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THERMAL HYDRAULIC ANALYSIS OF THE CIRCE-HERO POOL-TYPE FACILITY

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ABSTRACT

To support the activities carried out by the ENEA Brasimone Research Center on the Lead-cooled European Advanced Demonstration Reactor (LEADER) project, University of Pisa has improved the RELAP5/Mod3.3 code introducing the Lead and Lead-Bismuth Eutectic (LBE) as coolant fluids. This new version of the STH code was applied to perform several analyses for the steam generator HERO (Heavy liquid mEtal pRessurized water-cOoled tubes) installed in the CIRCE (CIRColazione Eutettico) pool-type facility that uses LBE as working fluid. HERO consists of a bundle of seven Double-Wall Bayonet Tubes (DWBT) with a leakage monitor system, and it was tested in the CIRCE facility to support the development of the steam generator proposed for ALFRED (Advanced Lead Fast Reactor European Demonstrator).

A preliminary analysis was performed comparing the RELAP5/Mod3.3 results against available experimental data. In particular, an isothermal test of the CIRCE-HERO facility allowed to set-up the RELAP5/Mod3.3 nodalization. As a second analysis, a steady state at full power was investigated. This steady-state condition was employed to perform a sensitivity study on the influence of the thermal conductivity of the stainless steel powder characterizing the HERO steam generator. Finally, the analysis of unprotected and protected loss of flow transients, and the analysis of a protected loss of flow with a simultaneous partial loss of heat sink were performed. These last transients were investigated to assess the behavior of the HERO steam generator, especially to verify the possibility to establish a natural circulation capable to safely remove the “decay heat”.

The results of the first analysis (isothermal hydraulic characterization) demonstrated the good capabilities of improved RELAP5/Mod3.3 code to reproduce the forced circulation conditions. The results of the second analysis (steady-state at full power) highlighted the strong influence of the stainless steel powder thermal conductivity on the achieved steady-state conditions. The simulations of the last tests provided the time evolution of the LBE mass flow rate and of the temperatures in different regions inside the pool during unprotected and protected loss of flow transients. In the paper, a critical discussion of the obtained results is performed.

INTRODUCTION

Six innovative reactor concepts are actually under development under the Generation IV International Forum (GIF) [1]. Among these concepts, Lead-cooled Fast Reactor (LFR) is contemplated as the most promising alternative fast neutron reactor solution (middle term) compared to the Sodium Fast Reactor (SFR), considered the reference technology for the short term. Actually, significant projects on LFRs are ALFRED Advanced Lead Fast Reactor European Demonstrator) and FALCON: ALFRED is devoted to the development of the namesake reactor, while FALCON is a consortium created to foster the collaboration among international organizations to build ALFRED [2].

Latest R&D activities resulted in the development of an innovative Steam Generator (SG) concept based on Double-Wall Bayonet Tubes (DWBT) with leakage detection system [3]. The advantages of this concept are mainly two: the increase of the safety margins reducing the probability of lead-water interaction, and the capability to monitor any leakage through the monitoring system [3].

To support the research activities on the ALFRED reactor, the ENEA Brasimone laboratories developed a mock-up of this SG concept called Heavy liquid mEtal pRessurized water-cOoled tubes (HERO). HERO performances will be studied in the CIRColazione Eutettico (CIRCE) facility, which is a pool facility designed to study the circulation of Heavy Liquid Metal (HLM) [4] [5].

UNIversity of PIsa (UNIPI) supports the activities of ENEA Brasimone through numerical analysis. As part of this collaboration, the RELAP5/Mod3.3 code was improved by UNIPI introducing the Lead and the Lead-Bismuth Eutectic (LBE) coolant fluids to develop a coupling tool between RELAP5 and ANSYS FLUENT codes. Relevant works on this field led to a thorough validation of RELAP5 and the coupling strategy [6] [7] [8].

Therefore, the present paper shows some numerical analysis performed on the CIRCE-HERO facility. A numerical model of the experimental apparatus was created and then it was tested against different scenarios:

- A steady-state analysis at full power to demonstrate that the code and the model are capable to reproduce the design conditions.
- A sensitivity study on the influence of the thermal conductivity of the mixture composed by stainless steel powder and helium. This mixture is used in HERO SG, as specified in the following sections. The lack of reliable data about the thermal conductivity of this powder was deemed as an issue of main concern during the development of this model. For this reason, a sensitivity analysis was performed comparing the few available data.
- An analysis of the isothermal hydraulic characterization test. This is the only test already performed in the facility, thus it was used to verify the performances of the code/model against experimental data.
- Four transients analyses: two Unprotected Loss Of Flow (ULOF) and two Protected Loss of Flow (PLOF) accidents. In the ULOF transients the thermal power source is supposed to remain active at full power while a loss of primary flow occurs. Instead, in the PLOF both the partial deactivation of the thermal power source (the power decreases to the 7% of the nominal value in 3 s) and the loss of primary flow occur. The two investigated ULOF and PLOF scenarios differ for the complete or partial availability of the heat sink. These four transients were investigated to assess the capability of the HERO SG to establish a natural circulation capable to safely remove the "decay heat".

