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EXPERIMENTAL ANALYSIS OF STATIONARY AND TRANSIENT SCENARIOS OF ALFRED STEAM GENERATOR BAYONET TUBE IN CIRCE-HERO FACILITY

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ABSTRACT

One of the most promising Generation IV nuclear concept, fostered by GIF (Generation IV International Forum), is constituted by the innovative heavy liquid metal coolant systems, complying with all GIF requirements: sustainability, economics, safety, reliability and proliferation-resistance. The technological development and safety evaluation of the Advanced Lead Fast Reactor European Demonstrator (ALFRED) are supported by national and European research projects. In particular, the European HORIZON2020 project SESAME (Simulations and Experiments for the Safety Assessment of MEtal cooled reactors) financed a series of experimental and numerical analysis oriented to this reactor type. In this framework, an experimental campaign was performed at ENEA research centre of Brasimone in the large pool integral test facility CIRColazione Eutettico (CIRCE), implementing the dedicated Heavy liquid mEtal pRessurized water-cOoled tubes (HERO) test section, for characterizing ALFRED Steam Generator Bayonet Tube (SGBT) behaviour in both stationary and transient scenarios.

HERO test section was obtained implementing, in the pre-existing Integral Circulation Experiments (ICE) TS, a new heat exchanger composed by 7 bayonet tubes with geometry (scale 1:1) and operating conditions (liquid water inlet at 335°C and steam outlet of about 180 bar) coherent with ALFRED SGBT. HERO test section maintained the configuration of the Fuel Pin Simulator (FPS), fitting volume, riser and separator of ICE test section.

The performed experimental campaign consists of three Transient Tests (TTs), starting from the same steady state condition (as ALFRED) and reproducing Protected Loss Of Flow Accident (PLOFA) events. In steady-state conditions, the LBE mass flow rate is promoted by the injection of argon in the riser simulating the behaviour of the primary pump, while the thermal power is supplied with an electrically heated fuel pin simulator. The transients are obtained reducing the FPS power according to a characteristic heat decay curve, while the loss of the primary pump is reproduced by the reduction of the gas injection. The loss of the heat sink is simulated managing the HERO feedwater in the secondary loop.

The present work also reports the pre-test analysis carried out by RELAP5-3D simulations, for evaluating CIRCE LBE pool dynamics/stratification during TTs.

HIGHLIGHTS

- ✓ Experimental data on Heavy Liquid Metal flow in the CIRCE-HERO loop were presented.
- ✓ Experimental data on the CIRCE-HERO facility in support of ALFRED design.
- ✓ Bayonet tube heat exchanger.
- ✓ CIRCE-HERO protected loss of flow experimental campaign.

INTRODUCTION

In the framework of the HORIZON2020 SESAME European project (SESAME Project, EURATOM H2020, 2015), an experimental campaign has been carried out on the large LBE pool integral effect CIRCE facility at CR ENEA Brasimone (Tarantino M. et al., 2011). The experiments are based on the HERO Test Section installed into CIRCE (Rozzia et al., 2017), aiming at supporting the development of the ALFRED design (Frignani, et al., 2017). The secondary loop for the HERO SGBT unit has been designed and realized for the SESAME experimental campaign, and both the primary and secondary systems have been instrumented.

Three transient tests have been designed and carried out, consisting of a protected loss of flow accident occurring with the facility operated in nominal full power conditions for both primary side (LBE) and secondary side (high pressure water).

The three transient tests start from the same steady state conditions, characterized by ~0.33 kg/s of subcooled water entering into the 7 tubes of SGBT mock-up at about 180 bar and 335°C, and exiting in superheated steam condition at about 400°C. The Lead Bismuth Eutectic alloy (LBE), flowing in the shell side of the SGBT with a mass flow rate of about 40 kg/s, is cooled from about 480 to 400°C. The transient tests investigated PLOFA scenarios, discerned on the basis of different transient reduction of power supplied by FPS, liquid metal gas lift (enhanced circulation) and feedwater mass flow rate. More specifically, in the first TT power decreased following the decay heat curve, gas lift was set to 0 kg/s and feedwater to 30% mass flow rate (simulating Decay Heat Removal, DHR, system) in 2 s. The second TT differs from the first one only for the feedwater reduction to 0% in about 2 s (without DHR). The third TT simulated the power decay curve, DHR (feedwater to 30% in 2 s) and reactor pump flywheel by a gas lift reduction based on a defined table.

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This work aims to present the experimental data achieved, in terms of mass flow rates and temperature for both primary and secondary system, providing relevant information about the system behaviour when subjected to accidental scenarios.

CIRCE-HERO REVIEW

The LBE pool CIRCE is an integral effect facility set at CR ENEA Brasimone. Its main features, along with the implemented HERO test section geometry and instrumentation devices are detailed in Pesetti et al. (2018) and Lorusso et al. (2018). CIRCE consists in a cylindrical main vessel, having an internal diameter of 1170 mm, thickness of 15 mm and height of about 8500 mm, partially filled (up to 500 mm from the top flange) with about 70 tons of Lead-Bismuth Eutectic with argon as cover gas maintained at about 0.2 barg, LBE heating and cooling systems, a storage tank, a transfer tank and auxiliary systems for LBE circulation and the gas recirculation. The CIRCE main vessel and the main components of the test section are shown in Figure 1.

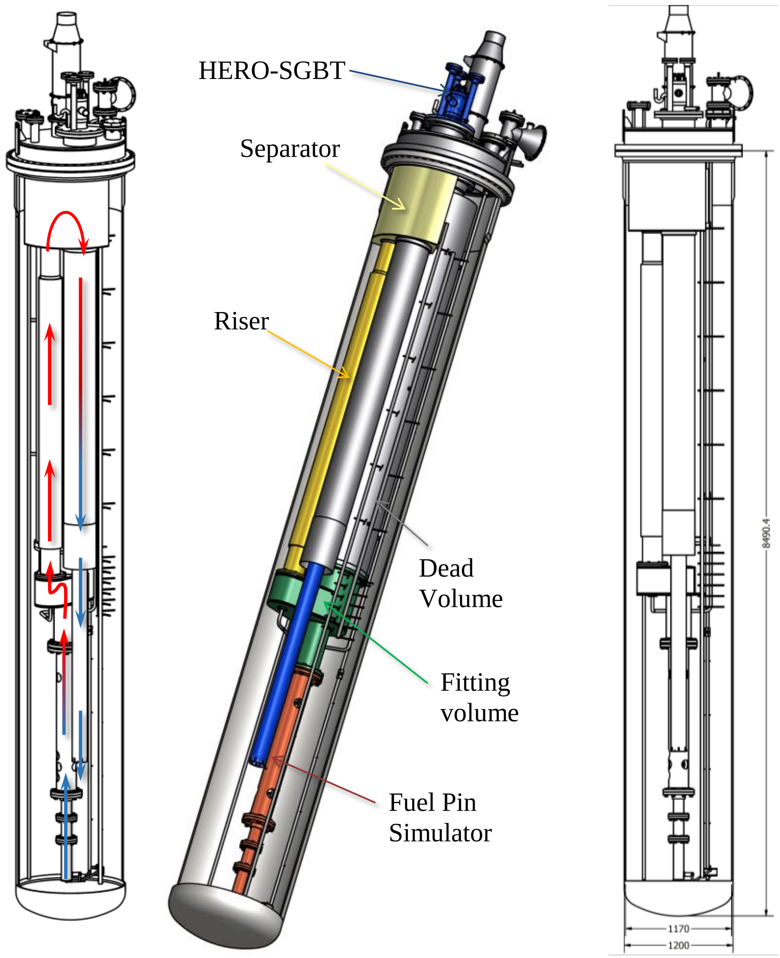


Figure 1 ***CIRCE-HERO Primary Loop (main vessel and HERO Test Section)***

The HERO Test Section is mounted inside CIRCE from the top of the main vessel through a coupling flange and it is mainly composed by the following components (see Figure 1):

- Fuel Pin Simulator electrically heated for the coolant heating; it consists of a pin bundle composed by 37 electrically heated pins with a nominal thermal power of ~1 MW;
- Fitting volume which collects the hot LBE rising from the FPS;
- Riser, in which the LBE flows upward up to the separator;
- Separator, located on the top of the test section acting as hot plenum;
- Steam Generator Bayonet Tube for the heat removal;
- Argon injection device located at the inlet section of the Riser, which enhances the LBE mass flow rate.

