EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF INTERACTION BETWEEN HEAVY LIQUID METAL AND WATER FOR SUPPORTING THE SAFETY OF LFR GEN. IV REATOR DESIGN

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ABSTRACT

Generation IV Heavy Liquid Metal (HLM) fast reactors have steam generators inside the reactor vessel. Therefore, the interaction between the secondary side coolant (water) and the HLM (e.g. steam generator tube rupture) has to be considered as challenging safety issue in the design and also in the preliminary safety analysis of these reactor types. In this framework, the separate effect facility LIFUS5/Mod2, installed at ENEA Research Center, has a new test section with a geometry representative of the SG tube bundle of ELSY design steam generator. Experiments were executed to study the interaction between LBE and water, with boundary and initial conditions relevant of the SGTR accident, the potential for tube-to-tube rupture propagation, as well as to demonstrate the reliability of computer codes in simulating the phenomena of interest. The paper presents LIFUS5/Mod2 facility and its capabilities, results from the tests' series B1 and preliminary post-test calculations by SIMMER-III code. The experiments provide pressure, temperature and strain trends versus time at a frequency up to 10 kHz, suitable for the analysis of interaction phenomena and the code validation. The experimental pressure trends highlights a remarkable damping of wave propagation generated because the presence of the tube bundle (that was not damaged). Codes are applied for supporting the experimental campaign, the design of experiments and for the experimental data analysis. RELAP5/MOD3.3 supported the analyses of the facility water injection line. The post-tests are mainly based on the comparisons of the experimental and calculated pressure trends. SIMMER-III provided an excellent simulation of the first pressure peak resulting from the rupture of the injector.

KEYWORDS
Generation IV, HLM-water interaction, LIFUS5/Mod2 facility, SIMMER-III

1. INTRODUCTION

The new generation Heavy Liquid Metal Fast Reactors (HLMFRs) and Accelerator Driven Systems (ADSs) are currently designed as pool type reactor, implementing the Steam Generators (SGs) or Primary Heat exchangers (PHXs) into the primary pool, where also the core, primary pumps and main components are set. This design feature allows increasing the reactor performance and simplifying the whole layout, by complete removal of intermediate circuit. In such configuration the secondary coolant (water), flowing in the heat exchanger tube bundle, at high pressure and subcooled conditions, could come into contact with the primary heavy liquid metal coolant, at higher temperature and lower pressure, in a hypothetical

Steam Generator Tube Rupture (SGTR) accident. During the SGTR event high pressure water enters in the low pressure liquid metal pool in which it rapidly evaporates. The consequent sudden increase of the water specific volume entails pressure waves propagation and cover gas pressurization, that could affect the structural integrity of the surrounding components. Moreover, the rupture of a single SG tube could affect, in principle, the integrity of the neighboring tubes (domino effect), making worse the consequences of the accident scenario. The SG-shell constitutes a shield to the pressure wave propagation into the LBE melt, its dumping effect needs to be studied and calibrated in concert with the implemented safeguard devices. The main of these devices are rupture disks and fast valves set on the dome of the reactor, flow limiters on the feedwater (Venturi nozzle) and SGTR detectors. The SGTR event, thus, should be considered as a safety issue in the design and preliminary safety analysis.
The LEADER project [1] aims to investigate such an accidental scenario. The FP7 LEADER project starts from the results achieved in the ELSY project with a deep analysis of the hard points of this reactor configuration. The focus of the first part of the project regards the resolutions of the key issues to reach a new consistent reactor configuration. Regarding the SGTR scenario it is required the availability of qualified experiments having two main purpose:

- direct extrapolation to full scale nuclear plant conditions, if the facility geometry, configuration and the experimental initial and boundary conditions are properly scaled and representative of the reactor prototype;
- supporting the development and demonstrating the reliability of specific computer codes in simulating multi-fluid multi-phase problems by means of high-quality measurement data.

Among the various goals pursued by the LEADER project, an experimental campaign is planned to be performed aiming to simulate the SGTR event in a LFR. The analysis and simulation of such a phenomenon is therefore expected, to define a SG configuration as safe as possible. ENEA CR Brasimone is involved in the LEADER project and the experimental activity foreseen to be carried out focuses precisely on the simulation of the SGTR accident in order to collect useful data for the phenomenon investigation and validation of simulation codes.
This paper provides a general overview of the LIFUS5/Mod2 facility[2],[3] installed at ENEA CR Brasimone and a description of assembling phases of the new LEADER test section, implemented in the facility. The main goal of the planned experimental campaign consists of simulating the tube bundle of ELSY steam generator, to study the interaction between Pb-Bi and water following a SGTR accident.

2. LIFUS5/ MOD2 FACILITY AND LEADER TEST SECTION

2.1 LIFUS5/Mod2 facility description

LIFUS5/Mod2 is designed to be operated with different heavy liquid metals like Lithium-Lead alloy, Lead-Bismuth eutectic alloy and pure lead. Currently, the facility is employed in LEADER project, to investigate the LBE/water interaction following the simulation of a SGTR event. The main objective is to investigate and to assess the damping of pressure waves by SGTR event, besides the generation of experimental data for the development and validation of codes to support the design and the safety analysis of innovative HLM reactors.
The main parts characterizing LIFUS5/Mod2 facility are shown in Figure 1. Four main components can be identified:

- main vessel S1 where LBE/water interaction occurs;
- S2 vessel where demineralized water is contained, it is injected in S1, simulating the SGTR event, by means of a pressurized gas cylinder connected to the top of S2;
- S3 vessel is a security volume connected with S1 to avoid an excessive increase of pressure during the test;
- S4 is the storage thank of LBE.

The cylindrical shell and the top flange of S1 have penetrations allowing the passage of the instrumentation (PTs, TCs and SGGs). The water injection system enters the bottom of the vessel S1 in central position. The injector orifice is covered by a protective cap, which is broken by the pressure of the water jet at the beginning of the injection phase. Therefore, the system shall be substituted at the end of each test. LEADER experiments provide a broken pressure of 180 bar, which is the design pressure for the secondary side of ELSY steam generator.

