Nuclear Engineering and Design
Volume 305, 15 August 2016, Pages 168-178 - DOI: 10.1016/j.nucengdes.2016.05.005

Thermal-hydraulic analysis of an innovative decay heat removal system for lead-cooled fast reactors

Fabio GIANNETTI, Damiano VITALE DI MAIO,
Antonio NAVIGLIO, Gianfranco CARUSO

SAPIENZA, Università di Roma – Department of Astronautical, Electrical and Energy Engineering - Nuclear Section - Corso Vittorio Emanuele II, 244 - 00186 Rome, ITALY

Abstract

Improvement of safety requirements in GEN IV reactors needs more reliable safety systems, among which the decay heat removal system (DHR) is one of the most important. Complying with the diversification criteria and based on pure passive and very reliable components, an additional DHR for the ALFRED reactor (Advanced Lead Fast Reactor European Demonstrator) has been proposed and its thermal-hydraulic performances are analyzed. It consists in a coupling of two innovative subsystems: the radiative-based direct heat exchanger (DHX), and the pool heat exchanger (PHX). Preliminary thermal-hydraulic analyses, by using RELAP5 (R5) and RELAP5-3D® computer programs, have been carried out showing that the whole system can safely operate, in natural circulation, for along term. A preliminary sensitivity analysis has been carried out for: the emissivity of the DHX surfaces, the PHX water heat transfer coefficient (HTC) and the lead HTC. In addition, the effects of the density variation uncertainty on the results has been analyzed and compared. It has been allowed to assess the feasibility of the system and evaluate the acceptable range of studied parameters. A comparison of the results obtained with R5 and RELAP5-3D® has been carried out and the analysis of the differences of the two codes for lead are presented.

The features of the innovative DHR allow to match the decay heat removal performance with the trend of the reactor decay heat power after shutdown minimizing at the same time the risk of lead freezing. This system, proposed for the diversification of the DHR in the LFRs, should be applicable in the other pool-type liquid metal fast reactors,

Keywords:

Decay Heat Removal, Thermal-hydraulics, Lead Cooled Fast Reactor, GEN IV, ALFRED, RELAP5

Nuclear Engineering and Design
Volume 305, 15 August 2016, Pages 168-178 - DOI: 10.1016/j.nucengdes.2016.05.005

1 Introduction

Among the next generation of nuclear reactors, well-known as Generation IV, the lead cooled fast reactor (LFR) is one of the most promising advanced technologies able to comply the targets of sustainability, economics, safety and proliferation resistance. For these reasons, LFRs are actually deeply investigated and effort on R&D is being carried out. Complying with GEN IV requirements, an innovative pre-conceptual LFR design, ELSY (European Lead-cooled System), was proposed within the 6th European Framework Program (Alemberti et al., 2011). The ELSY project was an LFR reactor design aimed at electricity production, characterized by several innovations and by the closure of the fuel cycle. Subsequently, the LEADER (Lead-cooled European Advanced DEmonstration Reactor) project, aimed at reviewing and improving results of the ELSY design, was funded in the frame of EU-FP7. This project was aimed at contributing to the design of ALFRED (the Advanced Lead Fast Reactor European Demonstrator) (Alemberti, 2012a; Alemberti et al., 2013) toward the full-scale first-of-a-kind ETDR (European lead fast reactor Technology Demonstrator Reactor).

ALFRED is a 300 MWth lead cooled fast reactor, characterized by a pool configuration (Alemberti, 2012b). Eight steam generators (SG) transfer the thermal power from the primary system (lead) to the secondary system (water); the primary coolant flow rate is assured by eight primary pumps (one for each SG). ALFRED normally relies on the secondary system to remove the decay heat power from the primary coolant, by-passing to the condenser.

