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PbLi/Water Reaction: Experimental Campaign and Modeling Advancements in WPBB EUROfusion Project

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Abstract: The Water-Cooled Lithium–Lead blanket concept is a candidate breeding blanket concept for the EU DEMO reactor and it is going to be tested as one of the Test Blanket Modules (TBM) inside the ITER reactor. A major safety issue for its design is the interaction between PbLi and water caused by a tube rupture in the breeding zone, the so-called in-box LOCA (Loss of Coolant Accident) scenario. This issue has been investigated in the framework of FP8 EUROfusion Project Horizon 2020 and is currently ongoing in FP9 EUROfusion Horizon Europe, defining a strategy for addressing and solving WCLL in-box LOCA. This paper discusses the efforts pursued in recent years to deal with this key safety issue, providing a general view of the approach, a timeline, research and development, and experimental activities. These are conducted to master dominant phenomena and processes relevant to safety aspects during the postulated accident, to enhance the predictive capability and reliability of selected numerical tools, and to validate and qualify models and codes and the procedures for their applications, including coupling and chains of codes.

Keywords: WCLL; in-box LOCA; LIFUS5; SIMMER; RELAP5

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1. Introduction

The Water-Cooled Lithium–Lead (WCLL) blanket concept is one of the main concepts under study regarding the breeding blanket (BB) of the future DEMO plant [1]. Furthermore, in future, the WCLL BB concept will be tested with a Test Blanket Module (TBM) inside the ITER reactor [2], to obtain design behavior data during ITER operation, whose conditions will be similar to those of DEMO reactors. It employs subcooled water to cool down lithium–lead alloy, whose function is to breed tritium inside the BB. Even though the water flows through double-walled tubes to reduce the probability of an in-box LOCA, the probability of such an accident remains relatively high [3]. Therefore, the possibility of the interaction between lithium–lead and water cannot be neglected and it is a main safety concern.

Safety evaluations of the WCLL blanket design candidate for the ITER and DEMO reactors are of primary importance, to ensure that the blanket module and its ancillary systems comply with safety design limits and operating conditions [3–5]. The main parameters affecting safety are:

- The pressure transient, governed by mixing and pressurization, which might exceed design limits;
- The chemical reaction contributing to pressure and temperature increases, which might generate a more serious system condition;
- The H_2 production, which might represent a potential source of energy;
- The release of radioactive products.

This issue has been investigated in the framework of FP8 EUROfusion Project Horizon 2020 [6] and is currently ongoing in FP9 EUROfusion Horizon Europe as part of the Work Package Breeding Blanket (WPBB), defining a strategy for addressing and solving WCLL in-box LOCA. In this context, the main identified R&D activities can be divided into two main branches:

1. The set-up and qualification of a numerical tool for predicting PbLi/water interaction. This requires code model improvements [7,8], the extension of the available (to date) experimental database [9–12], and validation activities [13–16], carried out during FP8 in separate effect test facility LIFUS5/Mod3;
2. The addressing of postulated in-box LOCA events by means of an approach that permits prevention of the occurrence, evaluation of the consequences, and investigation of countermeasures to mitigate the transient. This last point requires extensive numerical simulations and appropriate tools, i.e., the development of a coupling technique to perform transient analyses considering the chemical, thermo-hydraulic, and structural effects due to PbLi/water interaction [17–21] and numerical code to expand the simulation capabilities in fusion applications [22,23], validated against Integral Test Facility experiments [24] currently in progress as part of the FP9 Project.

2. Materials and Methods

In the past, extensive effort was put into investigating the response of WCLL-related systems to in-box LOCA scenarios. Therefore, an approach methodology has been established [8], here presented and illustrated in Figure 1.

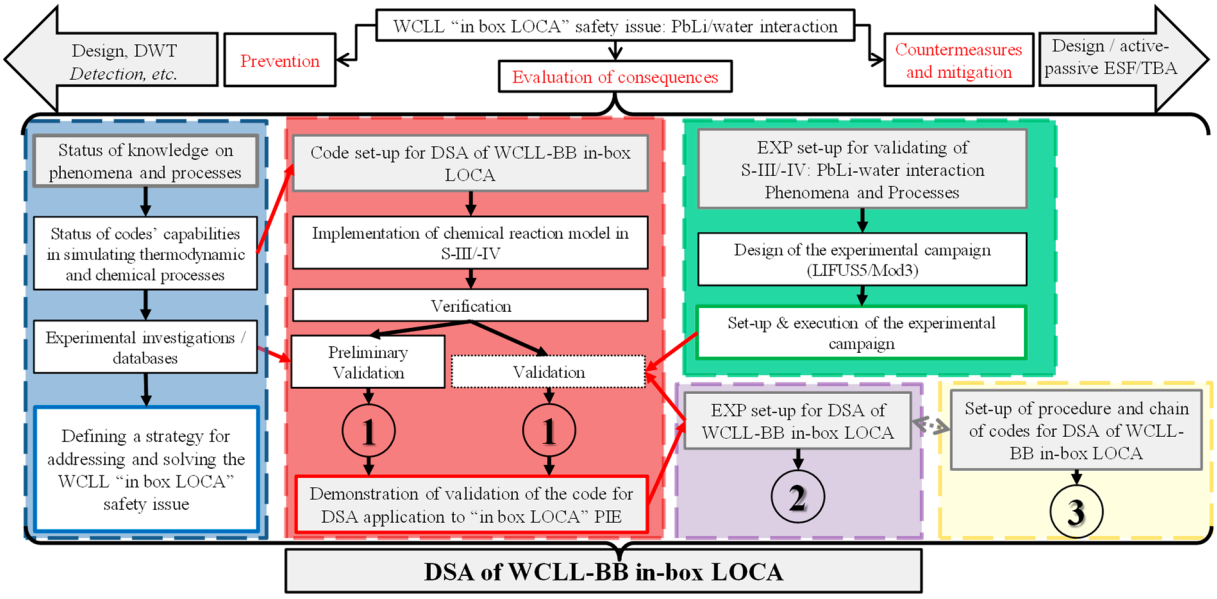

Figure 1. Flowchart of WCLL BB in-box LOCA safety issue approach [8].

The safety issues connected with PbLi/water interaction can be prevented by adequate design of WCLL components (e.g., the adoption of double-walled tubes, detection systems, etc.) and mitigated by active or passive systems. However, it is fundamental to evaluate the possible consequences of a postulated PbLi/water interaction due to an in-box LOCA accident, in order to ensure the mechanical resistance of the component itself or, in the

worst case, to avoid jeopardizing the entire system. R&D activities focused on the strategy in responding to WCLL in-box LOCA scenarios (Figure 1). The blue box highlights the literature survey, interpretation of studies, and status of code applications connected with PbLi/water interaction performed in the past, prior to FP8. Red and green boxes are those activities recently conducted in the framework of the Work Package Breeding Blanket in FP8 EUROfusion Project Horizon 2020. The former highlights the numerical activities, focusing on the implementation and V&V of the chemical models in SIMMER code. The latter focuses on the experimental activities performed in the new separate effect test facility LIFUS5/Mod3, which provided qualified and reliable data for code validation. The achievements attained as part of FP8 are the basis of the new R&D plan which is currently carried on in FP9. These activities (highlighted by violet and yellow boxes) are strictly connected, with the final goal of having a qualified numerical code for the deterministic safety analysis of WCLL in-box LOCA. The first is the execution of experiments in the LIFUS5/Mod4 integral test facility, testing the response of the WCLL TBS in case of an in-box LOCA scenario. The second involves the development of numerical codes able to deal with heavy liquid metals in ITER and DEMO reactors' relevant parameter ranges (considering also the chemical reaction and the MHD effect).

3. Results

In this section, the main results of the activities performed in recent years are presented, following the flowchart mentioned above.

3.1. Status of Knowledge on Phenomena and Processes

At the start of 2014, the first step was to review the open literature in order to have a complete overview and knowledge of the phenomena and processes occurring during PbLi/water interaction and the status of numerical codes' capabilities.

Experiments with lithium–lead alloy breeder material were performed in the US in the 1970s and 1980s, i.e., by Westinghouse Hanford Company [25–27], to characterize potential safety concerns, and the University of Wisconsin [28] focused on the chemical kinetics. More recently, separate effect experiments were carried out in Europe at JRC Ispra [29,30] and ENEA RC Brasimone [31–33]. The main validation activities of numerical models and computer codes that described these phenomena instead were carried out and applied at CEA [34,35] and UNIPI/ENEA [36,37].

As stated by Piet et al. [38], the process of PbLi/water interaction "falls into the generic category of Fuel-Coolant Interaction (FCI) . . . The FCI may involve also chemical reactions between the fuel and the coolant, which if exothermic, can dominate the consequences of the event". From the literature review and the activities performed prior to FP8, the following conclusions can be applied:

- Small-scale experiments highlighted that the interaction can be divided into two processes: (1) a short-time process caused by thermal interaction and (2) a long-time process due to chemical reaction. Two key parameters influence the severity of the interaction: the fragmentation and the chemical reaction;
- The favorable chemical reaction is the one forming LiOH. In fact, if H_2O excesses, a secondary reaction between Li_2O and H_2O occurs and, therefore, the stable product is LiOH. At the same time, if the temperature of the reaction zone is higher than 450 °C, the stable product is Li_2O;
- BLAST and LIFUS5 provided larger-scale data showing the same phenomenological subdivisions of the transient and the relevance of system compressibility (i.e., system layout);
- BLAST and LIFUS5 experimental tests permit the investigation of the phenomenology connected to PbLi/water interaction but they are not suitable to perform code validation because of the poorly defined BIC, missing documentation, and lack of experimental data on injected water and hydrogen produced by the reaction;

- The standard version of the SIMMER-III code, available and previously applied to BLAST and LIFUS5 post-tests, reasonably predicted the experimental pressure trends. However, it is worth underlining that the simulations were performed a posteriori, since an engineering approach was used, based on the knowledge of the pressure inside the reaction vessel. Therefore, the code in its standard version does not have predictive capabilities and it is not applicable to the deterministic safety analysis of WCLL BB in-box LOCA.

