# State-of-the-art review of the T/H system codes RELAP5 for HLM applications

P. LORUSSO1, M. POLIDORI1, A. DEL NEVO1, C. LOMBARDO1, D. MARTELLI1, P. MELONI1, M. TARANTINO1

1ENEA, Department of Fusion and Technology for Nuclear Safety and Security, Italy

Email contact of corresponding author: pierdomenico.lorusso@enea.it

**Abstract**

Thermal-hydraulic code RELAP5, originally developed by INEEL under NRC contract for LWRs LOCA analysis, has been extensively validated and it is actually used worldwide as a best estimate code for LWRs transient analysis. This code was chosen in the early 2000s as the reference code for the thermal-hydraulics and accident analysis of Heavy Liquid Metal Fast Reactors within the frame of Italian research programs. Several original RELAP5 routines have been updated in order to implement suitable correlations generating the reference physical and thermodynamic properties for Lead and Lead-Bismuth Eutectic fluids. Similarly, some specific heat transfer correlations for liquid metals have been added. In almost twenty years, ENEA has conducted an extensive validation program to demonstrate the capability of the code to simulate the thermal-hydraulic behaviour of heavy liquid metal systems. This program was mainly conducted on the facilities of the Brasimone center (CHEOPE, CIRCE, NACIE), but also used data from international programs (MEGAPIE International Experiment and LACANES Benchmark OECD/NEA). Furthermore, the participation of ENEA in the projects financed by the European Commission in several Euratom programs for the study and design of HLM-cooled reactors (ELSY, SEARCH, MAXIMA, LEADER, SESAME. MYRTE) has allowed to increase the confidence on the transient and accidental analyses conducted with RELAP5 also through the comparison with the results of other codes. RELAP5 is currently a reliable tool both as a support to reactor design (safety by design) and for accidental analyses.

## INTRODUCTION

As part of the Generation IV nuclear power plants, Lead cooled Fast Reactors (LFRs) are being developed to meet the highest requirements of safety and reliability, sustainability, economics, proliferation resistance, and physical protection. ENEA, the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development is supporting the core design, safety assessment, and technological development of innovative nuclear systems cooled by heavy liquid metals (HLMs) and, most recently, fully oriented on LFRs. In particular, ENEA plays a key role in the EU R&D program in both the experimental investigation on HLMs related technologies, thanks to one of the largest European fleets of experimental facilities [1] at ENEA Brasimone R.C. and the development and qualification of numerical tools for specific application to HLM systems, ranging from neutronics codes, system and core thermal-hydraulic codes, computational fluid dynamics (CFD) and fuel pin performance codes, including their coupling [2]. Thanks to the competencies developed so far, ENEA have provided a relevant contribution in several EU projects (e.g.., H2020 EC projects MAXSIMA, SESAME, MYRTE, PATRICIA, PASCAL, PIACE, GEMMA, INSPYRE, PUMMA), as well as to the ALFRED Project in the frame of the FALCON international consortium, mainly addressing the ongoing activity in terms of core design, technology development, and auxiliary systems design.

Focusing on numerical modelling approaches and computational tools development, the Validation and Verification [3] (V&V) process is a fundamental step to demonstrate their reliability when applied to HLM technologies, for which it is necessary an extensive and well documented qualification database. To fulfill this scope, ENEA has employed R&D efforts on code modifications, model improvements, and V&V, with particular emphasis on SYStem Thermal-Hydraulic (SYS-TH) codes (i.e., RELAP5), severe accident/multifluid (i.e., SIMMER) [4], fuel pin performance (i.e., TRANSURANUS) [5], fuel element thermal-hydraulics (i.e., ANTEO+) [6], and computational fluid dynamic codes (CFD) [7]. Experimental data are fundamental for supporting the development and demonstrating the reliability of computer codes in simulating the behavior of a nuclear power plant, or its systems and components, during normal operation or a postulated accident scenario. For this purpose, ENEA has undertaken a series of experimental campaigns involving different experimental facilities operating with HLMs, i.e., lead or Lead-Bismuth Eutectic (LBE), in order to create a wide database suitable for supporting the development and qualification of such computational tools.

