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An Assessment of TRACE V5 RC1 Code Separator Model with the Westinghouse Model Boiler 2 Experiments

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ABSTRACT

A TRAC/RELAP Advanced Computational Engine (TRACE) model of the Model Boiler 2 test facility has been built as part of the International Code Assessment and Maintenance Program (CAMP) validation case. Simulation cases with 100-percent and 50-percent power levels were run, and the results were compared to tests that were performed in the facility in the early 1980s. Because the main interest was in the functionality of the primary separator, the model includes no steam dryer assembly. The only heat structures built into the model were the primary-secondary heat transfer elements, since the model was run in a steady state and therefore the heat capacities of the structures had little effect on the results.

The Model Boiler 2 test facility failed to achieve the intended primary separator efficiencies in an oscillation-free system. Primary separator drain conditions had a major effect on the stability of the system and on the efficiency of the separation. A bigger drain area resulted in separation levels that were closer to the set value, but the system drifted easily into heavy oscillation. When the drain area was smaller, the separation levels were not achieved, but the system became more stable.

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1 INTRODUCTION

As a part of the International Code Assessment and Maintenance Program (CAMP) Agreement, the Finnish organizations have agreed to perform validation cases for the TRAC/RELAP Advanced Computational Engine (TRACE) code (RELAP/TRACE codes). For one validation case, these organizations built a TRACE model of the Model Boiler 2 test facility. They ran simulation cases with 100-percent and 50-percent power levels and compared the results to test cases that were performed in the facility in the early 1980s. The main interest was in the functionality of the primary separator.

Chapter 2 describes the Model Boiler 2, while Chapter 3 contains an introduction to TRACE and the TRACE model. Chapter 4 describes the simulation input data, and Chapter 5 contains the results of the tests.

2 DESCRIPTION OF THE MODEL BOILER 2

The Model Boiler 2 test facility is a 1-percent scaled-down version of the Westinghouse Model F steam generator. The scaling was done by steam generation rate and volume, while the height of the facility did not change. The riser area of this facility is built in a rectangular shape (wrapper box) and two tubes act as downcomers. The riser area is not separated, and there is only one primary separator. A dryer assembly is also present. This facility has 52 Inconel-600 U-tubes arranged in a rectangular array, with the same flow area and cladding thickness as the ones in the F model. Figure 1 represents the Model Boiler 2 riser cross section, Table 1 contains the geometric data, and Figure 2 shows the whole steam generator.

The steam separation of Model Boiler 2 takes place in three physical areas. The first separation stage is the primary separator. After this stage, the steam-water mixture flows into an open cavity, where gravitation causes some of the water drops to return to circulation through a channel located on the upper deck plate. The last stage of separation is the dryer, from which the saturated steam exits to the steam dome.

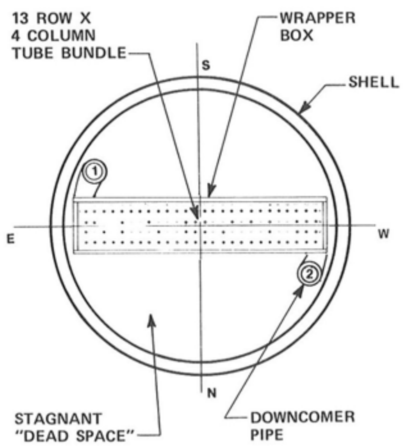

Figure 1 Model Boiler 2 riser cross-section (Ref. 1)

Table 1 Model Boiler 2 Geometric Data (Ref. 2)

Steam generator	
Total height	13.93 m
Height from bottom to primary separator	11.60 m
Height from bottom to upper deck plate	12.12 m
Riser	
Height of wrapper box	8.72 m
Length and width of wrapper box (inner dim.)	68.4 x 9.96 cm
Height of heat transfer area	6.92 m
U-tubes	
Number of tubes	52
Cladding thickness	1 mm
Outer diameter	1.75 cm
Material of tubes	Inconel 600
Downcomers	
Number of downcomers	2
Height of downcomer pipes	8.58 m
Inside diameter of downcomer pipes	7.79 cm
Primary separator	
Height of separator	0.51 m
Inside diameter of separator	17.8 cm
Steam shroud	
Height	0.94 m
Volume	0.111 m^3
Steam dome	
Height	0.94 m
Volume	0.379 m^3