The goal of these activities is to validate the CIRCE-HERO model in order to numerically support the experiments that will be performed by ENEA Brasimone once terminated the commissioning of the facility.

In the following, a brief description of the facility and the employed model is presented. Then, a discussion on the obtained results for the different investigated scenarios is provided. Finally, a summary of the paper is drawn in the conclusive section.

DESCRIPTION OF THE FACILITY

CIRCE [4] [5] is a cylindrical pool filled with molten LBE (90 tons maximum inventory), with argon cover gas, and a recirculation system (Fig. 1(a) – adapted from [9]). Several conduits and auxiliary equipment can be installed in the pool for separate-effects and integral-effects test. The main pool is 8.5 m in height and 1.2 m in diameter (outside). The outer shell made of AISI316L is 15 mm thick. The main auxiliary equipment installed in the CIRCE-HERO configuration are:

- The feeding pipe represents the beginning of the "conduit". It has the scope to route the LBE from the pool through the Fuel Pin Simulator (FPS) and the HERO DWBT-SG). It is composed by several tubes connected together, such as the feeding conduit, the Venturi nozzle, and the Fuel Pin Simulator (FPS) outer shell.
- The FPS consists of 37 electrically heated pins, with a rated power of 800 kW, designed to provide a coolant temperature gradient of 100°C with a coolant average speed of 1 m/s, and a pin power density of 500 W/cm^3.
- Pins have a hexagonal lattice with pitch/diameter ratio of 1.8, and an outer diameter of 8.2 mm. Only 1.0 m out of 1.88 m is heated, and the remaining part constitutes the upstream (0.53 m) and downstream (0.35 m) mixing zones. The pins are kept in position through different spacer grids installed at different heights.
- The fitting volume and the riser are designed to drive the LBE into the upper zone of the "conduit" characterized by the separator. The fitting volume has a complex shape to allow the connection between the release pipe and the riser. The riser is a double-wall tube designed to reduce the heat exchanges with the surrounding pool. A total length of 3.81 m and an inner diameter of 0.2 m characterizes the riser tube.
- The argon injection system is designed to inject argon inside the riser to enhance the LBE circulation.
- The separator is placed above the riser. The separator is made of 6 mm-thick steel sheets welded together, and its main aim is to allow the separation of argon and LBE.
- The HERO external shroud is a tube into which the HERO DWBT-SG is inserted. The HERO external shroud and the HERO DWBT-SG are joined together and inserted into a hole in the separator bottom. From the separator, the LBE goes down through this tube and exits into the pool about 1.15 m above the inlet position of the feeding conduit.
- The HERO-SGBT consists of a bundle of seven DWBT with a leakage monitor system. The seven tubes have a triangular lattice with pitch/diameter ratio of 1.42. These bayonet tubes are made of 4 concentric tubes

with an active length of 6 m (7.36 m in total). Figure 1(b) (adapted from [9]) shows a schematic view of a DWBT. The feedwater goes down through the inner tube, then it moves upward crossing the annulus tube. In the downward direction, a slight pre-heating of the water occurs while the evaporation and steam overheating takes place flowing upwards in the annular tube. The water/steam annular tube is in turn enveloped in another annular tube filled with helium and stainless steel powder. This helium annular tube is part of the leakage monitor system, and it prevents the direct contact of water/steam and LBE in case of Steam Generator Tube Rupture (SGTR) accidents.

- The dead volume is a sort of closed tube inserted in the pool that hosts the electrical instrumentation feeding the FPS. The dead volume reduces the available space for the LBE coolant.

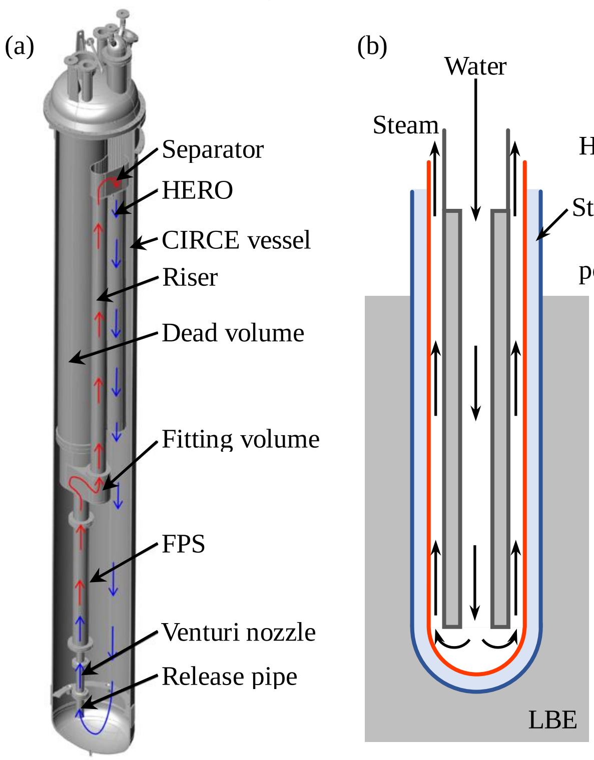

Figure 1: CIRCE-HERO test section (a), and schematic of a DWBT (b).

