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TRAC-M/AAA Code Assessment for Transient Analysis of Pb-Bi Cooled Fast-Spectrum Reactor Systems

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A coupled system of codes is currently under development at the Paul Scherrer Institute (PSI) for the comprehensive transient analysis of fast-spectrum critical and sub-critical reactors cooled by liquid metal or gas. The thermal-hydraulic calculations in this code system will be performed by the TRAC-M/AAA code version, specially developed to simulate liquid-metal and gas coolants. The purpose of the presented work is to assess some of the models employed in this code, which are important for transient analysis of fast-spectrum reactor systems cooled by heavy liquid metals. In particular, the code predictions have been verified against (a) three sets of experimental data on two-phase heavy metal/gas flow and (b) the predictions of other codes in the framework of a beam-trip calculational benchmark for a Pb-Bi cooled ADS. The main conclusion of the work is that the TRAC-M/AAA code can, with reasonable accuracy, predict the considered phenomena in fast-spectrum reactor systems cooled by heavy liquid metals.

KEYWORDS: advanced fast-spectrum systems, TRAC-M/AAA code, model verification, two-phase heavy metal/gas flow, beam-trip benchmark

1. Introduction

A coupled system of codes is currently under development at the Paul Scherrer Institute for the comprehensive transient analysis of fast-spectrum critical and sub-critical reactors cooled by liquid metal or gas. The thermal-hydraulic calculations in this code system will be performed by the TRAC-M/AAA code [1]. This version was specially developed at Los-Alamos National Laboratory (USA) to simulate additional working fluids (including liquid metals and helium), to add liquid-metal and gas heat transfer correlations, to simulate fluid power in the working fluid, and to simulate conduction within the working fluid important for liquid-metal coolants. The current paper presents the results of the TRAC-M/AAA code assessment carried out for transient analysis of Pb-Bi cooled fast-spectrum reactor systems. In particular, the code predictions have been compared with (a) experimental data on two-phase heavy metal/gas flow [2-4] and (b) the predictions of other codes (including those initially developed for fast reactors) in the framework of a beam-trip calculational benchmark for a Pb-Bi cooled ADS [5].

2. Verification Against Data on Two-Phase Heavy Metal/Gas Flow

A gas lift pump concept based on the bubbling of inert gas in liquid metal to enhance natural circulation of the primary coolant is currently considered in a number of Pb-Bi cooled reactor projects [6,7]. Thus, verification of two-phase heavy metal/gas flow models becomes an important issue.

We simulated three sets of experiments [2-4] with different geometry, coolants, flowrate and void ranges. Two sets of calculations were made for each test: with the standard TRAC model for bubble drag coefficient c_D (shown as "TRAC-M/AAA" in the plots) and with the coefficient reduced by

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a factor of 2 (shown as "TRAC-M/AAA mod" in the plots). The calculations, with the modified model, were performed to evaluate the sensitivity of the results to a change in the bubble drag coefficient.

2.1 Test Set 1: Nitrogen Bubbling in a Lead-Bismuth Pool

In order to provide a validation of the SIMMER-III code, a number of experiments was performed at Kyoto University (Japan) under a joint research contract with JNC [2].

The test section (Figure 1) was a rectangular tank of 530x100x20 mm^3 filled with molten lead-bismuth at a temperature of 200ºC. Nitrogen gas was injected into the liquid molten pool from nozzles at the tank bottom. A neutron radiography technique was used to visualize the bubble shapes. Time- and spatially-averaged void fractions in the pool were measured as a function of gas velocity by dynamic image processing. The average superficial liquid velocity equals zero in these experiments.

A two-dimensional (x-z) vessel component (10×14 nodes) in cartesian geometry was used for the TRAC-M/AAA simulation of the pool. Results of the comparisons made are shown in Figure 2. The predictions of the modified TRAC-M/AAA (with reduced c_D) are in slightly better agreement with the data in the higher void regions (typical for the reactor systems under investigation), as compared to the results obtained using the standard TRAC-M/AAA model. However, both calculations underestimate the data in the low void region (below 0.1).

