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Experimental Characterization of Leak Detection Systems in HLM Pool using LIFUS5/Mod3 Facility

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ABSTRACT

In the framework of EU MAXSIMA project, the safety of the Steam Generator adopted in the primary loop of the Heavy Liquid Metal Fast Reactors has been studied investigating the consequences and damage propagation of a Steam Generator Tube Rupture event and characterizing leak rates from typical cracks. Indeed, instrumentation able to promptly detect the presence of a crack in the steam generator tubes may be used to prevent its further propagation, which would 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 and decreasing the probability of the pipe break event. In this framework, a new experimental campaign (Test Series C) has been carried out in LIFUS5/Mod3 facility, installed at ENEA C.R. Brasimone, in order to characterize and to correlate the leak rate through typical cracks occurring in the pressurized tubes with signals detected by proper transducers. Test C1.3_60 was executed injecting water at about 20 bar and 200°C into Lead Bismuth Eutectic alloy. The injection was performed through a laser micro-holed plate of 60 micrometers in diameter. The analysis of the thermo-hydraulic data permitted to characterize the leakage through typical cracks which can occur in pressurized tubes of steam generator, while the analysis of the data acquired by the microphones and accelerometers highlighted that is possible to correlate the signals to the leakage, and the rate of release.

KEYWORDS
SGTR, safety, Generation IV, LIFUS5/Mod3, Leak detection

I. INTRODUCTION

The new generation IV Heavy Liquid Metal Fast Reactors (HLMFR) is designed as pool type reactor, implementing the Steam Generators (SG) into the primary pool, where also the core, primary pumps and main components are set [1]. This design feature allows increasing the reactor performance and simplifying the whole layout. However, in such configuration, the secondary coolant (water), flowing in the heat exchanger tube bundle, at high pressure and subcooled conditions, could come into contact with the primary heavy liquid metal coolant, at higher temperature and lower pressure, in a hypothetical SG Tube Rupture (SGTR) accident [2, 3]. During such event, high pressure water enters in the low pressure liquid metal pool and rapidly evaporates. The consequent sudden increase of the water specific volume entails pressure waves propagation, which could affect the structural integrity of the surrounding components, and cover gas pressurization [4, 5]. Moreover, the rupture of a single SG tube could affect, in principle, the integrity of the neighboring tubes (domino effect), making worse the consequences of the accidental scenario. Besides the damaging of the internal structures, a SGTR event could potentially induce an insertion of positive reactivity into the system or reduce cooling efficiency due to steam dragging into the core. It will also have an effect on the chemistry control of the cooling. These consequences may compromise the safety and the reliability of the system. Instrumentation able to promptly detect the presence of a crack in the SG 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.

The paper describes Test C1.3_60 of the new experimental campaign (Series C) executed in LIFUS5/Mod3 facility in order to characterize and correlate the leak rate through typical cracks occurring in the pressurized tubes with signals detected by proper transducers [6, 7]. The layout of the LIFUS5/Mod3 facility, the water injection line and injection device and the installed instrumentation have been reported and described in section II. The test matrix of the experimental campaign is reported in section III while section IV describes the execution and experimental data of Test C1.3_60. Water at about 20 bar and 200°C was injected into Lead Bismuth Eutectic (LBE). The injection was performed through a laser micro-holed plate of 60 micrometer. The experimental analyses aim to provide engineering feedbacks to promptly detect the presence of a crack in the SG tubes, which may be used to prevent its further propagation. Different instrumentation are installed and tested in the experimental campaign. Moreover, the acquired experimental data can be used for the validation of numerical models and calculation codes.

II. LIFUS5/MOD3 FACILITY DESCRIPTION

LIFUS5/Mod3 is a multi-purpose experimental facility installed at ENEA CR Brasimone (Fig. 1 and Ref. [7, 8]). It is designed to be operated with different heavy liquid metals like Lithium-Lead alloy, Lead-Bismuth eutectic alloy and pure lead. The test section S1A is devoted to the small leakage detection activity and can be operated at maximum temperature of 500 °C and maximum pressure of 200 bar, according to Pressure Equipment Directive (PED). The main parts characterizing LIFUS5/Mod3 facility are listed hereafter:

1. the interaction vessel S1A, where LBE/water interaction occurs;
2. S2V vessel, where demineralized water is stored for the injection in S1A by means of a pressurized gas cylinder connected to the top;
3. S4A is the storage tank of LBE;
4. S3V is a dump tank, used to collect vapor and gases during the test.

II.A. Main components description

The interaction vessel S1A is about 100 liters, and it is partially filled with LBE during the tests. A top flange closes it by means of a graphite gasket spiral wound. Penetrations are made in S1A top flange for allowing 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 dump tank. Internally, S1A can be divided into an upper cylindrical part and a lower hemispherical part. The main diameter is 420 mm and the overall height is 780 mm. The cylindrical shell of S1A has penetrations allowing the passage of the instrumentation, which consist of one fast pressure transducers (PT) and two thermocouples (TC). At the bottom of the vessel, a 2" sch.80 penetration provides the connection with the injection line and the LBE charging/discharging system.