Numerical simulations with HLMs as working fluid have been performed using RELAP5 SYS-TH code (i.e., RELAP5/Mod3.3 [8] and RELAP5-3D© [9]). In order to do this, RELAP5/Mod3.3 has been modified to simulate the LBE, Pb ([10]-[13]). The modifications were carried out in the framework of a larger activity aimed at setting up a code capable of dealing with HLMs technologies (i.e., implementation of liquid metals properties and related heat transfer correlations). Validation activities have been performed, starting from the LFR design and the analysis of the phenomena relevant for the simulations. Experimental data have been used to evaluate the reliability of the code results and, to some extents, also the accuracies of the predictions, as described in the present paper.

The MEGAWatt Pilot Experiment (MEGAPIE) [14], dedicated to the design, manufacturing and testing of a liquid metal spallation target have provided relevant data from the thermal hydraulic measurements, which offered the opportunity to qualify the codes used in the design phase (i.e., RELAP5 mod3.2.2β version).

In the framework of LACANES OECD/NEA benchmark [15][16][17], RELAP5 has been used to simulate the thermal-hydraulic behaviour of the Pb-Bi loop HELIOS both in forced and in natural conditions. In the first phase of the benchmark two different forced circulation steady states have been considered in order to assess the distributed and local pressure drops calculated by RELAP5. Lately, an upgraded model has been developed to characterize the natural circulation in the loop.

In the framework of the H2020 EC project SESAME, experimental data have been produced involving the NACIE-UP LBE- cooled loop-type facility [18] and used to qualify RELAP5 in simulating core related thermal-hydraulic phenomena (e.g., heat transfer, wall to fluid friction, transition from forced to natural circulation, and single-phase natural circulation) occurring in normal operation and accidental conditions, i.e., Protected Loss of Flow Accident (PLOFA) [19]. Furthermore, integral tests to study thermal-hydraulics and safety-related features of HLM-cooled fast reactors have been performed on the CIRCE (CIRColazione Eutettico, Eutectic Circulation) LBE-cooled pool-type facility [1]. The experimental outcomes have been used to assess overall performances of the RELAP5 SYS-TH code at a system level [20] and component level [21] (i.e., the steam generator).

## RELAP5 QUALIFICATION IN MEGAPIE

MEGAPIE Target Experiment has provided data on the T/H behavior of the cooling system to support the qualification of RELAP5 mod3.2.2β version for transient and safety analysis of LBE and Lead cooling systems. The code, which was used by PSI in the design phase to simulate the behavior of the target cooling system at different operational and off-normal conditions, has been firstly assessed on the single-pin tests (Brasimone) and MEGAPIE Integral Tests (MIT) [22]. In order to correctly predict the thermal exchange in the oil side of THX (LBE-oil Target Heat Exchanger), where exchange conditions are improved by means a spiral welded on the pipe wall, the Gnielinski correlation [2] has been implemented in RELAP5. These correlations extensively tested for curved ducts has allowed to reproduce the steady state conditions of the MEGAPIE cooling system with good agreement (see comparison reported in Table 1).

In order to verify the RELAP5 code in transient conditions, among nearly 4500 beam trips of the SINQ source recorded during the 127 days of the MEGAPIE target irradiation, a beam interruption event lasted a sufficient time to influence the thermal-hydraulic behaviour of the cooling loop in a significant way has been recalculated. Calculated temperature trends (see Figure 1) show the good capability of the model to predict the thermal hydraulic response of the circuit in term of the time scale. In particular, the three-way valve control, simulated in the code by means of a proportional-integral component reacts to the LBE temperature decrease with a realistic delay. An underestimation of the heat capacity of the target loop that brings to a faster cooling of the LBE in the THX component can explain slight discrepancies in the decrease of LBE and Oil temperatures.

