EUROfusion

WPBB-CPR(18) 20214

M. Eboli et al.

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Preprint of Paper to be submitted for publication in Proceeding of 30th Symposium on Fusion Technology (SOFT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Experimental activities for in-box LOCA of WCLL BB in LIFUS5/Mod3 facility

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The new experimental facility LIFUS5/Mod3 has been designed, manufactured and installed to investigate the phenomena connected with the thermodynamic and chemical interaction between lithium-lead and water in case of in-box LOCA (Loss of Coolant Accident) of the WCLL breeding blanket concept and to validate the chemical model implemented in SIMMER code for fusion application. In order to fulfill these objectives, the necessary step is to obtain data, suitable to code validation, by means of an experimental campaign in LIFUS5/Mod3 facility, executed with controlled initial and boundary conditions. Thus, specific instrumentation and dedicated data acquisition system are installed on the facility to provide meaningful and reliable data.

The final aim of the LIFUS5/Mod3 campaign is the SIMMER code validation, applying the standard methodology to post-test analyses. Besides, the expected outcomes of the tests are the improvement of the knowledge of physical behavior and of understanding of the phenomena, the investigation of the dynamic effects of energy release towards the structures and of the chemical reaction with the consequent hydrogen production, and the enlargement of the database for code validation.

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], [2]. 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 [3]. With this aim, the Verification and Validation activity ([4], [5]) requires to apply a standard methodology to experimental data with reproducible and defined initial and boundary conditions, provided by the new LIFUS5/Mod3 campaign. In parallel, a numerical simulation activity is ongoing [6], performed by the modified version of SIMMER-III code, which implements the PbLi/water chemical reaction [7]. Experimental results will also constitute a useful database for the support of new STH/2D coupling calculation tool [8].

The presented work aims to describe the experimental facility LIFUS5/Mod3, which has been designed and constructed at ENEA CR Brasimone.

2. LIFUS5/Mod3 facility

The LIFUS5/Mod3 separate effect test facility is an upgrade version of the previous configuration of LIFUS5/Mod2 [9]. The P&ID is shown in Fig. 1, and the main design characteristics are listed in Tab. 1. It is composed by four vessels and the water injection system:

- S1B reaction vessel, where the reaction between liquid PbLi and water occurs,
- S3V expansion vessel connected to S1B,
- S4B1 storage vessel for the fresh PbLi,
- S4B2 storage vessel for the depleted PbLi,
- SBL water injection system.

The main vessel S1B is about 30 liter of geometrical volume, filled with PbLi during tests up to about 50 mm from the top flange and covered with Argon inert gas maintained at about 0.2 barg. It is completely closed and isolated from the ambient by the top flange sealed with a Ring Joint gasket SA316. Penetrations are made in S1B top flange for allowing the installation of the instrumentation and connections (i.e. thermocouple, fast pressure transducer, absolute pressure transducer, hydrogen extraction line, expansion line, gooseneck sealing system for the passage of the thermocouples installed in the test section, top flange of differential pressure transducer). On the cylindrical shell, three penetrations are present to install PT positioned at 120° and one penetration to install the lower flange of the DP. On the external surface, three strain gauges are installed in circumferential position, one along the vertical axis and one on the bottom of S1B in radial position. The layout was chosen based on study of Ref. [10]. On the bottom, 2" penetration provides the PbLi charging and discharging, and the water injection. S1B is

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INSTRUMENTATION	
ID	**Description**
TC	Thermocouple
PT	Fast pressure transducer
PC	Absolute pressure transducer
LV	Level meter
DP	Differential pressure transducer
SG	Strain gauge
MS	Gas analyzer
MT	Mass flow meter

COMPONENT	
ID	**Description**
RP	Pressure reducer
VE	Electrovalve
VM	Manual valve
VP	Pneumatic valve
VS	Safety valve

