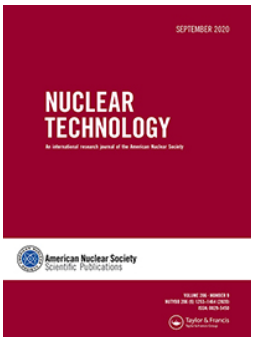

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Experimental Characterization of Leak Detection Systems in HLM Pool Using LIFUS5/Mod3 Facility

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Abstract — *In the framework of the European Union MAXSIMA project, the safety of the steam generator (SG) adopted in the primary loop of the Heavy Liquid Metal Fast Reactor has been studied investigating the consequences and damage propagation of a SG tube rupture event and characterizing leak rates from typical cracks. Instrumentation able to promptly detect the presence of a crack in the SG tubes may be used to prevent its further propagation, which would lead to a full rupture of the tube. Application of the leak-before-break concept is relevant for improving the safety of a reactor system and decreasing the probability of a pipe break event. In this framework, a new experimental campaign (Test Series C) has been carried out in the LIFUS5/Mod3 facility, installed at ENEA Centro Ricerche 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 bars and 200°C into lead-bismuth eutectic alloy. The injection was performed through a laser microholed plate 60 μm in diameter. Analysis of the thermohydraulic data permitted characterization of the leakage through typical cracks that can occur in the pressurized tubes of the SG. Analysis of the data acquired by microphones and accelerometers highlighted that it is possible to correlate the signals to the leakage and the rate of release.*

Keywords — *SGTR, safety, Generation IV, LIFUS5/Mod3, leak detection.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

The new Generation IV Heavy Liquid Metal Fast Reactor (HLMFR) is designed as a pool-type reactor, implementing the steam generators (SGs) into the primary pool, where the core, primary pumps, and main components are also set.[1] This design feature allows increasing the reactor performance and simplifying the whole layout. However, in such a 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 (HLM) coolant at higher temperature and lower pressure in a hypothetical SG tube rupture (SGTR) accident.[2,3]

During such an event, high-pressure water enters the low-pressure liquid metal pool and rapidly evaporates. The consequent sudden increase of the water specific volume entails pressure wave 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 the consequences of the accidental scenario worse.

Besides damaging the internal structures, a SGTR event could potentially induce an insertion of positive reactivity into the system or reduce cooling efficiency

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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 a further propagation of it that 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 a pipe break event.

The paper describes Test C1.3_60 of the new experimental campaign (Series C) executed in the 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 are described in Sec. II. The test matrix of the experimental campaign is reported in Sec. III while Sec. IV describes the execution and experimental data of Test C1.3_60.

Water at about 20 bars and 200°C was injected into lead-bismuth eutectic (LBE). The injection was performed through a laser microholed plate of 60 μm. The experimental analyses aim to provide engineering feedback to promptly detect the presence of a crack in the SG tubes, which may be used to prevent its further propagation. Different instrumentation is 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 multipurpose experimental facility installed at ENEA Centro Ricerche Brasimone (Fig. 1 and Refs. 7 and 8). It is designed to be operated with different HLMs like lithium-lead alloy, LBE alloy, and pure lead. Test section S1A is devoted to small leakage detection activity and can be operated at a maximum temperature of 500°C and a maximum pressure of 200 bars in accordance with the pressure equipment directive. The main parts characterizing the LIFUS5/Mod3 facility are

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

II.A. Main Component Description

The S1A interaction vessel is about 100 L, and it is partially filled with LBE during the tests. A top flange

