used in the rest of the upper plenum volumes including the outlet ring.

In the initial state the loop flows were tuned to match the given plant specific loop flows. A semi-implicit numerical scheme was used for time integration. The hydrodynamics and the heat conduction use the same time step, with a maximum value of 0.05 s.

Two options of the transverse discretization scheme of the RPV were tested:

- 12 azimuth sectors and no radial discretization
- 24 azimuth sectors and radial discretization with 4 radial nodes in the second axial layer of lower plenum and the first axial layer of upper plenum

The axial discretization scheme is illustrated in Figure 2.

Details of the RPV discretization are summarized below:

- The vessel inlet ring and the down-comer are modeled by 12 or 24 azimuth volumes respectively. Each volume is represented by a “pipe” component with 17 axial layers. The channels are connected in horizontal direction through “multiple junctions” components. (Cross-flow at several axial levels is taken into account).
- In the 12-sector vessel model the lower plenum is modeled by 2 axial layers (2 “branch” components) x 12 volumes
- In the 24-sector vessel model the lower plenum is represented by 2 axial layers: with 24 volumes in the first layer and 24 x 4 volumes in the second one. The cross-flow is modeled with horizontal junctions. Note that the nodes have different cross-section in radial direction.
- The assembly-by-assembly core inlet parameters are obtained through the inlet junctions from the coarser mesh values in the lower plenum
- The core is described by 163 channels with 12 axial nodes (163 pipe components). The crossflow between the fuel assemblies is not taken into account
- The core bypass is modelled with 12 (or 24) volumes with 12 axial nodes
- In the 12-sector vessel model the upper plenum is modeled by three layers of branch components x 12 volumes
- In the 24-sector vessel model the upper plenum is modeled by three layers of branch components:24 x 4 volumes for the first axial layer and x 12 volumes for the next layers
- The upper head is modeled with one volume.

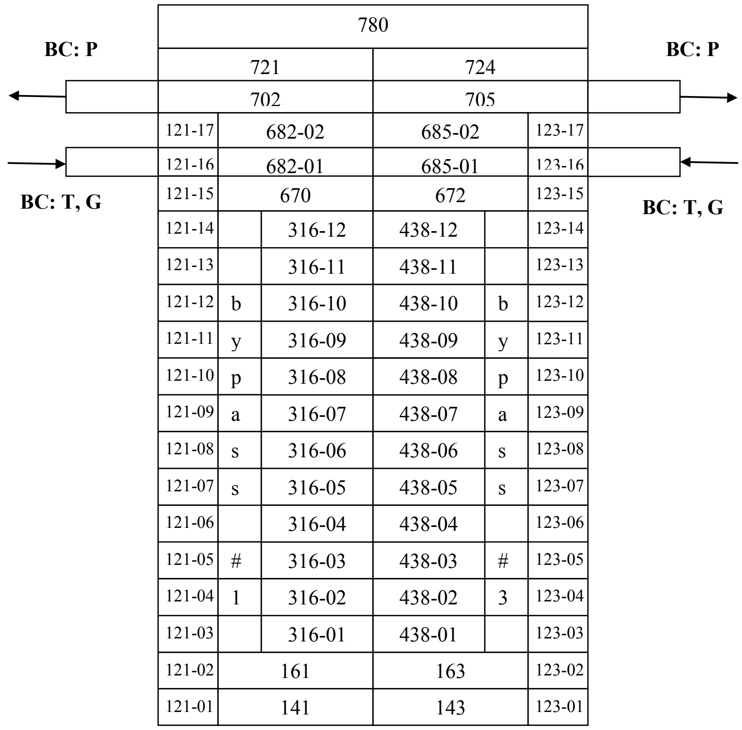


**FIGURE 2.** 12 sector models: Axial discretization scheme

## RELAP/SCDAPSIM Results

*Integral Parameters in the Initial and Final States*

The RELAP/SCDAPSIM computed integral parameters in the initial and final state are presented in Tables 1 and 2, as compared to plant data and computed results obtained with a CATHARE2.5 [9] multi-1D vessel model described in refs. [4], [10] which used 24 azimuth sectors and no radial discretization.

Table 1 illustrates the computed and plant measured integral parameters in the initial state. The base case results from the RELAP 12-sector and 24-sector models are in good agreement with the plant data and the CATHARE results.

Table 2 illustrates the computed and plant measured parameters in the final state. The RELAP 12-sector results are in good agreement with the reference plant data. The maximum absolute deviation in the predicted hot leg mass flow rates is +63,2 kg/s in hot leg #1.This deviation indicates a slight overestimation of the loop #1 flow mixing between the reactor inlet and outlet. The maximum deviation in the predicted hot leg temperatures is app. +0.65 K in hot leg #3.

The results from the RELAP 24-sector model with radial discretization in the lower plenum agree well with the reference data in terms of integral parameters. The maximum deviation in the predicted hot leg temperatures is +0.7 K in hot leg #3.

The maximum deviation in the predicted mass flow rate in the final state is +77 kg/s in hot leg #1 which is within the ±110 kg/s error tolerance of the plant data.

