Test Series D experimental results for SIMMER code validation of WCLL BB in-box LOCA in LIFUS5/Mod3 facility

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The in-box LOCA (Loss of Coolant Accident) is a relevant safety issue for the design of the WCLL BB. Research activities are ongoing to master phenomena and processes occurring during the postulated accident, to enhance the predictive capability and reliability of numerical tools, and to validate computer models, codes and procedures for their applications. Current status of knowledge requires the availability of qualified and reliable experimental data to support these activities. In view of this, the new separate effect test facility LIFUS5/Mod3 has been commissioned and the Series D experimental campaign is in progress. The tests are focused on the generation of reliable experimental data for the validation of the modified version SIMMER codes for fusion application. Moreover, data will be also used to investigate the dynamic effects of energy release on the structures and to provide relevant feedbacks for the follow up experimental campaigns. The experimental data and results of Test D1.1 are reported and critically discussed, focusing on pressures, temperatures, amount of injected water, and hydrogen production quantification.

Keywords: Chemical Reaction, Code Validation, Test Experiments, LIFUS5/Mod3, WCLL breeding blanket.

1. Introduction

Water Cooled Lithium Lead (WCLL) BB is considered a candidate option for the European DEMO nuclear fusion reactor [1]-[4], and recently considered in the TBM program [5]. A comprehensive study is conducted to address the safety response of WCLL BB system in case of a postulated in-box LOCA. Besides, the reliability of qualified system code for deterministic safety analysis is of primary importance, in view of the evaluation of accidental consequences and mitigating countermeasures. Nevertheless, the separate effect experiments executed in the past are few and not designed to perform validation activity of DSA code [6]. With this aim, the Verification and Validation activity [7] requires to apply a standard methodology to experimental data with reproducible and defined initial and boundary conditions, provided by the new LIFUS5/Mod3 campaign [8]. The methodology is based on a three-steps procedure and through qualitative and quantitative evaluations: 1) the initial condition results, 2) the reference calculation results, and 3) the results from sensitivity analyses. The qualitative accuracy evaluation is performed through a comparison between experimental and calculated time trends based on the engineering analysis, the resulting sequence of main events, the identification of phenomenological windows and of relevant thermo-hydraulic aspects. Finally, the accuracy of the code prediction is evaluated from quantitative point of view by means of selected, widely used, figures of merit [9]. In parallel, a numerical simulation activity is ongoing [10],[11], performed by the modified version of SIMMER-III code, which implements the PbLi/water chemical reaction [12]. Experimental results will also constitute a useful database for the support of new STH/2D coupling calculation tool [13],[14].

The present work describes the results of Test D1.1, executed at ENEA C.R. Brasimone [15]. In particular, pressures, temperatures, amount of injected water, and hydrogen production quantification are reported and critically discussed. The experimental data are used to continue the validation activity on SIMMER code, based on a standard methodology and qualitative and quantitative approaches [11].

2. LIFUS5/Mod3 experimental campaign

2.1 Objective of the experimental campaign

During a postulated WCLL BB in-box LOCA, the phenomena and processes occurring during PbLi/water interaction are governed firstly by the thermodynamic parameters, and then by chemical reaction.

The Series-D experimental campaign focuses on the chemical interaction between PbLi and water, in particular on the validation of the implemented chemical model in SIMMER code. Therefore, focus is given to the relevance of parameter ranges relevant for the WCLL BB and the model object of the validation, as well as, to parameter ranges suitable for the reliable quantification of the test data.

2.2 Series D Test Matrix

Series-D test matrix is reported in Tab. 1. Parameters have been chosen to be representative of the WCLL BB and PHTS systems:

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- The injection pressure is fixed at the same pressure of the WCLL BB PHTS;
- The temperature of the PbLi is fixed to the inlet/outlet temperature of the PbLi in the WCLL BB breeding zone;
- The temperature of the water is set as the inlet and outlet temperatures of the water in the WCLL BB breeding zone;
- The diameter of the injector orifice is not relevant to SIMMER-III chemical model validation, while the amount of water injected is. The 4 mm size is thus adopted for D-series and a fixed amount of water is loaded into SBL.