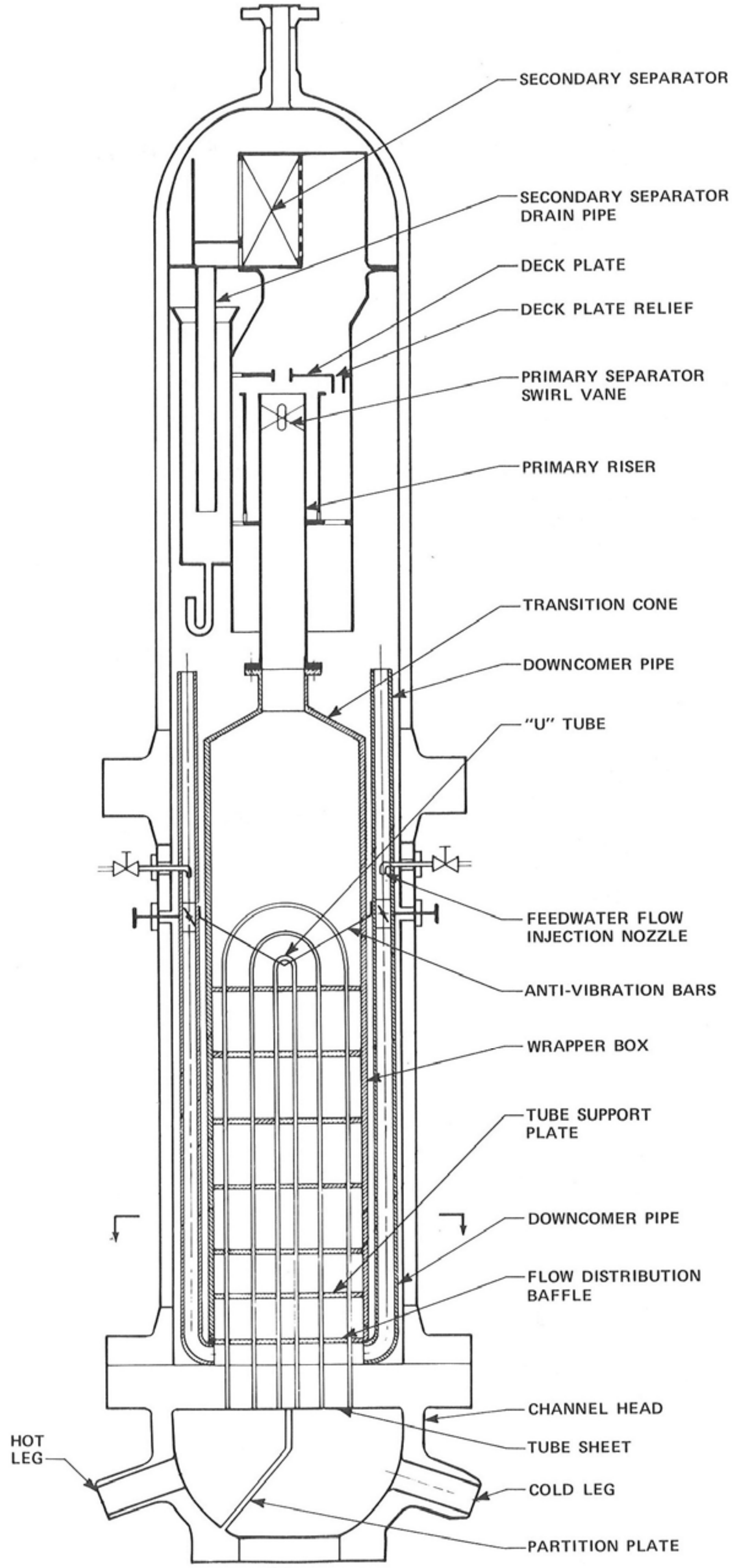

Figure 2 Model Boiler 2 (Ref. 1)

3 TRACE

The TRACE model retains all the functionality of RAMONA, RELAP5, TRAC-PWR, and TRAC-BWR codes. The most recent release at the time when this report was written was Version 5, Release Candidate 3 (launched in December 2006), and the final version was expected to be released at the end of July 2007 (realeased August 2007). The simulations in this report used Version 5, Release Candidate 1. At the time of these simulations The U.S. Nuclear Regulatory Commission was stating that making the documentation is the priority and focus of its attention until the final release (Ref. 3).