Increasing standards of safety in GEN IV reactors require more reliable safety systems, among which the decay heat removal system is one of the most important. Over the years, several DHR systems have been analyzed taking into account the reactor type. The major trend of the last years, in order to enhance design safety features, is to design as passive as possible emergency systems (e.g. Jae-Hyuk et al., 2007, Krepper and Beyer, 2010 and Hyun-Sik et al., 2008). The main goals to be reached in a well-designed passive DHR system for a liquid metal reactor are:

1. being able to maintain primary fluid temperature in an optimal range, preventing the fluid to freeze and the primary system structure to suffer physical damage from creep or excessive thermal expansion of the fluid;
2. managing to guarantee an as long as possible autonomy of operation, preferably without requiring any active external support or intervention;
3. not recurring to any active component such as pumps, blowers or external motors.

Several analyses have been carried out about the reliability (Burgazzi et al., 2012, Arul et al., 2006 and Sajith et al., 2008) and the performances (Hung et al., 2011, Parthasarathy et al., 2012) of such passive DHR systems.

In particular, in Risk and Safety Working Group (RSWG), 2011, the importance of the diversification of the safety systems is evidenced and, for this, an addition of a back-up solution is an improvement of the reliability of this fundamental safety function. The strict working temperature range for the primary coolant to avoid lead freezing and to guarantee the integrity of the components, makes difficult the development of passive systems.

For this, despite the thermal inertia given from the pool, the temporal response of the DHR system is fundamental for lead reactors. In case of a loss of flow incident, the system must be follow the trend of decay heat and reduce proportionally the thermal power removed.

The DHR system here proposed as an additional and diversified option for the ALFRED reactor.

The main peculiarity of this DHR are:

1. radiation-based heat transfer mechanism, exploiting the void annulus between the primary and the secondary systems, enhanced by fins;
2. passive heat sink, able to automatically switch the heat releasing from water to air.

These two elements, which characterize the main components of the proposed DHR, are detailed described in Vitale Di Maio et al., 2012 and De Santis et al., 2012, while a focus on the decay heat exchanger component can be found also in De Santis et al., 2013.

2 Detailed decay heat removal (DHR) system description

A functional scheme of the DHR is presented in Fig. 1. The hot secondary coolant, exiting from the decay heat exchanger (DHX), flows towards a pool heat exchanger (PHX) submerged in cold water. In the first phase, after the activation of the DHR system, just a liquid-phase heating of the pool occurs; when saturation temperature is reached, water boiling starts in the pool, causing an increase in the heat transfer coefficient but also a decrease in the pool level. Before the complete evaporation of the water, some openings, located in the pool heat exchanger fins, allow air to flow and to give a partial contribution to the cooling, determining a transition heat transfer condition (boiling water and air). In the last phase all the water is vaporized and the heat removal function is accomplished only by the air flow, in natural circulation.

Nuclear Engineering and Design
Volume 305, 15 August 2016, Pages 168-178 - DOI: 10.1016/j.nucengdes.2016.05.005