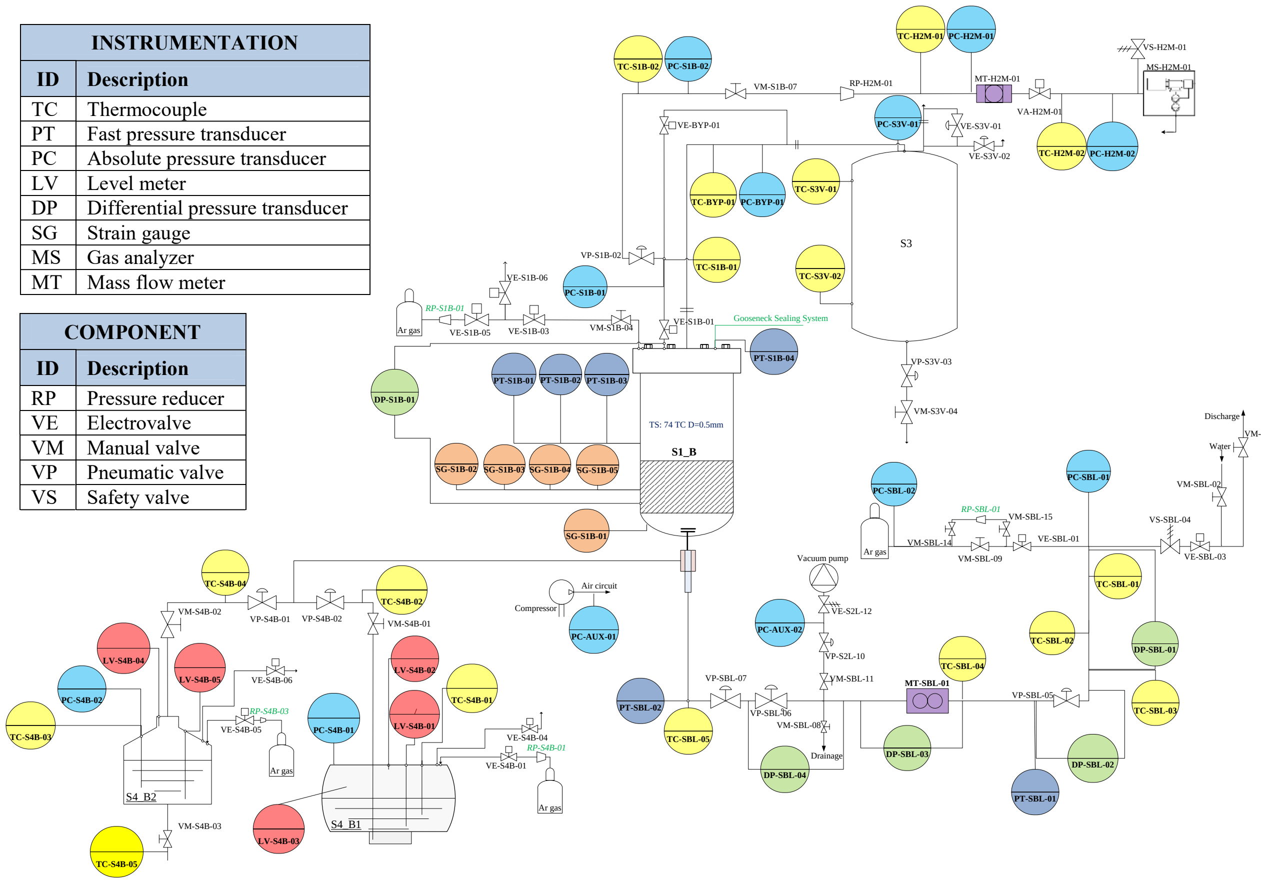

Fig. 1. P&ID of LIFUS5/Mod3 facility

Tab. 1. LIFUS5/Mod3: vessels design features

COMPONENT	PARAMETER	VALUE
S1B Reaction vessel	Volume [m^3]	0.03
	Inner diameter [m]	0.257
	Height [m]	0.5555
	Design pressure [barg]	200
	Design temperature [°C]	500
SBL Water pipe	Volume [m^3]	0.004047
	Inner diameter [m]	0.0429
	Design pressure [barg]	200
	Design temperature [°C]	350
S3V Dump vessel	Volume [m^3]	2.0
	Inner diameter [m]	1
	Design pressure [barg]	10
	Design temperature [°C]	400
S4B1 Fresh PbLi	Volume [m^3]	0.40
	Inner diameter [m]	0.544
	Length [m]	1.56+ends
	Design temperature [°C]	450
S4B2 Depleted PbLi	Volume [m^3]	0.40
	Inner diameter [m]	0.544
	Length [m]	1.56+ends
	Design temperature [°C]	450

connected to the dump tank S3V by means of a 2” to 3” line. Two rupture disks are in charge to ensure that the pressure in S1B does not exceed 200 bar during the test.

PbLi in S1B is filled and drained, just before and after each test respectively (Fig. 2). Fresh PbLi is stored in the liquid metal storage vessel S4B1 from which the filling is operated. The vessel is instrumented by one continuum level meter and two on/off (for high and low level), one PC, one TC. Depleted PbLi is drained in the pivot vessel S4B2 after each experiment.

The injection line (Fig. 3) varies from 1½” to ½” Swagelok line. It is instrumented to achieve a reliable measure of total mass and mass flow rate of injected water, relevant to the validation of the chemical model in SIMMER-III code. To characterize the injected water, four DP and a Coriolis mass flow meter are installed in the line. The differential pressure transducers are installed:

