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Pre-test analysis of protected loss of primary pump transients in CIRCE-HERO facility

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Abstract. In the frame of LEADER project (Lead-cooled European Advanced Demonstration Reactor), a new configuration of the steam generator for ALFRED (Advanced Lead Fast Reactor European Demonstrator) was proposed. The new concept is a super-heated steam generator, double wall bayonet tube type with leakage monitoring [1]. In order to support the new steam generator concept, in the framework of Horizon 2020 SESAME project (thermal hydraulics Simulations and Experiments for the Safety Assessment of MEtal cooled reactors), the ENEA CIRCE pool facility will be refurbished to host the HERO (Heavy liquid mEtal pRessurized water cOoled tubes) test section to investigate a bundle of seven full scale bayonet tubes in ALFRED-like thermal hydraulics conditions. The aim of this work is to verify thermo-fluid dynamic performance of HERO during the transition from nominal to natural circulation condition. The simulations have been performed with RELAP5-3D[®] by using the validated geometrical model of the previous CIRCE-ICE test section [2], in which the preceding heat exchanger has been replaced by the new bayonet bundle model. Several calculations have been carried out to identify thermal hydraulics performance in different steady state conditions. The previous calculations represent the starting points of transient tests aimed at investigating the operation in natural circulation. The transient tests consist of the protected loss of primary pump, obtained by reducing feed-water mass flow to simulate the activation of DHR (Decay Heat Removal) system, and of the loss of DHR function in hot conditions, where feed-water mass flow rate is absent. According to simulations, in nominal conditions, HERO bayonet bundle offers excellent thermal hydraulic behavior and, moreover, it allows the operation in natural circulation.

1. Introduction

The Horizon 2020 SESAME project supports the development of the heavy liquid metal (HLM) system. The project aims to develop and validate advanced numerical code for design and safety evaluation of innovative HLM cooled reactors. Intense experimental campaigns will be performed in order to achieve a suitable database for the verification and validation of numerical codes.

In this frame, CIRCE (CIRColazione Eutettico) pool facility, at ENEA Brasimone Research Center, will be refurbished to host a test section aimed at investigating the primary system of a fast liquid metal cooled reactor. The test section will be equipped with an innovative heat exchanger (HX),



named HERO. The objective of the experimental campaign will be to simulate the transition from forced to natural circulation in a protected loss of flow accident scenario, in order to provide an experimental database to promote the realization of a validation benchmark.

The objective of this work is to carry out pre-test simulations aiming to provide the preliminary test-matrix of the experimental campaign, which will be performed at the end of this year. Simulations are carry out with RELAP5-3D[®] (R5-3D) code upgrading the nodalization scheme validated during post-tests analysis on the CIRCE-ICE test facility [2].

The results of R5-3D simulations are presented comparing different accident scenario.

2. CIRCE-HERO test facility

CIRCE is a multipurpose pool facility designed to study innovative heavy liquid metal (HLM) cooled nuclear system. It consists of a main cylindrical vessel, which aims to contain different test sections, and two auxiliary tanks to store liquid metal during the maintenance phases and to host LBE during the transfer phases [3].

Previous test section installed in CIRCE, named ICE (Integral Circulation Experiment), has been upgraded in order to host the innovative HERO heat exchanger (HX) which consists of seven double wall bayonet tubes representing, as much as possible, ALFRED Steam Generator conditions. Figure 1 shows longitudinal section of the bayonet tubes, composed of four concentric tubes with an active length of 6 m (1:1 to ALFRED SG tubes). Feed-water enters the unit at the top edge of the slave tube; it flows downward, slightly increasing the temperature, and it is collected into the lower plenum. Then water flows upward through the volume between inner and second tubes, reaching superheated conditions. Finally steam is collected into the steam chamber, at the top of the unit. The main feature of HERO steam generator bayonet tubes (SGBTs) is the leakage monitoring system. It is obtained by filling the volume between second and third tubes (which offer a double physical separation between primary and secondary fluids) with pressurized helium and high thermal conductivity powder in order to detect any leakages, monitoring helium pressure, and while maintaining excellent heat exchange capability thanks to the metallic powder. Moreover the gap between slave and inner tubes is filled by an insulator layer in order to prevent the steam condensation on the outer surface of the inner tube [1].

HERO SGBTs are arranged into the hexagonal wrapper with a pitch-to-diameter ratio of 1.42 and the relative position between tubes and wrapper are fixed by five hexagonal spacer grids. The heat exchanger is contained into a double-wall cylindrical shell with air gap, in order to reduce heat losses towards the cold pool [1].

