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RELAP5 and TRACE Simulation of Bethsy 9.1b Test with Accuracy Quantification

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ABSTRACT

In this study the TRACE advanced thermal-hydraulic system code has been used to simulate the BETHSY 9.1b integral experimental test. The TRACE results are compared with the RELAP5 computer code predictions. In addition, the accuracy of both simulations has been evaluated. BETHSY is an integral test facility, which was designed to simulate most pressurized water reactors (PWR) accidents of interest, to study accident management procedures and to validate the computer codes. The BETHSY 9.1b experiment represents the Small Break Loss-of-Coolant Accident (SBLOCA) with loss of high pressure injection system. After the Fukushima-Daiichi nuclear accident, this type of accident is considered as a part of Design Extension Conditions (DEC). As no DEC safety features for high pressure injection are available in BETHSY 9.1b test, a delayed operator action for secondary system depressurization has been analysed in this study. For accuracy quantification the Fast Fourier Transform Based Method by signal mirroring (FFTBM-SM) and original FFTBM have been used. The comparison of the simulated results with the experimental data is presented. Finally, the results of code accuracy quantitative assessment are shown.

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EXECUTIVE SUMMARY

In this study the TRACE advanced thermal-hydraulic system code has been used to simulate the BETHSY 9.1b integral experimental test. The TRACE results are compared with the RELAP5 computer code predictions. In addition, the accuracy of both simulations has been evaluated. BETHSY is an integral test facility, which was located in Grenoble, and was designed to simulate most PWR accidents of interest, to study accident management procedures and to validate the computer codes. It is a scaled down model of three loop Framatome nuclear power plant with the thermal power 2775 MW. There were 428 electrically heated rods, which could reach 1273 K.

The Bethsy 9.1.b test is a scaled 5.08 cm cold leg break in loop 1 without high pressure safety injection (HPSI) and with delayed operator action for secondary system depressurization. The test was analyzed in the frame of International Standard Problem 27 (ISP-27) performed to validate the thermal-hydraulic computer codes. ISP-27 was prepared and coordinated by the Committee on the Safety of Nuclear Installations (CSNI) of the Nuclear Energy Agency within the Organisation for Economic Co-operation and Development (OECD/NEA).

The simulations were performed with the TRACE V5.0 Patch 5 and RELAP5/MOD3.3 Patch 5 computer codes. The first RELAP5/MOD2 input model was developed, when participating to ISP-27. The input model was continuously adapted to newer versions of RELAP5 computer code. This input model was adapted for the use with RELAP5/MOD3.3 and all its patches, too. The hydrodynamic view was generated by SNAP from RELAP5 input model (in ASCII) and then arranged manually using Model Editor of SNAP in 2011. Finally, the TRACE input model has been developed by conversion of the standard RELAP5 input model of BETHSY into TRACE.

The TRACE results have been compared to RELAP5 results qualitatively (by visual comparison) and quantitatively by using method for code accuracy quantification. The original fast Fourier transform based method (FFTBM) and the FFTBM by signal mirroring (FFTBM-SM) have been used. FFTBM-SM has been developed later to eliminate the edge effect (periodic signals form edge, if first and last data points are not the same), which influences the amplitude spectrum and by this the figures of merit.

The differences in code accuracy of RELAP5 and TRACE calculation, calculated both by the FFTBM and FFTBM-SM are small, indicating that both code calculations are comparable to each other.

ACKNOWLEDGMENTS

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ABBREVIATIONS AND ACRONYMS

ATWS	anticipated transient without scram
BETHSY	Boucle d'Etudes Thermohydrauliques de Systemes
CSNI	Committee on the Safety of Nuclear Installations
DEC	design extension conditions
ECCS	emergency core cooling system
FFTBM	Fast Fourier Transform Based Method
FFTBM-SM	FFTBM by Signal Mirroring
IAEA	International Atomic Energy Agency
HPIS	high pressure injection sytem
HPSI	high pressure safety injection
LOCA	loss of coolant accident
LPIS	low pressure injection system
LPSI	low pressure safety injection
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
PWR	pressurized water reactor
RHRS	residual heat removal system
RPV	reactor pressure vessel
SBLOCA	Small Break Loss Of Coolant Accident
SI	safety injection
SG	steam generator
TRACE	TRAC/RELAP Advanced Computational Engine
U.S.NRC	U.S. Nuclear Regulatory Commission
WENRA	Western European Nuclear Regulators Association

1 INTRODUCTION

The TRAC/RELAP Advanced Computational Engine (TRACE) is today the state-of-the-art and one of the world's leading best estimate system codes in the field of thermal-hydraulics [1]. It is intended for safety analyses of loss-of-coolant accidents and operational transients, as well as other accident scenarios in pressurized light-water reactors (PWR) and boiling light-water reactors (BWR). For TRACE code assessment, the 9.1b test performed on Boucle d'Études Thermo-Hydraulique Système (BETHSY) has been selected, representing beyond design basis accident with non-degraded core. After the Fukushima-Daiichi accident, International Atomic Energy Agency (IAEA) [2] and Western European Nuclear Regulators Association (WENRA) [3] listed this type of loss of coolant accident as a design extension conditions (DEC). No DEC safety features for high pressure injection were available in BETHSY 9.1b test. Rather, delayed operator action for secondary system depressurization has been studied. This test is important, since after the Fukushima Dai-ichi accident, besides the design basis accidents (DBAs), the use of computer codes is required also for safety evaluation of light water reactors (LWRs) during the design extension conditions (DECs).

The TRACE results have been compared to RELAP5 results qualitatively (by visual comparison) and quantitatively by using method for code accuracy quantification. The original fast Fourier transform based method (FFTBM) and FFTBM by signal mirroring (FFTBM-SM) have been used. FFTBM-SM has been developed later to eliminate the edge effect (periodic signals form edge, if first and last data points are different), which influences the amplitude spectrum and by this the figures of merit.

The report is organized as follows. In Section 2 the BETHSY facility and the BETHSY 9.1b test, representing 5.08 cm (2 inch) small break loss of coolant (SBLOCA) accident is presented. Section 3 describes the RELAP5 and TRACE computer codes and input models, respectively. In Section 4 the methods for code accuracy quantification are described. The results are presented in Section 5, while conclusions are given in Section 6.

2 BETSY FACILITY AND TEST DESCRIPTION

2.1 BETHSY Facility Description

BETHSY is an integral test facility, which was located in Grenoble, and was designed to simulate most PWR accidents of interest, to study accident management procedures and to validate the computer codes [4]. It is a scaled down model of three loop Framatome nuclear power plant with the thermal power 2775 MW. There were 428 electrically heated rods, which could reach 1273 K.

Six important choices have been made which characterize the general design of the BETHSY facility. They concern the number of loops, the rated pressure of both the primary and the secondary side, the maximum core power level, the maximum flow rate of primary pumps, the general scaling factors and the connected circuits and systems.

Because BETHSY has three equally sized loops that differ only in the possible break geometries and in the presence of a pressurizer in loop I, the facility is ideal to investigate asymmetric phenomena which can occur in a large number of accident scenarios. Hot legs and cold legs were built to preserve the pipe length to root pipe diameter scaling between the reference plant and BETHSY.

BETHSY is a full pressure facility, leading to higher cost and increased instrumentation difficulty. However, difficulties are avoided for pressure extrapolation for some physical phenomena, like conditions required for emergency operating procedure implementation. The maximum operating pressure of the primary coolant system is 17.2 MPa while the secondary side can withstand pressures up to 8 MPa.

The BETHSY core power has been limited to decay heat levels. This is consistent with the main objectives: code assessment is especially useful for physical situations involving two-phase flow and operators cannot act upon the events early in the course of an accident. So, in both cases the scaled nominal power is not required, provided that it is possible to represent the actual energy distribution in the system correctly for initial conditions of some transients.

The BETHSY primary pumps have been designed to be capable of delivering the scaled nominal flow rate of the reference Reactor Coolant Pumps (RCPs). This is of interest in cases where either the operator is not requested or omits to trip one, two or three RCPs during an accident transient.

The BETHSY facility is a 1/100 (more precisely $1.032 \cdot 10^{-2}$) volumetrically scaled model, with 1:1 elevation scaling, designed to simulate most PWR accident situations of interest while minimizing the distortions of relevant physical phenomena.

Finally, the BETHSY facility includes all corresponding circuits and systems which are likely to play a role in case of accident transient as far as thermohydraulic aspects are concerned: pressurizer (heaters, spray system, relief valves), control volume system, safey injection system (high pressure, low pressure and accumulators) and secondary side (steam generator valves, atmospheric and condenser dumps, normal and auxiliary feedwater, blowdown lines). The facility consisted of pressure vessel, reactor coolant pumps and piping, heat tracing system, the system for break simulation, instrumentation and the control systems.

The break system enabled simulation of the break in different locations, i.e. in cold leg, lower plenum, pressurizer, steam generator U tubes and feedwater pipe. The instrumentation data system measured all data needed for the transient analysis. The control system could simulate the plant control systems and operator actions.

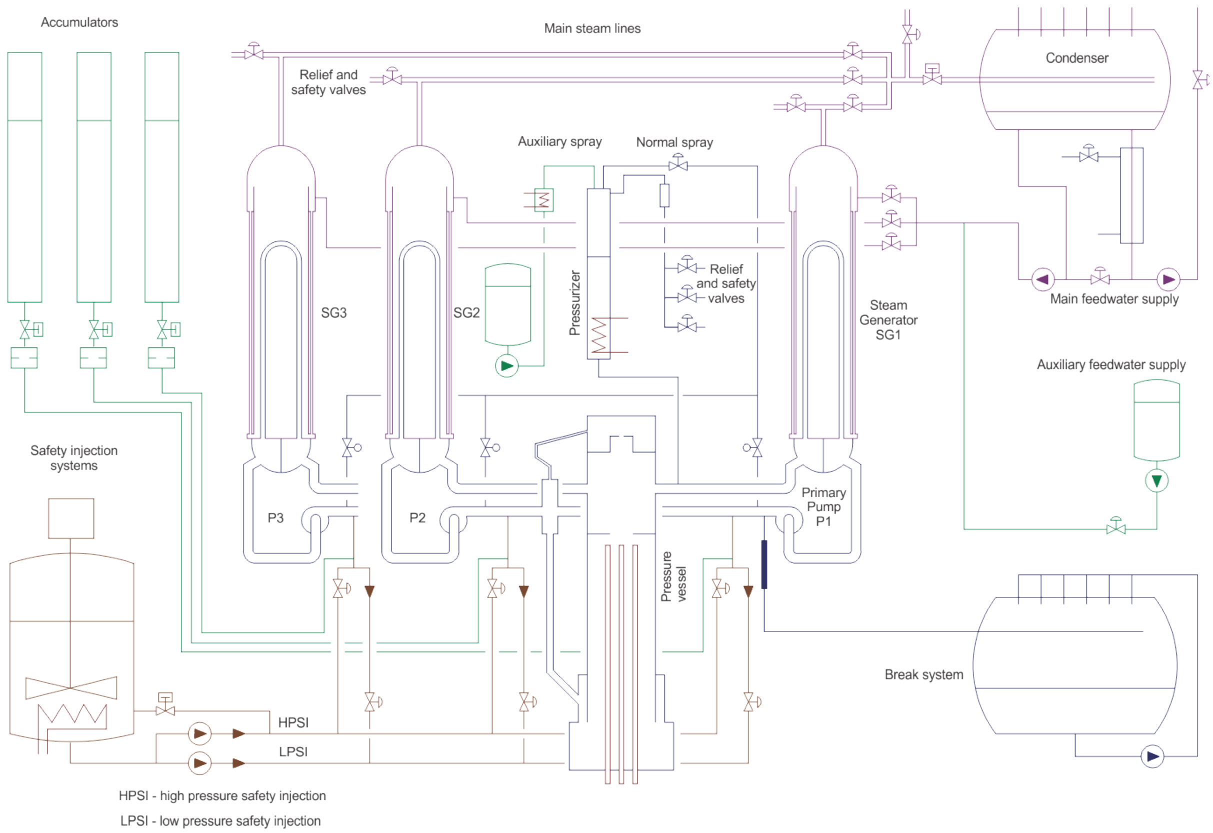


Figure 2-1 BETHSY Schematic Diagram

2.2 <u>BETHSY 9.1b Test Description</u>

The test was analyzed in the frame of International Standard Problem 27 (ISP 27) performed to validate the thermal-hydraulic computer codes [5]. ISP 27 was prepared and coordinated by the Committee on the Safety of Nuclear Installations (CSNI) of the Nuclear Energy Agency within the Organisation for Economic Co-operation and Development (OECD/NEA).

This test addresses, besides typical problems relevant to Small Break Loss Of Coolant Accidents (SBLOCA) such as critical 2-phase flow, loop seal clearing, heat-transfer during boil-off or accumulator injection, specific aspects related to the fast depressurization (primary to secondary and structural heat transfer), uncovered core behavior when intense condensation takes place in the SG, and primary side refilling by the Low Pressure Injection System (LPIS).

The BETHSY 9.1.b test is a scaled 5.08 cm cold leg break in loop 1 without high pressure safety injection (HPSI) and with delayed operator action for secondary system depressurization. In that case, the state oriented requires operators to start an Ultimate Procedure, which consists opening the Steam Generator (SG) atmospheric dumps as soon as informed of the unavailability of the HPIS. Due to the core heatup, the operator depressurized the secondary side by atmospheric relief steam dump valves. In the presently studied scenario, the start of the procedure is delayed, and the following trigger criterion is used: when the maximum heater rod cladding temperature reaches 723 K, the 3 steam generator steam dumps to atmosphere are fully opened (condenser is unavailable). This action allows the primary coolant circuit to depressurize, up to the accumulator injection threshold, then to LPIS actuation. The end of the test is reached as soon as a safe state of the coolant circuit is recovered, i.e. when the conditions required actuation of the Residual Heat Removal System (RHRS) are obtained.

The main sequence of events is shown in Table 2-1. The test scenario is the following: the break is opened in the cold leg no. 1 (initiation of the transient). The break opening is obtained through a quick acting valve, with an operating time of 1 s. When the maximum heater rod cladding temperature reaches 723 K, the ultimate procedure started by opening three steam line dumps to the atmosphere. When pressurizer pressure drops below 4.2 MPa accumulators started to inject and they stopped to inject below 1.46 MPa. The low pressure safety injection (LPSI) system is activated at the primary pressure below 0.91 MPa. When stable residual heat removal system operating conditions prevailed, the transient is terminated.

Table 2-1 Main Sequence of Events for BETHSY 9.1b Test

Event	**Time (s)**
Break opening	0
Scram signal (13.1 MPa)	41
Safety injection (SI) signal (11.9 MPa)	50
Core power decay start (17 s after scram)	58
Auxiliary feedwater on (30 s after SI signal)	82
Pump coastdown start (300 s after SI signal)	356
End of pump coastdown	971
Start of the first core level depletion	1830
Start of second core uncovery	2180
Ultimate procedure initiation	2562
Accumulator injection starts (4.2 MPa)	2962
Primary mass inventory is minimum	2970
Maximum core clad heatup	3053
Accumulator isolation (1.5 MPa)	3831
Low pressure injection system start (0.91 MPa)	5177
End of test (RHRS stable operating conditions are reached)	8200-8330

3 COMPUTER CODES AND INPUT MODELS DESCRIPTION

The simulations were performed with the TRACE V5.0 Patch 5 and RELAP5/MOD3.3 Patch 5 computer codes.

3.1 RELAP5 Computer Code Description

For calculation the latest officially released RELA5/MOD3.3 Patch 5 computer code has been used [8]. The RELAP5 computer code is a light water reactor transient analysis code developed for the U.S. Nuclear Regulatory Commission (U.S. NRC) for use in rulemaking, licensing audit calculations, evaluation of operator guidelines, and as a basis for a nuclear plant analyzer. Specific applications of this capability include simulations of transients in LWR systems, such as loss of coolant, anticipated transients without scram (ATWS), and operational transients such as loss of feedwater, loss of offsite power, station blackout, and turbine trip. For further details the reader is referred to [8].

3.2 TRACE Computer Code Description

For calculation the TRACE V5.0 Patch 5 computer code has been used [1]. The TRAC/RELAP Advanced Computational Engine (TRACE) is the latest in a series of advanced, best-estimate reactor systems codes developed by the U.S. NRC for analyzing transient and steady-state neutronic-thermal-hydraulic behavior in light water reactors. TRACE has been designed to perform best-estimate analyses of loss-of-coolant accidents (LOCAs), operational transients, and other accident scenarios in pressurized light-water reactors (PWRs) and boiling light-water reactors (BWRs). For further details the reader is referred to [1].

3.3 RELAP5 Input Model Description

The first RELAP5/MOD2 standard input model has been developed at Jožef Stefan Institute during its participation in the OECD/NEA international standard problem ISP 27 and has been later continuously updated to further RELAP5 versions, up to RELAP5/MOD3.3 Patch 04. There was no need to make modifications of the input model for the latest RELAP5/MOD3.3 Patch 05 computer code [8].

The base RELAP5/MOD2 model of Bethsy facility for pre-test calculations contained 196 volumes, 207 junctions and 191 heat structures [7]. This base RELAP5/MOD2 input model was further upgraded to RELAP5/MOD3.1 and RELAP5/MOD3.1.2. The base RELAP5/MOD2 input model was renodalized, increasing the number of nodes in reactor coolant system piping, reactor coolant pumps, core bypass section, reactor vessel and downcomer. The elevations of parallel volumes of the reactor downcomer, in bypass, reactor core, hot leg and cold leg were preserved. Nodalization of the reactor core, pressurizer, reactor head, upper plenum and lower plenum remained the same. This RELAP5 input model of BETHSY facility was called middle input model. This middle RELAP5 model was further refined, increasing the number of nodes in the steam generator. The U-tubes were modeled with 20 nodes instead of 10, and the downcomer and riser region of steam generator were modeled with 11 nodes instead of five, what gives 22 more nodes per steam generator and 66 more nodes in total. In 2000 a common RELAP5/MOD3.2 input model was developed. The common input model for all available BETHSY tests consisted of 398 volumes, 408 junctions and 402 heat structures with 1573 mesh points. This input model was adapted for the use with RELAP5/MOD3.3, with no changes to the geometry and the number of hydrodynamic components and heat structures. The hydrodynamic view was generated by SNAP from RELAP5 input model (in ASCII) and then arranged manually using Model Editor of SNAP (see Figure 3-1). The RELAP5/MOD3.3 input model in terms of SNAP consists of 147 hydrodynamic components and 72 heat structures. The difference is that pipes consist of several volumes; however they are considered as one component. Similar is the case with the heat structures. For further details of the RELAP5 input model for BETHSY 9.1b test can be found in [6].