Table 1. Series-D Test Matrix.

Test Series D	Mass of water [g]	Water T [°C]	PbLi T [°C]	Injection Pressure [bar]
#1	50	295	330	155
#2	50	330	330	155
#3	50	295	450	155
#4	100	295	330	155
#5	150	295	330	155

2.3 LIFUS5/Mod3 facility description

The LIFUS5/Mod3 is a separate effect test facility, designed and constructed at ENEA CR Brasimone [15]. It can operate with different heavy liquid metals like Lead-Lithium and Lead-Bismuth eutectic alloys and pure lead. The P&ID is shown in Fig. 1, while the extensive description of the facility is reported in Ref. [8]. The main part of the facility are:

- Reaction vessel S1B where the reaction between liquid PbLi and water occurs;
- Water storage and injection line: SBL pipe is used to store and bring water to test condition, an injection line connects the bottom of SBL to the bottom of S1B; pressure is maintained by an argon tank connected to the top of SBL;
- Safety expansion vessel S3V connected to S1B by two rupture disks;
- PbLi storage tanks S4B1 and S4B2 for fresh and exploited alloy;
- Hydrogen extraction and measurement line.

The installed instrumentation and dedicated data acquisition system (up to 10 kHz) provides meaningful and reliable data such as pressure wave propagation, temperatures, strain on structures, and quantification of the hydrogen production.

3. Description and Analysis of Test D1.1

3.1 Test execution phase

Test D1.1 was executed on April 12th 2019 at 14:47:49. It corresponds to Test #1 of the test matrix (Tab. 1).

The initial test conditions were achieved accordingly with the specifications with satisfactory accuracy. The main parameters at the Start of the Transient (SoT) are summarized in Tab. 2. The injection is executed using the valve VP-SBL-06 (identified as VP6 in Fig. 1). The acquisition system worked properly. The strain gages and pressure transducers signals were acquired at 10 kHz, thermocouples signals at 50 Hz. The closure of valve VP-SBL-06 was automatically activated after 1 second. The water injection in S1B lasted 1.10 s (from cap rupture to VP-SBL-06 fully closed). The amount of water injected in S1B was pre-defined, as 50 g.

Table 2. Test D1.1 main parameters at Start of Transient.

Parameter	Unit	Design	Actual
Pressure $_{S1B}$	bar	1	2.1
Temperature $_{PbLi}$	°C	330	327
Gas Volume $_{S1B}$	liter	3.423	3.457
Pressure $_{SBL}$	bar	155	161
Temperature $_{H2O}$	°C	295	298
Mass $_{H2O}$	g	50	50

In detail, Test D1.1 can be divided in three main phases:

1. Pressurization of water injection line [-7.2 ms to 42.5 ms], *from pressure rise in injection line (valve VP-SBL-06 start to open, Start of Transient SoT) to rupture cap occurrence (Start of Injection SoI)*. The pressure trend in the injection line was acquired by the fast pressure transducers PT-SBL-01 and PT-SBL-02 at a frequency of 10 kHz, see blue lines in Fig. 2. It seems that the three injection valves are subject to partial leaking, allowing water and gas to move forward and pressurizing the piping between VP-SBL-07 and the injector device to about 12.5 bar. Moreover, it is noticed that the pressure in the injector line (recorded by PT-SBL-02) started to rise at -7.2 ms, thus before the low level of the micro-switch signal of valve VP-SBL-06 open was on, set to t = 0 ms. The sensor recorded a pressurization rate of 2470 bar/s. The same behavior can be visible in the pressure recorded by PT-SBL-01, which recorded a decrease of pressure. The possible reason can be explained as twofold: 1) there is a delay in the micro-switch signal record, thus the valve actually opened slightly before the low level of micro-switch signal passed from 1 to 0, 2) there is a leakage through the valve VP-SBL-06. The valve opening time was 10.1 ms, as recorded by the high level of the micro-switch signal of valve VP-SBL-06. During this time, the pressure upstream the injecting valve (PT-SBL-01) was affected by a trifling water hammer effect due to the VP-SBL-06 movement. Indeed, the pressure slightly increased up to the high level of the micro-switch signal is 1. Once valve VP-SBL-06 was fully opened, the 50 g pre-charged of water filled the injection line among valve VP-SBL-06 and injector cap inside S1B.