For the simulations in this report, the separator component of TRACE disables itself if one or more of three conditions are recognized. These conditions are backward flow, void fraction of under 5 percent, or flow which is essentially all vapor ($1 - q_{vapor}/q_{total} < 10^{-6}$). If these conditions are no longer present later in the simulation, the separator is automatically turned on (Ref. 4).

The thermal-hydraulic model of the Model Boiler 2 facility was created with the Symbolic Nuclear Analysis Package (SNAP), and the code used in the simulation was TRACE. The parts of the facility included in the model were the downcomer, riser, separator, steam shroud, and steam dome. The steam dryer assembly was not modeled, since the main interest in these tests was in the functionality of the primary separator. Also, there were few data showing just how much water passes through the primary separator but returns into circulation through openings in the upper deck plate. This was problematic, since the intended test data contained the liquid flow entering the steam dryer (i.e., liquid flow passing through both of the previous separation stages). Therefore, the separator component of the built model actually represents not only the primary separator but also the gravitational separation that occurs in the steam shroud.

The built model consists of the primary and secondary circuits. The primary circuit has a simple design that includes only the inlet and outlet components and four tube components. Two of the tubes represent the U-tubes and are equipped with heat structures, while two shorter tubes are only added for measuring purposes. In these studies, where the power level was constant, the circuit had constant mass flow, pressure, and inlet temperature.

The secondary circuit consists of an inlet for feedwater, an outlet for steam, a riser, a downcomer, a separator, and a dome. There are also two small pipes that connect the dome and separator components to the downcomer.

In the selected tests, the feedwater flow was directed evenly to both downcomers. This, and the fact that the riser was not separated, allowed the modeling of the downcomer as a single pipe. The Model Boiler 2 downcomer consists of five physical areas: barrel, funnel, pipes, ducts, and annulus. The downcomer barrel surrounds the riser barrel and separator, while the funnel is the volume that spreads the water to both downcomers. In the built model, the barrel and funnel heights and volumes were treated as one, and the volume was evenly split into three. The downcomer pipes were split into four nodes. The ducts exist as one node. The annulus was spread to 80-percent and 20-percent parts, and the smaller bottom part was bent towards the riser. The length of the object was slightly increased to compensate for the height loss that resulted from bending it. Figure 3 presents the built model, and Table 2 contains the model geometry.