The water tank S2V is a pipe, closed at the edges with two flanges. It has a volume of about 14 liters. It is connected on the top with the gas line, which is used for setting and keeping the pressure of the water according with the test specifications. On S2V top flange, a threaded penetration is provided allowing the passage of a magnetostrictive level measurement device, having a volume of 3 liters. The filling level in the S2V vessel is continuously monitored also by a Differential Pressure (DP) meter inserted between the lower part of S2V and bottom part of injection line, for a height of about 2.15 m. At bottom, S2V is connected to the water injection line. LBE in S1A is filled and drained, just before and after the test respectively. It is stored in the liquid metal storage tank S4A, which is connected to the bottom of the main vessel S1A. On lateral surface 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 is connected by means of a 3” line to the top flange of S1A. The S3V volume is equal to 2 m^3 and the design pressure is 10 bar. It represents a safety volume used to collect the vapour and the gas generated by the interaction between LBE and water.

II.B. Injection line

The injection line (Fig. 2) starts from S2V water storage tank and it is connected to the S1A reaction vessel. A Coriolis mass flow meter (MT-S2L-01) is placed between the pneumatic valves VP-S2L-07 and VP-S2L-08, in order to measure the mass of water that flows in the line and is injected in reaction tank S1A. A manual drainage valve (VM-S2L-11) is located downstream the mass flow meter, with the aim to empty the line after every experimental procedure. The Coriolis has the capability to measure the mass flow rate in the range of 50-2000 g/h. The water injection line is heated from VP-S2L-08 (downstream the Coriolis) to S1A. There are 5 heating wires in charge to warm-up the water before its entering in the reaction vessel (up to 200°C). These heating wires are controlled by means of thermocouples for both safety and regulation. The temperature of the fluid is controlled by 4 thermo wells. Line is insulated from the external environment by an insulating layer, this reduces the heat losses and therefore limits the power of heating wires.

II.C. Injection system and injector device

The injection system (Fig. 3) is constituted by two separate parts, connected by a 2"ANSI 2500 Ring Joint flange. The first one is completely integrated and welded to the bottom of S1A vessel. The second one is manufactured by four coaxial tubes and it can be dissembled at the end of each test to allow the replacement of the injector device. The water injection line enters into a second tube which permits the inlet of the gas for the injection system cooling. The gas flows towards up to the injector device 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. 3) is characterized by a micro-holed AISI 316 plate with a thickness of 1 mm and a diameter of 1" (25.4 mm). 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. The plate is installed into the injector device between two sealing rings. An injector cap closes the injector device by means of a spanner, designed ad hoc. In this way, at each test, the injector device can be disassembled and the plate can be replaced with another one with different micro-hole diameter. All of these components are manufactured by ENEA workshop.

II.D. Detection System: Real Time Data Acquisition for Microphones, Accelerometers and Acoustic Emission Sensor

The top flange of the LIFUS5/Mod3 facility has 5 penetrations where microphones are installed. Moreover, a series of alternative detection system, which are constituted by accelerometers and acoustic emission sensor, are placed on the flange and inside the vessel of the LIFUS5/Mod3 facility. The layouts are depicted in Fig. 4. These are:

1. One microphone at high temperature in central position (i.e. HT ADS).
2. Four microphones at low temperature along the same circumference (i.e. LT ADS);
3. Inductive proximity sensor (i.e. High Sensitivity Accelerometer – HSA) installed outside the vessel;
4. Accelerometer sensor installed inside the vessel (i.e. High Temperature Accelerometer – HTA) on a metallic support;

5. Acoustic Emission (AE) sensor installed outside the vessel, measuring the high frequency signals by means of a waveguide.