*Disturbed Sector Formation at the Core Inlet*

Figures 3-5 illustrate the plant estimated and the computed core maps with the disturbed sector formation and angular shift of the Loop #1 flow center in the final state. Here, in order to visualize the disturbed sector at the core inlet, the temperature differences dTk=Tcold leg1-Tin,k, k=1,163 between the disturbed loop and the assembly inlets are used. The red color marks the zone of minimal mixing where the loop-to assembly inlet temperature differences are below 1.2 K. (This threshold is chosen to approximately correspond to loop-to-assembly outlet mixing coefficients between 90 and 100% used to determine the zone of minimal mixing in the original experimental data). The disturbed loop flow center is defined as the centerline of the zone of minimal mixing and is used to determine the azimuth shift of the loop flow relative to the loop axis. Differences between 1.2 and 5 degrees are marked in yellow, 5 to 8 degrees in green and above 8 degrees in blue.

Figure 3 shows the disturbed sector formation at the core inlet in the final state as estimated from the plant data. This distribution is used as reference in the discussion of the computed results. Note that in this particular figure the 1.2 K threshold is used to mark the core inlet zone of minimal mixing but the red color here marks the zone with loop-to-assembly outlet mixing coefficients between 90 and 100% used to determine the zone of minimal mixing in the original experimental data. These two zones approximately overlap.

Figure 4 illustrates the disturbed core inlet sector computed with the RELAP 12-sector RPV model without radial discretization. The computed zone of minimal mixing is in reasonably good agreement with the reference one. The computed angular shift of Loop #1 flow center is 25 degrees counterclockwise vs. 26 degrees in the plant data. The flow mixing is underestimated in the transition zone between Loop #1 and Loop #2, and a little overestimated between Loop #1 and Loop #4, which can be expected for such a coarse azimuth discretization.

Figure 5 shows the preliminary RELAP results using a 24-sector vessel model with four radial nodes in the lower plenum. The cross-flow in the lower plenum was modeled with horizontal junctions applied to radial nodes with variable section. The first results show a wider computed zone of minimal mixing of loop #1 flow compared to the reference one. The computed angular shift of Loop #1 flow center is 22 degrees. The flow mixing is overestimated in the transition zone between Loop #1 and Loop #2 (more than with the 12-sector model), and is slightly underestimated between Loop #1 and Loop #4 (less than with the 12-sector model). The results are qualitatively similar to the multi-1D CATHARE2 24-sector results from ref. [6] obtained without radial discretization, and the ATHLET 16-sector result from ref. [6] with more detailed radial discretization as described in [11], but the RELAP computed transition from minimal mixing to significant mixing between Loop #1 and Loop #2 is sharper. Testing of other 24-sector vessel models without radial discretization and with more detailed radial discretization is ongoing and the results will be subject of further analysis.

*Time Histories of Integral Parameters*

Figures 6-9 illustrate the computed time histories of the hot leg temperatures vs. plant reference data when using the 12-sector vessel model without radial discretization. The computed base case results are in generally good agreement with the reference data. The largest absolute deviations are seen in the first 90 s of the transient when the cold leg #1 temperature increases sharply due of the loop heat-up and exceeds the hot leg #1 temperature at 90-100 s. The max transient deviation is 2.3 K for hot leg #1. In the smoother part of the transient the maximum temperature deviation is 0.6 K.

Figures 10-13 show the computed time histories of the loop mass flow rates at the hot leg nozzles vs. reference data obtained from the 12-sector vessel model. The transient results agree well with the reference ones. The maximum deviation during the transient is +74 kg/s in hot leg nozzle #1 (+65 kg/s in the final state). The deviations in all the other nozzles are below 36 kg/s (0.8%).

The uncertainty bounds in Figures 6-13 and uncertainty analysis aspects are discussed in the next section of the paper.

**TABLE 1.** Initial state integral parameters

| **Parameter** | **Plant data** | **CATHARE2.5 24 sectors** | **R/S mod 3.5 12 sectors** | **R/S mod 3.5 24 sectors** | **Measurement error** |
|---|---|---|---|---|---|
| Core power, MW | 281 | 281 | 281 | 281 | ± 60 |
| Pressure above the core, MPa | 15.59 | 15.605 | 15.622 | 15.620 | ±0.3 |
| Cold leg #1 temperature, K | 541.75 | 541.75 (BC) | 541.75 (BC) | 541.75 (BC) | ±1.5 |
| Cold leg #2 temperature, K | 541.85 | 541.85 (BC) | 541.85 (BC) | 541.85 (BC) | ±1.5 |
| Cold leg #3 temperature, K | 541.75 | 541.75 (BC) | 541.75 (BC) | 541.75 (BC) | ±1.5 |
| Cold leg #4 temperature, K | 541.75 | 541.75 (BC) | 541.75 (BC) | 541.75 (BC) | ±1.5 |
| Mass flow rate #1, kg/s | 4737 | 4737.0 | 4733.2 | 4734.7 | ±110 |
| Mass flow rate #2, kg/s | 4718 | 4718.0 | 4721.0 | 4719.3 | ±110 |
| Mass flow rate #3, kg/s | 4682 | 4682.0 | 4682.1 | 4684.1 | ±110 |
| Mass flow rate #4, kg/s | 4834 | 4833.9 | 4834.7 | 4832.9 | ±110 |
| Reactor mass flow rate, kg/s | 18971 | 18970.9 | 18971 | 18971 | ±450 |
| Hot leg #1 coolant temp, K | 545.0 | 544.65 | 544.64 | 544.66 | ±1.5 |
| Hot leg #2 coolant temp, K | 545.0 | 544.68 | 544.60 | 544.60 | ±1.5 |
| Hot leg #3 coolant temp, K | 544.9 | 544.71 | 544.72 | 544.70 | ±1.5 |
| Hot leg #4 coolant temp, K | 545.0 | 544.83 | 544.74 | 544.73 | ±1.5 |
| Reactor pressure drop, MPa | 0.418 | 0.418 | 0.421 | 0.422 | ±0.043 |

