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The LIFUS5 separate effect test facility experimental programme

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A B S T R A C T

The LIFUS5 facility is a separate effect test facility aimed at investigating the heavy liquid metal-water interaction. It has been designed and constructed to withstand high pressure and temperature (i.e. up to 200 bar and up to 500 °C) and to record the fast pressure transients in heavy liquid metal melt. This type of transient is typical of a Steam Generator Tube Rupture event in a pool type Gen IV Heavy Liquid Metal cooled Fast Reactor system, and should be investigated from the safety point of view because it could potentially induce, beyond the damaging of the internal structures (HX tube bundle, above core structures, Fuel Assembly, Control Rods, etc.) several negative effects on the operation of the reactor. These include an insertion of positive reactivity into the system or reduced cooling efficiency due to steam dragging into the core. It will also have an effect on the chemistry control of the cooling. All these effects compromise the safety and the reliability of the system. The twenty years experimental programme and the different LIFUS5 configurations are presented in the paper, as well as the experimental campaigns and test matrix characterizing the heavy liquid metal-water interaction phenomena and data for codes validation.

1. Introductory remarks

The LIFUS5 experimental infrastructure is a separate effect test facility installed at ENEA C.R. Brasimone. It is designed to be operated with different heavy liquid metals like Lithium-Lead alloy, Lead-Bismuth eutectic alloy and pure lead, in a wide range of operative conditions (maximum temperature of 500 °C and maximum pressure of 200 bar). It is a multi-purpose facility employed in fission and fusion technologies to address the issues related the HLM/water reaction interaction. In particular, it was operated under the EU FP6 and FP7 programme to investigate the effect of a Steam Generator Tube Rupture event in a pool type Gen IV Heavy Liquid Metal cooled Fast Reactor system.

The first configuration was operated during 2000–2010 with LBE in support of R&D activities for the accelerator-driven sub-critical reactor (i.e. XT-ADS and EFIT) and for the Gen. IV Lead Fast Reactor (i.e. ELSY). The experimental campaigns were financed by EC through FP6 IP-EUROTRANS and FP6 ELSY projects and by the Italian Ministry of Economic Development (AdP 2009–2010).

The first refurbishment of the facility (LIFUS5/Mod2) was made to provide more reliable and highly detailed experimental data. The modifications involved the facility configuration, the injection line, the support frame, the test section, the instrumentation, the control room, the control and the acquisition systems and the procedures for executing the experiments. The facility operated between 2010 and 2015 to support the design of MYRRHA and ELSY reactors. It was involved in the EC FP7 THINS and LEADER projects and supported by the Italian Ministry of Economic Development.

The second and final refurbishment of the facility (LIFUS5/Mod3) was necessary to install proper transducers able to promptly detect the effect of the presence of a crack (thus a leakage) in the pressurized tube of the Steam Generator. In this framework, the facility operated between 2016 and 2018 to support the MYRRHA reactor design (EC FP7 MAXSIMA Project), and was funded by the Italian Ministry of Economic Development.

2. Research objectives

The LIFUS5 facility has been mainly oriented towards the generation of an experimental database relevant to the Heavy Liquid Metals-Water interaction in nuclear fission technologies. The reference scenarios are the SGTR (Steam Generator Tube Rupture) and the Steam Generator Small Leak detection in Heavy Liquid Metals Fast Reactors. Specific research objectives included:

- Safety investigations, in particular the experimental investigation of dynamic effects of energy release on tubes and shell structures of SGTR, the characterization of the initial propagation of the pressure

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wave followed by two-phase flashing and expansion, the liquid sloshing due to the two-phase mixing zone expansion, the evaluation of the water mass flow rate in LBE through a characterized crack (leak before break concept);
- the knowledge improvement of physical behaviour and phenomena understanding and interpretation;
- the development and reliability demonstration of computer codes in simulating the multi-fluid multi-phase phenomena of interest, also to support the design of innovative HLM reactors;
- the generation of detailed and reliable experimental data for the development and validation of CFD/SYS TH codes and the enlargement of existing database;
- Testing instrumentation and engineering solutions. Elaborating and disseminating of engineering feedbacks for STSG designers.

The experimental programme has been supported by comprehensive code application and assessment activities. SIMMER-III and SIMMER-IV, RELAP5/Mod3.3 and FEM codes have been largely used for test design and test prediction calculations, as well as for validation against the experimental data provided by the facility.

3. EU projects involving LIFUS5 facility

Pioneering activities were carried out in LIFUS5 test facility in the framework of the EC FP6: IP-EUROTRANS Project, within the domain of DEMETRA (Knebel et al., 2005) and ELSY (European Lead-cooled SYstem) Research Project (Alemberti et al., 2011).

The IP EUROTRANS project (6th Framework Program EU Grant Agreement 516520) was devoted to transmutation of high-level waste in an Accelerator Driven System (ADS). The objective was the design and the feasibility assessment of an industrial ADS prototype dedicated to transmutation. The work was carried out by a consortium of 29 partners from 14 countries. The objectives of the DEMETRA domains are the development and assessment of structural materials, thermal-hydraulics, and heavy-liquid metal technologies for transmutation systems with respect to spallation target material and to coolant.

The ELSY project (6th Framework Program EU Grant Agreement no. 36439) aimed at the demonstration that it is possible to design a competitive and safe lead fast power reactor using simple technical engineered features. The high lead density can serve as a safety feature in nuclear reactors by minimizing the risk of a core disruption because it is less likely to result in the core becoming more compacted which might cause the insertion of large amounts of reactivity in a short time. The use of compact in-vessel steam generators paired with a simple primary circuit configuration, designed in a way that allows for the potential removal of all internal components are among the reactor features for competitive electric energy generation and long-term investment protection. The activity consisted of management and technical activity subdivided into six Work-Packages: WP1: Design objectives, cost estimate, future R&D needs. WP2: Core design and performance assessment. WP3: Main components and systems. WP4: System integration. WP5: Safety and transient analysis WP6: Lead technology.

THINS (7th FP THINS, 2009) (Thermal Hydraulic of Innovative Nuclear System) Large Scale Collaborative Project (7th Framework Program EU Grant Agreement no. 249337) was devoted to crosscutting thermal–hydraulic issues for innovative nuclear system. The objectives were pursued by means of: generation of experimental databases; development and validations of physical models for selected phenomena; improvement and qualification of numerical tools for the design and the safety analysis of the reference innovative nuclear systems, i.e. Gen-IV reactors and the transmutation sub-critical systems. The Work Package 4 addresses the modeling capabilities of system codes for multi-phase problems by means of newly generated high-quality measurement data. In this framework, the Task 4.1.2 was aimed at providing experimental data for developing and validating physical modeling and for improving and qualifying computer codes in relation to HLM/water interaction. The issue was connected with the preliminary designs of lead fast reactor (LFR) and of subcritical transmutation system prototypes. Current pool-type configurations have the steam generators inside the reactor vessel, thus the interactions between the secondary side coolant and the HLM may occur. This implies that the primary to secondary leak (e.g. steam generator tube rupture) shall be considered as a safety issue in the design, but also in the preliminary safety analysis, of this reactor type.

LEADER (7th FP LEADER, 2009) project (7th Framework Program EU Grant Agreement no. 249668) dealt with the development of such a technology and was mainly based on previous achievements obtained during the 6th FP of the EU in the ELSY project. Further advances were proposed and the conceptual design of a scaled down facility for ELFR (the European Technology Demonstrator Reactor – ETDR) were the main topics of LEADER project. The LEADER project started from the results achieved in ELSY project with a deep analysis of crucial points of current LFR reactor configurations. The focus of the first part of the project was on the resolution of key issues to reach a new consistent reactor configuration. In this framework the design of a low cost and fully representative scaled down demonstrator of a suitable size (European lead fast reactor Technology Demonstrator Reactor – ETDR) was pursued. In the framework of LEADER project Task 6.4, at ENEA CR Brasimone an experimental campaign on LIFUS5/Mod2 facility was carried out for investigating the postulated SGTR event in a relevant configuration for STSG (Spiral Tube Steam Generator) of ELFR.

MAXSIMA (7th FP MAXSIMA, 2012) project (7th Framework Program EU Grant agreement no. 323312) aimed to contribute to the "safety in MYRRHA" assessment. The safety of the Steam Generator is treated by looking at consequences and damage propagation of a SG Tube Rupture event (SGTR) and by characterizing leak rates and bubble sizes from typical cracks in a SGTR. Additionally a leak detection system and the drag on bubbles travelling through liquid LBE are studied. Task 4.2, named "SGTR Bubbles Characteristics", studies this last aspect. A SGTR event could potentially induce, beyond the damaging of the internal structures (HX tube bundle, above core structures, Fuel Assembly, Control Rods, etc.) several negative effects on the operation of the reactor. These include an insertion of positive reactivity into the system or reduced cooling efficiency due to steam dragging into the core. It will also have an effect on the chemistry control of the cooling. All these compromise the safety and the reliability of the system. Instrumentation able to promptly detect the presence of a crack in the HX's tube may be used to prevent its further propagation which would possibly lead to a full rupture of the tube. Indeed, the application of the leak before break concept is relevant for improving the safety of a reactor system. In particular, it decreases the probability of the pipe break event. Therefore, early detection might be applied, if endorsed as a technically justifiable approach, for making the consequences of a postulated accident acceptable, or even for eliminating the accident (i.e. in this case the SGTR scenario) altogether. A second argument for an early detection system is the fact that an assessment of the total water injection coming from multiple small leaks, as occurs in normal operation of PWR reactors must be performed since the combined effect of these could also pose a safety problem. The goal of this task was to implement an experimental activity, supported by the numerical simulations that is able to characterize the leak rate and bubbles sizing through typical cracks occurring in the pressurized tubes. Basic tests in LIFUS5/Mod3 facility were carried out to correlate the flow rates of the leakage through selected cracks with signals detected by proper transducers. Different crack sizes and geometries were analysed, while the injection pressure and the temperature are kept constant.

4. The experimental installations

4.1. LIFUS5 facility description

The LIFUS5 facility, schematically showed in Fig. 1, operated during

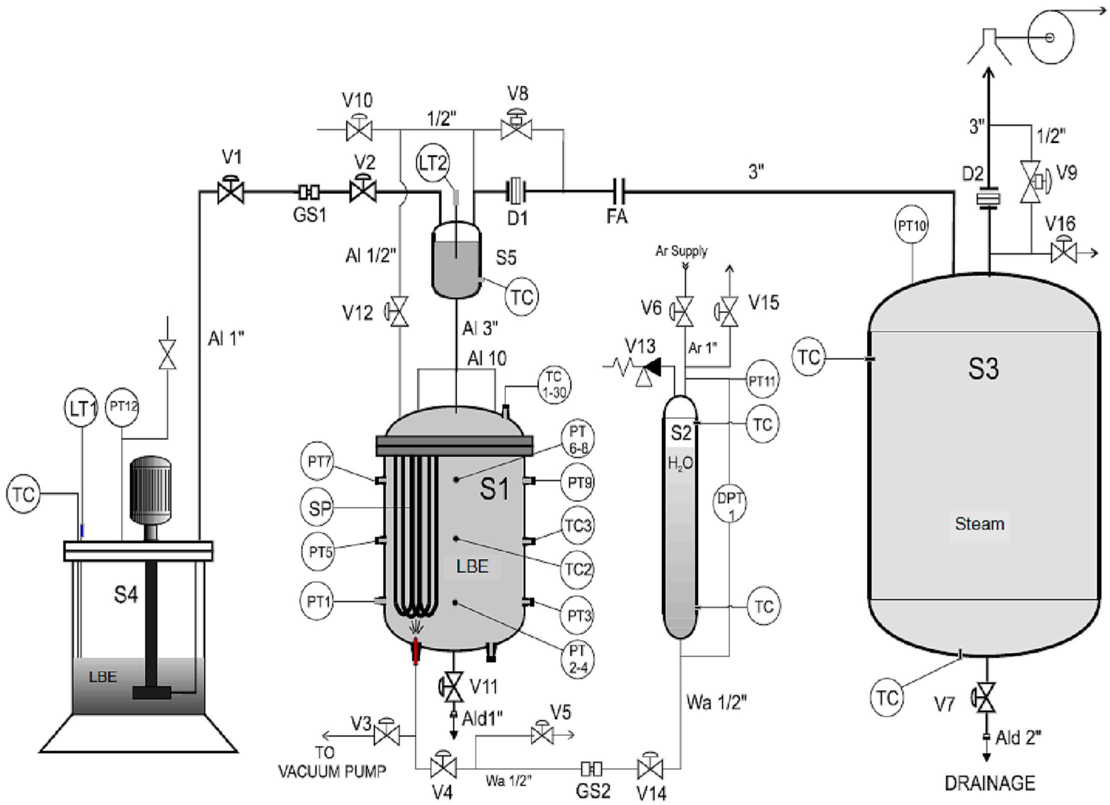


Fig. 1. LIFUS5 facility P&ID.