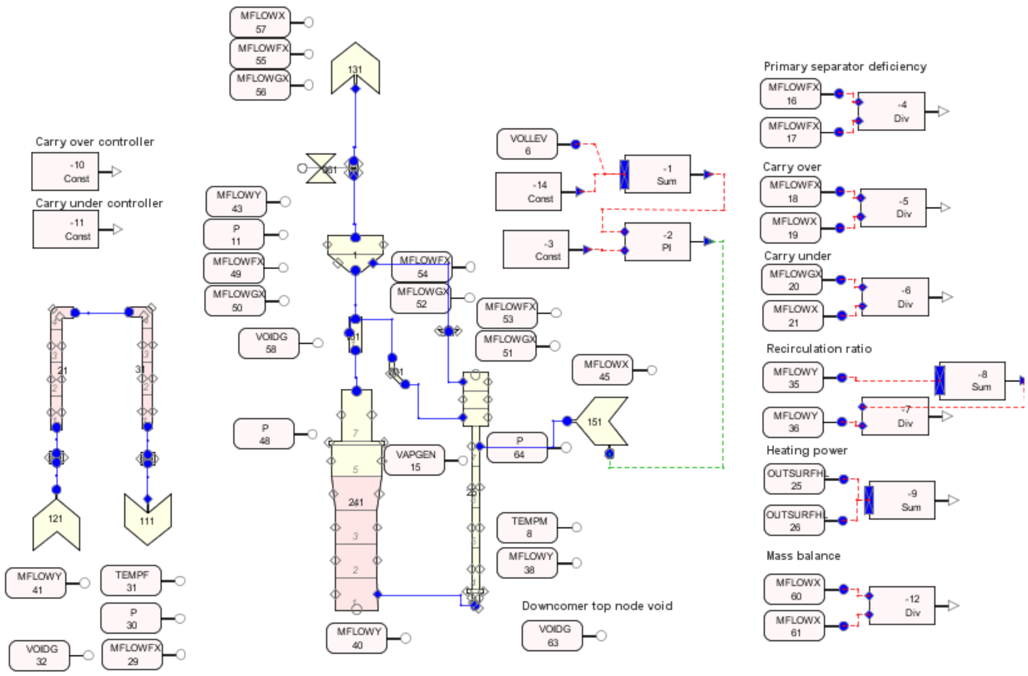

Figure 3 SNAP view of the Model Boiler 2 TRACE model

Table 2 Model Boiler 2 TRACE Model Geometry

	Volume [m³]	Length [m]	Hydraulic diam. [m]	Area [m²]	Additive loss	Number of nodes
RISER						
pipe	0.067	2.734	0.177	0.025	1.1	1
cone	0.012	0.152	0.321	0.081	0.1	1
risertop	0.116	1.703	0.295	0.068	0.1	1
tube area	0.297	7.017	0.232	0.042	0.2	4
total	0.493	11.606			1.5	7
SEPARATOR						
separator	0.013	0.510	0.177	0.025	2.5	1
DOWNCOMER						
barrel+funnel	0.255	2.750	0.344	0.093	0.1	3
pipes	0.082	8.582	0.110	0.010	0.1	4
ducts	0.008	0.191	0.224	0.040	0.1	1
annulus 80%	0.004	0.475	0.102	0.008	0.1	1
annulus 20%	0.001	0.119	0.102	0.008	10.1	1
total	0.350	12.116			10.5	10
DOME						
dome	0.379	0.940	0.716	0.403	0.2	1
shroud	0.111	0.946	0.387	0.117	1	1
total	0.490	1.886			1.2	2
CONNECTION PIPES						
sep. -> downc.	0.066	1.657	0.010	0.040	1	1
shroud -> downc.	0.008	0.005	0.150	0.150	1	1

The separator was used in "carryover/carryunder" mode. In this mode, a controller is defined for both carryover and carryunder. However, in this case, the controller was a constant arithmetic block. Different values were manually set for different power levels. The same functionality would have been achieved by using the separator in ideal separator mode (Ref. 5) and by changing the carryover and carryunder parameters when the power level changes. In this mode, the separation efficiency stays constant, regardless of the state of the incoming flow.

The heat transfer from the primary to the secondary circuit was determined by two means. The first was to define the tube wall and the second was to use heat structures. In this model, the heat transfer was arranged with heat structures. They were connected between the eight cells of primary tubes and the first four cells of the riser. The model included no other heat structures, because the conditions remained constant during the tests.

In addition to the primary and secondary circuit components, Figure 3 shows the number of signal variable modules and control blocks. These are used to extract relevant information from the model and also to calculate primary separator deficiency, carryover, carryunder, and heating power variables. Equations 1, 2, and 3 define these variables. There is also a proportional-integral (PI) controller that controls the feed water inlet component. The controller observes the collapsed water level signal variable, which measures the water level in all 10 downcomer nodes. A constant block sums 0.877 meters to the collapsed water level signal to correct the misreading produced by the downcomer being connected to the crossflow face of the riser's bottom node. A constant signal variable is attached to the controller; its purpose is to define the desired water level.

$$\text{Carryover} = \frac{\text{Water mass flow in vapor outlet}}{\text{Total mass flow in vapor outlet}} \qquad (1)$$

$$\text{Carryunder} = \frac{\text{Vapor mass flow in liquid outlet}}{\text{Total mass flow in liquid outlet}} \qquad (2)$$

$$\text{Primary separator deficiency} = \frac{\text{Liquid mass flow carried to dryer inlet}}{\text{Liquid mass flow entering separator node}} \qquad (3)$$

Once the simulation had been run, the results were opened in the animation model, which offers a graphic view of the process. The animation view was built by copying the components from the simulation model and adding some playback control and indicator components. In this case, a fluid conditions range was also added to the view. Figure 4 presents the simulation model.