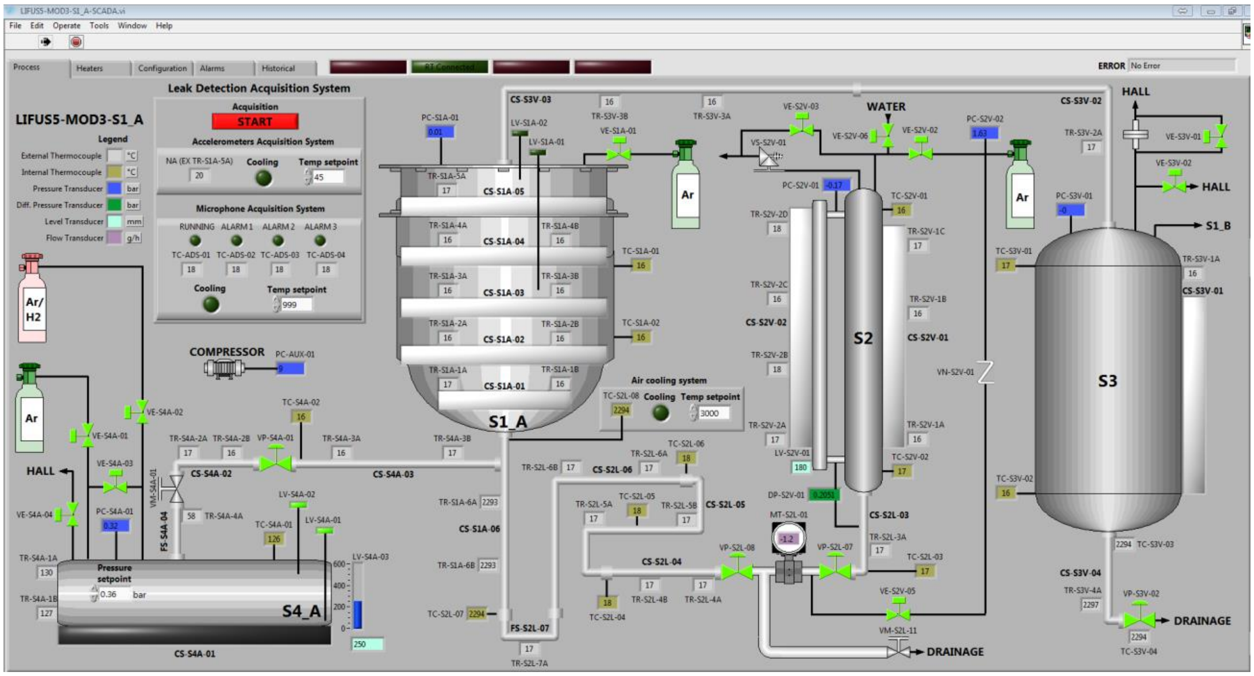
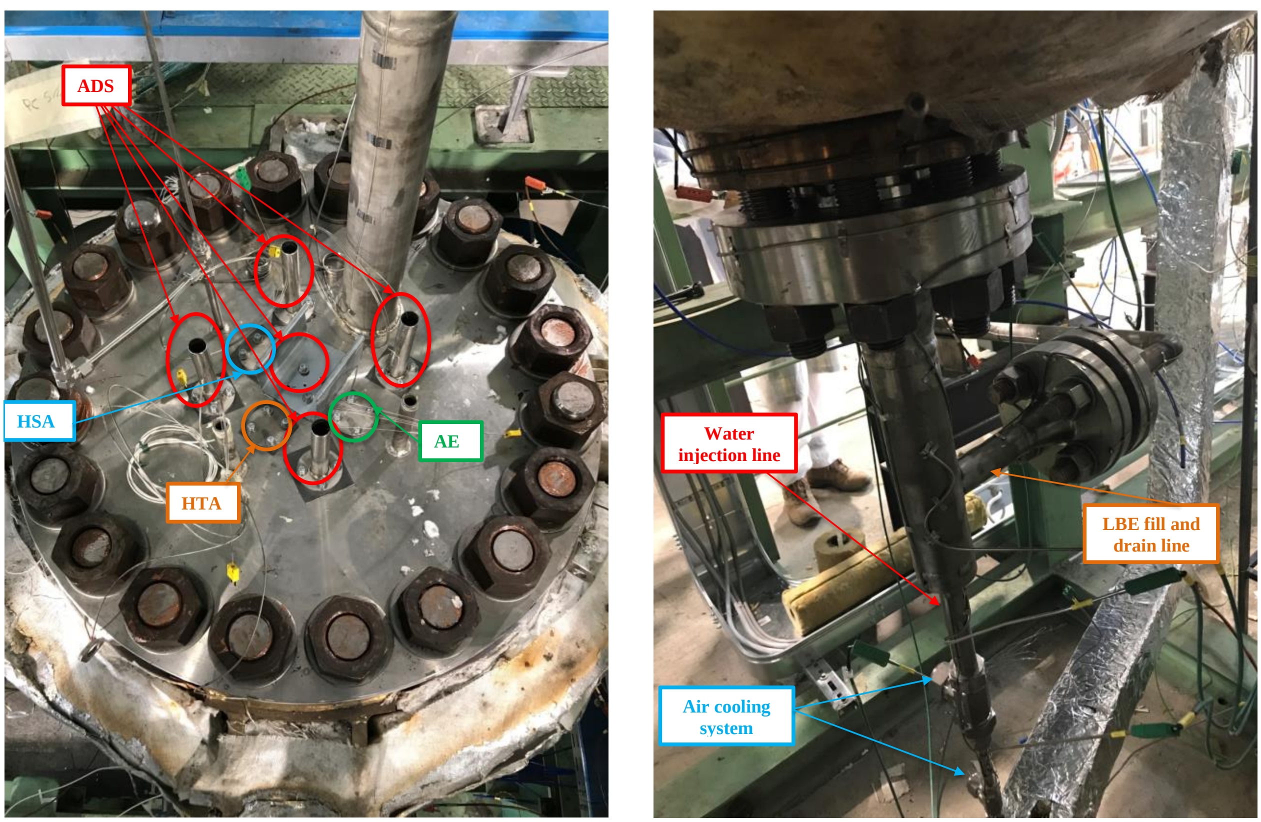


Figure 1. LIFUS5/Mod3 synoptic.