2000–2010 (Ciampichetti et al., 2003; Ciampichetti et al., 2008; Ciampichetti et al., 2009; Ciampichetti et al., 2011; Del Nevo et al., 2016; Maes, 2008.). It mainly consisted of:

- A reaction vessel S1, where the interaction between LBE and water takes place. Its volume is 100 L and it is filled with the liquid metal alloy. S1 contains a mock-up of U shaped cooling tubes made by 10 tubes of 16.5 mm of external diameter and about 0.7 m in length (Fig. 2). This pipe bundle is located in one of the four sectors in which the vessel has been divided by two AISI 316 plates. The two plates are welded on the top flange and develop in the vertical direction up to 50 mm from the bottom of the vessel so that the four sectors are communicating with each other. The introduction of the tube bundle mock-up has been done in order to evaluate if an enhanced mixing between water and eutectic alloy may produce relevant interaction effects. Moreover, on the plates and the tube bundle are placed different thermocouples useful to detect the evolution of the water jet and interaction zone. On the bottom of S1, in the sector containing the tube bundle, the water injection device is placed. It consists of a 1/2 in. tube which penetrates into the reaction vessel. On the top of the injector device, an orifice and a protective cap are installed, which broke by the water jet at the beginning of the injection phase.
- A pressurised water vessel S2, containing the water that has to be injected in S1. During the test the pressure in S2 is kept fixed by connecting directly this vessel to an Ar bottle charged at the test pressure.
- A safety vessel S3, which allows to collect the gaseous and aerosol reaction products from S1 and S5 at the end of the test.
- A storage tank S4, for melting the liquid metal and filling the reaction vessel S1 and, in case, a part of the expansion vessel S5 by pushing inert Argon gas.
- An expansion vessel S5, connected with the reaction tank through four pipes, one per sector. Depending on its filling level, the compressibility of the whole volume can be varied, giving the possibility of evaluating the different responses of the system in terms of pressure evolution.

Concerning the instrumentation, the reaction system is equipped with water-cooled high precision piezometric pressure transducers directly exposed to the liquid metal. Their short time constant (about 10^{-4} s) allows the rapid pressure transients to be monitored in the system under a time scale of some seconds. A number of K-type quick response thermocouples are also present. A fast data acquisition system with a dedicated software acquires the main test parameters in different positions of the system during the experiment.

4.2. *LIFUS5/Mod2 facility*

On the basis of the experience acquired, LIFUS5 has been renewed to provide more reliable and highly detailed experimental data (Figs. 3 and 4). The modifications involve the facility layout, the injection line, the support frame, the test section, the instrumentation, the control room, the control and the acquisition systems and the procedures for executing the experiments. The new version of the facility, named LIFUS5/Mod2 (Del Nevo et al., 2019; Di Maio et al., 2019; Pesetti et al., 2015; Del Nevo et al., 2015; Pesetti et al., 2014; Pesetti et al., 2016; Pesetti et al., 2016; Pesetti et al., 2017), operated between 2010 and 2015. In particular, all the main vessels were kept (excepting S5) and new sensors on the water injection line and on S1 interaction vessel (in Figs. 5 and 6). The water injection system is characterized by the following measuring instruments:

1. level measurement gauge is mounted on the water tank support. The measure will quantify the total amount of the water injected with a maximum resolution of 20 g;
2. fast pressure transducers placed on the bottom of the water tank and on the water injection line downstream the injection valve (V4) will

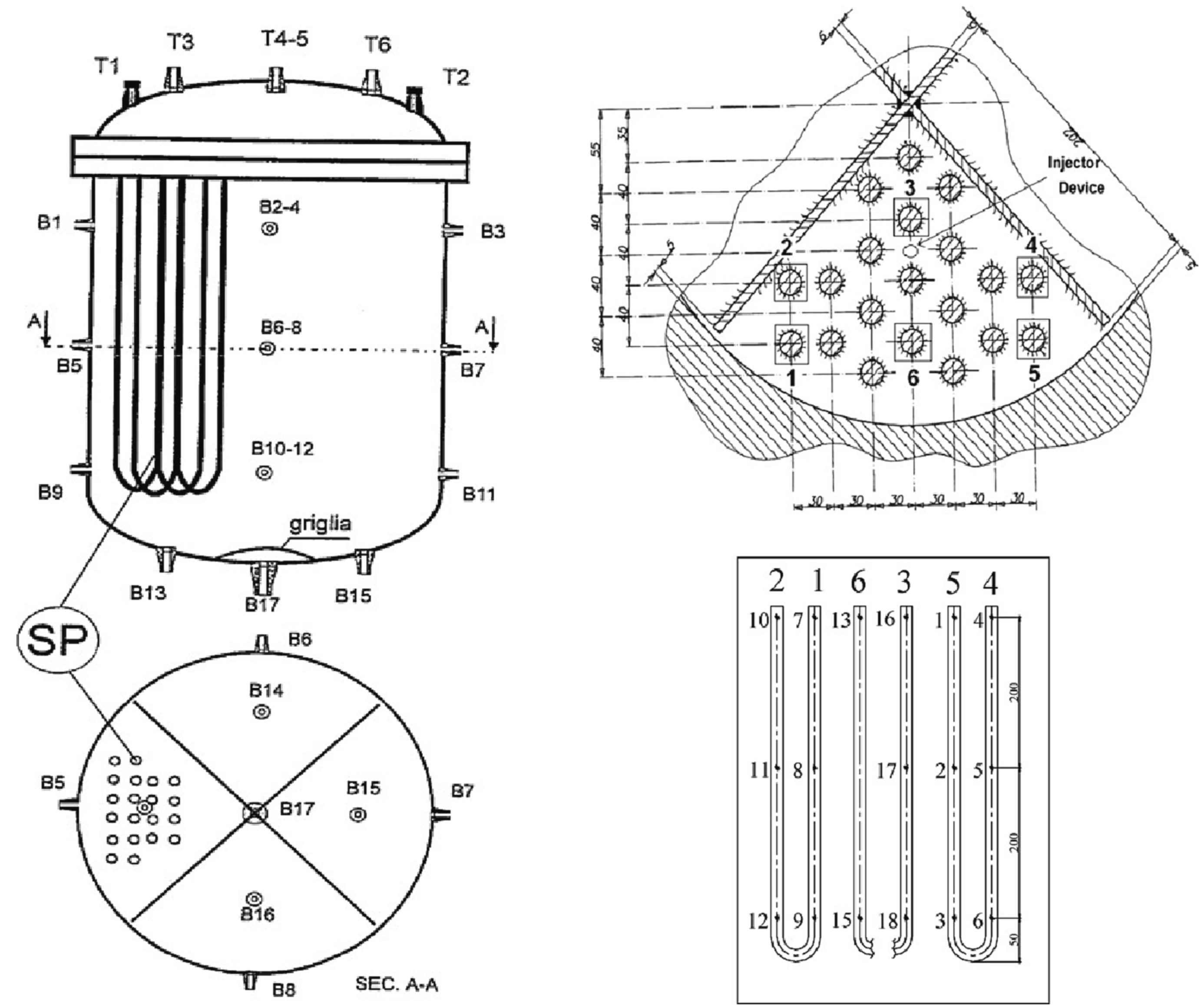


Fig. 2. U-tube test mock-up and thermocouples layout.

give information of the parameter trend during the evolution of the transient;

3. thermocouples are installed in the injection system for measuring the temperature of the water injected: one in the gas zone of the water tank (S2), the second in the water side of S2 and the third downstream the injection valve (V4);
4. Coriolis flowmeter placed on the water line is in charge to provide an accurate measurement of the mass flow of the water injected.

The acquisition system of the interaction vessel (S1) is based on the following measurements:

5. fast pressure transducers (PT) are installed as follows: one on the top of the vessel, and four on the vessel main wall at different elevations. The pressures in the HLM is recorded to explore the fluid–structure interaction and, with some extent, the wave reflection on the structure;
6. high temperature strain gauges are installed on the main vessel wall, for measuring the strain during the pressure transient. Five strain gauges are placed in a cross shape on the internal wall (i.e. in the LBE melt), whereas one is attached on the external wall in correspondence with the central internal gauge (see Fig. 6). The positions of the measurements are reported in Fig. 5.

LIFUS5/Mod2 DACS (Data Acquisition and Control System) is realized using National Instruments hardware and software. Exception is the acquisition of the strain gauges signals, which have dedicated hardware and software. A mix of Compact Field Point and Compact RIO modules are used as hardware. LIFUS5/Mod2 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 (Human Machine Interface) and SCADA (Supervisory Control And Data Acquisition) run on standard x86 PC/Workstation and it is developed using LabVIEW software. All components will be connected using standard Ethernet.

4.2.1. THINS configuration

The supporting frame of the THINS test section was configured in order to have an axial-symmetric geometry, reducing as far as possible,

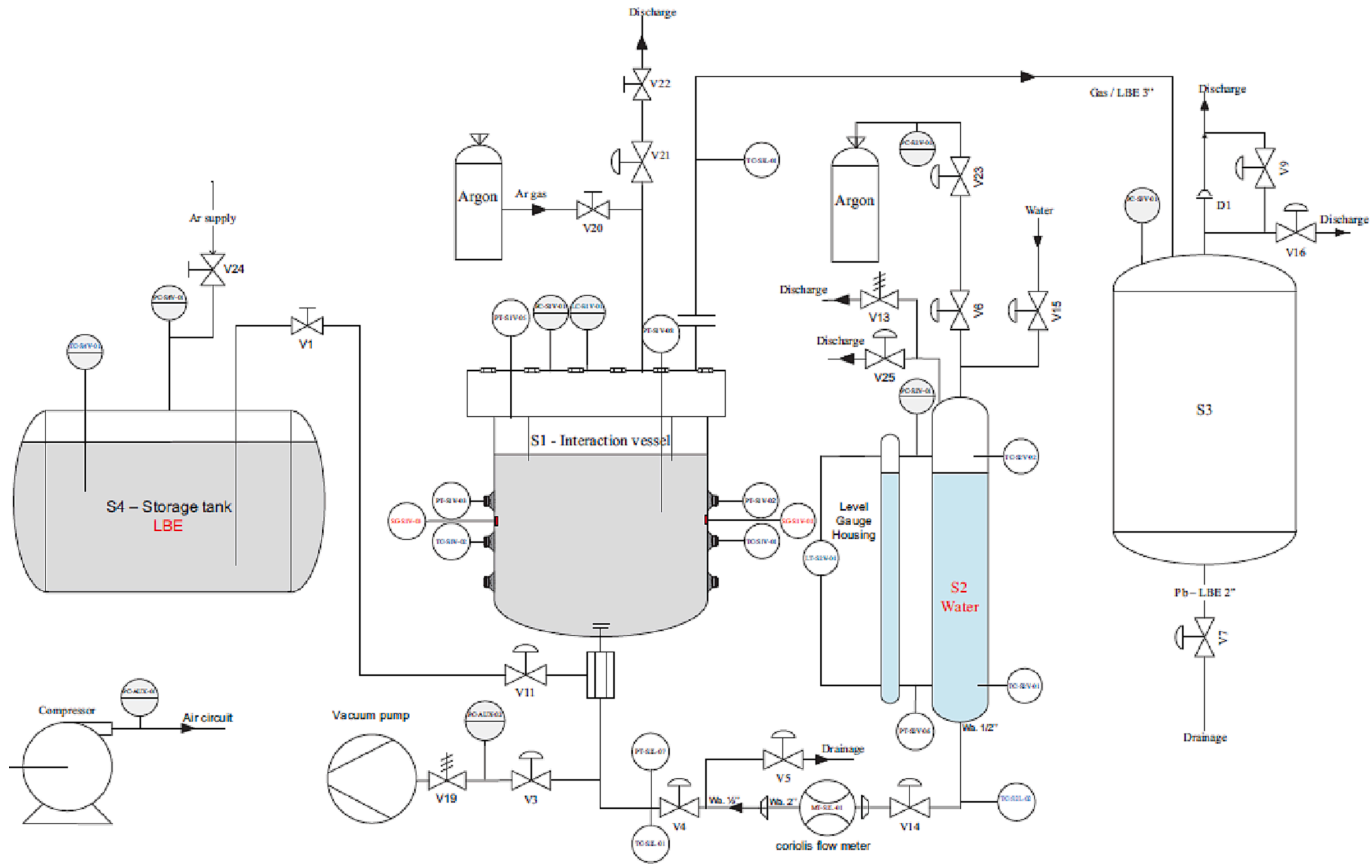


Fig. 3. LIFUS5/Mod2 facility P&ID.