**TABLE 2**. Final state integral parameters

| **Parameter** | **Plant data** | **CATHARE2.5 24 sectors** | **R/S mod 3.5 12 sectors** | **R/S mod 3.5 24 sectors** | **Measurement error** |
|---|---|---|---|---|---|
| Core power, MW | 286 | 286 | 286 | 286 | ± 60 |
| Pressure above the core, MPa | 15.593 | 15.585 | 15.601 | 15.600 | ±0.3 |
| Cold leg #1 temperature, K | 555.35 | 555.35 (BC) | 555.35 (BC) | 555.35 (BC) | ±1.5 |
| Cold leg #2 temperature, K | 543.05 | 543.05 (BC) | 543.05 (BC) | 543.05 (BC) | ±1.5 |
| Cold leg #3 temperature, K | 542.15 | 542.15 (BC) | 542.15 (BC) | 542.15 (BC) | ±1.5 |
| Cold leg #4 temperature, K | 542.35 | 542.35 (BC) | 542.35 (BC) | 542.35 (BC) | ±1.5 |
| Mass flow rate #1, kg/s | 4566 | 4567.5 | 4629.2 | 4642.6 | ±110 |
| Mass flow rate #2, kg/s | 4676 | 4676.2 | 4673.9 | 4664.5 | ±110 |
| Mass flow rate #3, kg/s | 4669 | 4668.2 | 4640.8 | 4638.3 | ±110 |
| Mass flow rate #4, kg/s | 4819 | 4818.2 | 4784.2 | 4782.7 | ±110 |
| Reactor mass flow rate, kg/s | 18730 | 18730 | 18728.1 | 18728.1 | ±450 |
| Hot leg #1 coolant temp, K | 554.85 | 555.24 | 554.72 | 554.51 | ±1.5 |
| Hot leg #2 coolant temp, K | 547.50 | 547.54 | 547.56 | 547.49 | ±1.5 |
| Hot leg #3 coolant temp, K | 545.75 | 545.48 | 546.53 | 546.51 | ±1.5 |
| Hot leg #4 coolant temp, K | 546.45 | 546.89 | 546.62 | 546.89 | ±1.5 |
| Reactor pressure drop, MPa | 0.419 | 0.411 | 0.414 | 0.415 | ±0.043 |

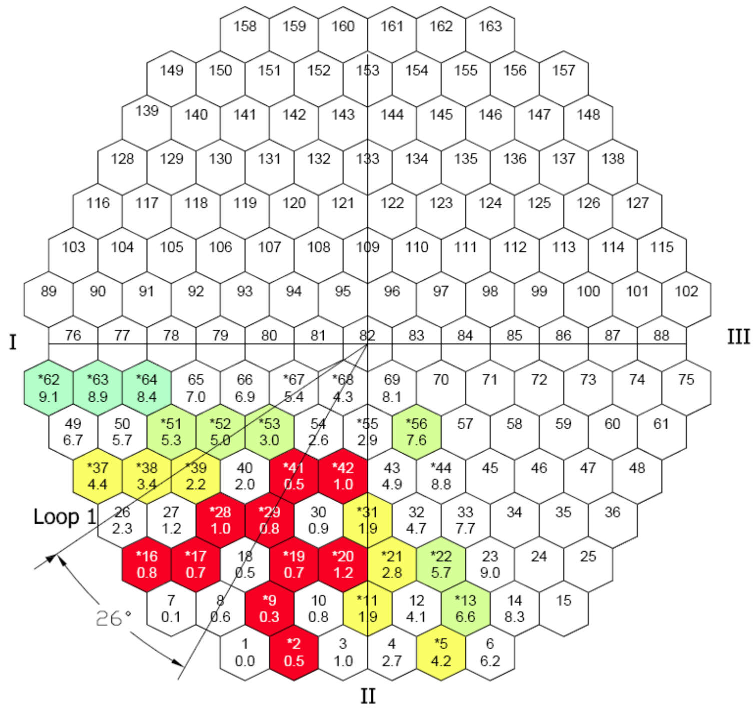


**FIGURE 3.** Plant data: estimated temperature differences from cold leg to assembly inlets, and angular turn of loop#1 flow center in the final state. Here $dT_k = T_{cold\ leg1} - T_k$, k=1,163

