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International Agreement Report

Assessment Against ACHILLES Reflood Experiment with TRACE V5.0 Patch3

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ABSTRACT

At present time, the development of the U.S. Nuclear Regulatory Commission RELAP5 has been ceased in favor of the newer TRACE best estimate system code. The present work presents the assessment of the Achilles natural reflood experiment with the TRACE V5.0 Patch 3. In addition, comparison calculations with TRACE V5.0 Patch 1 and latest RELAP5/MOD3.3 Patch 4 were performed. The TRACE input deck has been obtained by conversion of the already existing RELAP5 input deck. The calculated results were compared against the experimental data. The results show that both TRACE and RELAP5 are capable of reproducing the reflood phenomena at a satisfactory level. However, some discrepancies between the predicted variables and the experimental data suggest further investigation of the TRACE reflood model.

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EXECUTIVE SUMMARY

At present time, the development of RELAP5 has been ceased in favor of the newer US NRC TRACE best estimate code and it is expected that, in the future, TRACE will be one of the main codes used for performing nuclear power plant thermal-hydraulic safety analysis. Therefore, the importance of assessing the TRACE code capability to predict various thermal-hydraulic transients in reactor systems becomes evident. One such transient that can occur in pressurized water reactor is the core reflooding, following a large break loss of coolant accident. The core reflood is of particular interest for code assessment as it requires the system code to accurately predict specific core heat transfer and two-phase flow phenomena.

The present work presents the assessment of the Achilles natural reflood experiment with the TRACE V5.0 Patch 3. In addition, comparison calculations with TRACE V5.0 Patch 1 and latest RELAP5/MOD3.3 Patch 4 were performed. Given the fact that the TRACE Achilles natural reflood input model was obtained from the previously developed RELAP5 input model using the JSI RELAP5 to TRACE input deck conversion method, a RELAP5 and TRACE code comparison was also performed, using the calculation results of the above mentioned code versions. Mainly, this conversion method is based on SNAP and enables more direct comparison between the RELAP5 and TRACE calculations, given the same origin of data (RELAP5 input deck) and the same model geometry.

The Achilles natural reflood experiment was simulated using TRACE and RELAP5. Such TRACE and RELAP5 code comparison to experimental data can provide valuable insight into the advancement of code capability as the TRACE code is intended to consolidate and further extend the capabilities of the RELAP5 code. Thus the presented work contributes to the TRACE code assessment, by particularly addressing the TRACE V5.0 Patch 3 code capability to predict the reflood phenomena, and also by performing a code comparison against the latest RELAP5/MOD3.3 Patch 4 code.

The results show that both TRACE and RELAP5 are capable of reproducing the reflood phenomena at a satisfactory level. However, some discrepancies between the predicted variables and the experimental data suggest further investigation of the TRACE reflood model.

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ABBREVIATIONS

AEA	Atomic Energy Authority
ASCII	American Standard Code for Information Interchange
ISP	International Standard Problem
JSI	Jožef Stefan Institute
LB LOCA	Large Break Loss of Coolant Accident
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RBHT	Rod Bundle Heat Transfer
RELAP	Reactor Excursion and Leak Analysis Program
SNAP	Symbolic Nuclear Analysis Package
TRACE	TRAC/RELAP Advanced Computational Engine
US NRC	United States Nuclear Regulatory Commission

1. INTRODUCTION

The RELAP5 thermal-hydraulic safety analysis code is one of the best-estimate system codes that were developed by the US NRC for light water reactors thermal-hydraulic analysis. The first RELAP5 version was released in 1979 and has evolved continuously, through the development of new models and improvement of existing ones. This 30 years continuous evolution culminated with the release of the latest version RELAP5/MOD 3.3 Patch 4 in 2010 (Ref. 1). In the past, the RELAP5 computer code was one of the most used system codes in the international community. At present time, the development of RELAP5 has been ceased in favor of the newer US NRC TRACE best estimate code (Ref. 2) and it is expected that, in the future, TRACE will be one of the main codes used for performing nuclear power plant (NPP) thermal-hydraulic safety analysis. Therefore, the importance of assessing the TRACE code capability to predict various thermal-hydraulic transients in reactor systems becomes evident. One such transient that can occur in pressurized water reactor (PWR) is the core reflooding, following a large break loss of coolant accident (LB LOCA). The core reflood is of particular interest for code assessment as it requires the system code to accurately predict specific core heat transfer and two-phase flow phenomena (Ref. 3, Ref. 4).

In the present work the simulation of the Achilles natural reflood experiment (Ref. 5) with RELAP5/MOD3.3 Patch 4, TRACE V5.0 Patch 1 (version V5.141) and the latest released TRACE V5.0 Patch 3 (version V5.333) is presented and the calculation results are compared against experimental data and discussed. Given the fact that the TRACE Achilles natural reflood input model was obtained from the previously developed RELAP5 input model using the JSI RELAP5 to TRACE input deck conversion method (Refs. 6 and 7), a RELAP5 and TRACE code comparison was also performed, using the calculation results of the above mentioned code versions. Mainly, this conversion method is based on SNAP and enables more direct comparison between the RELAP5 and TRACE calculations, given the same origin of data (RELAP5 input deck) and the same model geometry.

The assessment of the TRACE reflood model was performed in the past against the GOTA Reflood test 43, FLECHT-SEASET Forced Reflood Tests and RBHT tests (Ref. 8) and the Achilles natural reflood experiment (Ref. 9). However, the latter work presents the Achilles natural reflood TRACE V5.211 calculation results using a model of the test bundle and shroud vessel only, with inlet and outlet boundary conditions imposed by a FILL and BREAK component respectively. The published works did not address the Achilles natural reflood experiment simulation using the latest TRACE V5.0 Patch 3 code employing a detailed model of the Achilles test rig. Also, TRACE and RELAP5 code comparison can provide valuable insight into the advancement of code capability as the TRACE code is intended to consolidate and further extend the capabilities of the RELAP5 code. Thus the presented work contributes to the TRACE code assessment, by particularly addressing the TRACE V5.0 Patch 3 code capability to predict the reflood phenomena, and also by performing a code comparison against the latest RELAP5/MOD3.3 Patch 4 code.

2. THE ACHILLES NATURAL REFLOOD EXPERIMENT DESCRIPTION

The Achilles natural reflood experimental study was performed at AEA Winfrith Technology Center, UK in 1991 aiming at investigating the end phase of the accumulator injection in the primary system of a PWR and the heat transfer in the core during the reflood phase of a postulated LB LOCA. The Achilles natural reflood experiment was the basis for the International Standard Problem no. 25 (ISP-25) (Ref. 5). A simplified schematic of Achilles separate effect test facility is presented in Figure 1.

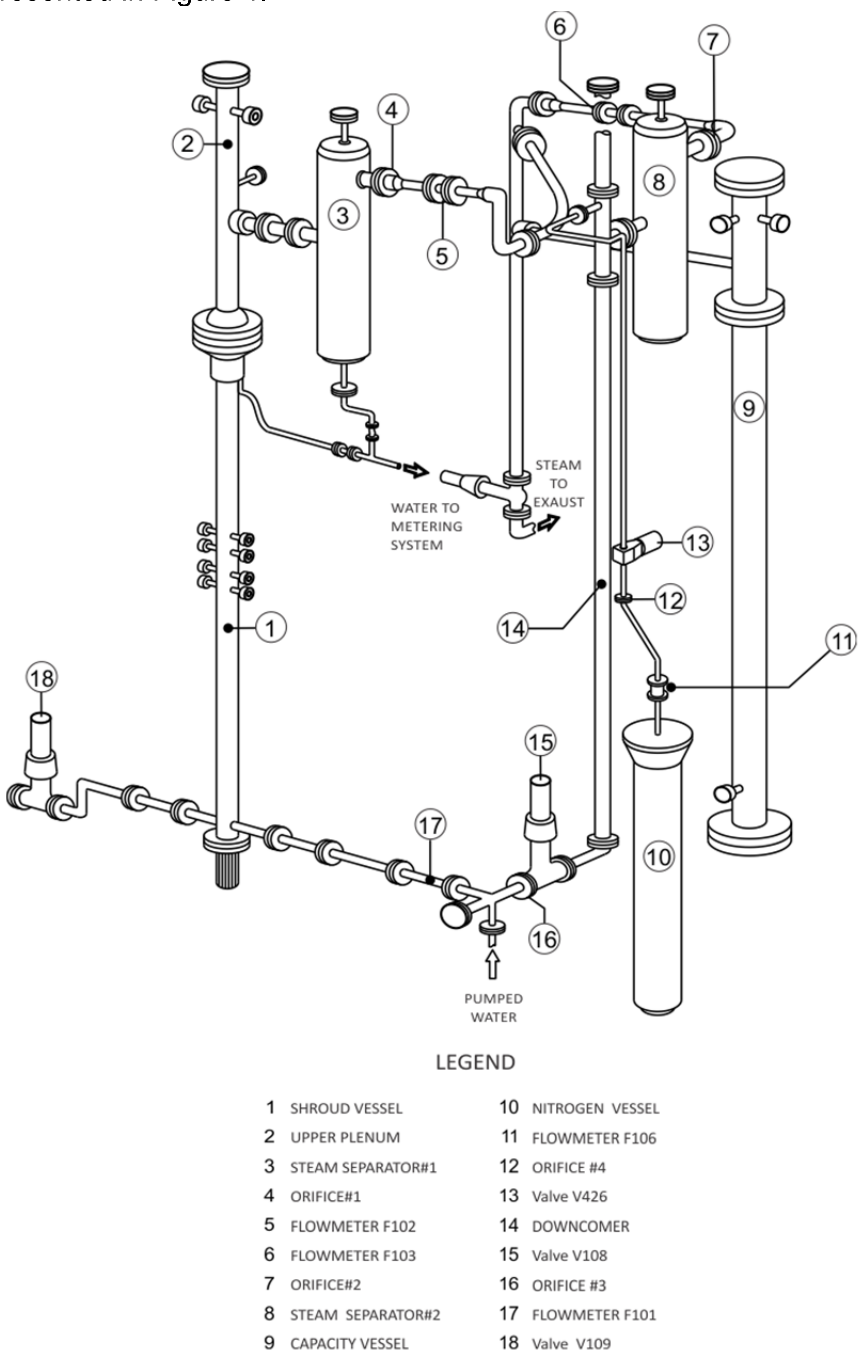


Figure 1 Schematic of Achilles separate effect test facility (adaptation from Ref. 5)