The test section is completed with a Venturi-nozzle flow meter, installed upstream the fuel pin simulator (FPS), which represents the core of the facility. The heat source (HS) consists of a bundle of 37 electrical pins, arranged in a wrapped hexagonal lattice with p/d of 1.8, characterized by the nominal thermal power of 800 kW and an active length of 1000 mm. The argon injection system is installed downstream the FPS, at the inlet section of the riser. At the top of the test section, the separator allows separation of hot LBE, flowing downward into the HX, and the argon, which flows upward to the gas plenum of the facility [2].

The test section is not equipped with a decay heat removal system (DHR) but this function will be performed by HERO heat exchanger, reducing the mass flow rate of the feed-water.

The main flow path of the test facility is depicted in Figure 2.

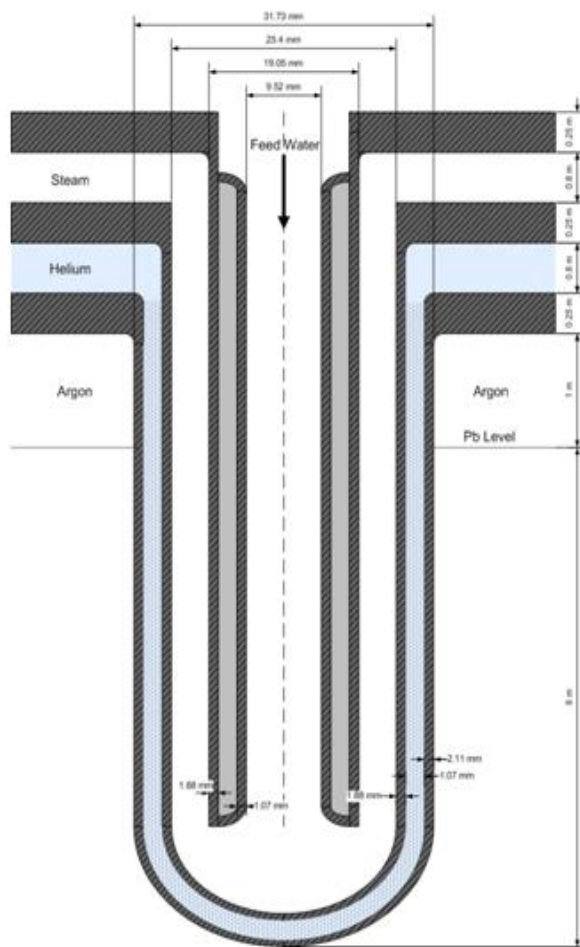


Figure 1. HERO steam generator bayonet tube

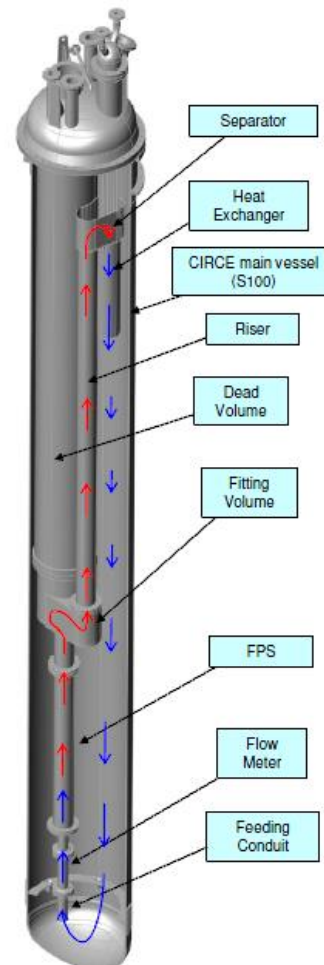


Figure 2. HERO test section: primary system main flow path caption.

3. RELAP5-3D[®] modelling

RELAP5-3D[®] is the last version of R5 series, which was developed to simulate accidental thermal-hydraulic transient in light water cooled reactors. The two main improvement of R5-3D from previous versions are the capability to simulate multi-dimensional component and the addition of new working fluids, including HLM [4].

The validated R5-3D nodalization scheme of CIRCE-ICE test facility [2] have been upgraded in order to carry out pre-test analysis of HERO experimental campaign. Three are the main differences between two test sections: HERO SGBTs substitutes for previous HX, the holes on the cylindrical shell of HS are closed, in order to limit the heat losses between FPS and cold pool, and the DHR system is removed.

R5-3D nodalization scheme consists of two macro regions, coupled to simulate the global facility: a mono-dimensional model is conceived to simulate thermal-hydraulic behaviour of the primary main flow path (see Figure 3) and three-dimensional component, shown in Figure 4 where the internals are depicted only to display the positioning, investigates thermal stratification and mixing convection phenomena into CIRCE main pool.