This condition was maintained until cap rupture, which occurs slightly before as expected at a pressure of 117 bar (Fig. 2 and Fig. 3). Fig. 4 shows the pressure time trend measured in the injection line, the corresponding saturation temperature and the water temperature upstream (TC-SBL-04) and downstream (TC-SBL-05) valve VP-SBL-06. It is possible to note that during phase 1 (i.e. before cap rupture), water was in subcooled condition. Moreover, before VP-SBL-06 opening TC-SBL-05 measured about 198°C and was heated by injected hotter water up to about 250°C. However, due to the peculiarity of this test and the low amount of injected water, the pipeline was filled almost completely with Argon. Therefore it should be better to consider the structure temperatures instead of the fluid temperatures, which were fixed at 300 °C.

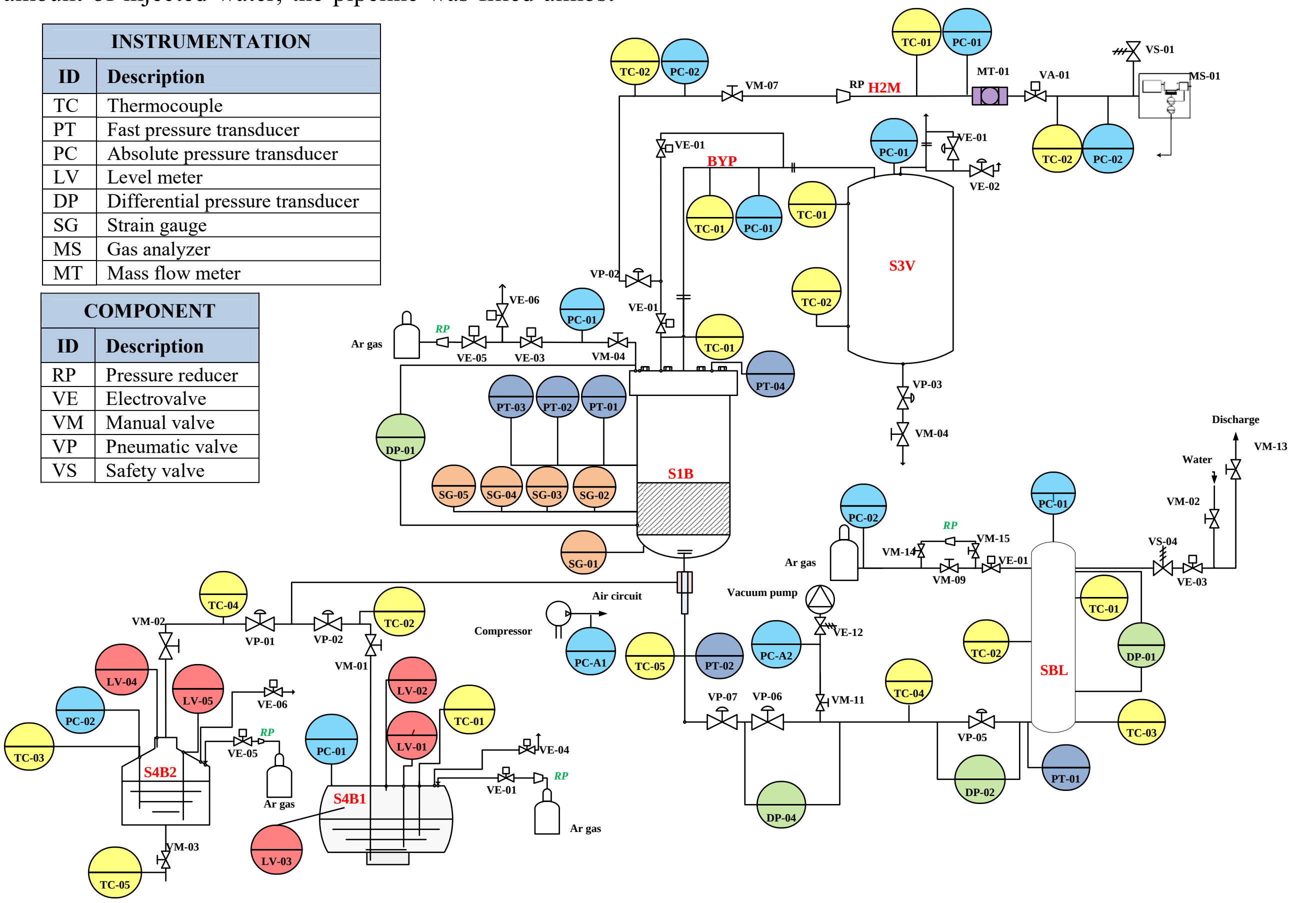

Fig. 1. P&ID of LIFUS5/Mod3 facility.

2. Water - PbLi interaction [42.5 ms to 1145.2 ms], *from cap rupture occurrence to valve VP-SBL-06 fully closed (End of Injection EoI)*. This phase can be divided into three different sub-phases:

2a. Flashing of injected water [42.5 ms to 48 ms], *from cap rupture occurrence to ending of first pressure peaks*.

2b. Thermodynamic interaction [48 ms to ~100 ms], *from ending of first pressure peaks to start increase of temperatures*.

2c. Chemical interaction [~100 ms to 1145.2 ms], *from start increase of temperature to valve VP-SBL-06 fully closed (EoI)*.

As soon as cap rupture occurred and water started to be injected in S1B, the pressure in injection line (Fig. 2) decreased rapidly. PT-SBL-02 upstream the injector (dotted blue line) recorded a decrease from 119.2 bar to 105 bar, then its decrease was stopped by the counter pressure arisen in S1B due to PbLi-water interaction and rise again up to about 120 bar. It is worth to underline that the discontinuity of pressure recorded by PT-SBL-02, and evidence of cap rupture, showed a lag of 1.4 ms in which corresponded an increase of pressure