- in the vertical section of the line to characterize the water level and therefore the amount of injected water,
- across valves VP-SBL-05, VP-SBL-06 and Coriolis mass flow meter to characterize the pressure drops.

Valves VP-SBL-05 and VP-SBL-06 are fast actuated, with an opening time < 0.3 s to reach a complete opening position. For this reason, an independent air compressed line was needed to feed the 1” connector on the valve actuator. Moreover, TC and PT are installed in the line and before the injector device to characterize the water from thermo-hydraulic point of view. The water is charged from the top of SBL, and the connection with the Argon gas line provides to set and keep the injection pressure according with the test specifications.

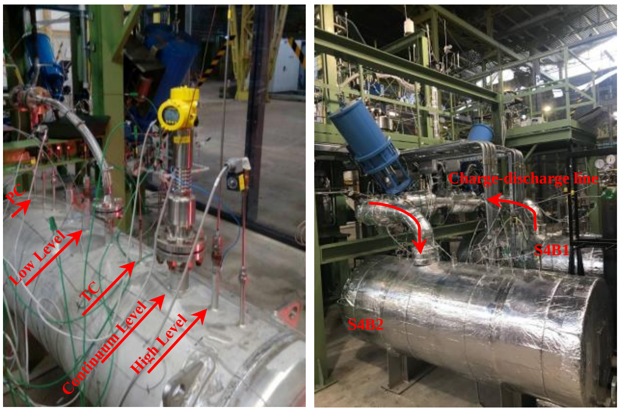

Fig. 2. PbLi storage vessels and charge/discharge line

2.1 Injection device

The water injection system enters from the bottom of the vessel S1B in central position (Fig. 3). The injector orifice is covered by a protective cap, made of brass, 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, after the drainage of PbLi. The dimensions of the orifice and of the notch permit to calibrate the mass flow rate of the injected water and the pressure at which the protective cap will be broken and therefore the injection pressure. To ensure that cap rupture occurred at scheduled pressure, a calibrated notch was executed by the ENEA workshop. Tests were carried out to calibrate the depth of the notch and, consequently, the value of the resisting section.