Figure 3-1 shows the steady state RELAP5 input model. All important systems and components of BETHSY facility are modelled like reactor pressure vessel (RPV), reactor coolant pumps and piping for all three loops, pressurizer with relief valves, safety injection system (high pressure, low pressure and accumulators) and secondary side (steam generators, atmospheric dumps, main and auxiliary feedwater).

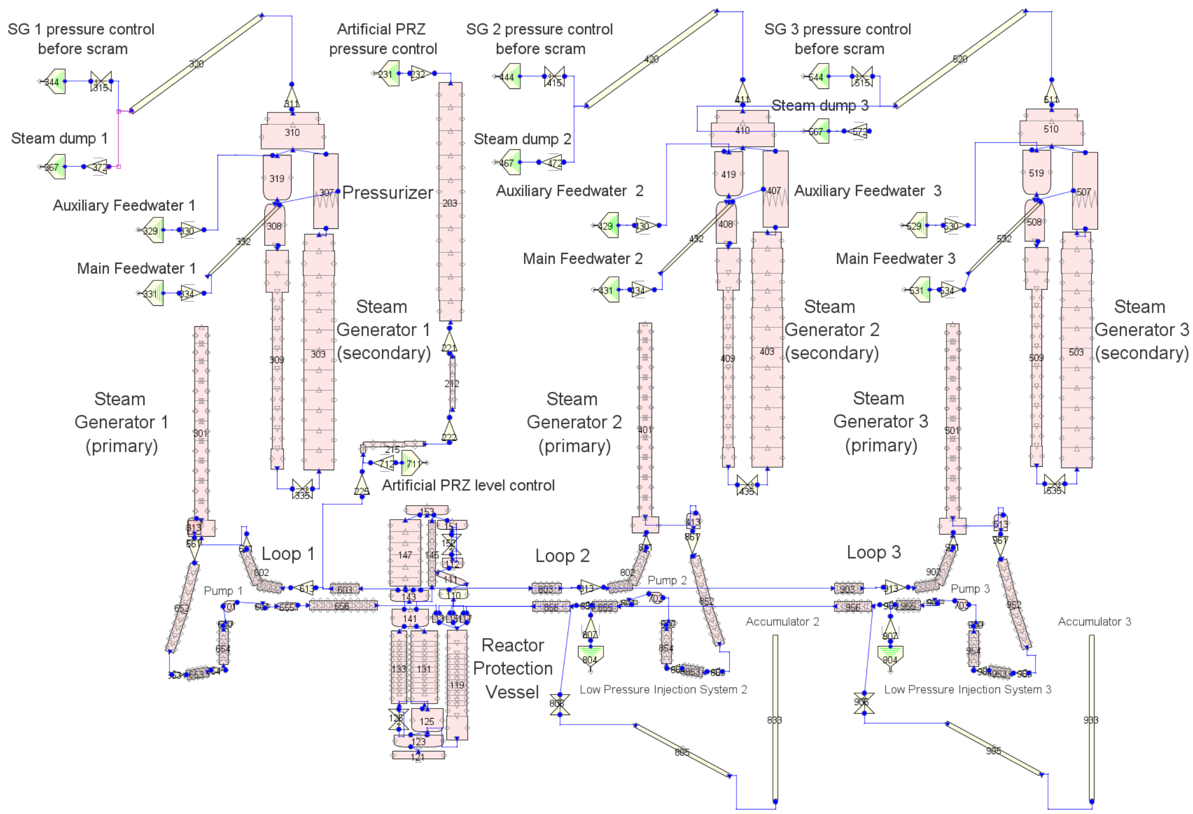


Figure 3-1 RELAP5 Hydraulic Components View of BETHSY Facility

The break system was modeled in the restart input file, as shown in Figure 3-2. Break is located in the cold leg 1, connected to BRANCH 656. In the BETSHY facility the break nozzle is located on the cold leg 1, 332 mm downstream of the outlet flange of the pump. The break is side oriented, the axis of the nozzle is horizontal and perpendicular to the cold leg axis. It is a 70 mm long nozzle, mounted flush with the inner wall of the cold leg. It has a rounded inlet edge (radius = 6 mm) and is 5.16 ± 0.01 mm in diameter, giving a L/D ratio of 13.6. The outlet of the 5.16 mm diameter part is sharp edged, and enlarged to a 46 ± 0.03 mm diameter pipe, connected to the break spool pieces.

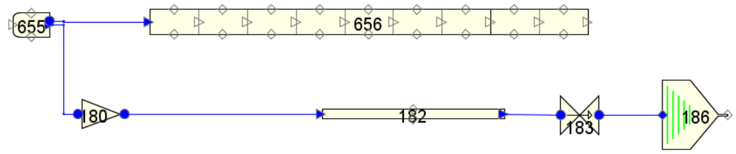


Figure 3-2 RELAP5 Nodalization of Break Flow in Cold Leg 1

The TRACE input model has been developed by conversion of the standard RELAP5 input model of BETHSY into TRACE, requiring manual corrections. The TRACE hydraulic components view is shown in Figure 3-3, where SG, RPV and ACC indicate the steam generator, the reactor pressure vessel and the accumulator, respectively. The TRACE steady state model consists of 160 hydraulic components, 74 thermal components and 1 power component. The break flow model is also included with the valve in closed position.

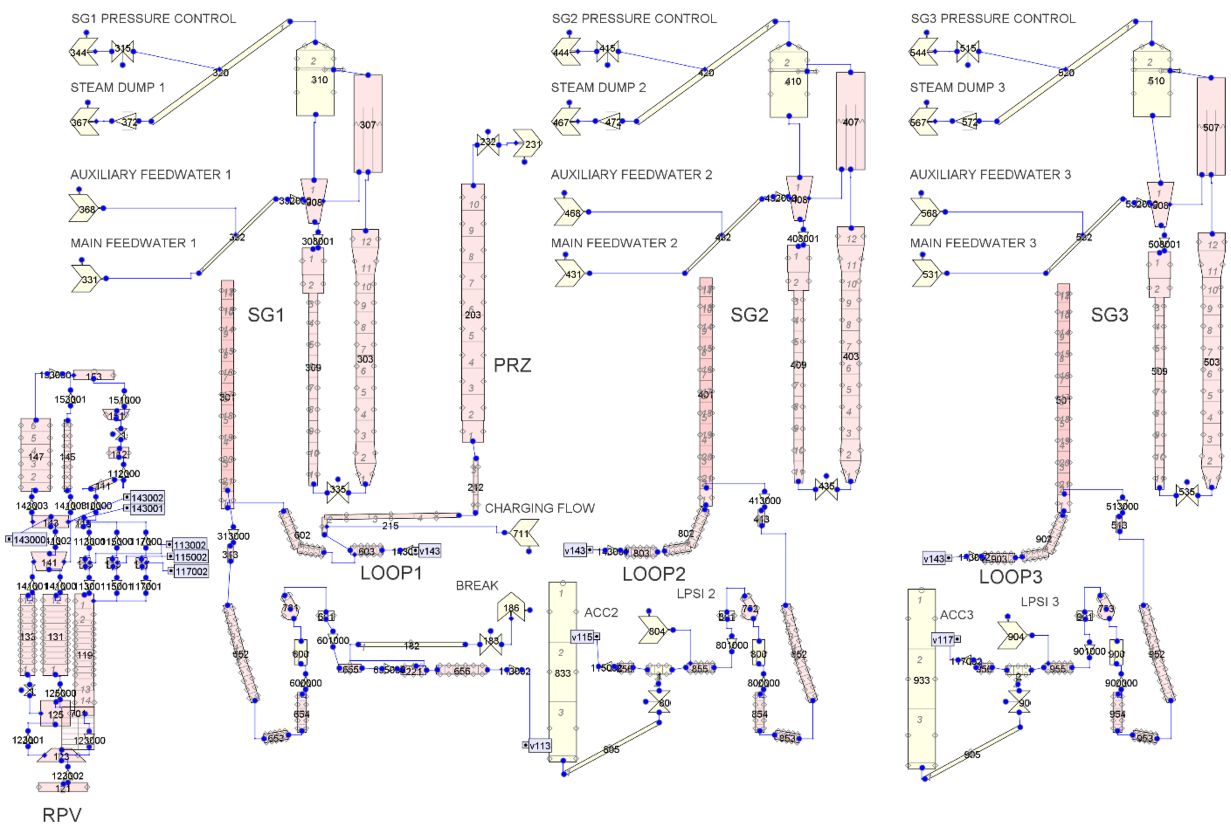


Figure 3-3 TRACE Hydraulic Components View of BETHSY Facility

4 METHODS FOR CODE ACCURACY QUANTIFICATION

For code accuracy quantification two methods are used. The first is the original fast Fourier transform based method (FFTBM), which was developed to quantify the accuracy of thermal-hydraulic code calculations [10] versus the corresponding experimental data. Later, a FFTBM method improved by signal mirroring (FFTBM-SM) has been developed, in which the signals are symmetrized [11] to eliminate the edge effect. Both methods will be briefly described. For more details refer to [12].

4.1 Fast Fourier Transform Based Method (FFTBM) Description

4.1.1 Input Parameters for Fast Fourier Transform

To apply fast Fourier transform (FFT), the function must be identified by a number of values that is a power with the base equal to 2 (this was a requirement for older FFT algorithms, such as the one used in the original FFTBM). Thus, if the number of points defining the function in the time domain is

$$N = 2^{m+1}, \tag{4-1}$$

where m = 0, 1, 2,…, the FFT algorithm gives the transformed function defined in the frequency domain by $2^m + 1$ values corresponding to the frequencies

$$f_n = \frac{N}{T_d}, \qquad (n = 1, 2, \ldots, \; 2^m), \tag{4-2}$$

where T_d is the transient time duration of the sampled signal.

To use the FFTBM, the number of points must be selected for the FFT calculation. This is the same as selecting the sampling frequency. In FFT, the sampling frequency of interpolated data is used; therefore, for FFT, the sampling theorem must be fulfilled. After selecting the number of points $N = 2^{m+1}$, the maximum frequency of transformed functions by FFT is given by:

$$f_{max} = \frac{f_s}{2} = \frac{1}{2\tau} = \frac{N}{2T_d} = \frac{2^{m+1}}{2T_d} = \frac{2^m}{T_d}, \tag{4-3}$$

where T_d is the transient time duration of the sampled signal. The relation in Eq. (4-3) shows that the number of selected points is strictly connected to the sampling frequency of interpolated data. In the FFTBM algorithm, the minimum number of points is limited to 512.

The interpolation using a linear method changes the slope, but it was verified that this effect is negligible because these spurious frequencies are at higher frequencies having lower amplitudes than typical frequencies characterizing the signal. To filter this spurious contribution, the cut-off frequency (f_{cut}) was introduced as the second input parameter.

4.1.2 Average Amplitude and Weighted Frequency

The FFTBM shows the measurement-prediction discrepancies in the frequency domain. For the calculation of these discrepancies, the experimental signal ($F_{exp}(t)$) and the error function $\Delta F(t)$ (difference signal) are needed. The error function in the time domain is defined as

$$F(t) = F_{cal}(t) - F_{exp}(t), \qquad (4\text{-}4)$$

where $F_{cal}(t)$ is the calculated signal. The code accuracy quantification for an individual calculated variable is based on amplitudes of the discrete experimental and error signal obtained by FFT at frequencies f_n (see Eq. (4-2)). These spectra of amplitudes are used for the calculation of the average amplitude (AA) that characterizes the code accuracy:

$$AA = \frac{\sum_{n=0}^{2^m} |\tilde{\Delta}F(f_n)|}{\sum_{n=0}^{2^m} |\tilde{F}_{exp}(f_n)|}. \qquad (4\text{-}5)$$

A weighted frequency (WF) is defined as the sum of frequencies multiplied (weighted) by error function amplitudes, normalized to the sum of error function amplitudes:

$$\mathrm{WF} = \frac{\sum_{n=0}^{2^m} |\tilde{\Delta}F(f_n)| \cdot f_n}{\sum_{n=0}^{2^m} |\tilde{\Delta}F(f_n)|}. \qquad (4\text{-}6)$$

In the past, several applications calculated the values of WF [14]. However, no judgment was based on WF.

4.1.3 Accuracy of Code Calculation

The overall picture of the accuracy of a given code calculation is obtained by defining average performance indices (i.e., the total weighted AA (total accuracy)):

$$\mathrm{AA_{tot}} = \sum_{i=1}^{N_{var}} (\mathrm{AA})_i \cdot (w_f)_i \qquad (4\text{-}7)$$

and the total WF

$$\mathrm{WF_{tot}} = \sum_{i=1}^{N_{var}} (\mathrm{WF})_i \cdot (w_f)_i \qquad (4\text{-}8)$$

with

$$\sum_{i=1}^{N_{var}} (w_f)_i = 1, \qquad (4\text{-}9)$$

where N_{var} is the number of the variables analyzed, and $(\mathrm{AA})_i$, $(\mathrm{WF})_i$ and $(w_f)_i$ are the AA, the WF, and the weighting factors for the i th analyzed variable, respectively [15].

The weighting factor for the i th variable is therefore defined as:

$$(w_f)_i = \frac{(w_{exp})_i \cdot (w_{saf})_i \cdot (w_{norm})_i}{\sum_{i=1}^{N_{var}} (w_{exp})_i \cdot (w_{saf})_i \cdot (w_{norm})_i}, \qquad (4\text{-}10)$$

where w_{exp} is the contribution related to the experimental accuracy, w_{saf} is the contribution that expresses the safety relevance, and w_{norm} is the contribution of primary pressure normalization. Table 4-1 shows the weighting factors.

The definition of weighting factors introduces a degree of engineering judgment in the development of the FFTBM method. In the later applications of FFTBM, these weighting factors have been fixed. The weights must remain unchanged during each comparison between code results and experimental data concerning the same class of transient.

Table 4-1 Weighting Factor Components for Analyzed Quantities [15]

Quantity	w_{exp}	w_{saf}	w_{norm}
Pressure drops	0.7	0.7	0.5
Mass inventories	0.8	0.9	0.9
Flow rates	0.5	0.8	0.5
Primary pressure	1.0	1.0	1.0
Secondary pressure	1.0	0.6	1.1
Fluid temperatures	0.8	0.8	2.4
Clad temperatures	0.9	1.0	1.2
Collapsed levels	0.8	0.9	0.6
Core power	0.8	0.8	0.5

4.1.4 Methodology for Quantifying Code Accuracy

Given a qualified user and qualified nodalization scheme, the code assessment process involves three steps: (1) selection of an experiment from the Committee on the Safety of Nuclear Installations (CSNI) validation matrices [17] (or a plant transient), (2) qualitative assessment, and (3) quantitative assessment.

The qualitative assessment gives the first indications about the accuracy of the calculated predictions. The qualitative assessment phase is a necessary prerequisite for a subsequent quantitative phase. It is meaningless to perform this last phase through the FFTBM if any relevant thermalhydraulic aspect (RTA) is not predicted.

The quantitative assessment can be managed by applying the FFTBM. Normally, 20 to 25 variables are selected for the accuracy analysis. The most suitable factor for the definition of an acceptability criterion is the total average amplitude, $\mathrm{AA_{tot}}$. With reference to the accuracy of a given calculation, the following acceptability criterion can be defined:

$$AA_{tot} < K, \qquad (4\text{-}11)$$

where K is the acceptability factor valid for the whole transient and is set to $K = 0.4$. The previous studies showed the following:

- $AA_{tot} \leq 0.3$ characterizes very good code predictions.
- $0.3 < AA_{tot} \leq 0.5$ characterizes good code predictions.
- $0.5 < AA_{tot} \leq 0.7$ characterizes poor code predictions.
- $AA_{tot} > 0.7$ characterizes very poor code predictions.

In addition, the acceptability factor $= 0.1$ has been fixed for the primary pressure, because of its importance.

4.2 Fast Fourier Transform Based Method Improved by Signal Mirroring (FFTBM-SM) Description

To make FFTBM applicable for all variables, signal mirroring is proposed to eliminate the edge effect in calculating AA. Namely if the values of the first and last data point differ then there is a step function present in the periodically extended time signal. This step function gives several harmonic components in the frequency domain thus increasing the sum of the amplitudes. The problem of the edge effect was resolved by signal mirroring.

4.2.1 Signal Mirroring

By combining the original signal and its mirrored signal (signal mirroring), a signal without the edge between the first and the last data sample is obtained, which is called a "symmetrized signal." The edge is not visible in the plotted signal when the signal is not shifted or not plotted as a periodic signal. However, in the performance of FFT, the aperiodic signal is treated as a periodic signal, and therefore the edge is part of the signal, which is not physical.

The edge effect influences both numerator and denumerator of Eq. (4-5). In the case, the sum is in the numerator for AA calculation, the larger sum of the amplitudes means a larger AA. For the denumerator, the larger sum of amplitudes means a smaller AA.

As the edge effect is eliminated in both the experimental signal amplitude spectrum and in the difference signal amplitude spectrum, the new values of AA may be larger or smaller than D'Auria AA (Eq. (4-5) applied to original signals with no signal mirroring, depending on how the numerator and the denominator change.

4.2.2 Calculation of Average Amplitude by Signal Mirroring

For the calculation of the average amplitude by signal mirroring (AA_m), Eq. (4-5) is used for the calculation of AA, except that, instead of the original signal, the symmetrized signal is used. The reason to symmetrize the signal was to exclude the edge from the signal. The signal is automatically symmetrized in the computer program for the FFTBM improved by signal mirroring as is described in [11].

As already mentioned, the edge has no physical meaning, but it causes FFT to produce harmonic components. By mirroring, the shapes of the experimental and error signal are symmetric and their spectra are different from the original signals spectra, mainly because they are without nonphysical edge frequency components. Because of different spectra, the sum of the amplitudes changes in both the numerator and the denominator of Eq. (4-5). For further use in distinguishing between the error and experimental signal edge contribution, two new definitions are introduced for the AA of the error and experimental signal, related to the numerator and denominator of Eq. (4-5):

$$AA_{err} = \frac{1}{2^m+1}\sum_{n=0}^{2^m}\left|\tilde{\Delta}F(f_n)\right|, \qquad (4\text{-}12)$$

$$AA_{exp} = \frac{1}{2^m+1}\sum_{n=0}^{2^m}\left|\tilde{F}_{exp}(f_n)\right|. \qquad (4\text{-}13)$$

When both the original and error signal are without the edge, in principle, different AA_{err} and AA_{exp} may be obtained by the original FFTBM and the FFTBM improved by signal mirroring. Indeed, AA and AA_m are slightly different measures if the signals are without an edge. The values obtained with the original FFTBM and improved FFTBM by signal mirroring are the same only for symmetrical original signals, but this is not really a deficiency of the proposed improved FFTBM by signal mirroring, since it is important only that the method judges the accuracy realistically and that it is consistent within itself.