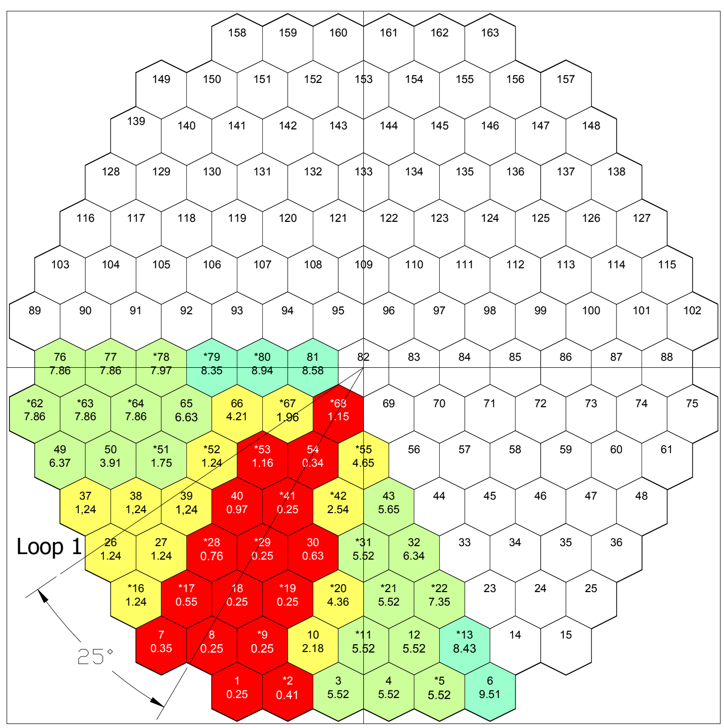


**FIGURE 4.** RELAP 12-sector vessel model: Computed disturbed sector and angular turn of the loop#1 flow center in the final state

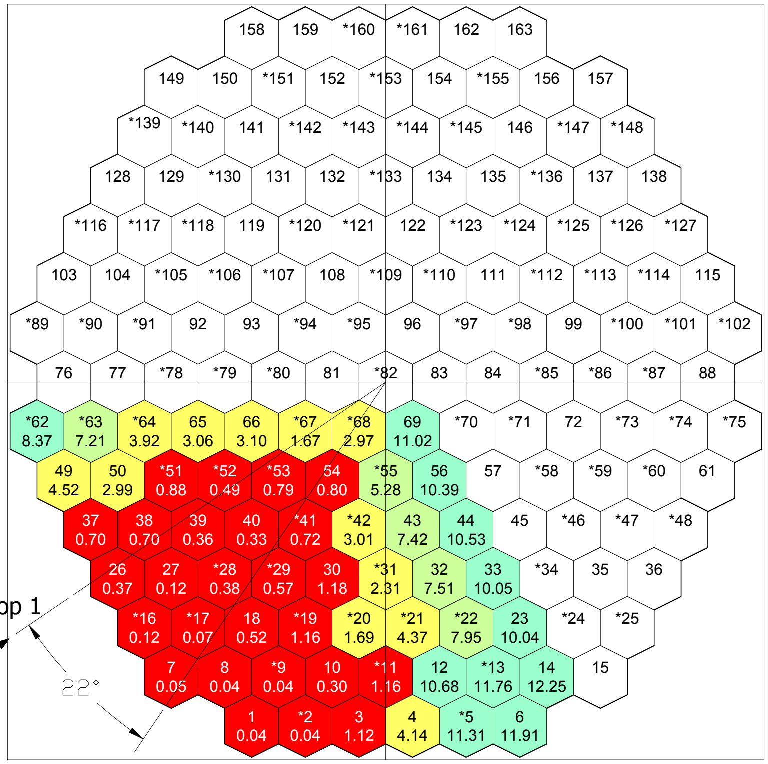

FIGURE 5. RELAP 24-sector vessel model: Computed disturbed sector and angular turn of loop#1 flow center in the final state