NUMERICAL MODEL

The model scheme employed (Fig. 2) to reproduce the facility was created according to the latest available geometrical data [3]. The model consists in three main zones:

- the pool;
- the "conduit";
- the HERO SG secondary water side.

The pool is mainly composed by parallel pipes (in light blue) connected at the beginning and at the end by means of branches (in dark blue). Cross-junctions are also used to connect the nodes composing each pipe. The outer pool shell is simulated as a 15 mm thick stainless steel structures with imposed heat transfer coefficients on the outside (0.5 W/m^{2}K), to take into account heat losses to the environment. The argon cover gas is kept at atmospheric pressure and at 320°C by means of a time-dependent volume.

The "conduit" represents the upward and downward tubes guiding the LBE through the FPS and the HERO DWBT-SG. The "conduit" is schematized as a succession of pipes (light red) and branches (dark red). Each volume composing the "conduit" refers to a specific zone: volume 20 simulates the release pipe (feeding conduit and Venturi nozzle in Fig. 1), volumes 50 and 70 the mixing zones before and after the FPS (volume 60, in red in Fig. 2), volumes 80 and 90 the fitting volume, volume 130 the riser, volume 132 the separator, and volume 172 the descending tube in which HERO is inserted. The pressure drop coefficients across the different volumes have been preliminarily calculated according to Idel'cik [10] and then finely tuned according to the isothermal test results. Except for the riser (volume no. 130) all the other volumes are supposed to exchange heat with the LBE contained in the pool. The argon injection system is simulated with a time-dependent volume ("TDPV 3" in Fig. 2) and with a junction having imposed mass flow rate.

The last part of the model is the secondary side of HERO SG. The feedwater properties (~17.2 MPa and 335°C) and mass flow rate (~0.33 kg/s) are imposed with a time-dependent volume (no. 410). The feedwater then splits into two streams: the first crosses the volumes simulating the central bundle tube (volumes no. 4**), and the second crosses the volumes simulating the remaining six lateral bundle tubes lumped together (volumes no. 5**). Except for branches no. 418, 435, and 460 (in dark green), all the other volumes are pipes (light green). Two structures (in yellow) reproduce the heat transfer regions of the HERO SG. These two structures are composed of (from the inside to the outside) 2.11 mm of stainless steel (AISI 304), 0.62 mm of a mixture of stainless steel powder (AISI 316) and helium gas, and 3.38 mm of stainless steel (AISI 304). Table 1 summarizes the main design data of HERO, leakage detection system, and CIRCE pool.