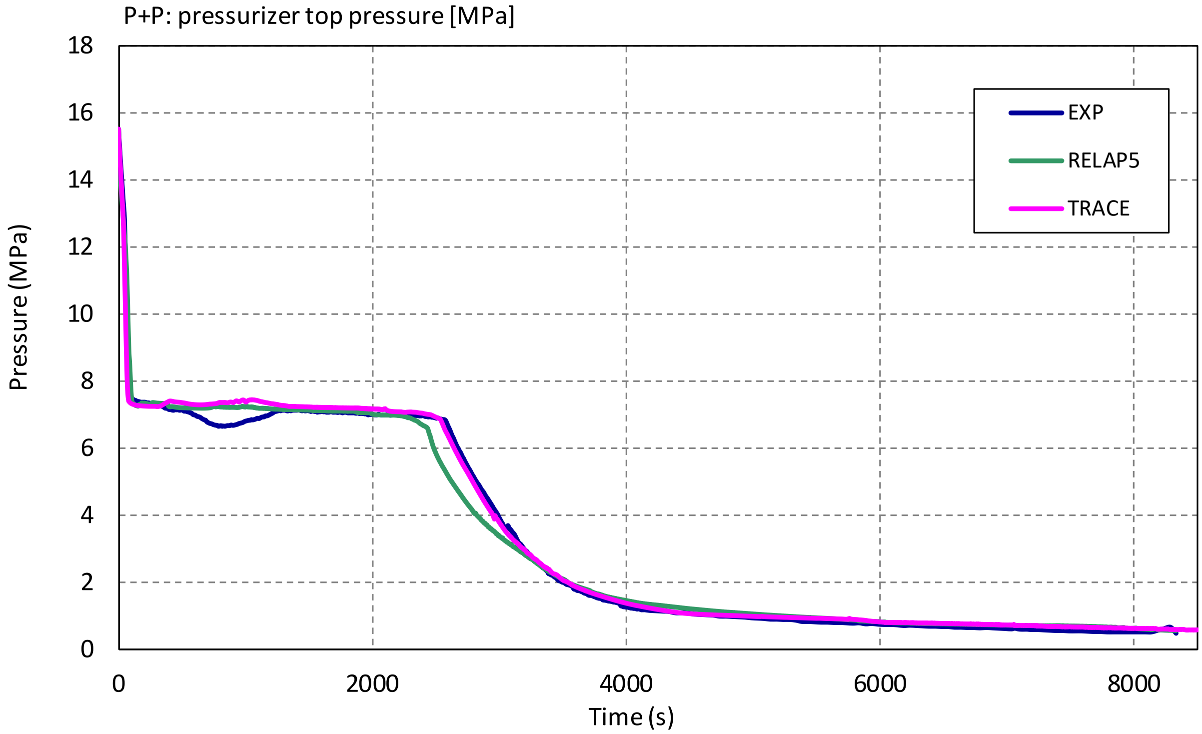
5 RESULTS

The results are shown in Table 5-1 and Figures 5-1 through 5-22. Table 5-1 shows the results of steady state calculation. The core power is an input value. In general, the agreement is good for both, RELAP5 and TRACE code. The initialization of the cold leg temperature is used, therefore the secondary pressure is not exactly matched. The difference comes from the code models for heat transfer from primary to secondary side.

Table 5-1 Comparison of Initial Conditions for BETHSY 9.1b Test

Parameter	Measured	RELAP5	TRACE
core thermal power	2864 ± 30 kW	2864 kW	2864 kW
cold leg temperature (per loop)	559.9 ± 0.5 K	559.9 K (core inlet)	559.9 K (core inlet)
downcomer mass flow rate	150.0 ± 5.0 kg/s	155.2 kg/s	151.1 kg/s
reactor coolant pump speed (per loop)	2940 ± 30 rpm	2970 rpm	2970 rpm
pressurizer pressure	15.51 ± 0.09 MPa	15.51 MPa	15.51 MPa
pressurizer level	4.08 ± 0.1 m	4.08 m	4.08 m
reactor coolant system mass	1960 kg	1948 kg	1948 kg
secondary side pressure (per SG)	6.91 ± 0.04 MPa	6.77 MPa	6.78 MPa
steam generator level (per SG)	13.45 ± 0.05 m	13.41 m	13.46 m
feedwater temperature	491.1 ± 2.0 K	491.0 K	491.0 K
secondary coolant mass (per SG)	820 ± 30 kg	820 kg	803 kg

Comparison of the selected calculated variables with the experimental data and their time dependent accuracy measure is shown in Figures 5-1 through 5-21. The time dependent accuracy measure shows the time evolution of the agreement between the code predictions and the experimental data. For pressurizer pressure, secondary pressure, accumulator pressure, core collapsed liquid level and rod temperatures the TRACE predictions seem slightly better and this is confirmed by the accuracy measure AA_m. On the other hand, integrated emergency core cooling system (ECCS) and upper head temperature are comparable, while for e.g. core power and break mass flow seems to be better RELAP5 predictions and this is confirmed by the accuracy measure AA_m. The accuracy measure also successfully indicates that the TRACE calculation of the core inlet temperature is better predicted in the first 6000 s. As shown in Table 5-2, the total accuracy obtained by both FFTBM and FFTBM-SM suggests that calculations are comparable.



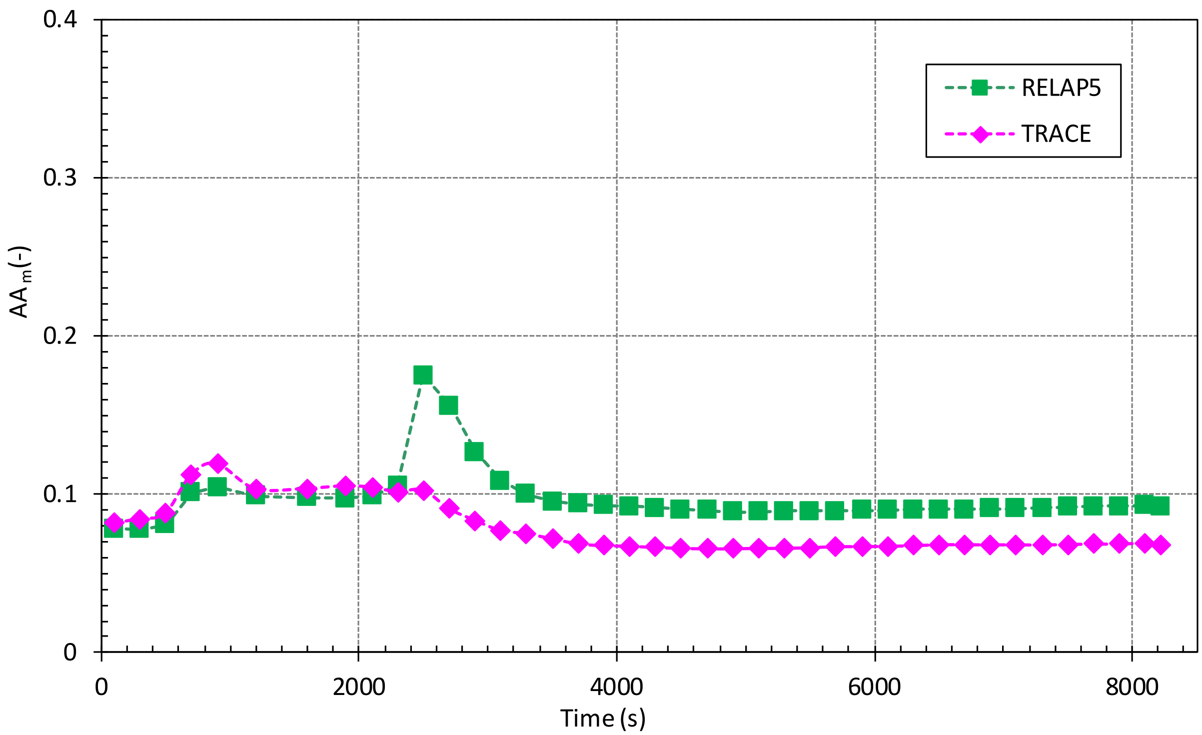


Figure 5-1 Pressurizer Top Pressure (P+P): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

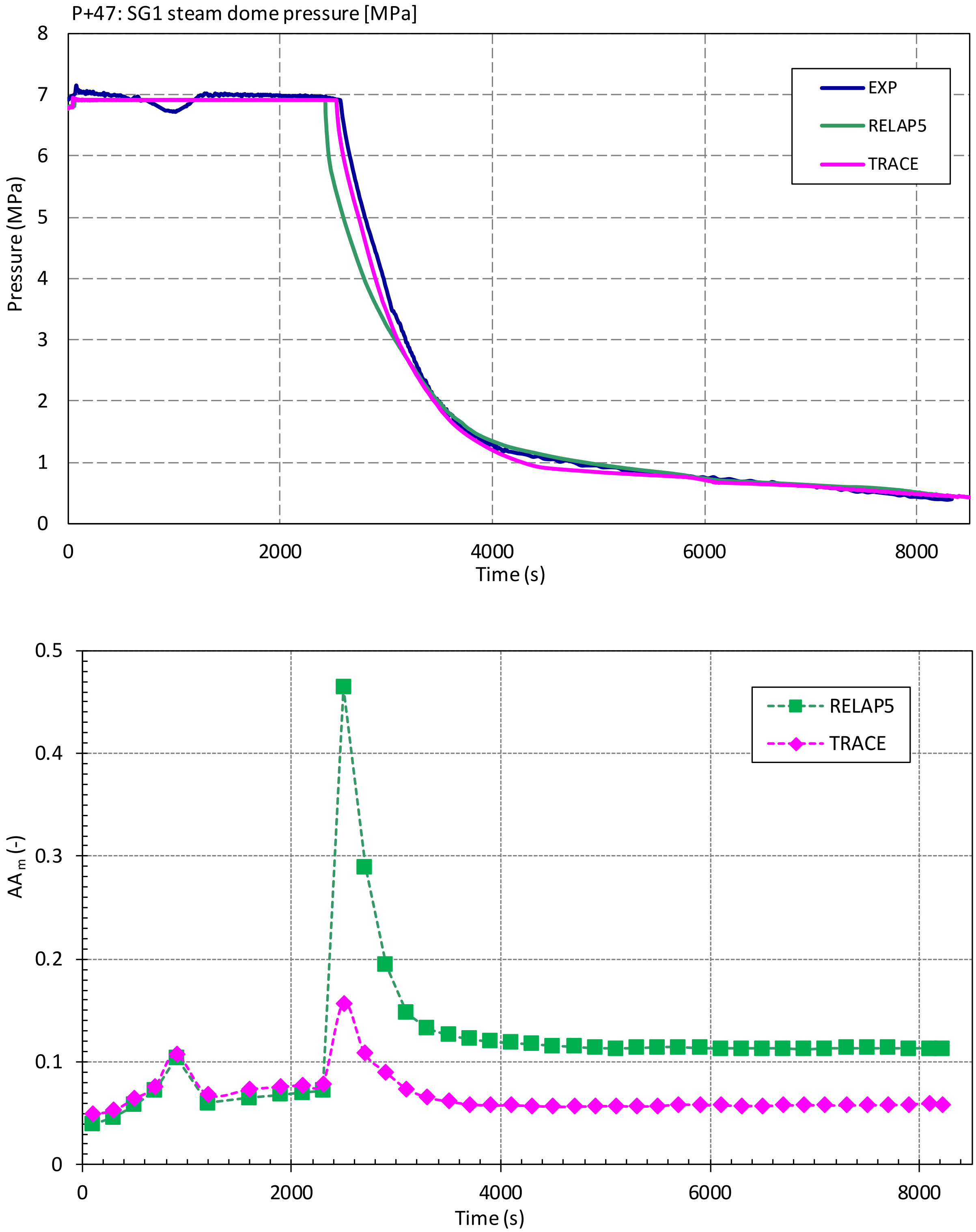


Figure 5-2 SG1 Steam Dome Pressure (P+47): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

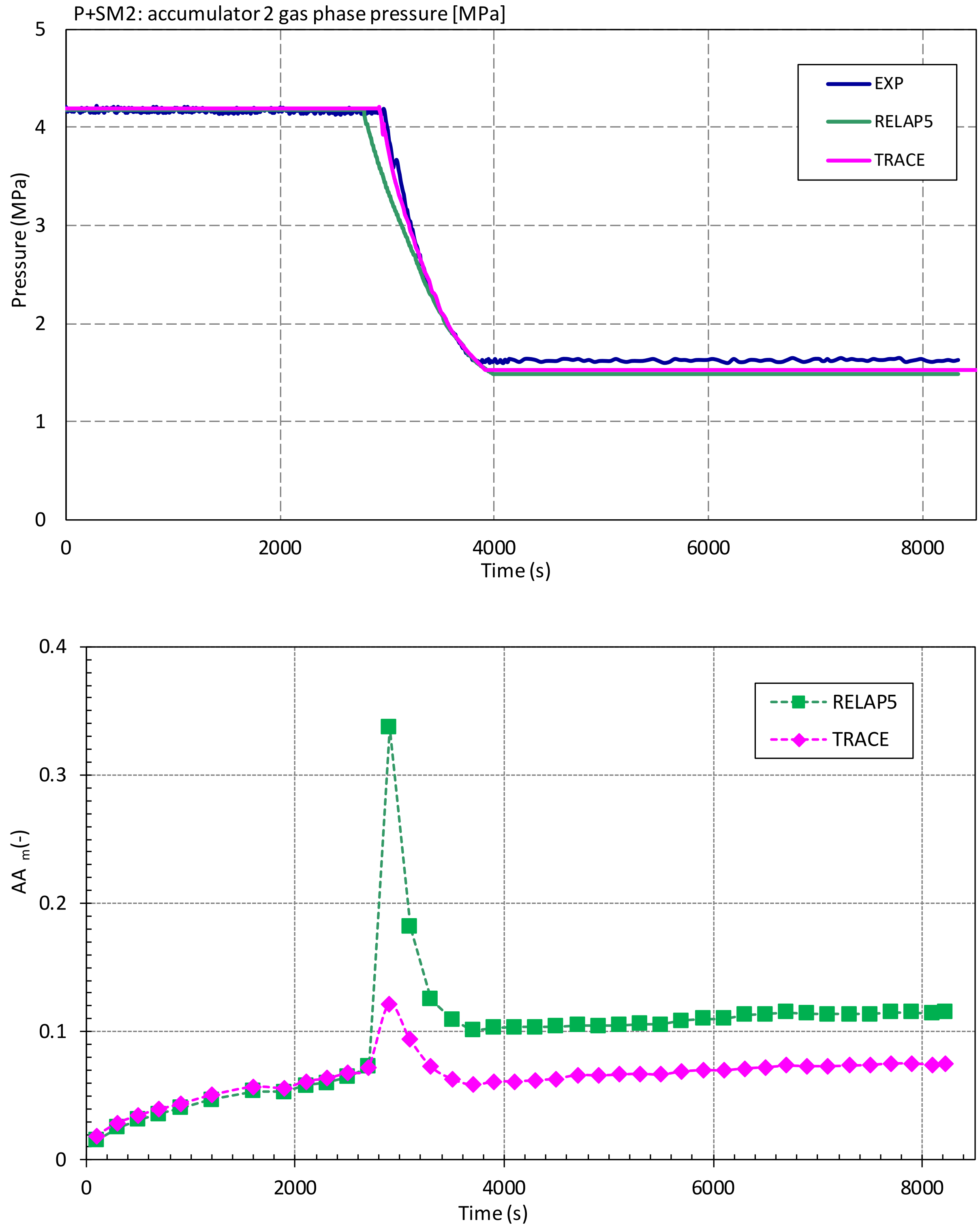
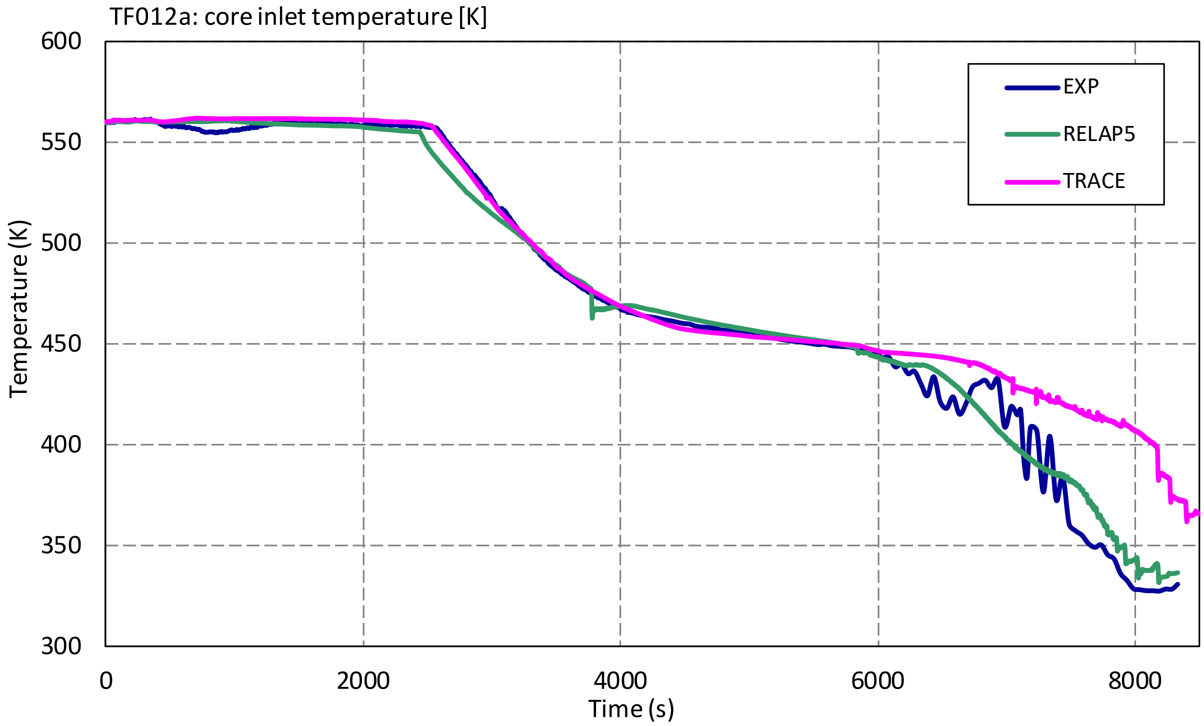