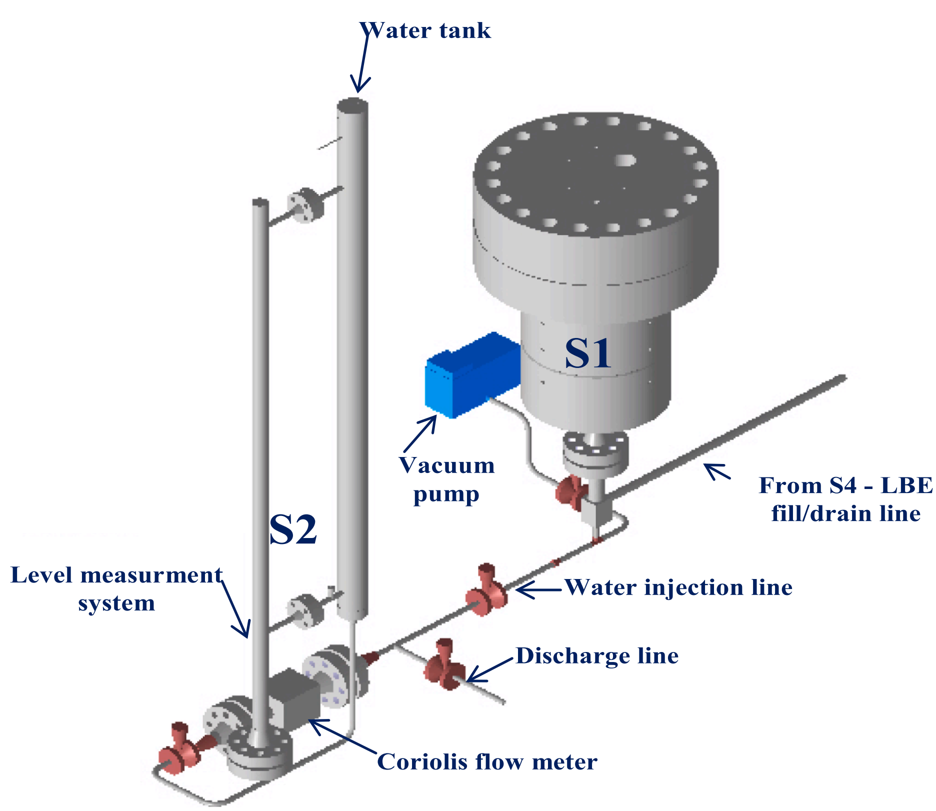


Fig. 4. LIFUS5/Mod2: overall sketch.

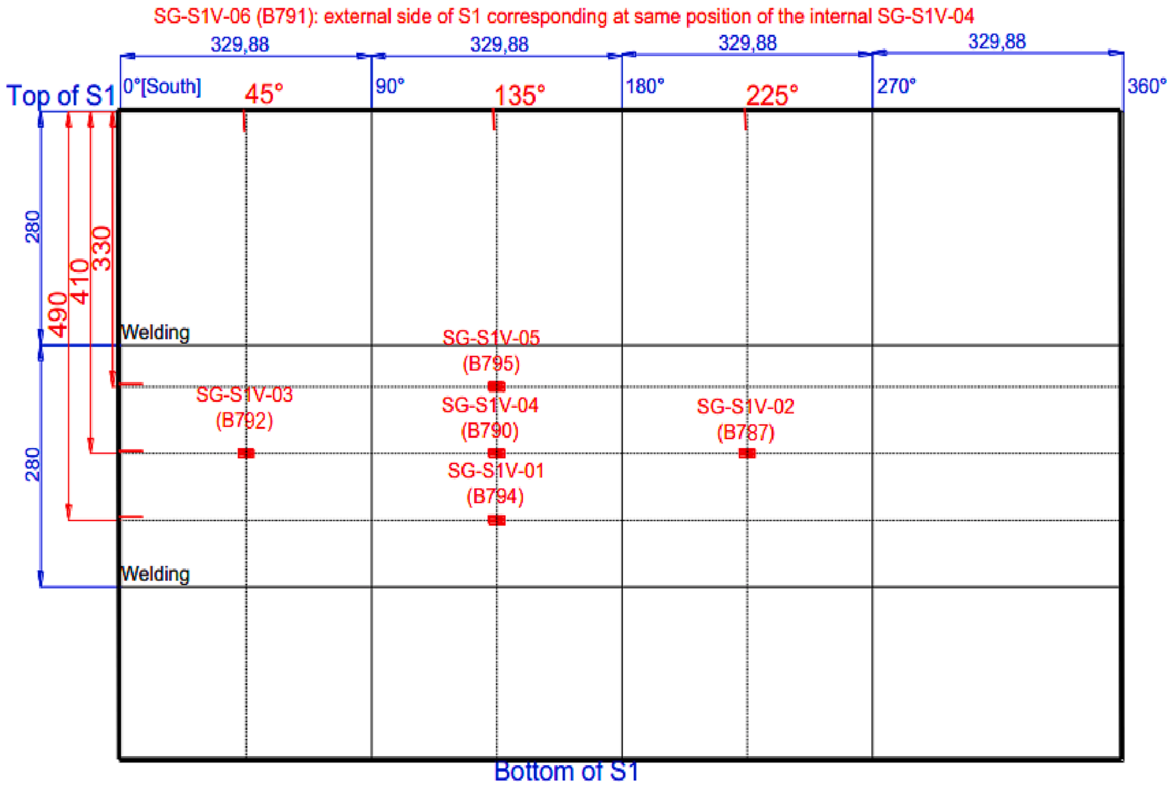


Fig. 5. LIFUS5/Mod2: arrangement of the strain gauges on the vessel s1 inner and outer surface.

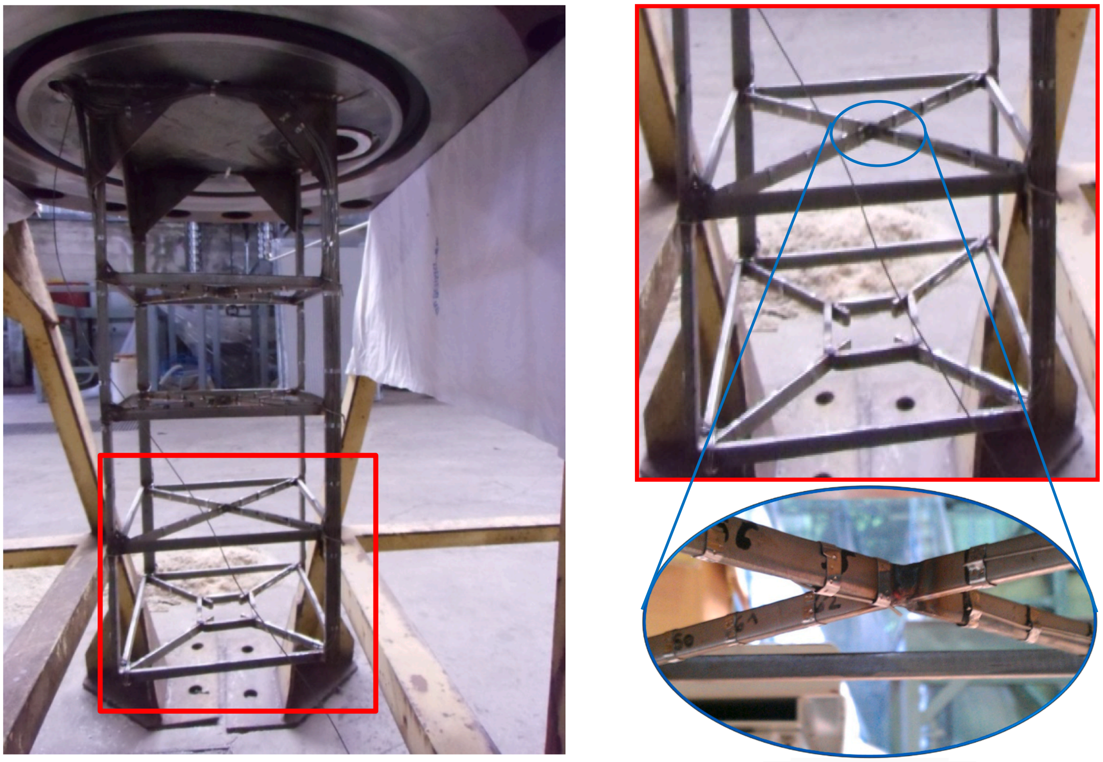
(a) View of the inner vessel *(b) View of the outer vessel*

Fig. 6. LIFUS5/Mod2: view of the strain gauges installed inside and outside the vessel S1.

the perturbations due to structures inside the vessel (Pesetti et al., 2014; Pesetti et al., 2015; Pesetti et al., 2016; Di Maio et al., 2019). During the experimental campaign, the vessel S1 is closed and isolated, thus the dump tank is disconnected.

Inside the S1 vessel a support frame is placed (Fig. 7), where 68 thermocouples are installed for fast temperature acquisitions. The frame, welded on the top flange, has an overall length of 590 mm. The thermocouples, fastened to such a support structure, are immersed into the LBE melt when the reaction tank S1 is closed. The structure has four horizontal cruciform levels supporting thermocouples, providing measures at different radial, azimuthal and axial positions, as depicted by red dots in Fig. 8. The lower cruciform support, Level 1, is the nearest to the injection orifice and it has a vacuum (the central thermocouple is absent) in the central position to avoid the impact with the water jet. The second level, as the higher ones, presents the frame supporting thermocouples that reaches the axis of symmetry of the structure, therefore it constitutes an obstacle that fragments the water jet flowing upwards into the LBE melt. The thermocouple set in the center of the horizontal support structure is coaxial with the reaction tank S1 and the injection orifice. Each one of the four horizontal branches constituting the cruciform support, called level, hosts four thermocouples. The thermocouples nearest to the central one are considered belonging to the first ring, the outer ones instead, are considered belonging to the fourth ring.

The water injection nozzle enters in the bottom of the vessel S1 in



(a) View of the test section

(b) Zoom of the test section and detail of the thermocouple installed

Fig. 7. LIFUS5/Mod2: view of the test section in THINS configuration.

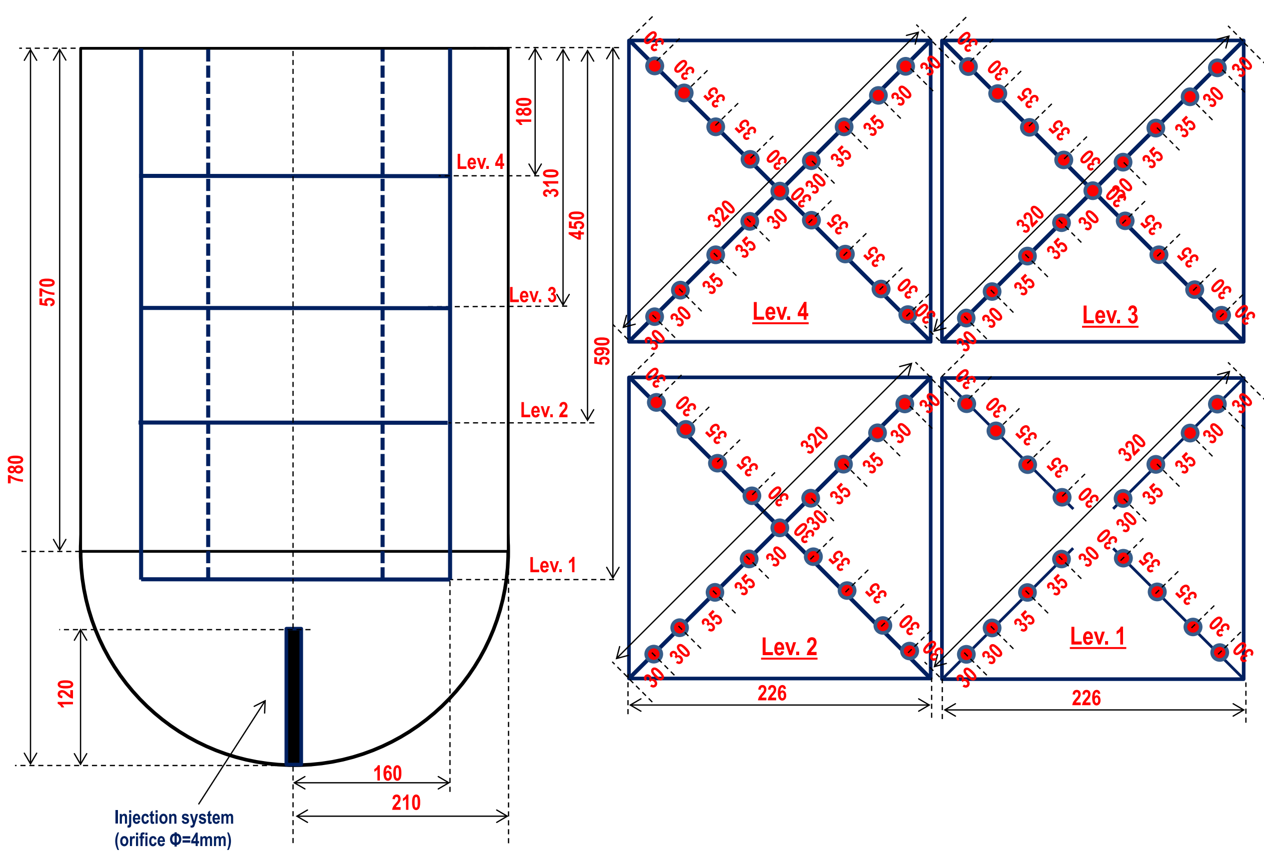


Fig. 8. LIFUS5/Mod2: THINS test section and arrangement of the thermocouples (measurements are in mm).

central position, see Fig. 9. The injection is carried out about 120 mm above the internal lower edge of the vessel. The injector orifice is covered by a protective cap, which is broken by the pressure of the water jet at the beginning of the injection phase. Therefore, the system shall be substituted at the end of each test. The injection nozzle has a diameter equal to 4 mm. It is mounted at the end of the water injection line based on a ½” sch 80 pipeline.