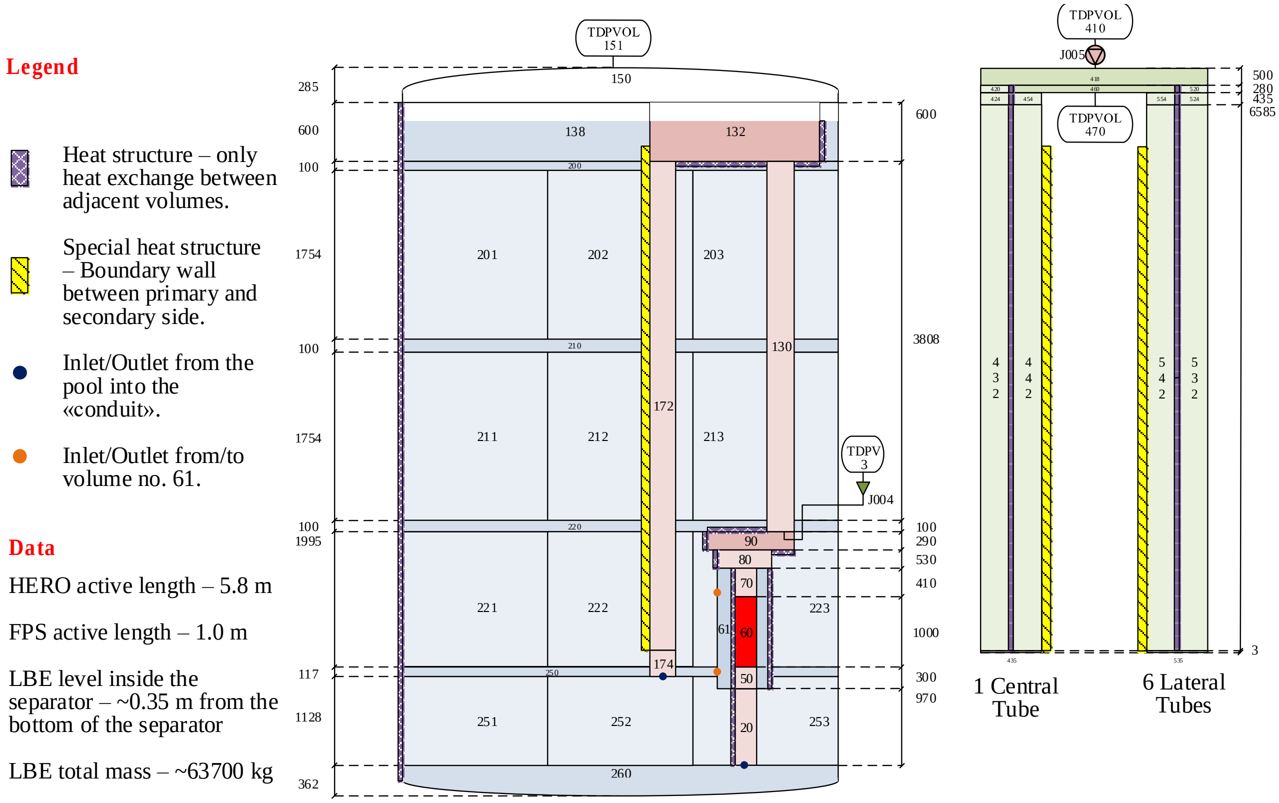

Figure 2: CIRCE-HERO RELAP5 nodalization.

Table 1: HERO, leakage system, and CIRCE pool design data.

Parameter	HERO	Leakage system	CIRCE
Inlet temperature [°C]	335	-	480
Operating mass flow rate [kg/s]	~0.33	Stagnant	44.6
Design pressure [MPa]	17.2	0.45	0.1
Design temperature [°C]	432	432	550

THE ISOTHERMAL TEST

The isothermal hydraulic characterization test was performed to observe the variation of the LBE mass flow rate as a function of the inlet argon flow rate. To reproduce the conditions of this test in RELAP5, only the pool and the "conduit" were considered. The outer walls connecting the pool with the outer environment were removed (adiabatic conditions) and the power provided by the FPS was set to 0 W. The argon flow rate was then assumed as boundary condition.

Figure 3 shows the experimental and the RELAP5 time evolution of LBE mass flow rate. A quite good agreement between the experiment and the RELAP5 predictions exists, especially at high LBE flow rate (~45 kg/s).

Being the test performed in isothermal conditions, the temperatures are almost identical in all the zones of the facility, and they remain almost constant for the entire test duration. This phenomenon is well captured also by the RELAP5 code, as shown in Fig. 4.

Finally, in Fig. 5 the pressure inside the fitting volume, and at the inlet and outlet of the riser is reported. The pressure at different heights is mainly due to the LBE column above, thus a good reproduction of the pressure means that the free volume available for the coolant is well reproduced in the model.

STEADY STATE ANALYSIS

In the analysis of the steady-state at full power, both the water and the argon mass flow rates were employed as boundary conditions. The water flow rate across HERO SG was set to the design value, while the argon inlet flow rate was tuned to obtain a good reproduction of the LBE flow rate across the conduit. Finally, also the inlet water temperature and pressure, and the power injected through the FPS were employed as boundary conditions. These data were taken from Ref. [11], except the HERO outlet temperature and flow rate that were taken from Refs. [3] and [12], respectively.

In table 2 a brief comparison of the design data and the results achieved with RELAP5 is shown. The inlet and the outlet temperatures of the HERO SG are set identical to that of the ALFRED SG, but the achievement of these value seems quite challenging. Except for the outlet HERO temperature, the other design data are well reproduced by RELAP5 (differences well below 1%).

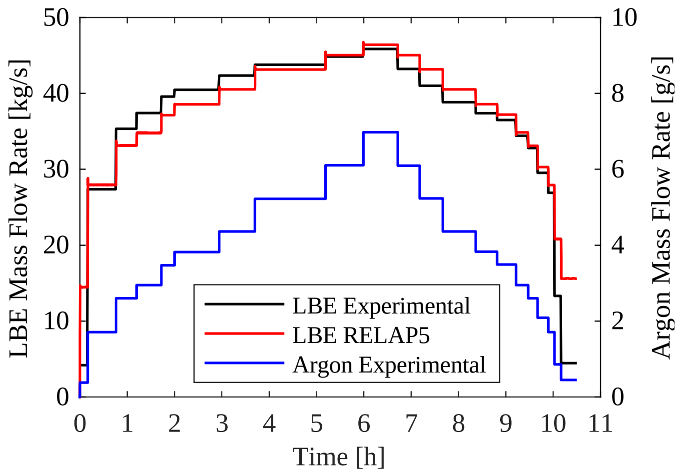

Figure 3: LBE mass flow rate during the isothermal hydraulic characterization test.