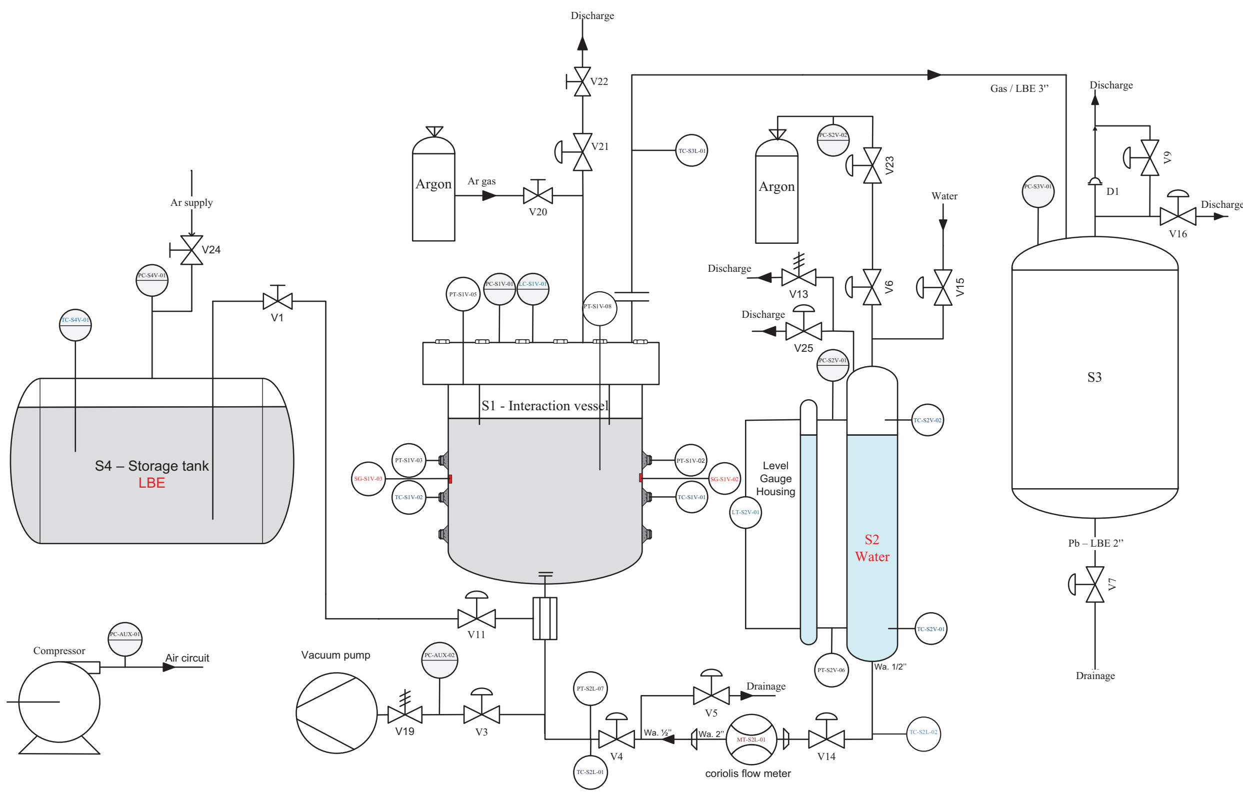

Figure 1. LIFUS5/Mod2 facility.

2.1 LEADER test section

The LEADER test section [4], shown in Figure 2, is placed vertically inside the vessel S1. This orientation is more favorable because the vertical axis is the longest. The test section is connected with the top flange of S1 and can be removed for maintenance, if needed. LEADER test section has a cylindrical shape characterized by an height of 400 mm. The thickness of the two closing flanges is 20 mm each. The radius of the test section is 155 mm, as shown in Figure 2. The test section is inserted inside S1, at 570 mm of distance from the bottom of the S1 top flange. The injection tube penetrates into the test section from its bottom flange for about 100 mm. The levels A and B, shown in the same figure, identify two planes at which instrumentation (TCs and SGs) is implemented. The test section is composed by a bundle of 188 tubes (see Figure 3), having external diameter equal to 18 mm and pitch of 19.8 mm, coherently with the geometrical parameters of the STSG (Single Tube Steam Generator) design of ELSY reactor. These tubes are grouped into ranks. With rank 2 is indicated the group near the center of the test section. The outermost group is the ninth rank.

The tube bundle is composed by three different types of tubes:

- 12 tubes pressurized at 180 bar during the test execution. This is the value at which water in ELSY steam generator works;
- 128 holed dummy tubes that during the test are filled by LBE;

- 48 closed dummy tubes, containing air at atmospheric pressure and ambient temperature.

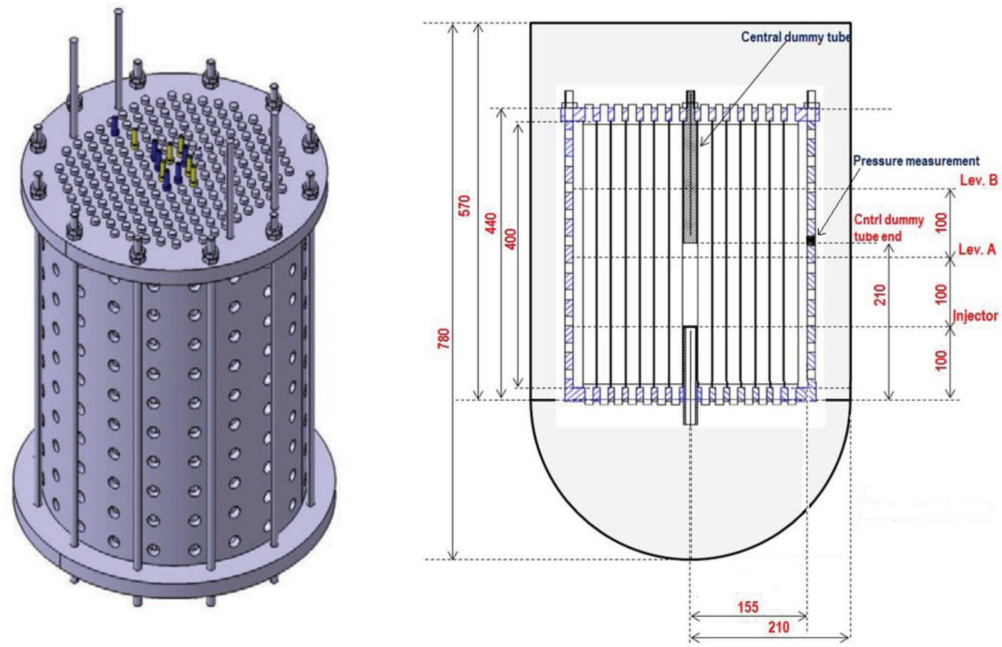

Figure 2. LIFUS5/Mod2 facility.