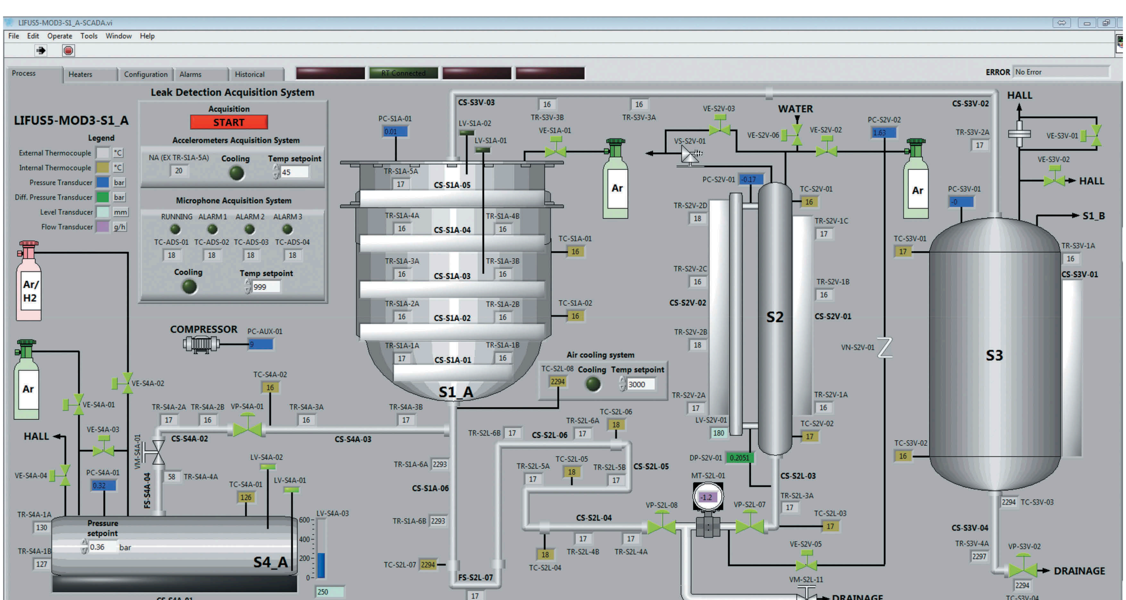

Fig. 1. LIFUS5/Mod3 synoptic.

closes it by means of a graphite spiral wound gasket. Penetrations are made in the S1A top flange to allow the installation of the instrumentation and connections, in particular, for two on/off level meters, five acoustic detection systems (ADSs), one absolute pressure transducer, two accelerometers, and an acoustic emission (AE) detection system, and for the connection to the 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 transducer and two thermocouples. At the bottom of the vessel, penetration of a 2-in. Schedule 80 pipe connects the injection line and the LBE charging/discharging system.

The S2V water tank is a pipe closed at the edges with two flanges. It has a volume of about 14 L. It is connected on the top with the gas line, which is used for setting and keeping the pressure of the water in accordance with the test specifications. On the S2V top flange, a threaded penetration is provided allowing the passage of a magnetostrictive level measurement device having a volume of 3 L. 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 the 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. LBE in S1A is filled and drained just before and after the test, respectively. It is stored in the S4A liquid metal storage tank, which is connected to the bottom of the S1A main vessel. On the S4A lateral surface, penetrations are provided allowing the passage of instrumentation, in particular, one absolute pressure transducer, one thermocouple, two on/off level meters, and one continuous level meter.

The S3V dump tank is connected by means of a 3-in. line to the top flange of S1A. The S3V volume is equal to 2 m^3, and the design pressure is 10 bars. It represents a safety volume used to collect the vapor and the gas generated by the interaction between the LBE and water.

II.B. Injection Line

The injection line (Fig. 2) starts from the S2V water storage tank, and it is connected to the S1A reaction vessel. A Coriolis mass flowmeter (MT-S2L-01) is placed between 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 the S1A reaction tank. A manual drainage valve (VM-S2L-11) is located downstream from the mass flowmeter, with the aim to empty the line after every experimental procedure. The Coriolis flowmeter has the capability to measure the mass flow rate in the range of 50 to 2000 g/h. The water injection line is heated from VP-S2L-08 (downstream from the Coriolis flowmeter) to S1A. There are five heating wires in charge of warming up the water before it enters 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 four thermowells. The line is insulated from the external environment by an insulating layer, which reduces the heat losses and therefore limits the power of the heating wires.

II.C. Injection System and Injector Device

The injection system (Fig. 3) is constituted by two separate parts connected by a 2-in. ANSI 2500 ring joint flange. The first one is completely integrated and welded to the bottom of the 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 a second tube, which permits the inlet of the gas for the injection system cooling. The gas flows up to the injector device and then flows in the countercurrent 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 microholed AISI 316 stainless steel plate with a thickness of 1 mm and a diameter of 25.4 mm (1 in.). At the center of the plate, a single microhole is manufactured by laser technology. The orifice diameter varies from 40 to 200 μm in accordance with the test specification. The injector penetrates the 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 a different microhole diameter. All of these components are manufactured by the ENEA workshop.