4.2.2. LEADER configuration

The LEADER test section shown in Fig. 10 was placed vertically inside S1 vessel. The test section was connected with the top flange of S1 and was removable for maintenance, if needed. LEADER test section had a cylindrical shape characterized by a height of 400 mm. The thickness of the two closing plates was 20 mm each one. The radius of the test section was 155 mm, as shown in Fig. 11. The test section was inserted in S1, at 130 mm of distance from the bottom of S1 top flange. The injection tube penetrated into the test section through the bottom plate for about 100 mm. Levels A and B (LA and LB, respectively), shown in the same figure, identify two planes at which thermocouples were placed. Strain gauges were positioned only at LA. The test section was composed by a bundle of 188 tubes, having external diameter of 18 mm and equilateral triangular pitch of 19.8 mm, coherently with the geometrical parameters of the STSG design of ELFR reactor (Del Nevo et al., 2019; Del Nevo et al., 2015; Pesetti et al., 2016; Pesetti et al., 2017). Scaling down the STSG parameters was performed according with to the following rationales: 1) the area between the tubes was reduced at 60% in order to preserve the velocity of the fluid; 2) the length of the tubes was 400 mm, which corresponded to the distance between two consecutive grids of the STSG bundle, corrected on the basis of the tube diameter scale; 3) the thickness of the tubes was reduced to 1 mm in order to have larger mechanical effect during the injection. The tubes deformation was measured online by means of high temperature strain gauges. The tubes were surrounded by a cylindrical shell having 200 holes of 15 mm of diameter. This provided a porosity of 30% that was coherent to STSG configuration. The tube bundle was composed by three different types of tubes:

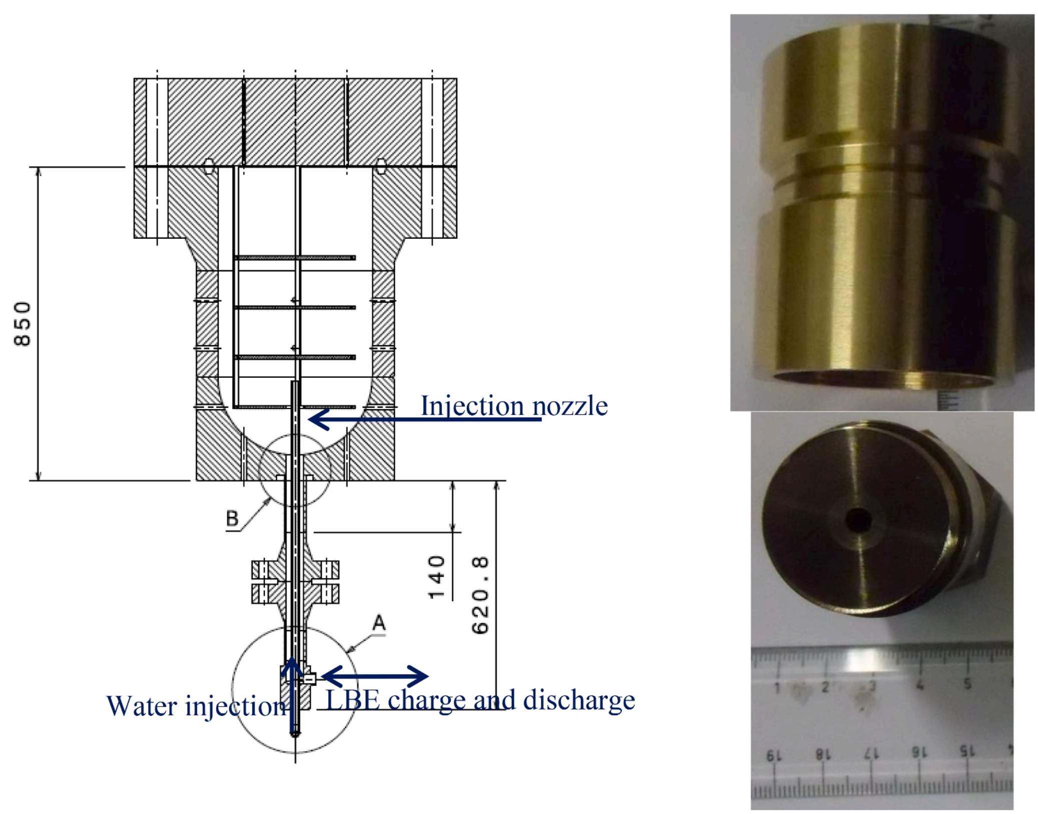
- two series of 6 tubes each one (see green and orange tubes in Fig. 12) pressurized at 180 bar during the test execution, coherently to secondary side pressure of STSG;
- 128 opened dummy tubes that during the test were filled by LBE;
- 48 closed dummy tubes, containing air at atmospheric pressure and ambient temperature.

The first part of the test section assembly activity concerned the positioning of 70 TCs and 7 SGs. In particular, regarding thermocouples:

- 20 TCs with a diameter of 0.5 mm were installed on the inner tubes (blue circles in Fig. 12);
- 36 TCs having diameter of 1 mm were set on outer tubes (red circles in Fig. 12);
- 6 TCs of 1 mm were positioned on the inner wall of perforated plate;
- 8 TCs of 1 mm were set for LBE free level control in S1.

For what concern strain gauges:

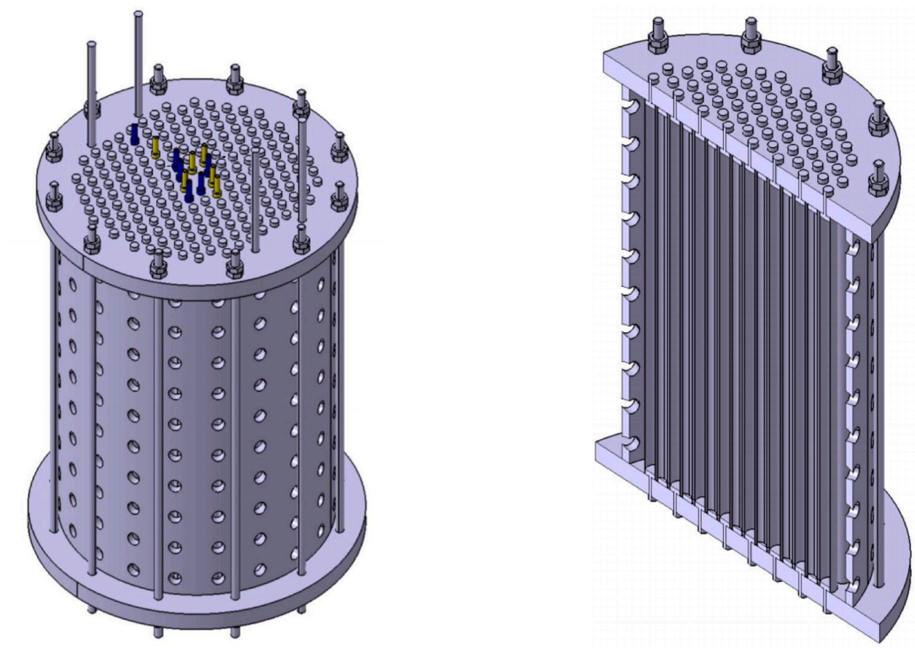
- 2 SGs were set on tubes of second rank in North and South direction, tubes 201 and 204 respectively (see black rectangles in Fig. 12);
- 3 SGs were positioned in radial direction (East), tubes 304, 507 and 710, to study the effect of pressure wave propagation from the center to the outer region of the bundle; and
- 2 SGs were set on the outer surface of the perforated cylindrical shell, at North and East directions, respectively.



(a) Configuration of the water injection and LBE charge/discharge systems

(b) View of the injection nozzle, orifice and the calibrated notched-section

Fig. 9. LIFUS5/Mod2 facility: water injection system in THINS configuration.



(a) isometric view of LEADER test section *(b) isometric section of LEADER test section*

Fig. 10. LIFUS5/Mod2: sketch 3D of LEADER test section.

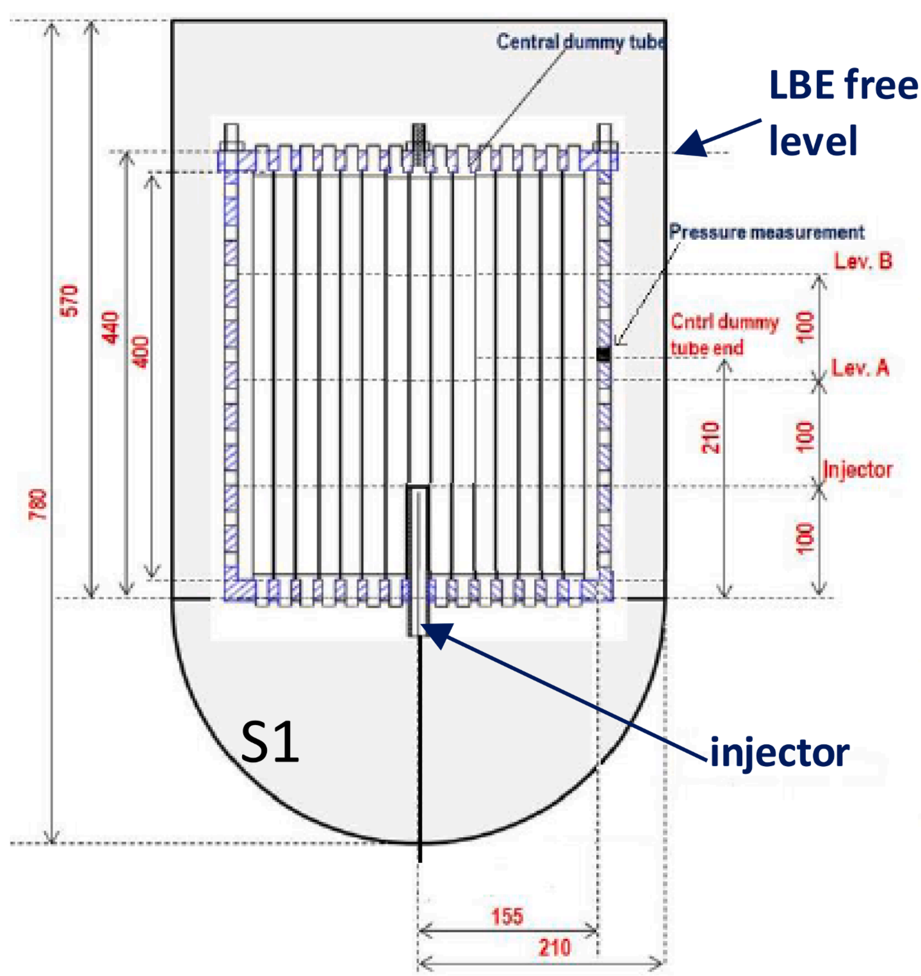


Fig. 11. LIFUS5/Mod2: vertical section of LEADER test section in S1 (dimensions in mm.