Figure 5-3 Accumulator 2 Gas Phase Pressure (P+SM2): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



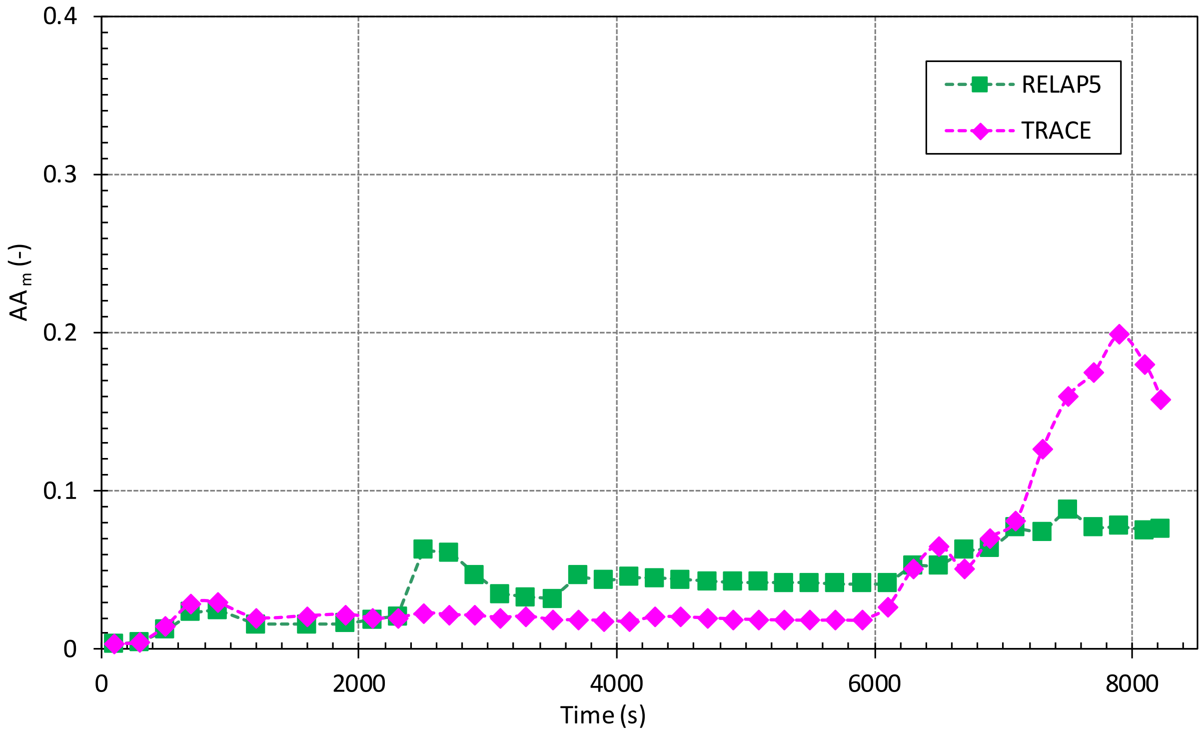
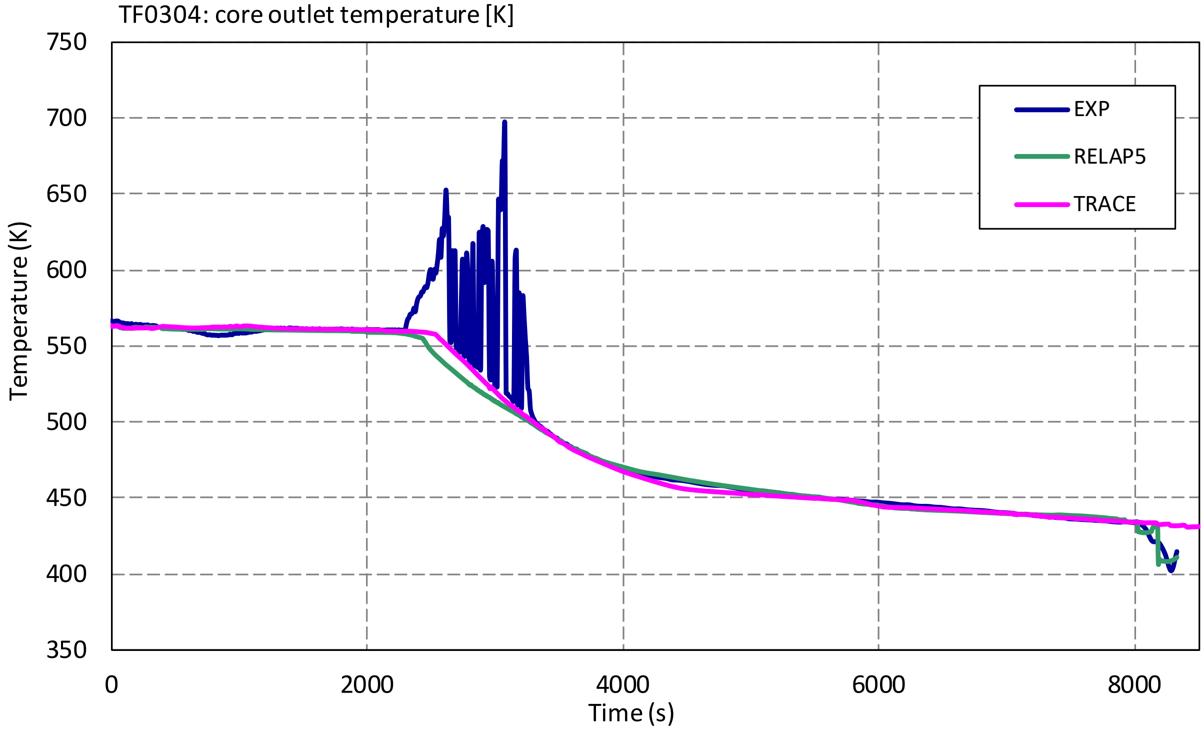


Figure 5-4 Core Inlet Temperature (TF012A): a) Visual Observation (top), b) Accuracy Measure AA_m (Bottom)



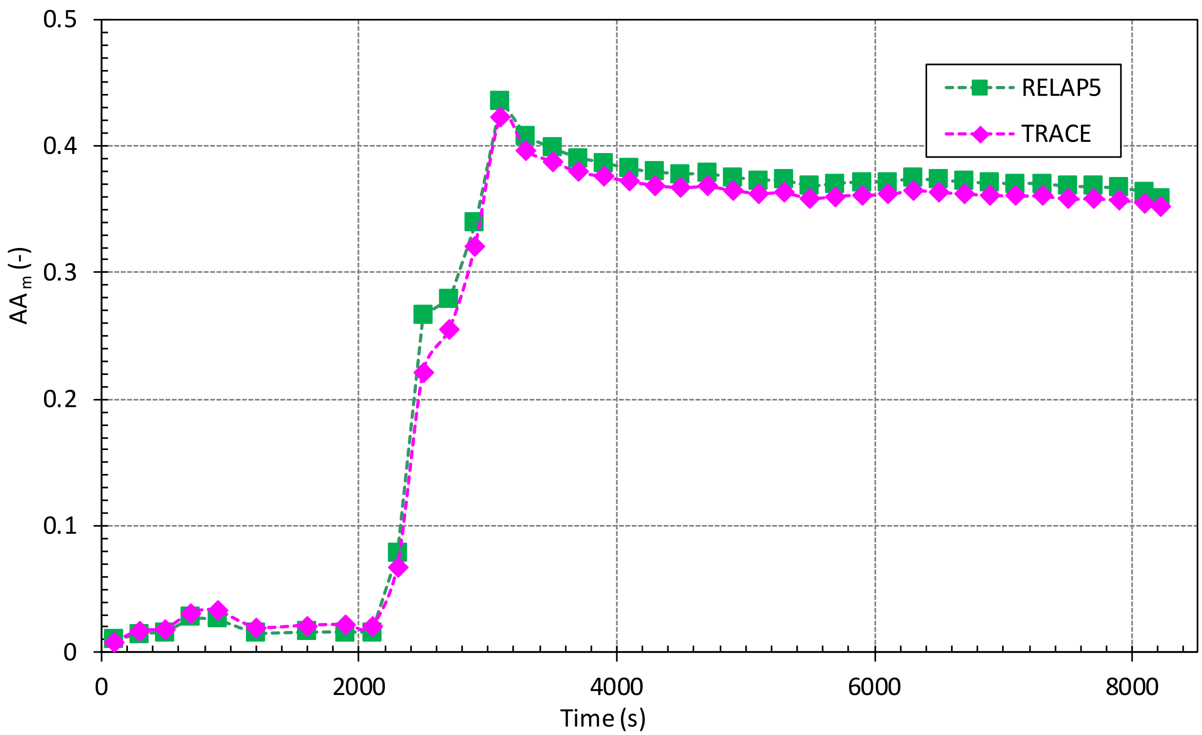
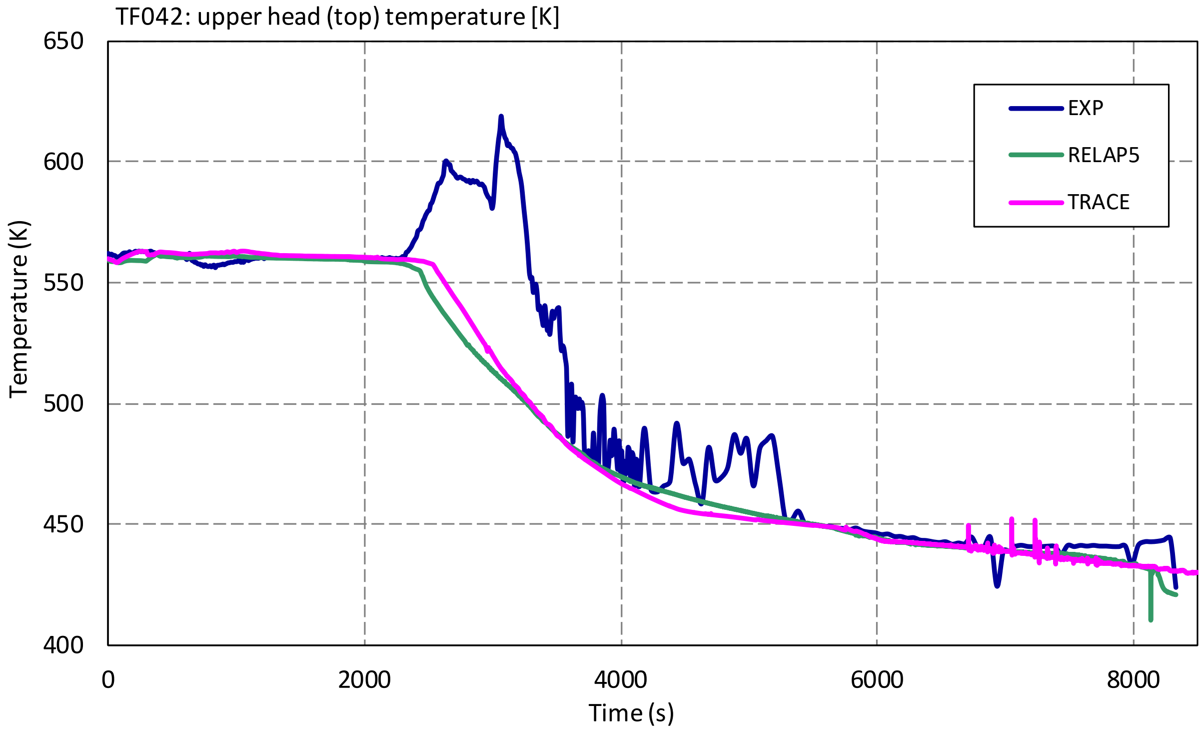


Figure 5-5 Core Outlet Temperature (TF0304): a) Visual Observation (top), b) Accuracy Measure AA_m (Bottom)



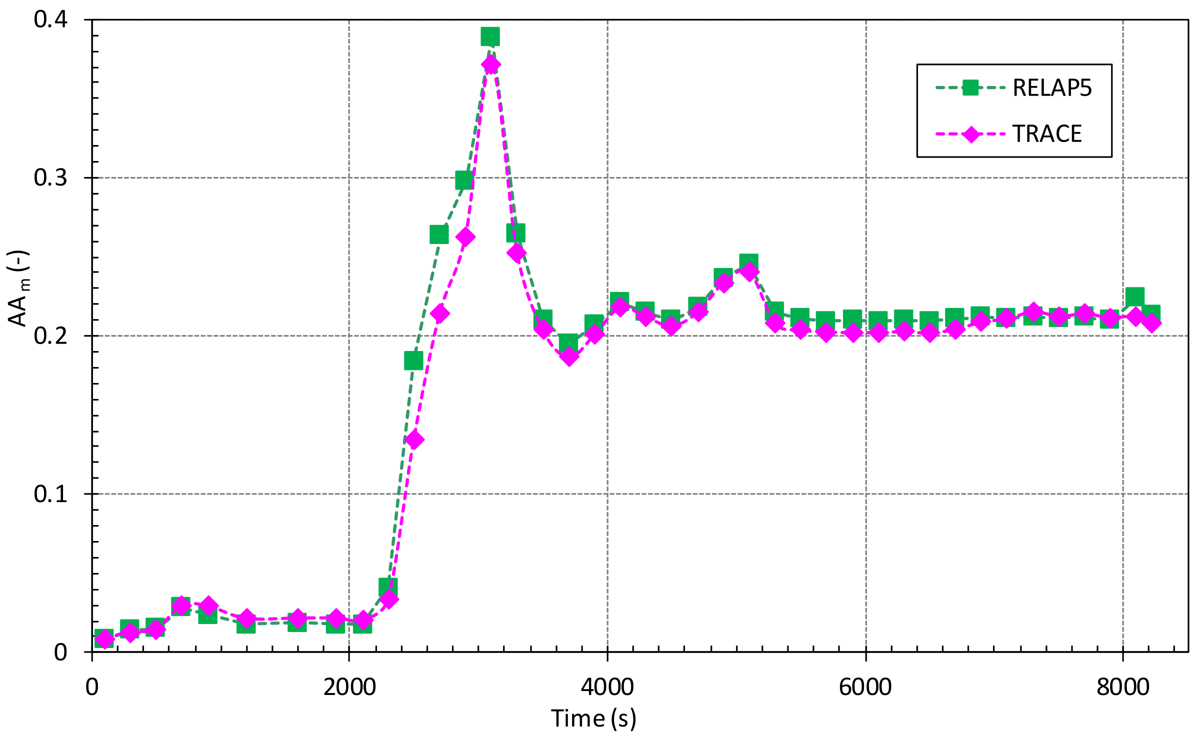
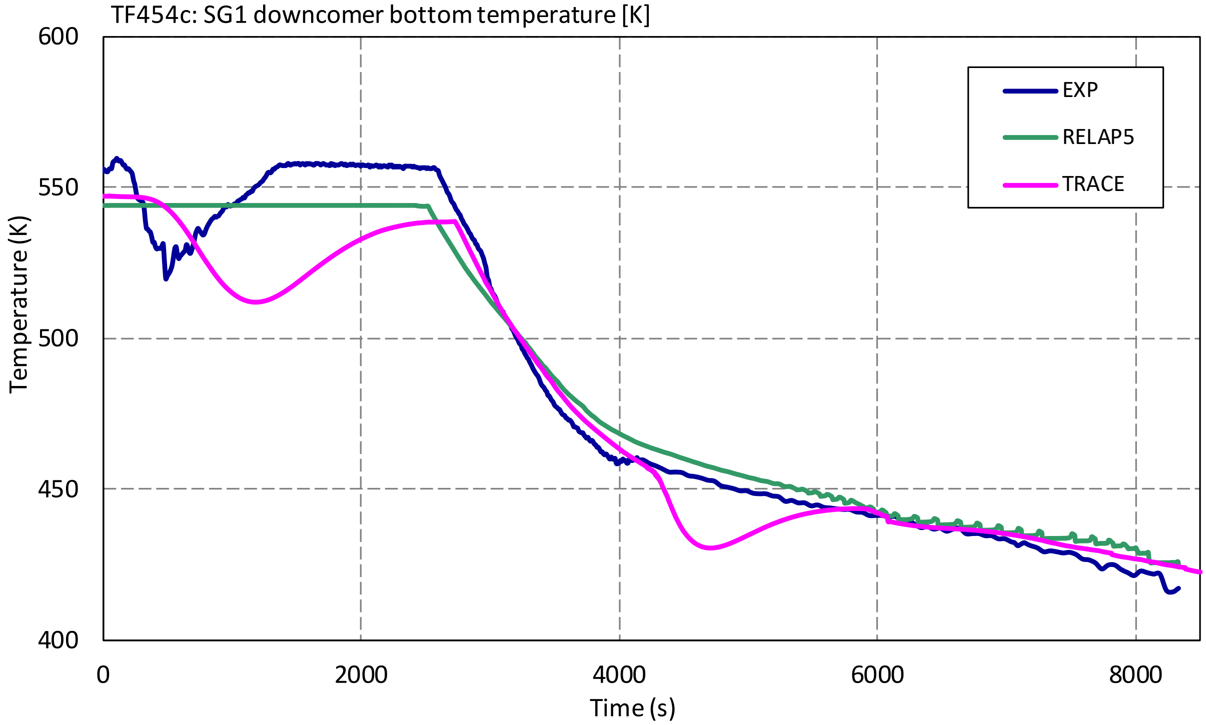


Figure 5-6 Upper Head (Top) Temperature (TF042): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