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

The top flange of the LIFUS5/Mod3 facility has five penetrations where microphones are installed. Moreover, a series of alternative detection systems, which are constituted by accelerometers and the AE sensor, are placed

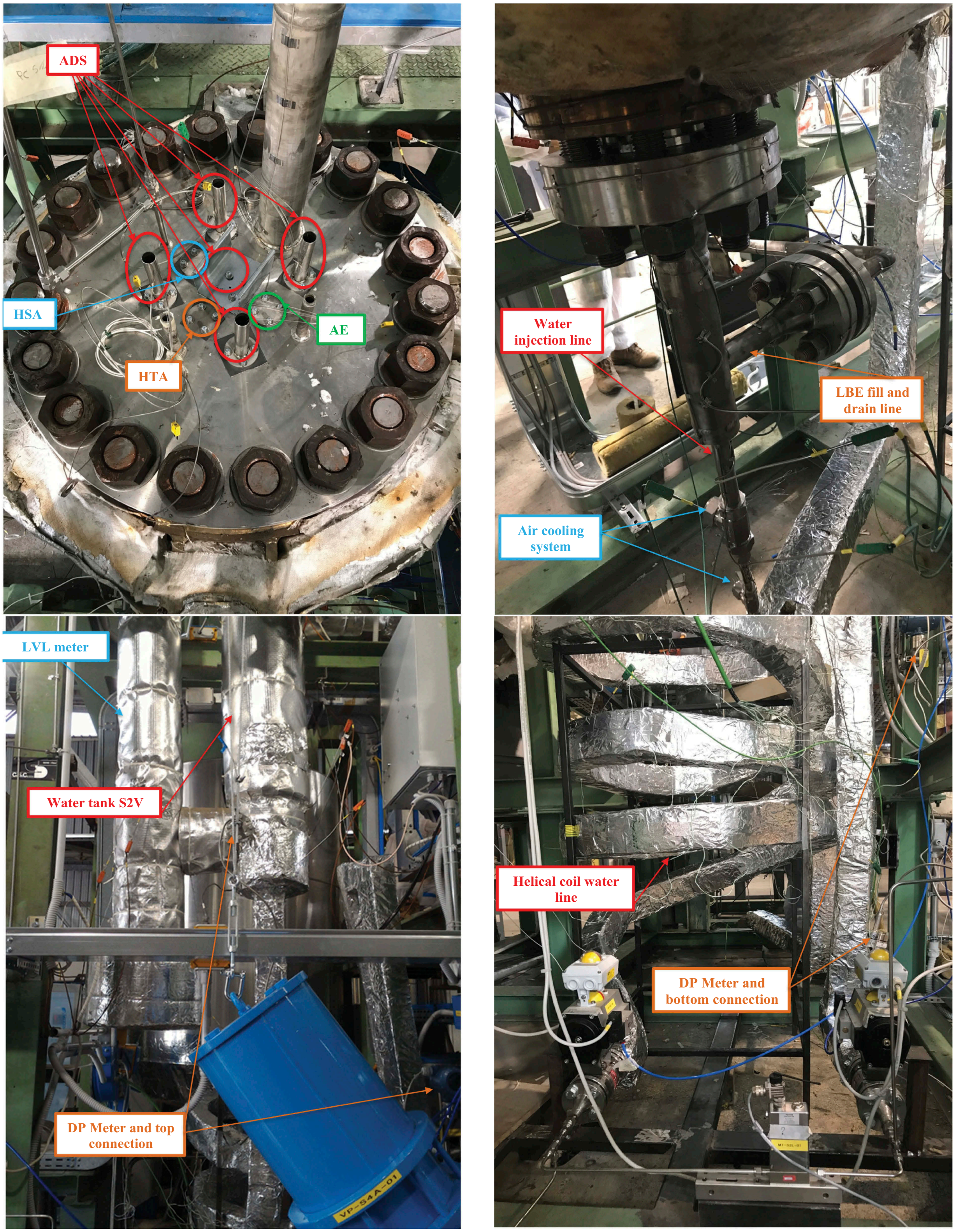

Fig. 2. LIFUS5/Mod3 view of S1A flange penetrations and water injection line.

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., high-temperature (HT) ADS]