3.2. Code Set-Up for WCLL-BB in-Box LOCA: SIMMER Model Implementation, Verification, and Preliminary Validation

Considering the conclusion stated above, a huge effort was made in order to set up a code able to deal with water and liquid metal, able to predict the evaluation of pressure and temperature trends, and able to evaluate the hydrogen production due to the chemical reaction. SIMMER code was chosen because of its capability to calculate mass, momentum, and energy exchange between different working fluids in the same mesh cell. Indeed, to the best of the authors' knowledge, SIMMER is the most complete and flexible code for dealing with liquid metal–coolant interaction, being able to simulate pressure trends, pressure peaks, and wave propagation thanks to the FCI model implemented in the standard version of the code. As an advanced computer code for safety analysis, SIMMER was primarily developed to investigate postulated disruptive accidents in liquid metal fast reactors (LMFRs) [39,40]. There are two main branches of the code, namely SIMMER-III and SIMMER-IV, which differ only in the fact that SIMMER-III is two-dimensional while SIMMER-IV is three-dimensional. Adding to this difference, both codes are multicomponent, multiphase, multivelocity, Eulerian fluid dynamics codes that can be coupled with an embedded-space-dependent model of neutron kinetics. One major shortcoming to mention is the lack of flexibility in mesh construction, as both codes can only work with structured rigid meshes. SIMMER codes can model up to five LMFR base materials simultaneously: in the same numerical domain, it is possible to simulate up to four working fluids (three in liquid phase and one in gas phase), together with a single material for solid structures. For each one, it is possible to vary the thermo-physical properties to customize the type of material. Furthermore, each material can be assigned a different velocity (and, consequently, a transport equation) and can undergo phase changes.

SIMMER codes have been applied in the past to reactor integral calculations and other complex multiphase flow problems. However, the standard version was not able to simulate the chemical reaction between lithium–lead and water; therefore, this feature was included by ENEA and the University of Pisa [7] by implementing the thermo-physical properties of PbLi and the chemical model of PbLi/water reactions, replacing it with the default models incorporated in the code (which simulated the reaction between sodium and water).

In order to obtain a qualified code for deterministic safety analysis, a verification and validation (V&V) procedure is established and conducted. The former, verification, consists in the process of determining whether a computational model correctly implements the intended conceptual model or mathematical model. The results of the verification in simple geometries of both SIMMER-III and SIMMER-IV, comparing the calculated and theoretical stoichiometric amounts of reactants and products, evidenced a maximum error between the calculated and theoretical values of less than 1%. The latter, validation, was considered of primary importance in order to perform reliable deterministic safety analysis and to obtain a qualified numerical code. Therefore, a standard methodology for validation was set up and applied to preliminarily validate SIMMER codes against the LIFUS5 experimental campaign performed during '00 at ENEA RC Brasimone [8]. The main results of reference post-test analyses and sensitivity calculations highlighted open issues of test execution and experimental data as well as code limitations and capabilities:

- The post-test analyses and sensitivity calculations of all LIFUS5 tests highlighted open issues of experimental data (i.e., the injected mass of water calculated by experimen-

talists a posteriori and reported in the literature). Moreover, the analyses permitted the improvement of the knowledge of test execution and operative conditions (i.e., the injected pressure trend and the pressure at which the injector cap breaks, which do not correspond to design specifications);

- The correct knowledge of initial and boundary conditions affects the SIMMER code results. Nevertheless, the code demonstrated promising capability in predicting phenomena connected with PbLi/water interaction, considering also the chemical reaction and hydrogen production;
- Post-tests and sensitivity analyses of all LIFUS5 tests highlighted the importance of jet-breaking modeling, affected by users' choices and experiences combined with a lack of needed geometrical information. In particular, the parameters that affect the code results are connected with the knowledge of initial and boundary conditions (i.e., the pressure trend imposed at the injector, the temperature of the injected water, and the free gas volume in the expansion vessel), with code models (i.e., predominant reaction and kinetics velocity), and with nodalization and user choices (i.e., the U-tube mock-up model which is responsible for breaking the water jet). Moreover, interaction phenomena are extremely complex to simulate because they are affected by a large number of parameters (i.e., interfacial area, dimensions of the vapor bubble, HTC, and fragmentation mode due to the jet-breaking). The results are strongly affected by users' choices and experiences combined with a lack of needed geometrical features;
- Specific outcomes from the post-test analyses performed by the SIMMER code highlighted the transient division into the following three phenomenological windows: Phase 1, characterized by coolant flashing and reaction vessel pressurization; Phase 2, characterized by expansion vessel pressurization; and Phase 3, characterized by system pressure equilibrium. During Phase 1, the SIMMER-III code predicts very well the first pressure peak due to water flashing, and the pressure trend is qualitatively in line with the experimental results. Some differences occur during Phase 2; indeed, the code calculates an anticipated onset of expansion vessel pressurization. This behavior is affected by the fragmentation model. The code results are satisfactory also during Phase 3. From the qualitative behavior of the temperature trends, SIMMER-III reasonably predicts the experimental results. Indeed, the code correctly predicts the zones where the temperatures are higher, i.e., the expansion vessel and zone 1 of the mock-up. However, the temperatures are underestimated in the reaction vessel and overestimated in the expansion vessel. These differences are connected with modeling issues, i.e., the accurate representation of the U-tubes and, therefore, the prediction of coolant fragmentation during injection;
- Comparing SIMMER-III with SIMMER-IV results, a different pressurization trend is evidenced due to a lower hydrogen generation predicted by SIMMER-IV. The reasons are twofold: (1) SIMMER-IV calculates different binary contact areas between water in vapor or in liquid phase, (2) SIMMER-IV calculates frozen PbLi, which does not take part in the chemical reaction. The latter aspect is coherent with the experimental and calculated temperature trends, correctly evaluated by SIMMER-IV.

3.3. LIFUS5/Mod3 Experimental Facility for Validating SIMMER Code

It appeared clearly the need of experimental data (1) with "more controlled" initial and boundary conditions, (2) with suitable and reliable instrumentation and (3) specifically designed for supporting the development and implementation of the chemical reaction model and for providing qualified data for code validation purposes. Therefore, in parallel, a new separate effect test facility was designed and built, LIFUS5/Mod3 [9]. The details of the facility are reported in Refs. [9,10] and a piping and instrumentation diagram is reported in Figure 2. The main components of the facility are:

- Reaction vessel S1B where the reaction between liquid PbLi and water occurs;
- Water storage and injection line;
- Safety expansion vessel S3V which is connected to S1B with two rupture disks;

- PbLi storage tanks S4B1 and S4B2 for fresh and exploited alloy;
- Hydrogen extraction line.

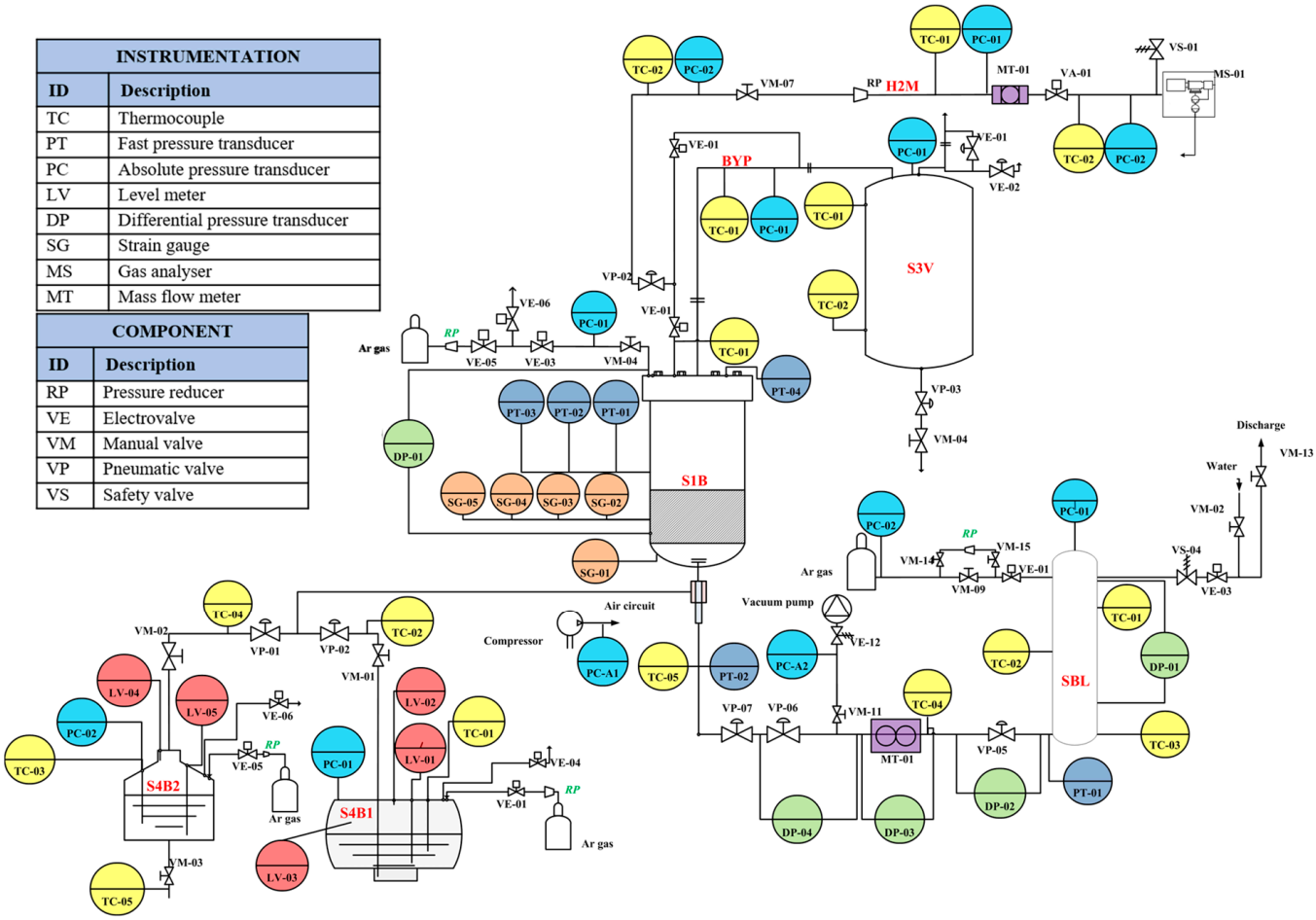

Figure 2. LIFUS5/Mod3 piping and instrumentation diagram [11].