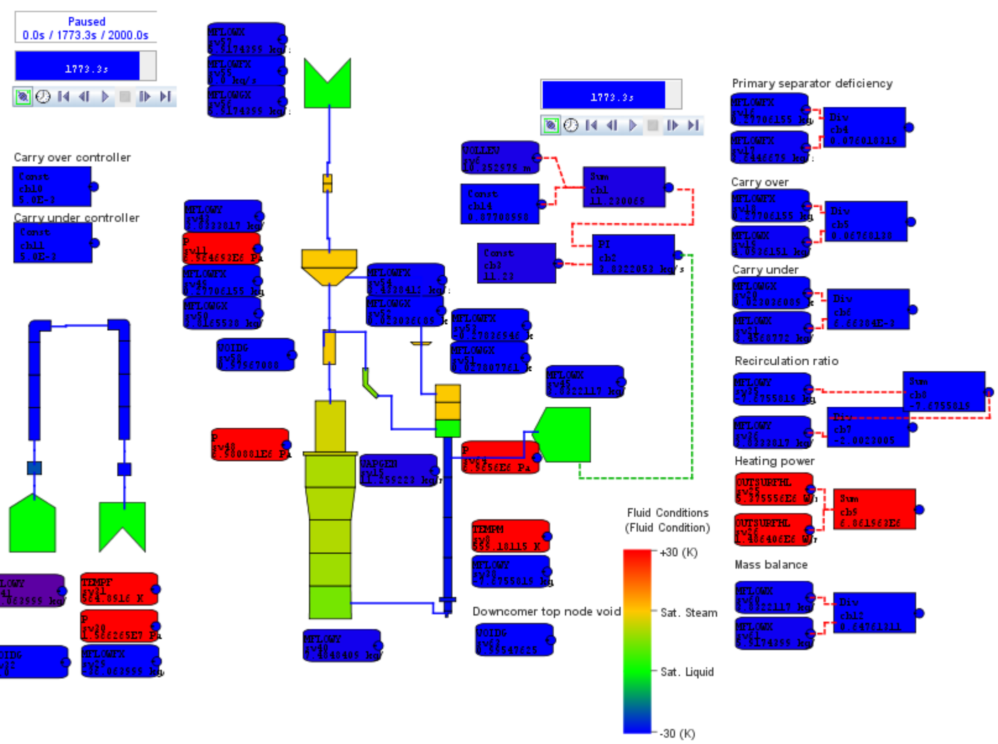

Figure 4 SNAP animation view of the Model Boiler 2 model

4 SIMULATIONS

Extensive transient and steady-state testing was performed in a Model Boiler 2 facility in the early 1980s, and some of the data can be found in the ATHOS2 code verification report ("Thermal and Hydraulic Code Verification: ATHOS2 and Model Boiler 2 Data. Final Report," issued 1983 (Ref. 6)). The material contained data from the steady-state runs at 25-percent, 50-percent, and 100-percent power levels. The most important pieces of information were the recirculation ratio, pressures, primary side temperatures, and heat transfer rates. The feedwater flow was also very useful in verifying the correct heat transfer rate. These data allowed adjustments to the secondary-side form losses and heat transfer rates. However, the data gave little information regarding the state of the primary separator. More useful information was found from the report "MB-2 Steam Generator Transient Response Program: Loss of Feed Flow, Steam Generator Tube Rupture and Steam Line Break Thermohydraulic Experiments" (Ref. 2), which provided far more geometric data and construction drawings.