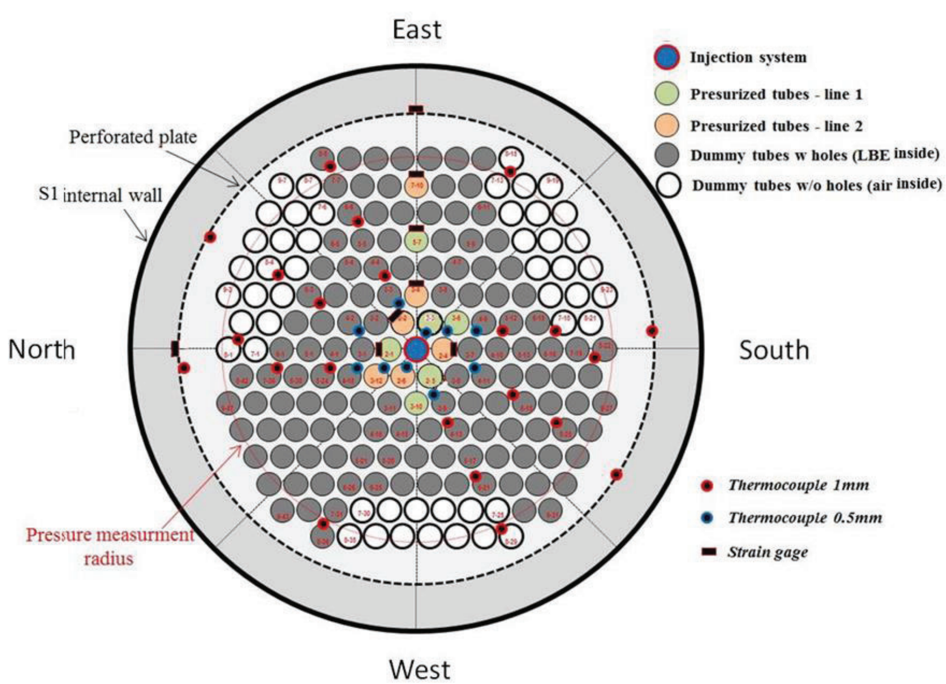

Figure 3. LEADER test section layout.

3. LIFUS5/Mod2 water injection line analysis

The objective of the activity is to investigate the behavior the water injection line during injection [5]. The analysis is performed with RELAP5/Mod3.3 code[6], through a set of sensitivity analyses aimed at characterizing the form loss coefficients of valves and of the Coriolis flow meter. SIMMER-III[7] is then applied on the post-test analysis of LIFUS5 experiments. The tests selected are the tests A1.2_1 [8] and A1.2_2 [9] executed in the framework of THINS project [3]. LIFUS5 water injection line is modelled with RELAP5 through the following components:

- 129 sub-volumes representing the hydraulic volumes of the pipeline;
- 10 single junctions that join the components;
- 3 motor valves, two representing the valve V14 and V4 installed in the plant and one simulating the injection cap;
- 2 time dependent volumes aimed at imposing the boundary conditions of the test, i.e. pressure versus time in S1 and in the gas line connected at top of S2

Hereafter the following activities are described:

- Description of the RELAP5 code nodalization modeling the water injection line;
- Characterization of the injection line by RELAP5 code, through a set of calculations based on the test A1.2_1;
- Assessment of the nodalization using the data of the test A1.2_2;
- Simulation of the test A1.2_2 by SIMMER-III, to qualify the modeling of the water system and injection line, which will be used for the post-test analysis of LEADER experiments.

A sketch of the nodalization developed is shown in Figure 4. The duration of the transient is equal to 110 s and it is divided into three parts:

I. at 100 s, the stationary ends and the opening of the injection valve V14 happens;
II. from 100s to 102s, pressure increases in injection line, rupture of the cap occurs and the injection starts. The closing of the valve V4 itself, that stops the injection, is also included in this phase;
III. The final part ends at 110 s and it delivers a phase of equalization after the interaction.

Boundary conditions are set by imposing pressure trends in the Argon line connected with S2 (TMDPVOL-100 in Figure 4), and in S1 (TMDPVOL-240). These are based on the experimental data of THINS tests A1.2_1 and A1.2_2. A set of code calculations is defined to correlate the effect of selected parameters, i.e. form loss coefficients of valves and the Coriolis flow meter, and opening/closure time of injection valve, on the pressure versus time trend of water injection line. The code results are then compared with the experimental data recorded during the test, see below. A reference code RUN (Table 1) is carried out. Based on the code results, a set of calculations is defined by changing one input parameter. Reference physical quantity for this analysis is the pressure in the injection line.
Best results are achieved for the case “q”, where:

- the opening time of the valves is equal to 0.25 s;
- K of the valve is 10;
- K of Coriolis is 2.5;

- the area of single Coriolis tube is equal to 4.53e-05 m^2.

The pressure trends obtained from the simulation with these parameters in comparison with the experimental data are shown in Figure 5.