from 117 to 119.2 bar. This is due to a damping effect of gas in the injection line: water had been already injected but the gas occupied the same volume with an increase of pressure. Then, when also gas moved, the sensor recorded the discontinuity in pressure. In the same figures the pressure time trends in SBL (continue blue line, PT-SBL-01 installed upstream VP-SBL-05) is reported. Both of pressures decreased monotonously down up to about 99 and 110 bar, respectively for PT-SBL-02 and PT-SBL-01, in 0.8 s and then kept constant up to VP-SBL-06 closure instant.

The pressurization of S1B (red lines in Fig. 2 and Fig. 3) was characterized by three initial very narrow pressure peaks, lasting about 4 ms (see PT-S1B-01/02/03), due to the flashing of water inside the tank. Their maximum value decreased from 209 to 82 bar. In particular, the first peak seems to be the instantaneous flashing of the injected water, followed by the expansion of steam and gas through the perforated top plate of the test section towards the gas plenum (decrease of pressure), then water is injected again in S1B causing the second pressure peak, and again the expansion of steam/gas towards the plate, and so on. The high frequency acquisition time (10 kHz) permitted to recognize in each of the three pressure peak the different signals recorded by the pressure transducers positioned at 120° at the same level in circumferential direction (Fig. 3). This behavior reflects the pressure wave propagation inside the reaction vessel. The first narrow peaks were acquired by only PTs positioned below PbLi free level (PT-S1B-01, PT-S1B-02 and PT-S1B-03), thanks to the sampling frequency working successfully at 10 kHz. The PT set in S1B cover gas (PT-S1B-04) provided a characteristic oscillating measurement (dark red line in Fig. 2) due to the sloshing phenomena occurred in the reaction tank. After about 100 ms, the pressure inside S1B recorded a monotonously increase up to about 87 bar, which stabilized at valve VP-SBL-06 closure.