The main flow path of the coolant inside the pool is reported in Figure 1. The LBE flows upwards trough the FPS (red in Figure 1), passes the Fitting Volume (green) and it enters into the Riser (yellow). At this position argon could be injected for performing enhanced circulation (gas lift). Then LBE enters into the Separator, in which the free level reaches about the middle height of the wall. From this small pool, the LBE comes in the SGBT (blue) and starts its downwards flow, shell side. Then, LBE completes its loop into the pool bottom. Figure 2 reports a view of the top flange, showing the position of the FPS and the HERO SGBT.

The tube bundle is composed of 7 double wall bayonet tubes, with an active length of 6 m, arranged in a hexagonal shell with a triangular pitch. Each Bayonet Tube (BT) is composed of four coaxial tubes (for details see Pesetti et al., 2018): the feedwater enters from the top of the inner feedwater tube (named slave tube), flowing downward and then rising through the annular riser between the first and second tube, where the steam is produced. The gap between slave and first tube is filled by air (slight vacuum) as insulator in order to avoid steam condensation. The gap between second and third tube is filled with AISI316L powder and slightly pressurized helium at ~8 bar to detect any leakages, and maintaining a good heat exchange capability, thanks to the metallic powder.

A dedicated once-through loop (Lorusso et al., 2018) has been realized to supply liquid water at the SGBT inlet at nominal working conditions of ~335°C, producing superheated steam at ~172 bar at the SGBT outlet. The main components are:

- a demineraliser;
- a volumetric piston pump regulated by a bypass valve and inverter and equipped with a 40 bar accumulator and a check valve;
- a helical heating system (Figure 2);
- a manifold with seven outlet ½" tubes connected to the inlet of the bayonet tubes (Figure 2);
- a 3” discharge line thanks to which the steam produced in the HERO test section outflows in the environment; the pressure along the loop is maintained at the operating pressure through the regulation of valve V3 (Figure 2);
- a ¾" bypass line used for the start-up phases, equipped with the regulation of valve V2 (Figure 2);
- a helium line, for pressurizing the stainless steel powder gap of bayonet tubes at ~8 bar.

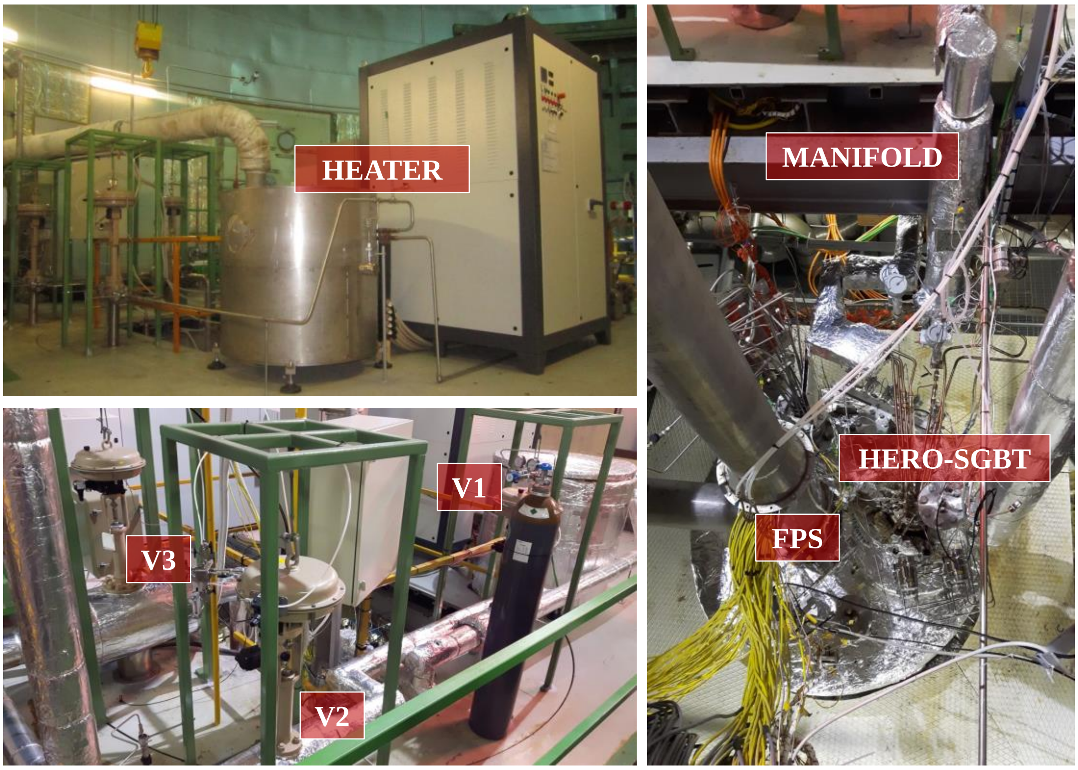
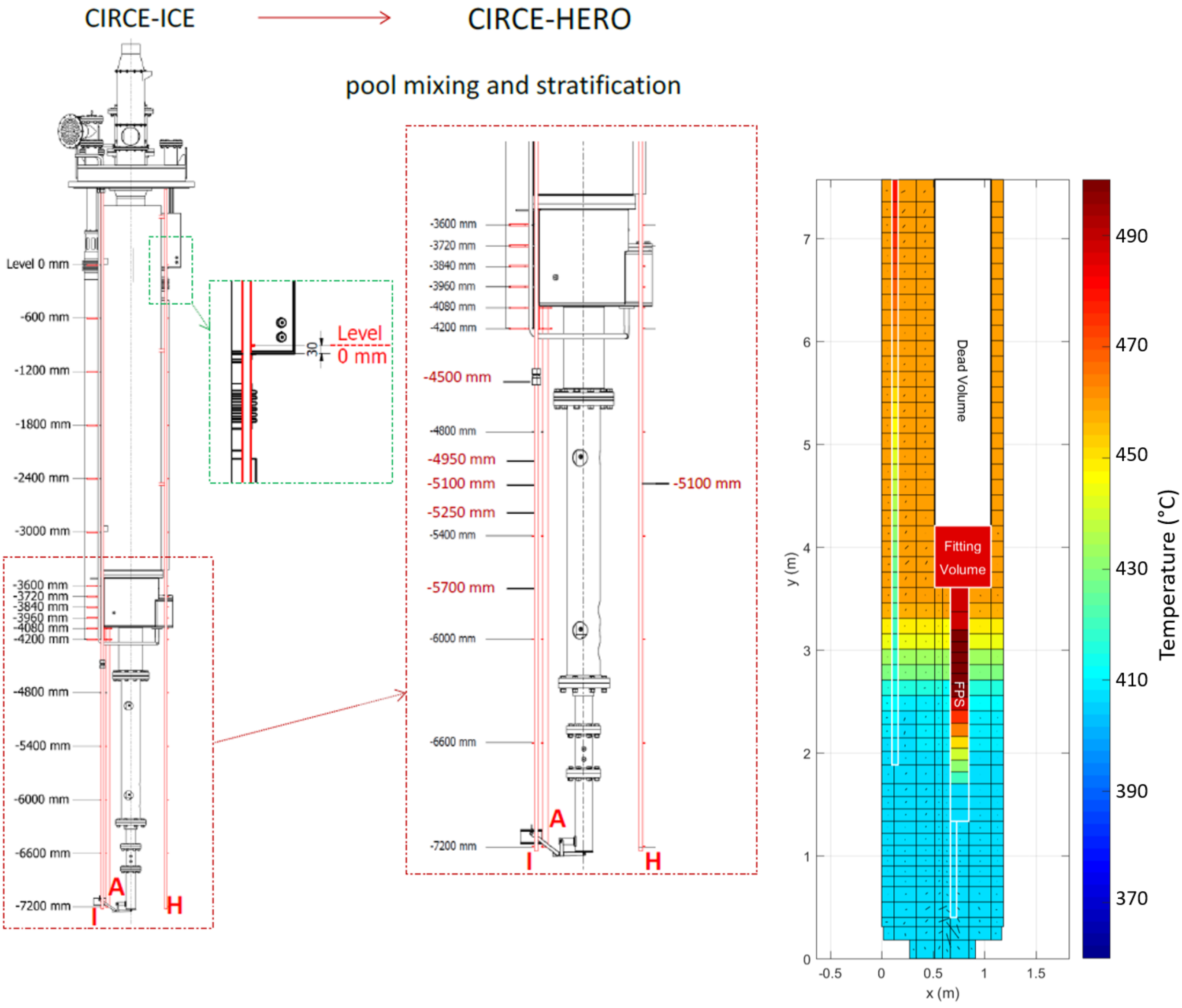


Figure 2 ***View of the HEATER component (top, left), the secondary loop valves (bottom, left) and the top flange of the main vessel (right)***

In the primary loop, the instrumentation installed in HERO test section is composed by an overall number of about 170 thermocouples (TCs), 10 bubble tubes, 1 Venturi flow meter and 3 LBE level meters. Two pressure transmitters are set in S100 cover gas. Moreover, an argon flow meter measures the normal litres per second injected in the riser, for gas lift occurrence.