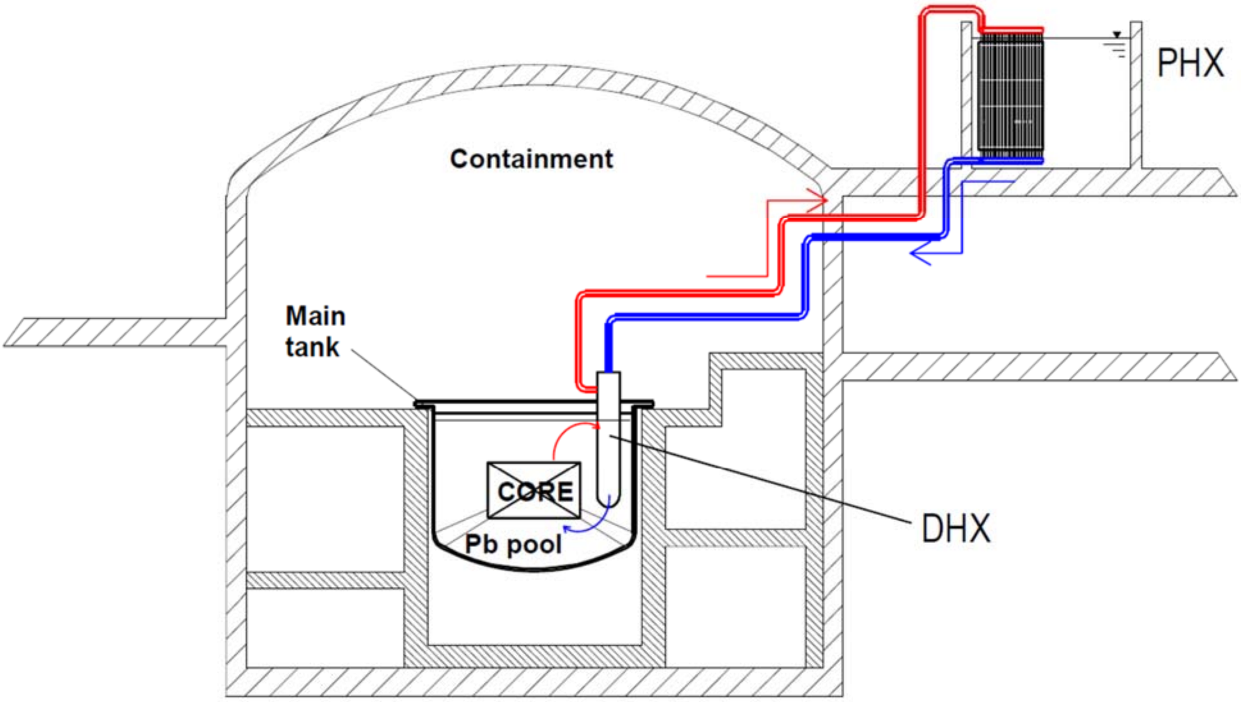

Fig. 1 - Schematic DHR layout

The proposed DHR system is a natural circulation loop, which is aimed at removing the decay heat from the core and transferring heat to the atmosphere. The DHR loop is based on 4” schedule 80 piping, with about 15 m in height from the hot source to the heat sink for guaranteeing the natural circulation.

Despite the heat removal from the core is the basic function of a DHR system, in lead-cooled reactors it is also needed to maintain a temperature level above the freezing temperature of the coolant, (about 600 K for lead).

The combination of the features of the two heat exchangers in the proposed system allows to maintain the lead temperature within a preselected range, delaying by few days the possibility of coolant freezing, without any actions.

In addition, the backup DHR should be actuated by a check valve which guarantees the activation only in case of the malfunction of the main DHR systems.

Direct heat exchanger - DHX

The main innovation of this component consists in replacing the more commonly used shell and tubes heat exchanger with a radiation-based bayonet tubes heat exchanger. Each bayonet tube is made of three coaxial tubes: the inner and the intermediate ones belong to the DHR secondary system with secondary fluid inside, while lead flows around the outer one. The secondary coolant enters the decay heat exchanger from the top of the inner tube, flowing downwards; then, inverting its direction, it flows upwards between the inner and the intermediate tubes, removing the power irradiated from the outer tube to the intermediate one. The void annulus is placed between the intermediate and the outer tube and fins are present to enhance heat exchange surface.

The DHX (De Santis et al., 2012) is made of several bayonet tubes (a schematic view is reported in Fig. 2) enclosed within a cylindrical structure which guarantees that the primary coolant (flowing downward) is in contact with the external surface of the submerged bayonet tubes. This structure also provides mechanical constraints for the bayonet tubes in case of earthquake (several grids are provided for this purpose).

A more accurate design of the DHX behavior under seismic condition, which is beyond the scope of the present work, could be required to optimize the mechanical constraints. The cylindrical structure of the top head is equipped with three tube plates, which allow (Fig. 2):

- the cold secondary fluid distribution within the inner tubes of each bayonet tube present in the DHX unit;
- the hot secondary fluid collection;
- the vacuum system pressure control, needed for the initial vacuum creation and successive monitoring.