The data for adjusting the steam separator were taken from "Prototypical Steam Generator Testing Program: Test Plan/Scaling Analysis," issued 1984 (Ref. 1). The report included a chart where the primary separator deficiency was plotted as a function of power. As the 25-percent, 50-percent, and 100-percent power levels were obtained from the other report, these data allowed the correct adjustment of the primary separator for these three power levels. Figure 5 contains the chart. The primary separator deficiencies for 100-percent, 50-percent, and 25-percent power levels are approximately 2.5 percent, 0.6 percent, and 0.4 percent, respectively. It should be noted that the 25-percent power level is slightly outside the chart, and therefore, the value was considered unreliable.

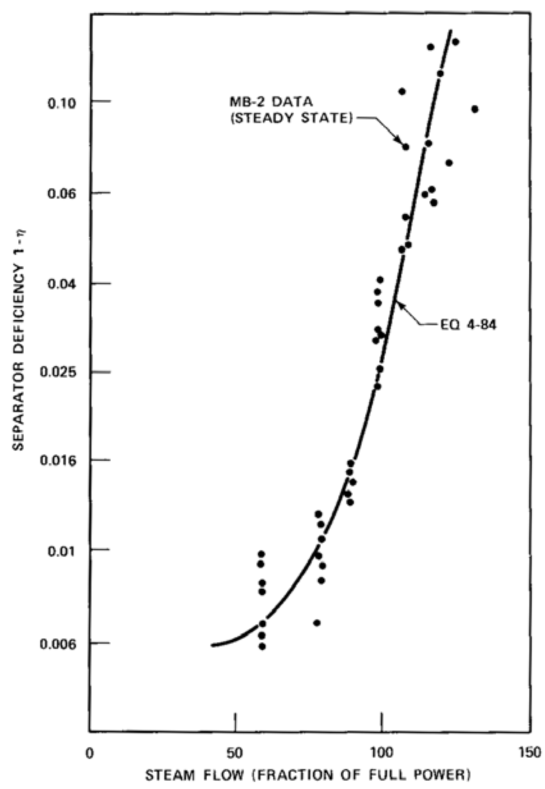

Figure 5 Primary separator deficiency as a function of power level (Ref. 1)

5 RESULTS

With each power level, there were difficulties in obtaining as high a recirculation ratio as was measured in the actual tests. It seemed that form losses along the flowpath had a major impact on model behavior. If the form losses were too small, the downcomer water level dropped and led to a situation where the target water level was never achieved and too much feedwater flowed into the system. The system also had a tendency to oscillate if not enough friction was present. With higher additional losses, recirculation was lower than desired.

5.1 100-Percent Power Level

In this simulation, a pattern was observed where the carryunder vapor instantly condensed when it came in contact with the feedwater. This produced a small but very noticeable oscillation in the whole system. Because of this, the feedwater inlet was moved downwards from its original position. With this arrangement, the inlet was positioned under the water level, and the problem was avoided.

Getting the steam generator model to work properly at all power levels proved to be difficult, and ultimately, good results were not achieved. The targeted primary separator deficiency levels were not achieved in a stable system. The problem seemed to be related to the separator drain. There were no specific data regarding the drain flow area, and therefore, many geometries were tried. If the flow area of this pipe was set to be large, the system and especially the gas mass flow (in the particular pipe) oscillated. If the flow area was set to be small, the separator could no longer achieve the targeted separation levels. With a geometry and form losses that produced a stable system, a primary separator deficiency level of 7.6 percent was achieved. Table 3 contains the results from this simulation.

Table 3 100-Percent Power Level Simulation Results, 0.005-Second Timestep

	Simulated	Measured
Pressure in steam dome [bar]	69.64	69.57
Transferred power [MW]	6.86	6.625
Feedwater flow [kg/s]	3.83	3.76
Water level [m]	11.23	11.23
Recirculation ratio	2.0	3.0
Primary separator deficiency [%]	7.6	2.5
Carryover [%]	6.7	-
Carryunder [%]	0.7	-
Primary circuit pressure [bar]	156	155
Primary circuit flow [kg/s]	36.064	36.064
Primary circuit inlet temperature [°C]	325.2	325.1
Primary circuit outlet temperature [°C]	291.7	293.3

The fact that decreasing the carryunder value led to flow oscillations in the system was studied. In this model, the behavior became clearer after the set value decreased to below 0.005. Since there were no primary separator carryunder data available from the tests, and since, with this carryunder, the flows were still stable, it was decided to use this value.