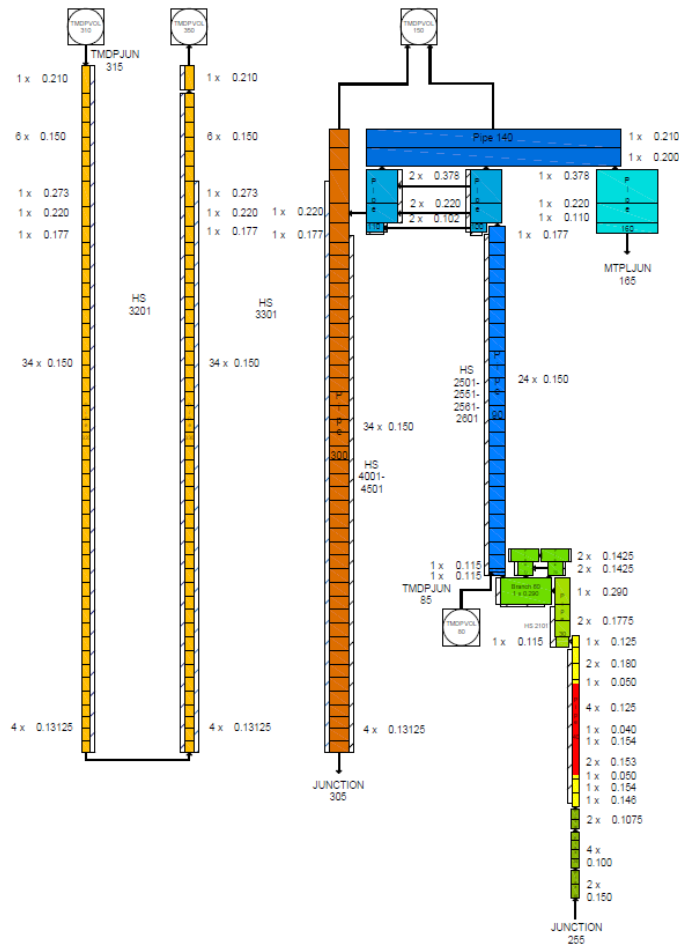


Figure 3. Region #1: mono-dimensional scheme

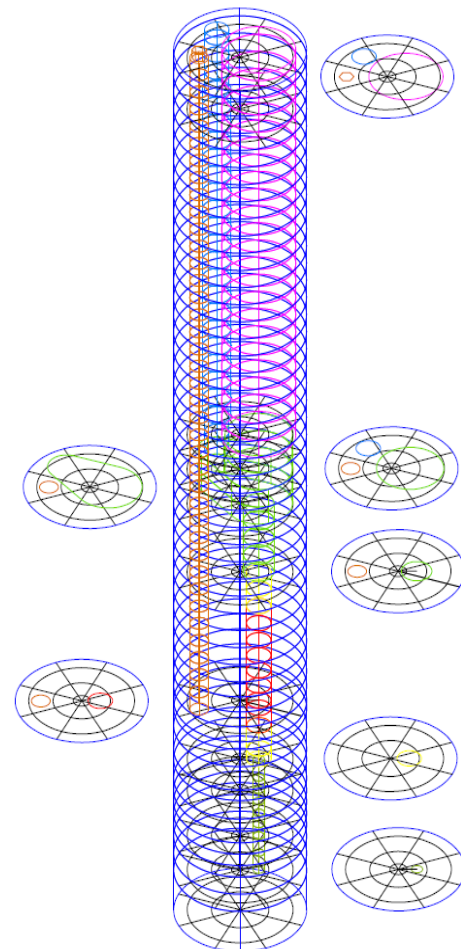


Figure 4. Region #2: multi-dimensional scheme

The 1-D nodalization scheme are hydraulically coupled with multi-dimensional component by three junctions (J). J-255 achieves connection between the feeding conduit and CIRCE lower plenum. The HS is simulated by a single equivalent pipe and one heat structure, which models the thermal power supplied by 37 electrical pins. The artificial fouling factor of 0.86, calibrated during post-test analysis on CIRCE-ICE campaign [2], is applied in order to correct the p/d value (the maximum allowed by R5-3D is 1.6) and to improve the heat transfer coefficient (HTC) according to Ushakov correlation [5], which better evaluates Nusselt number than the R5-3D default HTC correlation (Todreas & Kazimi correlation [6]), as showed in [7] for HLM system characterized by pitch-to-diameter ratio greater than 1.3.

At the inlet section of the riser, the argon injection system is simulated by boundary conditions, defining pressure, temperature and mass flow rate of the gas.