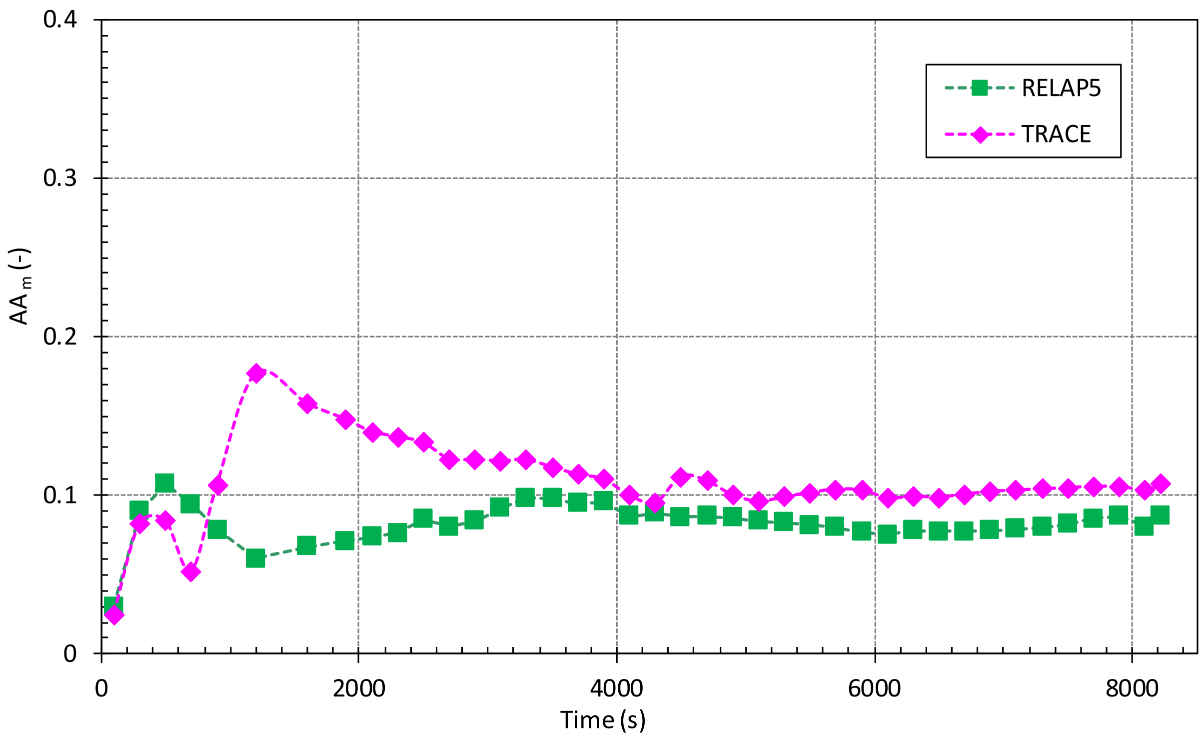
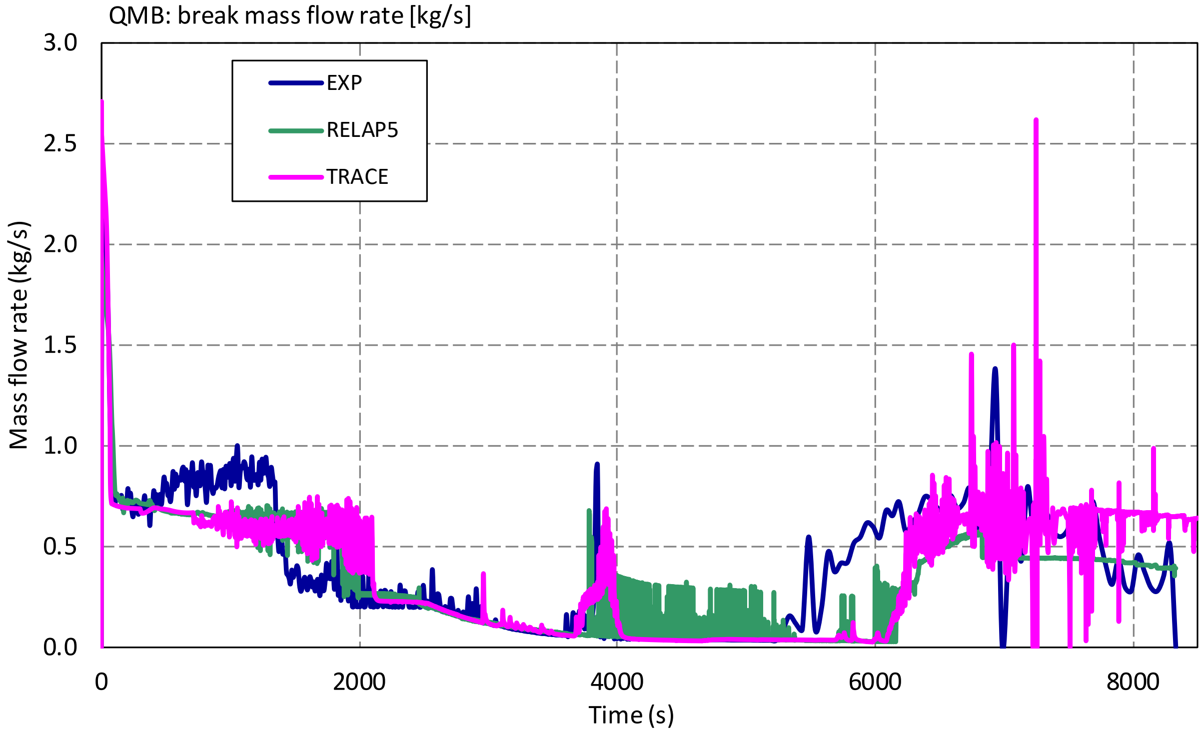


Figure 5-7 SG1 Downcomer Bottom Temperature (TF454C): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



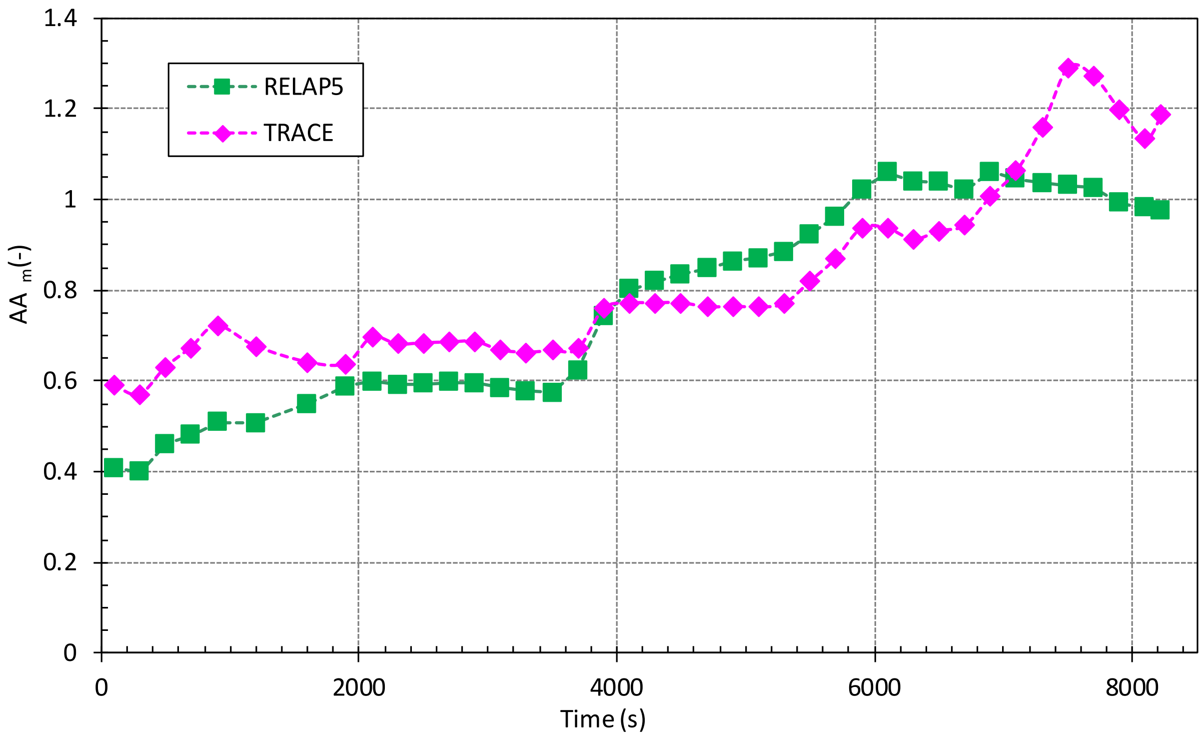
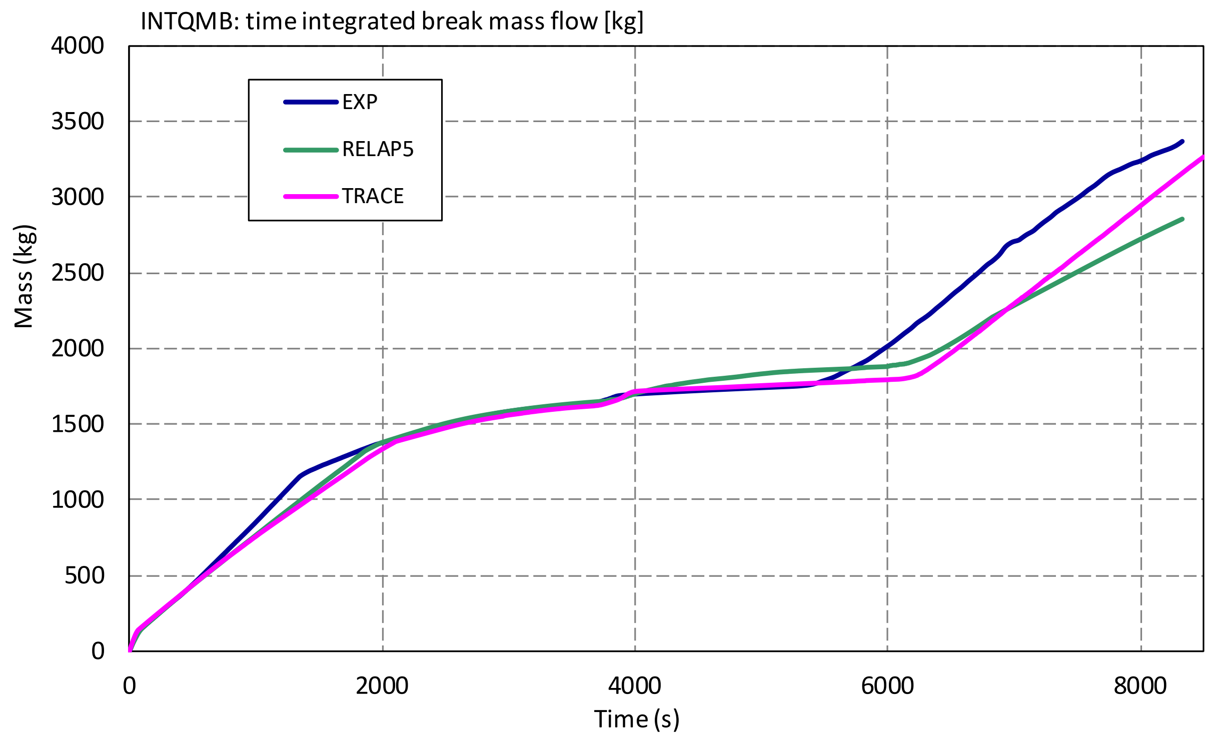


Figure 5-8 Break Mass Flow Rate (QMB): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



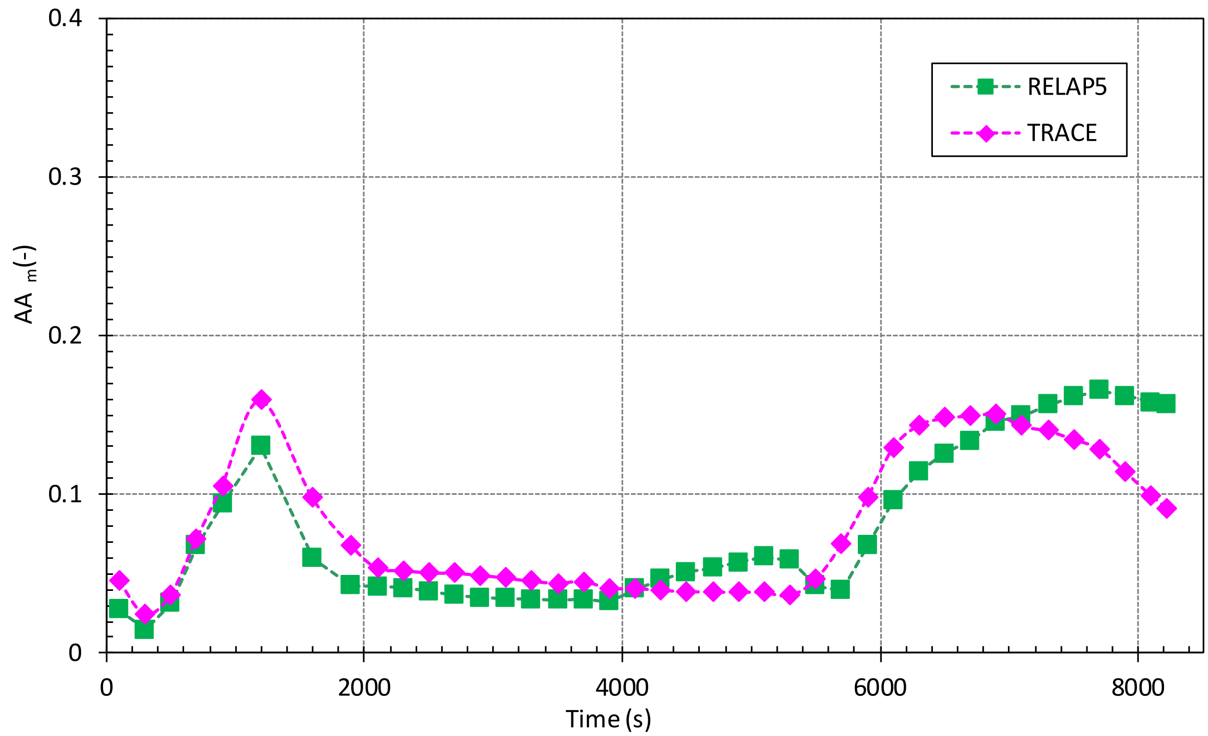
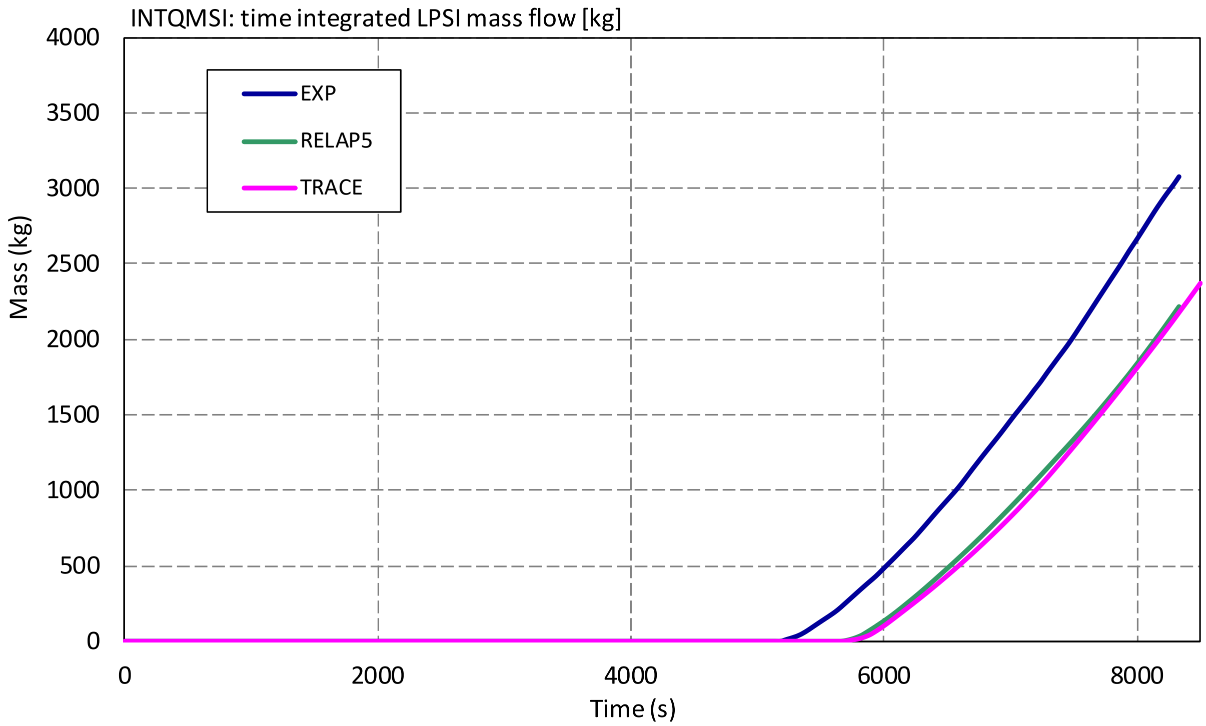


Figure 5-9 Time Integrated Break Mass Flow (INTQMB): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



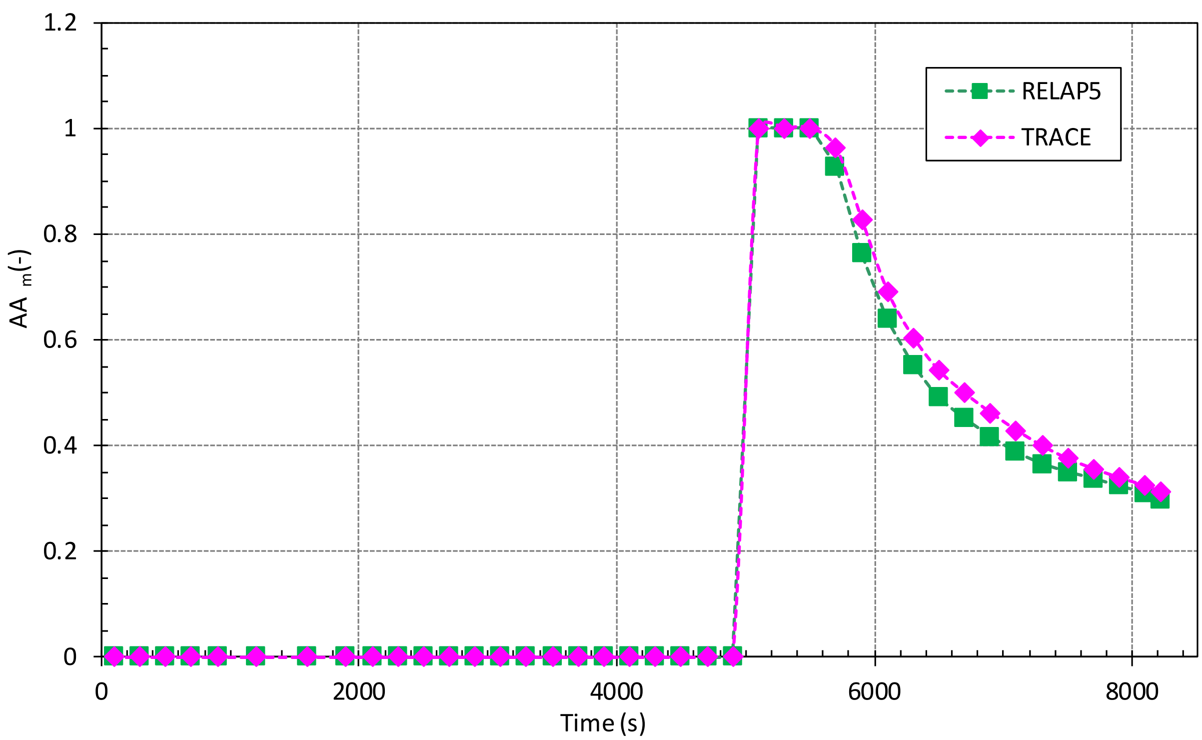


Figure 5-10 Time Integrated LPSI Mass Flow (INTQMSI): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