The simulated core test section comprised of 69 rods corresponding to Westinghouse 17x17 geometry was electrically heated over a length of 3.66 m. The electrical rod simulators had a diameter of 9.5 mm and were comprised of a kanthal wire heating coil, an inner insulating layer of boron nitride and an inconel 600 sheath (see Figure 2). The rod simulators, together with the temperature and pressure measurement instrumentation were housed inside the shroud vessel. A centrifugal steam separator located at the top of the shroud vessel discharges the test section output liquid flow. Additionally, a steam separator located downstream of shroud vessel, ensures the separation and collection of the liquid phase flowing out of the upper plenum, and outputs the single phase steam flow through an orifice, designed to simulate the hot leg associated flow losses. The liquid is separated from the flow exiting the upper part of the downcomer by means of another steam separator and the output gas phase flows through a second orifice that simulates the cold leg associated flow losses. The experimental procedure started with a full water inventory in downcomer and no water in the test section vessel. The rig is heated and circulated with steam until saturation temperature and pressure are attained and the rods and shroud have reached the required temperatures. When all initial conditions are reached, the valve between the downcomer and the shroud vessel is opened. Under the effect of both gravity head and nitrogen pressure, the water in the downcomer enters the simulated core. After the decay of the flow oscillations that are occurring at this point in the transient, the reflooding continues by means of pumped water injection, until all the test section rods have been quenched.

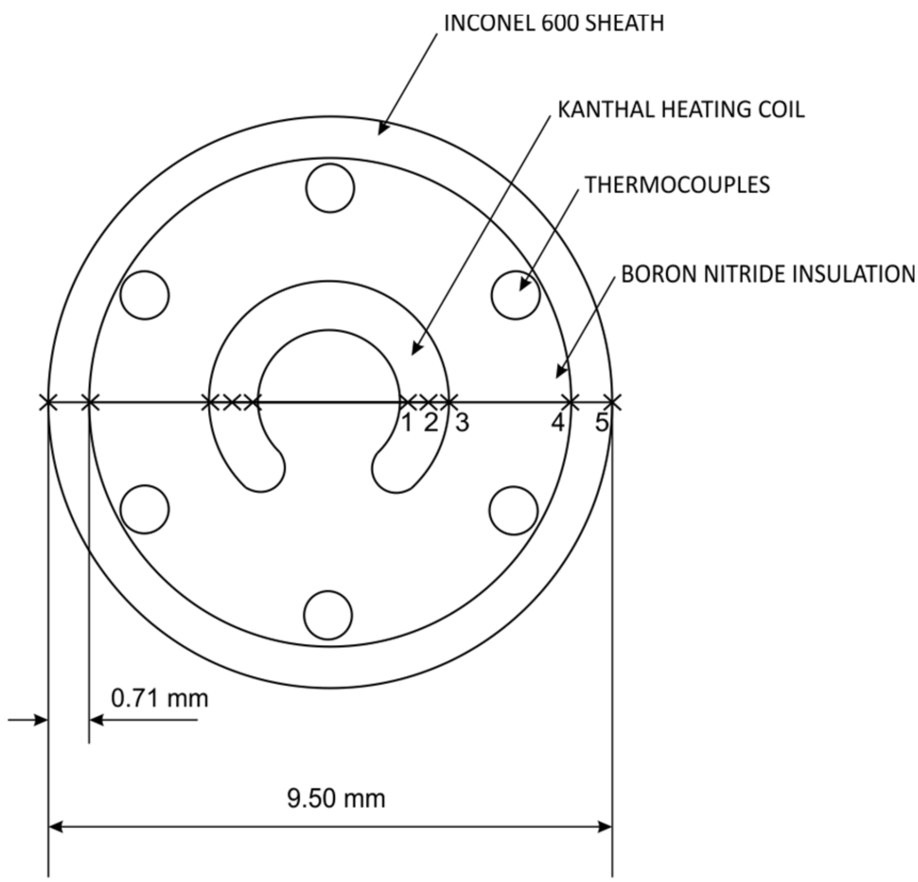


Figure 2 Achilles facility fuel simulator section view (adapted from Ref. 5)

3. JSI RELAP5 TO TRACE INPUT DECK CONVERSION METHOD

The JSI RELAP5 to TRACE input deck conversion method (Refs. 6 and 7) is based on SNAP and covers a wide range of aspects related to input deck conversion, input data verification and post-processing of the calculation results. This method also brings some additional benefits to the analyst. Firstly, more direct comparison between RELAP5 and TRACE analysis is possible, given the same origin of data (RELAP5 input deck) and consequently, the same model geometry. Secondly, using SNAP post-processing capabilities enables displaying the calculation results in an advanced way, in a straight foreword procedure, using the Hydraulic Components view model in SNAP (Refs. 10 and 12). The JSI RELAP5 to TRACE input model conversion method consists of 15 steps and is illustrated in Figure 3.

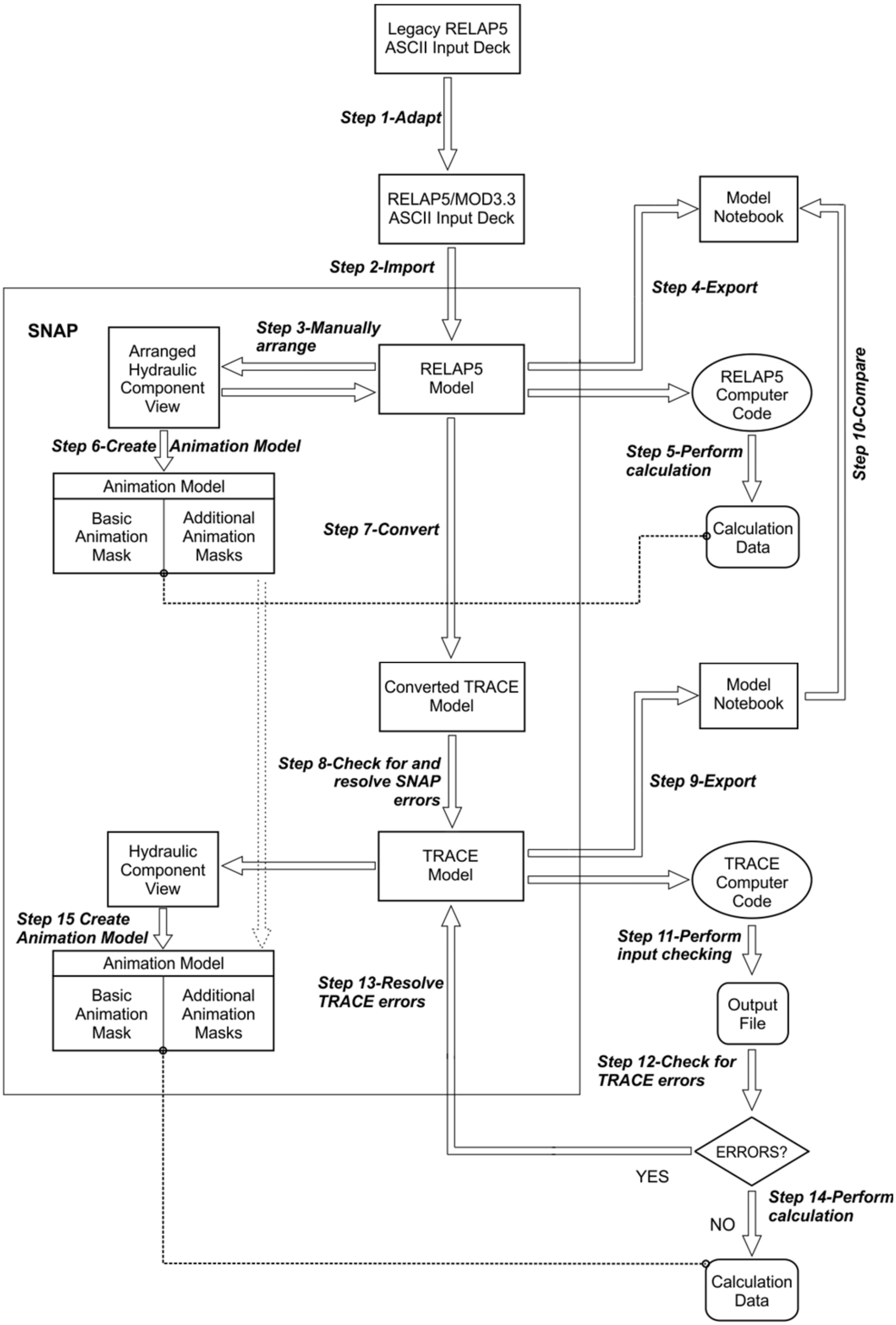


Figure 3 JSI RELAP5 to TRACE input deck conversion method

4. RELAP5 AND TRACE INPUT MODELS

4.1 Achilles facility RELAP5 input model

The RELAP5/MOD3.3 input model originated from a RELAP5/MOD2 input model, created at JSI, in the framework of ISP-25 participation (Ref. 13). The original RELAP5/MOD2 nodalization consists of 50 volumes, 50 junctions and 13 heat slabs and is presented in Figure 4. The nitrogen vessel is modeled by an accumulator component and the assumption is made that this component is not initially in injection mode. For that reason a valve was placed in between the accumulator and top of the downcomer. The accumulator was modeled as containing nitrogen only. The separators were modeled by RELAP5 branch components.

So prepared, the RELAP5/MOD2 model served for adaptation to RELAP5/MOD3.3 model (Figure 3, step 1). Some additional errors were identified while running the modified Achilles facility input deck under RELAP5/MOD3.3 code, mostly related to heat structure boundary data. Consequently, some additional left and right boundary data were added for the heat structure. The RELAP5/MOD3.3 ASCII input deck was imported into SNAP Model Editor (Figure 3, step 2) and the Hydraulic Components view was generated and manually arranged (Figure 3, Step 3) in order to provide a clear graphical representation of the RELAP5/MOD3.3 model nodalization. The RELAP5/MOD3.3 SNAP nodalization is presented in Figure 5.