HERO LBE side is simulated by a single pipe composed of 43 volumes and coupled with the separator, at the top, and the downcomer of the 3-D component at the bottom. Seven bayonet tubes are concentrated into a single equivalent tube which includes feed-water inlet (boundary conditions define temperature, pressure and mass flow rate), descending tube, water/steam annular riser, steam chamber and steam outlet. Eight heat structures achieve thermal behavior of the unit; in particular, heat exchange between the water/steam and the LBE sides is increased by the calibrated fouling factor equal to 1.01, according to Ushakov correlation.

The pressure drop along the main flow path was evaluated during ICE post-tests and the same calibrated coefficients, depended on the flow conditions, are used on HERO model [2].

Multi-dimensional component consists of 51 axial levels, 4 radial meshes and 8 azimuthal intervals. The whole facility is modelled by 1877 control volumes, 4797 junctions and 15235 heat transfer nodes.

4. Pre-Test Calculations

4.1. Identification of full power steady state conditions

The experiment consists of the transition from forced to natural circulation in a protected loss of flow accidental scenario. In order to identify the initial conditions of the transient test, several calculations are performed.

Case 1 is set to achieve a constant temperature drop across the FPS equal to 80 K in the range of about 673-753 K, representative of the temperature drop across ALFRED core. The thermal power supplied by FPS is set to the nominal value of 450 kW, temperature pool is initialized to the average value of 690 K and argon and feedwater mass flow rate are respectively to 1.28 NI/s and 0.3308 kg/s.

Cases from 2 to 7 consist of the same boundary conditions of case 1, except pool initial temperature, which is respectively set to: 670, 675, 665, 662, 660 and 655 K.

Case 8 aims to achieve LBE mass flow rate across the HX equal to 44.7 kg/s, representative of the scaled down SG of ALFRED. Boundary conditions are the same of case 3, except argon injection, set to the value of 2.354 NI/s. Cases from 9 to 12 also use same conditions of case 3, except gas flow rate, respectively 2.242, 2.13, 1.85 and 1.79 NI/s.

All simulations show that the trend of the main variables result stable up to 2500 s. The main results are summarized in Table 1. Cases from 1 to 7 show the temperature drop across the HS equal to 80 K but only cases from 4 to 7 comply with the range of temperature previous established.

Table 1. Preliminary calculations: main results

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
FPS inlet T [K]	673.4	668.4	669.3	667.2	662.1	665.5	663.7	672.4	672.2	672.0	671.4	671.1
FPS outlet T [K]	754.2	749.7	750.9	748.4	747.4	746.8	745.1	740.8	741.3	741.9	743.7	744.2
LBE - HERO inlet T [K]	745.1	738.9	740.6	737.0	736.2	735.6	732.8	732.2	733.1	733.5	734.6	734.8
LBE - HERO outlet T [K]	671.8	668.3	669.4	667.6	666.8	666.4	665.1	672.4	672.1	672.1	671.4	671.0
LBE mass flow HERO inlet [kg/s]	37.6	37.5	37.5	37.5	37.4	37.4	37.3	44.5	43.9	43.4	42.1	41.7
Power removed by HERO [kW]	421.0	405.0	409.7	400.2	398.1	395.0	389.0	410.0	409.1	409.1	407.9	410.0
Steam max temp T [K]	663.4	657.8	659.0	682.8	654.6	656.6	652.0	659.1	659.0	659.0	659.0	658.7

The full power steady state, identified as initial conditions of the transient testes, is case 4, characterized by a temperature drop across the FPS of about 80 K and the average temperature into the pool in the range 665 to 680 K. Figure 5 shows LBE mass flow rate at the inlet section of the heat exchanger. The Ar injection starts at 50 s and it reaches the nominal value after 5 s. LBE mass flow

rate immediately assumes the value of 35 kg/s, due to the enhanced circulation only. At 220 s from the beginning of the simulations, HS starts to supply thermal power up to the nominal value at 390 s. LBE temperature at the outlet section of the FPS reaches the maximum value of 750 K and temperature at inlet and outlet section of the HX starts to increase with a delay time (see Figure 6); meanwhile LBE mass flow rate reaches the maximum value of 38.5 kg/s. After 488 s from the beginning of the test, feedwater system is activated, instantly reaching the nominal mass flow rate value. Temperature at the outlet section of the HX decreases to the minimum value of about 658 K and then increases to the steady state value. After a delay time, LBE temperature at the inlet section of the FPS reaches the value of 748 K and the primary mass flow rate decrease to the nominal value of 37.5 kg/s.