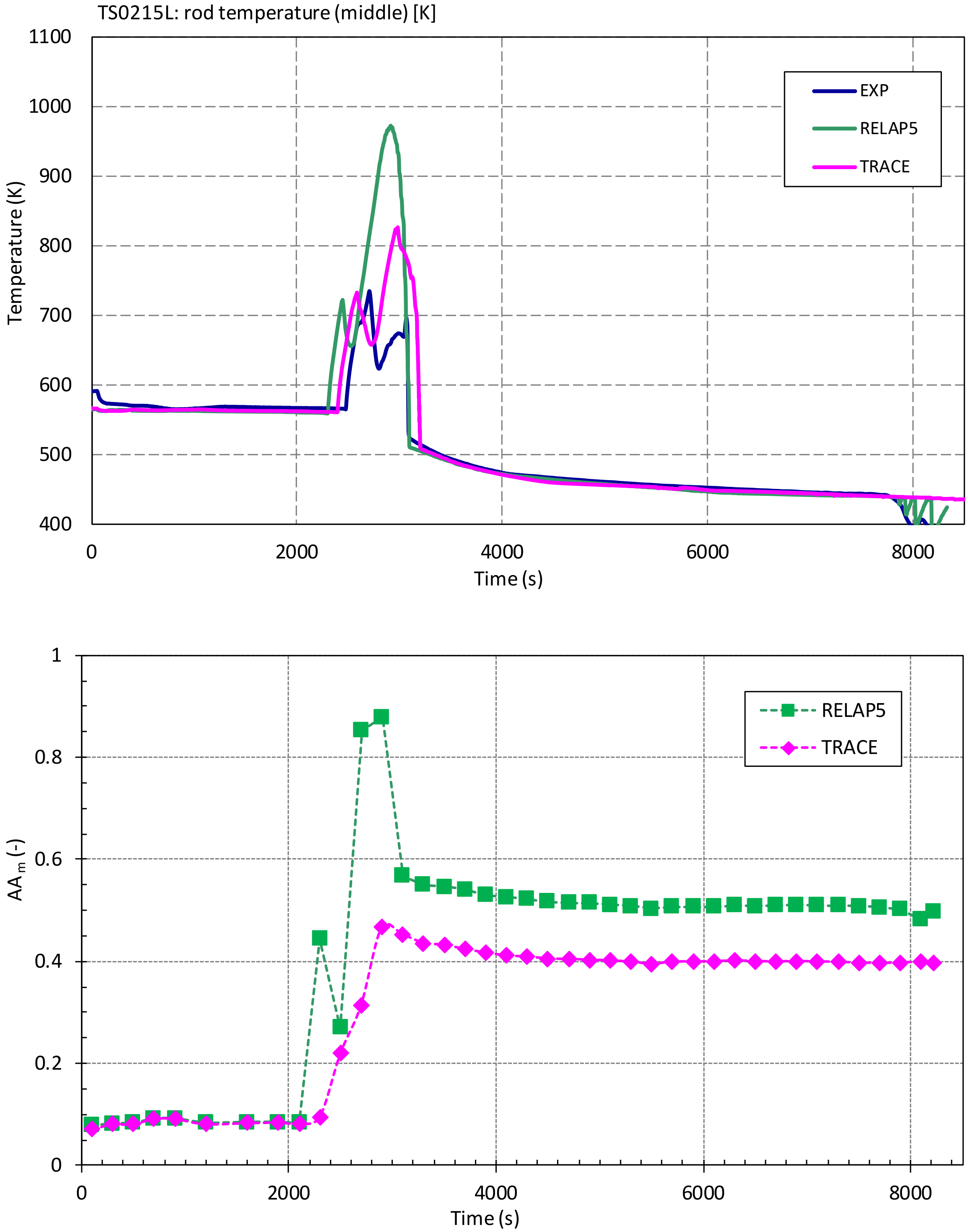


Figure 5-11 Rod Temperature (Middle) (TS0215L): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

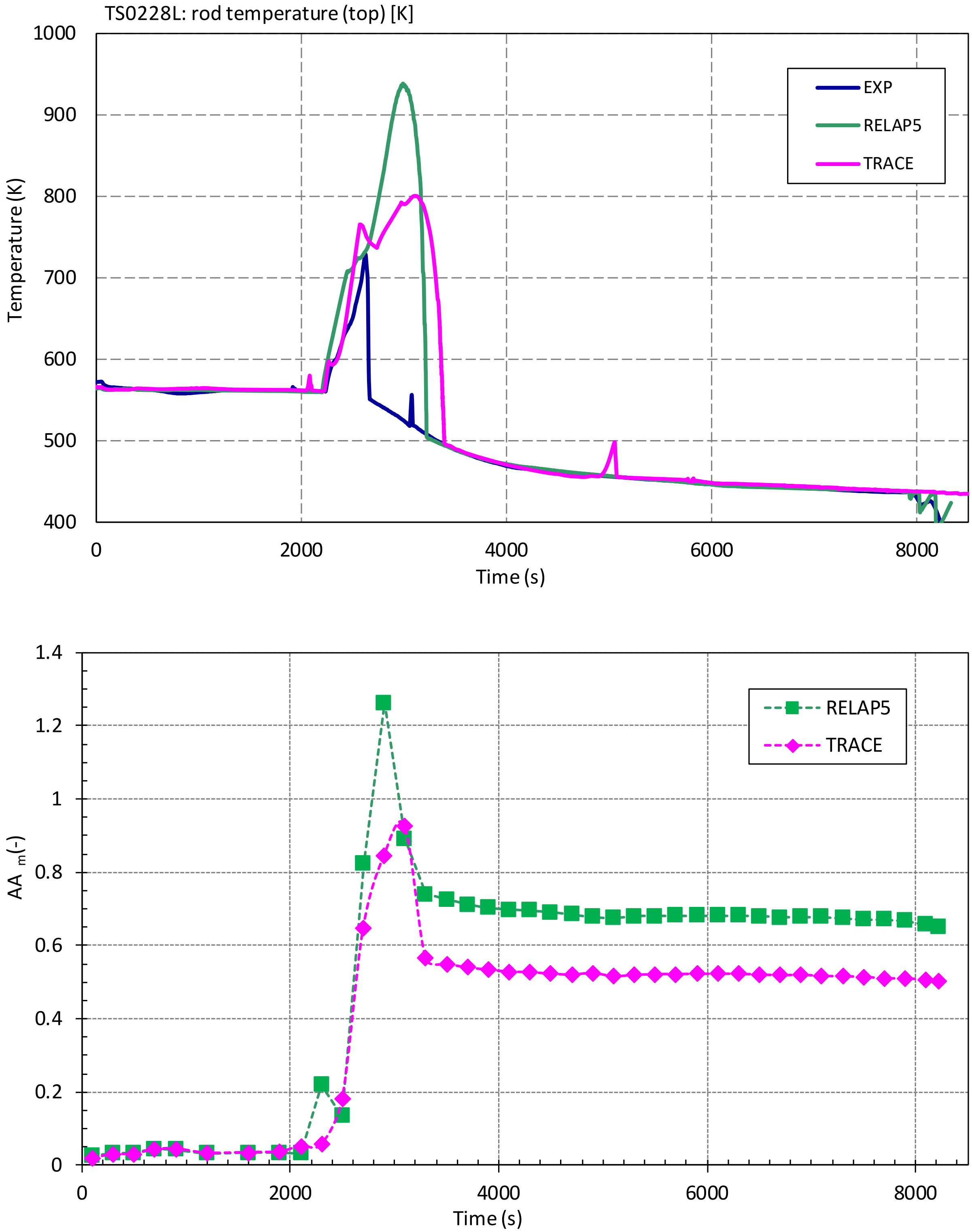
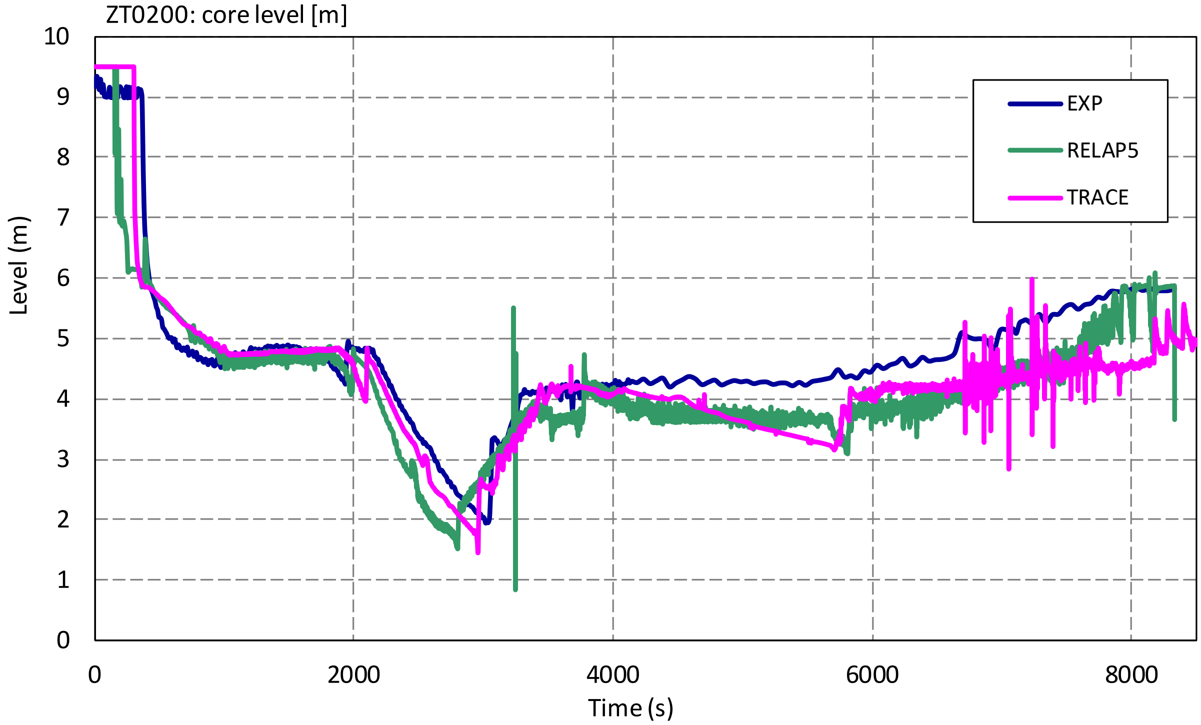


Figure 5-12 Rod Temperature (Top) (TS0228L): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



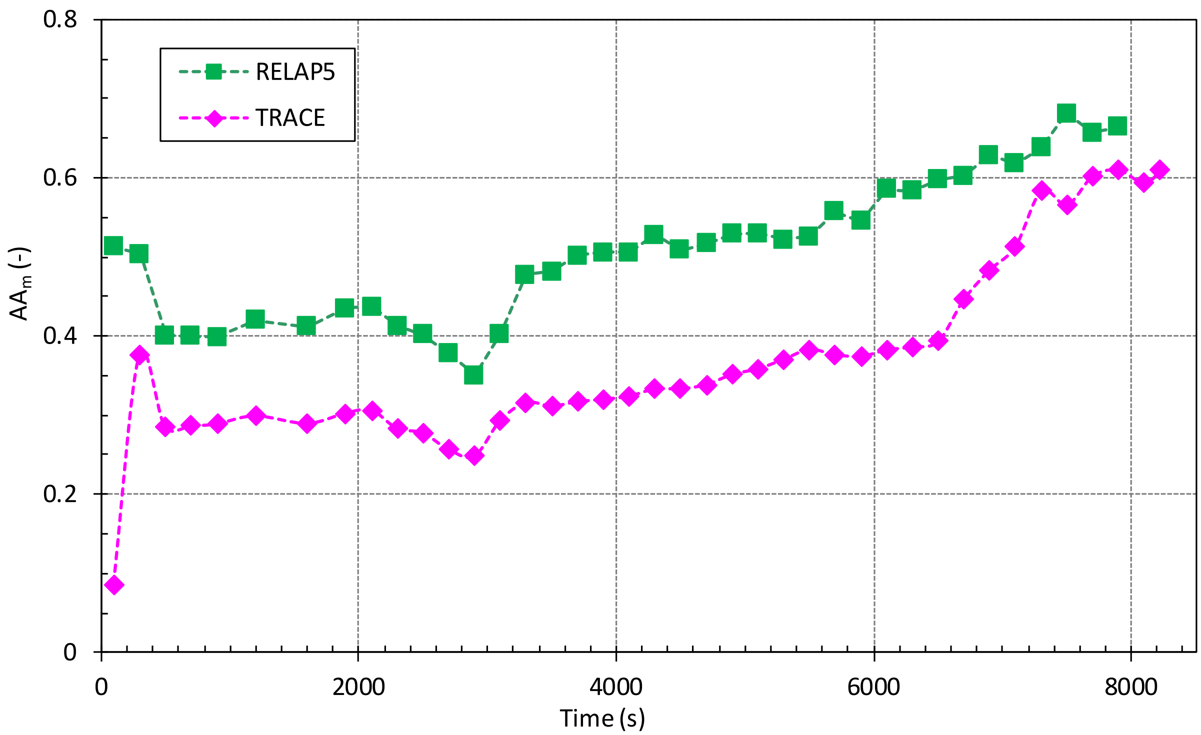


Figure 5-13 Core Collapsed Level (ZT0200): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

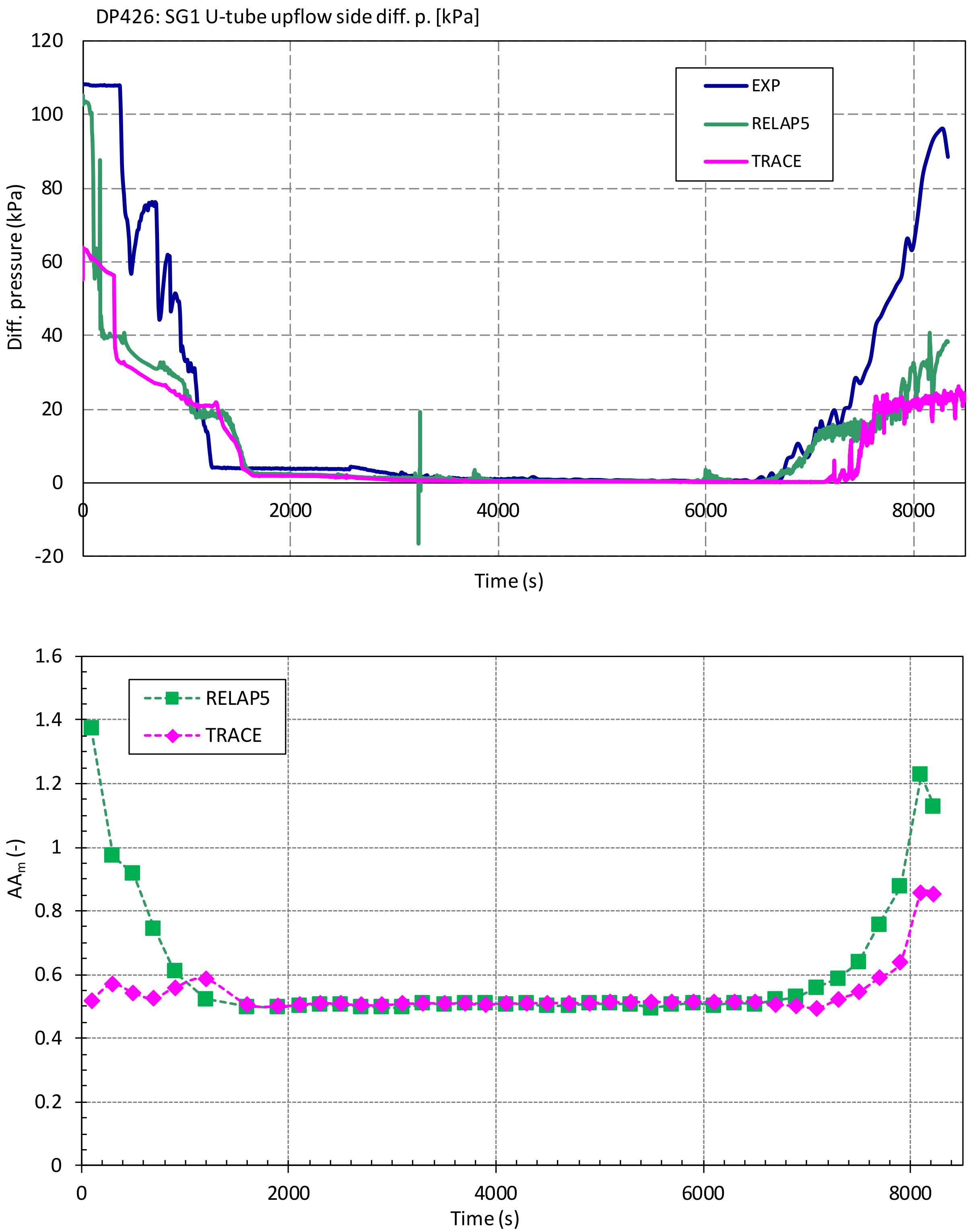


Figure 5-14 SG1 U-Tube Upflow Side Differential Pressure (DP426): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