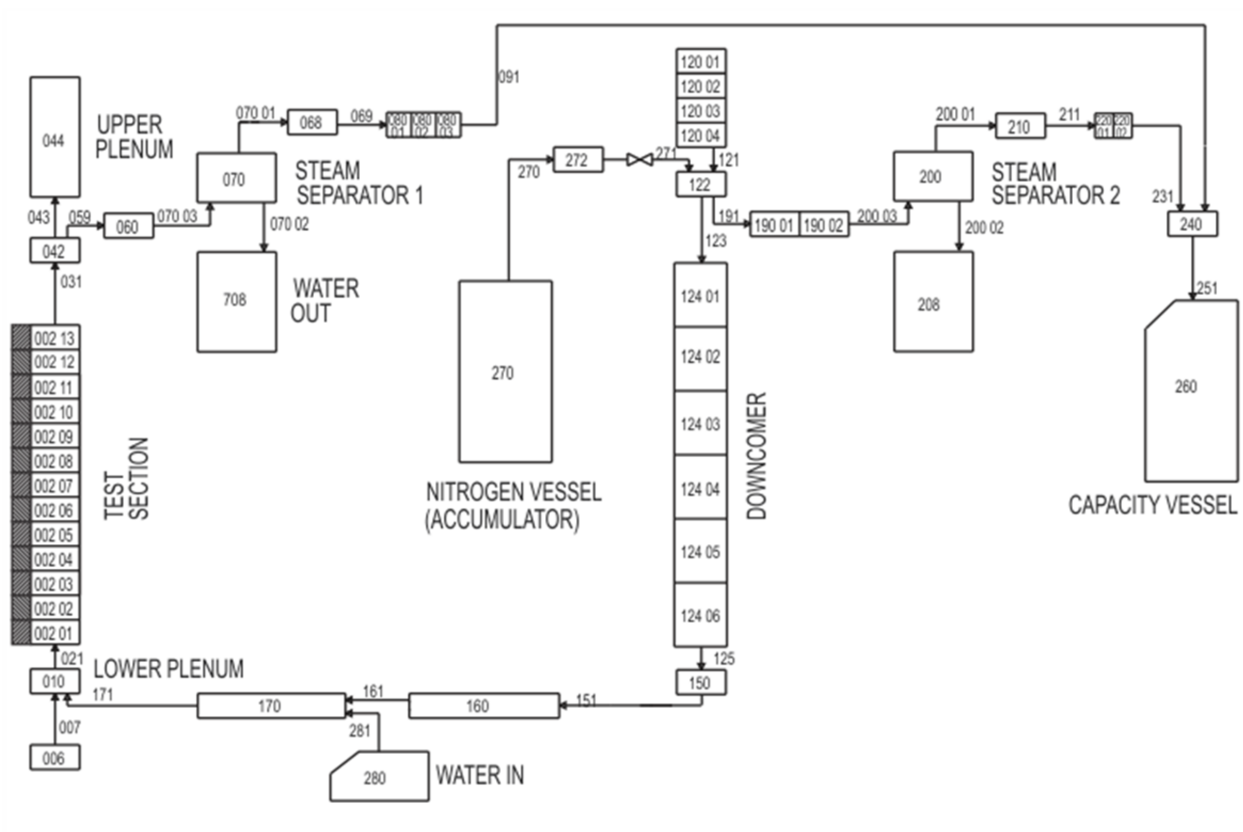


Figure 4 Achilles facility RELAP5/MOD2 input model nodalization

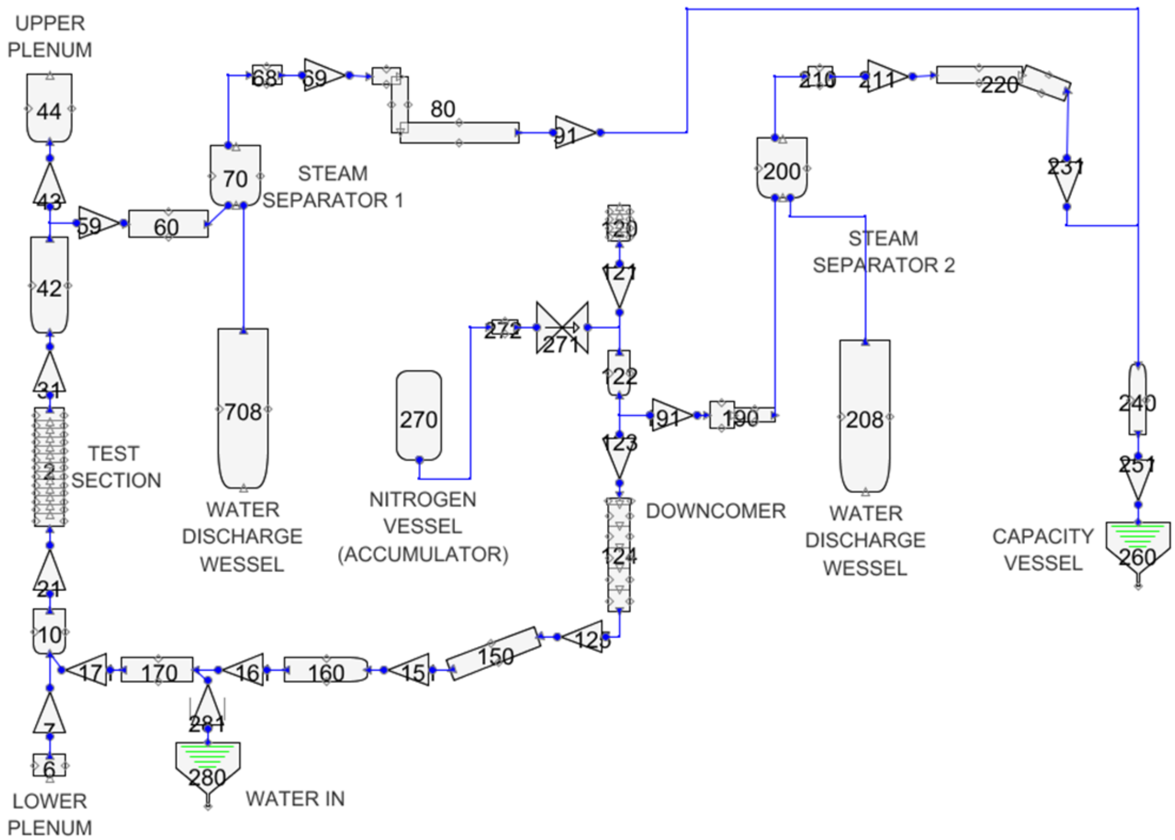


Figure 5 SNAP Hydraulic Components view of RELAP5/MOD3.3 Achilles facility model

4.2 Achilles facility TRACE input deck conversion and model description

The conversion of the RELAP5 input model to TRACE input model was performed in SNAP using the RELAP5 to TRACE conversion tool (Figure 3, Step 7). After checking for and resolving all errors reported in SNAP (Figure 3, Step 8), a model notebook for the TRACE model (Figure 3, Step 9) was generated in order to perform a comparison of the RELAP5 model against the converted TRACE model and several inconsistencies were identified in the converted model. The nitrogen vessel modeled by an Accumulator component in the RELAP5 input model was converted to Liquid separator pipe type in TRACE. The pipe type was manually changed to Accumulator type. The Accumulator surge line present in the RELAP5 input model as a part of the Accumulator component was not preserved in the converted TRACE model and was modeled using a Pipe component. The nitrogen non-condensable gas option and reflood model option were not successfully converted to the TRACE input model, and were specified accordingly. The hydraulic diameters for the Hydraulic Components in the TRACE model were either recalculated or obtained from the RELAP5/MOD3.3 calculation output file.

The Achilles facility SNAP Hydraulic Components view for the TRACE input is presented in Figure 6 and it comprises of 36 hydraulic components with a core test section nodalization divided in 13 cells, and a downcomer nodalization of 11 cells.

A TRACE heat structure component is used to model the 69 electrical rod simulators. As the outside surface boundary condition for each axial level is given by the thermal-hydraulic cells of the Pipe component that models the test section, the heat structure is subdivided into 13 axial nodes. In the radial direction, 6 radial mesh points are used, corresponding to 5 material regions (Figure 7). The rod simulator inconel 600 sheath, boron nitride insulator and kanthal heating coil are modeled in TRACE by specific material properties tables comprising of density, specific heat and thermal conductivity as a function of temperature. The bundle power in the core simulator is specified using a TRACE POWER component. The reflood phenomena are simulated using the TRACE heat structure reflood model. The fine mesh reflood option was specified employing 500 maximum axial nodes with a minimum node distance of 7 mm. The semi-implicit numerical method is used for the TRACE calculation.