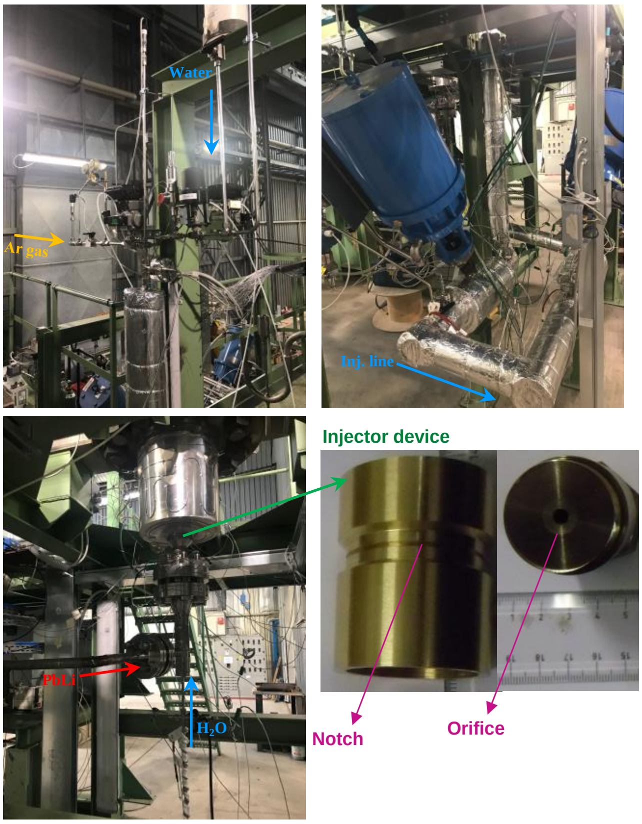

Fig. 3. Water injection line and injector device

2.2 Instrumentation, control and data acquisition systems

Several types of instrumentation are connected to the vessels and pipes to acquire a full range of mechanical and thermo-dynamical records such as pressure, temperature, strain, level, mass flow rate, and hydrogen concentration during the experiments. The data acquisition frequency is up to 10 kHz.

LIFUS5/Mod3 DACS (Data Acquisition and Control System) is realized using National Instruments hardware and software. In particular, a mix of Compact Field Point and Compact RIO modules are used as hardware. LIFUS5/Mod3 DACS architecture is logically divided in two separate sections: real time control and data acquisition (CTRL) and control, interlock and safety system (CISS). CISS is a separate subsystem dedicated to the protection of the operators and of the plant. CTRL is divided into the Human Machine Interface (HMI) and Supervisory Control And Data Acquisition (SCADA). The HMI and SCADA run on standard x86 PC/Workstation and it is developed using LabVIEW software. All components will be connected using standard Ethernet lines.

2.3 Test section design and assembling

The test section (Fig. 4 and Fig. 5) is configured in order to have an axial-symmetric geometry. With this configuration, the phenomena related to HLM/water interaction take place inside the region delimitated by the test section itself, maximizing, as far as possible, the interaction and therefore the chemical reaction between PbLi and water.

The design of the frame and of the holed plate (Fig. 4) was established considering the temperature map evaluated by SIMMER-III pre-test analyses. The frame, welded on the top flange, is completely immersed in the PbLi. A holed plate delimits the interaction zone of the PbLi and water. The jet of subcooled water, in fact, hitting on the plate, breaks down and the water is forced to interact with the PbLi. At the same time, the holes permit to the vapor and to the hydrogen generated by the reaction to rise towards the upper plenum of the S1B vessel. The lateral side of the frame, instead, is completely open. In this way, the dynamic pressure transducers and the strain gauges positioned on the cylindrical surface of the vessel are able to record the pressure waves and the elastic deformation, respectively.

Thermocouples are installed at six different levels between the injector and the holed plate, in circular layout on six diameters. By means of this configuration, the thermocouples are uniformly distributed in radial direction and are able to map the temperature trend during the exothermic chemical reaction. Moreover, two thermocouples are positioned between the holed plate and the inner surface of the top flange to control the level of the PbLi during the charging phase. A total of 74 K-types thermocouples of 0.5 mm diameter are installed in the test section.