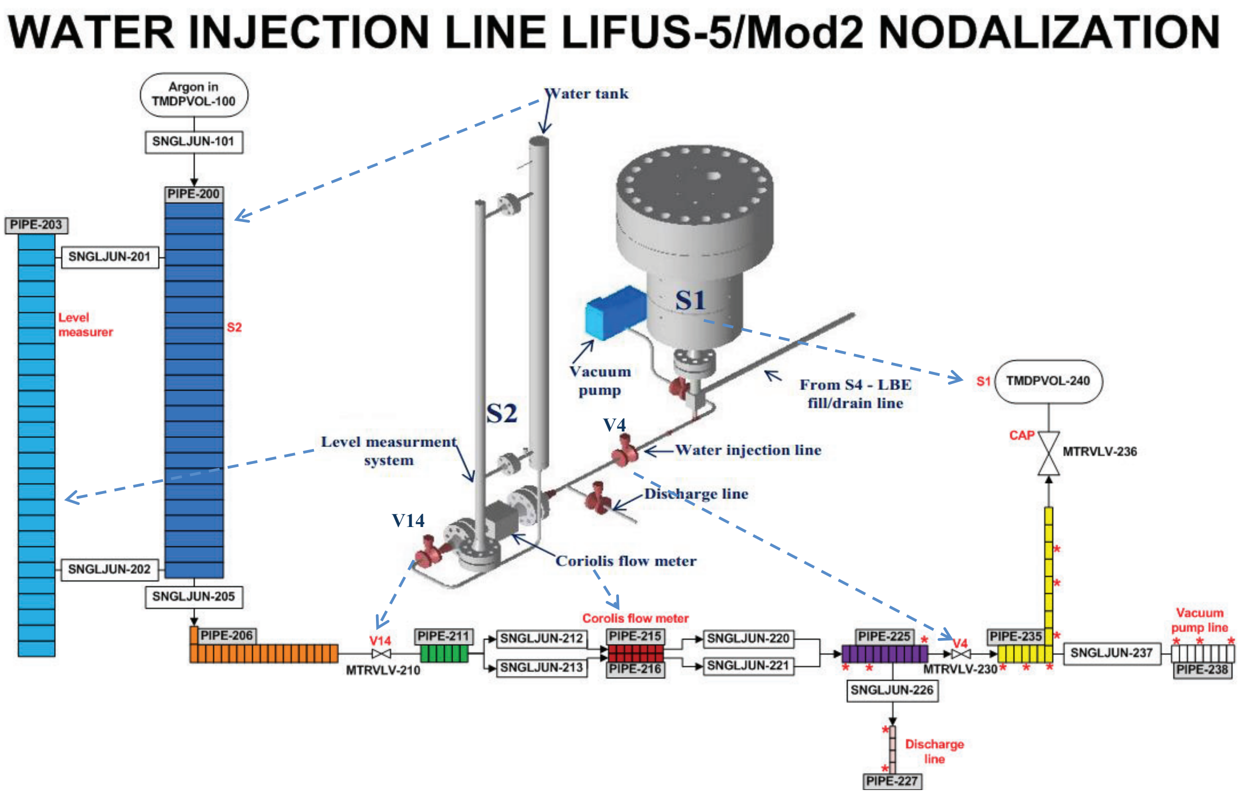

Figure 4. Water injection line nodalization.

Table I. reference code RUN parameters

#	T vlv opening [s]	K [V4],[V14]	K [Coriolis]	A Coriolis [m^2]
a	0.25	7	0.5	9.06613e-05

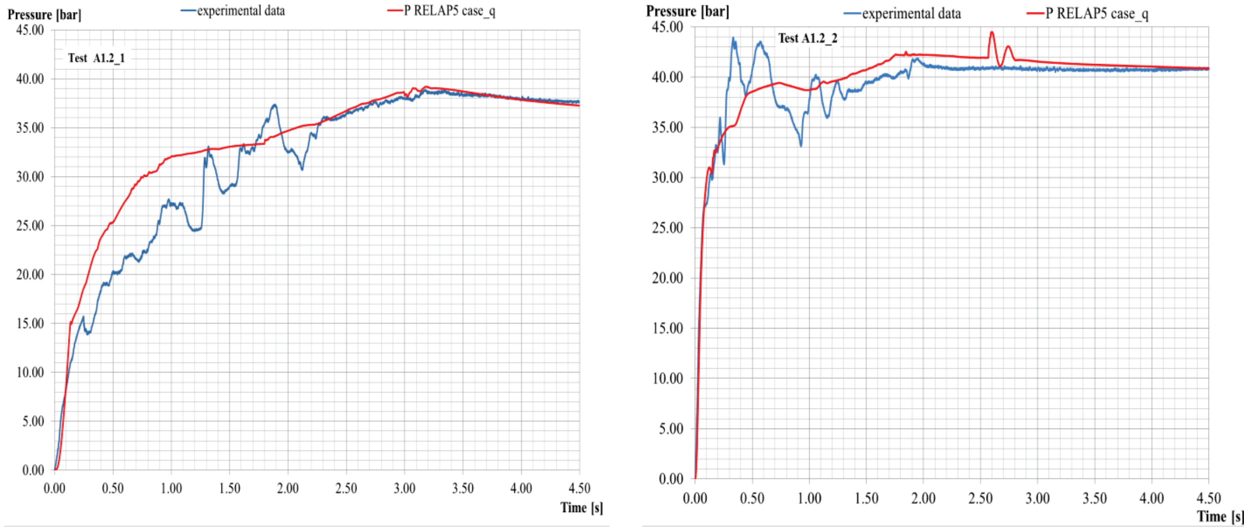

Figure 5. comparison between the experimental pressure trend, and the case "q".

4. LEADER experimental camping

The expected outcomes of LEADER experimental campaign tests are:

- the generation of detailed and reliable experimental data;
- the improvement of the knowledge of physical behavior and of understanding of the phenomenon;
- the investigation of the dynamic effects of energy release on the structures; and
- the enlargement of the database for code validation.

Present section presents the first three experiments planned in LEADER project (B series). The project specifications plans 3 type of tests, having the same facility configuration, the same initial conditions and 3 different orifices diameter sizes: about 4mm, 8mm, and 13mm. Table II summarized the main parameters of the tests. In test B1.1 the injection time is not reported because the injection cap was broken when the injection valve was already closed. Therefore, injection time is not a parameter affecting the transient.

Table II. list of parameters

T# B1.--	Interaction system	LBE temperature [°C]	Water pressure [bar]	Water temperature [°C]	Test section tubes pressure [bar]	injection time [s]	Injector orifice diameter [mm]
1	S1	400	180	260	180	2	4
2	S1	400	180	270	180	2	4
3	S1	400	180	270	180	2	4

4.1 Test B1.1 analisys

The test execution did not follow the plan of the experiment. Indeed, following the commissioning tests, the protective cap should be broken immediatly. On the opposite, rupture occurred with 16 seconds of delay. The following reasons might have an impact on this delay: 1) the gas cylinder tank had a pressure lower than the test sepcifications (174 bar against 180 bar planned), 2) the conditions of the experiments

increase the ductility of the protective cap, which brokes but after some seconds of delay (phenomena observed in tests B1.2 and B1.3). In case of test B1.1 the injection procedure envisaged 2 seconds. Therefore, the injection valve closed before the cap was broken. This implied that the injection device at 400°C because in equalibrium with the melt in S1 heated the water in the injection line. Following the valve closure, the pressure rised because the heating up to the rupture of the cap. This is demosntrated by the experimental data trends and by code simulations (in the following sections).
In detail, test B1.1 can be divided into 3 main phases:

I. Water injection phase;
II. Pressure increase in injection line due to heating;
III. LBE-water interaction phase.

I Water injection phase [0 to 2.2595 s] *from valve V4 opening to valve V4 closing*. Once valve V4 is opened, water fills injection line line between the V4 and V3 and up to the cap. The pressure of S2, drecreases slightly see trends of transducer PC-S2V-01 and PT-S2V-06 (see Figure 6). The injection has a duration of approximately 2.25 seconds, up to the complete closure of the valve. Indeed, the total opening time of the valve lasts approximately 250 ms and the signal of valve opened is set about 125 ms after the stem starts to move, according with the analysis of THINS tests. The rupture of the cap does not occur as quickly as expected. This implies that the total amount of water injected has a volume equivalent to the volume of the injection line downstream valve V4. Therefore, the total mass of water incted is 250 g, which is evaluated considering the volume and the density of water at time of valve closure. The pressure trend in the injection line is recorded by the pressure trasducer PT-S2L-07 at a frequency of 10kHz (see Figure 6). The pressure in the injection line rises rapidly, reaching an initial peak of about 210 bar, full scale of the dynamic transducer and, then, begins to oscillate. The high initial peak and the subsequent oscillations are probably due to phenomena of flashing and condensation insiede the closed injection tube. During phase I the water temperature is below the saturation. At time 0 s, the water temperature measured in the injection line has a value of 222°C, despite S2 water temperature is set to 260°C. This is because the water entering in the line flashes, cooling the thermocouple installed in the line. On the opposite, the heating cable correctly heats the tube structure at 260°C.