The 39 TCs set in the fuel pin simulator, 3 TCs at riser inner and 3 TCs at outlet section and 119 TCs distributed in the pool for mixing and stratification feedback are maintained in the same position of ICE test section (for details see Pesetti et al., 2018).

Some TCs were added using the information derived from the pre-test analysis (Narcisi et al., 2018), based on the RELAP5-3D model (Narcisi et al., 2017) experimental validated using the ICE tests (Tarantino et al., 2015) and adapted for the HERO test section. As highlighted during the pre-tests, the fitting volume offers a large non-insulated surface for the heat losses; in order to quantify the heat dissipations, five TCs were added on the outer surface of the fitting volume. One of the main tasks of the experimental campaign is to investigate three-dimensional phenomena inside a heavy liquid metal pool, such as thermal stratification. At this purpose, a detailed temperature measuring system has been adopted inside the pool, as shown in Figure 3(a). Three additional TCs were set for increasing measurement points at the expected thermal stratification level, obtained with RELAP5-3D calculation during the pre-test activity (Narcisi et al., 2018).



(a) (b)

Figure 3 ***TCs axial positions (a) and thermal stratification investigation (b) inside the S100 pool***

Regarding the 10 bubble tubes, six of them are connected to 3 differential pressure transmitters for measuring ΔP: in the Venturi flow meter (inlet and throat section), between LBE free level in the pool and separator and across the lower spacer grid of the FPS.

Remaining 4 bubble tubes are acquired by 4 absolute pressure transmitters, for measuring time trends inside the fitting volume, along the riser (inlet and outlet section) and in the pool cover gas.

The secondary loop is equipped with 9 relative and 4 differential pressure transmitters, one Coriolis and 7 mini turbine flow meters TFMs, each one positioned upstream the BTs inlet, highlighting possible unbalanced flow. The water pressure and the temperature are monitored at inlet and outlet sections of the heater, manifold and BTs, as well as downstream V3. Differential pressure measurements across 4 BTs characterize single and two-phases pressure losses.

The loop is equipped with about 30 K-type thermocouples Three thermocouples set at the steam chamber exit aim to detect possible condensation and radial stratification. An overall number of 12 TCs, having a diameter of 0.5 mm, was positioned in the annular gap of central BT (5 TCs, for characterising water evaporation) and at the exit of each BTs gap (7 TCS). LBE temperature is measured at four different levels (+1500, +3000, +4200 and +6000 mm) on three azimuthal positions of central BT (12 TCs), at lower three levels on outer surface of two outer BTs (6 TCs) and at the centre of one central and three outer subchannels at three lower levels (12 TCs), besides 3 TCs at BT-SG outlet section (+0 mm). Three TCs are set at middle height of LBE inlet windows, about 150 mm from the separator bottom. All the signals are acquired at 1 Hz. The P&ID of the entire system is reported in Figure 4. A detailed description of the secondary loop instrumentation is reported in Lorusso et al., 2018.

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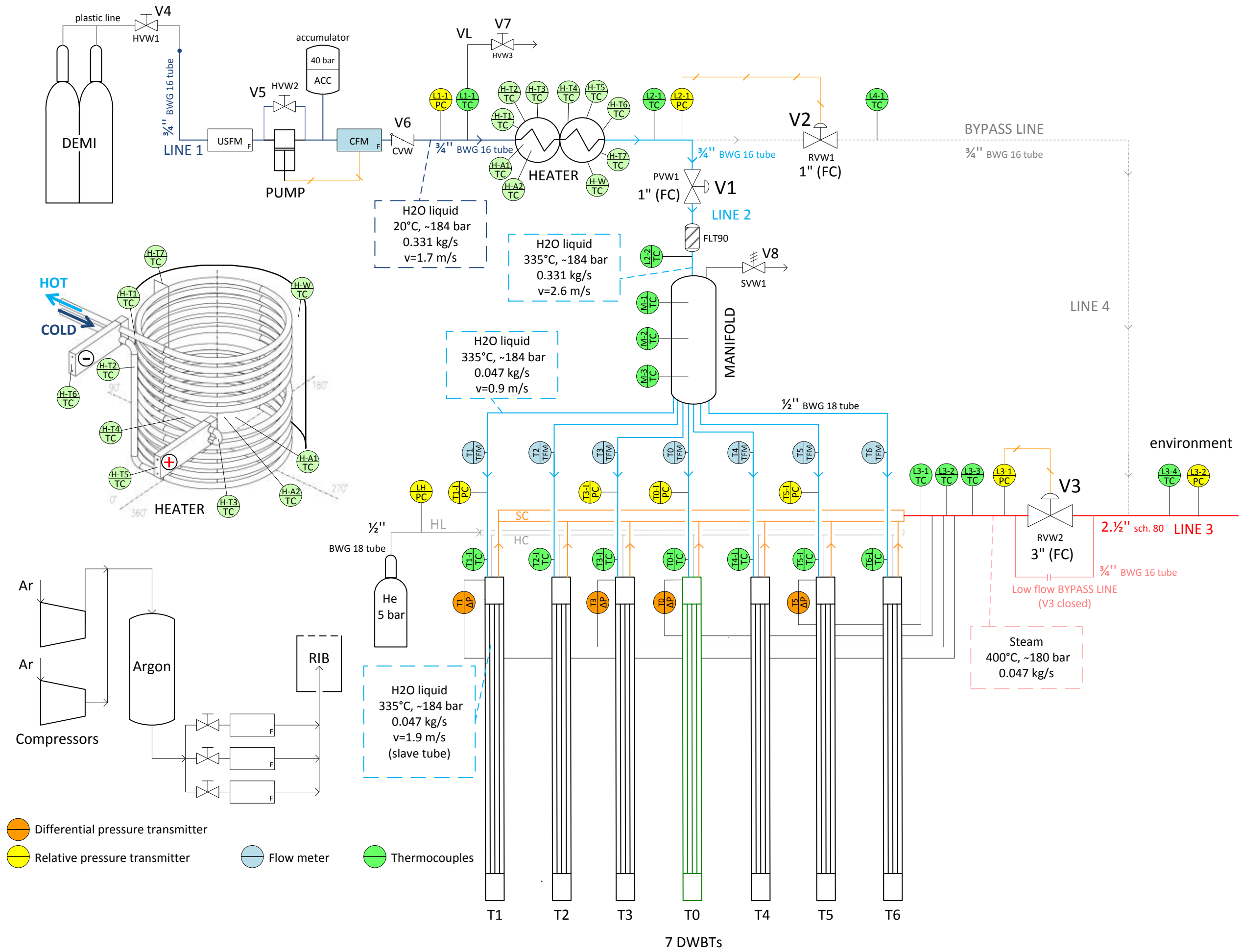

Figure 4 Secondary Loop P&ID

SESAME EXPERIMENTAL CAMPAIGN

In the framework of the SESAME Project, a set of tests has been set for CIRCE facility in HERO configuration in order to achieve experimental data relevant for the ALFRED Steam Generator (SG) (Narcisi et al., 2018). In the following, the three experimental tests are presented and the results of the experimental campaign are described.

The tests consist of three PLOFA, occurred during the normal operation of the facility. The nominal working conditions, for both primary and secondary loop, have been maintained constant for a relevant time lapse; after that, a PLOFA has been carried out, managing the FPS power supplied, the argon injection device and the water mass flow rate to the HERO Steam Generator. After the transient, the system continues the operation with the primary loop working in Natural Circulation (NC) regime and the HERO SG acting as DHR system.

The designed nominal working conditions in the SGBT unit assumed before the transitions are reported in Table 1. The LBE SG inlet temperature is kept constant at 480 °C, with an LBE mass flow rate set to ~39 kg/s. In the secondary loop, the operating pressure of 172 bar is maintained constant at the BTs through the regulation of valve V3 with a water inlet temperature of ~335°C, while the pump provides a total water mass flow rate of ~0.33 kg/s.