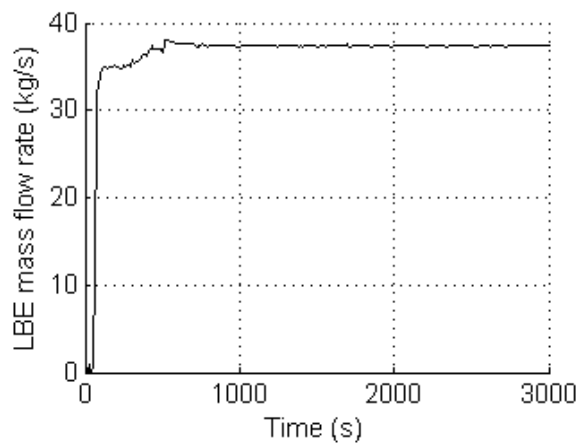


Figure 5. Case 4: LBE mass flow rate

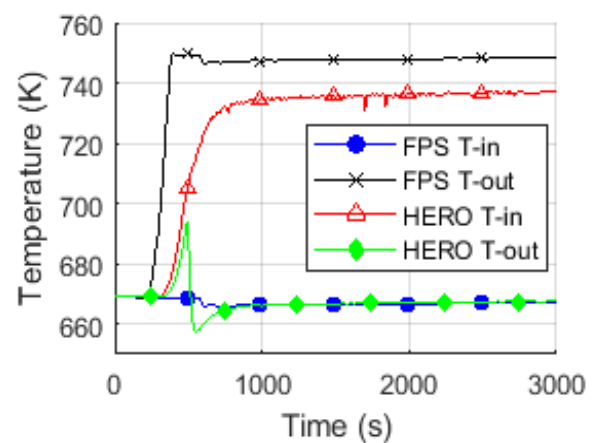


Figure 6. Case 4: LBE temperature at FPS and HX inlet/outlet

Previous analysis was carried out using thermophysical properties correlations implemented in R5-3D. The same simulations are repeated using the most recent correlations derived from [9], which have been implemented in Relap5-3D [10]. Figure 7 and Figure 8 show the comparison between R5-3D and NEA properties correlations on case 4. Figure 7 compares LBE mass flow rate at the inlet section of the HX. At the beginning of the test (from 50 to 220 s) the calculation with NEA properties underestimates mass flow rate following the overestimation of the concentrated and wall friction pressure drop. After the activation of HS and feedwater pump, temperature drop across FPS and HX increases of about 5% with NEA correlations (Figure 8) and it causes an increase in the driving force which compensates the overestimation of the total pressure drop.

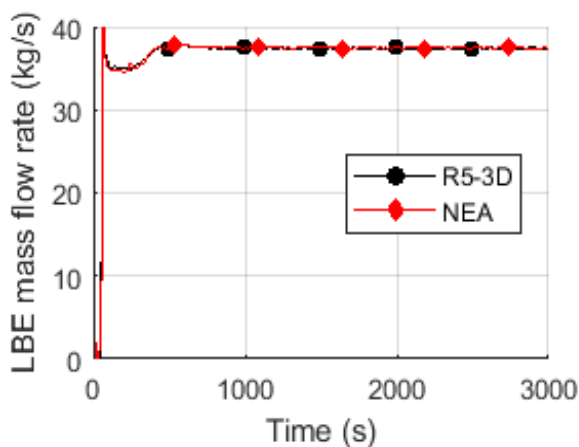


Figure 7. LBE mass flow rate: R5-3D and NEA properties comparison

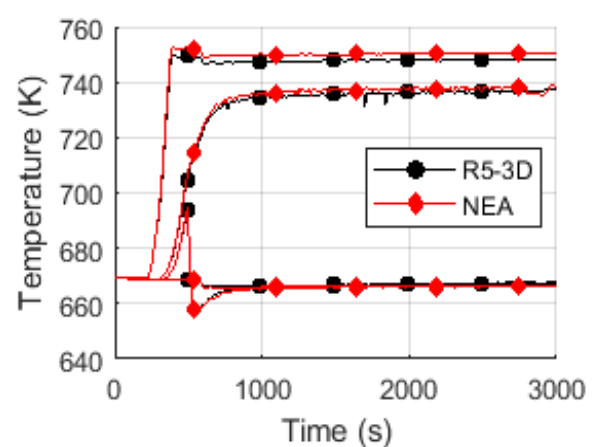


Figure 8. LBE temperature: R5-3D and NEA properties comparison

4.2. Transient analysis

The starting point for the transient analysis is considered case 4. Seven transient tests are considered in order to individuate the reference accidental conditions.

Test 1 consists of a protected loss of LBE pump, decreasing to 0 the argon injection with a curve simulating the presence of a pump flywheel. The FPS power simulates a decay heat curve, scaled down by a typical curve for fast reactor and compensated with heat losses through main vessel, and feedwater mass flow rate decreases to 10% of the nominal value to simulate the activation of the DHR system.