Fig. 4. Test section assembly and instrumentation

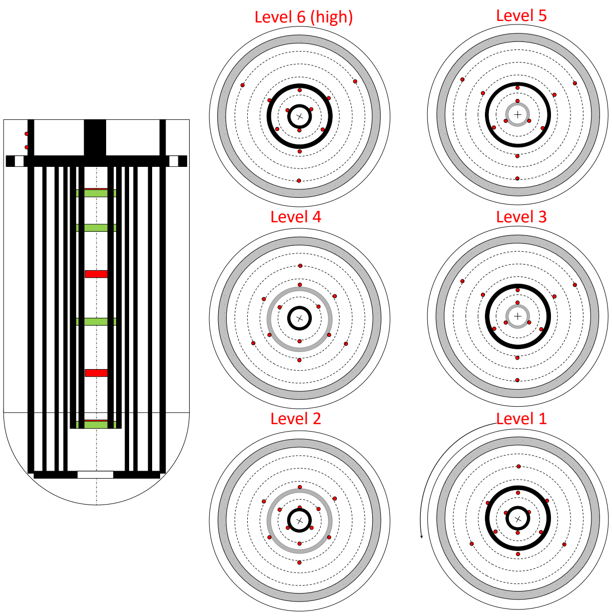

Fig. 5. Layout of thermocouples

2.4 Hydrogen measurement system

A gas analyzer detects the hydrogen produced by the chemical reaction between PbLi and water. The instrument is able to quantify and continuously analyze the gas flowing from two different parts of the facility, from the hydrogen extraction line in normal operation, or from the expansion line, if the first rupture disk between S1B and S3V breaks.

Once the injection of water is completed, the gas produced in the reaction vessel S1B, and containing argon, water vapor and hydrogen, flows towards the hydrogen system measurement by valve VP-S1B-01. The operator actuates the system opening the valve. The pressure is reduced from 155 bar to 2 bar by a pressure regulator, and then the gas mixture flows through a mass flow controller, which has a double purpose: measuring the gas mass flow rate, and maintaining a constant flow rate at the gas analyzer. A safety release valve (VS-H2M-01) is installed in the line to protect the instrument if the pressure is above the limit.

If the pressure in the S1B reaches peak values above the vessel design pressure, a rupture disk breaks and the gas discharges in the expansion vessel S3V. Thus, in the connecting line between S1B and S3V two different rupture disks are installed and between them, the second point of sampling is foreseen.

3. Test matrix

The experimental campaign is planned executing ten tests (D series: five with fresh PbLi and a pre-defined amount of injected water, listed in Tab. 2) in order to:

- obtaining reliable, reproducible, and detailed experimental data with controlled initial and boundary conditions by means of accurate instrumentations, to be compared with the numerical pre-and post-test calculations;
- improving the knowledge of physical behavior and understanding the phenomenon involved during the interaction/reaction;
- quantifying of the energy released by the exothermal chemical reaction and the hydrogen production;
- validating SIMMER code with focus on the implemented chemical model by means of the hydrogen measurement system;
- investigating the dynamic effects of energy release on the structures,
- assessing the reliability of the coupled RELAP5/SIMMER approach and providing the preliminary feedbacks to set-up the chain of codes for analysis of the "in-box-LOCA" in support to the design of WCLL BB.

Tab. 2. LIFUS5/Mod3 D Series test matrix with fresh PbLi

#	$D_{orifice}$ [mm]	P_{ini} [bar]	Injected water [g]	T_{PbLi} [°C]	T_{H2O} [°C]
1	4	155	50	330	300
2	4	155	100	330	300
3	4	155	150	330	300
4	4	155	50	330	285
5	4	155	50	330	325

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. Indeed, experiments performed in the past were not designed for code validation purposes.

In view of this, the new facility LIFUS5/Mod3 has been set-up and an experimental campaign (D series) has been designed. The main objective of the tests are the generation of reliable experimental data for the validation of the modified version SIMMER codes for fusion application. Moreover, the data will be also used to investigate the dynamic effects of energy release on the structures; to assess the reliability of the coupled RELAP5/SIMMER approach, besides to provide relevant feedbacks for the follow up experimental campaigns.

Acknowledgments

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