Table 1 Designed Boundary Conditions for the SGBT unit in the three Transient Tests

Parameter	*Unit*	*Value*
LBE SG inlet temperature	°C	480
LBE mass flow rate	kg/s	39
H2O SG inlet temperature	°C	335
H2O mass flow rate	kg/s	0.33
H2O outlet pressure	bar	172

The transient conditions are reported in Table 2. All three tests are characterized by a FPS power transient with a power reduction according to a characteristic heat decay curve. In Test #1 and Test #2 the argon flow rate is reduced with a linear ramp from 100% to 0% in a time lapse of 10 s, simulating in such a way the loss of the primary pump, while in Test #3 the argon flow rate follows a particular curve which simulates the effect of the pump flywheel. Concerning the secondary loop, the water mass flow rate is reduced from 100% to 30% in 2 s in Test #1 and Test #3, simulating the activation of the DHR, while in Test #2 the water mass flow rate passes from 100% to 0%, simulating the total loss of the heat sink. The beginning of the transients for the FPS power, argon flow rate and water mass flow rate occurs simultaneously.

Table 3 reports the time trends of the FPS power and argon flow rate implemented in the data acquisition and control system of the facility to perform the transitions described above.

Table 2 Designed Boundary Conditions for the transient

Parameter	*TT #1*	*TT #2*	*TT #3*
FPS Power	Characteristic decay heat curve	Characteristic decay heat curve	Characteristic decay heat curve
Argon Flow Rate	From 100% to 0% in 10 s	From 100% to 0% in 10 s	Curve simulating pump flywheel
H2O Mass Flow Rate	From 100% to 30% in 2 s	From 100% to 0% in 2 s	From 100% to 30% in 2 s

Table 3 Designed PLOFA trends for FPS power (TT #1, TT #2, TT #3) and argon flow rate (TT #3)

FPS Power	*Time [s]*	0	1	2	3.5	5	7.5	10	15	22	30	50	60	90	180	300
	Value [%]	100	25	22	19	17	15	14	12	10	9	8	7	6	6	5
Argon Flow Rate	*Time [s]*	0	1	2	3	4	5	10	20	30	50	100	150	200	300	350
	Value [%]	100	90	83	77	71	67	50	33	25	17	9	5	2	0	0

SESAME EXPERIMENTAL RESULTS

The following section reports the experimental results of the PLOFA Transient Tests, in terms of LBE mass flow rate and temperatures for both LBE and water. The boundary conditions set-up before and after the transients are summarized in Table 4.

At the beginning of each test, the power supplied by the FPS is set to compensate the power removed by the HERO SGBT and the heat losses to the environment, achieving an electric power of 352 kW supplied in TT #1, ~379 kW in TT #2 and ~356 kW in TT #3.

The argon flow rate injected in the riser reaches the values of ~2.75 Nl/s in TT #1 and TT #3, and ~3.35 Nl/s in TT #2. The electrical power and argon flow rate trends realized during the tests are reported in Figure 5, Figure 6 and Figure 7 for TT #1, TT #2 and TT #3 respectively. Concerning the argon flow rate supplied in TT #3, the slight discrepancy between the experimental trend reported in Figure 7 and the values of data acquisition and control system listed in Table 3 is due to the uncertainty on measure of the argon flow meter (FE400).

Figure 8 reports the LBE mass flow rates achieved in the three tests, showing that before the transient, in gas-enhanced circulation regime, the values achieved are in the range of 34-37 kg/s, which decrease rapidly in the range of 4-6 kg/s when the natural circulation is established. It can be noticed that the decrease of the LBE mass flow rate in TT #3 (green line in Figure 8) occurs with a short delay (about 2 minutes) respect to the other two tests, because of the slower reduction of the argon flow rate injected.

In the secondary loop, the volumetric pump supplies the water mass flow rate which is measured by the mini-turbine flow meters installed upstream the inlet section of each bayonet tube. The measured mass flow rates for the entire duration of the three TTs are reported in Figure 9, Figure 10 and Figure 11, and summarized in Table 5. In nominal working conditions, the total water mass flow rate measured is about ~0.25 kg/s in TT #1 and ~0.26 kg/s in TT #2 and TT #3, assuming a water density of ~640 kg/m^3 and a uniform distribution of the water flow among the 7 tubes (verified during the commissioning tests). After the transient, the water mass flow rate is reduced up to 0 kg/s in TT #2 (Figure 10), while it is reduced to 30% in TT #1 and TT #3, reaching the final value of ~0.095 kg/s in TT #1 and 0.078 kg/s in TT #3. The loss of signals of TFM-T5 and TFM-T6 in TT #1 and TFM-T3 and TFM-T5 in TT #3 is due to the low flow rate achieved after the transient, which is close to the lower limit of the measure range of the instruments.

Alternatively, the water mass flow rate can be calculated applying the thermal balance equation on the HEATER component:

$$\dot{m}_{H2O} = \frac{\dot{Q}_{H2O}}{hout-hin} \tag{1}$$

where:

- Q_{H2O} is the electrical power supplied to the water by the HEATER before and after the transient;
- h_{in} is the water enthalpy at the inlet section of the HEATER;
- h_{out} is the water enthalpy at the outlet section of the HEATER;

The values of mass flow rate obtained from Equation (1) are reported in Table 5. From the same table, it can be noticed that the mass flow rates calculated are slightly higher than the measured ones. This discrepancy is most probably due to the use of the electrical power in Equation (1) which is slightly higher respect to the effective thermal power supplied to the water, because of the efficiency of the electrical devices and the fraction of thermal power lost in the environment.

The water temperature at the inlet section of the BTs is maintained at about 336°C, managing the power of the HEATER component. The pressure of the helium line in the AISI316L powder gap has been maintained at 8.0 bar.

Table 4 ***Boundary conditions before and after the transients for the three PLOFA tests***

Test	*Parameter*	*Unit*	*Before Transient*	*After Transient*
TT #1	FPS Power	[kW]	352	20
	Argon flow rate	[Nl/s]	2.75	0
	Water mass flow rate	[kg/s]	0.274	0.095
	Water T inlet SG	[°C]	~336	~336
TT #2	FPS Power	[kW]	379	22
	Argon flow rate	[Nl/s]	3.35	0
	Water mass flow rate	[kg/s]	0.270	0
	Water T inlet SG	[°C]	~335	----
TT #3	FPS Power	[kW]	356	20
	Argon flow rate	[Nl/s]	2.75	0
	Water mass flow rate	[kg/s]	0.294	0.078
	Water T inlet SG	[°C]	~336	~336