From test 2 to 6, boundary conditions are the same of test 1, except feedwater mass flow rate, set to 15%, 20%, 5%, 2% and 1% of the nominal value.

The last test 7 consists of a loss of LBE pump plus loss of DHR function in hot conditions: boundary conditions are the same of test 1, except feedwater mass flow rate which decreases to 0.

Figure 9 and Figure 10 depicts the evolution of LBE mass flow rate and LBE temperature for 1500 s from the transient test 1 start up. Immediately after the beginning of the accident, LBE temperature at the inlet section of the heat exchanger start to increase, reaching the maximum value of 740 K after 24 seconds. At the same time, thermal power has nearly reached the value of the compensated decay power and LBE mass flow rate is close to 50% of the nominal value. It results in the minimum value of temperature drop across the FPS and, with a delay time, across the HX; LBE reaches the temperature of 685 K at the FPS outlet and 705 K at the end of HERO. Figure 11 depicts the trend of the temperature into the pool, considering the main representative longitudinal section, which includes the inlet of the feeding conduit and the outlet of the steam generator, and also highlights the hot-spot downstream the HX at 85 seconds. Then, LBE mass flow rate reaches the minimum value and temperature at the outlet section of FPS and HX assumes the peak value at about 350 seconds; after mass flow tends to the nominal natural circulation value and the average temperature of the system starts to decrease. At the end of the transient test, the thermal stratification level, which occurs at 2.5 m above the bottom of the main vessel at the beginning of the transient test, is shifted downward of about half meter (see Figure 11).