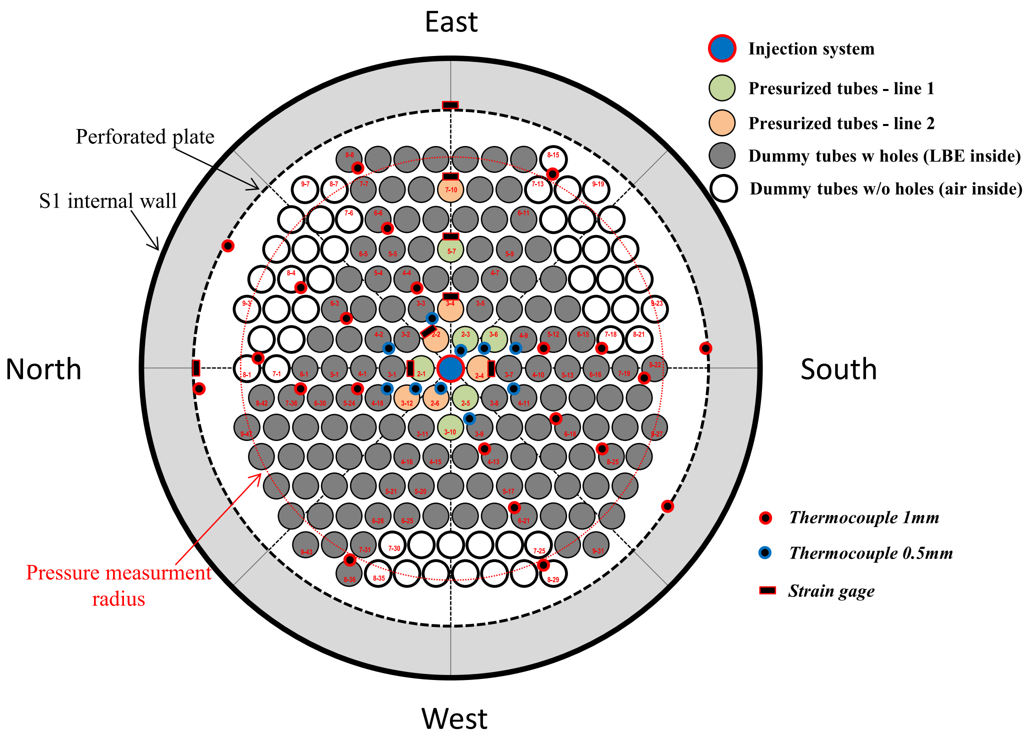


Fig. 12. LIFUS5/Mod2: horizontal section of LEADER test section in S1, with TCs, SGs, injector and open, closed and pressurized tubes arrangement.

The sketch of the horizontal section of S1 and test section, highlighting the disposition of the tube types, TCs and SGs, is shown in Fig. 12. The thermocouples were placed axially at two different levels A and B (see Fig. 11). The strain gauges were located at level A. The TCs were fixed on tubes and their sensible endings were slightly bent for measuring fluid temperature, facing towards the center of the test section in order to be impacted directly by the jet of steam during the water injection. The SGs were welded vertically on tubes and facing outward, in order to work in tensile conditions during the initial propagation of the pressure waves. The SG set on tube 202 (rank 2 position 2, north-east direction) did not work due to fault during the assembling. Two groups of 6 tubes (green and orange circles in Fig. 12) were pressurized at 180 bar, at the beginning of each test, by two separate lines with manifolds positioned in S1 above the test section top plate. The pressure monitoring at the end of each test aimed to provide feedback on tube rupture propagation. A tube of ¼ in. was used to connect the internal of the test section with a fast pressure transducer installed on S1 top flange (PT-S1V-08). This tube went inside the test section, passing through one hole of the perforated plate at 210 mm from the bottom of the test section, until it almost got in contact with tubes inside test section.

On the top flange of S1 a 3 in. hole was set. Through this, S1 and S3 were connected with a 3 in. pipeline. Heating wires were installed on S1 top flange and on the connecting pipe with S3. Besides these exception, the heating system of LIFUS5/Mod2 was maintained as it was designed for THINS project configuration.

The water injection system passed through the bottom of the vessel S1 in central position. The injection was carried out about 300 mm above the lower part of S1, where the injector orifice was covered by a protective cap, made of brass, which was broken by the line pressurization at the beginning of the injection phase. LEADER experiments provided a broken pressure of 180 bar, which was the design pressure for the secondary side of STSG. To ensure that cap rupture occurred at

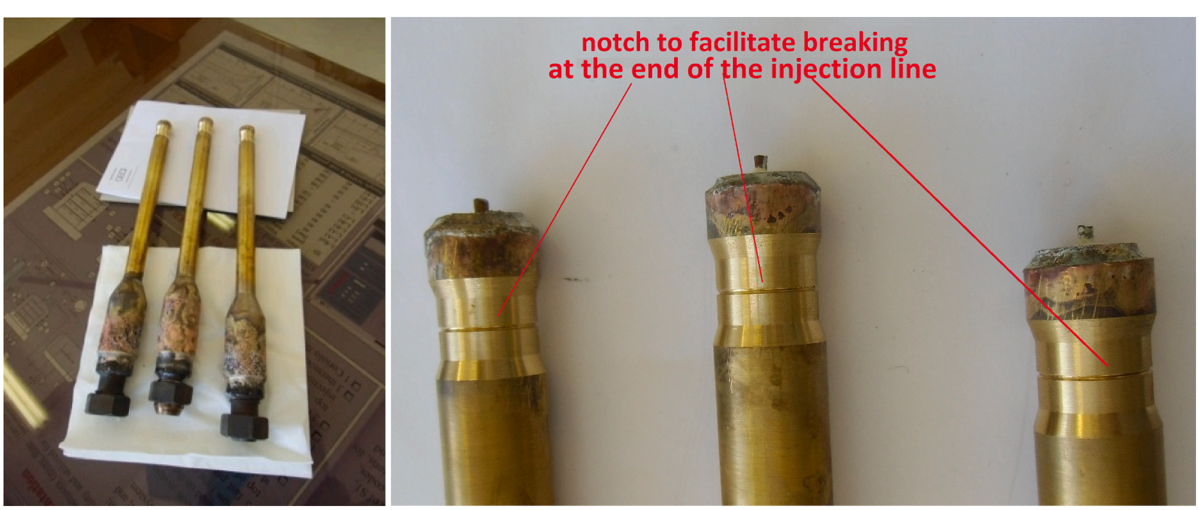


Fig. 13. LIFUS5/Mod2: view of injectors with protective caps.

scheduled pressure, a calibrated notch was executed by the ENEA workshop (see Fig. 13). Tests were carried out to calibrate the depth of the notch and, consequently, the value of the resisting section.

Considering the acquisition and control system, it is important to highlight that compared to the previous THINS experimental campaign, LEADER fast pressure transducers (PTs) measurements were acquired at 10 kHz instead of 1 kHz. Such a decision aimed to measure with higher resolution the first narrow pressure peaks measured under LBE free level in S1 at the LBE-water interaction starting instant. Also strain gauges signals were sampled at 10 kHz. Thermocouple measurements were registered at 50 Hz. All acquired data from acquisition, control and regulation systems, were available to facility operators via graphical interface (synoptic).

4.3. LIFUS5/Mod3 facility

The second and final refurbishment of the LIFUS5 facility was completed in 2016 and it operated between 2016 and 2018 (Eboli et al., 2019; Eboli et al., 2020; Eboli et al., 2022). The main vessels are kept from the previous LIFUS5 configurations excepting for the storage tank and the water injection line. The components characterizing LIFUS5/Mod3 facility (Fig. 14) are renamed and they are:

- the interaction vessel S1A, where LBE/water interaction occurs;
- S2V vessel, where demineralized water is stored and pressurized by means of a gas cylinder connected to the top;
- S4A is the storage tank of LBE;
- S3V is a dump tank, used to collect vapour and gases during the test.

4.3.1. Main components description

The interaction vessel S1A is filled with LBE covered by Argon inert gas during the tests. Penetrations are made in S1A top flange to allow the installation of the instrumentation and connections, in particular for two on/off level meters (LV), for five Acoustic Detection Systems (ADS), for one absolute pressure transducer (PC), for two accelerometers and an Acoustic Emission detection system, and for the connection to S3V safety tank.

The water tank S2V is a pipe, closed at the edges with two flanges. The filling level in the S2V vessel is continuously monitored by the magnetostrictive level measurement device and by a Differential Pressure (DP) meter inserted between the lower part of S2V and bottom part of the injection line, for a height of about 2.15 m. At the bottom, S2V is connected to the water injection line.

The LBE is stored in the liquid metal storage tank S4A and it is charged into and discharged from the main vessel S1A just before and after each test. On the cylindrical shell of S4A penetrations are provided allowing the passage of instrumentation, in particular one absolute pressure transducer (PC), one thermocouple (TC), two on/off and one continuous level meters (LV).

The dump tank S3V, used to collect the vapour and the gas generated by the interaction between LBE and water, is connected by means of a line to the top flange of S1A.

4.3.2. Injection line

The injection line (Fig. 15) connects the S2V water storage tank to the S1A reaction vessel. A Coriolis mass flow meter (MT-S2L-01) is placed between two pneumatic valves VP-S2L-07 and VP-S2L-08, in order to measure the mass of water flowing in the line. The Coriolis has the capability to measure the mass flow rate in the range of 50–2000 g/h. A manual drainage valve (VM-S2L-11) is located downstream of the mass flow meter to empty the line after every experimental procedure. The water injection line is heated from VP-S2L-08 (downstream the Coriolis) to S1A. Five heating wires heat up the water up to 200 °C before its entering into the reaction vessel. The temperature of the fluid is controlled by 4 thermos-wells. Line is insulated from the external environment to reduce heat losses.

4.3.3. Injection system and injector device

The injection system (Fig. 16) is constituted by two separated parts, connected by a flange. The first one is completely integrated and welded to the bottom of S1A vessel. The second part is manufactured by four coaxial tubes and it is dismounted at the end of each test to allow the replacement of the injector device. The water flows into the inner tube, meanwhile the gas flows towards up to the injector device in the second coaxial tube and then flows in counter-current direction into a third tube, designed for the gas outlet. The LBE is charged and discharged through the fourth tube.

The injector device (Fig. 16) is composed by a support and an injector cap which is closed by a spanner, designed ad hoc and manufactured by ENEA workshop. Inside the injector device, a micro-holed AISI 316 plate with a thickness of 1 mm and a diameter of 1″ (25.4 mm) is installed between two sealing rings. At the center of the plate, a single micro-hole is manufactured by laser technology. The orifice diameter varies from 40 to 200 μm according to the test specification. The injector penetrates into S1A interaction tank of 170 mm. In this way,

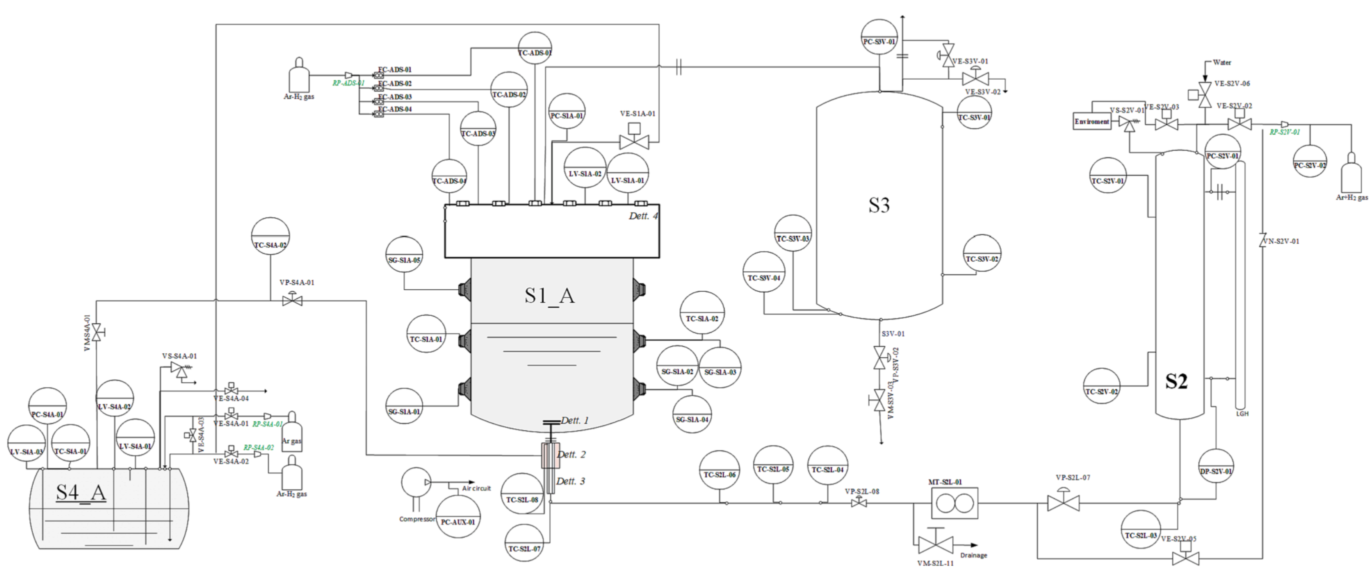


Fig. 14. LIFUS5/Mod3 facility P&ID.