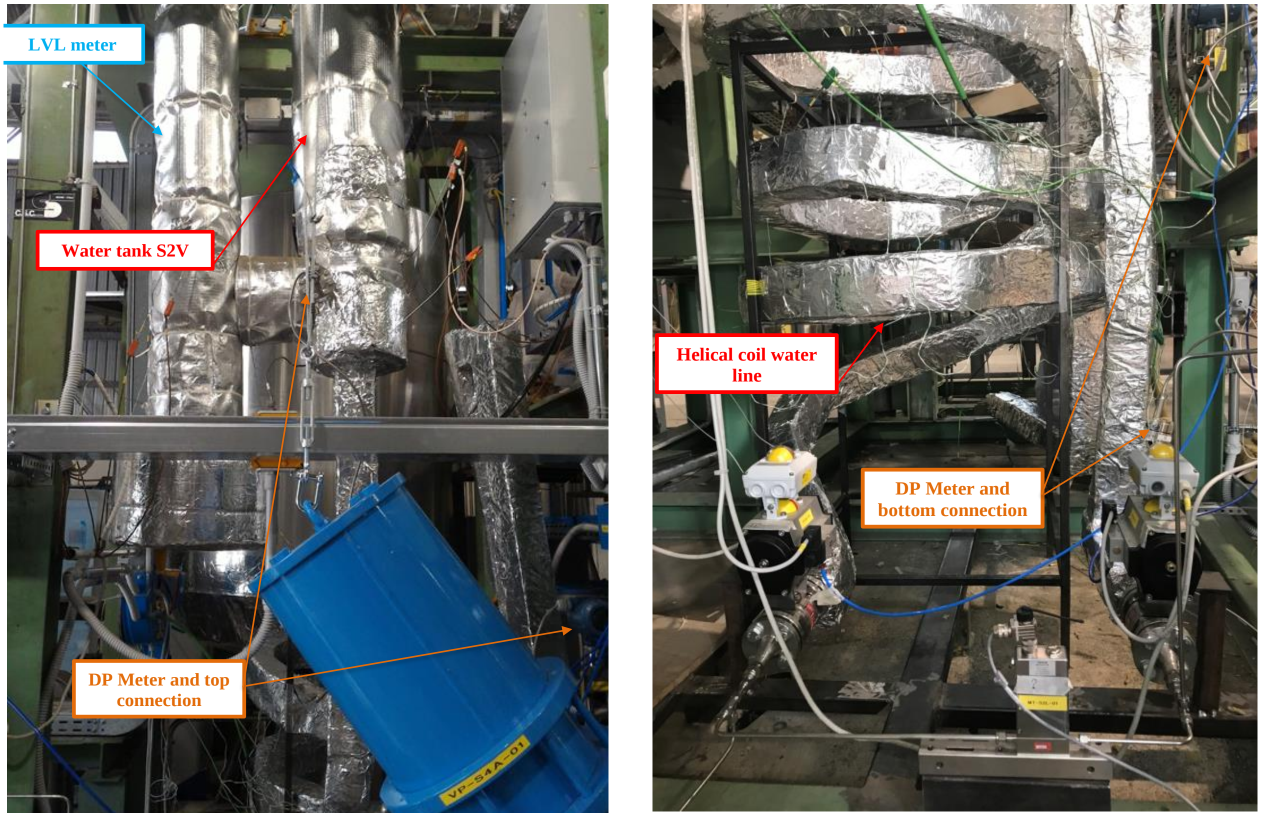


Figure 2. LIFUS5/Mod3 view of S1A flange penetrations and water injection line.

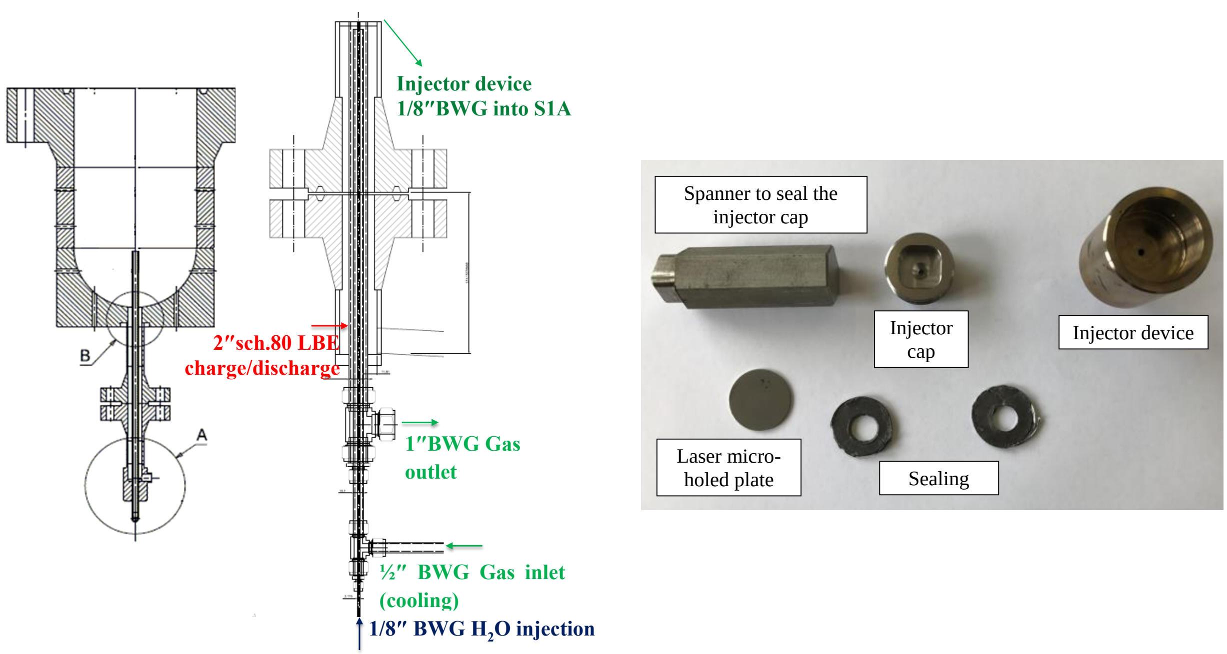


Figure 3. LIFUS5/Mod3 sketch of the injection system and injector system device.