The LIFUS5/Mod3 facility was used to conduct two series of experiments, named Series D and Series E ([10,11]). The first campaign focused on the chemical interaction between PbLi and water with particular attention paid to the validation of the implemented chemical model in the SIMMER code. Therefore, attention was given to the relevance of the parameter ranges important for the WCLL BB and the model of the SIMMER code, the object of validation. The Series D test matrix parameters (Table 1) were chosen in order to be representative of the WCLL BB and the cooling system (PHTS), the temperature and pressure of the water, and the temperature of the PbLi. On the other hand, the Series E experimental campaign was designed to fully simulate a LOCA event, from the break in the water pipe to the complete equilibrium between the water line and the PbLi zone. All the tests were conducted with the same procedures: the S1B was filled with liquid lead–lithium and, contemporarily, the injection line was partially filled with subcooled water and then connected to a tank containing pressurized argon; once the connection was established, the pressure in the line increased rapidly, until the cap that separated the water line and the S1B vessel broke abruptly. Considering Series E, the injection procedure was slightly different because water completely filled the water tank (not a pre-defined amount of water) and was injected according to chocking flow instauration and injection time (Table 2).

Table 1. LIFUS5/Mod3 Series D test matrix.

Test Series D	D Orifice(mm)	Water Injected (g)	Water T (°C)	PbLi T (°C)	Injection Pressure (bar)
1.1	4	50	295	330	155
1.2	4	50	295	330	155
1.3	4	50	295	330	155
1.4	4	50	295	330	155
1.5	4	50	295	330	155
2.1	4	100	295	330	155
2.2	4	100	295	330	155
3.1	4	50	295	450	155
4.1	4	50	330	330	155
5.1	4	150	295	330	155

Red color highlights the parameter changed in the test matrix.

Table 2. LIFUS5/Mod3 Series E test matrix.

Test Series E	D Orifice (mm)	Water T (°C)	PbLi T (°C)	Injection Time (s)	Injection Pressure (bar)
#1.1	4	295	330	1	155
#2.1	4	295	430	1	155
#3.1	1	295	330	0.5	155
#4.1	2	295	330	1	155
#5.1	1	295	330	1.5	155
#6.1	4	295	380	1	155
#7.1	2	295	380	1.3	155
#8.1	1	295	380	2	155

Red color highlights the parameter changed in the test matrix.

All the experimental tests showed the same phenomenology [10,11] characterized by three different phases and occurring with similar timing:

1. Pressurization of water injection line, from pressure rise in injection line to rupture of the cap (from start of the transient to start of the injection);
2. Water–PbLi interaction, from start of the injection to end of the injection. Considering the phenomena occurring in this phase, it can be divided in three subphases:
    a. Flashing of injected water, from the cap rupture to ending of first pressure peaks;
    b. Thermodynamic interaction, from ending of first peaks to start of increase in temperature;
    c. Chemical interaction, from start of increase in temperature to the end of the injection.
3. Ending phase, from the end of the injection to the end of the transient.

Moreover, the following conclusions can be drawn:

- The influence on the compressibility of the system is confirmed, due to the relatively elastic response depending on the volume of cover gas present in the reaction vessel;
- The flashing of the water jet and its expansion upwards and outwards led to a decrease in temperature inside the melt;
- The increase in temperature is due to the chemical reaction occurring between PbLi and water, at the interface between the two fluids;

- The time window is confirmed, where the thermodynamic interaction is relevant in the first hundreds of milliseconds after the injection, while the chemical interaction becomes significant following the reduction in thermodynamic interactions, causing an increase in temperature and generation of hydrogen;
- Some phenomena connected to the interaction are still under investigation, i.e., the influence of the chemical reaction in the transient. Even though the first pressure peak is due to the flashing of the water inside the melt, thus mainly being a thermodynamic process, the chemical reaction would, in principle, affect the amplitude of the peak. It would be useful to investigate this phenomenon by performing experiments with different liquid metals (LBE or depleted PbLi). Moreover, the chemical reaction is confirmed to be a secondary process and, therefore, it would be useful to perform experiments with longer injection times;
- The kinetics of the reaction and the properties of the chemical products (i.e., Li_2O and LIOH) are still missing information. These data are needed in order to have full knowledge of the interaction phenomena and must be implemented into the numerical codes as part of the validation process.

Experimental data were analyzed [12] with the aim of finding correlations between quantities that would support or deny the current understanding of the phenomenology and processes occurring during the tests:

- From the analysis of the Series D1.# tests, executed as a series of repetitions of test #1, with the main goal of investigating the reliability of the experimental data and the repeatability of the test, four main correlations arise:
    - An inverse correlation between the pressure in the SBL gas line and the first peak pressure after the injection (Figure 3a). This inverse correlation might exist due to a higher pressure in the gas line at the beginning of the test which would keep the water in a more subcooled condition, diminishing its capacity for flashing after being injected inside the PbLi;
    - An inverse correlation between the volume of free gas inside vessel S1B and the first peak pressure (Figure 3b). This phenomenon might be associated with the fact that the free volume inside the vessel can compress and absorb the pressure wave caused by the water flashing, as proposed in the previous sections;
    - A direct correlation between the first peak pressure and the H_2 concentration (Figure 3c). This correlation is probably associated with the increased contact area between water and PbLi when the jet of water can flash strongly and penetrate deeper into the alloy;
    - A direct correlation between H_2 concentration and PbLi temperature variation (Figure 3d). This correlation is quite simple to explain, since a higher H_2 production (and, thus, concentration) is associated with a larger energy release due to the chemical reaction and, thus, to an increase in the temperature variation between the initial and final conditions of the PbLi.
- From the analysis of Series E tests, various relations between important parameters were found:
    - A correlation between the mass of hydrogen produced by the reaction and the injector's cross-sectional area. This correlation is shown in Figure 4a. Here, we can see how higher injector cross-sectional areas correspond to a higher production of hydrogen. This is partially related to the fact that higher cross-sectional areas are associated with a greater amount of water injected into the vessel, but the different spreading of the jet inside the alloy might also play a role in the amount of water that is able to react;
    - A correlation between the injection time and the minimum PbLi temperature reached during the injection. Figure 4b shows how the minimum temperature registered during the injection phase is related to the injection time. However, only three of the eight tests report this data. These tests are the same as those

during which the rupturing of the protection disk happens, thus suggesting that the drop in pressure and the consequent water flashing cause a cooling effect of the PbLi alloy. Longer injection times, as shown in the graph, are associated with a longer flashing phase of the water and, thus, a deeper cooling of the alloy, before the chemical reaction takes over;

- A correlation between the injector's cross-sectional area and the maximum PbLi temperature reached during the injection. Figure 4c shows the relation that subsists between the maximum temperature of the PbLi reached during the injection and the cross-sectional area of the injector. This might be explained by considering that a higher cross-sectional area corresponds to a higher mass of injected water and, thus, a greater energy release through the chemical reaction. However, we do not see the same correlation between the injector's cross-sectional area and mass of water injected. This suggests that the peak temperature is not solely related to the absolute amount of water injected, but mostly to the shape of the jet during the injection. Thus, the correlation between the maximum PbLi temperature and the injector's cross-sectional area can be associated with the spread of the jet and, thus, with a higher localized reaction rate, which raises the temperature of the system in small-volume regions. This local rise is then recorded by the single thermocouples, while the average variation is recorded by the remaining ones;
- A correlation between the mass of hydrogen generated and the maximum PbLi temperature reached during the injection. Figure 4d shows the existing correlation between the mass of hydrogen produced during the injection of water and the maximum temperature reached by the PbLi alloy. From this graph, it is evident that the main contributor to the overall energy release inside the vessel is the chemical reaction between the two components.

- In the last analysis, all the data from both Series D and E were utilized. The objective is to understand the estimation of the reaction ratio between path A (LiOH formation) and path B (Li_2O formation). The result is shown in Figure 5. The figure includes a scatter plot of the H_2 and water mass for each test, including theoretical estimations. The scales are log–log to group the different tests, for which the varying amounts of water and hydrogen produced would stretch the data and make them less readable. As we can see, the new fitting line obtained by including all the tests is coherent with what was found previously, with an angular coefficient value of 0.0691 and an R-squared of 0.9455. The line equation, shown in the graph, relates the masses of hydrogen and water according to the equation:

$$m_{H2} = 0.0691 m_{H2O}$$

which falls into the range predicted by the stoichiometry:

$$\begin{cases} m_{H2O} = 0.056 m_{H2}, & reaction\ A\ only \\ m_{H2O} = 0.11 m_{H2}, & reaction\ B\ only \end{cases}$$

Using this information, we can calculate the percent amount of water that reacts with lithium, either through reaction path A or reaction path B. This is achieved using the ratio:

$$x = \frac{\left(\frac{m_{H2}}{m_{H2O}}\right)_{exp} - \left(\frac{m_{H2}}{m_{H2O}}\right)_{A}}{\left(\frac{m_{H2}}{m_{H2O}}\right)_{B} - \left(\frac{m_{H2}}{m_{H2O}}\right)_{A}}$$

which, in our case, yields x = 0.242. This means that around 24% of the injected water mass reacts according to reaction path B, producing lithium oxide, while 76% of it reacts to produce lithium hydroxide, either directly or by conversion of Li_2O into LiOH.