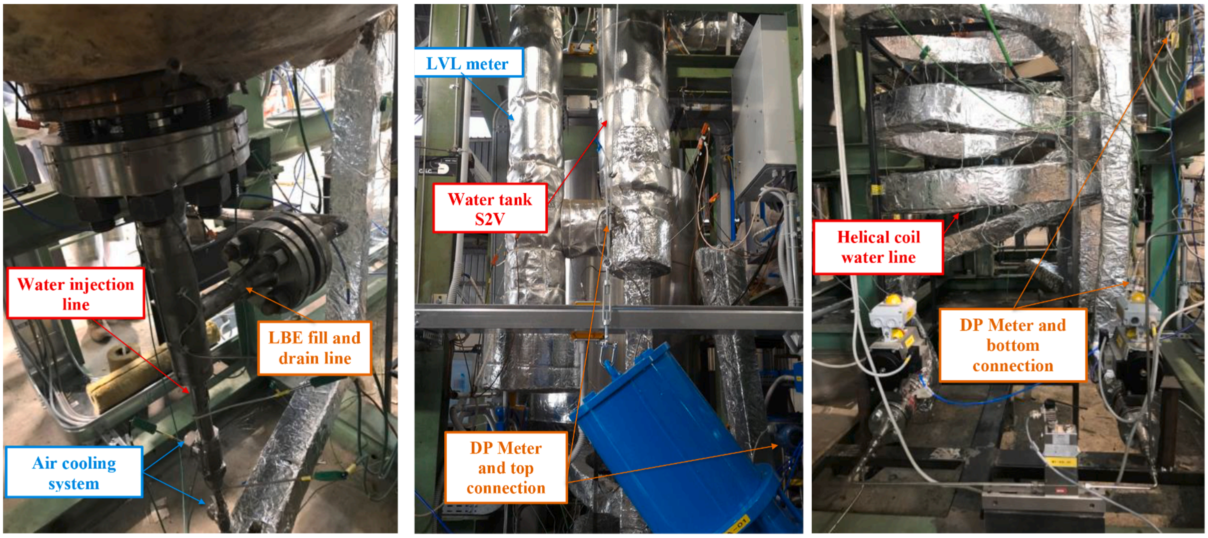


Fig. 15. LIFUS5/Mod3 view of S1A penetrations and water injection line.

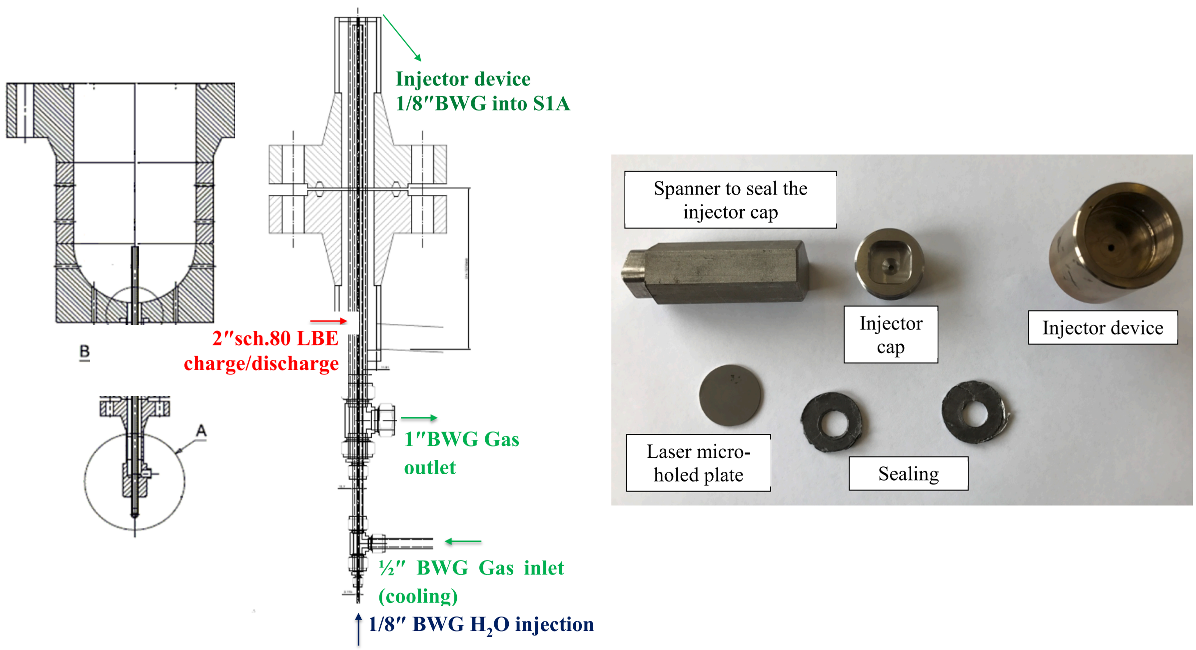


Fig. 16. LIFUS5/Mod3 sketch of the injection system and injector system device.

at each test, the injector device can be disassembled and the plate can be replaced with another one with a different micro-hole diameter.

4.3.4. Detection system: real time data acquisition for microphones, accelerometers and acoustic emission sensor

The top flange of the LIFUS5/Mod3 facility has several penetrations where microphones are installed. In addition, a series of alternative detection systems, which are constituted by accelerometers and acoustic emission sensors, are placed on the flange and inside the vessel of the LIFUS5/Mod3 facility. The layouts are depicted in Fig. 17. These are:

- One microphone at high temperature in central position (i.e. HT ADS).
- Four microphones at low temperature along the same circumference (i.e. LT ADS);
- Inductive proximity sensor (i.e. High Sensitivity Accelerometer – HSA) installed outside the vessel;
- Accelerometer sensor installed inside the vessel (i.e. High Temperature Accelerometer – HTA) on a metallic support;
- Acoustic Emission (AE) sensor installed outside the vessel, measuring the high frequency signals by means of a waveguide.

The HT ADS is a compact unit for sound pressure measurement in small enclosures, harsh environments, and close proximity to sound sources. The high acoustic input impedance of the probe tip minimizes the influence on the acoustic field, while the 160 mm stainless steel probe tube can withstand temperatures of up to 800 °C. The probe is constructed with a detachable stainless steel tip, which guides the acoustical signal to a microphone inside the probe housing. After being measured, the acoustical pressure wave is passed on to an impedance-matched wave guide, which eliminates internal reflections. This results in a smooth frequency response from 2 Hz to 20 kHz. The internal microphone is connected to a low noise preamplifier with a high dynamic range. The LT ADS are pre-polarized, condenser microphones

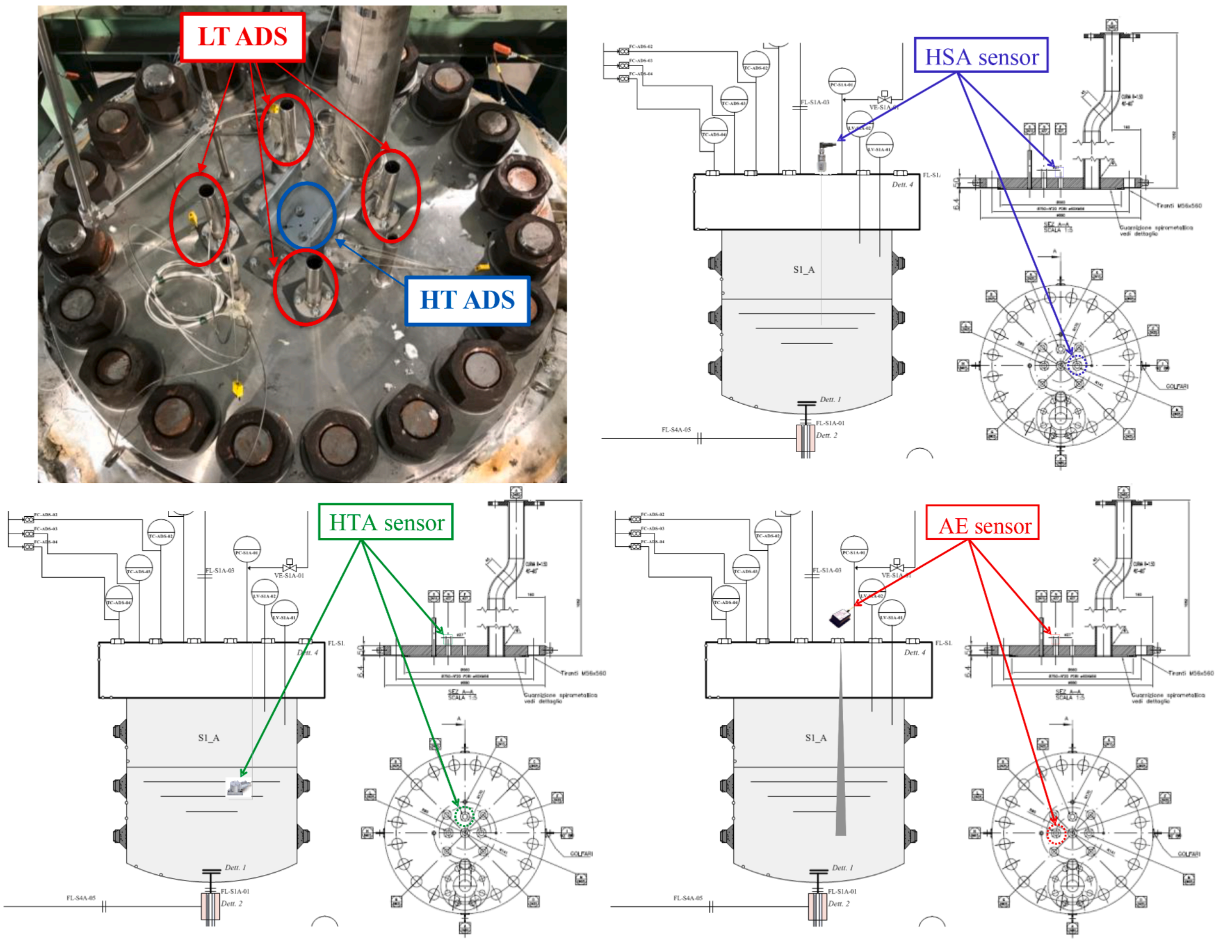


Fig. 17. ADS and accelerometers positions on LIFUS5/Mod3 facility.

coupled with ICP sensor powered preamplifiers. These Microphones are 7 mm in diameter and have a dynamic range up to 122 dB. The maximum temperature for this kind of microphone is 50 °C. Therefore, a dedicated cooling system has been designed and installed. It is composed of three parts: a metallic support which prevents the leakage of gas and leaves the space to the microphone to measure the sound coming from the liquid, a ceramic support which grants the thermal insulation between the cover/metallic support and the microphones, and a cooling gas system in charge of keeping the temperature below the design values.

The High Sensitivity Accelerometer (HSA) is an inductive proximity and a low frequency sensor with a ± 5% sensitivity tolerance. The High Temperature Accelerometer (HTA) is installed inside the vessel S1A by means of a supporting structure of AISI316L, designed and manufactured in ENEA Workshop. It withstands temperature up to 482 °C. The Acoustic Emission (AE) sensor is installed outside the vessel, measuring the high frequency signals by means of a waveguide. The active face (base) of the sensor detects the high frequency component of naturally occurring structure borne stress waves (known as Acoustic Emission). To do this, the base of the sensor must be acoustically coupled to the surface of the item of interest using a suitable coupling material. In this case, the use of a waveguide is necessary to interface the base of the sensor with the material being monitored (the LBE and the water bubbles due to the micro-crack inside). The AISI316L waveguide is designed and manufactured by ENEA Workshop. Both of the sensors positioned externally on the S1A top flange withstand temperature up to 120 °C and 75 °C, respectively for HSA and AE, therefore a compressed air flow cooling system has been installed on the flange surface.