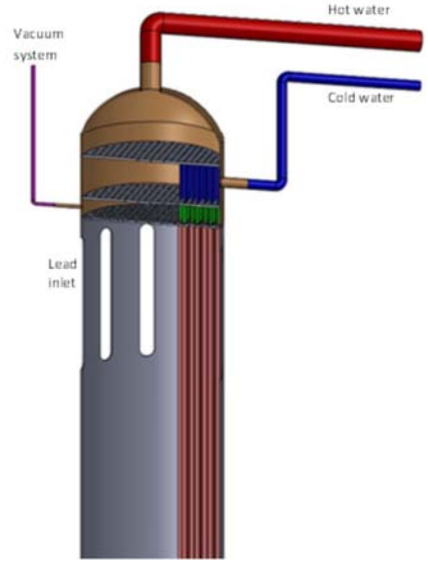

Fig. 2 - DHX layout (thinner tube: vacuum control line, medium tube: cold water inlet, larger tube: steam outlet)

2.1.1 Radiative-based bayonet tube

Each bayonet assembly is composed by three coaxial tubes (outer, intermediate and inner tubes), as shown in Fig. 3-a. The intermediate (yellow) and outer (red) tubes, are separated by a gap in which a rough vacuum condition (about 100-200 Pa) is maintained. This gap is the key-feature of the entire system, which relies only on the radiating heat transfer (suitable fins are provided to improve it). The absence of any heat conducting medium greatly reduces the heat transfer "efficiency" (which impacts on heat exchanger size), but allows for a substantial difference between the primary fluid (at 670-770 K) and the coolant (at 550K). Looking at each bayonet assembly, the outer tube is heated by lead and radiates towards the intermediate tube, as shown in Fig. 3-b. The cold secondary coolant enters the inner tube from the top, and flows downward. Once the fluid reaches the bottom edge of the bayonet tube, it inverts its direction and flows upward in the annular volume between the inner and the intermediate tubes. When flowing upward, the secondary fluid removes heat from the intermediate tube (externally heated by radiation) and increases its temperature accordingly.
Both primary and secondary fluids, in compliance with the requirement for pure passive DHX system, do work in natural circulation.