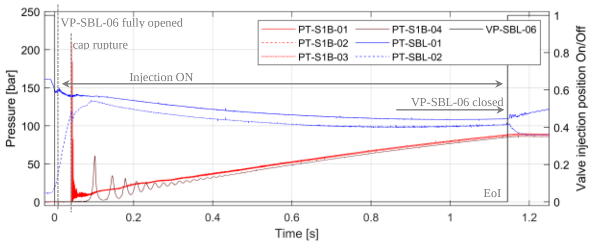

Fig. 2: Pressure time trends in S1B reaction vessel and SBL injection line (zoom on 0÷1.2 s)

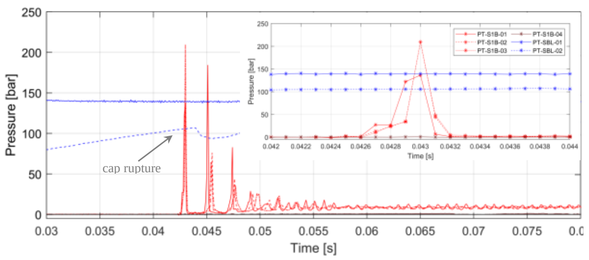

Fig. 3. Pressure time trends in S1B reaction vessel and SBL injection line (zoom on 30÷80 ms).

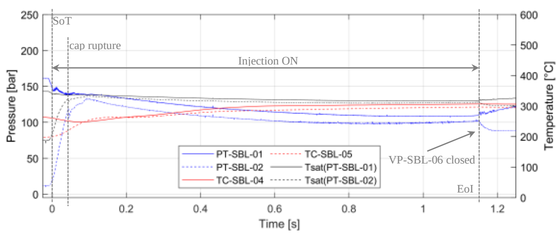

Fig. 4. Pressure and temperature time trends in the injection line (zoom on 0÷1.2 s).

During the second phase of the transient, water temperature in the injection line remained slightly lower than saturation temperature (see Fig. 4 the red and black dotted lines for TC-SBL-05 upstream the injector).

The relevant temperature time trends measured by TCs set on levels and rings of the test section are shown in Fig. 5. For example, the code TC-R31-L2 specifies the first TC in Ring 3 and Level 2. Ring 1 and Level 1 are the closest to the injector, Ring 6 and Level 6 are the farthest one. During the PbLi-water interaction, the TCs positioned at lower levels, closest to the injector (TC-R13-L1, TC-R11-L2 in Fig. 5) were cooled by the initial expansion of water jet in S1B. The cooling effect was reduced in higher levels and delayed in time, because steam moved upwards. The minimum value of temperature was reached by 195.04 °C recorded by TC-R13-L1. The cooling effect was reduced also moving radially, indeed the lower values of temperature were recorded by the TCs positioned in the internal radius, and moving outwards, the temperatures are slightly higher (reduced cooling effect) or the peaks are delayed in time (radial expansion of water jet). This behavior reflects the thermodynamic interaction between PbLi and water, which characterize the phase 2.b. The flashing and cooling effect of water jet, and its expansion upwards and outwards led to a decrease of temperatures inside the melt. The temperature behaviors changed drastically during the transient. The cooling effect is due to the water jet inside the reaction vessel. However, at the interface between PbLi and water, the jet expands and the contact area between two fluids increases. At this interface, the chemical reaction occurs, generating hydrogen and heat. Indeed, the expansion of the jet upwards and outwards during the transient led to a delayed increase of temperatures due to the chemical reaction between PbLi and water at the interface and the temperatures increased as recorded by outer and higher thermocouples (TC-R13-L1, TC-R11-L2, TC-R13-L5, and TC-R12-L6). The highest value of 546.67 °C was reached by TC-R12-L6. The experimental data seem to confirm the dynamic of the PbLi/water interaction, indeed the thermodynamic interaction is the predominant process occurring in the first hundreds of milliseconds after the cap rupture, followed by the secondary process involving the chemical reaction, which generates hydrogen and the increase of temperature.