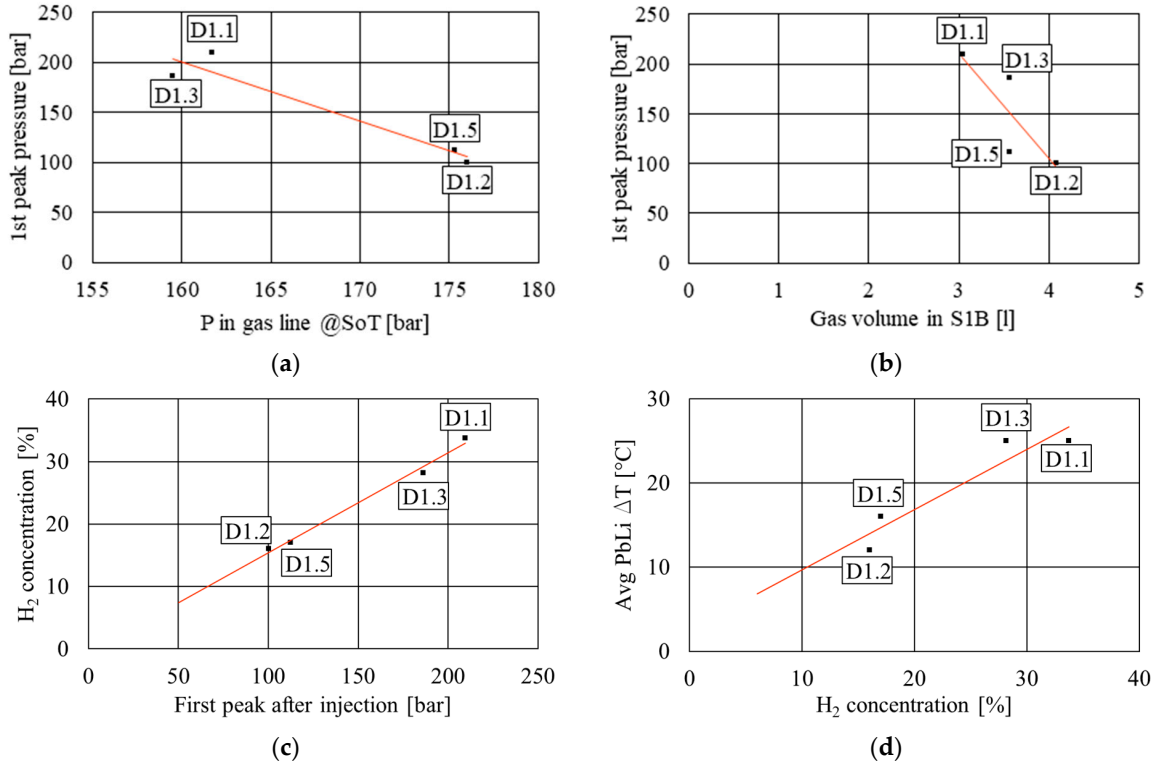

Figure 3. Correlations between relevant parameters of the interaction (series D). (**a**) pressure in injection line vs. first pressure peak. (**b**) free gas volume in reaction vessel vs. first pressure peak. (**c**) first pressure peak vs. H_2 concentration (**d**) H_2 concentration vs. PbLi temperature.

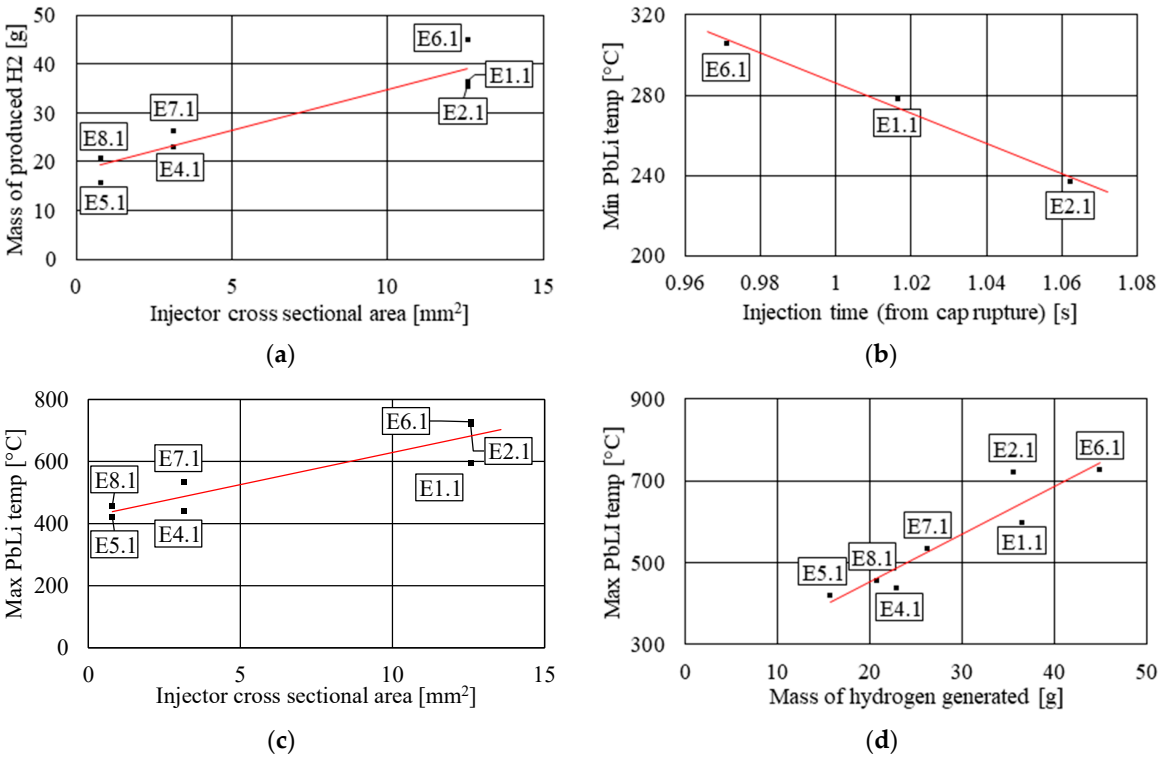

Figure 4. Correlations between relevant parameters of the interaction (Series E). (**a**) injector cross-sectional area vs. H_2 produced. (**b**) injection time vs. min PbLi temperature. (**c**) injector cross-sectional area vs. max PbLi temperature (**d**) H_2 procuded vs. max PbLi temperature.

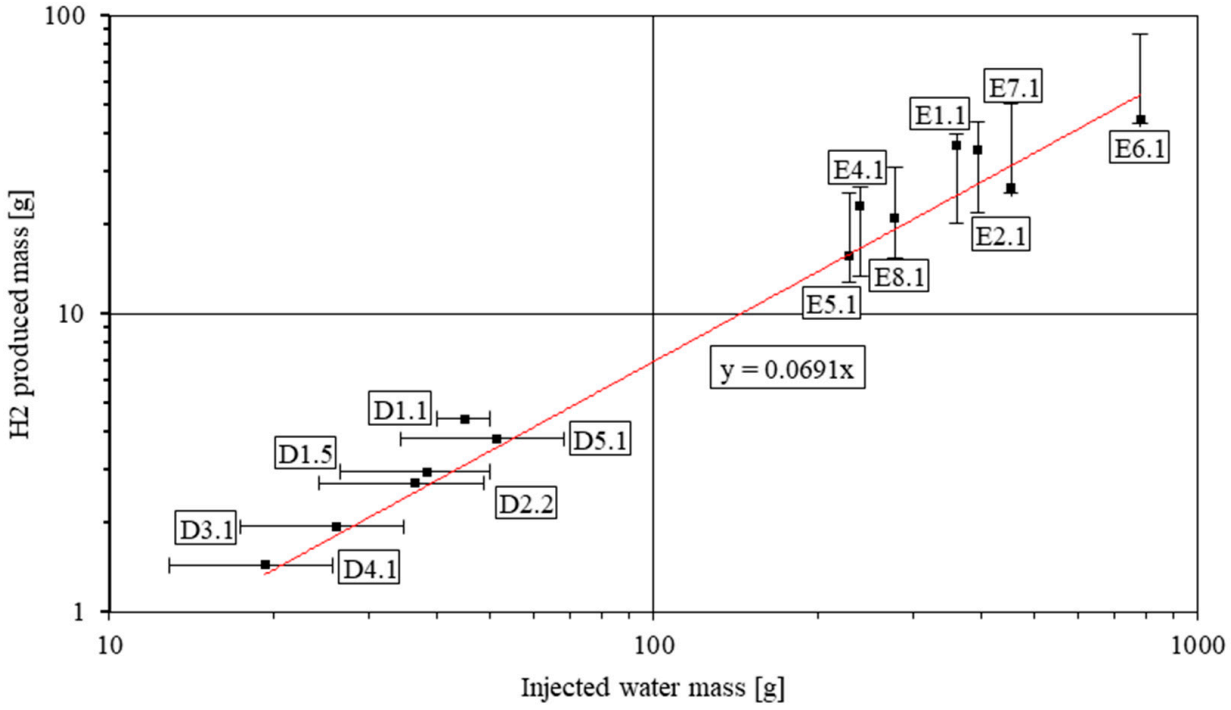

Figure 5. Hydrogen produced mass vs. injected water mass, log–log scale. The red line represents the linear fitting of all the data.

3.4. SIMMER Numerical Code Validation against LIFUS5/Mod3 Tests

The experimental data provided by the separate effect test facility LIFUS5/Mod3 were used to continue the validation activity of SIMMER codes, both in 2D and 3D versions [10,13–16]. A standard methodology, widely used in fission-related activities, is applied [8], consisting in a three-steps analysis. The initial condition results (step 1) constitute part of the assessment process, being relevant for the characterization of the thermo-hydraulic conditions at the beginning of the experiment. The reference calculation results (step 2) are those achieved by qualified nodalization. Sensitivity analyses (step 3) are carried out to demonstrate the robustness of the calculation, to characterize the reasons for possible discrepancies between measured and calculated trends that appear in the reference calculation, to optimize code results and user option choices, and to improve the understanding of experimental data. The analysis of results is based on a comprehensive comparison between measured and calculated trends or values, performed through (1) qualitative accuracy evaluation based on engineering judgments and (2) quantitative accuracy evaluation based on selected figures of merit.

The SIMMER-III geometrical domain is obtained by 50 radial and 100 axial mesh cells and the SIMMER-IV geometrical domain is obtained by 31 × 31 planar and 52 axial mesh cells (Figure 6). Colors distinguish the different fluids and structure material, as set at the beginning of the transient (t = 0 s). Therefore, PbLi is represented in red, water in blue, and argon cover gas (and hydrogen produced by the reaction) in white; the non-calculation zones are highlighted by a green mesh fence and SS316 (in black) is used as the structural material. The reference mesh cells for temperature analysis inside the S1B, representing the position of installed TCs in S1B, are highlighted in yellow and the reference cells for pressure measurement are highlighted in purple.