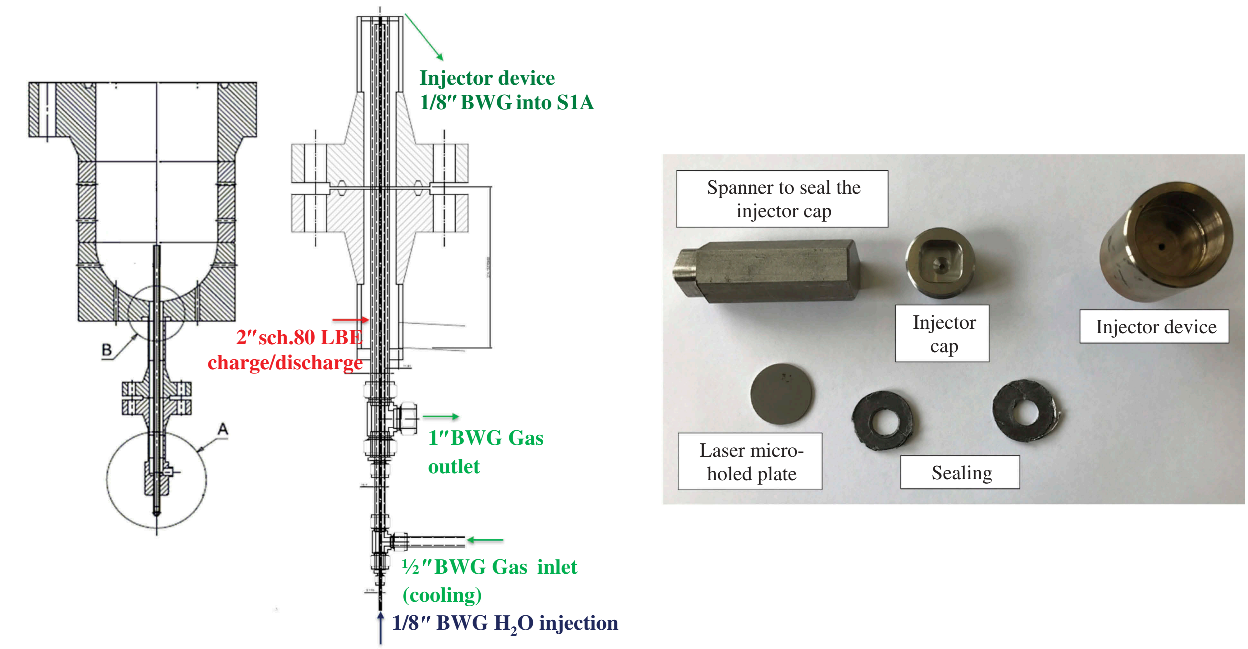

Fig. 3. LIFUS5/Mod3 sketch of the injection system and injector system device.

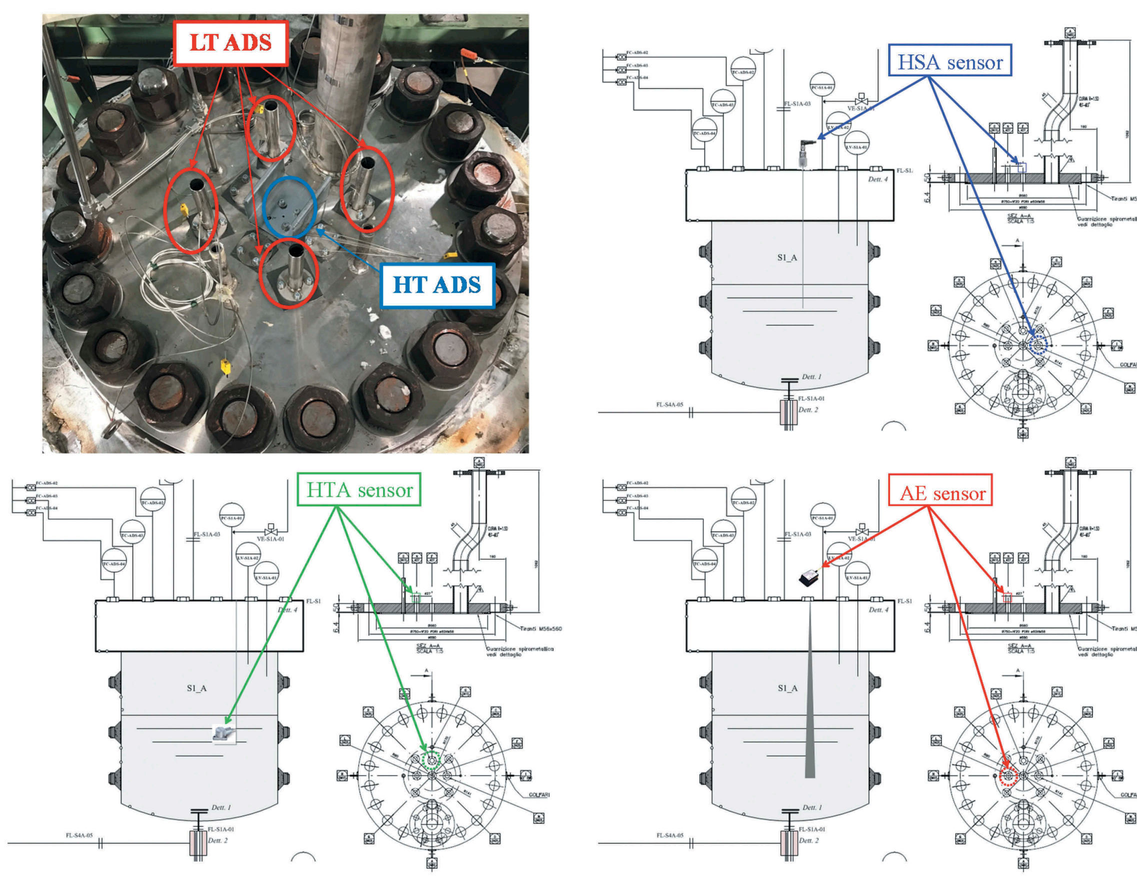

Fig. 4. ADS and accelerometer positions on LIFUS5/Mod3 facility.