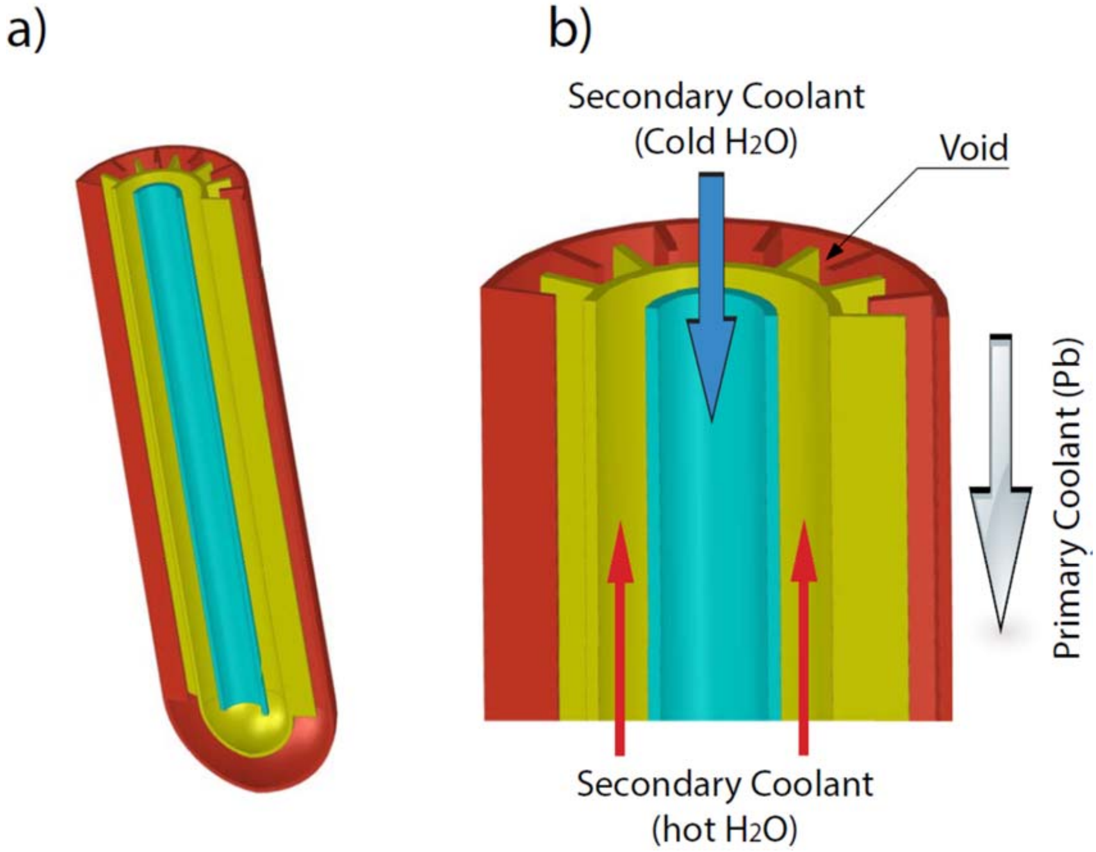

Fig. 3 - (a) DHX layout; (b) scheme of the DHX operating fluids (De Santis et al., 2013)

Two solutions were studied as secondary fluid:

1. diathermic oil, which features a liquid-phase operating range between 353 K and 658 K, with a boiling point (at atmospheric pressure) of 616 K. It is also characterized by a limited vapor pressure at higher temperature (e.g. about 0.215 MPa at 658 K) which means that, in any case, a limited pressurization of the system is needed;
2. Pressurized water (@10MPa, boiling temperature 584 K): this solution has been finally selected and analyzed in the present paper.

This proposed DHX solution implements some interesting safety features:

- no mix is possible under any "single failure" condition (two leakages, at the same time, are required to have a mix of primary and secondary fluid);
- a large leakage, on both sides, can be detected by continuously monitoring the vacuum gap pressure through the vacuum system pressure control.

Several bayonet assembly dimensions have been analyzed (i.e. outer diameter (OD) equal to 1½", 1 ¾", and 2"). The parametric studies described below have been carried out on the DHX smallest solution (OD = 1½"). Bayonet tubes, within the DHX, are arranged in a staggered array and their main characteristics are reported in Tab. 1.

Tab. 1- DHX geometrical dimensions

Number of tubes	**1400**
Tube height	6 m
Inner tube	½" BWG 18
Intermediate tube	¾" BWG 18
Outer tube	1 ½" BWG 18
Fin height	6 mm
Fin thickness	1 mm
Number of fins per tube	12
p/d ratio	1.25

If compared with the ALFRED reference design (Alemberti, 2012b), the proposed solution would increase the vessel diameter of about 0.5 m. Nevertheless, this solution would allow to obtain a completely independent DHR system from both physical and functional points of view.

The increase of the diameter could be reduced by a re-arrangement of the SG tubes.

Pool Heat Exchanger - PHX

The heat sink of the presented solution uses a pool heat exchanger (PHX) (Vitale Di Maio et al., 2012) which works towards the external atmosphere. This very reliable heat sink is characterized by special safety features:

- very good heat transfer capability;
- unlimited operating time without any external intervention (only the reaching of the lead freezing temperature has to be prevented);
- easy refilling.

The PHX is made of the following main components: a pool, a separating septum and a heat exchanger. A schematic view of the PHX system is reported in Fig. 4. In order to allow a variable heat removal capacity (decreasing with time) and to achieve a never-ending heat sink capability, the pool volume is virtually divided into two zones. The first includes the heat exchanger, while the other is a very simple water reservoir (with no hydraulic or mechanical component inside). The innovative component, expressly developed for this system, is the heat exchanger, which is characterized by special features. The heat exchanger is made of vertical tubes equipped with four special fins and arranged in a squared matrix. Each fin is provided, in its bottom part, with vertical slits (Fig. 5-a). The fins of adjacent tubes are almost linked together constituting about as many squared sub-channels as the number of tubes (Fig. 5-b).