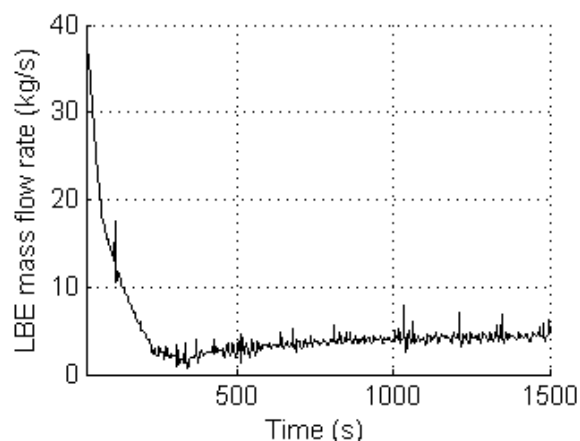


Figure 9. Transient test 1: LBE mass flow rate at HX inlet section

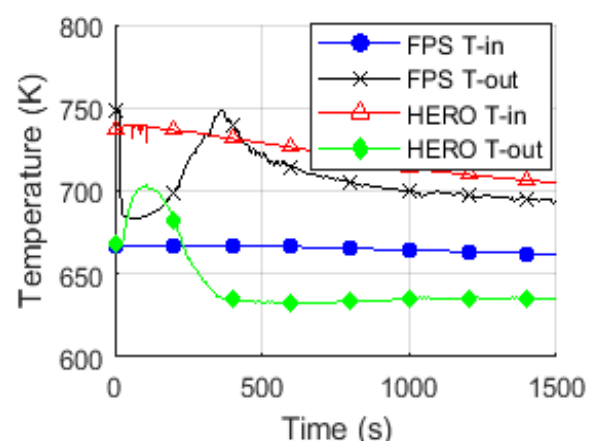


Figure 10. Transient test 1: LBE temperature at FPS and HX inlet/outlet

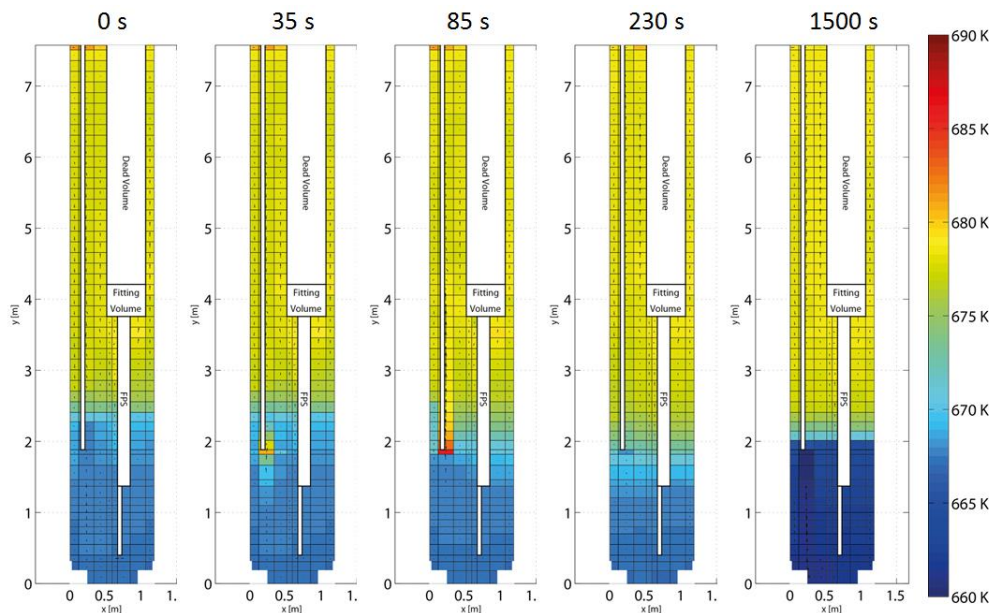


Figure 11. Transient test 1: pool temperature

Following figures highlight the comparison of test 3 and 7 with the reference transient test 1. Figure 12 shows the LBE mass flow rate at the inlet section of HERO. The driving force is deeply influenced by thermal power removed by the HX and LBE mass flow rate, during test 3, is constantly greater than test 1 and 7. In particular, during test 7, the driving force depends only on heat losses, since feedwater mass flow rate is stopped. Between 250 and 350 s the LBE reverse flow occurs caused by the hot fluid exiting the bottom edge of HX, which, meeting cold LBE into the pool (see Figure 14), starts to flow upward provoking the reverse flow into the heat exchanger.

Figure 13 depicts temperature at inlet and outlet of the FPS and the HX. Test 3 follows the same qualitative trend of test 1, while assuming lower temperature than the reference test. Significant differences occur during test 7; in the first 200 s of transient simulation, test 7 follows the same trend of the reference one, maintaining higher temperatures. After the establishment of the reverse flow, temperature at the inlet section of the HS reaches the pick value of about 740 K and the same effect occur at the outlet section of HERO, where LBE assumes the minimum value of 680 K. After that, the LBE mass flow rate reaches the nominal value of about 2 kg/s and temperature at the outlet section of the core assumes and maintains the maximum value of about 830 K.

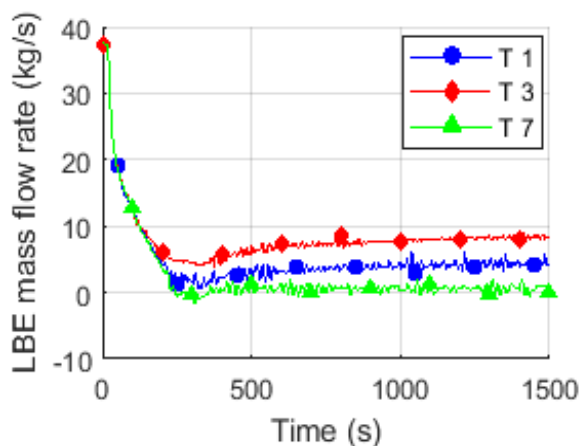


Figure 12. Transient test comparison: LBE mass flow rate

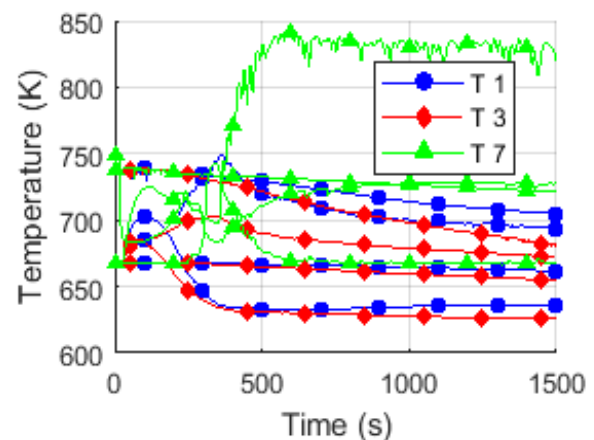


Figure 13. Transient test comparison: T at FPS and HX inlet/outlet

Figure 14 depicts the temperature evolution into the main vessel, showing, at the end of the simulation, the thermal stratification level is shifted downward of about one meter, above the outlet of the heat exchanger.