2. four microphones at low temperature along the same circumference [i.e., low-temperature (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. AE sensor installed outside the vessel, measuring the high-frequency signals by means of a wave guide.

III. TEST MATRIX AND OBJECTIVES OF THE EXPERIMENTAL CAMPAIGN

A test matrix of ten experiments was proposed in the framework of the European Union MAXSIMA Project[9] (Table I). Tests were performed adopting injection laser microholed plates having diameters of 40, 60, 80, 100, 150, and 200 μm.

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

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

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

Test LIFUS5/Mod3 C1.3_60 (Ref. 10) corresponds to test T#10 of the test matrix in Table I. The microholed injector plates used in the test were characterized by scanning electron microscope 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

The 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 the LIFUS5/Mod3 injection line, as built (Fig. 1). The injection pressure is set to 19 bars. The LBE system (i.e., S1A) is modeled as a boundary condition, where pressure and temperature are imposed (i.e., 1.1 bars 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°C to 275°C.

The results (Fig. 6) show that during the time interval of 0 to 2000 s (corresponding to the water temperature range of 15°C to 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°C to 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 saturation. The two-phase choked flow is established in the time interval 9000 to 12 000 s. In this condition, the mass flow rate varies from 530 to 320 g/h. Then, single-phase gas flow conditions are achieved.

IV.B. Analysis of the Test

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

The main parameter trends are reported in selected timescales in Figs. 7 and 8. Test C1.3_60 can be divided into two 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 32 400 s.

In order to prevent a plugging of the microholed 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 the accelerometer acquisition system are already activated.

When the LBE level is stable in S1A, in accordance with the continuum level meter LV-S4A-03, the filling procedure is completed (Fig. 7). The start of test (SoT) occurs at time t = 5158 s, and the end of test (EoT) occurs at time t = 27 017 s. During the test, the amount of water injected is measured in accordance with the data of the level meter LV-S2V-01. The mass flow rate is derived from this measure.

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
Orifice diameter (design) (μm)	60	60	60	80	80	40	40	100	100	150	200
Orifice (measured) (μm^2)	3188	3080	3257	4919	5508	1392	1329	8116	7676	18 768	32151
Execution	ok	Failed	ok	ok	ok	Failed	ok	Failed	ok	ok	ok
Acquisition time (hh:mm)	06:15	NA[a]	09:00	11:22	5:00	NA	5:29	NA	7:29	5:59	3:00
LBE temperature TC-S4A-01 (°C)[b]	203	NA	226	209	226	NA	NR[c]	NA	NR	226	246
Water pressure PC-S2 V-01 (bar)[b]	19.7	NA	20.1	20.2	19.3	NA	NR	NA	NR	20.3	20.2
Water temperature TC-S2 L-08 (°C)[b]	170	NA	219	200	210	NA	NR	NA	NR	203	247

[a]NA = not available.
[b]Pressure and temperature identified at SoT.
[c]NR = not recorded.