Table 1 – MEGAPIE Cooling System Reference Steady State

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Target Power 540.3 kW | | Exp. | RELAP5 standard | RELAP Gnielinsky |
| THX LBE | Mflow (kg/s)\* | 41.23 | imposed | imposed |
| T1(inlet) °C | 319.6 | 316.2 | 316.2 |
| T2(outlet) °C | 229.5 | imposed | imposed |
| THX Oil | Mflow (kg/s) | 9.25 | imposed | imposed |
| T3(inlet) °C\* | 185.8 | 175.4 | 185.3 |
| T4(outlet) °C | 212.9 | 203.5 | 212.6 |
| IHX Oil | Mflow (kg/s) | N.A. | 2.93 | 2.72 |
| T5(inlet) °C | 214.4 | 204.1 | 212.9 |
| T6(outlet) °C | 112.0 | 109.4 | 110.7 |
| IHX Water | Mflow (kg/s) | 8.04 | imposed | imposed |
| T7(inlet) °C | 33.8 | imposed | imposed |
| T8(outlet) °C | 49.3 | 50.3 | 50.1 |

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| --- | --- |
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Figure – THX LBE (left) and Oil (right) Temperatures

## RELAP5 QUALIFICATION IN LACANES BENCHMARK

To provide experimental data to LACANES benchmarking, thermal-hydraulic tests were conducted by using a twelve meters high LBE integral test facility, named as HELIOS (Heavy Eutectic liquid metal Loop for Integral test of Operability and Safety of PEACER), a thermo-hydraulic scaled facility of the LBE-cooled transmutation reactor PEACER-300, constructed in Seoul National University of Republic of Korea in 2005

The RELAP5 version used for the benchmark is the one previously qualified on the basis of the simulations performed within the experimental program carried out at ENEA Research Centre of Brasimone (Italy) on support of XADS design and MEGAPIE. As already mentioned above, the original version of the code was modified generating the physical and thermodynamics properties for Pb, Pb-Bi (soft sphere model) and for diathermic Oil and updating several original routines in order to implement new correlations for heavy liquid metal. Moreover specific heat transfer correlations were added: convective heat transfer for heavy liquid metals, evaluated according to Seban-Shimazky (pipe) or Subbotin-Ushakov (tube bundle), and for oil helical path (Gnielinsky).

The nodalization of the HELIOS loop has been developed with the simulation detail adopted in the reactor applications, in addition, the models for the singular pressure drops computation have been drawn from an hydraulic Handbook, usually used as a reference [23]. It represents a complete one-dimension description of the flow path, including also the pump by-pass line utilized in natural circulation mode of the HELIOS loop.

Geometrical features of the facility and information about the conditions of the experiments are reported in [15]. The calculation results have shown a quite agreement with the experimental data, confirming a general capability to predict the pressure drop behaviour in a liquid metal loop (see Figure 2). The main drawback, because of its mono-dimensionality nature, has resulted in the difficulty to simulate complex component, like core, valve and orifice, that are strongly dependent from tri-dimensional flow path. In these cases it has been necessary to realize a tuning of calculated pressure drop coefficient in the way to match the measured experimental values. A further refine of calculation has been obtained with a calibration, on experimental data of the concentrate pressure drop coefficients adopted for the more complex component geometries. A preliminary calculation in natural circulation has predicted pressure drops in the main components in quite good agreement with the pressure drop behaviour evaluated from measured experimental data (see Figure 3).



Figure 2 – Pressure drop in a tuned-calculation Vs experimental data for a mass flow rate of 13.57 kg/s