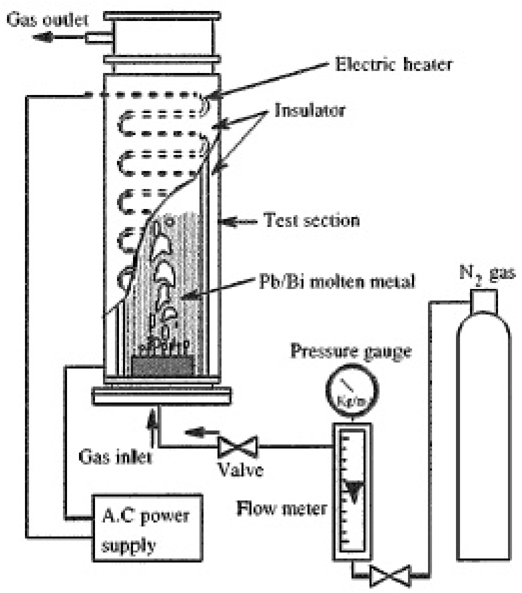


Fig. 1. Diagram of test section [2]

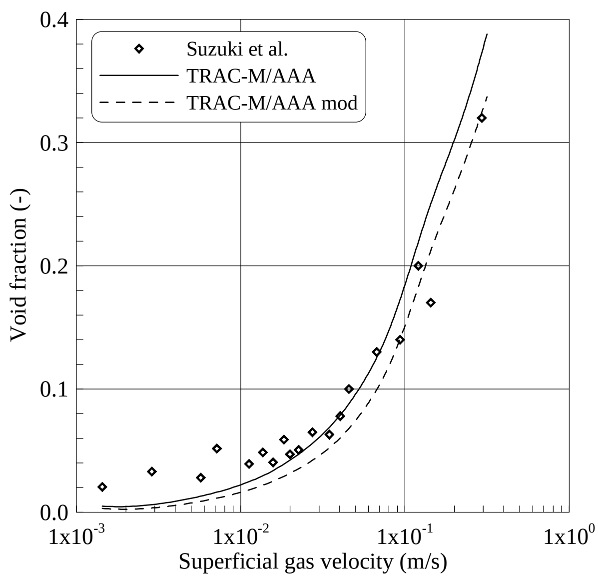


Fig. 2. Average void fraction versus superficial gas velocity

2.2 Test Set 2: Gas Lift Pump Performance in a Lead-Bismuth Loop

A series of experiments was conducted at the Central Research Institute of the Electric Power Industry (Japan) to evaluate the gas lift pump performance in a lead-bismuth loop [3]. A diagram of the test section is shown in Figure 3. Nitrogen was injected at the bottom of the riser. Three different riser diameters were used in the tests: 69.3 mm, 106.3 mm and 155.2 mm. In all the experiments, the test section was kept at a constant temperature of 200ºC. The average void fraction was calculated from the pressure difference between the inlet and outlet of the riser, measured by absolute pressure transducers.

The TRAC-M/AAA nodalization scheme used includes a two-dimensional (r-z) vessel component (10×11 nodes) for the riser and one-dimensional pipe components for the loop legs. Nitrogen was assumed injected uniformly over the radius of the riser.

The comparison of the calculated and experimental results for the average gas void in the riser as a function of the superficial gas velocity is given in Figure 4 for the three different riser diameters. The predictions of the modified TRAC-M/AAA (with reduced c_D) are in slightly better agreement with the data for the largest-diameter riser compared to the standard TRAC-M/AAA model for the bubble drag coefficient. In the two other cases, the predictions of the standard TRAC-M/AAA model is in better agreement with the test data.

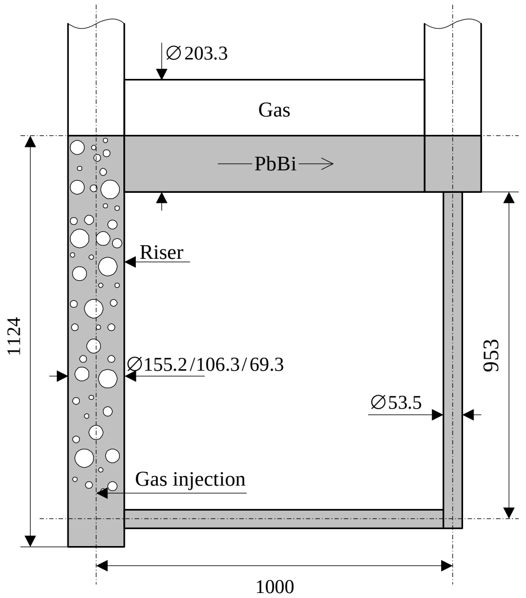


Fig. 3. Diagram of test section (dimensions are in mm)