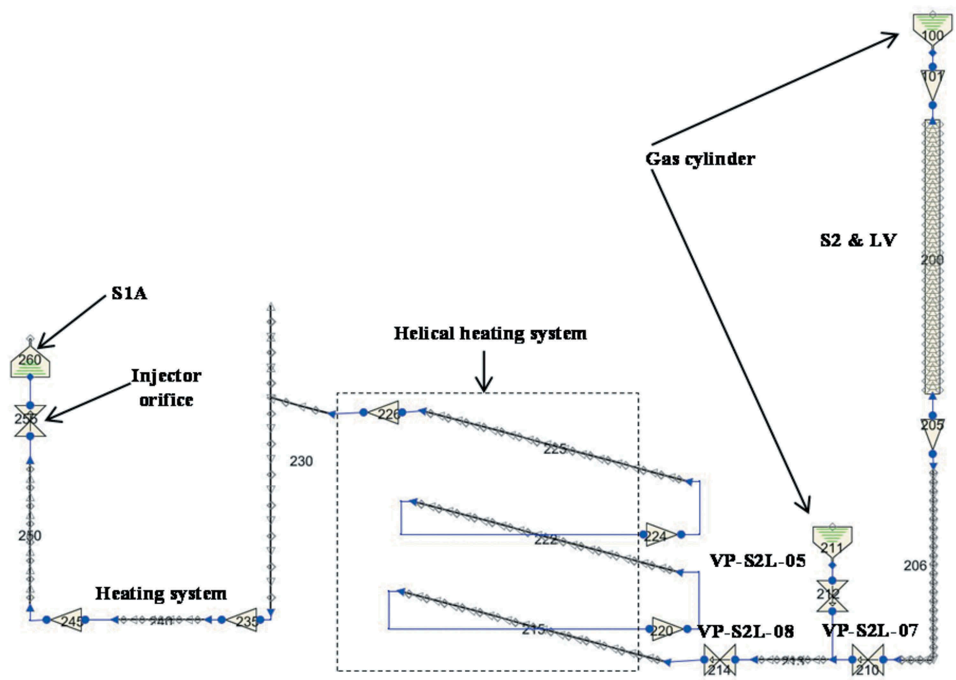

Fig. 5. LIFUS5/Mod3 sketch of the injection system and injector system device.

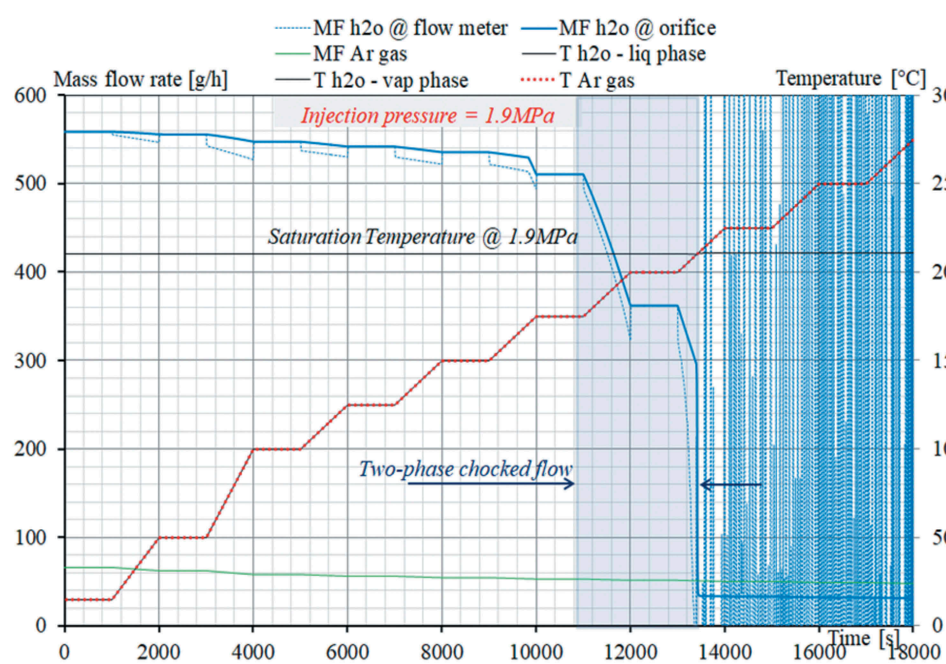

Fig. 6. RELAP5/Mod3.3 calculation of the Ar and H_2O mass flow rate through the orifice.

The Coriolis flowmeter results are 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 level decrease of 270 mm leads to an overall mass of injected water corresponding to 2.40 ± 0.088 kg in 21 859 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

TABLE II

Test C1.3_60: Time Schedule of Test Execution

Number	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	S1A filled in steady state.	LV-S4A-03
7	14:59:55 (t = 26 995)	Draining	LBE drain procedure starts.	VP-S4A-01
8	15:00:17 (t = 27 017)	End of test	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 = 27 669)	End of injection	Water injection off	VP-S2 L-07
12	15:10:05 (t = 27 605)	Leak detection systems off (HSA, HTA, AE)		UDV-ADS-A