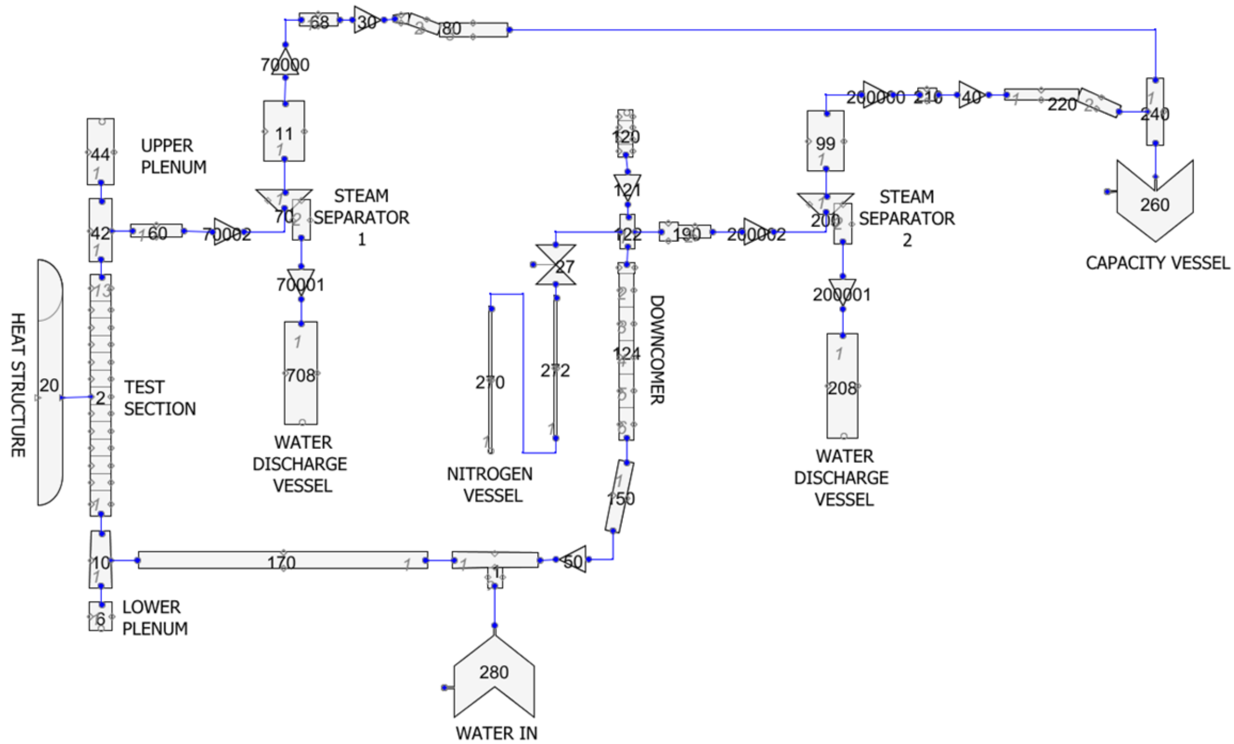
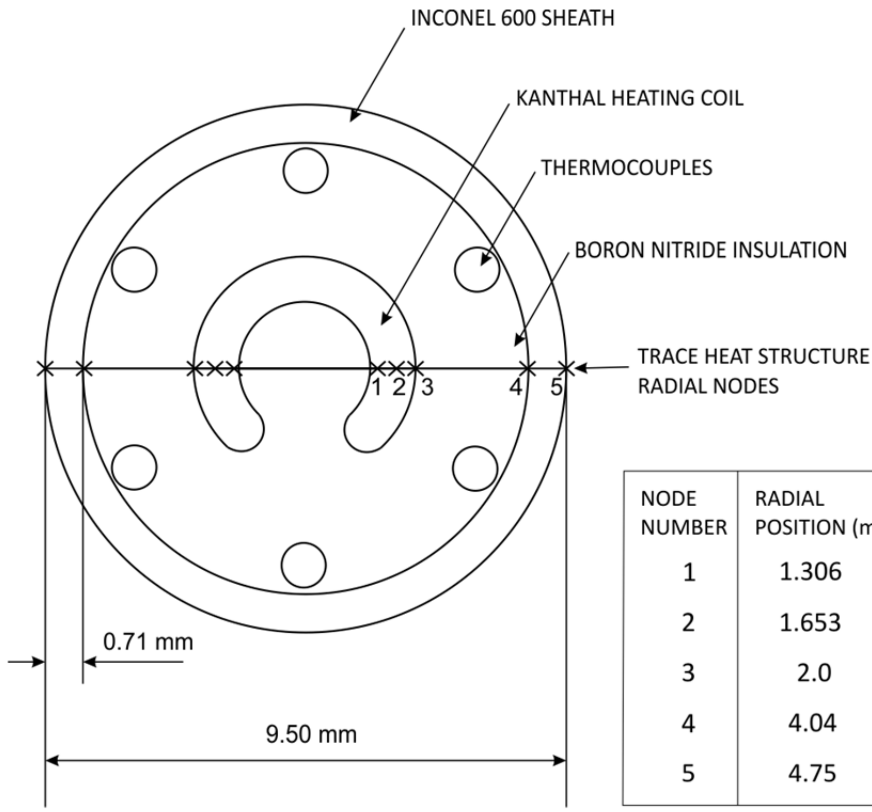


Figure 6 SNAP Hydraulic Components view of Achilles facility TRACE model



NODE NUMBER	RADIAL POSITION (mm)
1	1.306
2	1.653
3	2.0
4	4.04
5	4.75

Figure 7 TRACE heat structure radial mesh points location for the Achilles facility fuel simulator (adapted from Ref. 5)

5. RESULTS

5.1 Achilles calculations

The TRACE calculations data were compared against the experimental data and the RELAP5/MOD3.3 Patch4 calculation data as shown in Figures 8 through 14. The experimental data are labeled as “exp”, RELAP5/MOD3.3 Patch4 calculation data as “R5/MOD3.3”, TRACE V5.0 Patch 1 calculation data as “TRACEp1” and the TRACE V5.0 Patch 3 calculation data as “TRACEp3”.

During the reflood phase, the thermal behavior of the electrically heated rods is characterized by an initial gradual rise in temperature, followed by a temperature turn-around time when the peak cladding temperature is reached and a quench time, when the temperature of the rod drops in a very steep manner. This sudden drop in temperature is a consequence of an increase in heat removal rate due to the transition from dispersed droplet flow film boiling to nucleate boiling (Ref. 4). The TRACE V5.0 Patch 1 and Patch 3 calculations provide good agreement with the experimental data for the peak cladding temperatures at low and medium elevations in the test section, as presented in Figure 8 and Figure 9, showing rod cladding temperature evolution at 1.084 meters and 2.01 meters elevation in the test section, respectively. Although the RELAP5/MOD3.3 Patch4 is slightly over-predicting the peak cladding temperature for the 1.084 meters elevation in the test section (Figure 8), the predictions of the peak cladding temperature for middle (Figure 9) and higher test section locations (Figure 10) are in very close agreement with the experimental values. The peak cladding temperature at 2.01 meters (Figure 9) is of particular interest as the highest experimental peak cladding temperature was achieved at this elevation. For higher elevations in the test section the TRACE V5.0 Patch 1 calculation is slightly over-predicting the peak cladding temperature but the overall agreement with the experimental data in the first part of the heating up phase is maintained, as shown in Figure 10 that describes the cladding temperature evolution at 3.176 meters elevation in the test section. Figure 11 presents the quench front progression. For this parameter, the RELAP5/MOD 3.3 provides a closer agreement to the experimental values for the middle transient interval.