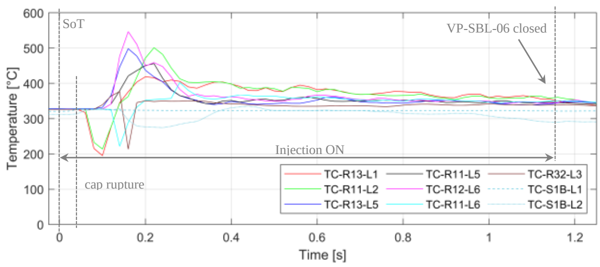

Fig. 5. Relevant temperature time trends in S1B test section (zoom on 0÷1.2 s)

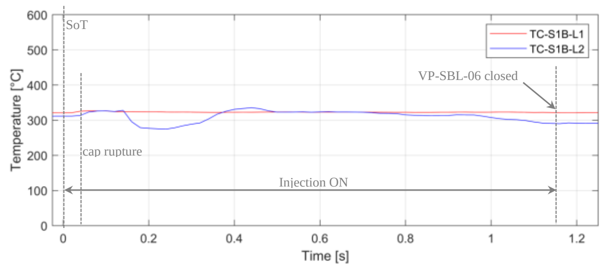

Fig. 6. Temperature time trends in the upper levels of S1B test section (zoom on 0÷1.2 s)

The temperature time trends measured by the 2 TCs set at PbLi free level on the upper side of perforated plate are depicted in Fig. 6. The temperature measured by TC-S1B-L1 did not show any significant variation, indeed it measured the temperature of the PbLi alloy and it was not affected by the cooling effect of injected water, neither by the heat generated by the chemical reaction, being positioned in the upper part of the perforated plate, outside the interaction zone. On the contrary, TC-S1B-L2 measured the characteristic oscillation behavior of the sloshing effect. The TC was invested by the free level of PbLi and covered and discovered during the transient. After the closure of the valve VP-SBL-06, the sloshing phenomena stopped and the thermocouple measured a lower value compared to SoT, indeed once the pressure in S1B and injection line equalized, PbLi dropped down towards the injection line and the thermocouple remained uncovered.

The strain time trends measured on the outer surface of S1B are depicted in Fig. 7, and the strain versus pressure time trends in Fig. 8. Zooming the interaction phase, it is possible to highlight first distinct peaks due to pressure waves propagated in PbLi as a result of cap breaking and the instantaneous water flashing. SG-S1B-01, positioned in the bottom part of the reaction tank in radial position, did not record any variation of strain during the second transient phase. On the contrary, the other strain gages positioned on the cylindrical shell of S1B recorded different peaks. The lower value of first peaks was recorded by SG-S1B-05 positioned in axial position which is -49 μm/m, while the others positioned in circumferential direction measured higher values, in particular 50, 51.2 and 53.2 μm/m, respectively for SG-S1B-02, SG-S1B-04, and SG-S1B-03. It is worth to underline two points:

1) Each initial peak showed the same profile and minimum/maximum value recorded by the strain gauges. Therefore, the cap breaking and the water injection seems to not occur perfectly in S1B axial direction but moved to one preferential direction. SG-S1B-03 recorded the maximum value.

2) The S1B structure seems to have a dynamic behavior due to a high acceleration. Indeed, the first peaks of SGs are perfectly overlapped with the pressure peaks recorded by PTs, as well as the third peaks of SGs are overlapped with the second pressure peaks recorded by PTs. These peaks are originated from the cap rupture and the pressure wave propagation due to the injected water. Instead, the second peaks recorded by SGs, which are in the middle of the pressure peaks, seems to be the effect of the dynamic behavior of the structure, like a spring, or an earthquake. This hypothesis should be confirmed only by a modal analysis, in which the dynamic properties of systems in the frequency domain are evaluated. The SGs showed a monotonously deformation rates up to valve VP-SBL-06 closure, as well as the pressure rates behavior. They were similar for SG-S1B-02/04, and lower for SG-S1B-05. In particular SGs measured deformation rates of 38, 70.7, 74.3 and 88.9 μm/m·s, respectively for SG-S1B-05, SG-S1B-02, SG-S1B-04 and SG-S1B-03. At valve closure, the same SGs measured values of 42, 78, 82 and 98 μm/m.