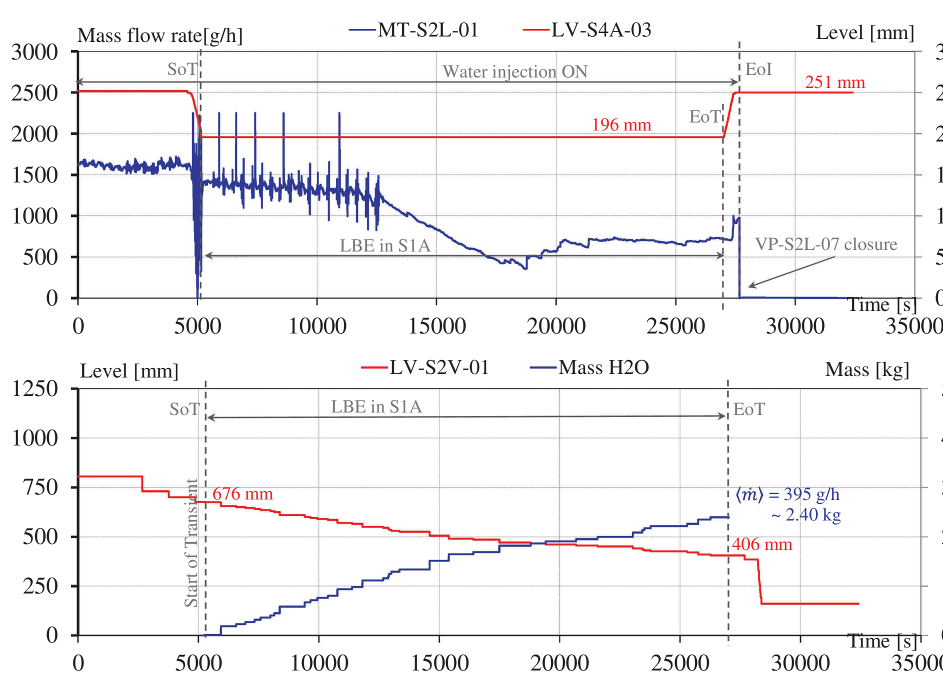

Fig. 7. Test C1.3_60, LBE level, water mass flow rate and water level experimental trends.

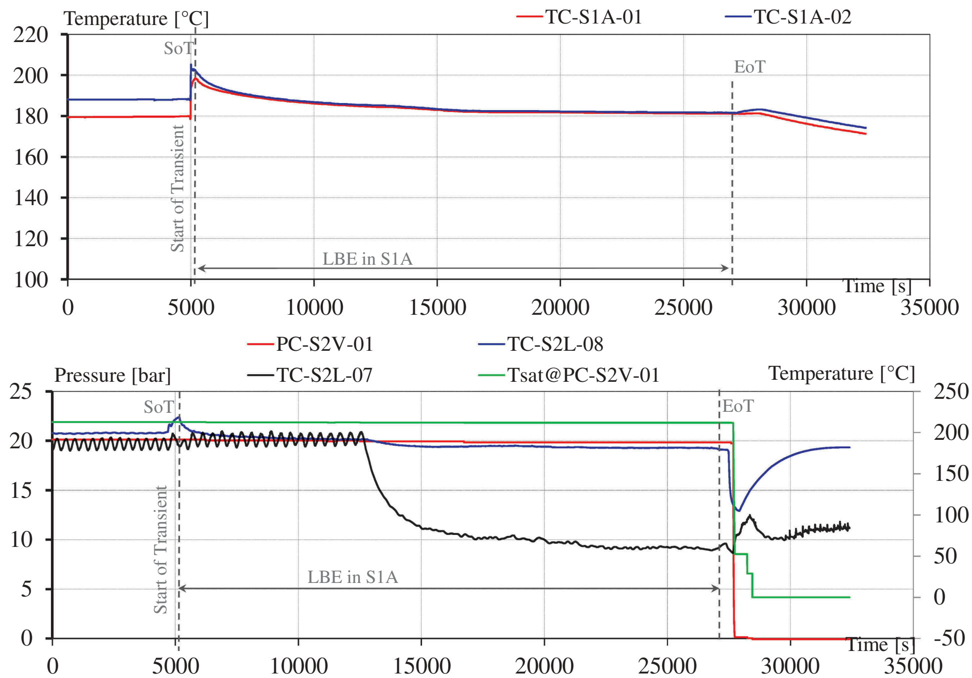

Fig. 8. Test C1.3_60, temperature trends in S1A vessel and water injection line.

flowmeter in Fig. 7. The measured data confirm the RELAP5/Mod3.3 results.

The second phase ends with the drainage of the LBE from the S1A interaction vessel toward the storage tank at t = 27 544 s. Meanwhile, the water continues to be injected up to t = 27 669 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 they are in contact with the LBE. Indeed, the LBE stored in S4A is maintained at a temperature of 230°C while the S1A vessel is preheated at about 210°C.

During the test (between SoT and EoT), the thermocouples in the water injection line from thermocouples 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. The thermocouple TC-S2L-07 records an average temperature of 192°C, which decreases when the heating cables of the injection line are switched off. On the opposite, the thermocouple TC-S2L-08, installed just before the injector, measures a nearly constant temperature during the injection, below the saturation.