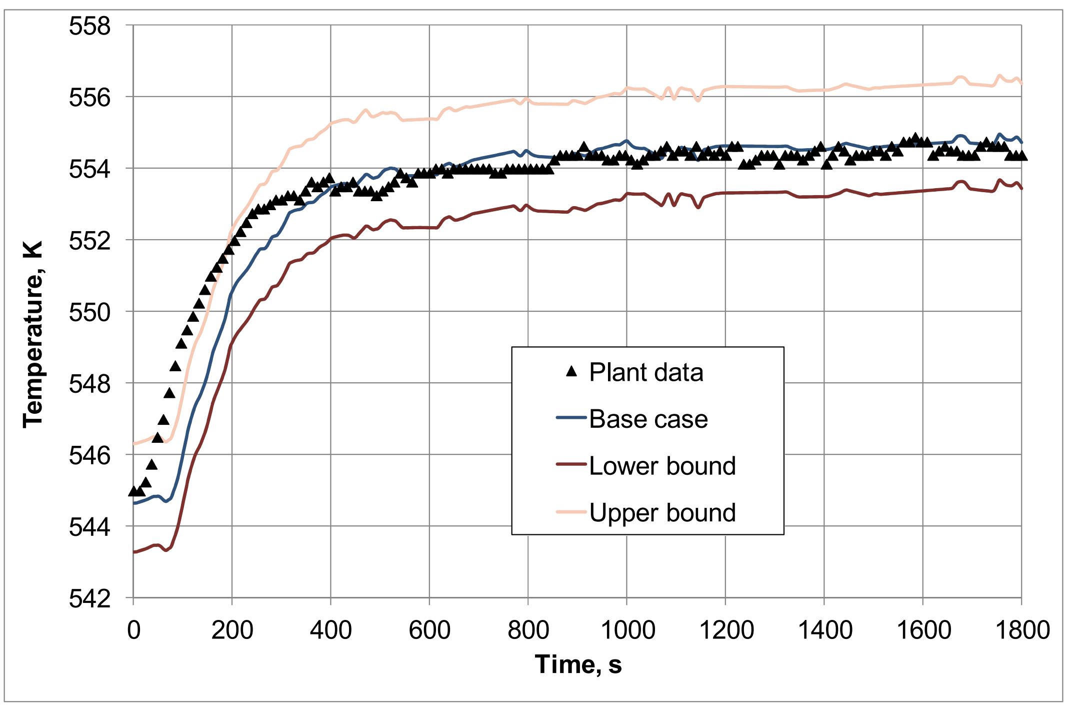


FIGURE 6. Time history of hot leg #1 temperature

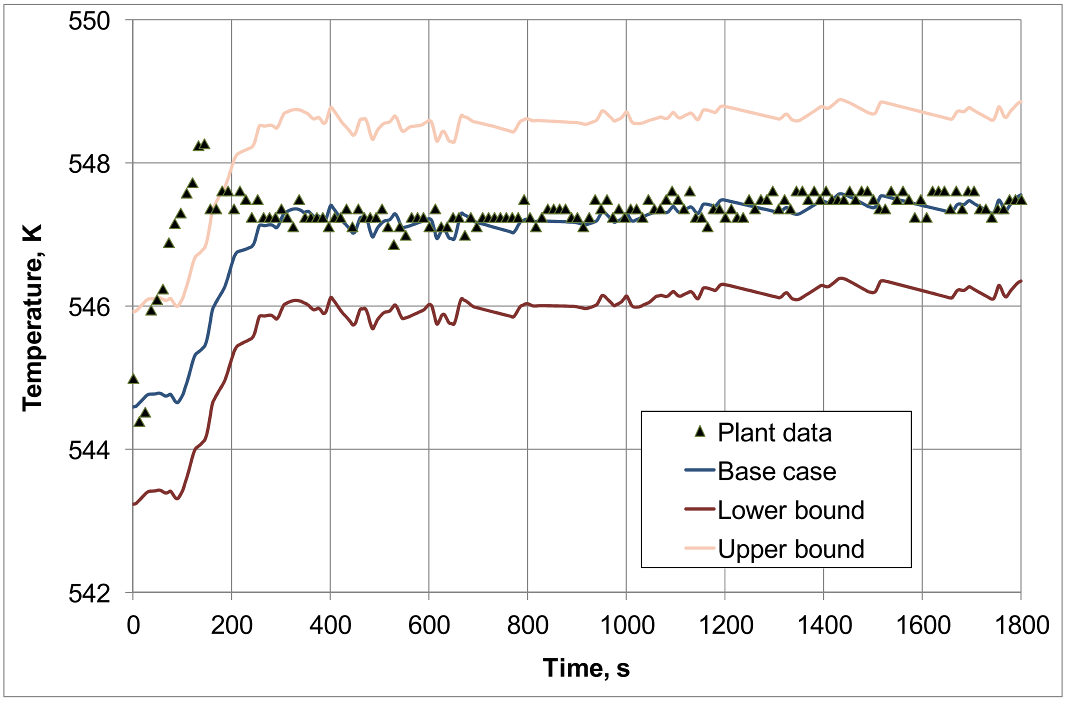


**FIGURE 7.** Time history of hot leg #2 temperature

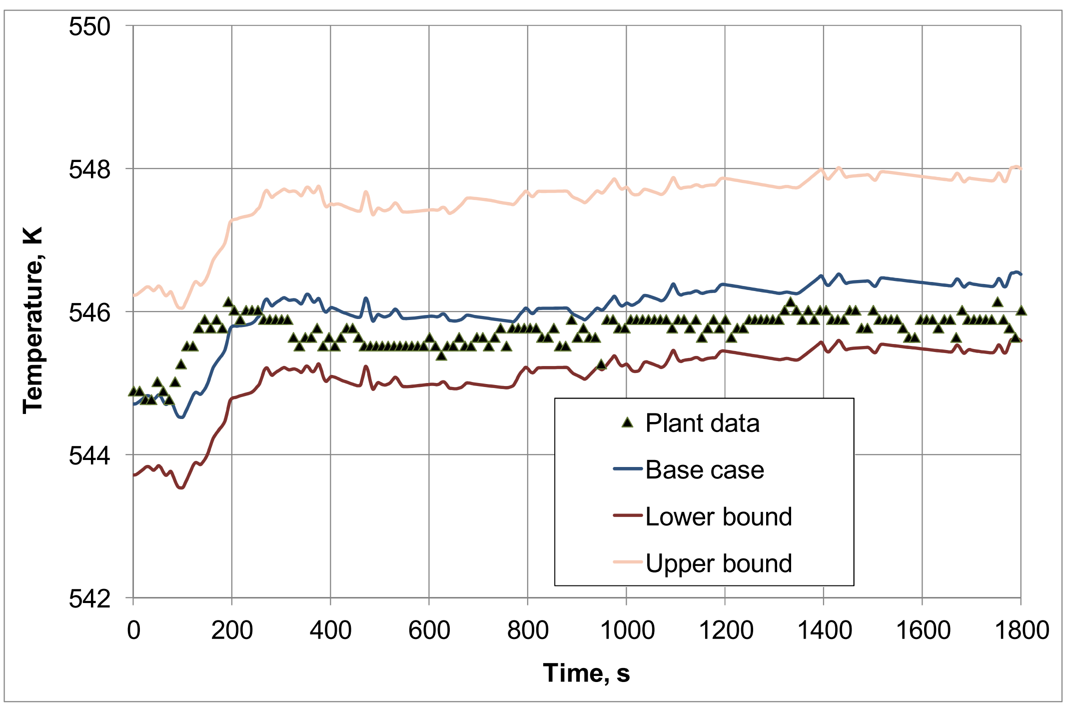


**FIGURE 8.** Time history of hot leg #3 temperature

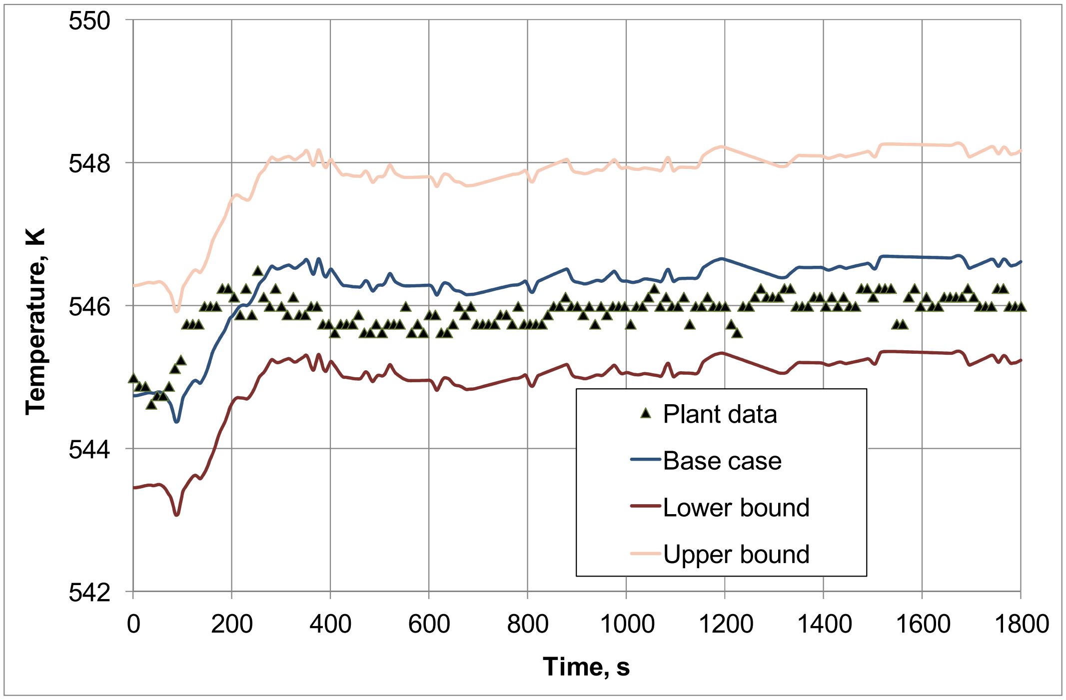


**FIGURE 9.** Time history of hot leg #4 temperature

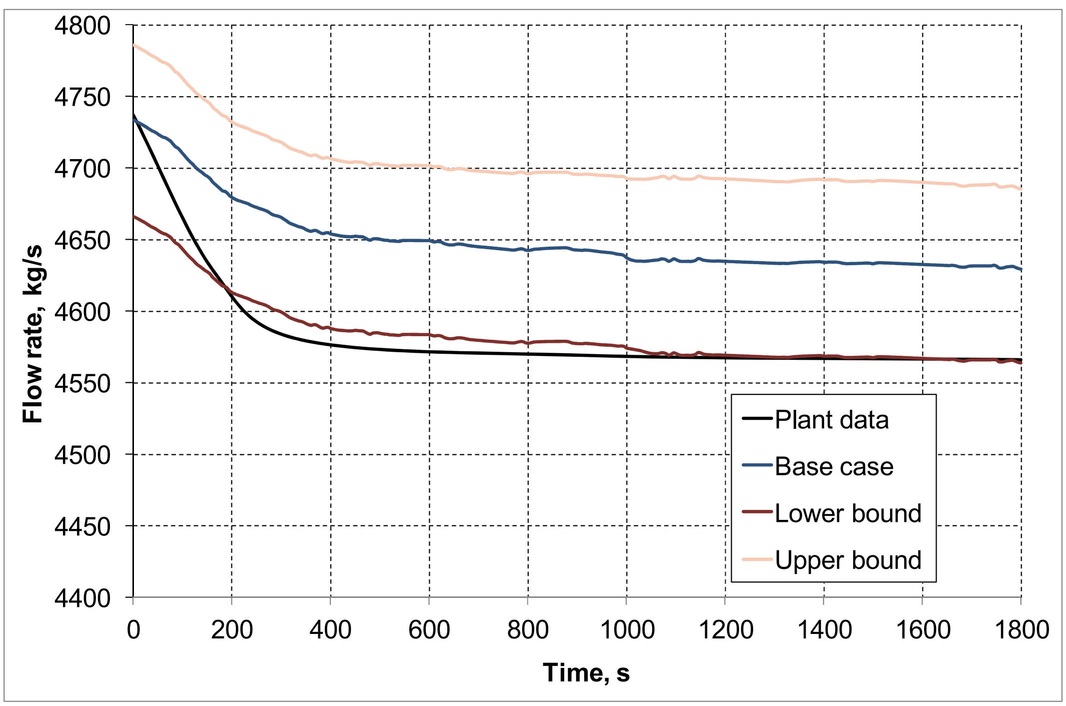


**FIGURE 10.** Time history of mass-flow rate in hot leg nozzle #1

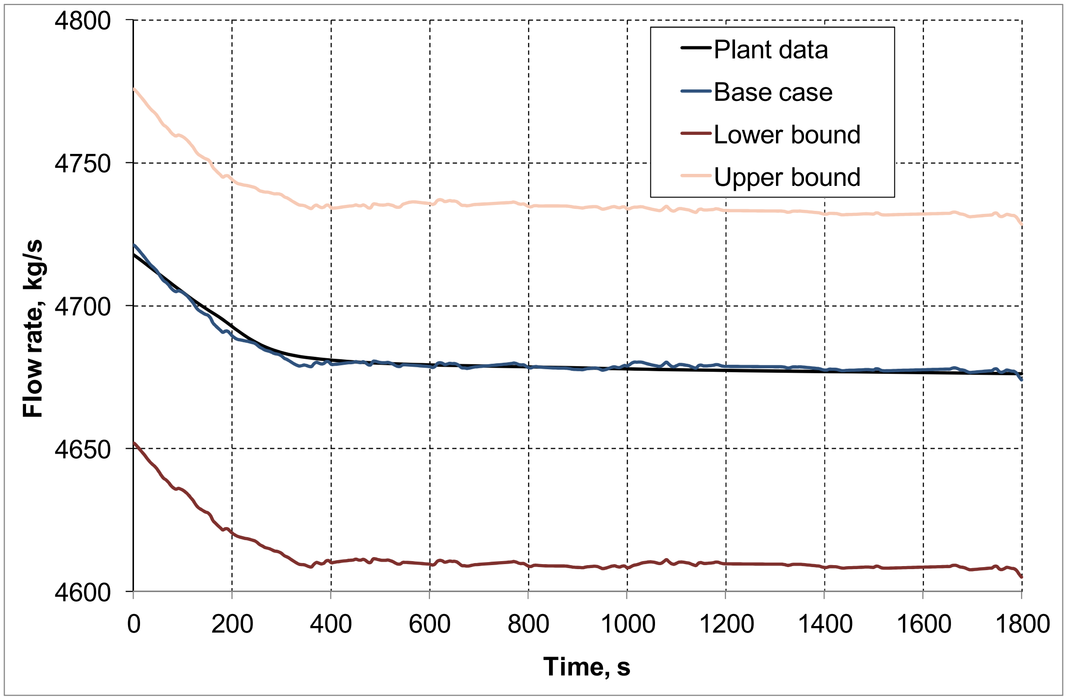


**FIGURE 11.** Time history of mass-flow rate in hot leg nozzle #2

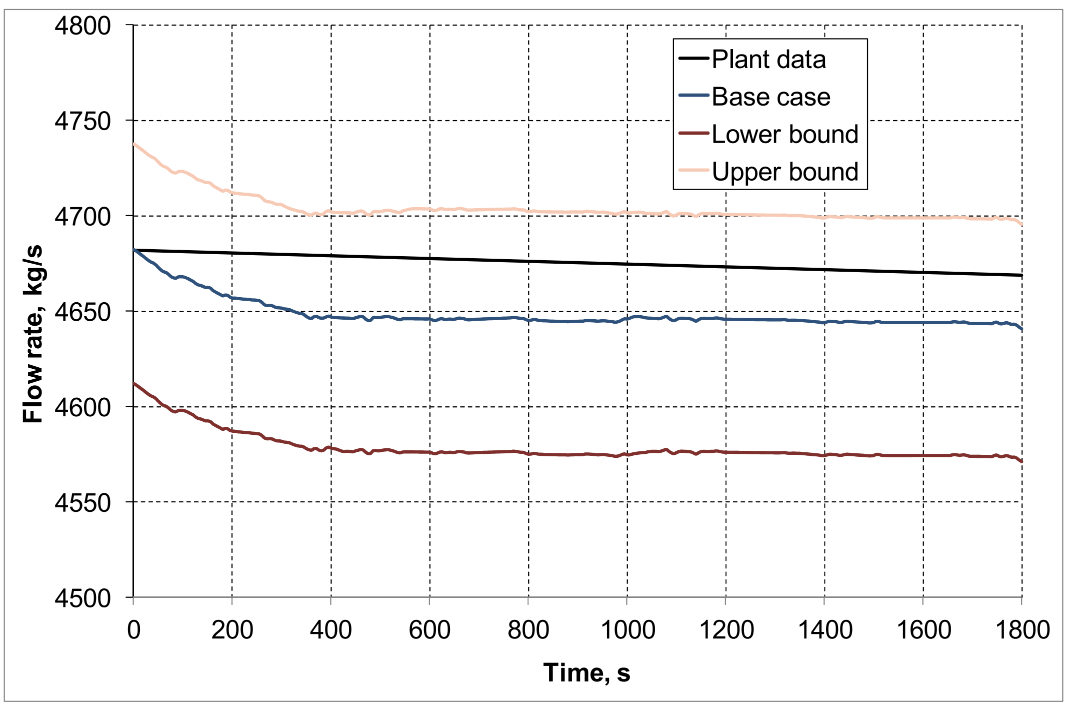


**FIGURE 12.** Time history of mass-flow rate in hot leg nozzle #3

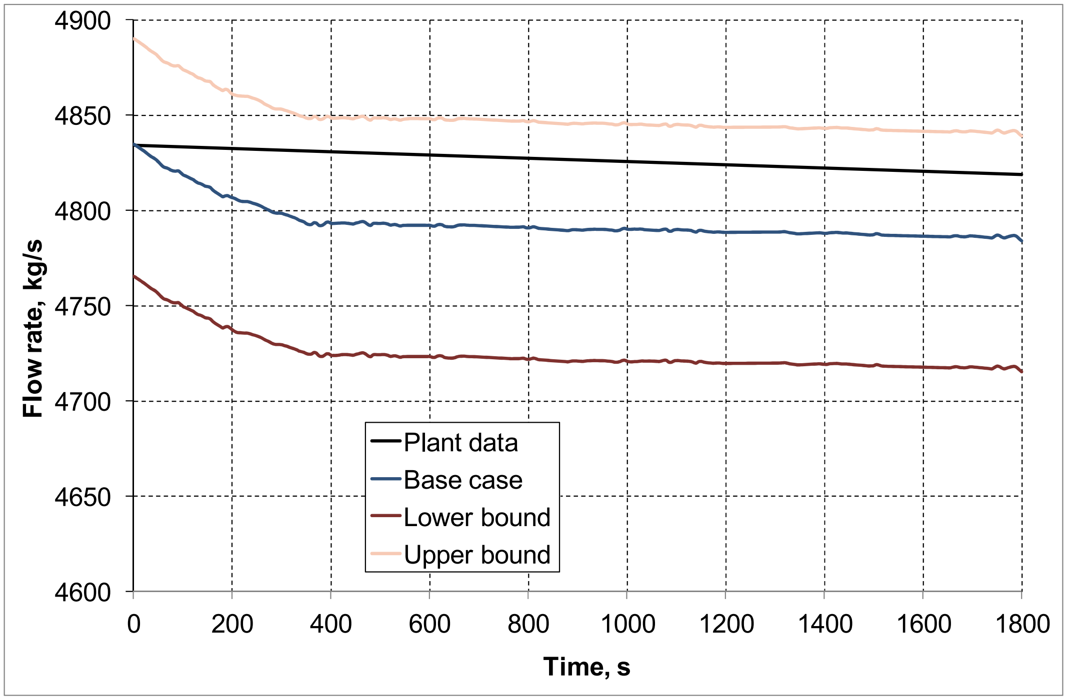


**FIGURE 13.** Time history of mass-flow rate in hot leg nozzle #4

## INTEGRATED UNCERTAINTY ANALYSIS WITH RELAP/SCDAPSIM

The integrated uncertainty analysis package in RELAP/SCDAPSIM uses probabilistic approach to propagate the input uncertainties. The approach represents a combination of CSAU methodology with use of the Wilk's method [12, 13] which incorporates both a tolerance limit and a confidence in its prediction, and consists of the following steps [5]:

- Selection of the plant