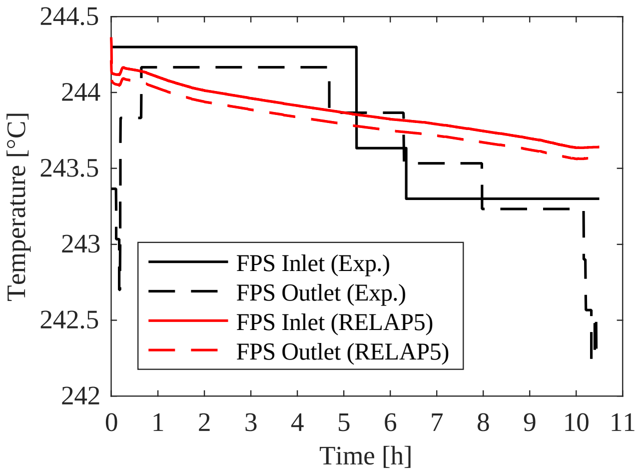

Figure 4: FPS inlet and outlet temperatures during the isothermal hydraulic characterization test.

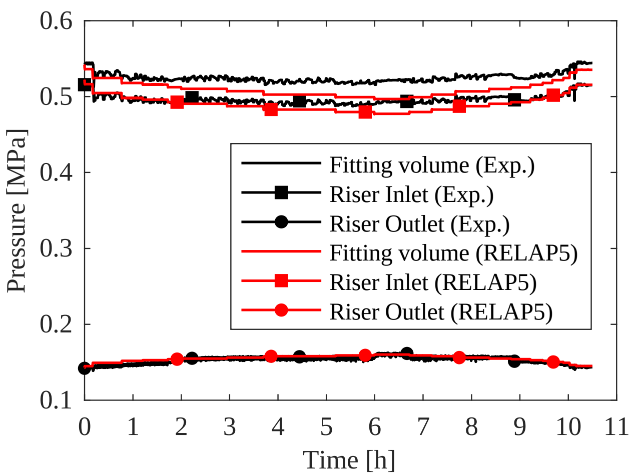

Figure 5: Pressure during the isothermal hydraulic characterization test.

Table 2: Steady-state results.

Parameter	**Design value**	**RELAP5 value**	**Error [%]**
Inlet FPS temperature [°C]	400	401.3	0.33
Outlet FPS temperature [°C]	480	484.6	0.96
Inlet HERO temperature [°C]	335	335.2	0.06
Outlet HERO temperature [°C]	432	394.6	12.3
LBE flow rate [kg/s]	38	37.93	0.18
Pressure in HERO SG dome [MPa]	17.2	17.17	0.17
FPS Power [kW]	450	450	-
Power removed through HERO [kW]	-	~430	-
Water flow rate (HERO secondary side) [kg/s]	~0.33	~0.33	-
Steam quality (HERO secondary side) [-]	~1.8	~1.41	22.1
Argon flow rate [g/s]	~3.09	3	2.9

STUDY ON THE THERMAL CONDUCTIVITY OF THE AISI 316/HELIUM MIXTURE

During the refinement and tuning of the model, an issue of main concern was underlined: a considerable uncertainty on the thermal conductivity of the AISI 316 powder and helium mixture in the HERO design conditions. To overcome this problem, some data were inferred from previous experiences [13], then a sensitivity study was performed. In the final calculations performed in Ref. [13], a thermal conductivity weakly influenced by the temperature was employed ("default" in Fig. 6). Although, still in Ref. [13], a correlation was proposed based on several tests performed in an experimental apparatus considering the operative HERO SG conditions:

$$k = 5 \cdot 10^{-6} T^2 + 0.0008T + 1.3198 \tag{1}$$

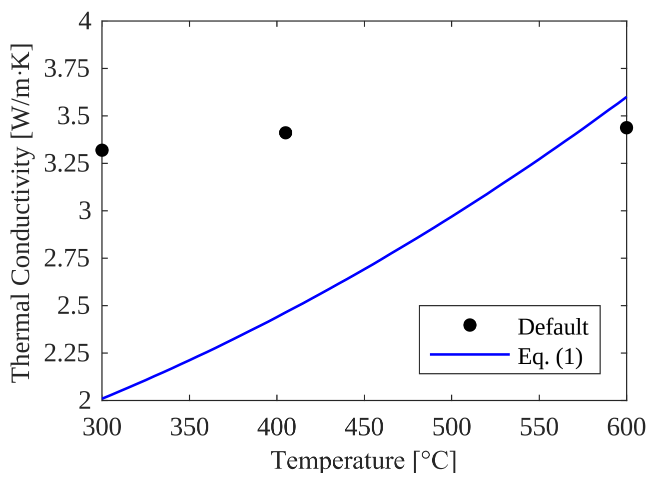

Figure 6: Thermal conductivity correlations.