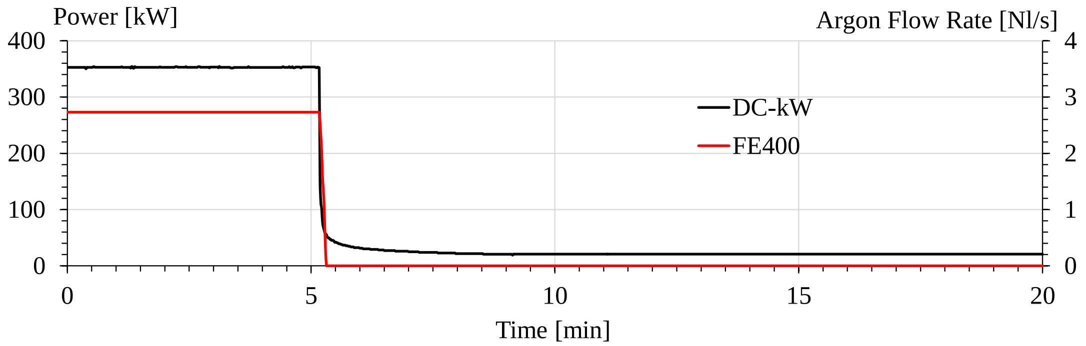

Figure 5 ***TT #1, FPS Power and argon Flow Rate experimental trends***

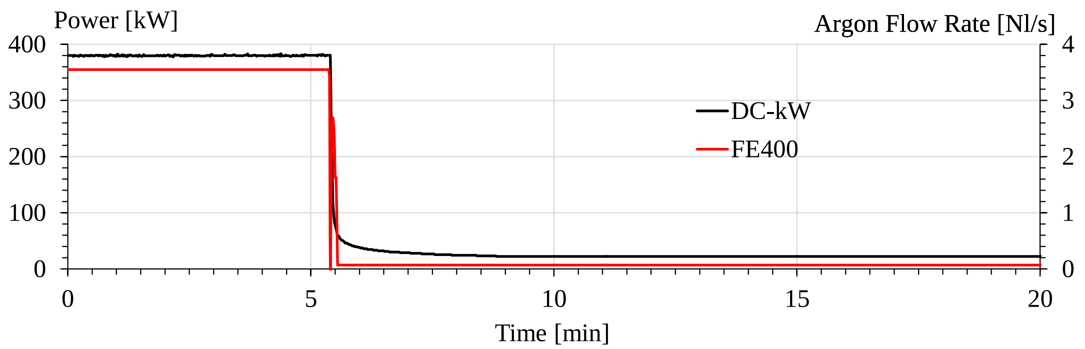

Figure 6 ***TT #2, FPS Power and argon Flow Rate experimental trends***

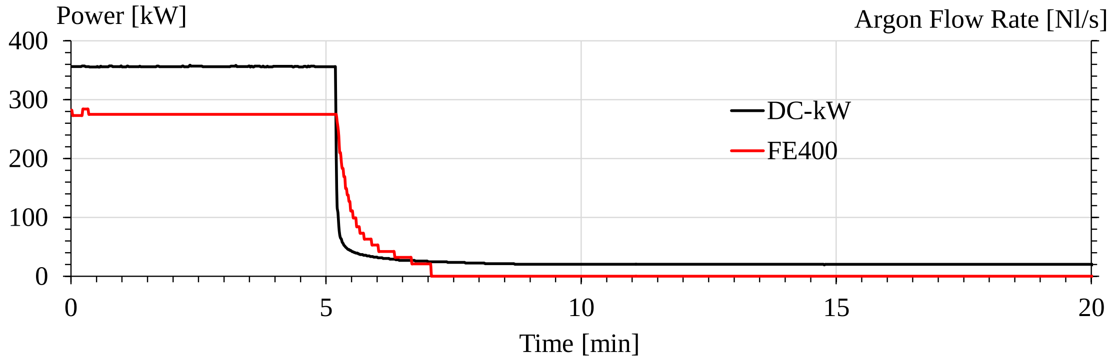

Figure 7 *TT #3, FPS Power and argon Flow Rate experimental trends*

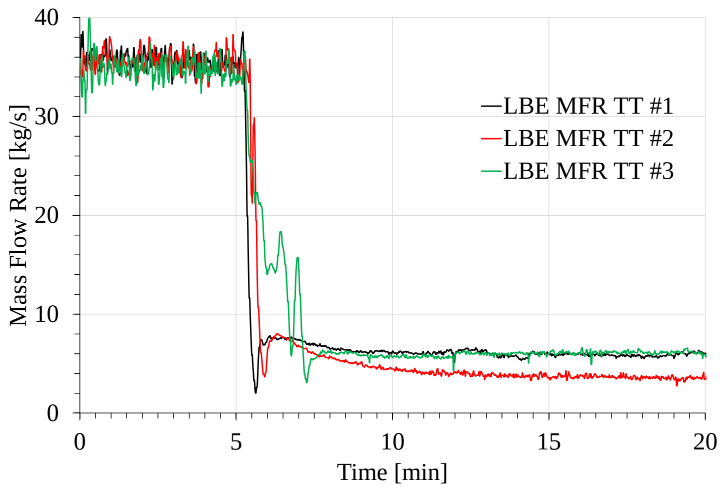

Figure 8 *LBE mass flow rate achieved during the three PLOFA transient tests*

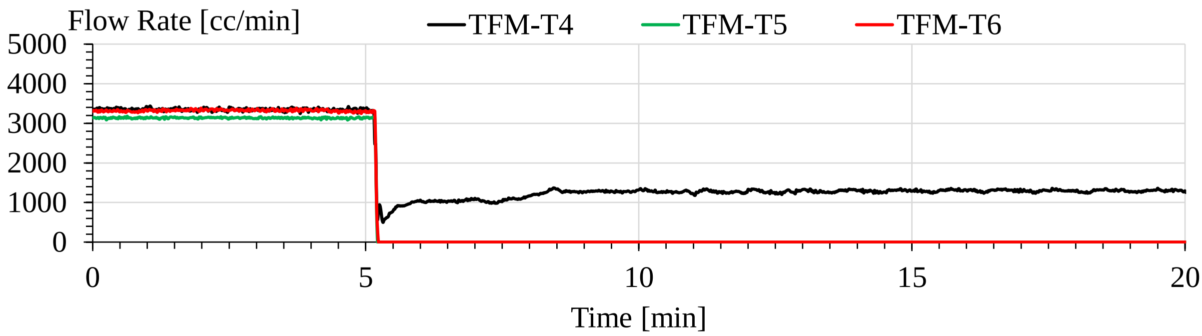

Figure 9 *TT #1, H2O mass flow rate trends during the PLOFA Test measured by turbine flow meters*

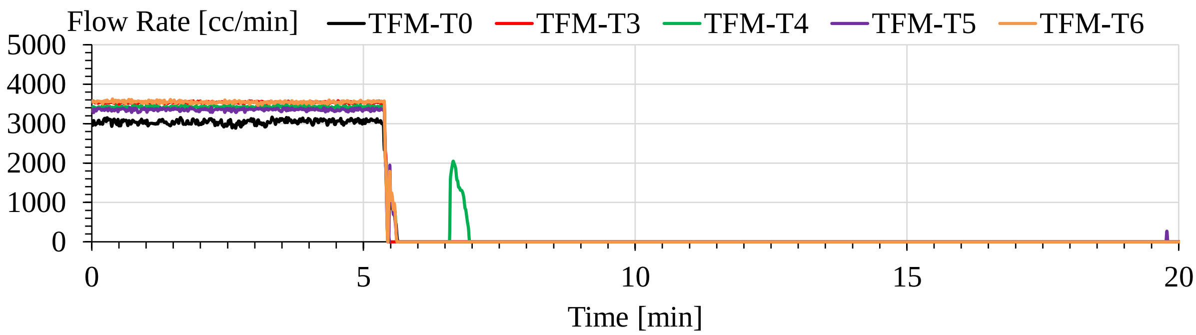

Figure 10 *TT #2, H2O mass flow rate trends during the PLOFA Test measured by turbine flow meters*

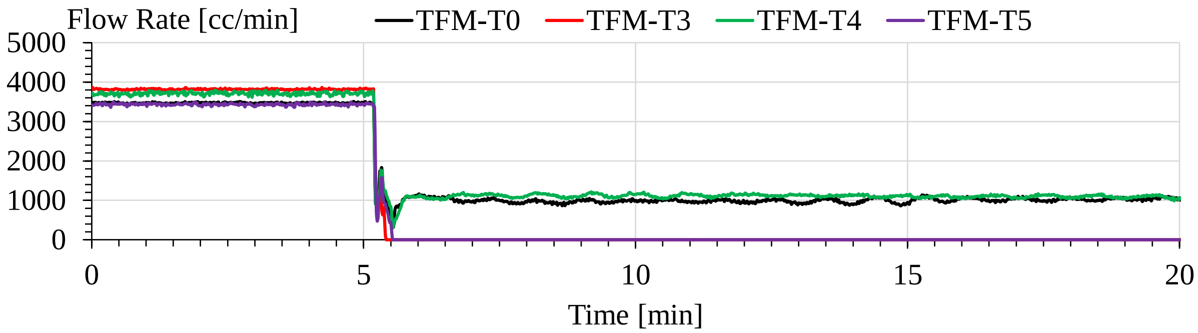

Figure 11 ***TT #3, H2O mass flow rate trends during the PLOFA Test measured by turbine flow meters***

Table 5 ***H2O Mass Flow Rate in PLOFA TTs, measured vs computed***

Test	*Time*	*Unit*	*H2O mass flow rate Measured (TFMs)*	*H2O mass flow rate Computed (Thermal Balance Equation)*
TT #1	Before Transient	[kg/s]	0.245	0.274
	After Transient	[kg/s]	0.09	0.08
TT #2	Before Transient	[kg/s]	0.253	0.27
	After Transient	[kg/s]	0	0
TT #3	Before Transient	[kg/s]	0.26	0.294
	After Transient	[kg/s]	0.078	0.078

Figure 12, Figure 13 and Figure 14 report the temperature inside the FPS for the coolant and the pin clad, during TT #1, TT #2 and TT #3, respectively.