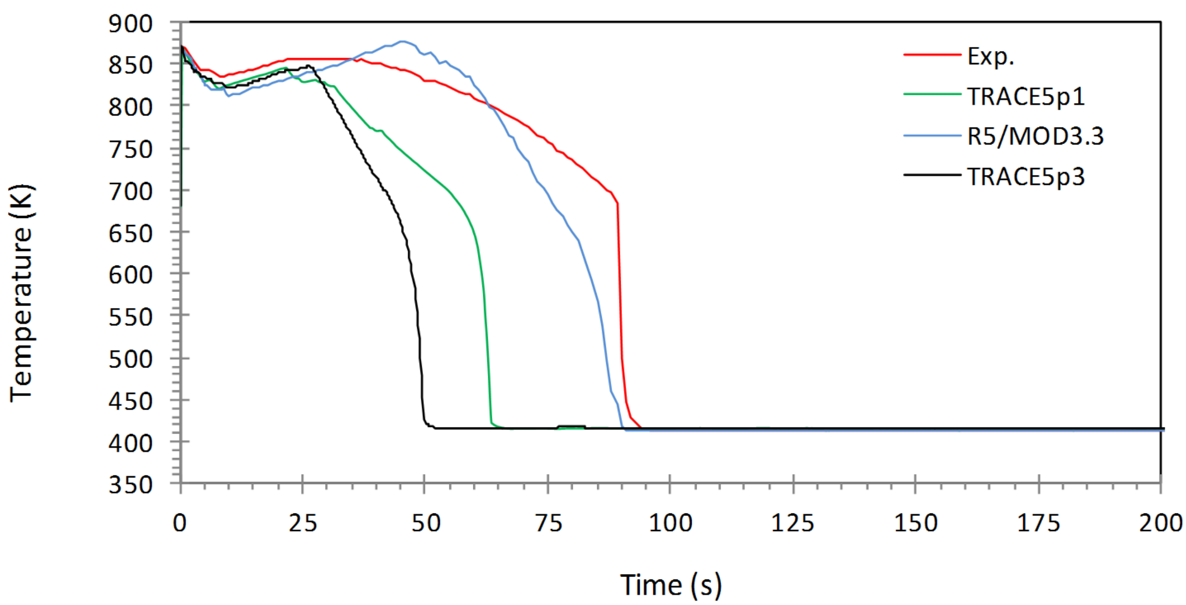


Figure 8 Rod cladding temperature at 1.084 m elevation

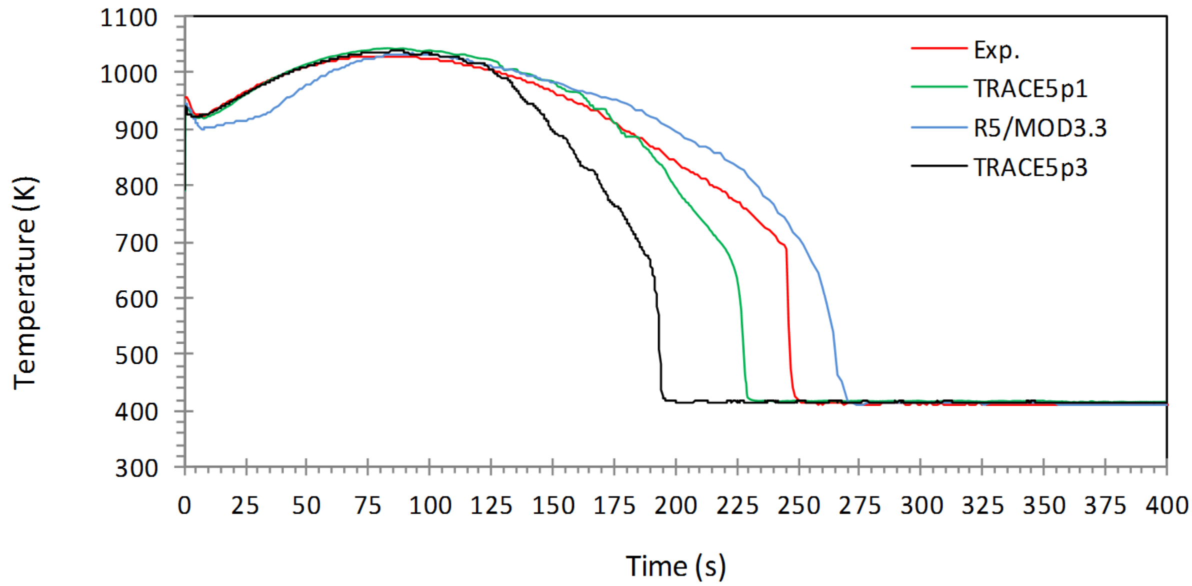


Figure 9 Rod cladding temperature at 2.01 m elevation

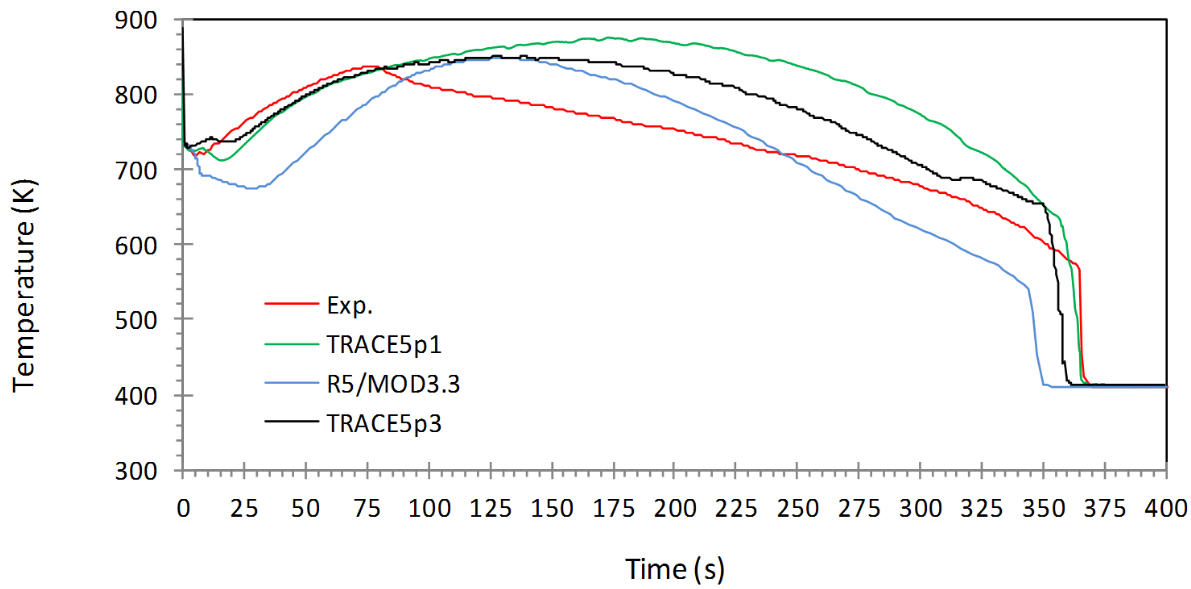


Figure 10 Rod cladding temperature at 3.176 m elevation

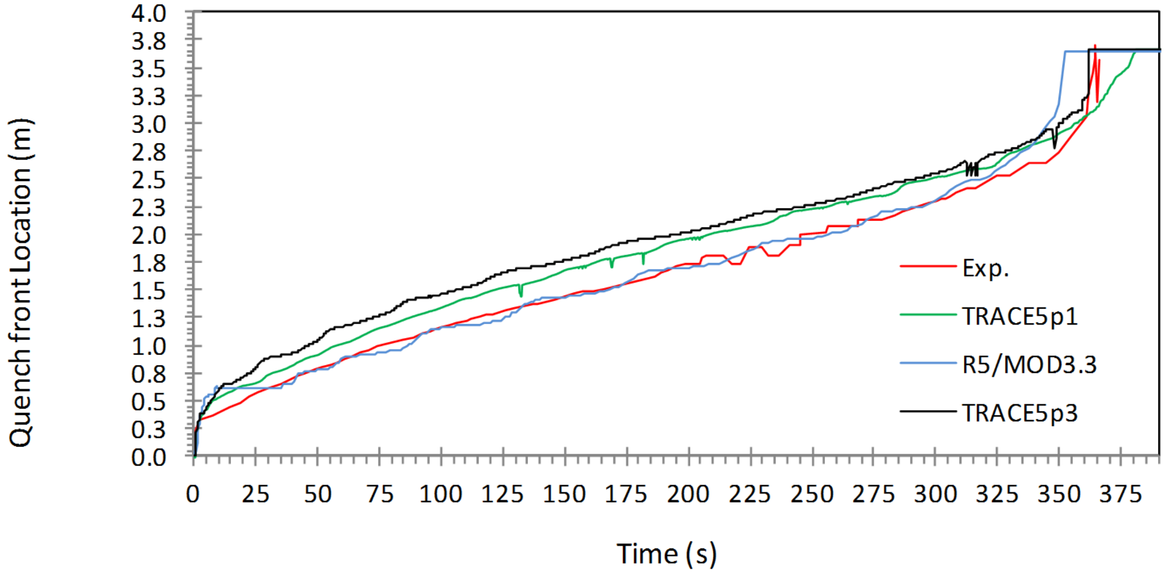


Figure 11 Quench front progression

The core collapsed liquid level predicted by RELAP5/Mod3.3 Patch4 and the TRACE versions is in reasonable agreement with the experimental results, although the magnitude of the level oscillations is greater than in the experimental results, as shown in Figure 12. The core collapsed liquid level is in close connection with the pressure conditions predicted in the core as the phase shift occurs in the coolant that is entering the test section. The pressure condition in the upper plenum predicted with RELAP5 and TRACE is presented in Figure 13. The higher pressure predicted by RELAP5/MOD3.3 Patch4 in the first 30 seconds of the transient represents the reason for the initial core collapsed liquid level mismatch in comparison to the experimental results (Figure 12). TRACE Patch 1 and Patch 3 calculations of pressure at the top of the upper plenum (Figure 13) and core collapsed liquid level (Figure 12) provide closer agreement to the experimental data for the early stages of the transient.

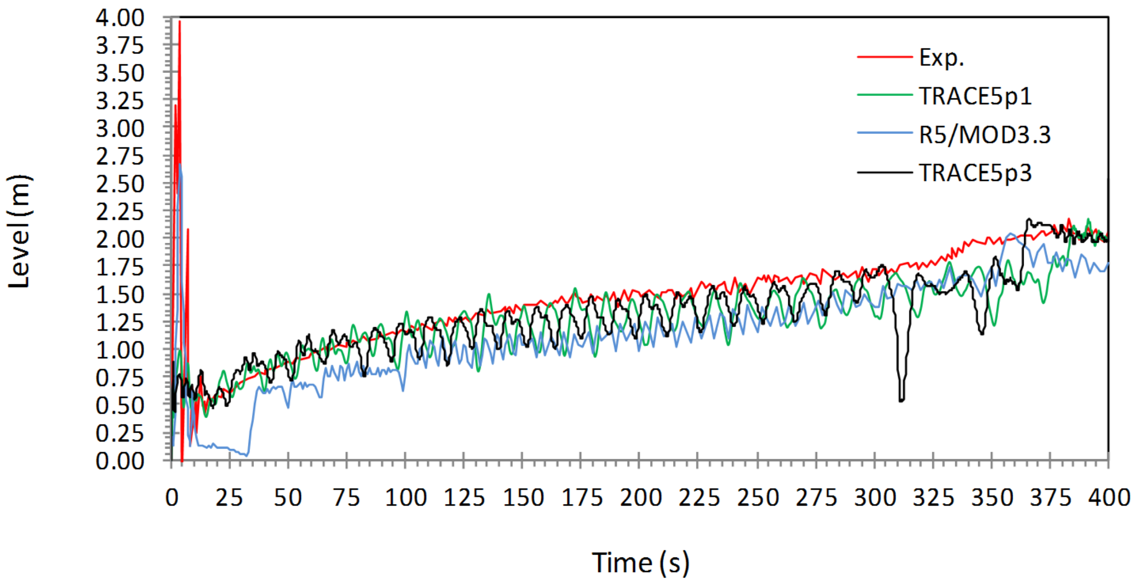


Figure 12 Core collapsed liquid level

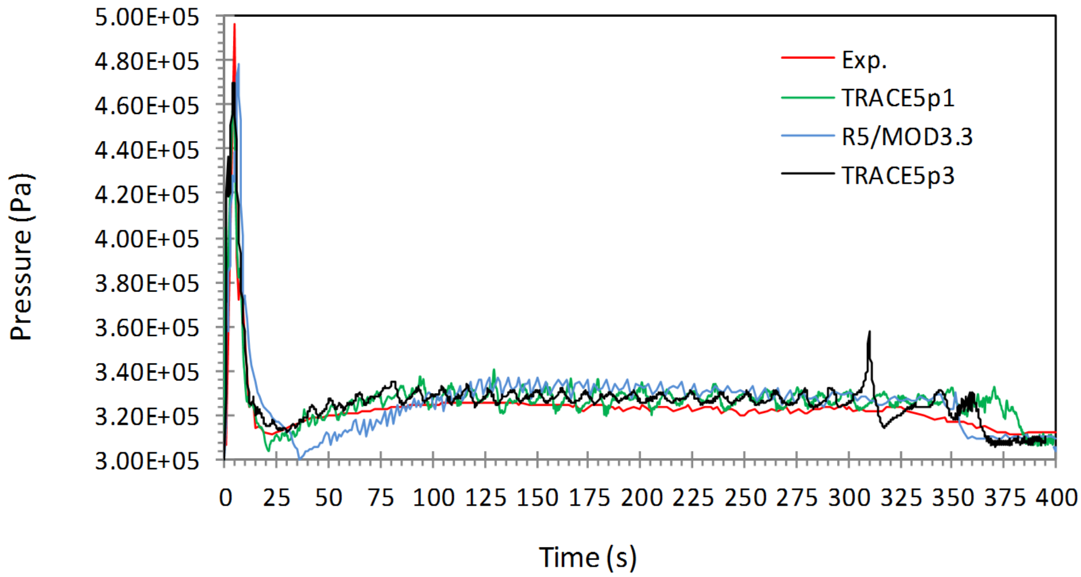


Figure 13 Pressure evolution in the upper plenum

The evolution of the downcomer collapsed liquid level is presented in Figure 14. The oscillatory behavior observed in the RELAP5 and TRACE calculated core collapsed liquid level is also noted in the calculated downcomer collapsed liquid level. However, it is observable that the TRACE calculations, and in particular the TRACE V5.0 Patch 1 results, provide the best match to the initial level swelling.