3. **Ending phase [1145.2 ms to End of Transient EoT],** *from valve VP-SBL-06 fully closed (EoI) to EoT (t = 60 s)*. After valve VP-SBL-06 closure (it occurred at 1.1452 s, see Fig. 2), tank SBL was isolated from S1B reaction vessel. Therefore the pressure in SBL started to increase due to the connection with upstream argon cylinder (see PT-SBL-01, blue continuum line). The PT-SBL-02 set in the injection line downstream VP-SBL-06, measured a sudden pressure decrease (see blue dotted line), as consequence of disconnected pressurization system (SBL). The pressure equalization between S1B and the injection line downstream VP-SBL-06 occurred just after the valve closure at about t = 1.145 s. The pressure in the injection line decreased to about 88 bar, maintaining the same pressure of S1B. Indeed, at this time, the injection system and the reaction vessel are in connection.

At valve VP-SBL-06 closure, the measured temperatures in S1B were generally higher than at SoT in any levels. The average values are 337, 344, 341, 345, 342 and 344°C, respectively from Level 1 to Level 6. In the phase following VP-SBL-06 closure, TCs acquired temperature changes in S1B towards thermal equalization. The TC set at PbLi free level in S1B in the upper part of test section, and in particular TC-S1B-L2, registered a sudden variation of temperature as soon as VP-SBL-06 closed, clear evidence of the PbLi drops down towards the injection line (see Fig. 6).

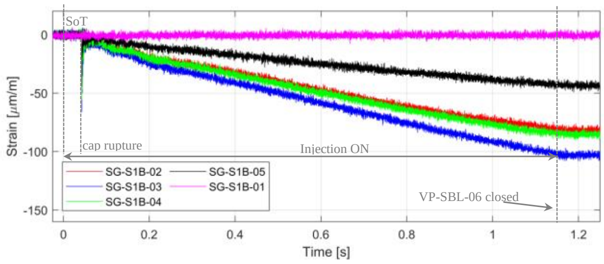

Fig. 7. Strain time trends in S1B (zoom on 0÷1.2 s).

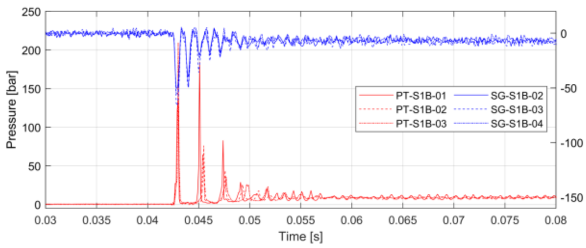

Fig. 8. Pressure and strain time trends in S1B (zoom on 30÷80 ms).

3.2 Hydrogen extraction phase

At the end of the injection procedure, the gas extraction line was opened. The mass flow controller and the hydrogen analyzer (Fig. 9) recorded data for almost a day, however, the majority of the gas has been analyzed within the reliable range of the flow meter, resulting in a total of 113.56 ± 1.06 nl and 3.07 ± 0.18 g of hydrogen at 4 hours 45 minutes from the beginning of the analysis (Fig. 10). This result is in the range foreseen and calculated by the stoichiometry. Indeed, for 50 g of injected water, the hydrogen produced by the reaction shall be in the range between 2.7 and 5.5 g, according to the predominant reaction between PbLi and water.

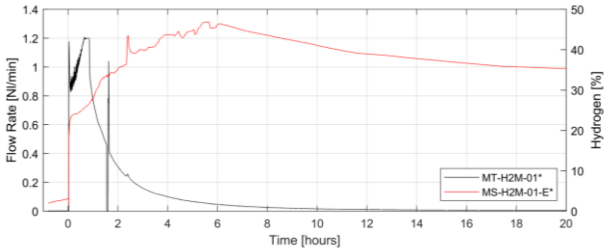

Fig. 9. Gas mass flow rate (MT-H2M-01) and hydrogen concentration percentage (MS-H2M-01) time trends during the extraction phase.