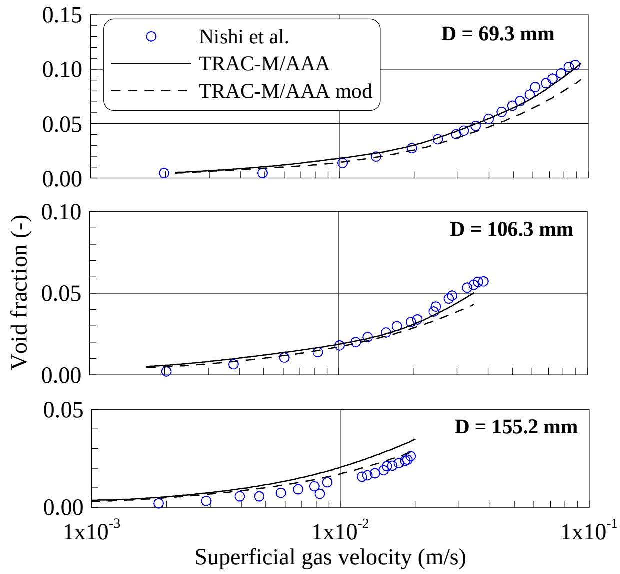


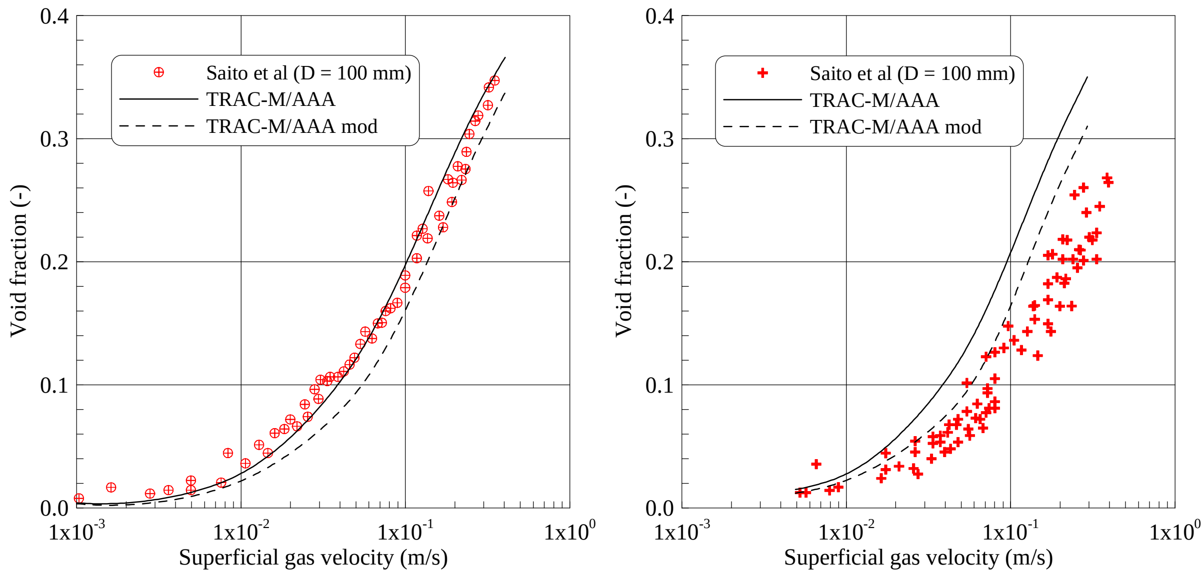
Fig. 4. Average void fraction versus superficial gas velocity

2.3 Test Set 3: Nitrogen Bubbling in Water and Gallium Pools

Experiments were performed at the Tokyo Institute of Technology (Japan) to examine the hydraulics characteristics of gas-liquid two-phase pools [4]. In the tests, nitrogen gas was injected into different liquids in pools of different diameters. The average superficial liquid velocity equals zero in these experiments. The data for water at 20ºC and liquid gallium at 80ºC (density: 6060 kg/m^3) for a pool diameter of 100 mm were used for comparison with the TRAC-M/AAA code predictions.