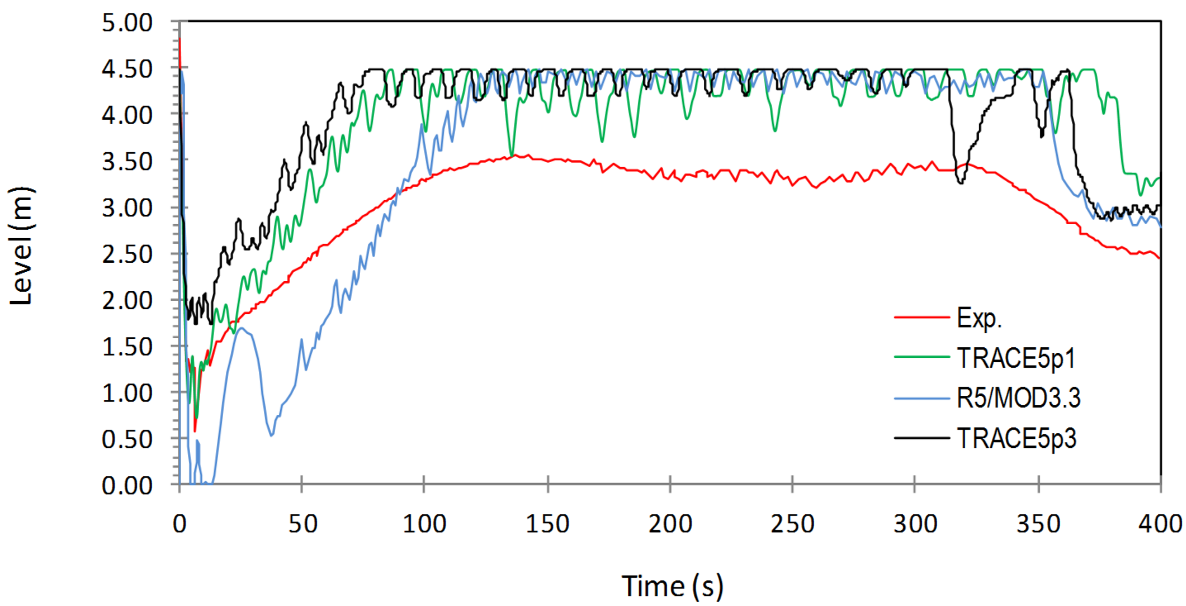


Figure 14 Downcomer collapsed liquid level

Finally, the pressure in the nitrogen vessel is shown in Figure 15. Calculated pressure of both TRACE versions is in good agreement with the experimental data.

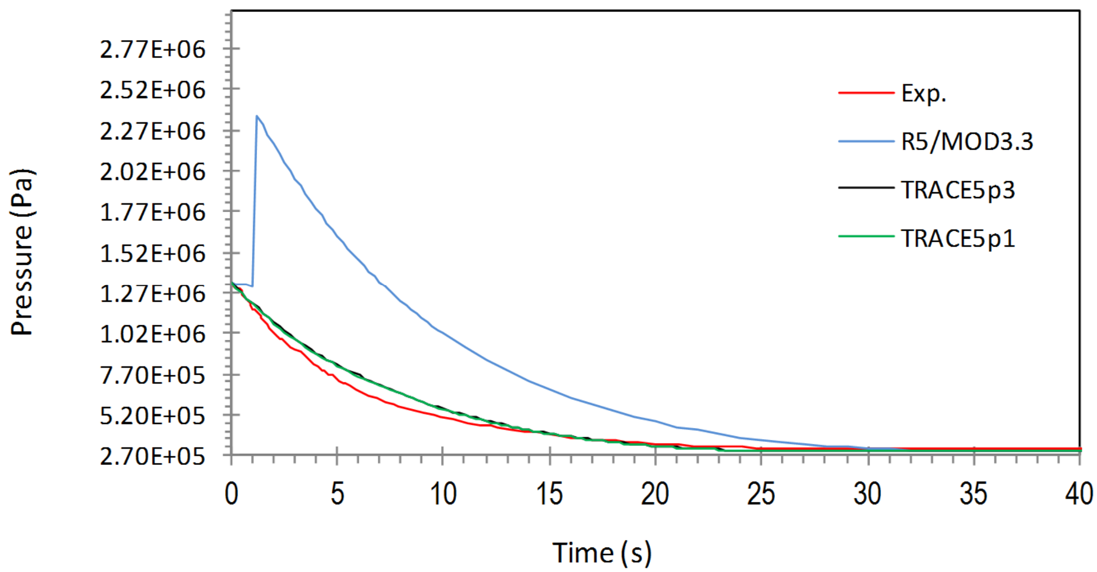


Figure 15 Pressure in the nitrogen vessel

5.2 Achilles natural reflood experiment animation model

Several SNAP animation masks were developed for the Achilles natural reflood experiment TRACE model, graphically displaying the evolution of different phenomena during the 400 seconds transient.

The simple animation mask shown in Figure 16 contains the SNAP Hydraulic Components View of the TRACE model transferred to a SNAP animation model by simple “Copy-Paste” method. The basic animation mask is similar, however the mask was further elaborated in the Model Editor. A snapshot of such animation mask for the Achilles natural reflood TRACE V5.0 Patch 3 calculation at 152.3 seconds into the transient is presented in Figure 17.

In Figure 18 is presented a snapshot of the control system and fluid mass balance animation mask at 39.1 seconds into the transient. Figure 19 presents a snapshot of the TRACE V5.0 Patch 3 calculation at 244.5 seconds into the transient. In a similar approach, a core condition animation mask was generated, displaying the void fraction in the test section, core collapsed liquid level, rod temperatures and quench front progression. A snapshot of this animation mask is presented in Figure 20, displaying the TRACE V5.0 Patch 3 calculation data for 98.1 seconds into the transient.

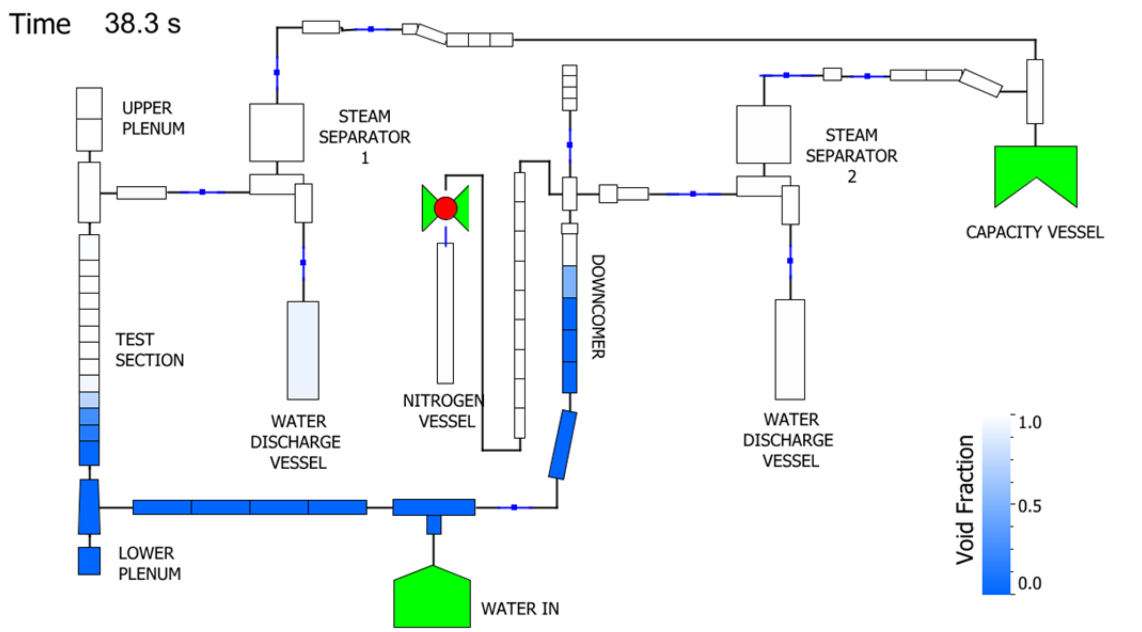


Figure 16 Simple SNAP nodalization animation mask of the Achilles natural reflood TRACE calculation