This correlation (Eq. 1 in Fig. 6) shows a greater influence of the temperature, with thermal conductivity values spanning from 2 W/mK to 3.6 W/mK in the 300-600°C temperature range.

The cause behind this difference is unknown, thus a sensitivity study was performed to check the influence on the code's predictions. At a first glance, the results shown in table 3 suggest that the experimental correlation tends to slightly overestimate the inlet and outlet HERO temperatures (LBE side). In turn, the outlet steam temperature from HERO does not change (394.6°C).

Therefore, even with the experimental correlation, the HERO SG design conditions were not met. For this reason, in the present work the values employed in the final calculations of Ref. [13] were employed also for the following transients analysis.

Table 3: Results of the sensitivity analysis on the thermal conductivity of the AISI 316 powder and helium mixture – Inlet and Outlet LBE temperature from HERO SG.

	Outlet Temp. [°C]	Inlet Temp. [°C]
Design	400	480
First assumption	401.3	484.6
Eq. (1)	410.5	493.15

OFF-NORMAL TRANSIENTS ANALYSIS

Four off-normal transients have been investigated to check the decay-heat removal performances of the HERO SG. The analyzed transients are:

- An ULOF and a PLOF both without loss of heat sink;
- An ULOF and a PLOF both with a partial loss of heat sink (HERO water flow rate down to the 10% of the nominal figure);

ULOF transients are characterized by the FPS at full power, while, a liner decrease (3 s) to the 7% of the nominal FPS power is assumed for PLOF transients. In both ULOF and PLOF a complete loss of argon flow rate occurs.

As expected, the most demanding scenario is the ULOF with a partial loss of heat sink. The instantaneous stop of the argon flow rate creates some instabilities in the internal loop: depending on the local conditions, an increase or decrease of the LBE flow occurs (Fig. 7). Then, a new equilibrium of the LBE flow is found in about 30 s. In the meantime, a continuous increase of the temperature in all the zones of the system occurs due to the partial loss of heat sink. At about 1000 s (~17 min), the temperature at the FPS outlet reaches 800°C (Fig. 8); at the same time, the increase of the temperature affects also the density of the LBE coolant. In about 3600 s (1 hr) the separator fills with LBE (Fig. 9). Similarly, also the adjacent pool zone (volume no. 138) fills with LBE in about 7000 s (~2 hr). The different time needed to "fill" these two zones is related to the temperature of the LBE in the separator and the pool (Fig. 10), and to the size of each volume. Once both the separator and volume no. 138 are full of LBE, the coolant starts to flow into the pool bypassing almost completely the HERO downward tube. This can be clearly seen in Fig. 7: at 10,000 s (2 hr 45 min) the mass flow rate crossing the riser is about 14 kg/s but only 2 kg/s of LBE exits from the HERO downward tube.

In turn, the ULOF without loss of heat sink presents a complete different evolution. The initial part of the transient is similar to that of the previous transient, but then the intact capabilities of the SG limit the maximum temperatures. The complete filling of the separator does not occur in the present scenario, and a stable flow rate across the conduit is established (Fig. 11). The maximum temperature (620°C) is reached at the FPS outlet when the LBE flow rate is at the minimum, but then it stabilizes below 560°C (Fig. 12).

Finally, the PLOF with and without loss of heat sink transients does not pose any risk to the integrity of the facility. In both cases the maximum temperature reached is well below 500°C (Fig. 13).

Of the four investigated transients, the only one posing any risk to integrity of the facility is the ULOF plus the partial loss of heat sink. In case of complete availability of the heat sink, the temperature initially increases to ~610°C but then it decreases thanks to the established natural circulation. Instead, during PLOF transients the temperature remains always below 500°C. In any case, a safety system is present to shut-down the FPS once the outlet LBE temperature (from the FPS) increases up to 600°C. Therefore, a rapid intervention of this FPS shutdown safety system seems mandatory in the ULOF transients, because the LBE temperature may increases up to 800°C in about 15 min (1000 s) in case of unavailability of the heat sink.

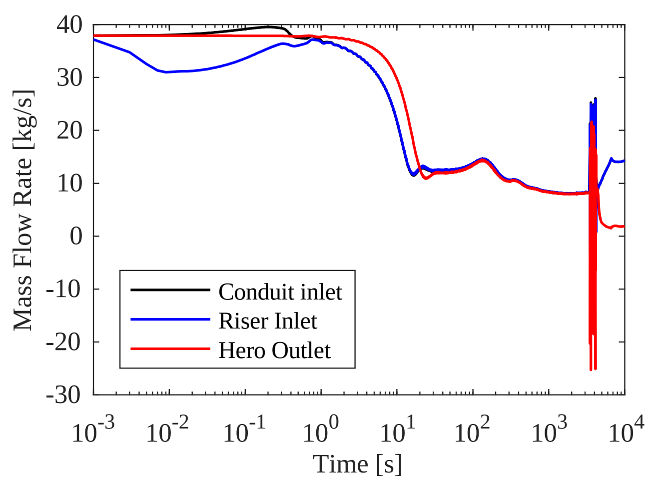

Figure 7: LBE Mass flow rate (ULOF plus partial loss of heat sink).