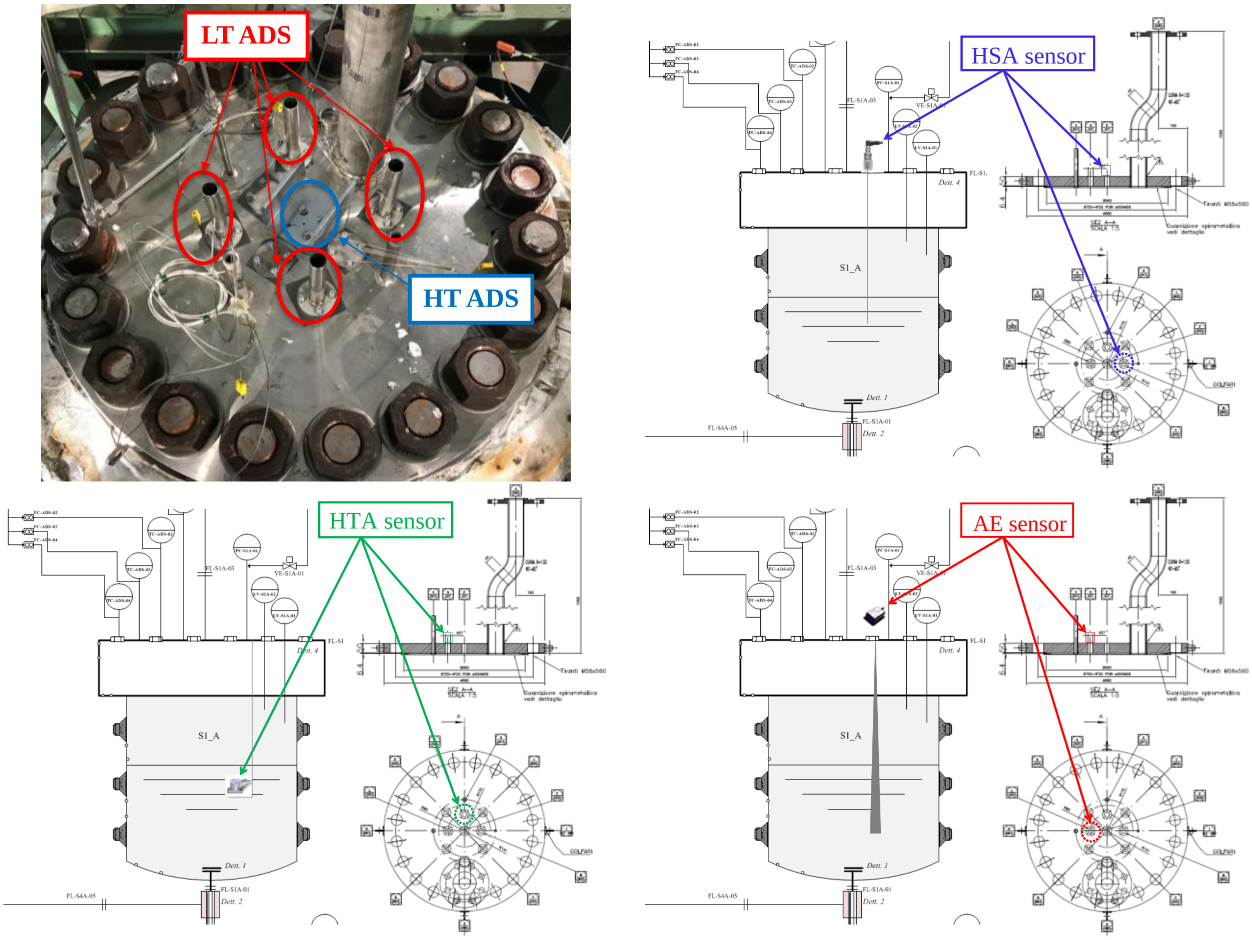


Figure 4. ADS and Accelerometers positions on LIFUS5/Mod3 facility.

III. TEST MATRIX AND OBJECTIVES OF THE EXPERIMENTAL CAMPAIGN

A Test Matrix (TM) of 10 experiments was proposed in the framework of the EU MAXSIMA Project [9] (Tab. I). Tests were performed adopting injection laser micro-holed plates having the diameter of 40, 60, 80, 100, 150 and 200 micrometers.

The objective of the experimental campaign is connected with the SGTR accidental scenario. In particular, the aim is to investigate and correlate the size of a micro-crack in a tube of MYRRHA Primary Heat exchanger tubes bundle with the signal induced by the vapor bubbles formed and flowing in the liquid metal. The expected outcomes of the tests are:

1. the generation of reliable experimental data;
2. the evaluation of the water mass flow rate in LBE through a characterized crack;
3. the correlation of the crack sizes with proper signals;
4. the enlargement of the database for code validation.

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Table I. LIFUS5/Mod3 experimental campaign – C series (2017 - 2018).