In TT #1 (Figure 12), the LBE temperatures at the FPS outlet decreases significantly due to the power decrease, reaching a maximum of ~495 °C before the transient and then a minimum of ~460 °C immediately after, from which it starts to decrease slowly, when NC of the LBE is established. The temperatures at the FPS inlet section remain almost the same during the test at ~420 °C, with a low decrease after the transient. The pin clad temperature decreases from ~530 °C before the transient, to ~450 °C, passing through a minimum of 445 °C and a subsequent maximum peak of 486 °C, corresponding to the minimum of LBE mass flow rate.

In TT #2 (Figure 13), during the power reduction, the LBE temperatures at the FPS outlet decreases rapidly, reaching a maximum of ~495 °C before the transient and then a minimum of ~470 °C immediately after, from which it reach a constant value of ~475 °C. The temperatures at the FPS inlet section remain almost constant during the test at ~415 °C. A particular trend can be noticed for the thermocouple T-FPS-32 at the FPS inlet, which measures an increase of the temperature after the transient. This can be due to the low mass flow rate achieved in NC, which can lead to a stagnation point near the thermocouple. The pin clad temperature decreases from ~535 °C before the transient, a minimum of 445 °C immediately after, a subsequent peak of ~480 °C and a new minimum of ~460 °C. From this last value, the temperature increases due to the small power supplied by the FPS, reaching slowly a maximum of 500 °C, from which it starts to decrease due to the heat losses which exceed the power supplied.

Concerning the TT #3 (Figure 14), the LBE temperatures at the FPS outlet decreases significantly due to the power decrease, passing from 496 °C to the minimum value (446 °C) immediately after the transient, and then reaching a maximum of 465 °C, from which it starts to decrease slowly, when NC of the LBE is established. The temperatures at the FPS inlet section remain almost the same during the test at ~420 °C, with a low decrease after the transient. The pin clad temperature decreases from ~530 °C, before the transient, to 460 °C, passing through a minimum of 435 °C and a subsequent maximum peak of 470 °C, corresponding to the minimum of LBE mass flow rate.

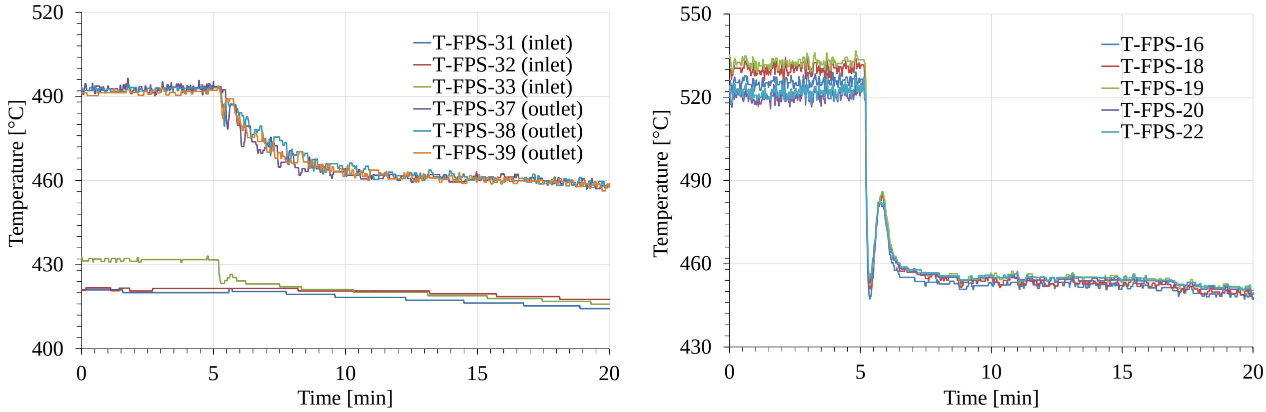

Figure 12 TT #1, LBE temperature trends at the FPS inlet-outlet (left) and FPS pin clad temperature (right)

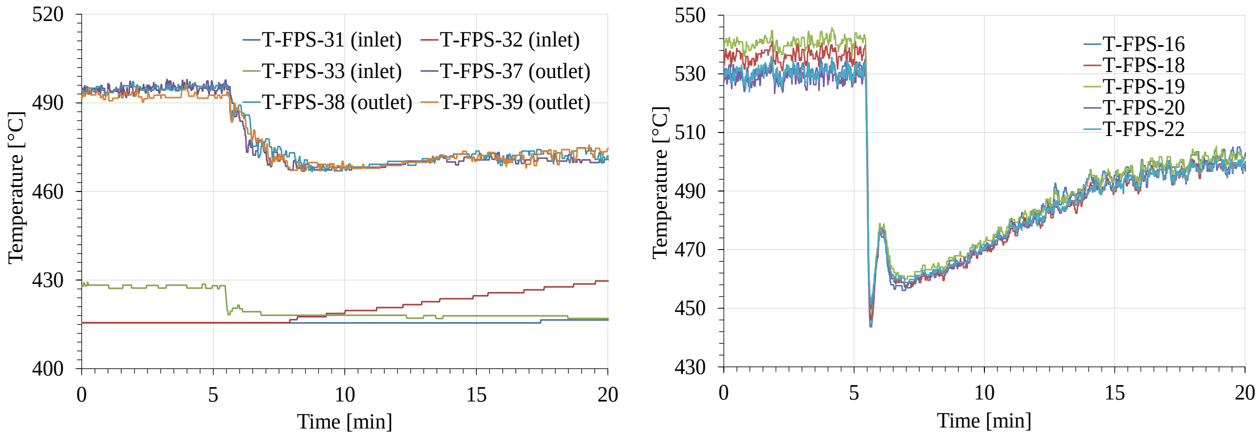

Figure 13 TT #2, LBE temperature trends at the FPS inlet-outlet (left) and FPS pin clad temperature (right)

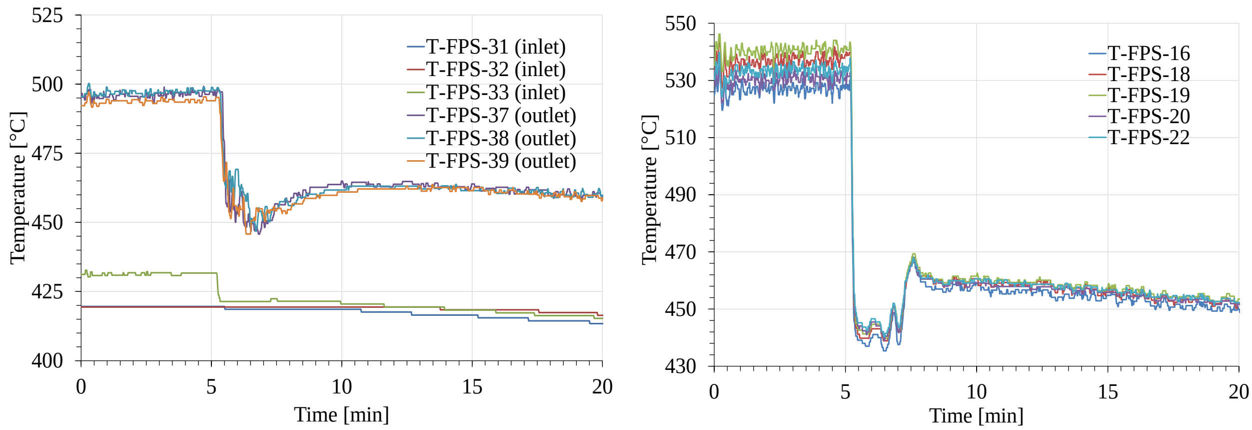

Figure 14 TT #3, LBE temperature trends at the FPS inlet-outlet (left) and FPS pin clad temperature (right)

The temperature trends at the inlet and outlet sections of the riser are shown in Figure 15, Figure 16 and Figure 17, in which it is possible to notice a similar behaviour in all of three the TTs.

Before the transient, the temperature at the inlet of the riser is about 495 °C. Arising from the bottom part of the riser up to the separator, the LBE temperature is subjected to a low decrease of about 6 °C due to the heat losses along the tube. During the transient, the significant reduction of the FPS power leads to a low LBE inlet temperature in the riser, which rapidly decreases to ~470 °C immediately after the transition, and then continues to decrease with a smooth ramp. However, the LBE in the top part of the riser and inside the separator does not suffer immediately the effects of the transient, due to the sudden reduction of the LBE mass flow rate, which delays the ascent of the coolant, and its temperature decreases slowly. This results in an inversion of the temperatures in the rising leg, in which the LBE on the top remains hotter than the coolant flowing up from the FPS.