Figure 3 – Core pressure drop Vs mass flow

## RELAP5 QUALIFICATION IN NACIE-UP LOOP-TYPE FACILTY

Within the framework of HORIZON 2020 Safety Assessment of Metal cooled reactor (SESAME) project, a test campaign was performed with the NACIE-UP (NAtural Circulation Experiment- UPgraded) facility, hosted at the ENEA Brasimone Research Centre, in order to achieve experimental feedback on HLM thermal-hydraulics and to support the qualification and validation process of numerical tools for HLM simulation. NACIE-UP [25] is a LBE loop facility to qualify and characterize components, systems and procedures relevant for HLM nuclear technologies. It is a rectangular loop (7.7 m height) consisting of two vertical pipes (O.D. 2.5”, S40), namely the downcomer and the riser, connected with two horizontal pipes (O.D. 2.5”, S40). In the lower part of the riser a prototypical wire-spaced fuel pin bundle simulator (FPS) consisting of 19 wire-spaced electrical pins, arranged in a triangular lattice is installed, whereas a heat exchanger (HX) is placed in the upper part of the downcomer. The difference in height, H, between the centre of the FPS and the centre of the HX is about 5.5 m ensuring the driving force to sustain natural circulation inside the loop. An argon gas injection device is placed inside the riser to promote the circulation inside the loop. An expansion vessel is installed, coaxially with the riser (on the top part), enabling the thermal expansion of the LBE during operational transient and allowing the separation of the argon from the LBE. The experimental campaign consisted in three transients (operative and accidental) relevant for HLM nuclear systems:

1. Gas flow transition (Test-1). It consists in a reduction of the injected argon flow from 20 to 10 Nl/min, maintaining the FPS power at 50 kW. The HX water inlet temperature is set to 170°C and the pressure at 16 bar. The water mass flow rate was maintained constant at 10 m3/h during the whole test.
2. Power transition (Test-2). It consists in a FPS power reduction from 100 to 50 kW (decreasing rate 1 kW/s) maintaining the injected argon flow to 18 Nl/min. The HX water inlet temperature is set to 170°C and the pressure at 16 bar, while the water mass flow rate was maintained constant at 6.6 m3/h.
3. Protected Loss of Flow Accident, PLOFA (Test-3). This kind of transition reproduces a protected loss of flow caused by the removal of the gas lift enhancing the loop circulation and the establishment of natural circulation. In particular, it consists in a decrease of the FPS power from 100 to 10 kW (decreasing rate of 10 kW/s) and the complete deactivation of the injected argon flow from 20 to 0 Nl/min. In this case, the water inlet conditions are identical to those of Test-1.

With the aim to support the qualification process of RELAP5 for HLM reactors, a numerical model of the loop-type facility NACIE-UP has been developed by means of RELAP5-3D© ver4.3.4 [26][27] and used in a post-test analysis for the simulation of three experimental tests described above, comparing the numerical results obtained with the experimental data available from the experimental campaign [29]. RELAP5-3D hydrodynamic model matches in a reliable way the experimental behaviour, with a good agreement between the LBE mass flow rate computed by the code and the one measured by the thermal flow meter. The transient trends for the three tests are well defined and the main phenomena have been well reproduced, even if in sudden transients (see .Figure 4)

The temperature trends of LBE obtained by the code are very similar to the experimental ones, both for steady state and transient conditions. A discrepancy between the computed and experimental temperatures ranges has been noticed, for both FPS and HX, with the numerical values which underestimate the experimental data. The sensitivity analysis carried out on the stainless steel powder thermal conductivity led to a good reproduction of the experimental temperature trends, reducing in relevant way the discrepancy between the computed and experimental temperatures ranges. [19].

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| --- | --- |
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Figure 4 – Test 3 (PLOFA) LBE mass flow rate (left) and FPS temperatures (right), experimental Vs. RELAP5-3D©

## RELAP5 QUALIFICATION IN CIRCE-HERO POOL-TYPE FACILITY

The LBE pool CIRCE (CIRcolazione Eutettico) is an integral effect facility set at ENEA CR Brasimone. Its main features, along with the implemented HERO test section geometry and instrumentation installed were detailed in [28]. The facility consists of a cylindrical main vessel (1.2m in diameter and 8.5m in height), with 9.0m3 of LBE, hosting ad-hoc test sections. A Fuel Pin Simulator (FPS) with 37 electrically heated rods in a hexagonal array with a total power up to 1 MW is placed at the lowest position, while the heat exchanger is placed at the top (see [28]). The LBE circulation due to buoyancy (given the height difference between heat source and sink) can be further enhanced by gas (argon) injection in the riser section.