A two-dimensional (r-z) vessel component (10×10 nodes) in cylindrical geometry was used in the TRAC-M/AAA code simulation of the pool. In the reference paper [4], only the total height of the facility is presented and there is no information about the pool height. However, the height of the liquid gallium pool is important, because due to the high gallium density the pressure level at the gas inlet strongly depends on the pool height. In the current calculations, the height of the gallium pool has been assumed to be 500 mm. This assumption could introduce additional uncertainties in the calculations.

The results of the present comparisons are given in Figure 5a for water and in Figure 5b for liquid gallium. The agreement for the water test is much better than for gallium. This is as to be expected, since the original TRAC interphase drag relations were developed for water. This particular comparison thus provides some basic justification for the application of TRAC-M/AAA. In the case of liquid gallium, the code significantly overestimates the test data. The reduction of the bubble drug coefficient (in the modified TRAC-M/AAA calculations) decreases this difference, but the discrepancy with the test data is still considerable, especially in the high void region.

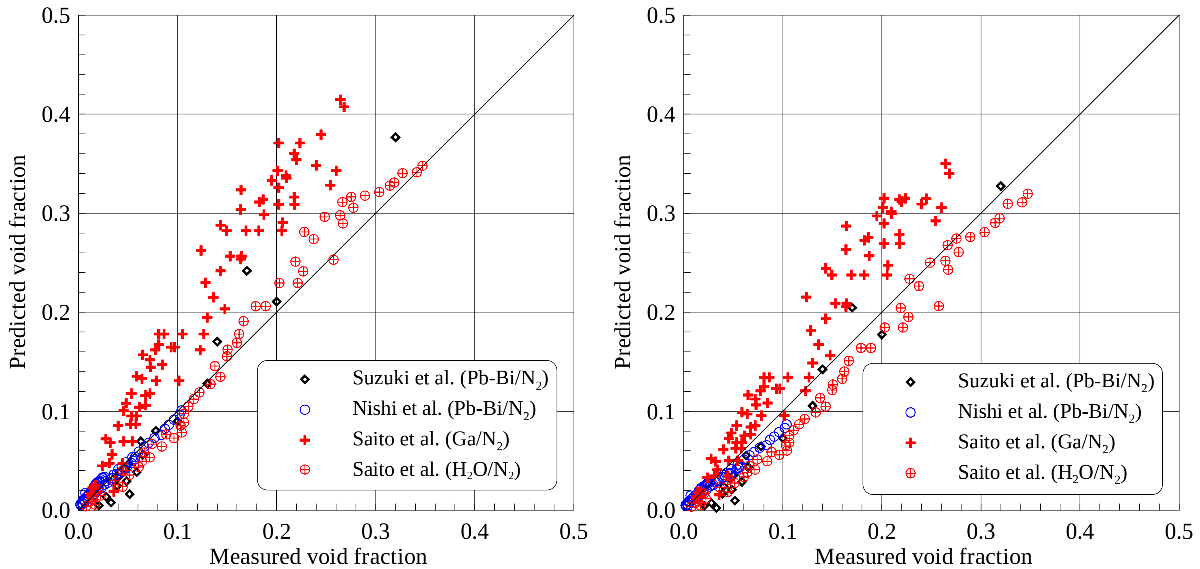


a) b)

Fig. 5. Average void fraction versus superficial gas velocity for (a) water and (b) liquid gallium

2.4 Summary of the TRAC-M/AAA Assessment against Two-Phase Flow Data

The TRAC-M/AAA predictions of void fraction versus the various test data considered are presented in summary form in Figure 6a for the standard bubble drag c_D model and in Figure 6b for the modified model. The reduction of the coefficient c_D by a factor of 2 slightly improves agreement with Pb-Bi data in the “high” void region ($\alpha > 0.1$), worsens it for water data and Pb-Bi data in the “low” void region ($\alpha < 0.1$), and does not drastically improve the overestimation for the gallium data. A separate comparison of the modified TRAC-M/AAA predictions against the three sets of experimental data for heavy liquid metals is shown in Figure 7.



a) b)

Fig. 6. Summary of TRAC-M/AAA code predictions for void fraction versus test data, using (a) the standard bubble drag model, and (b) the modified model