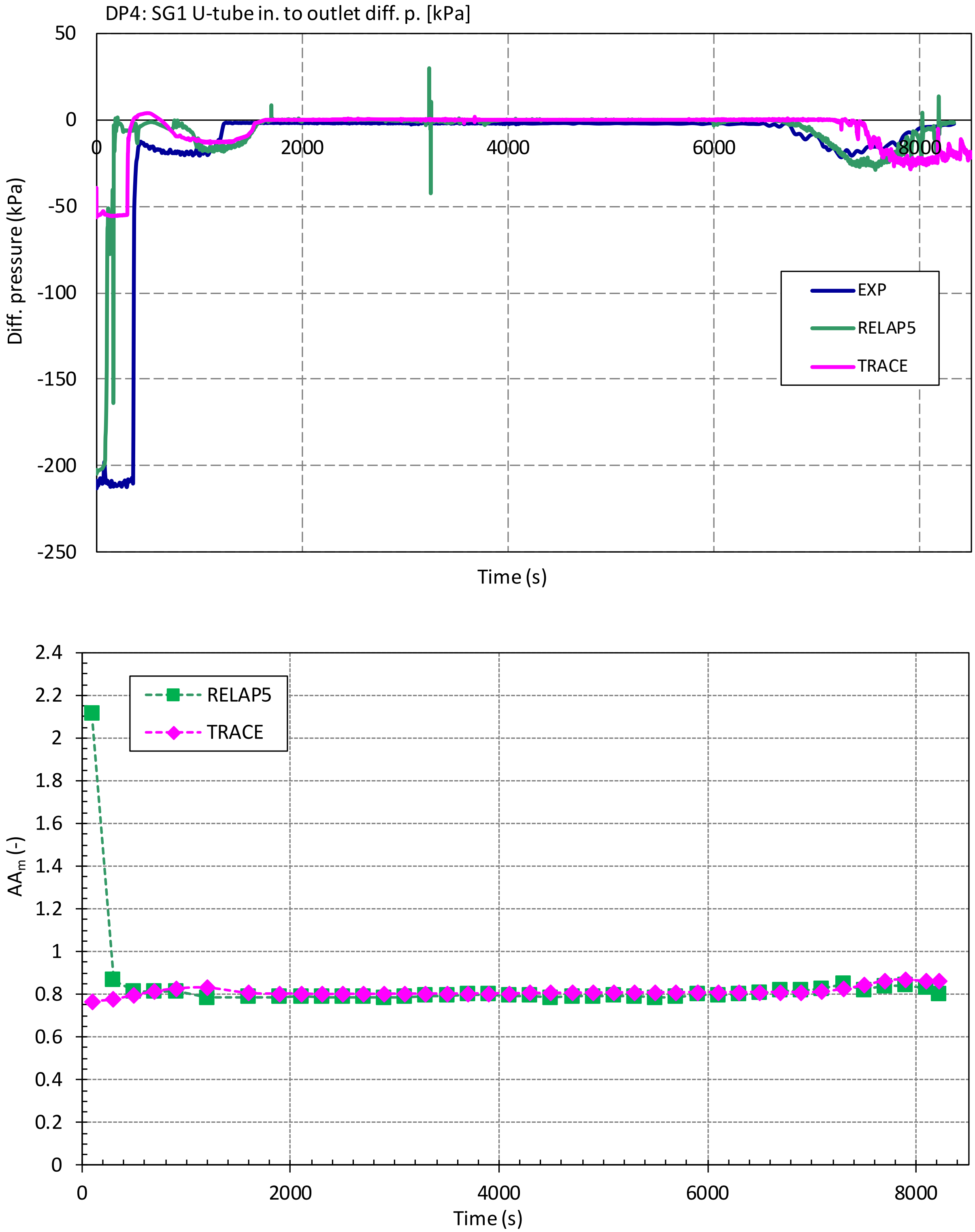


Figure 5-15 SG1 U-tube Inlet to Outlet Differential Pressure (DP4): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

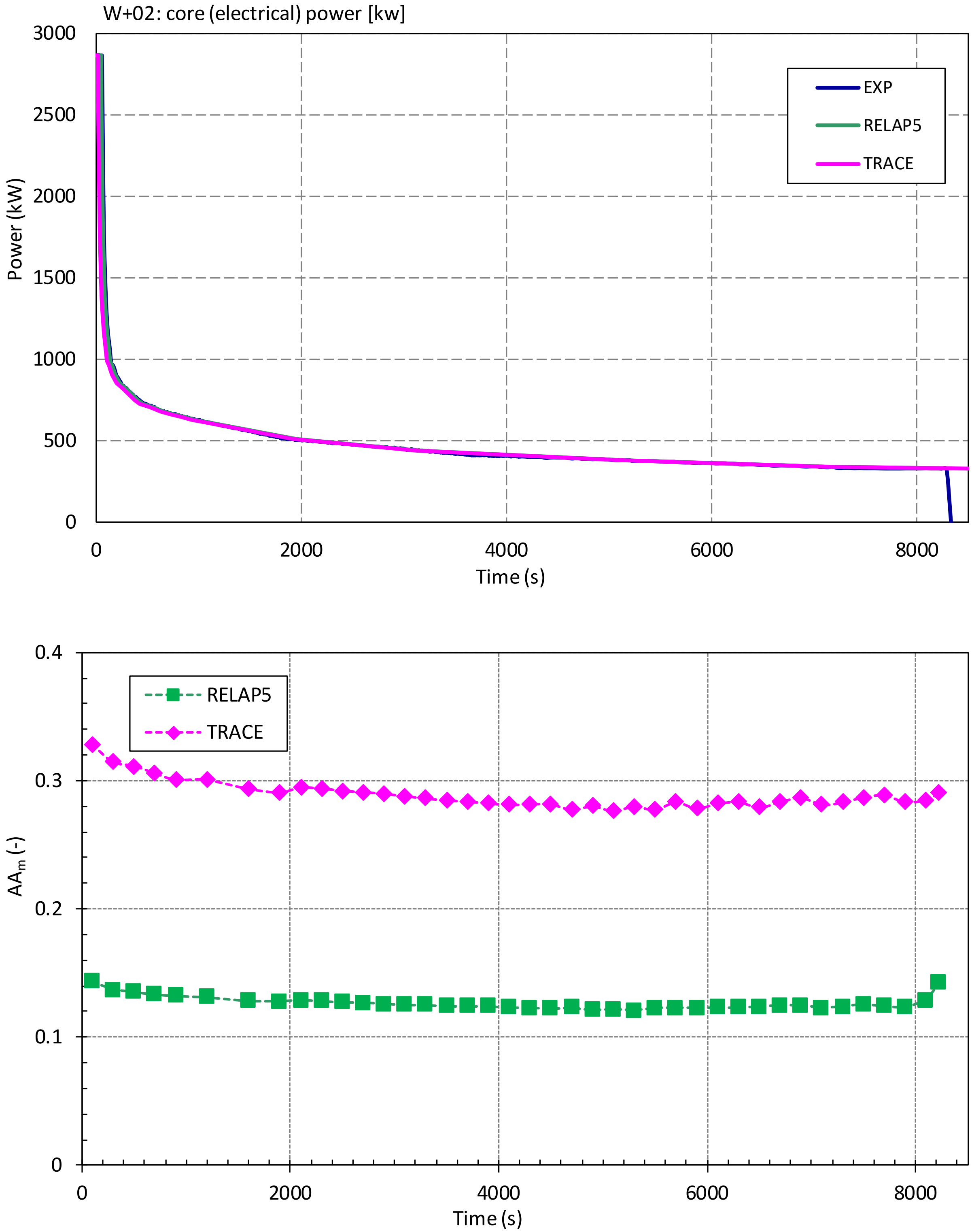


Figure 5-16 Core (Electrical) Power (W+02): a) Visual Observation (Top), b) Accuracy Measure AA$_m$ (Bottom)

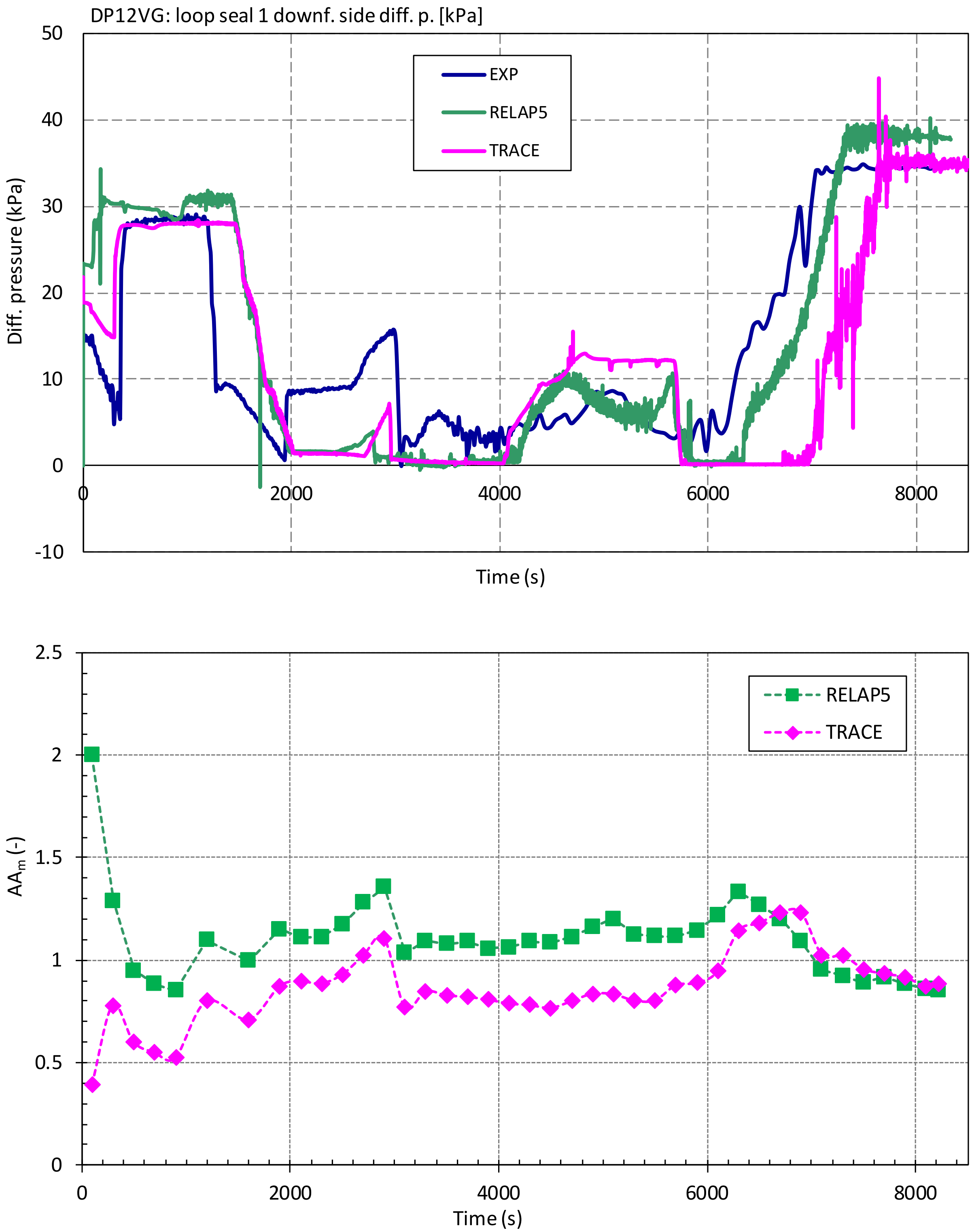
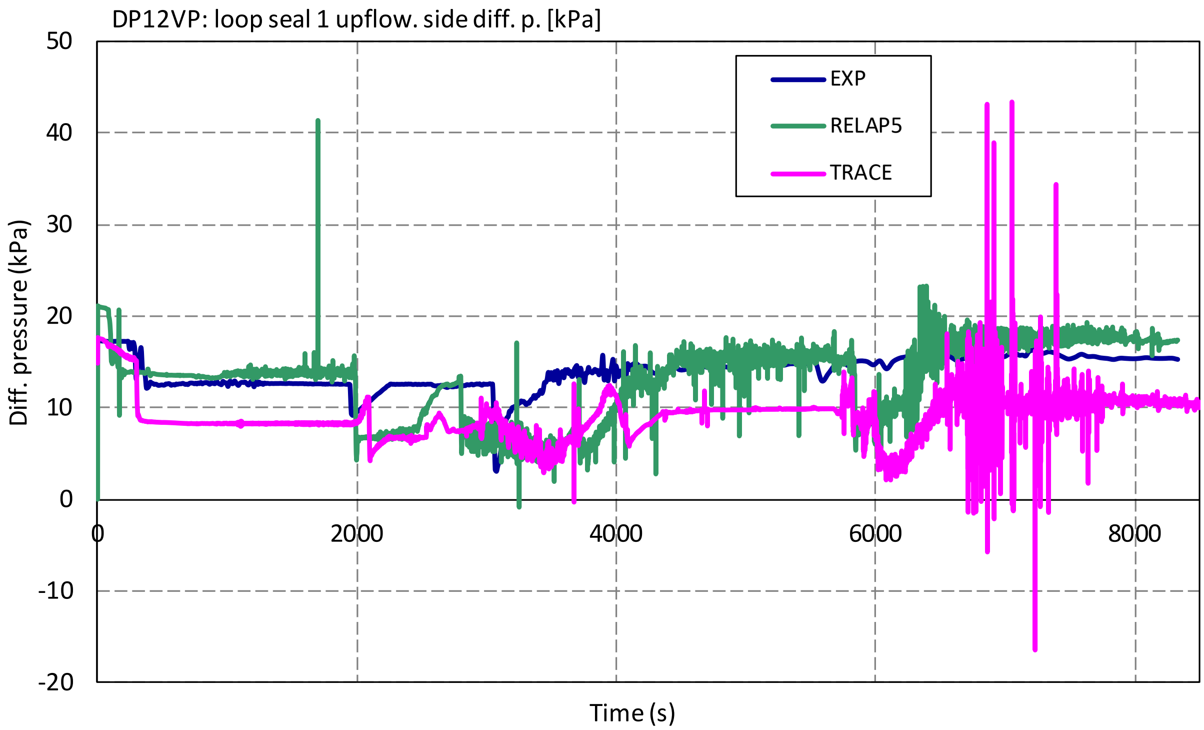


Figure 5-17 Loop Seal 1 Downflow Side Differential Pressure (DP12VG): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



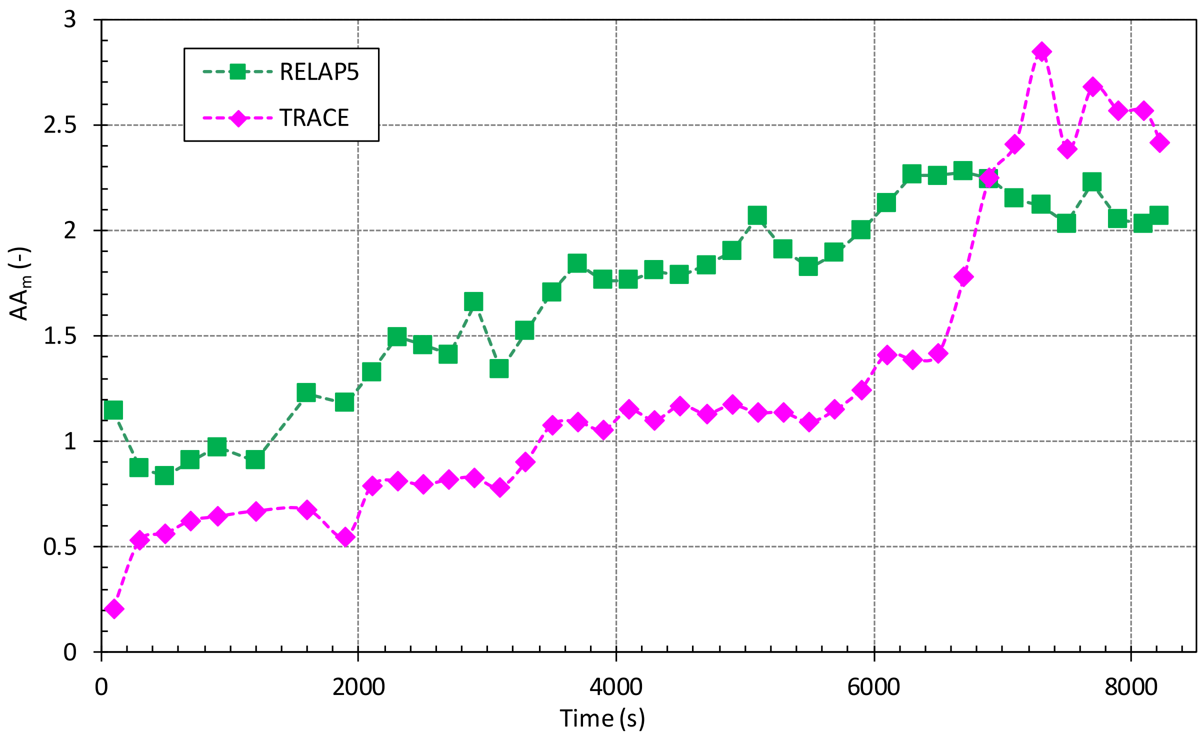


Figure 5-18 Loop Seal 1 Upflow Side Differential Pressure (DP12VP): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