This simulation run required use of a relatively small timestep. As shown in Figure 6, the water mass flow in the primary separator steam exit vibrated even with a 10-millisecond maximum timestep. The system was completely free of oscillations when the maximum timestep was reduced to 5 milliseconds. The minimum timestep time was 10^{-6} seconds in all the simulation runs, and plotting was set to 1-second intervals.

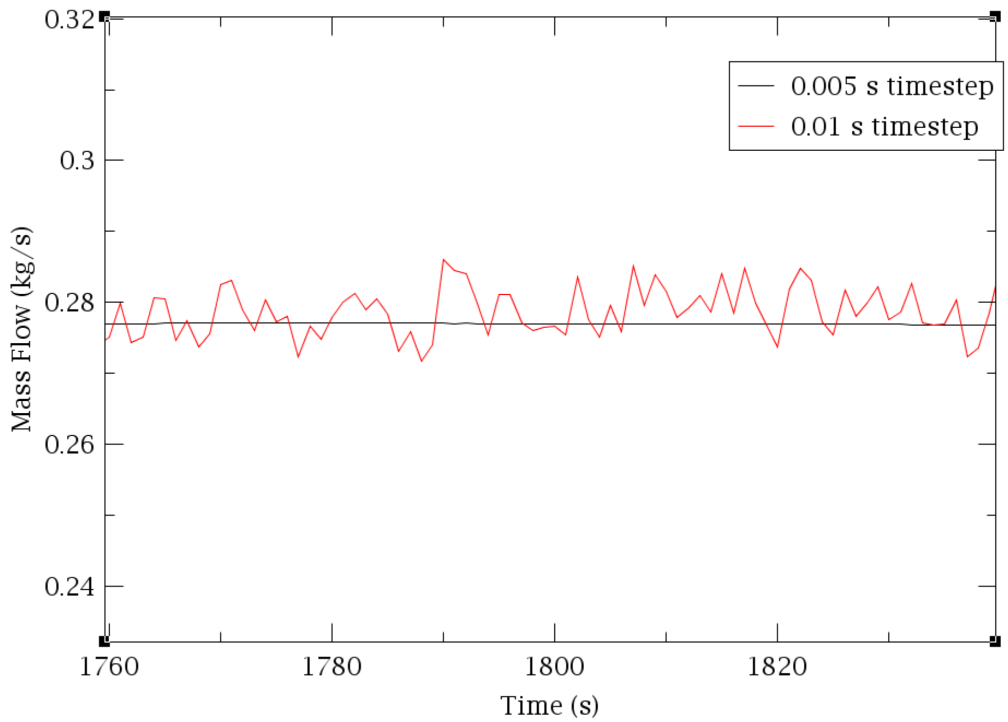

Figure 6 Liquid mass flow in the separator steam exit with two different timesteps (100-percent power)

5.2 <u>50-Percent Power Level</u>

The test demonstrated that the returning water pipe geometry and form losses that were set for a 100-percent power level were not suitable for the 50-percent power level. In this simulation, many parts of the system were oscillated heavily. This behavior was best shown in the gas and liquid flows of the pipe that returns water from the separator to the downcomer. Also, the water and steam flows in the separator steam exit were not stable (water flow presented in Figure 7). Table 4 presents the results of the simulation.