II Pressure increase in injection line due to heating phase [2.2595 s to 16.05 s] *from valve V4 closing to cap rupture.* In this phase, the water trapped between the valve V4 and the cap is heated due to the contact with the injector surface at 400°C. The pressure (Figure 6) increases until it reaches the full scale of the instrument. Hence, the final value of the pressure reached at rupture of the cap is not measured. RELAP5 was emplyed to simulate this phase and to calculate the water pressure trend beyond the measurment transducer capability. The difference in time between the temperature measured in the injection line and the pressure, is connected with the position of the thermocouple (TC-S2L-01) in the line and the occurrence of stratified conditions. The thermo-dynamic conditions evaluated of water at time of cap rupture are close to critical point (i.e. P_{crit}=221 bar).

III LBE-water interaction phase [16.05 to EoT] *from cap rupture to end of transient*. When the cap breaks, the pressure in the injection line decreases rapidly up to about 50 bar (Figure 6). At the same time, the pressure in S1 rises rapidly from 3.1 bar, reaching a maximum pressure peak of about 30 bar (PT-S1V-04). Figure 7 reports the trends of dynamic pressure (PT) and absolute pressure (PC) transducers installed in S1 and the absolute pressure transducer of S3. Figure 8 highlights the pressure peak and the extreme velocy of the pressure wave propagation, thanks the high frequency of the acquisition system 1 point each 0.1 ms. The results of the test B1.1 demonstrate that different meaured pressure peaks measured in THINS tests is due to undersampling of the pressure signal. The pressure peaks are conncted with the propagation of waves in LBE, that is the reason why they are not detected by PT-S1V-08 and PT-S1V-05. When pressure in the injection line is about 50 bar, the pressure decrease slowed dowwn for a while, because evaporation of liquid water in the pipeline. Two peaks are observed during the injection in S1. The first peak recorded in S1 is due to the pressure wave that propagates inside the vessel. The second is due to the expansion of water and steam in S1. At end of transient, the pressures measured in S1 and S3 are stabilized at about 3.6 bar. The measured strain is lower moving away from the center of the test section, in radius direction, from about 500 μm/m up to values of about 250 μm/m, measured in the seventh rank (see Figure 9). The strain gauges installed on the second rank in fact show the highest peaks (the maximum is recorded by the SG-204, about 535 μm/m). The two strain gauges installed on the lateral surface of perforated plate, measure a deflection equal to about 41 μm/m. Strain gauges in S1 still shows a residual strain value equal to about 20 μm/m. In the old tests THINS, which had a maximum injection pressure value equal to 40 bar, the peak of strain measured on the internal surface of S1 is equal to 10 μm/m. Whereas the highest injection pressure set for the LEADER tests, such a low strain values measured on the inner surface of S1 is comparable with the values achieved in THINS tests. This indicates a possible dumping of pressure waves by the " tubes tangle " and by perforated plate of the test section. This observation, will be further investigated, and it may be relevant to carry out evaluation of structures outside SG shell during a SGTR event. Another outcome is the structural integrity of pressurized tubes surrounding the injector, as demonstrated by their internal pressure at end of the test (180 bar).

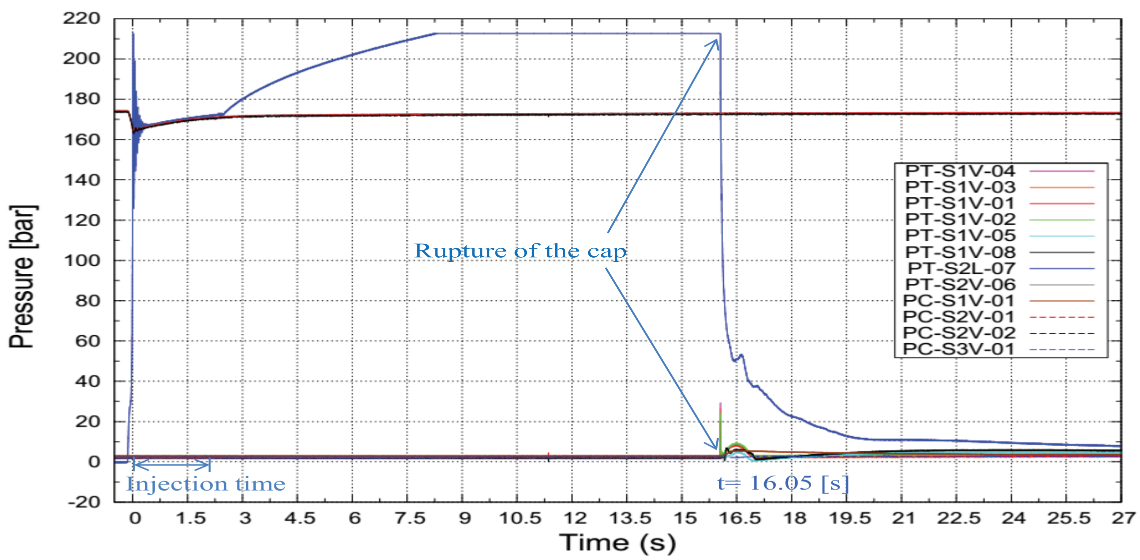

Figure 6. Test B1.1 pressure trends in injection line, S1 and S3.