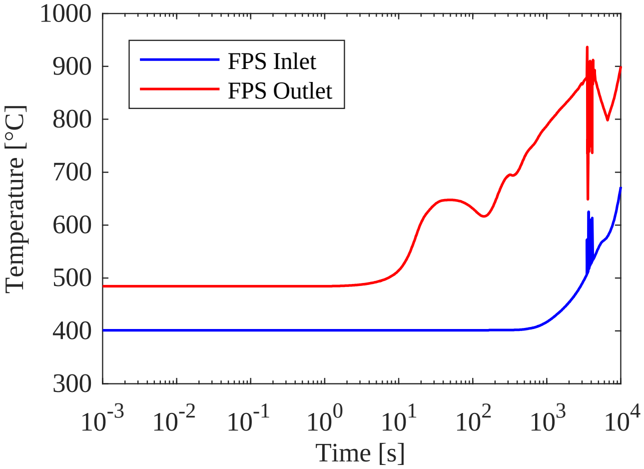

Figure 8: FPS inlet and outlet LBE temperature (ULOF plus partial loss of heat sink).

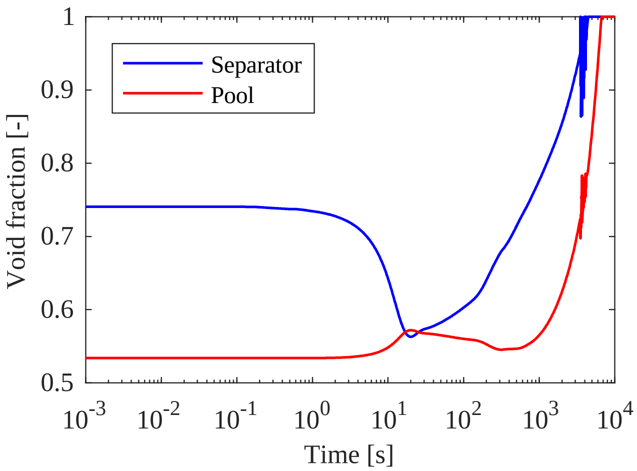

Figure 9: Void fraction in the separator and in the outer pool - volume no. 138 (ULOF plus partial loss of heat sink).

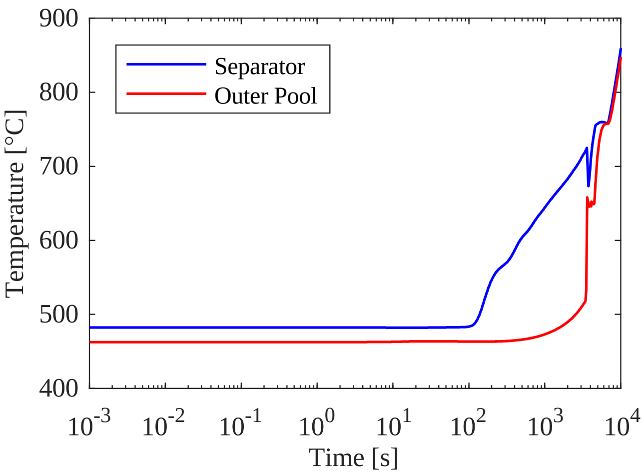

Figure 10: LBE temperature in the separator and in the outer pool - volume no. 138 (ULOF plus partial loss of heat sink).

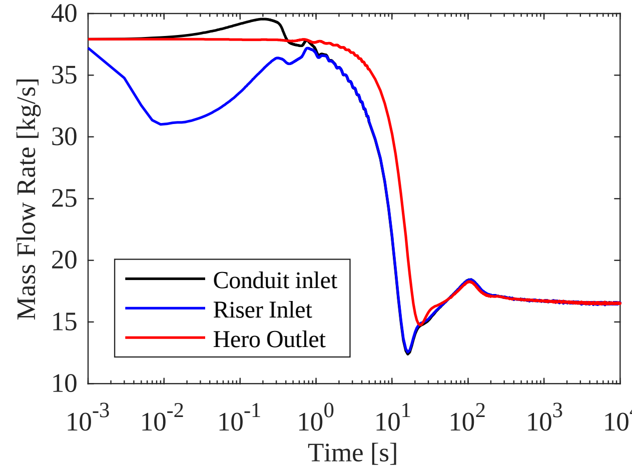

Figure 11: LBE Mass flow rate (ULOF without loss of heat sink).