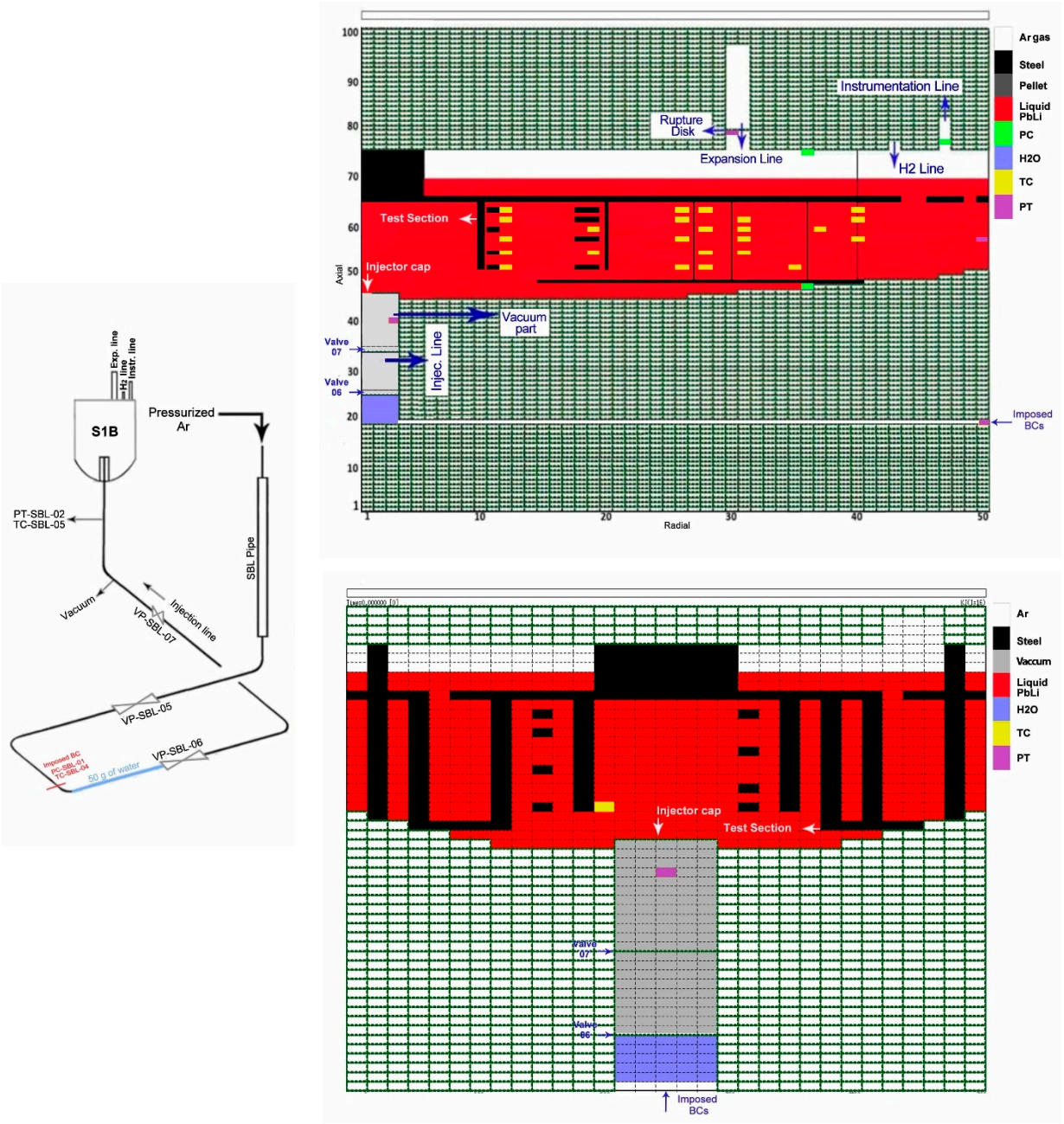

Figure 6. LIFUS5/Mod3 SIMMER-III (**top**) and SIMMER-IV (**bottom**) reference nodalization.

The reference calculation starts at t = 0 s, which represents the time at which the injection valve opens. The injector cap rupture is simulated by the disappearance of the virtual wall, which recreates an orifice. The time at which the injector breaks up is obtained from the specific tests' experimental data. The injection pressure trend recorded in the injection line is imposed as a boundary condition as well as the condition of continuous inflow. The initial conditions of pressure, temperature, and the filling level of lithium–lead in S1B are set coherently with the experimental data.

The main achievements regarding the standalone simulations of Series D and Series E tests in LIFUS5/Mod3 can be summarized as follows:

- The post-test analyses by SIMMER-III provide valuable and important overviews on the issues related to the long transient injection of water, i.e., the water jet inside the S1B vessel and the impact of the chemical reaction on the evolution of this jet.

Furthermore, the pressure of the injector break-up is reproduced and is in line with the experimental signals;

- The code results considering the hydrogen generation seem acceptable and coherent with the experimental results and the stoichiometric calculations, although, in a few tests, the hydrogen data acquisition process was not completely fulfilled due to an extraction line clogging problem;
- SIMMER-IV, thanks to its 3D geometry, provided a powerful improvement to the prediction of inhomogeneity of the pressure inside S1B, and the numerical results showed that the code is capable of correctly capturing the main phenomena involved in the experiments;
- From the qualitative behavior of the temperature trends, the prediction needs improvement for both SIMMER-III and SIMMER-IV. Indeed, the code correctly predicts the zones and times in which the temperatures change to lower and higher values. Nevertheless, the fast transients are not always well captured. These discrepancies occurring during fast transients might indicate the necessity of an assessment of the interfacial interactions between the phases, which can have a strong impact on the velocity of the reaction. Even more importantly, the implementation of the kinetics of the PbLi/water reaction is still in progress, since there has not been significant and comprehensive material described in the literature regarding this reaction. However, the temperatures are mostly underestimated in S1B and are overestimated in a few spots close to the test section. Many reasons may explain this behavior, for instance, the SIMMER codes' temperature calculation features in the mixture phase. Furthermore, even though the chemical reaction provided very good results for the calculation of the final hydrogen production, the energy released during the fast transient due to the reaction might need further assessment, both from experimental and numerical points of view; this might have a strong impact on the final value of the temperatures. On the other hand, the lower temperature values are due to the cooling effect of subcooled water and they are all perfectly captured in sensitivity analyses by decreasing the initial temperature of water to give more capacity to the physical interaction. Furthermore, it is concluded that fragmentation plays an important role in specifying the interfacial area between the fluids and, therefore, the interaction/reaction itself;
- Imposing the real initial temperature difference within the water injection line, the SIMMER codes can correctly predict the pressurization profile. The differing rates of evaporation between the colder upstream water and the hotter downstream water ensure that the right amount of water beneath the cap reproduces the initial pressure pulse;
- Progress is still ongoing as part of the SIMMER validation process. To align with the observed water flow path from experimental analysis, adjustments were made to the inner test section. Notably, the lower portion was extended to accurately replicate the impedance encountered by the pressure pulse propagation. Furthermore, modifications were made to the interface connecting the SBL line and the S1B to simulate cap penetration into the alloy. These sensitivity analyses led to results of well-captured pressure peaks and pressure wave propagation, during the initial phase of the interaction. The first peak is caused by both the mechanical impact of incoming water and the energy released during thermo-dynamic interaction. Once the water makes contact with the lithium–lead, SIMMER calculates a pressure pulse that travels to the location of the experimental pressure sensor. Afterwards, the pressure decreases due to the resistance offered by the test section against incoming lithium–lead and then secondary pressure peaks follow the initial one. These secondary peaks are closely linked to the level of lithium–lead in relation to the perforated plate. Consequently, additional investigations are necessary to assess the efficiency of water in displacing the lithium–lead, all while considering the influence of cap diameter and the level of lithium–lead. These factors emerge as the principal determinants that shape the subsequent pressurization profile;

- The main issue that is clear from the standalone simulations is the necessity in correctly imposing the boundary conditions to obtain meaningful results. Indeed, only by imposing reliable injection pressure and temperature are SIMMER codes results in good agreement with experimental data;
- The parameters that most affect the code results are connected with code models (i.e., the chemical model and the turbulence model) and with nodalization and user choices.

4. Discussion

The main achievements of the WPBB as part of the FP8 EUROfusion project can be summarized as the implementation, verification, and preliminary validation of the chemical reaction model in SIMMER as well as the design, construction, and operation of the new SET LIFUS5/Mod3 facility, which provides experimental data for code validation. Experimental campaigns were conducted and 18 tests were executed. Alongside this, a standard methodology widely used in fission fields was applied to continue the validation of SIMMER codes. From the considerations and the results stated above, these achievements can be considered the starting point of the new R&D plan in the framework of FP9 EUROfusion Horizon Europe, here presented, with the final aim of obtaining a qualified numerical tool for the deterministic safety analysis of WCLL in-box LOCA scenarios.

4.1. Integral Test Facility LIFUS5/Mod4 for the WCLL in-Box LOCA Experiments

One of the main activities currently ongoing to fulfill the objective of having a qualified code for DSA is the availability of an experimental infrastructure that can perform tests at an integral scale, being representative of the geometry and operational conditions of the WCLL blanket concept (Figure 1, see violet box).

With this purpose, a new integral test facility, named LIFUS5/Mod4, is being constructed at ENEA RC Brasimone [24], designed to be as representative as possible of the WCLL TBS PbLi loop [41]. The main expected scientific outcomes and technological advancements of this facility include:

- Generating data applicable to full-scale WCLL test blanket system (TBS) conditions that may be directly used for safety analysis;
- Providing integral test facility data for the understanding and study of the transient progression of a "in-box Loss Of Coolant Accident" in the WCLL BB of DEMO reactor;
- Supporting the development and demonstrating the reliability (i.e., validation and qualification) of computer codes, coupling techniques, and procedures for code use, when applied to simulating the behavior of a "in-box Loss Of Coolant Accident" at a system level.

The LIFUS5/Mod4 facility will be connected to a larger facility named Water Loop, in which water, under WCLL TBS operating conditions, will flow (155 bar and 295–328 °C). By coupling, the facilities will be able to simulate system operation and in-box LOCA scenarios, maintaining the representativeness of the thermodynamical phenomena, hydraulic conditions, and dynamical behavior of the loops.

The general layout of the facility is shown in Figure 7 and the operational characteristics are reported in Table 3. The main components of the facility are the recirculation tank SE-LSS-001, the tritium extraction unit (TEU) equivalent volume SE-LTS-001, the relief tank SE-LRS-001, and the breeding unit mock-up test section. These have been designed to be as representative as possible of the equivalent components foreseen to be installed in the WCLL TBS PbLi loop. The piping itself was designed with the main goal of maintaining the same dynamical pressure losses and heights. This ensures that, during tests, the phenomena are correctly represented and captured, so that significant data can be produced. The main difference between the two circuits is the absence of the recirculation pump in the LIFUS5/Mod4 circuit. This is mainly due to the "violence" of the experiments which will be tested. This led to an additional secondary circuit for the PbLi load and drain.