In the framework of the HORIZON2020 SESAME European project, the HERO test section [30] has been designed, including a Steam Generator Bayonet Tube (SGBT) as main cooler, representing the ALFRED steam generator (mock up 1:1 in length). The component consists of a tube bundle of seven double-wall bayonet tubes arranged with a triangular pitch in a hexagonal shell. When the facility is in operation, the LBE contained inside the pool is heated in the FPS and it reaches the separator on the top of the test section passing through the riser. Then, LBE flows down crossing the shell side of the tube bundle for six meters, leaving the component from the bottom. The SGBT is fed with demineralized water up to 180 bar and 335°C, reproducing the conditions of the ALFRED SG.

In this configuration, a high-pressure experimental campaign has been performed. The test matrix [28] is composed of three experimental transient tests aiming at reproducing Protected Loss Of Flow Accident scenarios (PLOFAs). The tests allow to evaluate the thermal-hydraulic performance of a HLM pool-type facility when an accidental scenario occurs, and to achieve experimental data relevant for the ALFRED SG and codes validation. In the first test, power decreased following the decay heat curve, gas lift was disabled in 10 s and feedwater to 30% mass flow rate (simulating DHR system) in 2 s. The second test differs from the first one only for the feedwater reduction to 0% in about 2 s (without DHR). The third test simulated the power decay curve, DHR (feedwater to 30% in 2 s) and reactor pump flywheel by a gas lift reduction based on a defined table.

The nodalization of the CIRCE-HERO facility [20] has been set-up by up-grading the former CIRCE-ICE nodalization [31], thus keeping the same basic modelling approach, using RELAP5/Mod3.3, modified to simulate the LBE ([10]-[13]), i.e., with the implementation of liquid metals properties and related heat transfer correlations). The model can be divided into three main parts: the pool zone, the main circulation zone (including the FPS, the riser and the LBE side of HERO test section), and the water side of the HERO test section. The elevations of the different parts of the facility are maintained in the nodalization. A sliced approach is applied at all zones, LBE and water systems. The node to node ratio is kept uniform with a maximum ratio of 1.2 between adjacent sub-volumes. The heat transfer correlations applied in the LBE zone are Ushakov in the bundle and Seban-Shimazaki, elsewhere. Further details of the components modelling are reported in [20].

The imposed boundary conditions have been implemented in the model and the steady state results achieved are compared with experimental data in Table 2. In particular, the transient test #3 (named SE-TEST3) [28] has been assumed as reference test for a numerical exercise.

Table 2 – RELAP5/Mod3.3: steady state results

| QUANTITY | UNIT | Exp | Calc |
| --- | --- | --- | --- |
| Core thermal power | kW | 356 | 356.0 *(0.0%)* |
| HERO power exchanged | kW | -- | 351.6 *(--)* |
| Pool vessel heat losses | kW | -- | 37.3 *(--)* |
| Feeding conduit and riser – pool heat exchange | kW | -- | 18.7 *(--)* |
| Pool cover gas | MPa(g) | 0.014 | 0.02 *(42.9%)* |
| Secondary system steam line pressure | MPa(g) | 17.1 | 17.2 *(0.6%)* |
| LBE FPS inlet | °C | 419.6/419.4/431.7 | 419.6 *(0.1°C)* |
| LBE FPS outlet | °C | 495.5/497.8/495.2 | 493.2 *(-3.0°C)* |
| LBE HERO inlet | °C | 470.3/485.3/485.3 | 489.4 *(4.1°C)* |
| LBE HERO outlet | °C | 395.7/413.4/400.9 | 417.4 *(14.0°C)* |
| Secondary side DWBT SG inlet (manifold zone) | °C | 336.7 | 336.0 *(-0.7°C)* |
| Secondary side DWBT SG outlet (steam line zone) | °C | 356.7/357.8/354.7 | 365.3 *(8.9°C)* |
| Ar injection | nl/s | 2.75 | 2.72 *(-1.1%)* |
| Primary system (venturi) | kg/s | 33.3 | 33.6 *(0.9%)* |
| FW total | kg/s | -- | 0.308 *(--)* |