- Selection of the scenario
- Selection of safety criteria
- Identification and ranking of the relevant phenomena based on the safety criteria
- Selection of the appropriate code parameters to represent those phenomena
- Association of uncertainty by means of Probability Density Functions (PDF) for each selected parameter and performing multiple computer runs to obtain uncertainty bands with a certain percentile and confidence level. The number of code runs is given by the Wilk's formula. It not depend of number of input parameters and is determined by the percentile and the confidence level of the desired uncertainty bands
- Processing the results of the multiple computer runs to estimate the uncertainty bands for the computed quantities associated with the selected safety criteria.

In this work only measurement uncertainties of integral input parameters used as vessel boundary conditions were analyzed. Uncertainties related to models and correlations, spatial discretization, numerical schemes, modeling options, material properties and user effects were not considered. A probabilistic approach to the propagation of input uncertainties was applied. Uniform uncertainty distributions were assumed for the input cold leg temperatures, mass-flow rates, total power and reactor outlet pressure.

Wilk's formula incorporates both a tolerance limit and a confidence in its prediction. When using the 1$^{st}$-order Wilk's formula with confidence level of 0.95 and coverage of tolerance limit of 0.95 the required number of sample simulations is 59. For this analysis the 12-sector vessel model was used. Sixty simulations were made: one for the base case and 59 runs with random sampling of boundary condition parameters (cold leg temperatures and mass-flow rates, reactor outlet pressure and total power).

Figures 6 through 9 illustrate the computed time histories of the hot leg temperatures along with the reference plant data and the unilateral uncertainty tolerance levels.

Figures 10 through 13 show the time history of hot leg mass flow rates along with the reference plant data and the unilateral tolerance levels.

Regarding the uncertainties in the prediction of the disturbed core inlet temperature sector, a wider zone of minimal mixing is predicted in 20 out of 59 simulations. It includes assemblies 16, 26, 27, 37, 38 and 39 in the azimuthal transition zone between loop #1 and loop #2. The sector formation predicted in the base case is reproduced in the other simulations.

## SUMMARY AND CONCLUSIONS

RELAP/SCDAPSIM multi-1D calculation models were tested vs. plant measured data in simulations of the OECD/NEA VVER-1000 vessel mixing benchmark.

The predicted integral parameters show generally good agreement with the plant data. The preliminary results for the disturbed core inlet sector obtained from the 24-sector vessel model with radial discretization show certain improvements in the predicted peripheral azimuthal and radial transition zones as compared to the 12-sector results, but indicate a need for further mesh refinement studies.

An integrated uncertainty analysis for the input parameters used as vessel boundary conditions was carried out with RELAP/SCDAPSIM for the 12-sector model simulation. A built-in probabilistic method with the Wilks' formula option of 1st order and one-sided tolerance limit was applied based on 59 simulations. The uncertainty analysis contributes to a better understanding of the observed differences between measured and calculated results.

The benchmark calculation results illustrate the applicability of such models with appropriate validation in the simulation of asymmetric vessel transients involving thermal mixing and azimuthal flow rotation.

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