A National Instruments PCI card was used to convert the microphones signals from analogic to digital. The software was developed in C and C++ language. The signals were analyzed in the time domain, sound pressure, sound intensity, sound power and frequency response. On the other hand, a specific electric cabinet, containing the multichannel DAWESOFT – SIRIUS® system was installed to acquire and process the experimental data of the accelerometers and acoustic emission sensor. The data are acquired and processed by means of its proprietary software. The accelerometers and the acoustic emission sensor are connected to the multichannel acquisition system, which produces electrical signals at high frequency. The multichannel amplifies, converts and sends the signals to the data acquisition system that run on an industrial PC. By means of the proprietary software, the data are saved as pure signals of sensors, and as elaborated data such as FFT, RMS or peak signals in a binary proprietary format.

5. Twenty years of experimental programme

5.1. *Execution of FP6 IP EUROTRANS and ELSY projects*

In the DEMETRA domain of the IP-EUROTRANS Project (Knebel et al., 2005), 4 experimental tests (see Table 1) were executed to assess the physical effects and the possible consequences of this interaction over a wide range of different conditions. Besides the experimental activities, a numerical simulation activity was performed with SIMMER code in order to better investigate the thermo-hydraulic phenomena involved in the interaction and to confirm the capabilities of the code to simulate this kind of phenomena.

Test n. 1 was carried out by injecting sub-cooled water (pressure equal to 70 bar and temperature equal to 235 °C) into the reaction vessel

Table 1
LIFUS5 Experimental Programme Test Matrix.

#ID Test	Project	Date	Test Conditions (p H2O, T H2O, T LBE, Inj. penetration, D inj, Gas Vol)	Phenomenology and Test Objectives
LIFUS5 configuration				
No.1	EUROTRANS	03/2006	70 bar, 235 °C, 350 °C, 80 mm, 4 mm, 5%	S1 + S5. Pressure evolution characterized by 4 phases. Cooling effect due to water expansion. S1 pressure equal to 111% the water injection pressure
No.2	EUROTRANS	N.A.	6 bar, 325 °C, 350 °C, 80 mm, 4 mm, 20%	S5 eliminated. Compressibility effect of the gas leads to the delayed pressure peak. Max pressure exceeded the water injection pressure.
No.3	EUROTRANS	N.A.	40 bar, 130 °C, 350 °C, 5 mm, 4 mm, 0%	S1 + S3 (by Rupture Disk). Maximum pressure reached during the test 22 bar
No.4	EUROTRANS	N.A.	40 bar, 235 °C, 350 °C, 5 mm, 4 mm, 20%	S1 + S3 (by Rupture Disk)
No.1	ELSY	N.A.	185 bar, 300 °C, 400 °C, 5 mm, 4 mm, 20%	S1 + S3 (by Rupture Disk)
No.2	ELSY	N.A.	185 bar, 300 °C, 400 °C, 255 mm, 4 mm, 20%	S1 + S3 (by Rupture Disk)
LIFUS5/Mod2 configuration				
A1.1	THINS	05/03/2013	40 bar, 240 °C, 400 °C120 mm, 4 mm, 40%	Pressurization rate 13.2 bar/s; pressure peak equal to 52% of pressure in the injection line; streamlines of the injection remain 65 mm from S1 vertical axis
A1.2	THINS	21/03/2013	40 bar, 240 °C, 400 °C120 mm, 4 mm, 30%	Max pressurization rate 23.4 bar/s; pressure peak equal to 32% of pressure in the injection line;
A1.2_1	THINS	03/07/2013	40 bar, 240 °C, 400 °C120 mm, 4 mm, 30%	Demonstration of test repeatability (A1.2 and A1.4). Injection affected by small changes in the initial S2 pressure
A1.2_2	THINS	12/07/2013	40 bar, 240 °C, 400 °C120 mm, 4 mm, 30%	Demonstration of test repeatability (A1.2 and A1.4). Injection affected by small changes in the initial S2 pressure
A1.3	THINS	04/04/2013	40 bar, 200 °C, 400 °C120 mm, 4 mm, 30%	Max pressurization rate 31.6 bar/s; pressure peak equal to 66% of pressure in the injection line
A1.4	THINS	17/04/2013	40 bar, 240 °C, 400 °C120 mm, 4 mm, 30%	Max pressurization rate 17 bar/s; pressure peak equal to 23% of pressure in the injection line
A2.1	THINS	08/05/2013	16 bar, 200 °C, 400 °C120 mm, 4 mm, 30%	Max pressurization rate 11.9 bar/s; pressure peak equal to 174% of pressure in the injection line
A2.2	THINS	22/05/2013	16 bar, 200 °C, 400 °C120 mm, 4 mm, 40%	Max pressurization rate 8.2 bar/s; pressure peak equal to 68% of pressure in the injection line
A2.3	THINS	04/06/2013	16 bar, 180 °C, 400 °C120 mm, 4 mm, 30%	Max pressurization rate 18.1 bar/s; pressure peak equal to 70% of pressure in the injection line.
A2.4	THINS	19/06/2013	16 bar, 200 °C, 400 °C120 mm, 4 mm, 30%	Max pressurization rate 9.3 bar/s; pressure peak equal to 64% of pressure in the injection line.
B1.1	LEADER	12/09/2014	180 bar, 260 °C, 400 °C310 mm, 4 mm, -	Break = 6% of the STSG tube flowing area. Cap rupture occurred with 40.5 s of delay. Max pressure peak 30 bar. Max strain value 535 µm/m
B1.2	LEADER	14/10/2014	180 bar, 270 °C, 400 °C310 mm, 4 mm, -	Break = 6% of the STSG tube flowing area. Max pressure peak 25 bar. Max strain value 700 µm/m
B1.3	LEADER	04/11/2014	180 bar, 270 °C, 400 °C310 mm, 4 mm, -	Break = 6% of the STSG tube flowing area. Max pressure peak 27.9 bar. Max strain value 650 µm/m
B2.1	LEADER	04/12/2014	180 bar, 270 °C, 400 °C310 mm, 8.9 mm, -	Break = 30% of the STSG tube flowing area. Max pressure peak 50 bar. Max strain value 350 µm/m
B2.2	LEADER	22/01/2015	180 bar, 270 °C, 400 °C310 mm, 8.9 mm, -	Break = 30% of the STSG tube flowing area. Max pressure peak 210 bar. Max strain value 350 µm/m
B2.3	LEADER	19/02/2015	180 bar, 270 °C, 400 °C310 mm, 8.9 mm, -	Break = 30% of the STSG tube flowing area. Max pressure peak 209 bar. Max strain value 400 µm/m
B3.1	LEADER	02/04/2015	180 bar, 270 °C, 400 °C310 mm, 12.6 mm, -	Break = 60% of the STSG tube flowing area. Max pressure peak 49 bar (leakage in injection line) Max strain value 450 µm/m.
LIFUS5/Mod3 configuration				
C1.1	MAXSIMA	06/09/2017	19.7 bar, 170 °C, 203 °C170 mm, 60 µm, -	Frequency of bubbles: 1550 and 1730 Hz; Average mass flow rate: 312 g/h; Correlation found
C1.2	MAXSIMA	19/01/2018	NA, NA, NA170 mm, 60 µm, -	failed
C1.3	MAXSIMA	08/02/2018	20.1 bar, 219 °C, 226 °C170 mm, 60 µm, -	Frequency of bubbles: 1400 Hz; Average mass flow rate: 394 g/h; Correlation found
C2.1	MAXSIMA	13/09/2017	20.2 bar, 200 °C, 209 °C170 mm, 80 µm, -	Frequency of bubbles: NA; Average mass flow rate: 787 g/h; Correlation found
C2.2	MAXSIMA	02/02/2018	19.3 bar, 210 °C, 226 °C170 mm, 80 µm, -	Frequency of bubbles: NA; Average mass flow rate: 346 g/h; Correlation found
C3.1	MAXSIMA	20/10/2017	NA, NA, NA170 mm, 40 µm, -	failed
C3.2	MAXSIMA	15/12/2017	19.6 bar, 213 °C, 223 °C170 mm, 40 µm, -	Frequency of bubbles: 500, 650, 1470, 2300, 2830, 3100 Hz; Average mass flow rate: NA
C4.1	MAXSIMA	10/11/2017	NA, NA, NA170 mm, 100 µm, -	failed
C4.2	MAXSIMA	22/11/2017	19 bar, 216 °C, 208 °C170 mm, 100 µm, -	Frequency of bubbles: 1500, 2700, 3800, 4300 Hz; Average mass flow rate: NA;
C5.1	MAXSIMA	26/02/2018	20.3 bar, 203 °C, 226 °C170 mm, 150 µm, -	Frequency of bubbles: 400, 3100 Hz; Average mass flow rate: 2551 g/h. Correlation found
C6.1	MAXSIMA	06/04/2018	20.2 bar, 247 °C, 246 °C170 mm, 200 µm, -	Frequency of bubbles: 370, 1050, 3200 Hz; Average mass flow rate: 1240 and 5120 g/h. Correlation found

filled with LBE at 350 °C. LIFUS5 had the same geometrical configuration used for the first experimental campaign (Ciampichetti et al., 2003) in the frame of the European Fusion Technology programme where lead–lithium was used.

The configuration was changed in the Test n. 2 by removing the expansion vessel S5. The test was designed to support the assessment of the accidental scenario of "heat exchanger tube rupture" in the safety analysis of the Integral Circulation Experiment (ICE) (Del Nevo et al., 2016). ICE is a test section which was installed in CIRCE facility. It aimed at reproducing the primary flow of a heavy liquid metal cooled reactor. A water heat exchanger working at 6 bar was initially proposed to extract the power from the LBE pool. During this test, the water was injected at 6 bar and 130 °C into the reaction vessel containing LBE at 350 °C.

Test n.3 and Test n.4 were executed with the same facility configuration of test n. 2. The tests were designed considering the operative conditions of the heat exchanger of the XT-ADS (Maes, 2008.), injecting water at 40 bar and 235 °C with LBE at 350 °C. The difference between the tests was related to the compressibility of the interaction vessel S1: in test n. 3, the vessel was completely filled, whereas in in test n. 4, it was filled at 80% (i.e. with an expansion volume of gas equal to 20 L).

Two other tests were executed in the framework of ELSY project (Alemberti et al., 2011). The interaction vessel was filled at 80%. The selected boundary conditions were representative of ELSY fast reactor design, thus water was injected at 180 bar and 325 °C and the LBE melt was set to 400 °C.

These experimental campaigns were done in order to study in depth and analyse physical phenomena and possible consequences of LBE-water interaction for XT-ADS and ELSY designs. Moreover, a test was also executed to support the safety evaluation of CIRCE facility in ICE configuration and evaluate the possible consequence of the heat exchanger rupture. The data were also used to assess numerical codes, namely SIMMER-III, in pioneering multi-fluid multiphase simulations of the Steam Generator Tube Rupture (Ciampichetti et al., 2009; Del Nevo et al., 2016; Wang et al., 2008).

The analysis of experimental data and simulations results of the transients showed that the absence of cover gas causes an increase of the system pressure because of the limited possibility for the produced vapor to expand. Another result that emerged from the experimental data is the possibility that both shock wave peak pressure and maximum pressure caused by interaction may exceed the initial pressure conditions of water injection. The latter is clearly connected with the compressibility of the system, the melt temperature and the conditions of the secondary side coolant circulating in the steam generator.

5.2. Execution of FP7 THINS and LEADER projects

A Test Matrix of 8 experiments was commissioned in the framework of the THINS Project. However, during the campaign, ten tests were executed, and the original test matrix was modified by substituting the high pressure tests, planned at 180 bar, with low pressure tests executed at 16 bar. The change was decided for two reasons: a) 16 bar is the operating pressure of current MYRRHA heat exchanger design; b) THINS configuration of LIFUS5/Mod2 has the dump system S3 disconnected, thus the main vessel S1 is isolated therefore, it was preferred to avoid such high injection pressure, close to the limiting operating values of the facility (i.e. 200 bar). In conclusion, besides the safety reasons, the objective of the change was to provide separate effect experimental data, suitable for code validation, having thermal–hydraulic parameters ranges representative of MYRRHA operating conditions. Table 1 summarizes the specifications of actual test matrix. The experiments are divided into two groups of 4 tests each: 1) Water tank (S2) set at 40 bar; 2) Water tank (S2) set at 16 bar. Three quantities have been selected for performing single variant tests: temperature of the injected water, gas argon to LBE ratio in S1 and total amount of injected water, i.e. varying the opening time of the injection valve. Tests A1.2_1 and A1.2_2 are also valuable as demonstration of repeatability of the experiments. The main objectives of the tests were to provide experimental data for the development and validation of multi-fluid models and scope codes to support the design of innovative HLM reactors and to characterize the initial propagation of the pressure wave following two-phase flashing and expansion, the liquid sloshing due to the two-phase mixing zone expansion.