At time of the Start of Transient (SoT), the LBE coolant temperature at the FPS inlet is equal to the experimental measurements. The LBE temperature at the FPS outlet is 3°C lower than the experimental measures, which is considered acceptable, considering that it corresponds to a difference of about 3.9%. This implies that the difference can be justifiable if the uncertainty of the LBE fluid proprieties [32] and the accuracy in measuring the LBE mass flow rate are considered. Larger difference is observed considering the temperature at HERO test section inlet (i.e. +4.1°C in the calculation results). Indeed, the temperature of the coolant exiting form the FPS and flowing along the fitting volume and the riser drops of about 11°C during the experiment, while it decreases of only 4°C in the RELAP5/Mod3 simulation due to the effect of the energy removed by the air cooling system operated in the dead volume, as well as the effect of the heat exchange between the fitting volume and the riser and the pool zone. Comparing the LBE temperatures at HERO outlet the difference between the experimental datum and the calculation result is more relevant (i.e. about -14°C). However, the experimental value considered for the comparison is the average value between the 3 thermocouples having a relevant scattering between the maximum and the minimum values. The overall calculated values are considered acceptable to proceed with the transient simulation.

Transient is obtained by implementing in the model the sequence of events performed during the experiment. The results are qualitatively reported in the figures below. The mass flow rate of the code simulation predicts reasonably the experimental time trends, and the differences are easily connected with the real layout and behavior of the gas injection line of the facility (i.e. length >15m after the mass flow measurement, having the last part of the gas pipe descending inside the pool) reproduced in a simplified way in the code nodalization. In long term, the natural circulation is stabilized.



Figure 5 – LBE coolant mass flow rate – experimental data vs. calculated time trends

The FPS inlet and HERO inlet/outlet LBE coolant temperatures are equivalent to the experimental data time trends. On the opposite, the coolant temperature downstream the heated part (Figure 6) drops smoother than in the simulation. This effect can be explained with a more effective thermal coupling between the coolant flowing in the rising channel and the pool temperature, excluding the possibility that the nodalization under-estimates the thermal inertia of this zone. Looking the coolant temperatures in the HERO test section, these are apparently well predicted by the code simulation, considering that differences observed at SoT. and highlighted above are reduced during this phase. Nevertheless, a slower temperatures increase is observed at the beginning of the transient. On the opposite, the temperature increase of the water steam in HERO secondary side is over-predicted by the code (see Figure 7). Finally, the temperature profile in the pool is reasonably predicted by the code simulation (see Figure 8), notwithstanding the transition between the low and high temperature transition zones is placed about 30cm above.



Figure 6 – LBE coolant temperatures @ FPS inlet and outlet, @ HERO inlet and outlet – experimental data vs. calculated time trends



Figure 7 – Steam coolant temperature at BT outlet – experimental data vs. calculated time trends



Figure 8 – LBE coolant temperatures @ pool Line A – experimental data vs. calculated time trends

## CONCLUSIONS

The goal of the paper is to present the state of the art of the RELAP5 system code throughout the description of the results obtained in some of the main projects financed by the European Commission in several Euratom programs for the study and design of HLM-cooled reactors. The code underwent to modifications involving the implementation of suitable correlations generating the reference physical and thermodynamic properties for Lead and LBE fluids. Similarly, some specific heat transfer correlations for liquid metals have been added. To assess and to qualify the capabilities of the code in simulating the thermal-hydraulic behaviour of Gen-IV related HLM-cooled systems, several experimental data coming from different HLM-cooled facilities have been used. The comparison between the experimental data and numerical simulations showed a good capability of the code in simulating the main phenomena occurring in both loop-type facilities (e.g., NACIE-UP) and pool-type facilities (e.g., CIRCE), reproducing with good accuracy the time trends of the main operating parameters (e.g., mass flow rate, temperature, pressure) during the steady state conditions (forced and natural circulation regimes) and during postulated accidental transients (i.e., PLOFA).

Currently, further experimental campaigns are foreseen at ENEA Brasimone Research Centre, where a new test section for the CIRCE facility is under commissioning [33]. The new experimental device will be used to produce relevant experimental data suitable to support the code verification and validation process in simulating pool thermal-hydraulics phenomena, thermal mixing, multidimensional coolant temperatures, flow distributions and heat transfer in prototypical components for HLM pool-type reactors.

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