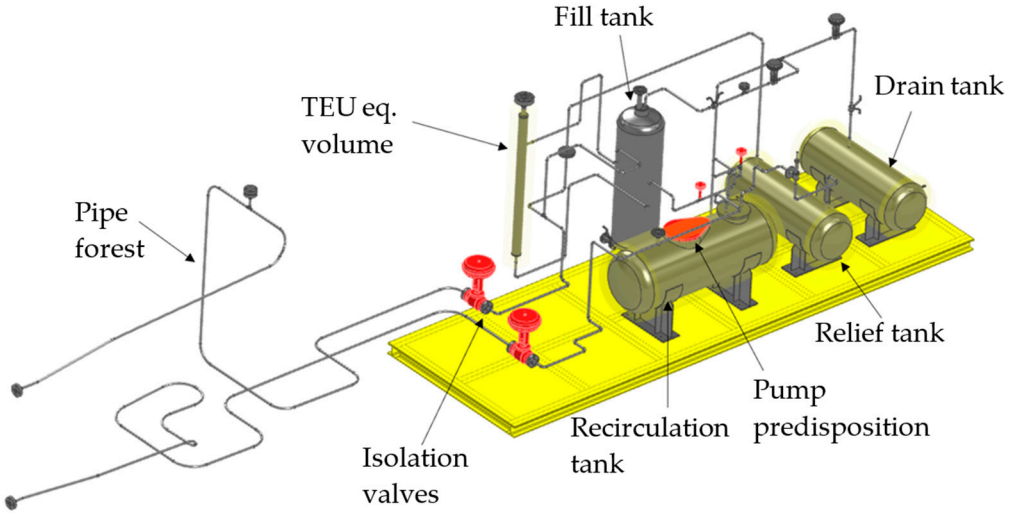

Figure 7. LIFUS5/Mod4 preliminary CAD drawing [24].

Table 3. LIFUS4/Mod4 Operational characteristics.

General Characteristics	
Facility type	Stagnant PbLi loop
Operating fluid	Eutectic PbLi alloy (Li 17%, Pb 83%)
Heat source and power	Heating wires and bands
Hydraulic Characteristics	
Fluid	Pb-83 Li-17 eutectic alloy
PbLi Inventory	0.593 m^3
Operating temperature range	350–450 °C
Operating pressure	0.1 MPa
Design pressure	18.5 MPa
Operating mass flow rate	0 kg/s
Key instrumentation	Fast pressure transducers, strain gauges, hydrogen analysis system, thermocouples, and level meters.

Currently, the project has finalized its conceptual design and is advancing through its final design phase. PFD, P&ID, and CAD drawings of the facility are available and procurement of the ancillary system has begun. All the design phases are being supported by extensive numerical analysis work, focusing on the prediction of the thermohydraulic behavior of the facility. Various simulations using the coupled SIMMER/RELAP5/Mod3.3 are ongoing to analyze the facility's response to in-box LOCA tests. The produced results will be used to choose the right sensor placement to produce significant data able to capture the main features of the underlying phenomena. In future, the design will be adapted to more recent updates on the layouts of the system, allowing the beginning of the engineering design phase. Construction is foreseen in 2024, and initial tests are set to begin by late 2024.

4.2. Code Set-Up for Deterministic Safety Analysis of WCLL in-Box LOCA

Following the methodology and the flowchart presented above (Figure 1), the last main activity currently ongoing is the development of a code for the deterministic safety analysis of WCLL in-box LOCA scenarios (see yellow box). In this framework, two steps have been identified: (1) RELAP5/Mod3.3 code development to expand simulation capabilities in fusion applications and (2) the development of coupling code tools in order to perform transient analyses considering the chemical, thermo-hydraulic, and structural effects due to PbLi/water interaction.

4.2.1. RELAP5/Mod3.3 Code Development

RELAP5/Mod3.3 was jointly developed by the Idaho National Engineering Laboratory (INEL) and several US and foreign organizations [42]. The code is suitable for the analysis of all transients and accidents affecting light water reactors (LWR) and CANDU nuclear power plants. The approach adopted by the code is based on a nonhomogeneous and nonequilibrium two-phase model solved by a fast implicit numerical scheme. The aim is to obtain cost-effective yet accurate reproductions of first-order effects so that parametric or sensitivity studies are possible.

In recent years, ENEA and its linked third parties (e.g., DICI of University of Pisa and DIAEE of Sapienza University of Rome) have started some development programs to extend RELAP5/Mod3.3 code simulation capabilities. The newly implemented features are needed to address issues arising from the modeling of tokamak fusion reactors. The work described in [43,44] can be summarized as follows:

- The inclusion of new coolant fluids, such as PbLi, lead–bismuth eutectic (LBE), HITEC©, and Pb;
- The adoption of new correlations to reproduce fluid–wall heat transfer phenomena with complex geometries and/or with liquid metal and molten salt coolants. The heat transfer phenomenon in liquid metals is dominated by thermal diffusivity due to their low Prandtl number (1). Correlations developed for water do not consider this aspect, thus making them unsuitable for use with liquid metals;
- The introduction of ad hoc correlations to consider magnetohydrodynamic (MHD) effects on system transport coefficients, i.e., pressure drops due to electromagnetic drag and modified heat transfer coefficients.

The inclusion of additional coolant fluids required little effort on the source code, but relevant ones under a mathematical point of view [45]. As a matter of fact, RELAP reads the fluid properties from ad hoc files containing pressure-vs-temperature tables for most of the properties of interest (density, specific volume, specific enthalpy, etc.), while few of them are hard-coded within the source code (thermal conductivity, surface tension, and viscosity). These properties must be given for both the liquid and the vapor phases.

In the literature, the properties for the liquid phase of liquid metals are usually provided only at atmospheric pressure and as a function of temperature. No data are available for the vapor phase since—apart from sodium—all liquid metals have a boiling point well above the melting point of steel. So, for the liquid properties, the re-construction strategy detailed by N. I. Kolev in [46] was followed to create a reliable set of pressure-vs-temperature tables with the data available at atmospheric pressure. for the vapor phase, the properties were calculated starting from the Van der Waals equation of state and considering the coolants as pure fluids.

The state of the art of heat transfer correlations available for liquid metals was also implemented [47], considering the main geometries of interest (tube, plates, and bundles). A total of seven correlations divided into two categories were introduced in the source code:

1. Correlations for circular tubes or plates:
    a. Seban—Shimazaki;
    b. Cheng—Tak.
2. Correlations for bundles:
    c. Sherbakov (shell side in helicoidal geometry only);
    d. Ushakov (rod bundle only);
    e. Mikityuk (rod bundle only);
    f. Kazimi—Carelli;
    g. Graber—Rieger (modified by Sha and Launder).

The geometry characterizing the PbLi flow path within the WCLL TBM set is different from the ones listed above [2]. Thus, the effectiveness of the implemented correlations in properly predicting the PbLi/water heat transfer phenomena occurring within the breeder

zone are evaluated as part of FP9 research activities by using the experimental data from the LIFUS5/Mod4 facility.

The RELAP5 MHD module is composed of three complete subroutines and several additions to pre-existing routines used to predict MHD effects on flow transport coefficients. The three entirely new subroutines are needed to compute the electrical conductivity of liquid/solid metals, calculate MHD pressure drops factors, and evaluate MHD heat transfer coefficients.

Magnetohydrodynamic phenomena occur whenever an electro-conductive fluid, such as a liquid metal, is forced to flow under the influence of an external magnetic field. Within the liquid domain, electrical currents arise that interact with the magnetic field itself and induce Lorentz forces that drastically alter the flow features. In the MHD regime, compared to ordinary hydrodynamic conditions, the fluid velocity profile is strongly affected; consequently, mass and heat transport mechanisms undergo substantial modifications and pressure drops are enhanced [48].

Among the several MHD phenomena that influence the operative performance of LM–BB systems, the additional pressure losses are often deemed the most impactful [49] and the goal of modeling is prioritized. In recent years, the capability of the RELAP5 MHD module in predicting MHD pressure losses has been demonstrated through several benchmarks with CFD numerical results and experimental data [23,43,50].

In its current state, the code reliably predicts distributed MHD friction losses, also referred to as two-dimensional (2D) drops, occurring in circular and rectangular/square cross-sectioned channels. The base formulation for the 2D friction factor is derived by the fundamental work carried out by Miyazaki et al. [51,52] and gathered in [53]. Moreover, models for MHD local pressure losses, or three-dimensional drops (3D), have been implemented. Data for 3D losses are relatively scarce compared with those available for 2D MHD phenomena. Evaluating these types of losses is much more complex as they are highly dependent on the flow geometry and governing parameters. Exclusively those configurations that have been researched the most have been deemed suitable for the derivation of a reduced model, i.e., expanding/contracting ducts [54,55], bending conduits [56], and channels with discontinuities in the wall electrical conductivity [57]. The heat transfer subroutine is able to handle forced convection in both rectangular and circular tubes for the boundary conditions of imposed heat flux and walls of negligible electrical conductivity. The V&V of this model is currently ongoing for simple geometries and will then be extended to more complex ones.

It is pivotal to underline that, while the MHD module can model with reasonable accuracy the liquid metal behavior under nominal conditions, the same is not true for accidental scenarios. How MHD effects could affect the interaction between PbLi and water during an in-box LOCA is still a matter of discussion. Preliminary activities for the quantification of MHD effects in a simplified in-box LOCA scenario are currently in progress and, in the future, could conceivably form the foundation for a reduced-order model, if supplemented by experimental data gathered by an upgraded LIFUS5/Mod4 facility equipped with an electromagnet.

The described modifications are fundamental to expanding the code's capabilities toward the unique features characterizing tokamak fusion reactors and the WCLL blanket concept. The final purpose of this RELAP5/Mod3.3 development activity is to obtain a suitable code to perform system-level transient analysis. In this way, the WCLL blanket design can be supported by evaluating its performance not only at full-power steady-state conditions but also in a wide range of operative and, above all, accidental scenarios. Preliminary studies in this field have already been performed with the modified version of RELAP5/Mod3.3, simulating the transient behavior of both the ITER WCLL test blanket system [4,5] and the EU-DEMO WCLL breeding blanket [58,59].