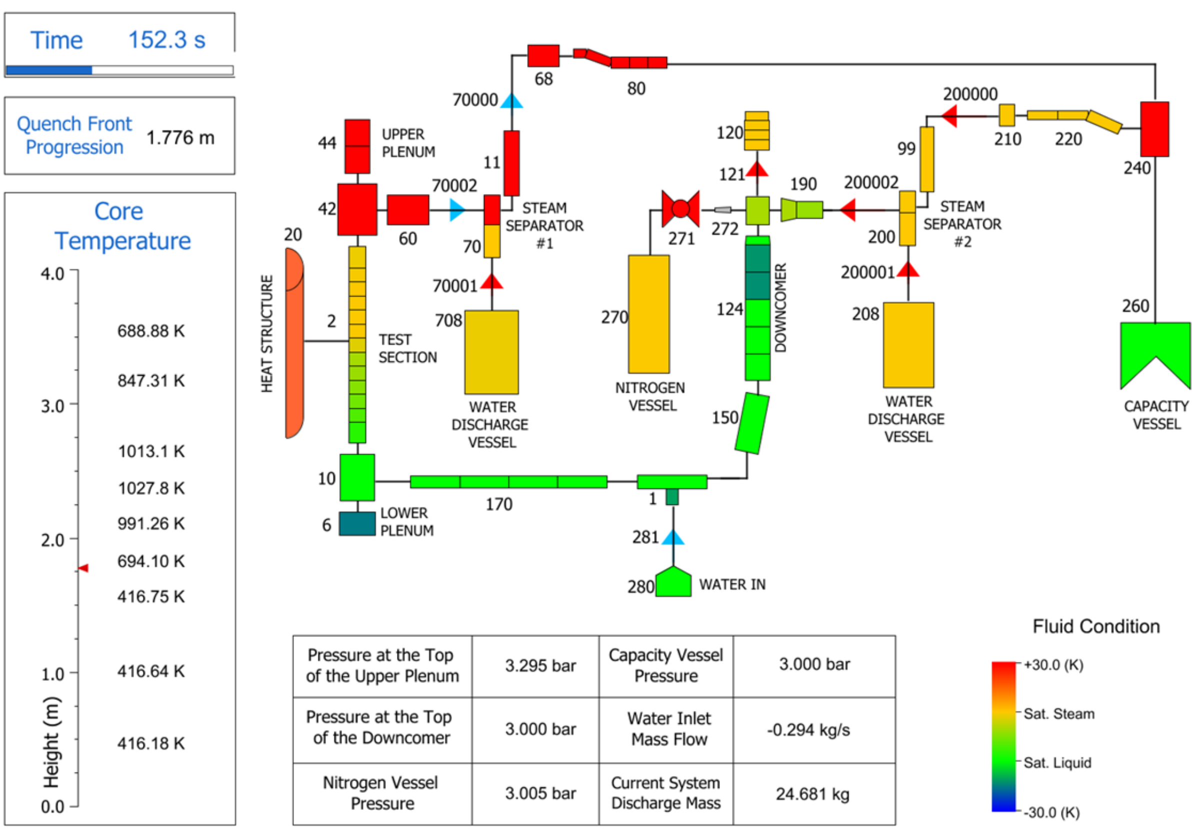


Figure 17 Basic SNAP nodalization animation mask of the Achilles natural reflood TRACE calculation

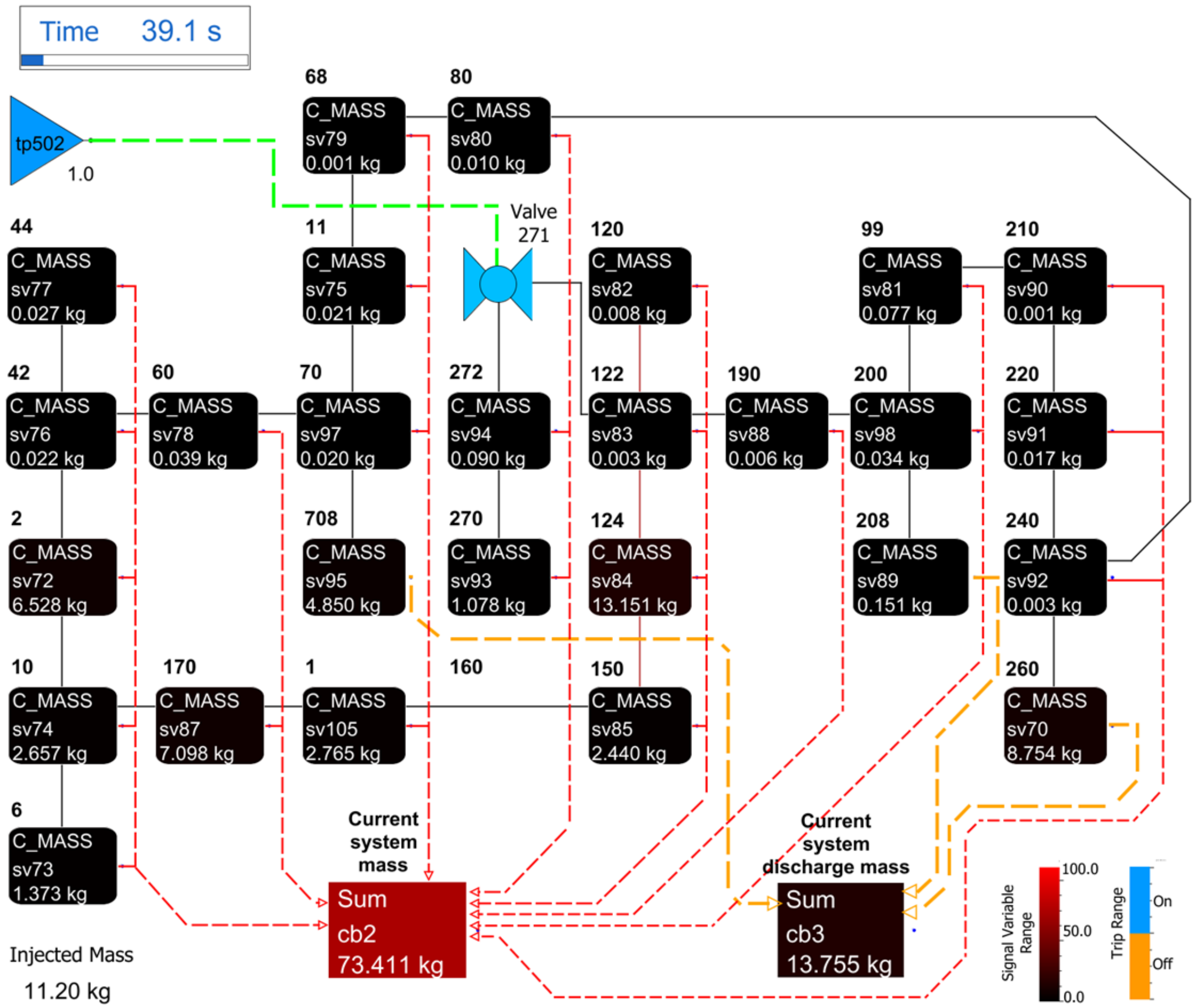


Figure 18 Control system and mass balance SNAP animation mask for the Achilles natural reflood TRACE calculation

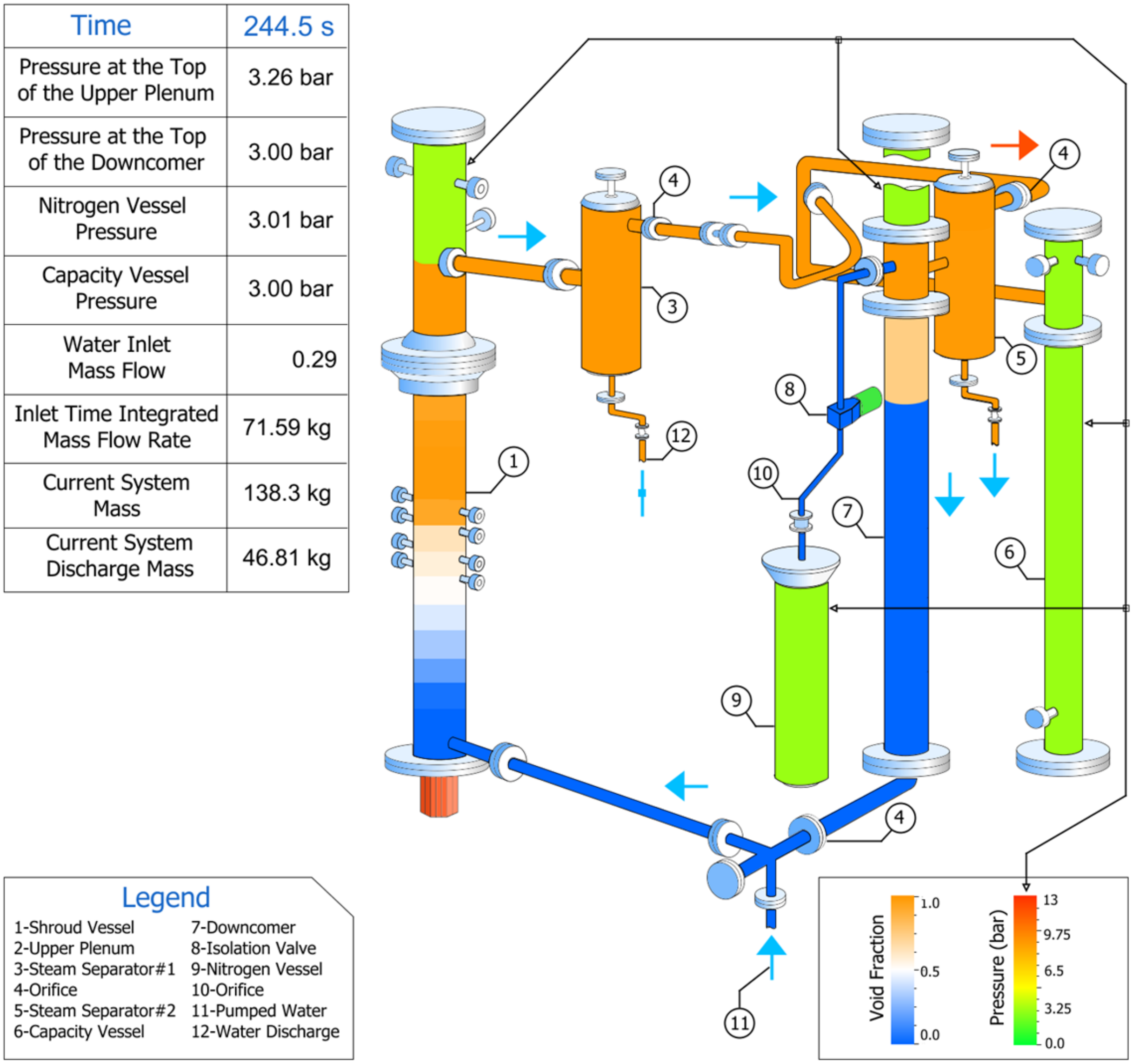


Figure 19 Facility view SNAP animation mask for the Achilles natural reflood TRACE calculation