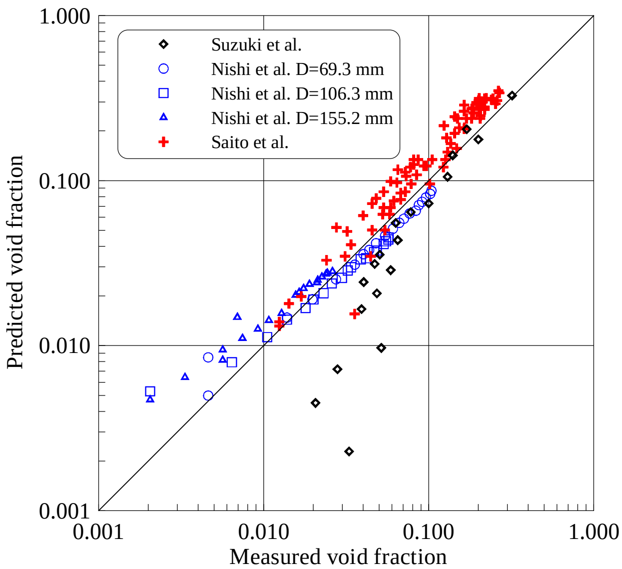


Fig. 7. Log-log representation of modified TRAC-M/AAA predictions for heavy liquid metals versus test data

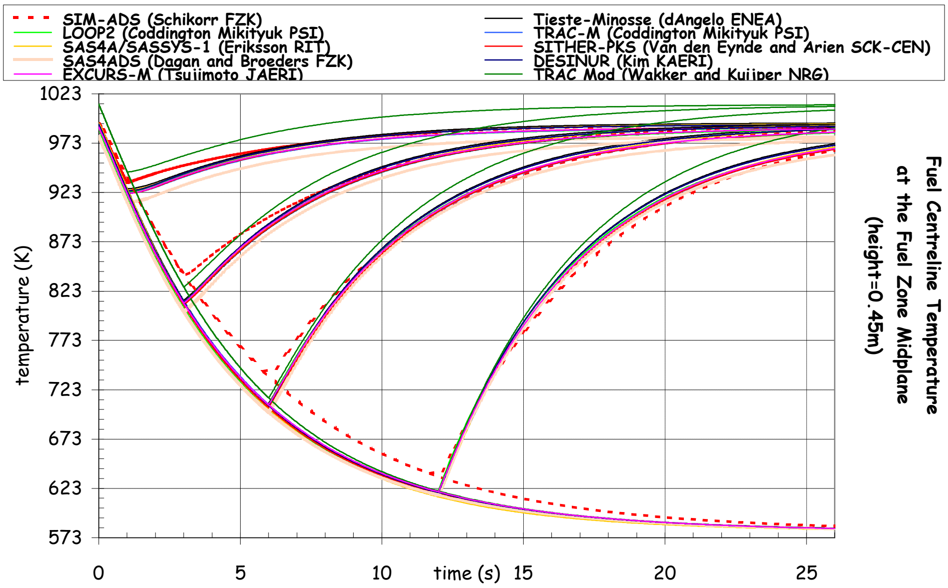
At first glance, the TRAC-M/AAA code predictions employing the reduced bubble drag coefficient appear to be globally quite reasonable. With the log-log representation used in Figure 7 serving to "amplify" the low void fraction comparison, however, two specific observations become clear on careful appraisal. These are: (a) that in the "high" void region ($\alpha > 0.1$) the modified TRAC-M/AAA (though better than the original) still overpredicts the heavy liquid metal data, and (b) that in the "low" void region ($\alpha < 0.1$) there is an inconsistency between the trends of deviations of the code predictions from the different experimental data sets. In order to resolve the latter inconsistency, further information (regarding measurement errors, multi-dimensional effects, etc.) is required. In any case, it is seen that great care needs to be taken when "adjusting" a correlation based on the analysis of a single data set.