4.2.2. RELAP5/Mod3.3 and SIMMER Code Coupling

In addition to the standalone calculations with SIMMER codes, the University of Pisa developed a coupling technique with the two versions of SIMMER and RELAP5 codes to reduce the computational effort and some geometrical limitations of SIMMER's numerical domains. By coupling, RELAP5/Mod3.3 is able to simulate the complex geometry of the piping systems as a 1D model while SIMMER is able to simulate the chemical and thermo-hydraulic multiphase interaction between PbLi and water.

The coupling methodology between SIMMER and RELAP5 codes can be categorized as a "two-way", "non-overlapping", and "online" technique [17–20], since the computational domains of the two codes transmit information on boundary conditions by separated interfaces (i.e., text files), which are utilized to interchange data in both directions, with a synchronized progress in time. The interaction is achieved through one single MATLAB script, which also has a role in verifying the synchronization of time.

An implicit method was employed as a numerical scheme: in this kind of scheme, each code completes the same time step various times ("inner iterations"), beginning from the same initial conditions each time, but with updated boundary conditions, up until some convergence criteria are reached. Once convergence for the specific time step is satisfied, the coupled variables are exchanged sequentially between the two codes at the end of the time step; therefore, the results found in the preceding time step from one code are used as novel boundary conditions for the other code, which simulates the succeeding time step. A more detailed explanation of the implicit scheme can be found in the next section and a flowchart of the scheme is shown in Figure 8.

The exchanged variables are different according to the direction of the coupling. This means that SIMMER provides the new pressure and temperatures to RELAP5, whilst RELAP5 imposes mass flow rates and temperatures (for both liquid and gas phases) to SIMMER. However, it is important to notice that, in SIMMER, it is possible to impose only the phase velocities; therefore, in order to impose the mass flow rate, the velocity calculated by RELAP5 must be weighted through the phase volumetric fraction in the interface cells of the SIMMER domain.

However, applying the tool to the LIFUS5/Mod4 integral test facility required an upgrade in the coupling between the two codes. It consists in the adaptation of the earlier MATLAB interface to handle multiple-input and multiple-output coupling (i.e., multiple sets of boundary conditions). The recently developed upgrade was put to the test using a basic loop geometry, which is depicted in Figure 9. As per the figure, the loop's components that were simulated using RELAP5 are marked in red, while the SIMMER domain is indicated in green. The interfaces that link the two domains, namely I01 and I02, are represented by the blue dash–dotted lines in Figure 9. To enable communication between the two interfaces, two cells were utilized, connected using BC components in RELAP5. I01 comprises one time-dependent volume and one single junction, whereas I02 is made up of one time-dependent junction and one time-dependent volume. To evaluate the effectiveness of the developed coupling technique, the quality of communication between the two codes was assessed by comparing the calculated values of several variables at the cells located in close proximity to the boundary interfaces. Upon comparison, it was found that all the variables were in perfect agreement, even when the mass flow rate was altered. This confirms the excellent quality of synchronization between the two codes, indicating that the developed coupling technique is highly effective (Figure 10).

4.2.3. SIMMER–ANSYS Code Coupling

The numerical code development activities so far presented focused on the implementation of chemical models that simulate the interaction between water and PbLi inside the SIMMER code, on the development of a SYS-TH code for PbLi fluid, and on the development of code chains to study the hydraulic behavior of the system in these accidental scenarios. However, all these codes and code chains focused on the goal of simulating the

behavior of the fluid part of the system, neglecting the response of structures under these dynamical loadings.

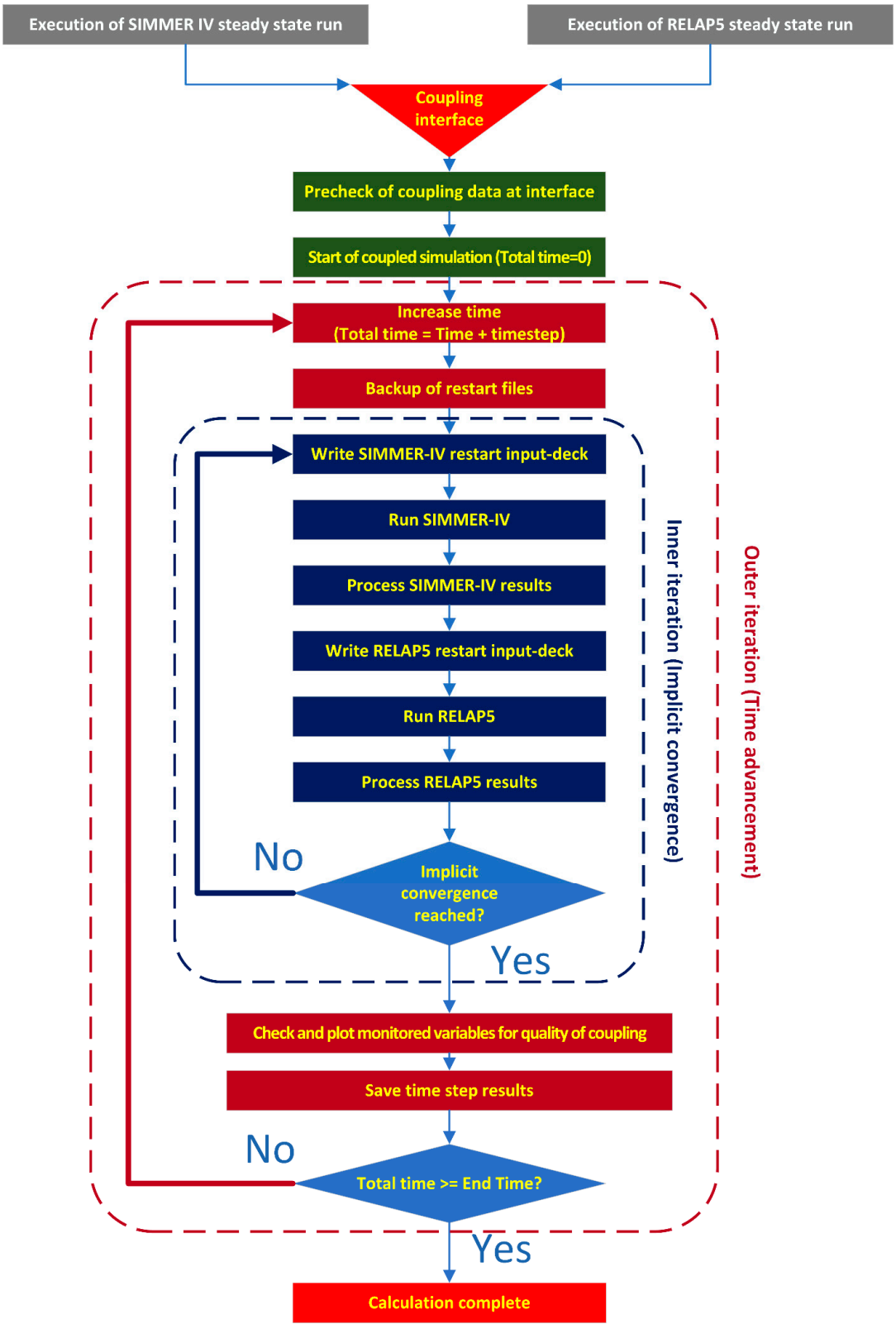

Figure 8. Flowchart of the coupling between SIMMER and RELAP5 [17].

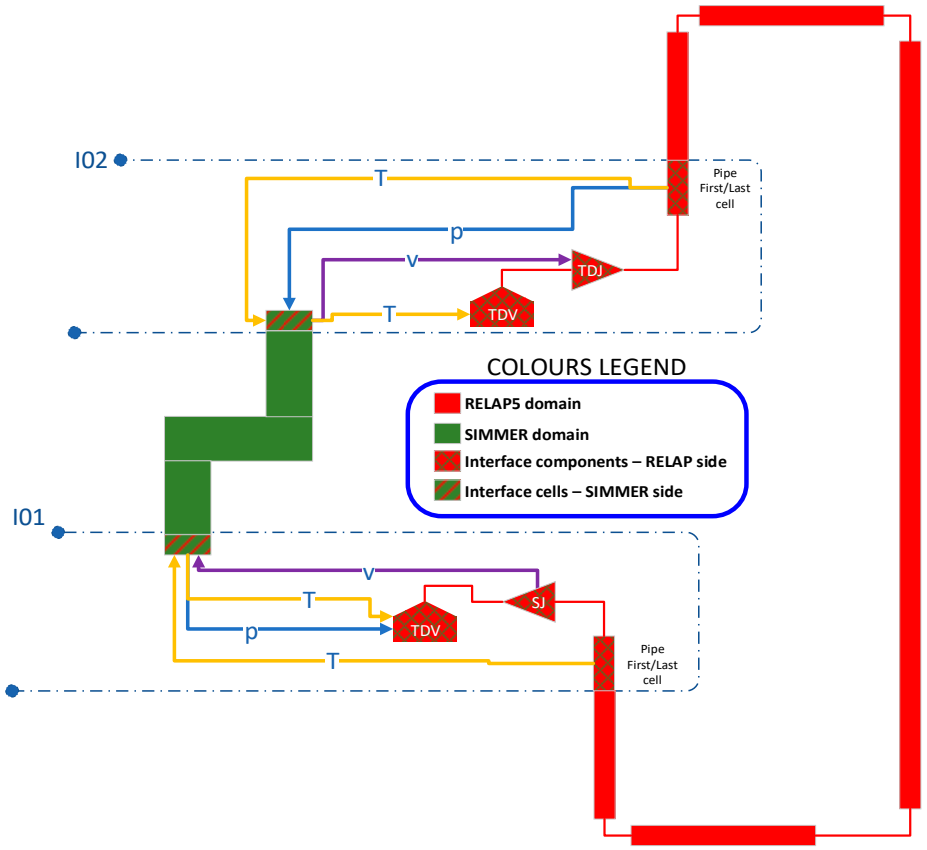

Figure 9. Coupling upgrade for LIFUS5/Mod4 simulations.