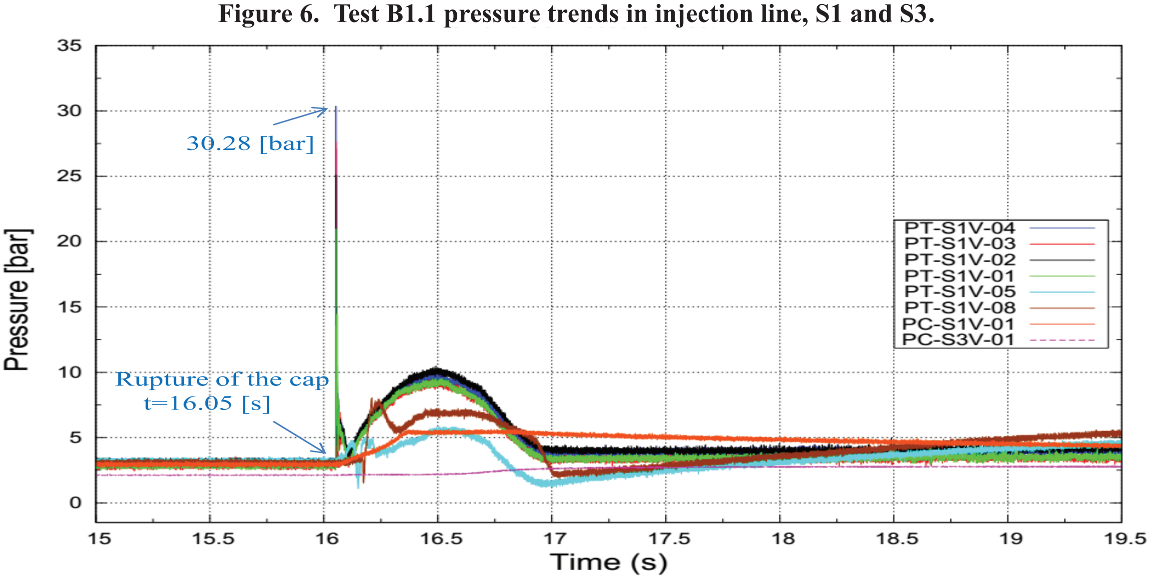

Figure 7. Test B1.1 pressure trends in S1 and S3.

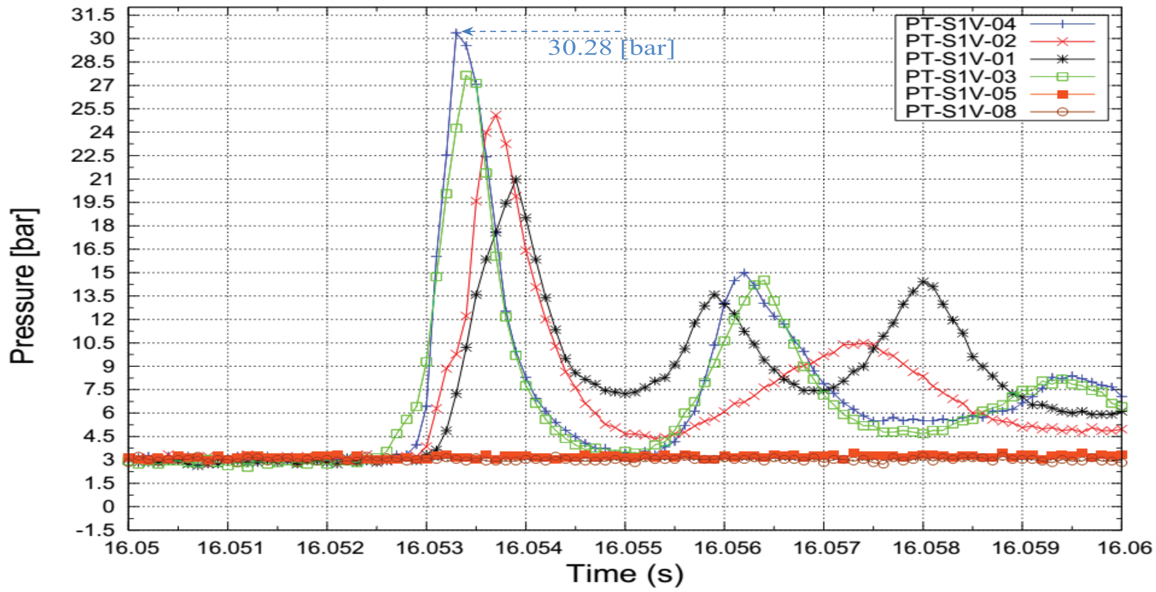

Figure 8. Test B1.1 zoom of pressure peak in S1.

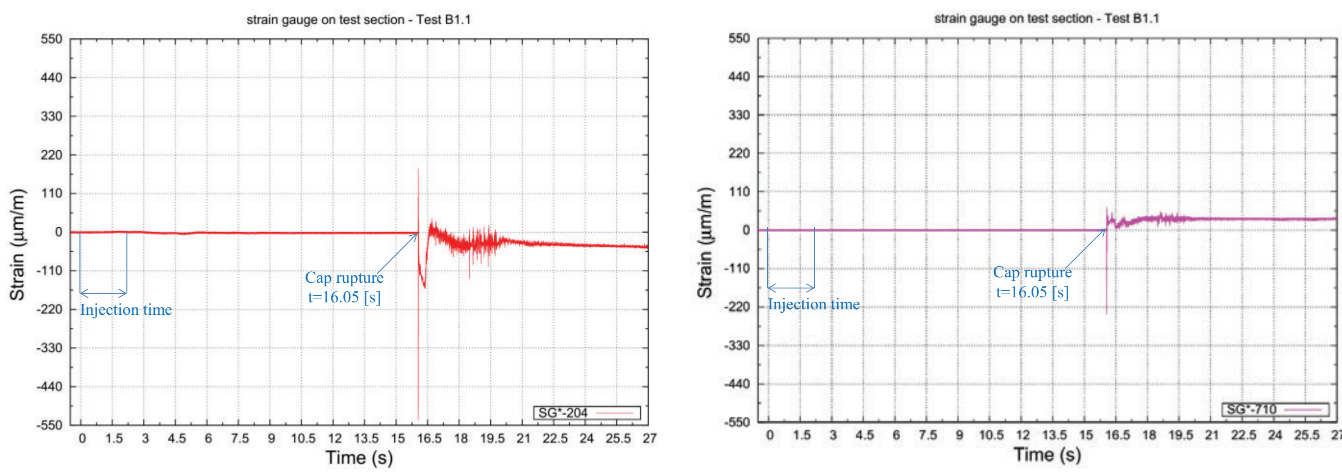

Figure 9. Test B1.1 strain trends.