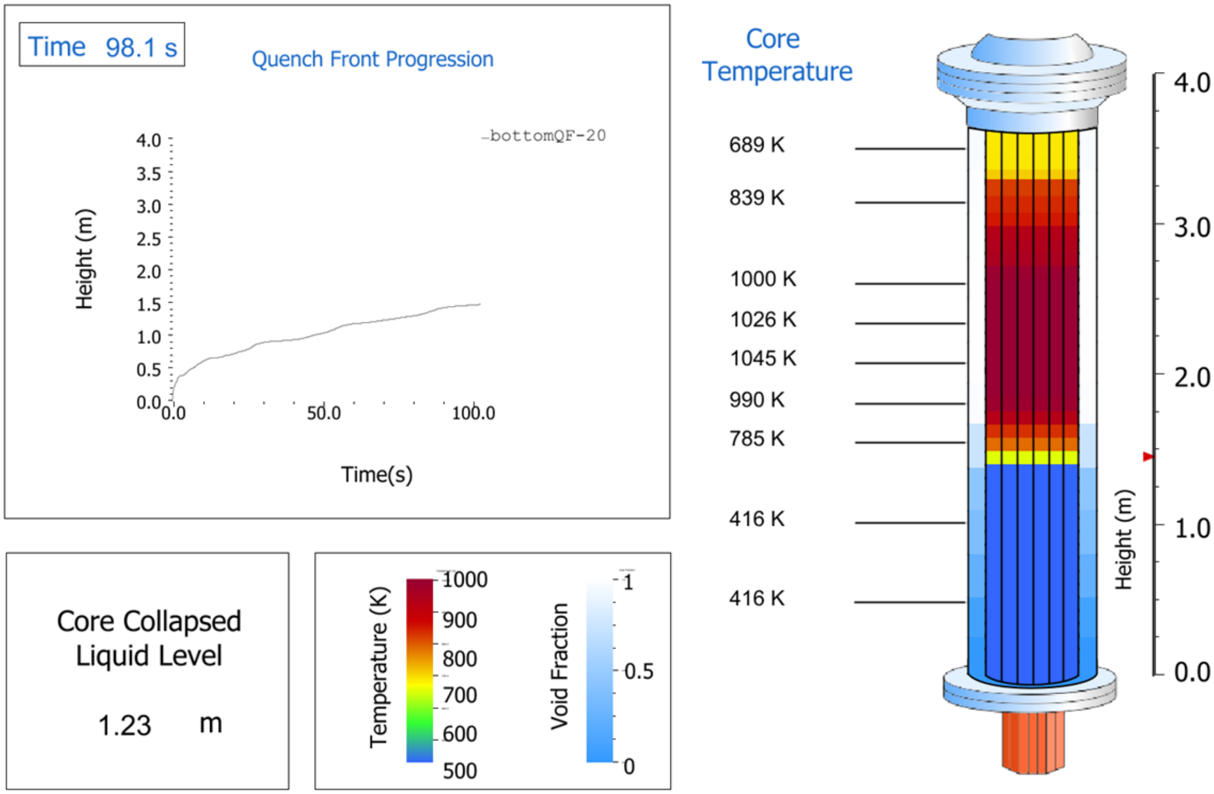


Figure 20 Core condition animation mask for the Achilles natural reflood TRACE calculation

5.3 <u>Results discussion</u>

Our previous studies employing RELAP5 to TRACE conversions using SNAP usually show that the TRACE calculation results are in general comparable to the RELAP5 calculation results (Ref. 6). This finding also applies in the case of Achilles natural reflood experiment TRACE and RELAP5 calculation results.

Nevertheless in the case of TRACE computer code Achilles natural reflood calculation, few observations can be made. Both TRACE V5.0 Patch 1and Patch 3 calculations present a tendency to under predict the quench time for the test sections located at low and middle elevations in the core (Figure 8 and Figure 9). This under-prediction of the quench times calculated by TRACE V5.0 Patch 1 and Patch 3 is in agreement with the conclusions of the TRACE assessment report (Ref. 8) which states that TRACE has a tendency to under predict quench times for low flow, low power cases. The tendency of TRACE to under-predict the quench times can be also observed in Figure 11 presenting the quench front progression. The RELAP5/MOD3.3 Patch4 calculation is providing closer agreement to the experimental values for the 40 seconds to 300 seconds interval. However, the RELAP5 calculation data deviates from the experimental trend towards the end of the transient, while the TRACE V5.0 Patch 3 calculation is converging to the experimental quench front location. Compared to the TRACE V5.0 Patch 3, the TRACE V5.0 Patch 1 calculation shows slightly better overall estimation of the quench front progression but exceeds the experimental quenching time for the last part of the transient.

The inherent oscillatory behavior of the reflood phenomena that was also observed in the experiment is present in both RELAP5 and TRACE calculations. The calculated magnitude of oscillations for the downcomer and core collapsed liquid levels is higher than in the experimental results. In the case of the TRACE V5.0 Patch 3 computer code several attempts were made to reduce the magnitude of the oscillations. Firstly, two different numerical methods for solution of the two-phase-flow equations were used. These methods are the semi-implicit method and the stability-enhancing two-step numerics (SETS). It was found that apart from some shift that is occurring in the phase of the predicted oscillations, the oscillation magnitude for the core and downcomer collapsed liquid level is maintained during the transient for both numerical methods (Figure 21). A sensitivity study was also performed in order to investigate the influence of the time-step size on the oscillations magnitude predicted by the TRACE V5.0 Patch 3. In order for the code to pass the nitrogen injection phase, the variation in the time-step size is performed only after the initial 50 seconds of the transient, however the variation in time-step size had minimum impact on the TRACE calculation results. Taking this into consideration, the oscillatory behavior observed in the codes calculations could relate to the ability of the codes to predict heat transfer mechanisms and two-phase flow regimes that characterize the reflood phenomena.

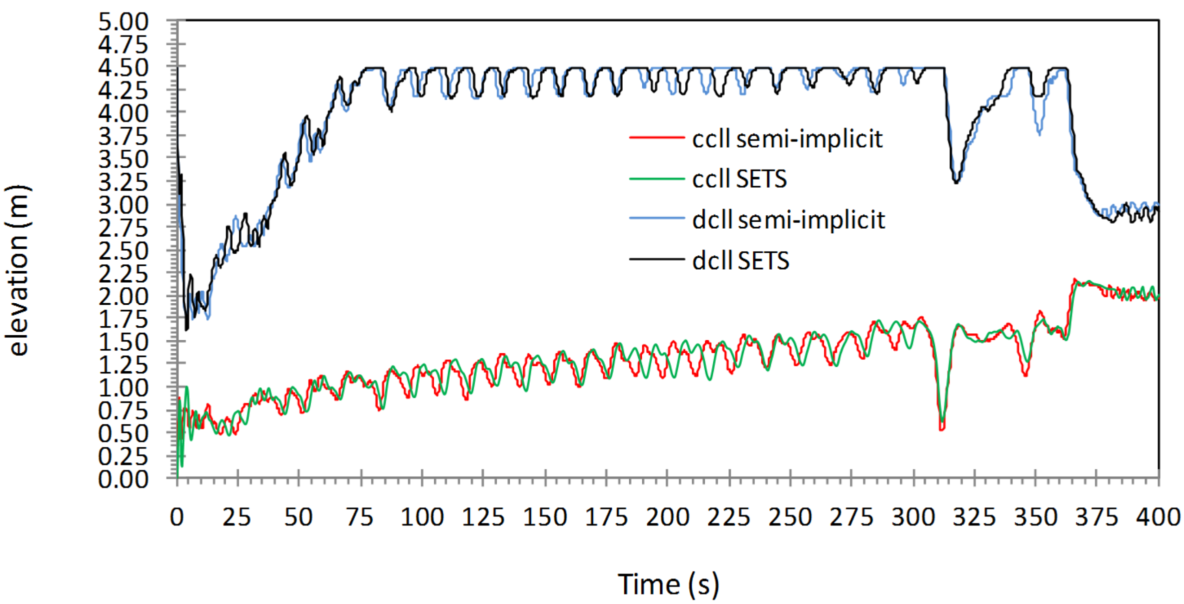


Figure 21 TRACE V5.0 Patch 3 predictions for core collapsed liquid level and downcomer collapsed liquid level using semi-implicit and SETS methods

6. RUN STATISTICS

The calculations were performed using Intel® Core™ i5 750 @ 2.676 GHz processor. The operating system is Windows 7 Professional.

Table 1 shows the run statistics for the codes TRACE Patch 1, TRACE Patch 3 and RELAP%/MOD3.3 Patch 4 calculations. As it can be seen RELAP5 is more than ten times faster in calculating the Achilles reflood experiment than TRACE.

Table 1 Run statistics

Code	Transient Time (s)	CPU Time (s)	CPU/Transient Time	Number of Time Steps
TRACE Patch 1	399.9	727.68	1.82	120448
TRACE Patch 2	399.84	506.18	1.27	130924
RELAP5/MOD3.3 Patch 4	400.01	55.15	0.14	34123

7. CONCLUSIONS

The Achilles natural reflood experiment was calculated using RELAP5/MOD3.3 Patch4, TRACE V5.0 Patch 1 and the latest TRACE V5.0 Patch 3. The calculation results were compared to the experimental data. In general the TRACE calculations reasonably agree with experimental data. This is especially true for peak cladding temperatures in the simulated core, proving that the TRACE code is capable of predicting the reflood phenomena in sufficient detail. The TRACE predictions for the core and downcomer collapsed liquid levels reproduce the reflood oscillatory nature. However, the calculated magnitudes were higher in comparison with the experimental data, suggesting further investigation of the TRACE code reflood model. The TRACE V5.0 Patch 1 and Patch 3 calculation results are comparable to the RELAP5/MOD3.3 Patch4 calculation implying the similar capabilities of the codes to model the reflood phenomena. Finally, the calculated results were animated using SNAP masks, which provide clear insight into the phenomena during transient.

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10. SUPPLEMENTARY NOTES

K. Tien, NRC Project Manager

11. ABSTRACT *(200 words or less)*

At present time, the development of the U.S. Nuclear Regulatory Commission RELAP5 has been ceased in favor of the newer TRACE best estimate system code. The present work presents the assessment of the Achilles natural reflood experiment with the TRACE V5.0 Patch 3. In addition, comparison calculations with TRACE V5.0 Patch 1 and latest RELAP5/MOD3.3 Patch 4 were performed. The TRACE input deck has been obtained by conversion of the already existing RELAP5 input deck. The calculated results were compared against the experimental data. The results show that both TRACE and RELAP5 are capable of reproducing the reflood phenomena at a satisfactory level. However, some discrepancies between the predicted variables and the experimental data suggest further investigation of the TRACE reflood model

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