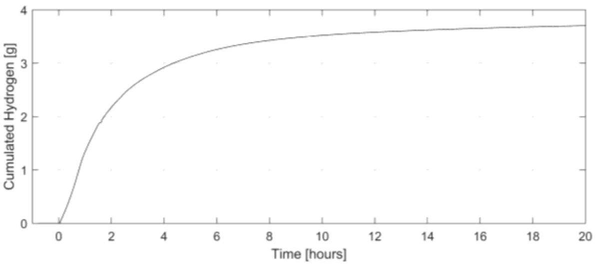

Fig. 10. Cumulated hydrogen time trends during the extraction phase.

4. Conclusions and perspectives

The in-box LOCA accident is a relevant safety issue for the design of the WCLL BB design. Research activities are ongoing to master phenomena and processes occurring during the postulated accident; to enhance the predictive capability and reliability of numerical tools, to validate the computer models and codes; and to qualify the computer codes and the procedure for their applications. Current status of knowledge requires the availability of qualified and reliable experimental data to support these activities. In view of this, the new facility LIFUS5/Mod3 has been set-up and D-series experimental campaign is in progress.

Test D1.1 has been executed on the basis of the planned test matrix. The objective of the Test D1.1 was successfully achieved and the acquired measurements contributed to enlarge existing databases for the validation of the modified version SIMMER codes for fusion application.

The analysis of the thermo-hydraulic data led to a comprehensive knowledge of the phenomena occurring during the test, as well as obtaining defined initial and boundary conditions. The transient can be divided into three phases according with the pressure trend. Data obtained by pressure transducers and strain gages permitted to investigate the dynamic effects of energy release on the structures. Indeed, PTs recorded the pressure waves propagation evidenced by narrow pressure peaks at which correspond a damping effect on the structure recorded by strain peaks. Data recorded by TCs permitted to analyze the effect of the interaction/reaction between PbLi and water. Firstly, a cooling effect was highlighted closer to the injector, then, at the jet expansion interface, the chemical reaction occurred. The minimum and maximum temperature were 195 and 547 °C, respectively. Finally, the quantification of the hydrogen produced by the reaction confirmed the theoretical stoichiometric evaluation of the hydrogen produced considering 50 g of water. Moreover, it permitted to obtain reliable data to be used for SIMMER code validation and of the coupled RELAP5/SIMMER approach.

In the next future, the V&V activity is going to step forward. Indeed, during a postulated WCLL BB in-box LOCA, the main phenomena occurring during the interaction strictly depend on the amount of water injected into PbLi, which is sensitive to pressure difference between water line and PbLi vessel, size of break and water flow condition, i.e. the instauration of the chocked flow. In order to investigate these phenomena, connected to the safety of the WCLL BB design, the LIFUS5/Mod3 facility will be modified so as to fully simulate the LOCA event, from the break in the water pipe up to the complete equilibrium between water line and the PbLi box.

Nomenclature

BB	Breeding Blanket
BYP	Bypass line
CR	Research Center
DEMO	DEMOnstration Fusion Reactor
DSA	Deterministic Safety Analysis
DP	Differential Pressure Transducer
EoI	End of Injection
EoT	End of Transient
H2M	Hydrogen measurement line
LOCA	Loss Of Coolant Accident
LV	Level Meter
MS	Gas Analyser
MT	Mass flow meter
PbLi	Lithium lead
PC	Absolute Pressure Transducer
PT	Fast Pressure Transducer
RP	Pressure Reducer
SBL	Water tank and Injection Line
S1B	Reaction vessel
S3V	Expansion vessel
S4B1	Fresh PbLi storage tank
S4B2	Depleted PbLi storage tank
SG	Strain Gauge
SoI	Start of Injection
SoT	Start of Transient
STH	System Thermo Hydraulic Code
TC	ThermoCouple
VE	Electrovalve
VM	Manual Valve
VP	Pneumatic Valve
VS	Safety Valve
WCLL	Water Cooled Lithium Lead

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