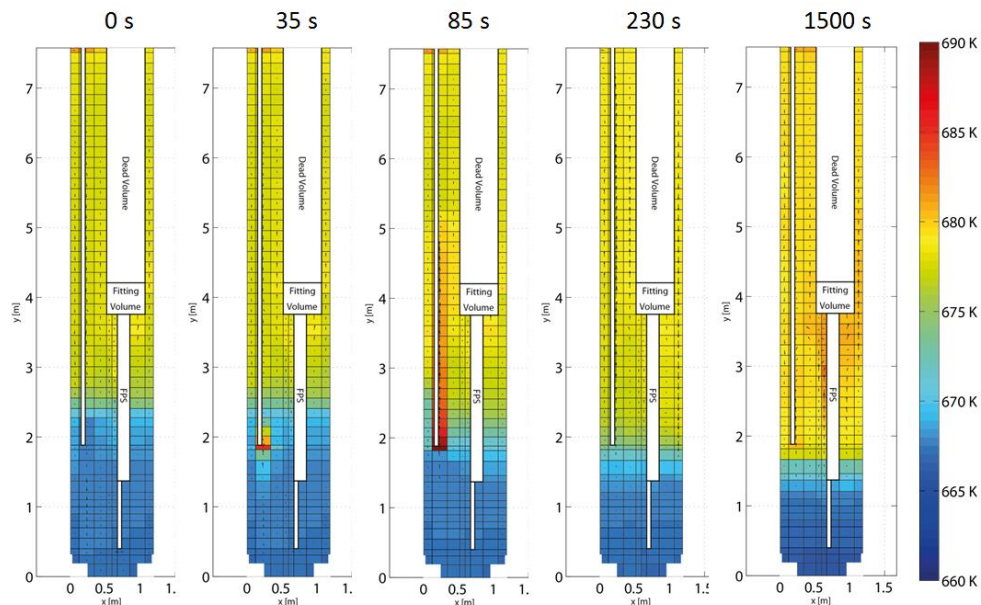


Figure 14. Transient test 7: pool temperature

The reference test is also performed using NEA recommended properties and comparison with R5-3D default properties is depicted in following figures which highlight same considerations of the steady state comparison.

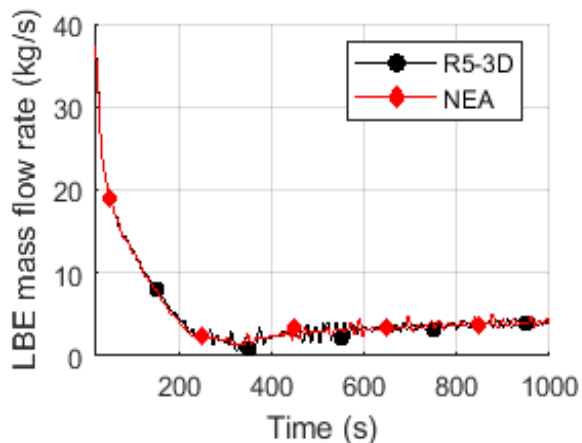


Figure 15. Transient test 1: LBE mass flow rate - R5-3D/NEA properties

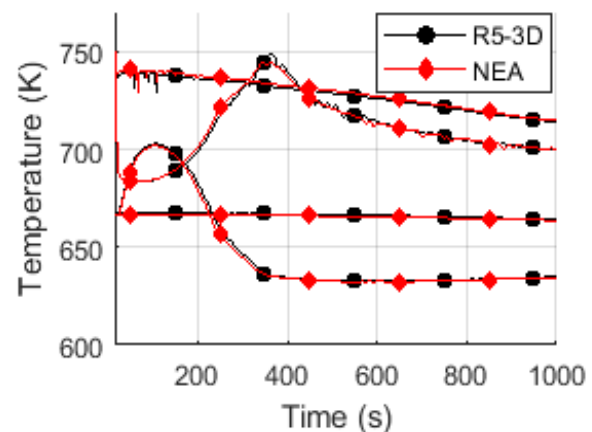


Figure 16. Transient test 1: temperatures - R5-3D/NEA properties

5. Conclusions

The main objective of this work is to present pre-test analyses on CIRCE-HERO test facility, to identify the test matrix for the experimental campaign. The simulations are performed with Relap5-3D[®] code, upgrading the validated model of CIRCE-ICE facility.

The analysis aims to investigate the transition from forced to natural circulation in a protected loss of flow accident scenario. At first a sensitivity analysis has been performed in order to identify steady state conditions which represents the initial conditions for the transient tests. After that, several

transient calculations have been carried out, reducing the feedwater mass flow rate from 20% to 0% of the nominal value. The simulation results highlight that HERO test section does not permit excellent natural circulation conditions. In particular, when feedwater mass flow rate decreases under 2% of the nominal value, code predicts the reverse flow of the primary coolant. In this frame, further investigations are necessary in order to confirm this phenomenon.

Transient test 1 is identified as the reference scenario; further researches will verify the physical feasibility of the compensated power shutdown curve, with control system of CIRCE facility, and the possibility to reproduce a pump flywheel curve with the argon injection system.

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