Figure 15, Figure 16 and Figure 17 also report the temperatures measured by the 119 TCs placed in the LBE pool, as function of their vertical position on the supporting bars (A-I), before and after the transient. In all the three TTs the stratification in the pool occurs between the positions at 5000 mm and 6000 mm (assuming 0 mm the bottom part of the separator, see Figure 3).

Before the transient, in nominal working conditions, the maximum temperature reached is ~475 °C, in the upper part of the pool, while the lower value is ~420°C in the lower part of the pool. After the transient, the temperature profile is shifted to lower values, with a maximum/minimum temperature reached of 465 °C/407 °C in TT #1 and 468 °C/406 °C in TT #3. In TT #2, the temperature profile achieved after the transient assumes values slightly lower than the previous ones, with a maximum and minimum temperature reached of 465 °C and 418 °C respectively. The temperature decrement in the pool achieved in this test is due only to the heat losses through the vessel, since after the transient the steam generator has been disabled.

As expected, in all the tests the thermal stratification in the LBE pool occurs in vertical direction only, with uniformity along the horizontal planes.

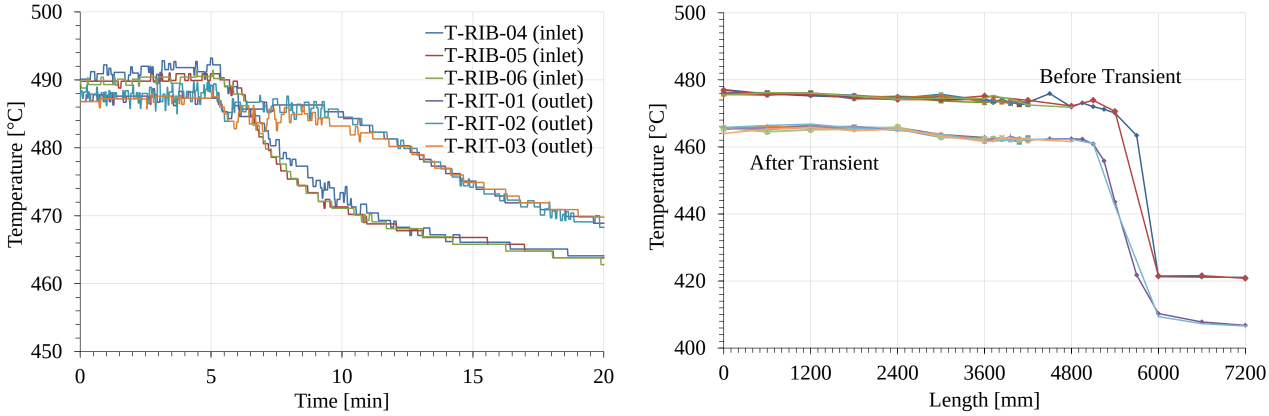

Figure 15 ***TT #1, LBE temperature trends at the inlet and outlet sections of the Riser (left) and axial temperature profile inside the S100 vessel before and after the transient (right)***

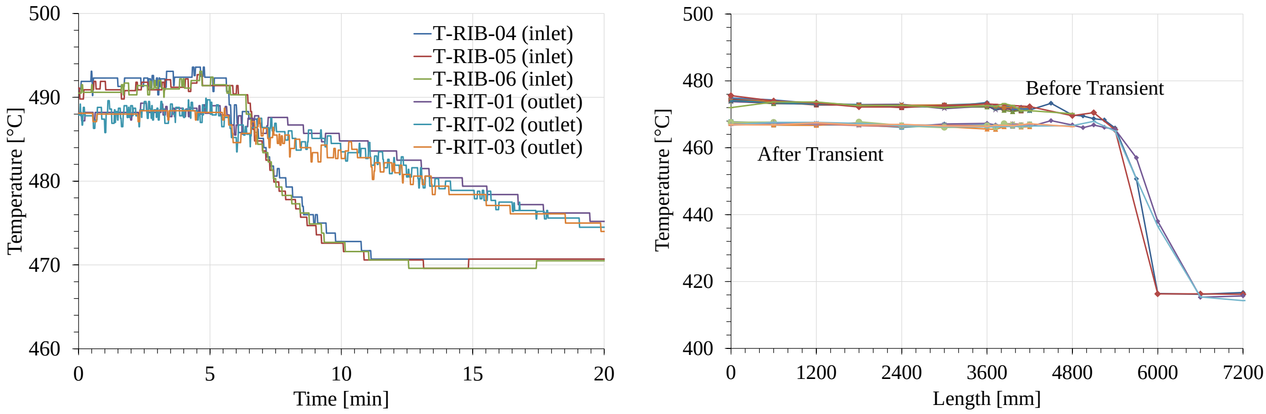

Figure 16 ***TT #2, LBE temperature trends at the inlet and outlet sections of the Riser (left) and axial temperature profile inside the S100 vessel before and after the transient (right)***

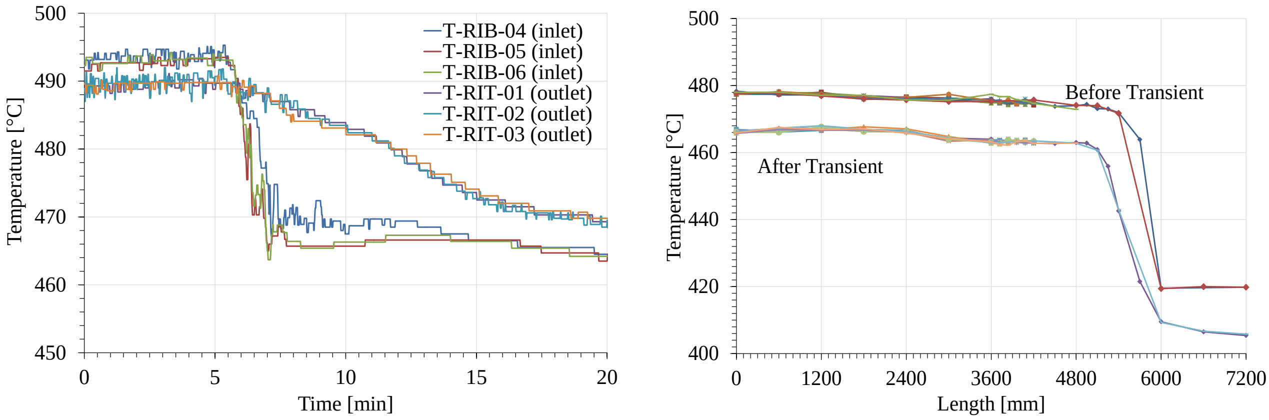

Figure 17 ***TT #3, LBE temperature trends at the inlet and outlet sections of the Riser (left) and axial temperature profile inside the S100 vessel before and after the transient (right)***

The LBE and water temperatures in the HERO SGBT are reported in Figure 18, Figure 19 and Figure 20 for TT #1, TT #2 and TT #3, respectively. In nominal working conditions the LBE temperature at the inlet section of the SG, is about 480 °C, while after the cooling it is ~408 °C. When the transient occurs, the inlet and outlet LBE temperatures in TT #1 (Figure 18) and TT #3 (Figure 20) start to decrease slowly, without abrupt changes. A different trend can be seen in TT #2, where, when the transient occurs, the complete loss of the heat sink leads to an increase of the temperatures along the SG shell side, with the LBE temperature at the outlet section which reaches in few minutes the same value of the SG inlet section. In all the three cases, it can be noticed that the temperature measured at the inlet by TC-SG-01 suffers of an instability in FC respect to the other two TCs, because of its position in the separator. In fact, this TC is directly exposed to the rising LBE, mixed to the argon injected at the bottom of the riser and this turbulence affects the measure acquired.

Concerning the secondary loop, Figure 18, Figure 19 and Figure 20 also report the inlet and outlet water temperatures. At the BTs inlet section, the temperature is maintained constant at ~336 °C for the entire test, excepting for few seconds of oscillations, when the transients occur, due to the re-balancing of the HEATER power, when the water mass flow rate is reduced. From Figure 18 and Figure 20, it can be seen as in TT #1 and TT #3 the steam temperature at the BTs outlet is subjected to a sudden variation, passing from an average value of ~390 °C before the transient to a maximum value of ~450 °C immediately after, due to the reduction of the water mass flow rate. From this value, the temperature starts to decrease slowly, because of the lower thermal field in the primary system (SG shell side), with the consequently reduction of power removed.