The objectives of the experimental campaign were fulfilled, and the experimental data were available for evaluating the performances of codes in reproducing the phenomena and processes in range of parameters relevant for MYRRHA. The availability of the experiments constituted an enlargement of the database for codes' validation in relation to HLM-water interaction phenomena. The availability of the strain gauges data gave information of the dynamic effects and of the energy release in the structures of the facility and provided a source of input for dynamic FEM analyses (Pesetti et al., 2015; Pesetti et al., 2016; Di Maio et al., 2019; Del Nevo et al., 2015; Lorusso et al., 2018).

A Test Matrix of 7 experiments was commissioned in the framework of LEADER Project. The tests were performed adopting an injection orifice having different diameters: 4, 8.9 and 12.6 mm (see Table 1). These diameters represented about 0.1A (B1 series), 0.5A (B2 series) and 1.0A (B3 series), with A equal to about 60% of actual STSG tube flowing area. This value (60%) was due to the upper limiting size of the water pipe diameter, because the orifice was at the end of the water injection line, based on a ½ in sch. 80 pipeline (Dint 13.88 mm). The series B1 and B2 were constituted by 3 runs each one. In the domain of the third series (B3) one run was carried out. The main objectives of the experimental campaign, in the framework of LEADER project, were the evaluation of safety aspects of SGTR event in ELFR system, in particular the investigation and evaluation of mechanical effects on tubes and shell surrounding the injector, besides the generation of experimental data for the development and validation of models and codes for supporting the design and safety analysis of innovative HLMFRs.

The objectives of the tests were successfully achieved and the experimental data were made available for evaluating codes performances in simulating SGTR phenomena and processes observed in the experiment. The initial pressure peaks (i.e. shock peak) were successfully characterized by the higher acquisition frequency of 10 kHz. The pressurized tubes at 180 bar, surrounding the injector, maintained their integrity during the whole experimental campaign. In particular, the availability of strain gauges data contributed to clarify dynamic effects and energy release on structural components (i.e. tubes, SG dumping shell and interaction vessel) due to SGTR occurrence.

5.3. Execution of FP7 MAXSIMA project

A Test Matrix of 10 experiments was proposed in the framework of the EU MAXSIMA Project. Practically, eleven tests were performed adopting injection laser micro-holed plates having the diameter of 40, 60, 80, 100, 150 and 200 μm (Table 1). A total of 50 laser micro-holed plates were specifically manufactured for the experimental campaign. The holes were supposed to vary from 5 to 200 μm. Nevertheless, SEM analyses showed that the laser was not able to drill the stainless steel in the case of 5 μm, and no experiment was successful with the orifices having diameters 10 and 20 μm. These were plugged during the commissioning tests before the installation in LIFUS5/Mod3, notwithstanding the presence of a PORAL filter 0.5 μm, upstream the injector device. The objective of the experimental campaign was connected with the evaluation of safety aspects of SGTR event in ELFR system and to correlate the size of a potential micro-crack present on a MYRRHA PHX tube (the "leak before break" concept). In particular, the main aim was to investigate bundle with the noise that the vapour bubbles produce bubbling from it. These outcomes were fulfilled and the acquired measurements contributed to enlarge existing databases for SGTR events, providing an advancement in supporting the design of innovative HLM reactors. Three tests failed because injector plugging occurred. The analysis of the thermo-hydraulic data permitted to characterize the leakage through typical cracks, which can occur in pressurized tubes of the steam generator. It is worth highlighting that the more reliable values of the mass flow rate come from the level meter experimental trends, instead of the Coriolis mass flow meter data. Indeed, the instrument results were not reliable, probably due to the presence of impurities or dirt compounds deposited in the device during the commissioning phase. For this reason, a further poral filter was added upstream of the Coriolis device prior to the experimental tests. The analysis of the ADS permitted to recognize the energy variation and the characteristic frequencies of the bubbles generated from the different orifice sizes, although the recorded raw data for a single test are numerous and the analyses require further efforts. The analysis of the data acquired and recorded by the High Temperature Accelerometer, High Sensitivity Accelerometer, Acoustic Emission sensors showed a correlation with the orifice diameter, proportional to the mass flow rate across the orifices, proportional to the leakage.

6. Conclusions

The LIFUS5 separate effect test facility has represented an important contribution to HLM fast reactors thermal–hydraulic safety research. Indeed, current pool-type configurations have the steam generators inside the reactor vessel, thus the interactions between the secondary side coolant and the HLM may occur. This type of transient (Steam Generator Tube Rupture SGTR) should be investigated from the safety point of view because it could potentially induce, beyond the damaging of the internal structures (HX tube bundle, above core structures, Fuel Assembly, Control Rods, etc.) several negative effects on the operation of the reactor. These include an insertion of positive reactivity into the system or reduced cooling efficiency due to steam dragging into the core. It will also have an effect on the chemistry control of the cooling. All these effects compromise the safety and the reliability of the system.

A comprehensive data base relevant to the understanding of governing phenomenology expected in HLM/water interaction accident conditions and to the validation of system codes used (SIMMER-III, SIMMER-IV and RELAP5/Mod3.3) has been provided by twenty years of experimental programme in LIFUS5 facility. The infrastructure has been employed under the framework of FP6 and FP7 EU projects (IP EUROTRANS DEMETRA, ELSY, THINS, LEADER, MAXSIMA), supported also by Italian Ministry of Economic Development. Moreover, the expected outcomes and the scientific objectives have been achieved, demonstrating the repeatability and reliability of the experimental tests, validating the numerical codes, and supporting the STSG design. In particular, the following conclusions can be stated:

- the absence of cover gas causes an increase of the system pressure because of the limited possibility for the produced vapor to expand.
- both shock wave peak pressure and maximum pressure caused by interaction may exceed the initial pressure conditions of water injection, which is clearly connected with the compressibility of the system, the melt temperature and the conditions of the secondary side coolant circulating in the steam generator.
- the initial pressure peaks (i.e. shock peak) have been successfully characterized by the higher acquisition frequency of 10 kHz. The tube rupture damage does not propagate to neighboring tubes which maintained their integrity during the whole experimental campaigns.
- concerning the “leak before break” concept, the analysis of the data acquired and recorded by detection system sensors (ADS and accelerometers) showed a correlation with the orifice diameter, proportional to the mass flow rate across the orifices, proportional to the leakage.
- considering the validation of numerical codes, the activity is still ongoing and the results showed good agreement between the experimental and the calculated trends, confirming the capabilities of the SIMMER codes and SIMMER-RELAP coupled tool to simulate such kind of transient scenario.

CRediT authorship contribution statement

M. Eboli: Methodology, Investigation, Writing – original draft, Writing – review & editing. **A. Ciampichetti:** Investigation, Writing – review & editing. **F. Giannetti:** Writing – review & editing. **N. Forgione:** Writing – review & editing. **A. Del Nevo:** Investigation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

References

7th FP of Euratom for Nuclear Research and Training Activities (2007-2011), Thermal-Hydraulics of Innovative Nuclear Systems (THINS), Annex I – “Description of Work”, Grant agreement no.: 249337, Nov. 2009.

7th FP of Euratom on Advanced nuclear systems for increased sustainability/ Fission 2009 2.2.1: Conceptual design of Lead and Gas cooled fast reactor systems, “ Lead-cooled European Advanced DEmonstration Reactor (LEADER) - Annex I - Description of Work ” Grant agreement no.: FP-249668, September 5, 2009.

7th FP THEME [Fission-2012-2.3.1] [R&D activities in support of the implementation of the Strategic Research Agenda of SNE-TP Nuclear Fission and Radiation Protection] – Annex I - “Description of Work”” Grant agreement no.:FP7- 323312, October 9, 2012.

Alemberti, A., Carlsson, J., Malambu, E., Orden, A., Cinotti, L., Struwe, D., Agostini, P., Monti, S., 2011. ELSY—european LFR activities. J. Nucl. Sci. Technol. 48 (4), 479–482.

Ciampichetti, A., Ricapito, I., Aiello, A., Benamati, G., 2003. Water large leaks into liquid Pb-17Li: first experimental results on LIFUS 5 facility. Fusion Eng. Des. 69 (1-4), 563–567.

Ciampichetti, A., Agostini, P., Benamati, G., Bandini, G., Pellini, D., Forgione, N., Oriolo, F., Ambrosini, W., 2008. LBE–water interaction in sub-critical reactors: first experimental and modelling results. J. Nucl. Mater. 376 (3), 418–423.

Ciampichetti, A., Pellini, D., Agostini, P., Benamati, G., Forgione, N., Oriolo, F., 2009. Experimental and computational investigation of LBE–water interaction in LIFUS 5 facility. Nucl. Eng. Des. 239 (11), 2468–2478.

Ciampichetti, A., Bernardi, D., Cadiou, T., Forgione, N., Poli, F., Pellini, D., 2011. LBE–water interaction in LIFUS 5 facility under different operating conditions. J. Nucl. Mater. 415 (3), 449–459.

Del Nevo, A., et al., 2019. “Experimental campaign in support of the safety studies of the STGR in LFR”, 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (Proc. Int. Conf. NURETH18), Portland, Page 2398.

Del Nevo, A., Ciampichetti, A., Tarantino, M., Burgazzi, L., Forgione, N., 2016. Addressing the heavy liquid metal-Water interaction issue in LBE system. Prog. Nucl. Energy 89, 204–212.

Del Nevo, A., et al., “Experimental and numerical investigations of interaction between Heavy Liquid Metal and Water for supporting the safety of LFR Gen. IV reactor design”, 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (Proc. Int. Conf. NURETH16), Chicago (2015), Page 7448.

Di Maio, P.A., Arena, P., D’Aleo, F., Del Nevo, A., Eboli, M., Forte, R., Pesetti, A., 2019. Thermal-hydraulic and thermo-mechanical simulations of water-heavy liquid metal interactions towards the DEMO WCLL breeding blanket design. Fusion Eng. Des. 146, 2712–2716.

Eboli, M., Del Nevo, A., Forgione, N., Giannetti, F., Mazzi, D., Ramacciotti, M., 2020. Experimental characterization of leak detection systems in HLM pool using LIFUS5/Mod3 facility. Nucl. Technol. 206 (9), 1409–1420.

Eboli, M. et al., “Characterization of Leak Detection in HLM system using LIFUS5/Mod3 facility”, 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (Proc. Int. Conf. NURETH18), Portland (2019), Page 2411.

Eboli, M. et al., “Experimental Studies of Leak Detection in LBE System”, 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (Proc. Int. Conf. NURETH19), Virtual (2022), Log nr.: 35462.

Knebel, J., et al., 2005. Integrated Project EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System, EUROTRANS. EC Project No. FI6W-CT-2004-516520 (2005).

Lorusso, P., et al., “GEN-IV LFR development: Status & perspectives”, Progress in Nuclear Energy, 105 (2018) 318-331, doi.org/10.1016/j.pnucene.2018.02.005.

Maes, D., XT-ADS Primary Heat Exchangers Sizing, SCK-CEN Technical Note reported in Eurotrans deliverable D1.27 D1.28 “Description and functional sizing of main components of the reference design of XT-ADS” issued by Ansaldo Nucleare in 2008.

Pesetti, A., Del Nevo, A., Forgione, N., 2015. Experimental investigation and SIMMER-III code modelling of LBE–water interaction in LIFUS5/Mod2 facility. Nucl. Eng. Des. 290, 119–126.

Pesetti, A., et al., "Water/Pb-Bi interaction experiments in LIFUS5/Mod2 facility modelled by SIMMER code", 22nd International Conference on Nuclear Engineering (Proc. Int. Conf. ICONE22), Prague (2014), Paper ICONE22-30191.

Pesetti, A., et al., "Experimental investigation of Spiral Tubes Steam Generator Rupture scenarios in LIFUS5/Mod2 facility for ELFR", 24th International Conference on Nuclear Engineering (Proc. Int. Conf. ICONE24), Charlotte (2016), Paper ICONE24-60715.

Pesetti, A., et al., "Assessment of SIMMER-III code based on Steam Generator Tube Rupture Experiments in LIFUS5/Mod2 facility", 24th International Conference on Nuclear Engineering (Proc. Int. Conf. ICONE24), Charlotte (2016), Paper ICONE24-60711.

Pesetti, A., et al., "Experimental investigation in LIFUS5/Mod2 facility of Spiral-Tube Steam Generator Rupture scenarios for ELFR", 25th International Conference on Nuclear Engineering (Proc. Int. Conf. ICONE25), Shanghai (2017), Paper ICONE25-67420.

Wang, S., et al., 2008. Evaluation of a steam generator tube rupture accident in an accelerator driven system with lead cooling. Prog. Nucl. Energy 50, 363–369. https://doi.org/10.1016/j.pnucene.2007.11.018.