Table 4 50-Percent Power Level Simulation Results, 0.005-Second Maximum Timestep

	Simulated	Measured
Pressure in steam dome [bar]	72.02	73.01
Transferred power [MW]	3.16	3.25
Feedwater flow [kg/s]	1.60	1.699
Water level [m]	11.23	11.23
Recirculation ratio	4.1	6.8
Primary separator deficiency [%]	<1	0.9
Carryover [%]	-	-
Carryunder [%]	-	-
Primary circuit pressure [bar]	154.8	154.9
Primary circuit flow [kg/s]	37.78	37.78
Primary circuit inlet temperature [°C]	308.6	308.6
Primary circuit outlet temperature [°C]	293.2	292.9

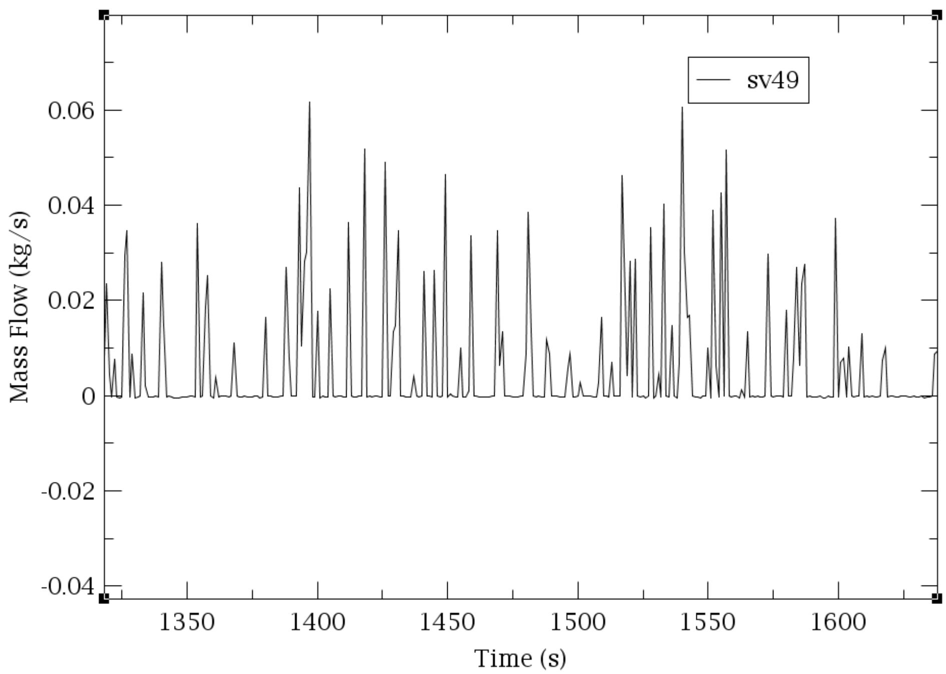

Figure 7 Water mass flow in separator steam outlet, 50-percent power level

It was possible to stabilize the system at this power level by widening the flow area of the small pipe that connects the separator back to the downcomer. This kind of geometry, however, led to heavy oscillation when used in 100-percent power level runs. Having faced difficulties in adjusting the separator for both 50-percent and 100-percent power levels, it was decided not to simulate the lowest power level.

6 CONCLUSIONS

Many attempts to find a working geometry for the returning water pipe and suitable form losses were made, but, ultimately, good results were not achieved. The 100-percent power level run fell behind its target separation level. Although the separation level in the 50-percent power level run may seem satisfactory at first glance, it must be noted that the system oscillated heavily and the results are unreliable.

The TRACE theory manual (Ref. 4) urges caution when using the TRAC-P separator component that was brought to TRAC-M (V3.0) and states that the functionality of the component will be improved in TRAC-M/F90. TRAC-M was renamed TRACE in 2003, so it is likely that the separator model has been improved. The results of these simulations, however, indicate that the component might not work as expected.

If the built Model Boiler 2 model is to be used again, the following aspects should be noted. First, in this study, it was decided that the simulation model would not include the dryer assembly. The transient test report (Ref. 2) included some carryover data for the whole separator, but this data was not used, since achieving the proper functionality of the primary separator component proved to be complicated. Secondly, the only built-in heat structures are the ones that transfer heat from the primary to the secondary circuit. This was sufficient, since the tests were all run in constant steady-state conditions and the heat capacities of the structures did not affect the results. If, however, a transient were to be simulated, more heat structures should be used.

7 REFERENCES

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APPENDIX 1. TRACE MB-2 MODEL INPUT DATA