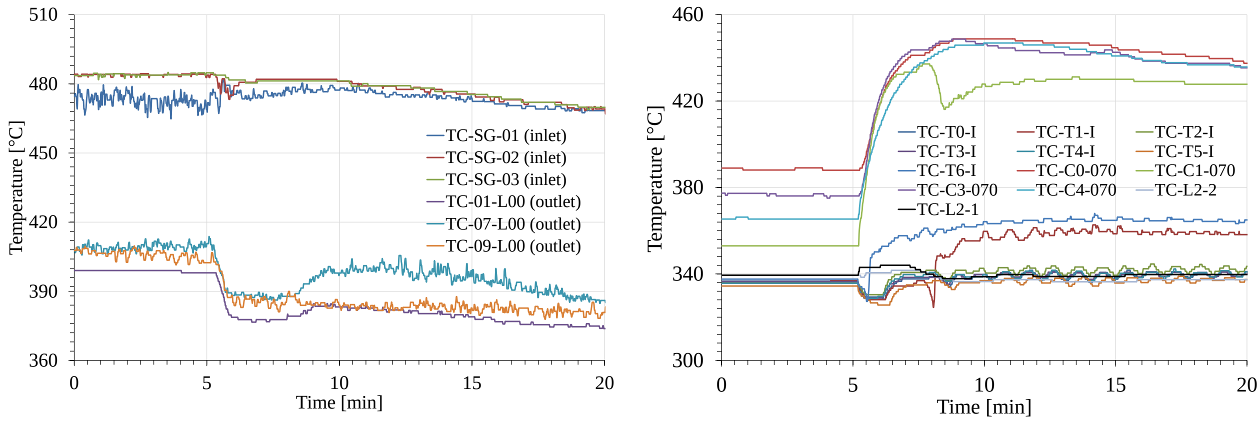

***Figure 18** TT #1, LBE temperature trends at the inlet and outlet sections of the SG (left) and H2O temperature trends at the inlet and outlet sections of the Bayonet Tubes (right)*

HIGHLIGHTS

- ✓ Experimental data on Heavy Liquid Metal flow in the CIRCE-HERO loop were presented.
- ✓ Experimental data on the CIRCE-HERO facility in support of ALFRED design.
- ✓ Bayonet tube heat exchanger.
- ✓ CIRCE-HERO protected loss of flow experimental campaign.

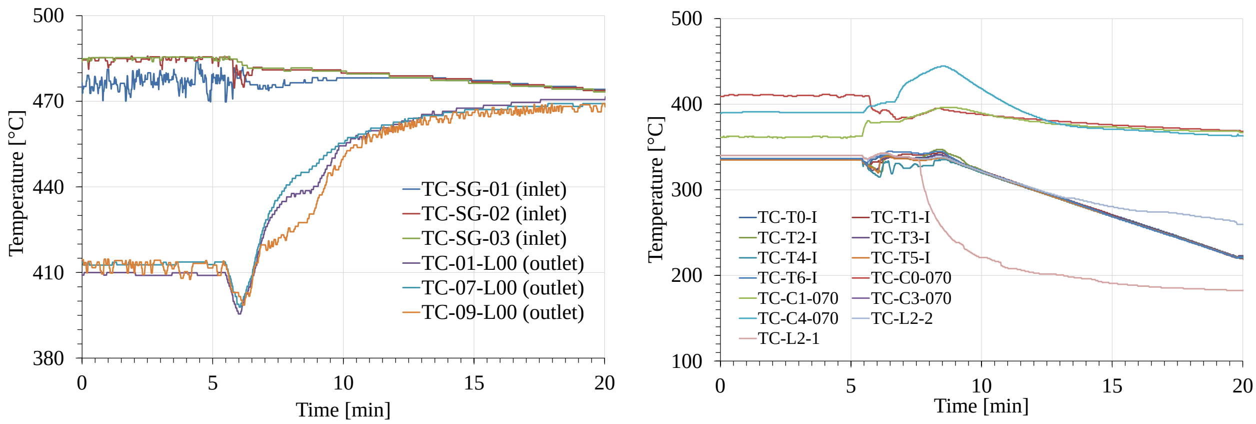

***Figure 19** TT #2, LBE temperature trends at the inlet and outlet sections of the SG (left) and H2O temperature trends at the inlet and outlet sections of the Bayonet Tubes (right)*

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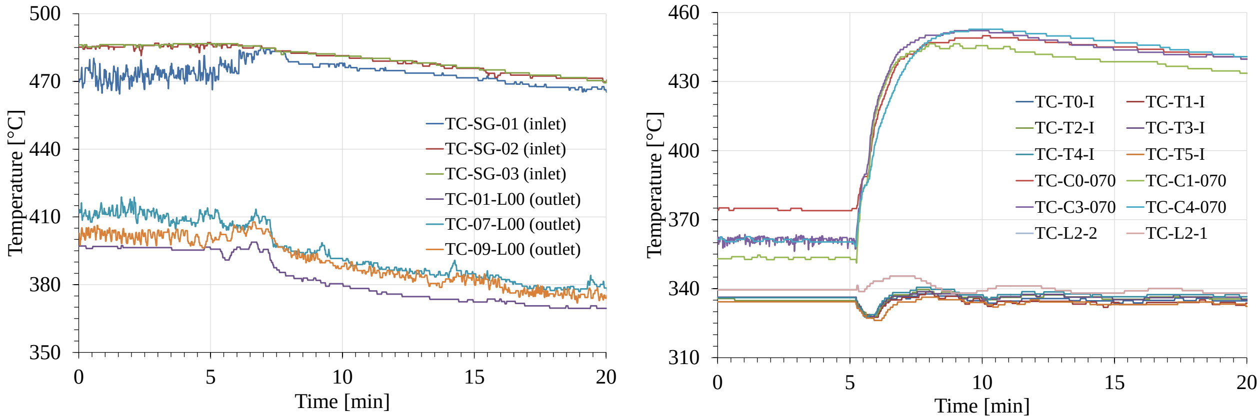

Figure 20 TT #2, LBE temperature trends at the inlet and outlet sections of the SG (left) and H2O temperature trends at the inlet and outlet sections of the Bayonet Tubes (right)

CONCLUSIONS

A high-pressure experimental campaign has been realized in the large LBE pool CIRCE facility, implementing HERO test section, in the framework of the HORIZON2020 SESAME European project. The test matrix is composed of three experimental transient tests aiming at reproducing PLOFA scenarios. The tests realized allow to evaluate the thermal-hydraulic performance of an LBE pool-type facility when an accidental scenario occurs, and to achieve experimental data relevant for the ALFRED Steam Generator and code validations.

During the tests, it has been possible to monitor the main thermal hydraulic parameters (temperatures, flow rates, pressures) for both primary and secondary systems, before and after the transient. The FPS power, the argon injection and the feedwater have been operated in order to reproduce as well as possible the features of the accidental scenario.

The results show that, despite the loss of the forced circulation regime of the coolant in the primary loop, the power transient leads to a sudden decrease of the LBE and pin clad temperatures along the FPS, avoiding dangerous peaks in the active region. The most severe condition has been achieved in TT #2, in which the full loss of the heat sick leads to a temporally increase of the temperatures along the active length of the FPS, as long as the thermal heat losses from the main vessel balance the power supplied by the FPS.

In TT #1 and TT #3, the overall reduction of the temperatures in the primary loop shows that, after the transients, the power removed by HERO acting as DHR system is higher than the power supplied by the FPS, leading the entire system to a safe long-term cooling condition.

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NOMENCLATURE

Q	Electric Power	W
h	Enthalpy	kJ/kg

ABBREVIATIONS

ALFRED	Advanced Lead cooled Fast Reactor European Demonstrator
BT	Bayonet Tube
CIRCE	CIRColazione Eutettico (Eutectic CIRCulation)
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile
FPS	Fuel Pin Simulator
GIF	Generation IV International Forum
HERO	Heavy liquid mEtal – pRessurized water cOoled tube
LBE	Lead-Bismuth Eutectic
PLOFA	Protected Loss of Flow Accident

SESAME	Simulations and Experiments for the Safety Assessment of MEtal cooled reactors
SG	Steam Generator
SGBT	Steam Generator Bayonet Tube
TC	Thermocouple
TFM	Turbine Flow Meter
TT	Transient Test

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