3. ADS Beam Trip Calculational Benchmark

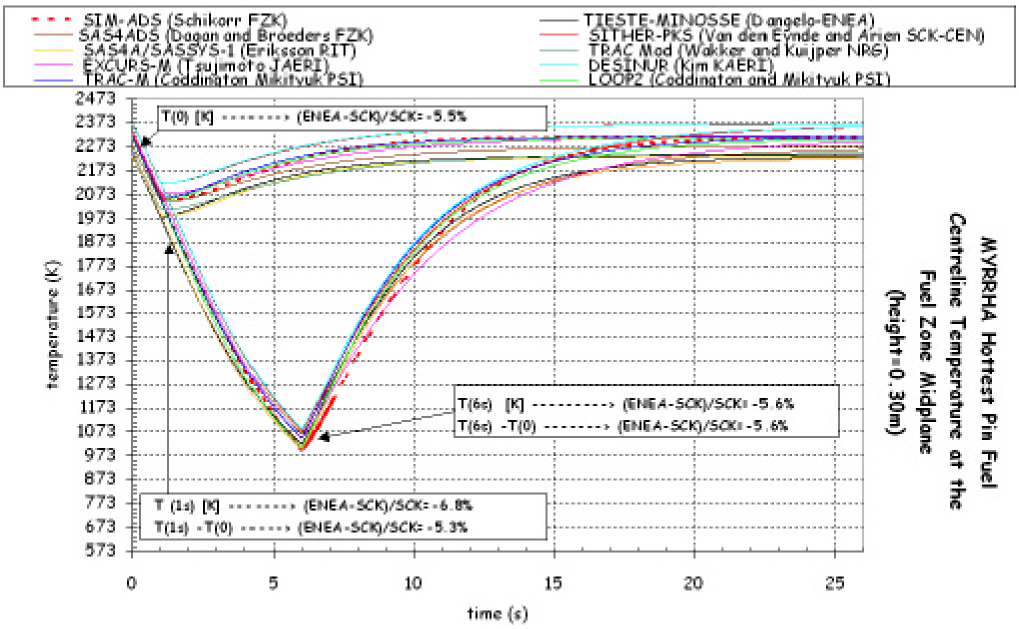
The results of the first phase of the calculational transient benchmark "Beam interruption in a lead-bismuth cooled and MOX fuelled accelerator-driven system" were published recently [5]. The goal of this first phase was to study the behaviour of a PDS-XADS-type lead-bismuth cooled system [6] during beam interruptions of various durations (1 s, 3 s, 6 s, 12 s and infinite trip), using pre-defined physical parameters.

The second stage is now close to completion and includes the analysis of the MYRRHA-type lead-bismuth cooled system [8] during beam interruptions of various durations (1 s and 6 s). The main differences between the PDS-XADS and MYRRHA models are in the fuel pin linear power levels (80 W/cm and 317 W/cm, respectively) and core heights (0.9 m and 0.6 m, respectively). These differences determine the significantly different fuel temperature levels in the two systems.

These two phases were analysed at PSI with the TRAC-M/AAA and LOOP2 [9] codes. Generally, the differences between all sets of provided results for fuel centreline temperatures may be considered insignificant (Figure 8). This follows from the nature of these phases of the benchmark, which were deliberately kept very simple in their formulation. However, this confirms that the TRAC-M/AAA code is able to simulate transients in a subcritical source-driven reactor system, using point kinetics.



a)



b)

Fig. 8. Comparison of fuel centreline temperature predictions in the beam-trip benchmark for (a) Pb-Bi cooled XADS and(b) MYRRHA type models

4. Conclusions

The TRAC-M/AAA code version was specially developed at LANL for the transient simulation of fast-spectrum critical and sub-critical systems cooled by liquid metal or gas.

The first steps taken at PSI in the assessment of the TRAC-M/AAA code for the transient simulation of Pb-Bi cooled systems include a comparison with (a) three sets of experimental data on two-phase heavy metal/gas flow and (b) the predictions of other codes in the framework of a beam-trip calculational benchmark for a Pb-Bi cooled ADS.

The analysis performed shows good agreement of the TRAC-M/AAA predictions with the data on two-phase heavy metal/gas flows under different conditions. However, the general trend is that the original TRAC-M/AAA code predictions overestimate the bubble drag coefficient and the average void, particularly for void fractions greater than 0.1. Moreover, there is an inconsistency between the trends of deviations of the code predictions from the different experimental data sets and, thus, great care needs to be taken when "adjusting" a correlation based on the analysis of a single data set.

The TRAC-M/AAA code results shows an excellent agreement with predictions of other fast-reactor codes in the two different beam-trip benchmark problems considered, viz. for a Pb-Bi cooled XADS and MYRRHA type models, which differ significantly in the fuel pin linear power level.

The main conclusion of the work is that the TRAC-M/AAA code can, with reasonable accuracy, predict the considered phenomena in fast-spectrum reactor systems cooled by heavy liquid metals.

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