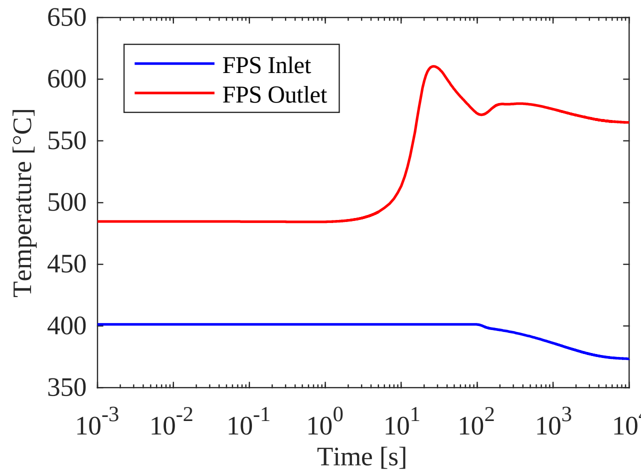

Figure 12: FPS inlet and outlet LBE temperature (ULOF without loss of heat sink).

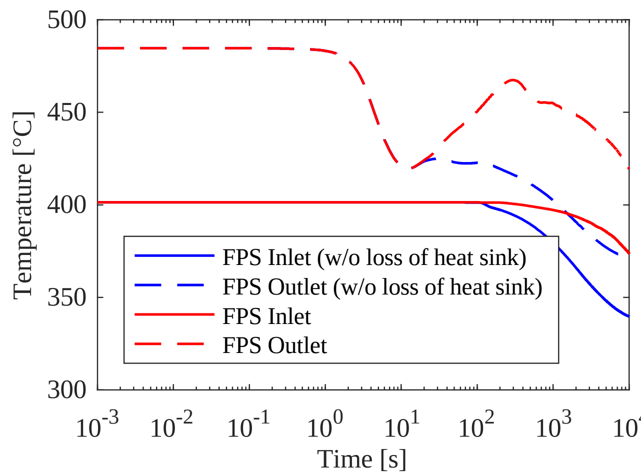

Figure 13: FPS inlet and outlet LBE temperature (PLOF with and without loss of heat sink).

CONCLUSIONS

In the present paper, several thermo-hydraulic analyses of the pool type CIRCE-HERO facility, built at ENEA Brasimone laboratories to investigate the circulation of the LBE and other heavy metal coolants, have been performed. HERO is a new SG concept proposed for the ALFRED reactor consisting of 7 DWBT disposed in a triangular lattice, and with a detection leakage system.

Four different analyses have been performed:

- the analysis of the isothermal hydraulic characterization test;
- a steady-state analysis;
- a sensitivity study on the thermal conductivity of the stainless steel AISI 316 powder and helium mixture;
- four incidental transients: Two ULOF and two PLOF with complete or partial availability of the heat sink.

The isothermal hydraulic characterization test, is the only one already performed in the facility. The test consists in a step-by-step increase/decrease of the argon flow rate keeping the FPS power to 0 W (HERO SG is inserted in the pool but it is deactivated). This test demonstrated the capabilities of the RELAP5 model to correctly reproduce the link between injected argon flow and LBE flow rate, especially at high argon flow rate.

The following steady-state analysis showed some limitations related to the reproduction of the HERO SG design conditions. The predictions of the RELAP5 code report a steam outlet temperature of about ~395°C instead of 432°C. The cause of this difference is unknown, and this remains an open issue due to the lack of experimental data. However, the other parameters were well reproduced by RELAP5 (differences well below 1%).

Basing on the findings of the steady-state analysis, a study on the thermal conductivity of the stainless steel powder and helium mixture was performed. Two data sets coming from Ref. [13] were employed. The obtained results showed that both data sets are capable to reproduce in a good way the nominal conditions of the facility, even if the experimental correlation seems to provide slightly overestimated values (about 10°C). However, no final conclusions on which data set is more reliable were drawn due to the important differences still shown for the HERO SG outlet water temperature.

Finally, the four PLOF and ULOF transients showed that only the ULOF with partial loss of heat sink pose undue risk to the integrity of the facility. In this scenario, the temperature increases quite rapidly, and management actions seem necessary to reduce the severity of the transient. In all the other cases, the establishment of natural circulation allowed the removal of the decay heat, assumed equal to the 7% of the nominal power. Observations made during these analyses led to a thorough understanding of the facility conditions under off-normal transients, thus allowing the definition of procedures for the execution of these transients without damaging the facility itself.

NOMENCLATURE

ALFRED	Advanced Lead Fast Reactor European Demonstrator
CIRCE	CIRColazione Eutettico
DWBT	Double-Wall Bayonet Tubes
FPS	Fuel Pin Simulator
GIF	Generation IV forum
HERO	Heavy liquid mEtal pRessurized water-cOoled tubes
HLM	Heavy Liquid Metal
LBE	Lead-Bismuth Eutectic
LFR	Lead Fast Reactor
PLOF	Protected Loss Of Flow
SG	Steam Generator
SGBT	Steam Generator Bundle Tube
SGTR	Steam Generator Tube Rupture
ULOF	Unprotected Loss Of Flow
UNIPI	University of Pisa

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