IV.C. Analysis of ADS 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 to extract 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 23 000 s. The results of bubble frequency analysis show two different peaks. A peak at 3300 Hz is constantly observed during the acquisition, thus both when the water injection is on and when it is off. Therefore, it is concluded that the signal at the frequency of 3300 Hz represents background noise. The other peak is measured at 1400 Hz, which is associated with the sound of a bubble rising and appearing on the melt surface. Figure 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 AE Sensor Data and Interpretation

The analysis of the acquisitions related to the HTA, HSA, and AE sensors is divided into the two phenomenological windows of the test:

1. water injection without LBE (up to t = 5158 s)

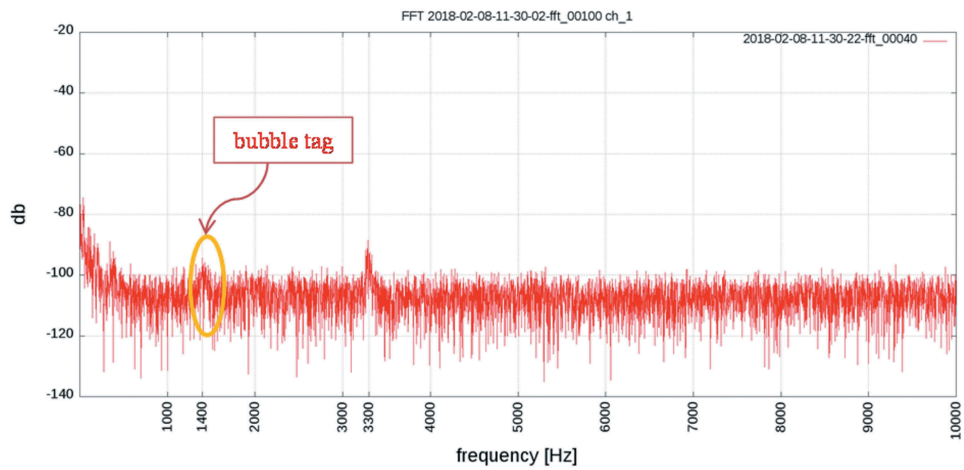

Fig. 9. Test C1.3_60, frequency spectrum at time 11:30.22,04.

2. water injection in LBE (from t = 5158 s SoT to t = 27 017 s EoT).

During the first phase (Fig. 10), the mass flow rate of injected water into the empty S1A interaction vessel is about 797 g/h. When the LBE starts to be charged into the S1A interaction vessel, 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 the injected water decreases from 586 to 253 g/h, leading to HTA data trend variations from 0.12 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.

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 interference, i.e., the compressed airflow of the sensor 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 in accordance with the mass flow rate variation; in particular, for a mass

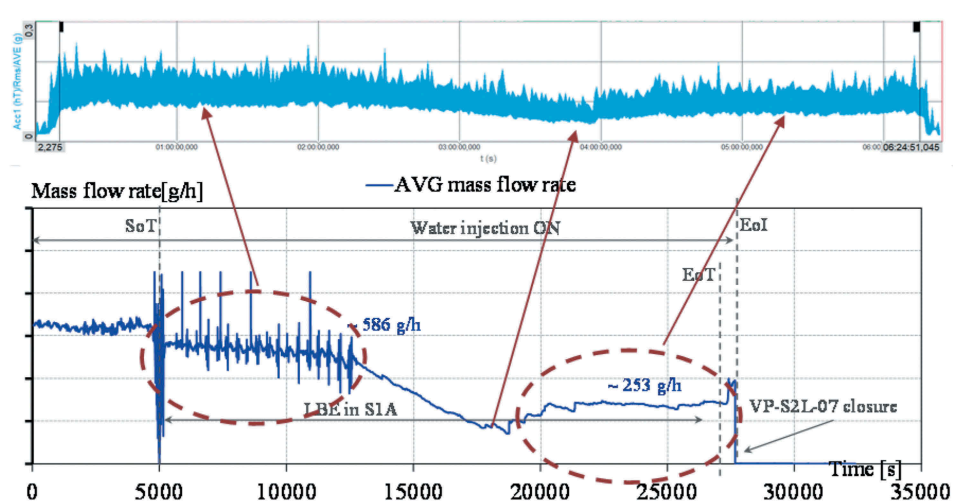

Fig. 10. Test C1.3_60, HTA rms average trend and corresponding injected mass flow rate.

flow rate equal to 586 g/h, the HTA recorded an average value of 0.12 g rms, and for a mass flow rate equal to 253 g/h, the HTA recorded an average value of 0.09 g rms.

V. CONCLUSIONS

Test C1.3_60 has been executed on the basis of the planned test matrix. The 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 Test C1.3_60 have been 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 one 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 and 0.09 g rms when the mass flow rate is equal to 586 and 253 g/h, respectively.

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