Parameter	**TEST**										
	C1.1 (_60)	**C1.2** (_60)	**C1.3** (_60)	**C2.1** (_80)	**C2.2** (_80)	**C3.1** (_40)	**C3.2** (_40)	**C4.1** (_100)	**C4.2** (_100)	**C5.1** (_150)	**C6.1** (_200)
Test Number	T#1	T#7	T#10	T#2	T#9	T#3	T#6	T#4	T#5	T#8	T#11
Execution Date	06/09	19/01	08/02	13/09	02/02	20/10	15/12	10/11	22/11	26/01	06/04
Number of laser-holed plate	21	22	23	16	19	27	28	11	13	6	4
Φ orifice (design)[μm]	60	60	60	80	80	40	40	100	100	150	200
A orifice (measured)[μm^2]	3188	3080	3257	4919	5508	1392	1329	8116	7676	18768	32151
Execution	ok	failed	ok	ok	ok	failed	ok	failed	ok	ok	ok
Acquisition time [hh:mm]	06:15	NA*	09:00	11:22	5:00	NA	5:29	NA	7:29	5:59	3:00
LBE temperature TC-S4A-01 [°C][(1)]	203	NA	226	209	226	NA	NR*	NA	NR	226	246
Water pressure PC-S2V-01 [bar][(1)]	19.7	NA	20.1	20.2	19.3	NA	NR	NA	NR	20.3	20.2
Water temperature TC-S2L-08 [°C][(1)]	170	NA	219	200	210	NA	NR	NA	NR	203	247

[(1)] Pressure and Temperature identified at SoT
* NA Not Available – NR Not Recorded

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IV. DESCRIPTION OF THE EXPERIMENT – TEST C1.3_60

The Test LIFUS5/Mod3 C1.3_60 [10] corresponds to test #10 of the test matrix above. The micro-holed injector plates used in the test was characterized by Scanning Electron Microscope (SEM) analyses ([6]): a mean diameter of 63.7 μm and an area of 3257 μm^2 were measured.

IV.A. RELAP5/Mod3.3 characterization prior to test

RELAP5/Mod3.3 code ([11]) is used to investigate the injection across the orifice at different temperature conditions. The nodalization (Fig. 5) is set-up modeling the actual geometry of LIFUS5/Mod3 injection line, as built (Fig. 1). The injection pressure is set to 19 bar. The LBE system (i.e. S1A) is modeled as a boundary condition, where pressure and temperature are imposed (i.e. 1.1 bar and 200 °C). No heat transfer is simulated between the LBE and the water system. The water temperature is varied stepwise in the range of 15–275 °C.

The results (Fig. 6) show that during the time interval of 0-2000 s (corresponding to the water temperature range of 15-50°C), the calculated mass flow is about 560 g/h. The amount of injected water in this time interval is about 0.3 kg. Considering the temperature range of 150-200 °C, which is representative of the experimental test conditions, the mass flow rate calculated by RELAP5 decreases once the temperature of the fluid is closer to the saturation. The two-phase chocked flow is established in the time interval 9000-12000 s. In this condition, the mass flow rate varies from 530 g/h to 320 g/h. Then, single phase gas flow conditions are achieved.

IV.B. Analysis of the Test

The initial test conditions are achieved accordingly with the specifications with satisfactory accuracy. The water injection is executed using the valves VP-S2L-07 and VP-S2L-08 across the Coriolis flow meter. The time schedule of the test execution is summarized in Tab. II.

The main parameter trends are reported in selected time scales in Fig. 7 and Fig. 8. The Test C1.3_60 can be divided in 2 main phases:

1. **Water injection without LBE**
2. **Water injection in LBE**

Time 0 s is assumed at 07:30:00, when the acquisition system is activated. The acquisition time lasts 32400 s.

In order to prevent a plugging of the micro-holed injector plate during the LBE filling phase, the injection of water is started in advance. Therefore, the first phase corresponds to water injection without LBE in the interaction vessel (S1A). This phase ends when the LBE filling procedure starts. The ADS and accelerometers acquisition systems are already activated.

When the LBE level is stable in S1A, accordingly with the continuum level meter LV-S4A-03, the filling procedure is completed (Fig. 7). The Start of the Test (SoT) occurs, at time t = 5158 s, whereas it ends at time equal 27017 s. During the test, the amount of water injected is measured according with the data of the level meter LV-S2V-01. The mass flow rate is derived from this measure. The Coriolis flow meter results out of calibration, therefore, only the qualitative trend is considered in the analysis, being consistent with the level measurement and the signals recorded by the accelerometers.

During the test, the water level decreases from 676 to 406 mm. The decrease of 270 mm in level leads to an overall mass of injected water corresponding to 2.40±0.088 kg in 21859 s. The average mass flow rate in this time span is therefore 395.2±1.5 g/h, in particular, it varies during the test from an average value of 586.7±1.5 g/h to 253.2±1.5 g/h, as shown from the qualitative trend of the Coriolis mass flow meter in Fig. 7. The measured data confirm the RELAP5/Mod3.3 results.

The second phase ends with the drainage of the LBE from S1A interaction vessel towards the storage tank at t = 27544 s. Meanwhile, the water continues to be injected up to t = 27669 s, when the injection stops

Concerning the temperatures (Fig. 8), the thermocouples TC-S1A-01 and TC-S1A-02, installed in the interaction vessel S1A, show a rapid increase of about 20 °C, when are in contact with the LBE. Indeed, the LBE stored in S4A is maintained at temperature of 230 °C, while the vessel S1A is pre-heated at about 210 °C.

During the test (between Start of Test - SoT and End of Test - EoT), the thermocouples in the water injection line from TC-S2L-03 to TC-S2L-06 record a maximum temperature of 130 °C. The water heating occurs in the last section of the injection line. TC-S2L-07 records an average temperature of 192 °C, which decreases when the heating cables of the injection line is switched off. On the opposite, the TC-S2L-08, installed just before the injector, measures a nearly constant temperature during the injection, below the saturation.