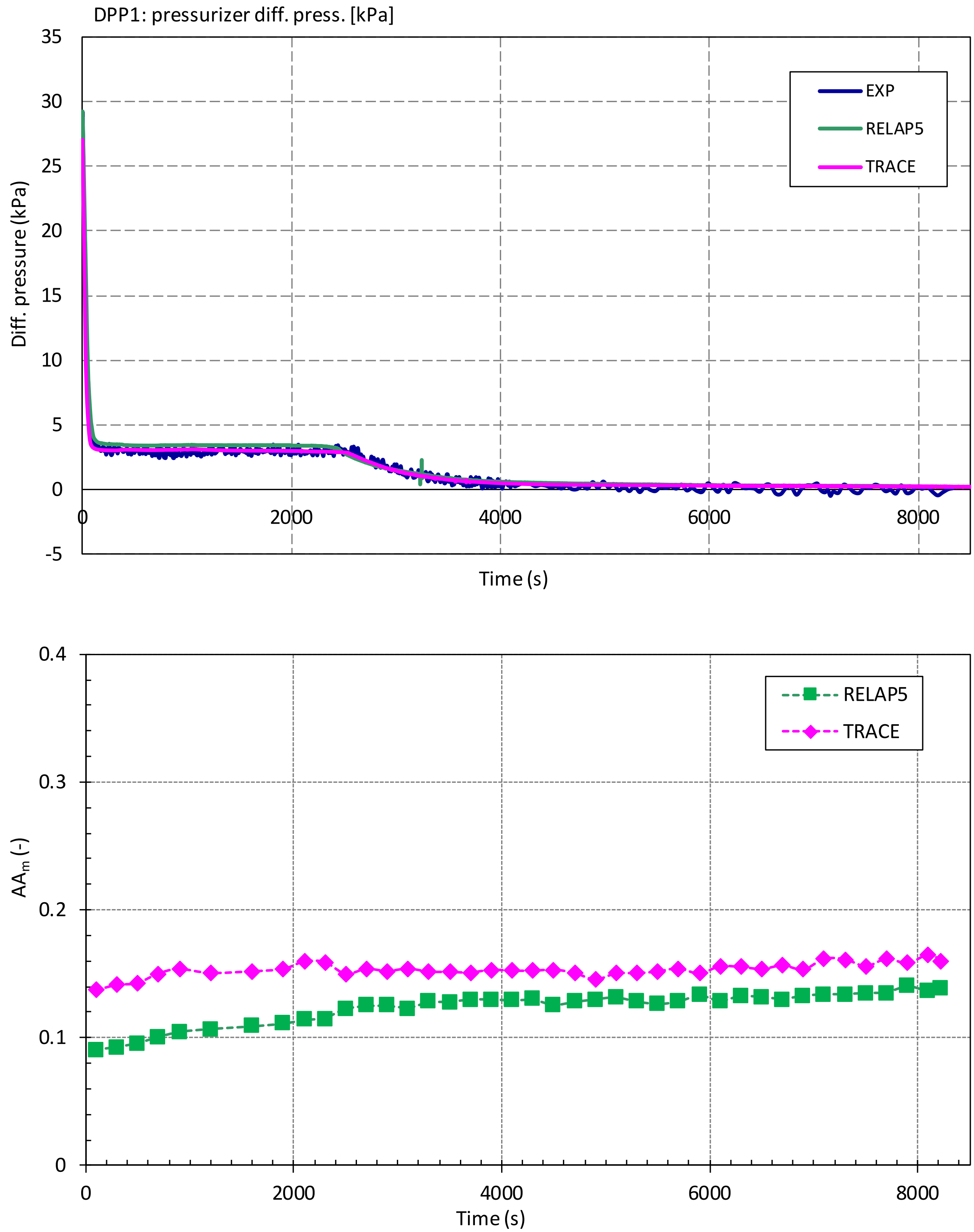


Figure 5-19 Pressurizer Differential Pressure (DPP1): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

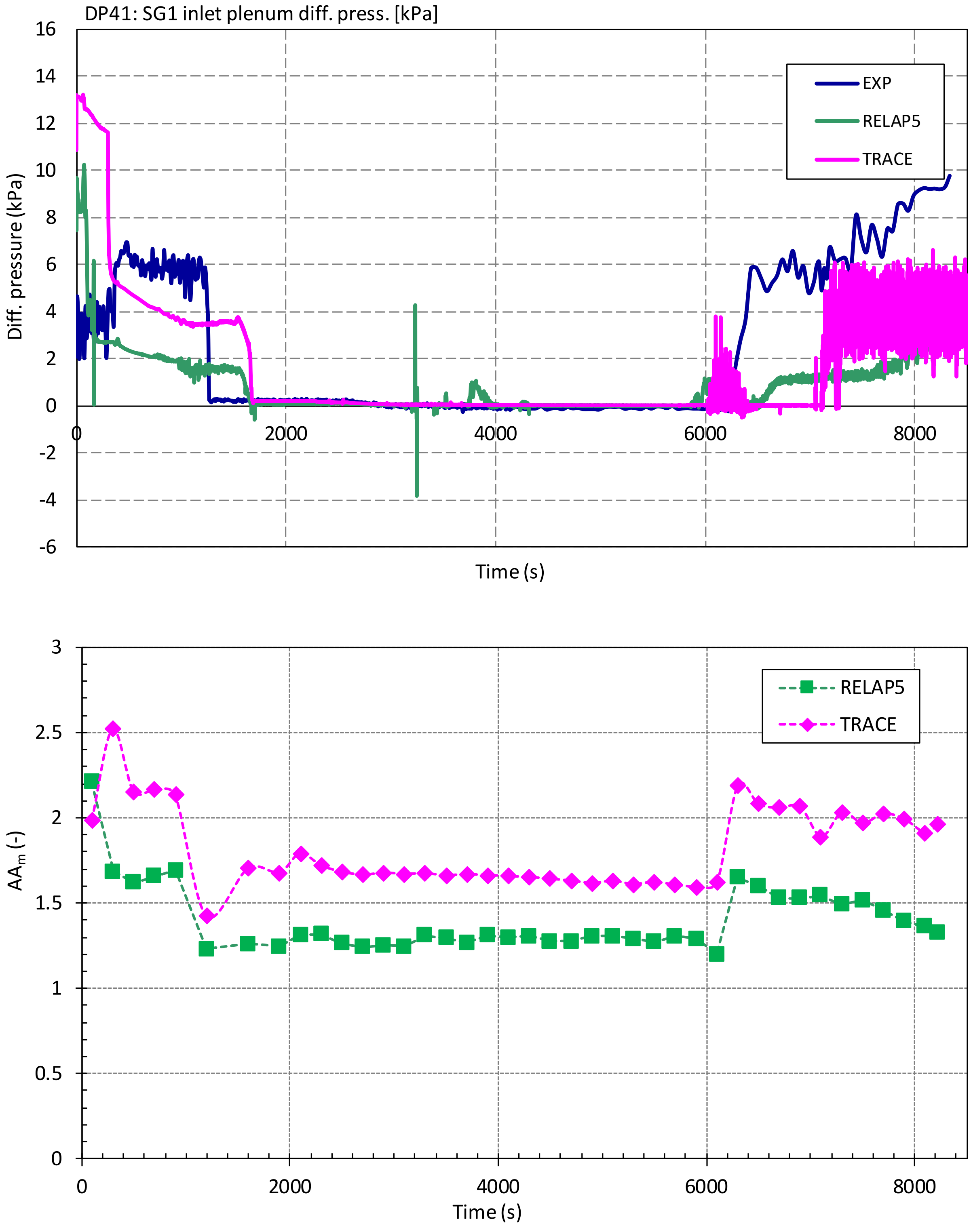
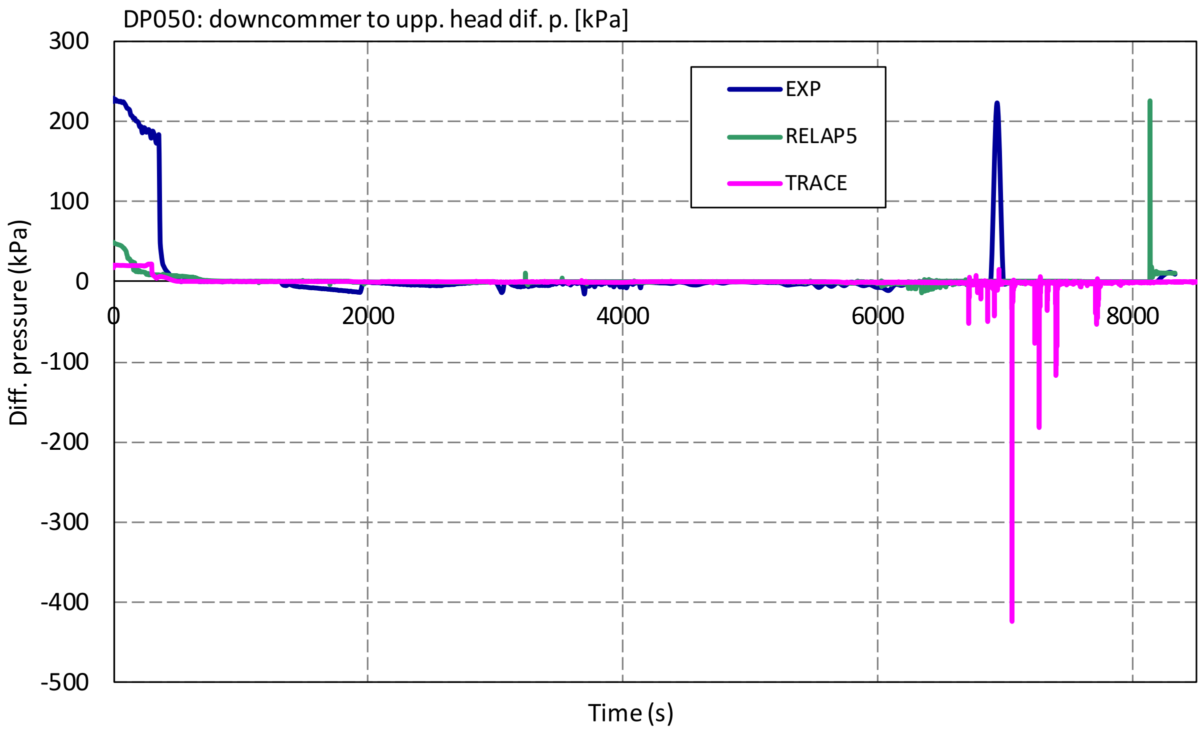


Figure 5-20 SG1 Inlet Plenum Differential Pressure (DP41): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)



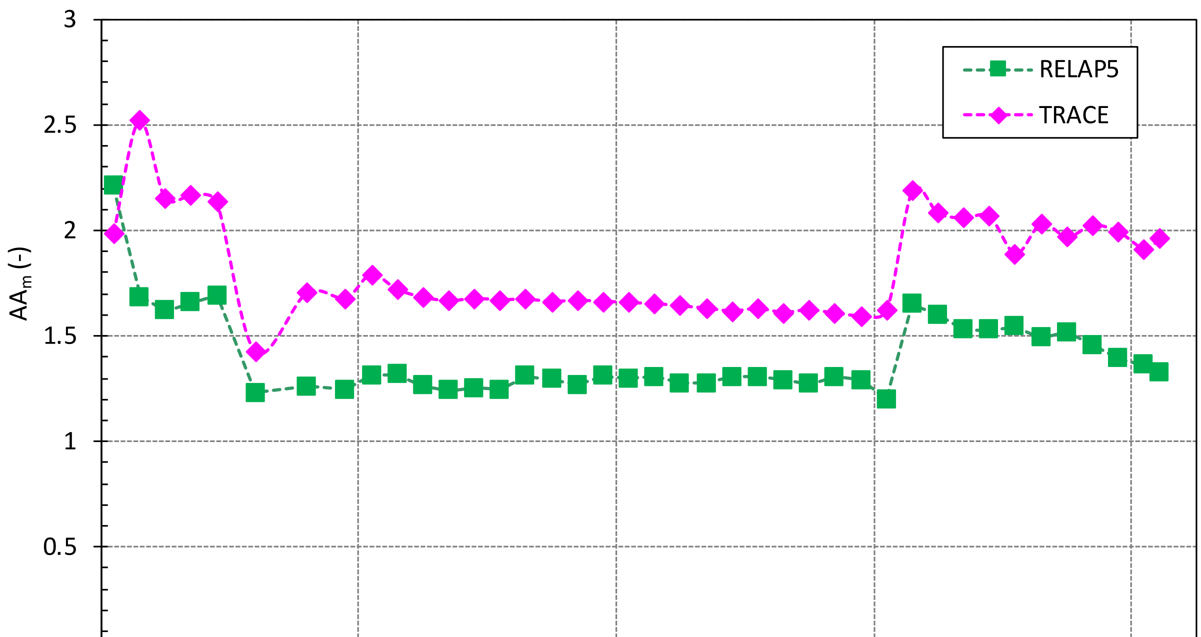


Figure 5-21 Downcommer to Upper Head Differential Pressure (DP050): a) Visual Observation (Top), b) Accuracy Measure AA_m (Bottom)

The total accuracy ($AA_{m\text{-}tot}$) trend is shown in Figure 5-22. It can be seen that for the first 8000 s, the TRACE calculation is slightly better, however at the end of transient the RELAP5 shows a somewhat better agreement with the experiment (it should be noted that FFTBM-SM has comparable uncertainty). For the total accuracy calculation 21 variables were used, as presented in Table 5-2, showing the results of FFTBM-SM analysis for time interval 0-8200 s (for RELAP5 the last calculated point at 8330 s is missing for core collapsed liquid level).

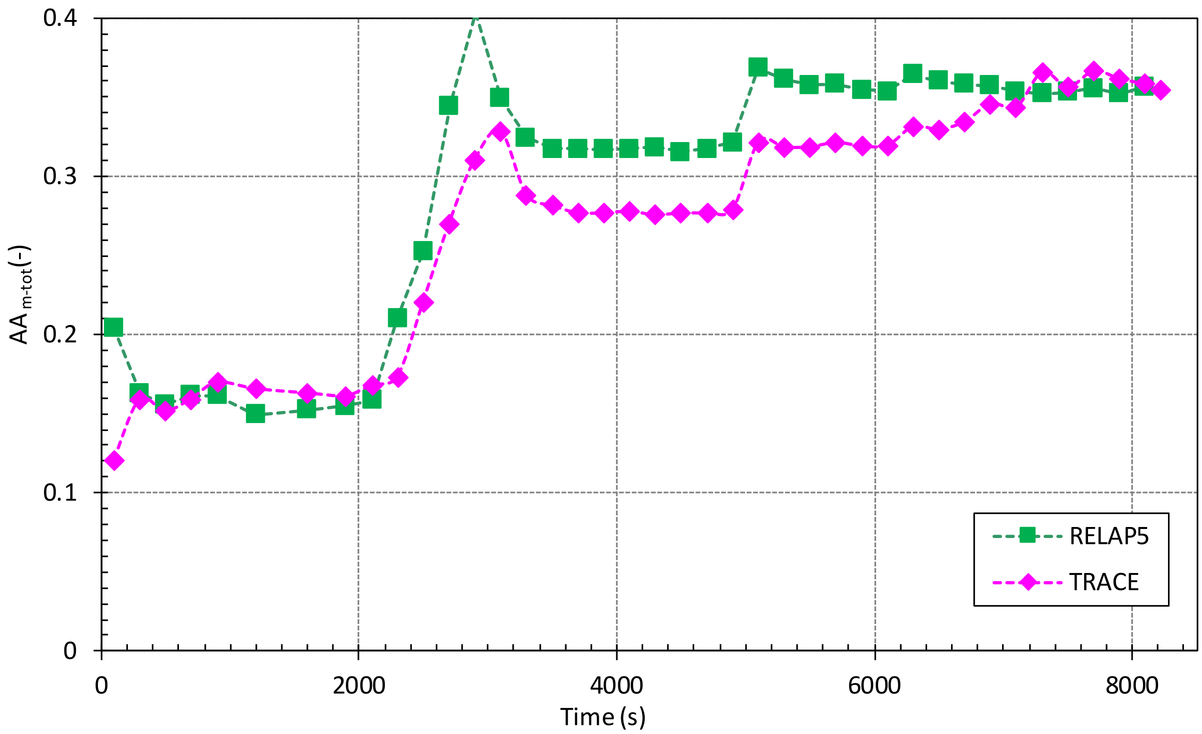


Figure 5-22 Total Accuracy ($AA_{m\text{-}tot}$) Trends

Table 5-2 Accuracy Results of BETHSY 9.1b Calculations for Interval 0-8200 s

ID	PARAMETER	RELAP		TRACE	
		AA	AA_m	AA	AA_m
1	Pressurizer pressure	0.09	0.24	0.07	0.16
2	Secondary pressure	0.11	0.28	0.06	0.14
3	Accumulator pressure	0.11	0.21	0.07	0.13
4	Core inlet temperature	0.08	0.15	0.18	0.22
5	Core outlet temperature	0.36	0.47	0.36	0.45
6	Upper head top temperature	0.22	0.31	0.21	0.30
7	SG1 downcomer bottom temperature	0.08	0.11	0.10	0.15
8	Break flow	0.98	1.07	1.13	1.21
9	Integrated break mass flow	0.16	0.21	0.10	0.20
10	Integrated ECCS component mass flow	0.31	0.32	0.32	0.34
11	Cladding temperature (middle)	0.48	0.67	0.40	0.51
12	Cladding temperature (top)	0.66	0.90	0.51	0.68
13	Core collapsed liquid level	0.70	1.02	0.59	0.82
14	SG1 U-tube upflow diff. pressure	1.23	1.13	0.86	0.85
15	SG1 U-tube inlet to outlet diff. pressure	0.83	1.20	0.86	0.90
16	Core power	0.13	0.26	0.29	0.57
17	Loop seal 1 downflow diff. pressure	0.86	1.15	0.87	1.18
18	Loop seal 1 upflow diff. pressure	2.03	2.21	2.57	2.80
19	Pressurizer diff. pressure	0.14	0.29	0.16	0.30
20	SG1 inlet plenum diff. pressure	1.36	1.28	1.91	1.93
21	Downcomer to upper head diff. pressure	1.01	1.30	1.05	1.32
	TOTAL	**0.36**	**0.48**	**0.36**	**0.46**

$AA_m < 0.1$ $0.1 < AA_m < 0.3$ $0.3 < AA_m < 0.5$ $AA_m > 0.7$

6 CONCLUSIONS

The RELAP5 and TRACE calculations of the Bethsy 9.1b tests have been performed. Besides code-to-code comparison, the quantitative assessment has been performed using the original fast Fourier transform based method (FFTBM) and the improved FFTBM by signal mirroring (FFTBM-SM). The obtained code accuracy of RELAP5 and TRACE calculation, calculated both by the FFTBM and FFTBM-SM showed that differences are small. This indicates that both code calculations are comparable to each other.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT (200 words or less)

In this study the TRACE advanced thermal-hydraulic system code has been used to simulate the BETHSY 9.1b integral experimental test. The TRACE results are compared with the RELAP5 computer code predictions. In addition, the accuracy of both simulations has been evaluated. BETHSY is an integral test facility, which was designed to simulate most pressurized water reactors (PWR) accidents of interest, to study accident management procedures and to validate the computer codes. The BETHSY 9.1b experiment represents the Small Break Loss-of-Coolant Accident (SBLOCA) with loss of high pressure injection system. After the Fukushima-Daiichi nuclear accident, this type of accident is considered as a part of Design Extension Conditions (DEC). As no DEC safety features for high pressure injection are available in BETHSY 9.1b test, a delayed operator action for secondary system depressurization has been analysed in this study. For accuracy quantification the Fast Fourier Transform Based Method by signal mirroring (FFTBM-SM) and original FFTBM have been used. The comparison of the simulated results with the experimental data is presented. Finally, the results of code accuracy quantitative assessment are shown.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)	13. AVAILABILITY STATEMENT
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