4.1 Post-test analysis of test B1.1 by means of SIMMER-III simulation

The model developed of the entire LIFUS5/Mod2 facility in the LEADER configuration by means of SIMMER-III code is shown in Figure 10. The model of LFUS5/Mod2 facility with the LEADER test section is developed starting from the model THINS[10] used for the analysis of test A1.2_2. The color black is added to identify the metallic structures of LEADER test section and the thermal structures (can wall) implemented to simulate the heat exchange between the hot tubes surface and the water in the water injection line before the breaking of the cap. To simulate the various ranks of tubes, identified by regular hexagons, a pairs of circumferences form toroidal cells with a thickness equal to the pitch of the lattice. Each toroidal cell includes a volume fraction of steel pin (SIMMER-III code structural component used to simulate the nuclear fuel). In this way, the obstacles (tube) of the test section are simulated. The simulation of test B1.1 is performed thanks to the support of RELAP5/Mod3.3 code. Indeed, the duration of the test would imply an excessive computational time. Therefore, the initial TH conditions are calculated with RELAP5/Mod3.3 and implemented in SIMMER-III model. SIMMER-III simulation starts

with the rupture of injector cap. The holes of the perforated shell are simulated considering ten toroidal cells of LBE, positioned at the same heights of the ten rows of holes and preserving the reference flow area of the test section. The height of the connecting tube is preserved, but the horizontal part is not simulated because it would origin distortions in the dynamic of the transient due to modelling constraints imposed by the limit of the code to work in axisymmetric. The modelling is therefore based on imposing equivalent concentrated pressure drop of all tubing in the vertical section. S3 is implemented preserving the volume, but changing the area and height.
The simulation is focused on the pressure trend in S1. The propagation of the pressure wave and the rapid evaporation, is the parameter that might affect the integrity of surrounding structures and therefore of interest from safety point of view. The achieved result is in Figure 11. The transient starts with an abrupt pressure spike in LBE due to injection. The code simulates the measured pressure peak with an excellent accuracy (see Figure 12). This is an encouraging results considering that the initial and boundary conditions of this test are better defined than in any other LIFUS5 test. Then, the liquid water evaporates causing a second pressure increase and pushing the LBE toward the dumping tank S3. The simulation shows a good agreement with the experimental data up to 0.3 seconds (point A in Figure 11). Indeed, the calculated pressure continues to increase, while the experimental data reach the maximum value of about 10 bar at 0.45 seconds from the beginning of the transient (point B in Figure 11).
be further investigated, and it may be relevant to carry out evaluation of structures outside SG shell during a SGTR event. Another outcome is the structural integrity of pressurized tubes surrounding the injector, as demonstrated by their internal pressure at end of the test (180 bar).

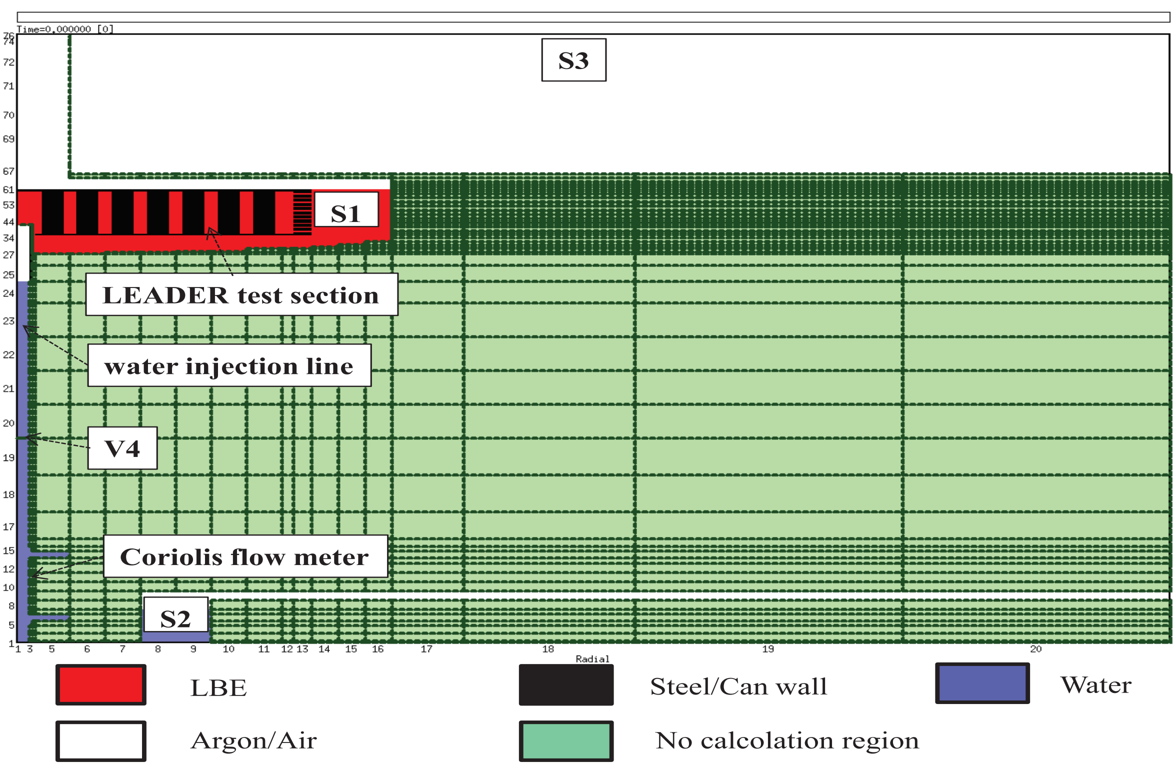

Figure 10. LIFUS5/Mod2 SIMMER-III model.

Another outcome is the structural integrity of pressurized tubes surrounding the injector, as demonstrated by their internal pressure at end of the test (180 bar).