IV.C.Analysis of Acoustic Detection System data and interpretation

The main target of this application is to correlate the dimension of the orifice with the sound pressure wave generated inside the tank. In order to achieve this result, the idea is to check the frequency response of the sound pressure waves and to correlate the frequency change with the diameter of the orifice.

The raw data recorded by microphones are sequentially loaded and continuously transformed in order to have a series of Fast Fourier Transform (FFT) files from which extracting the frequency spectrum of the bubbles.

During Test C1.3_60, the high temperature microphone in channel 1 (HT ADS) is available for the measure and records data from 0 to 23000 s. The results of bubble frequency analysis show two different peaks. The peak at 3300 Hz is observed during the acquisition constantly, thus both when the water injection is on and off. Therefore, it is concluded that the signal at the frequency of 3300 Hz represents a background noise. The other peak is measured at 1400 Hz, which is associated with the sound of bubble rising and appearing on the melt surface. Fig. 9 reports the FFT of a period of time during which a bubble is recorded. In this test, the characteristic frequency for the bubble generated from the 60 μm orifice is 1400 Hz.

IV.D.Analysis of the Accelerometers and Acoustic Emission sensors data and interpretation

The analysis of the acquisitions related to HTA (high temperature accelerometer), HSA (high sensitivity accelerometer) and AE (acoustic emission) sensors are divided into the two phenomenological windows of the test:

1. Water injection without LBE (up to t = 5158 s)
2. Water injection in LBE (from t=5158 s SoT to t=27017 s EoT,)

During the first phase (Fig. 10), the mass flow rate of injected water into empty S1A is about 797 g/h. When the LBE starts to be charged into the interaction vessel S1A, the HTA sensor (placed inside the vessel) records an average value of 0.07 g Root Mean Square (RMS), which represents the HLM-water interaction. During the second phase, the mass flow rate of injected water decreases from 586 g/h to 253 g/h, leading to HTA data trend variations from 0.12 g RMS to 0.09 g RMS, as shown in Fig. 10, which depicts the trend of the mean RMS value calculated over time intervals of 0.5 s.

The analysis of the data acquired by the Dewesoft system and recorded by the HTA, HSA, AE sensors highlighted the following:

1. the AE and HSA sensors, installed on the upper flange of the S1A vessel, recorded data affected by external interferences, i.e. the compressed air flow of the sensors cooling system. This correlation is evaluated by analyzing the start/stop signal of the sensor cooling system and checking the correspondence between the opening/closing times of the compressed air circuit within the acquisition of the sensors installed on the upper flange. Thus, the data acquired in these time intervals are excluded. During the phase “Water injection in LBE” the HSA records 0.01 g RMS and the AE records 0.35 V RMS;
2. the HTA sensor, positioned inside the S1A vessel, during the phase “Water injection in LBE” measured different values according to the mass flow rate variation, in particular for mass flow rate equal to 586 g/h, the HTA recorded an average value of 0.12 g RMS and for mass flow rate equal to 253 g/h, the HTA recorded an average value of 0.09 g RMS.

Table II. Test C1.3_60, time schedule of tests execution.

#	Time [Timing]	Phase	Description	Signal
C1.3_60 Experimental Test (08.02.2018)				
1	07.30:00 [t = 0]	Starting acquisition		
2	08:39:41 [--]	Leak detection systems on (ADS)		
3	08:45:17 [t = 4517]	Leak detection systems on (HSA,HTA,AE)		UDV-ADS-A
4	08:45:32 [t = 4532]	Filling	LBE fill procedure starts	VP-S4A-01
5	08:55:58 [t = 5158]	Filling	LBE fill procedure ends. S1A filled	VP-S4A-01
6	08:55:58 [t = 5158]	Start of Test – SoT	S1A filled in steady state	LV-S4A-03
7	14:59:55 [t = 26995]	Draining	LBE drain procedure starts	VP-S4A-01
8	15:00:17 [t = 27017]	End of Test – EoT	S1A filled in steady state	LV-S4A-03
9	15:07:45 [--]	Leak detection systems off (ADS)		
10	15:09:04 [t = 27544]	Draining	LBE drain procedure ends	VP-S4A-01
11	15:11:09 [t = 27669]	End of Injection – EoI	Water injection off	VP-S2L-07
12	15:10:05 [t = 27605]	Leak detection systems off (HSA,HTA,AE)		UDV-ADS-A

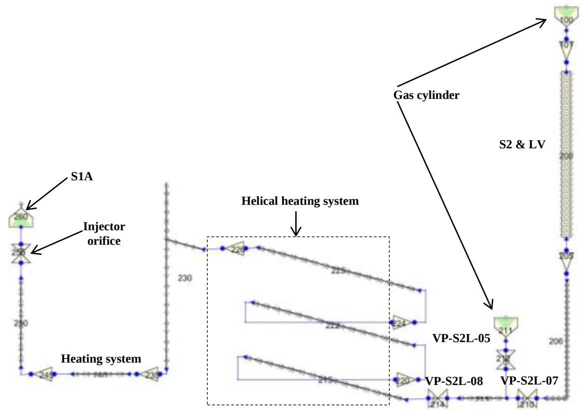

Figure 5. LIFUS5/Mod3 sketch of the injection system and injector system device.