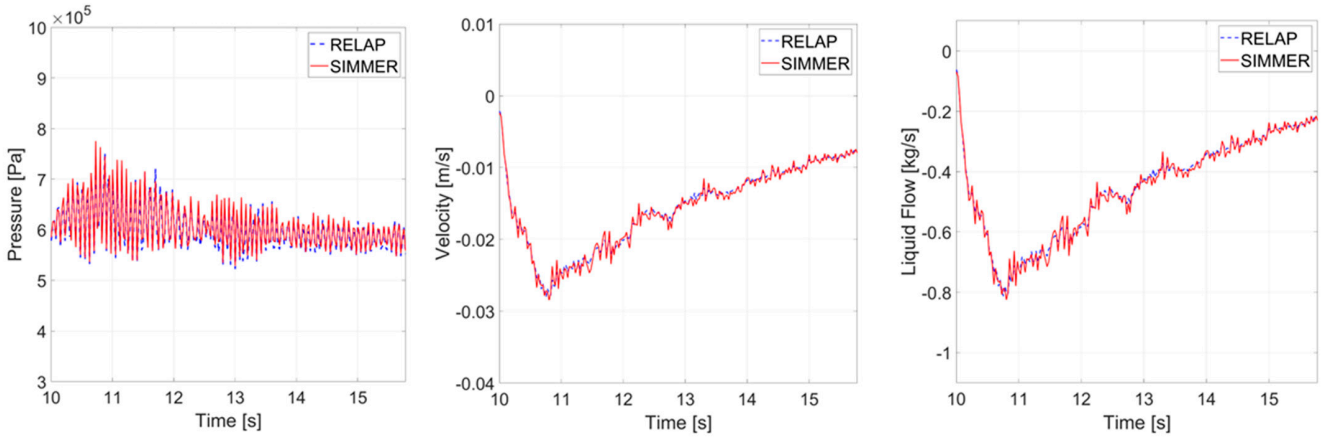

Figure 10. Steady-steady coupling pressure, velocity, and mass flow rate at the interface.

Currently, a new R&D activity is ongoing involving coupling SIMMER code with ANSYS code to simulate fluid–structure interaction [21]. The goal of this activity is to produce a tool needed for the complete analysis of the thermohydraulic and mechanical behavior of relevant systems during incidental scenarios. The tool will be tested and validated against experimental data, to ensure its performance once it is deployed to its designated activities.

The verification and validation activity will follow the schematic shown in Figure 11. Firstly, the SIMMER code, which implements chemical and thermodynamical models of PbLi/water interaction, has been extensively validated against experimental data. This validation activity allowed the complete evaluation of the error introduced when simulating

a real system with this code. The scheme refers to this error as Δ_1 and all these validation activities are extensively described in the literature.

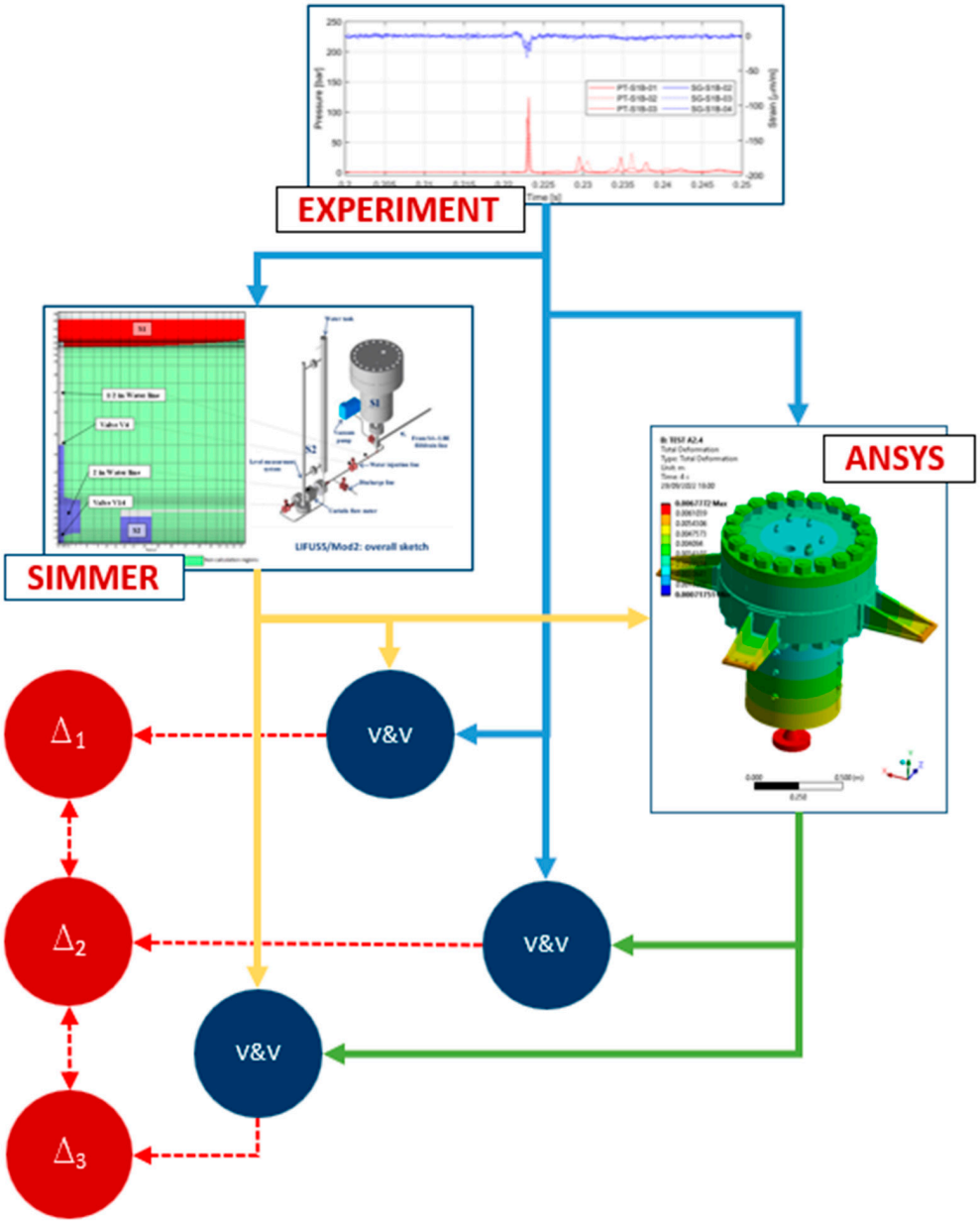

Figure 11. Schematic diagram of the SIMMER–ANSYS code chain's verification and validation (V&V) activity [21].

After this first step is completed, the focus shifts to the verification and validation of simulations performed with the ANSYS code. To do so, several simulations are foreseen to be carried out, replicating the same conditions as those of tests performed in the facilities of the Brasimone Research Centre and for which an extensive database collecting all the needed data is available. For validating the code against a test, the exact geometry of the system is modeled using CAD software (Inventor R2022) and simulated with the ANSYS mechanical code. The readout of the pressure sensors inside the vessel is used as a boundary condition during the simulation, and the readouts of the strain gauges are then compared to their numerical equivalent. This comparison between the experimental data and the ANSYS code alone allows the evaluation of the error introduced during the mechanical simulations, which in Figure 11 is referred to as Δ_2.

The last step of the validation process lies in the evaluation of the precision of the whole chain. In this respect, tests are simulated without the usage of experimental data and only using the codes. The SIMMER code evaluates the pressure transient inside the vessel starting from the geometry and initial conditions of the system. Then, the ANSYS mechanical code evaluates the deformation caused to the vessel. This output is then compared with the experimental output, leading to the error evaluation referred to as Δ_3 in Figure 11.

By performing this extensive validation, the individual errors committed by each code (Δ_1 and Δ_2) and the total error committed by the chain are known, allowing the identification of criticalities or steps viable for optimization. At the current time, validation activities are advancing through a first phase in which the performance of the ANSYS code is being evaluated against time-varying experimental data. In future, the coupling algorithm will be expanded and enhanced and simulations performed using experimental data will be repeated using the code chain method and the data provided by SIMMER as input. This will allow the evaluation of the whole code chain error and address the behavior of the transient during accidental scenarios.

5. Conclusions

The safety issue connected with PbLi/water reaction in the case of a WCLL in-box LOCA is a very complex topic that involves both experimental and numerical activities and has required a lot of effort in the last few years. The main achievements reached during WPBB FP8 EUROfusion Project Horizon 2020 lay the basis of new currently ongoing R&D activities to fulfill the objective of having a qualified code for DSA. This requires the availability of an experimental infrastructure that can perform tests on PbLi/water reaction during an in-box LOCA scenario at integral scale. The LIFUS5/Mod4 facility is designed to address this goal and is being constructed at ENEA Brasimone RC. Alongside this, the development of a code for the deterministic safety analysis of such scenarios is of primary importance. In this framework, the activity consists in RELAP5/Mod3.3 code development to expand simulation capabilities in fusion applications and the development of coupling code tools in order to perform transient analyses considering the chemical, thermo-hydraulic, and structural effects due PbLi/water interaction.

Future works on this topic will be considered once the experimental campaign in the LIFUS5/Mod4 facility is executed and the numerical tool is qualified against provided data.

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Nomenclature

BB	Breeding Blanket
BC	Boundary Condition
BIC	Boundary and Initial Condition
CAD	Computer-Aided Design
CEA	Commissariat Energie Atomique
CFD	Computational Fluid Dynamics
DEMO	DEMOnstration Power Plant
DIAEE	Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica
DICI	Dipartimento di Ingengeria Civile e Industriale
DSA	Deterministic Safety Analysis
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EU	European
FCI	Fuel–Coolant Interaction
FP	Framework Programme
HTC	Heat Transfer Coefficient
ITER	International Thermonuclear Experimental Reactor
JRC	Joint Research Centre
LBE	Lead–Bismuth Eutectic
LMFR	Liquid Metal Fast Reactor
LOCA	Loss Of Coolant Accident
LWR	Light Water Reactor
MHD	Magnetohydrodynamic
P&ID	Piping and Instrumentation Diagram
PbLi	Lithium–Lead
PFD	Process Flow Diagram
PHTS	Primary Heat Transfer System
R&D	Research and Development
RC	Research Center
SYS-TH	SYStem-ThermoHydraulic
TBM	Test Blanket Module
TBS	Test Blanket System
TC	ThermoCouple
TEU	Trititum Extraction Unit
UNIPI	University of Pisa
US	United States
V&V	Verification and Validation
WCLL	Water-Cooled Lithium–Lead
WPBB	Work Package Breeding Blanket

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