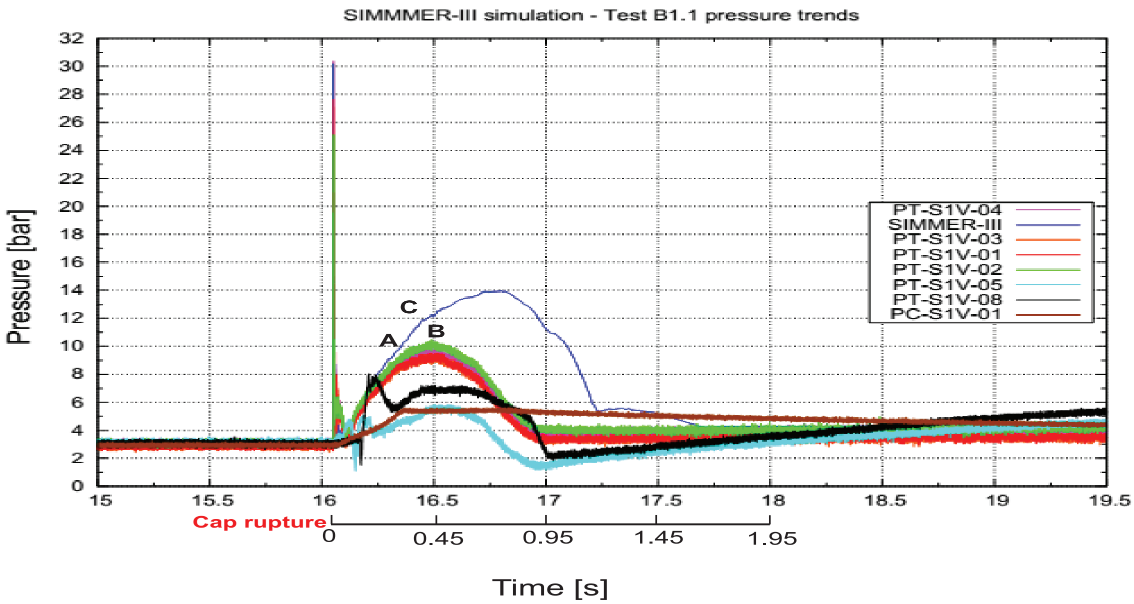

Figure 11. Test B1.1 SIMMER-III/experimental pressure trends comparison.

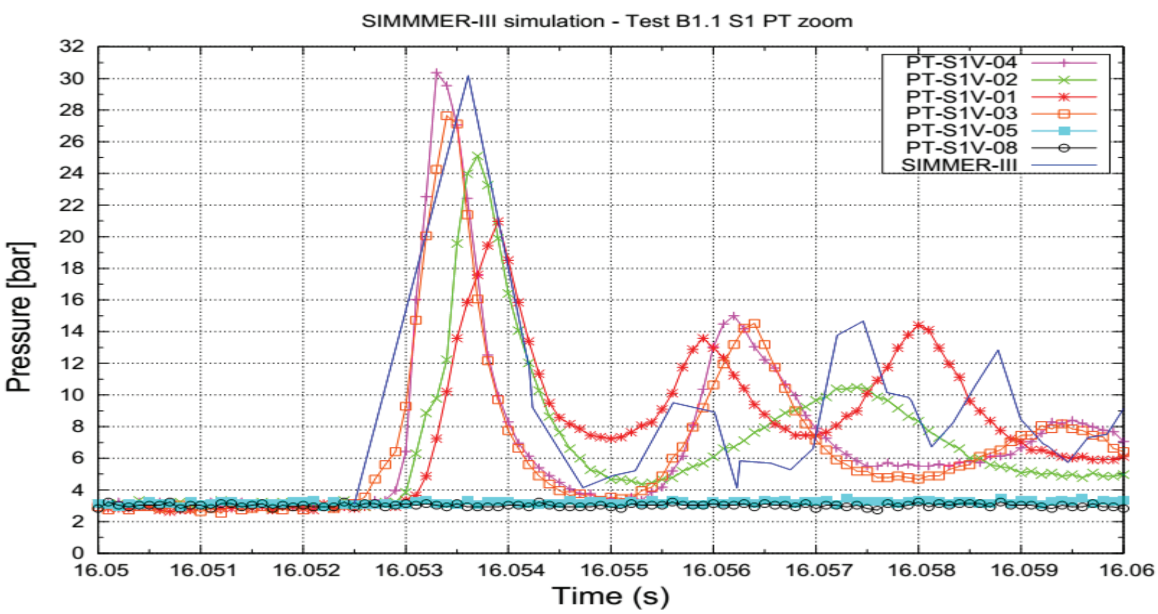

Figure 12. Test B1.1 initial peak SIMMER-III/experimental pressure trends comparison.

5. Conclusions

The paper presents LIFUS5/Mod2 facility and its capabilities, results of test B1.1 and preliminary post-test calculations by SIMMER-III code. The experiments provide pressure, temperature and strain trends versus time at a frequency up to 10 kHz, suitable for the analysis of interaction phenomena and the code validation. The interpretation of strain data for improving the knowledge of the energy, deposited during the tube rupture on surrounded structures, could be used for future structural mechanics code assessment as well for fluid structure interaction analysis. The experiment carried out is related the case 0.1A of ELSY SG tube. B2 and B3 series will address the cases 0.6A and 1.0A.
Main outcomes from the experimental and numerical activity apply.

- LIFUS5/Mod2 facility in LEADER configuration was completed. The documentation of the facility configuration and instrumentation, the execution of the preparatory (i.e. protective cap pressure tests) and commissioning (i.e. tests procedures and acquisition system) tests was also carried out.
- The availability of the experimental data of test B1.1 demonstrated that the pressure peak generated was lower than 30 bar; the pressure wave propagation is largely damped, by the "tubes tangle" present inside the test section and by perforated plate of the test section. This damping is also confirmed by the strain gauges' measurements. Indeed, the strain trends on the tubes of the test section decreases from the center of the test section in the radial direction. Moreover, there is a residual deformation peak in the inner surface of S1 comparable the previous THINS tests. Finally, this experiment highlights that no leakages are observed in the pressurized tubes of the test section. This might implies a low probability of propagation of the tube rupture on surrounding tubes. Confirmation is expected at end of the experimental campaign.
- The initial pressure peak are tracked by the improved acquisition up to a frequency of 10 kHz. This implies a better interpretation of previous LIFUS5 experiments.
- A RELAP5 nodalization was developed to support the characterization of the water injection line, confirming the timing of opening and closure of the injection valve, the pressure drops in the injection line, the behavior during the THINS tests A1.2_1 and A1.2_2. After the execution of the first test B1.1, the RELAP5 model has been modified (i.e. implementation of thermal structures) to support the SIMMER-III simulations of test B1.1 providing the conditions reached by water before being injected;
- A SIMMER-III nodalization of LIFUS5/Mod2 facility in LEADER configuration is developed and set-up. Preliminary qualification of the model is also achieved performing the post-test analysis of test B1.1. The analysis of results demonstrates that the code is able to simulate the first pressure peak measured when the cap is broken. The code predicts the maximum pressure value (30 bar) and the timing of the phenomenon (10^{-3} s). The second pressure peak due to the steam expansion in S1 is also correctly simulated by the code, even though overestimated (4 bars higher). The deviation is probably correlated to a plug that the LBE forms in the vertical section that connects S1 to S3 due to geometrical approximations of the model. The final experimental and simulated values of pressure in S1-S3 system are in agreement. This confirms that the amount of water and steam injected in the simulation is consistent with the experimental one. The final quantity of LBE dragged in S3 is higher in the simulation (100 kg against 25 kg experimental). This may be due to an overestimation in SIMMER-III of the drug coefficient between steam and LBE. Indeed, the code predicts comparable speeds of LBE and steam during the transient. In principle, higher speed of steam is expected.

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