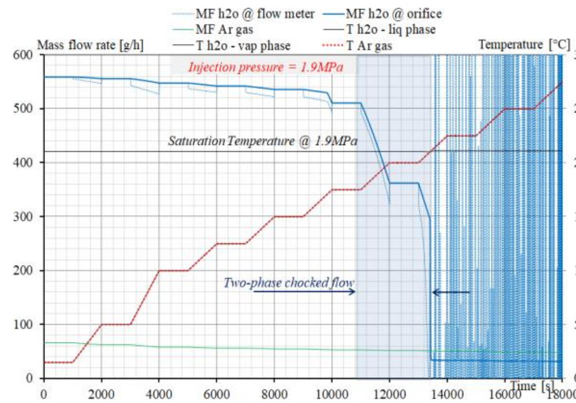

Figure 6. RELAP5/Mod3.3 calculation of the Ar and H_2O mass flow rate through the orifice

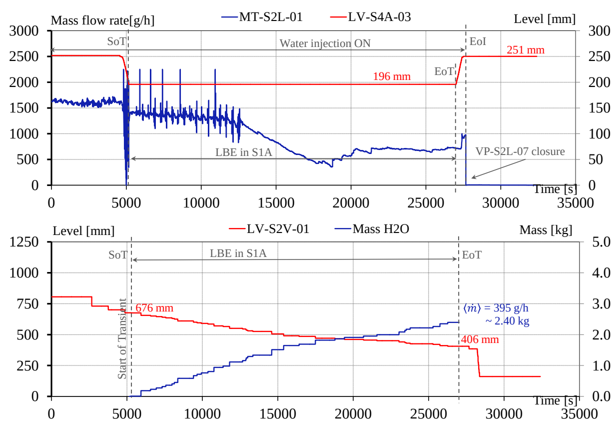

Figure 7. Test C1.3_60, LBE level, water mass flow rate and water level experimental trends.

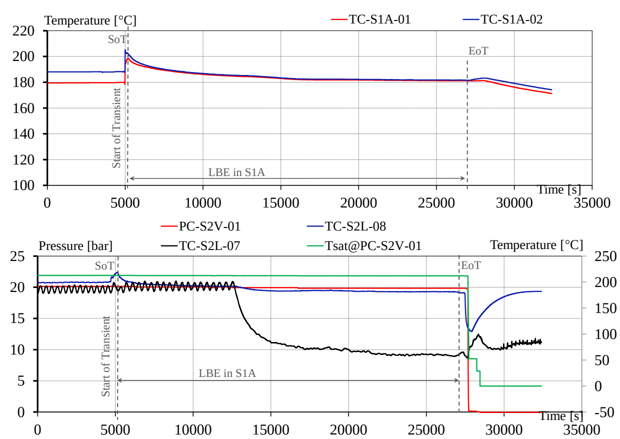

Figure 8. Test C1.3_60, Temperature trends in S1A vessel and water injection line.

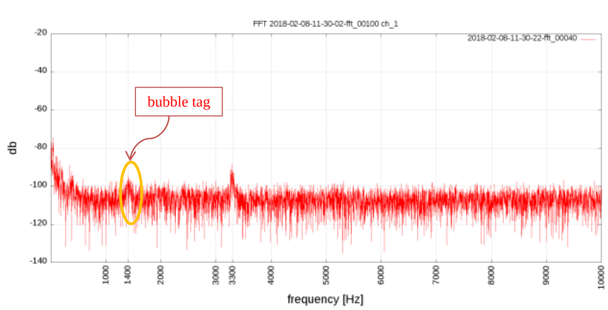

Figure 9. Test C1.3_60, frequency spectrum @ time 11:30.22,04

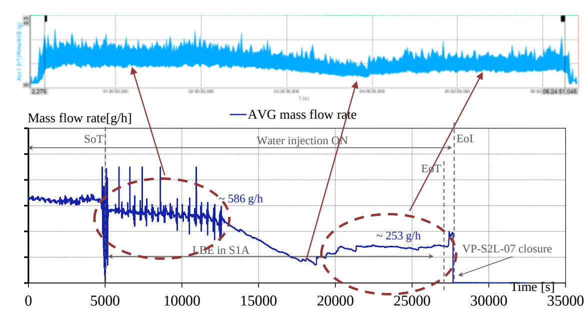

Figure 10. Test C1.3_60, HTA RMS average trend and corresponding injected mass flow rate

V. CONCLUSIONS

Test C1.3_60 has been executed on the basis of the planned test matrix. Main objectives of the experimental campaign are to provide experimental data to characterize the leak rate through typical cracks occurring in the pressurized tubes and to correlate the flow rates of the leakage with signals detected by proper transducers. The objectives of the Test C1.3_60 are successfully achieved and the measurements will be complemented with other tests in order to verify the correlation between orifice dimensions and signals.

The analysis of the ADS permits to recognize the energy variation and the characteristic frequency of the bubbles generated from this orifice size. For this test, the characteristic frequency for the bubble generated from the 60 μm orifice is 1400 Hz.

The analysis of the data acquired by the HTA, HSA, and AE sensors highlights the correlation of the signals with the mass flow rate across the orifice (thus the leakage). In particular, during the phase “Water injection in LBE”, the HSA and AE record 0.01 g RMS and 0.35 V RMS. The HTA records signals with average values of 0.12 g RMS and 0.09 g RMS, when the mass flow rate is equal to 586 g/h and 253 g/h, respectively.

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