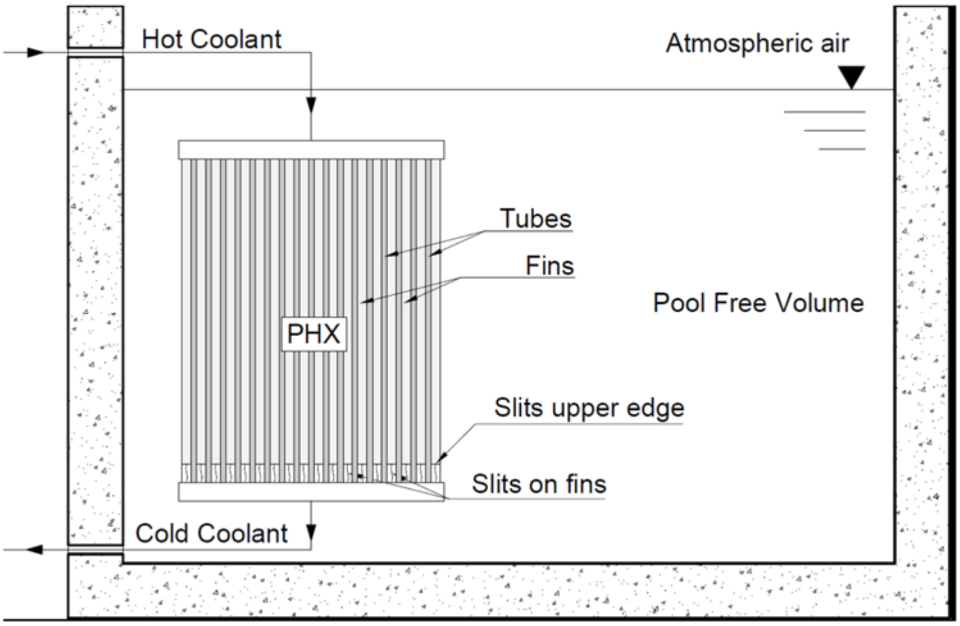

Fig. 4 - PHX main components schematic view

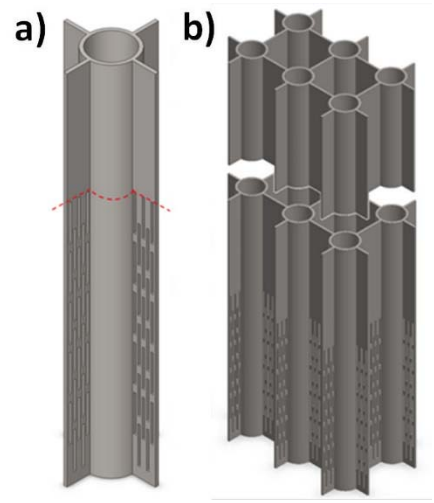

Fig. 5 - (a) Bottom part of a PHX single tube (dotted line: slits upper edge); (b) some PHX tubes assembled (cut in central zone is for representation purpose)

During the initial phase (when water is available in the pool), the design of the slotted fins allows water to flow through adjacent sub-channels. When the water runs out, air can flow and perform a similar job.

At the beginning, the PHX system releases heat to the water pool which slowly boils at atmospheric pressure. When water runs out, atmospheric air takes its place. Switching from the first condition to the second one occurs seamlessly, without any external intervention. An accurate description of the PHX operating conditions is reported below with reference to Fig. 6.

The main PHX operating phases are:

a. Normal operating condition: within the DHR loop, a limited flow circulates because of the check valve shutter design. A replenishing system, which feeds the water pool, is foreseen to compensate the water evaporation during this phase.
b. Pool boiling condition: reached the saturation temperature, the pool boiling condition guarantees high heat transfer coefficient and hence high heat removal efficiency.
c. Transition heat transfer condition: due to the water boiling, level and heat transfer surface are reduced with time. The special design allows an atmospheric air flow that contributes to the heat removal before the water complete vaporization. This is guaranteed by the terminal part of the tubes (about 0.2 m), where a series of openings in the fins (Fig. 6) permits the passage of the air into the channels delimited by fins.
d. Air only heat sink: once the water discovers completely the holes, the heat removal is guaranteed by air only (the waters remained under the holes not contributes to heat removal function). This last operating condition guarantees a never-ending heat removal capability.

The heat transfer performance reduction, due to the shift from a water to an air heat sink, is compensated by the reduction, at the same time, of the decay heat produced into the core.

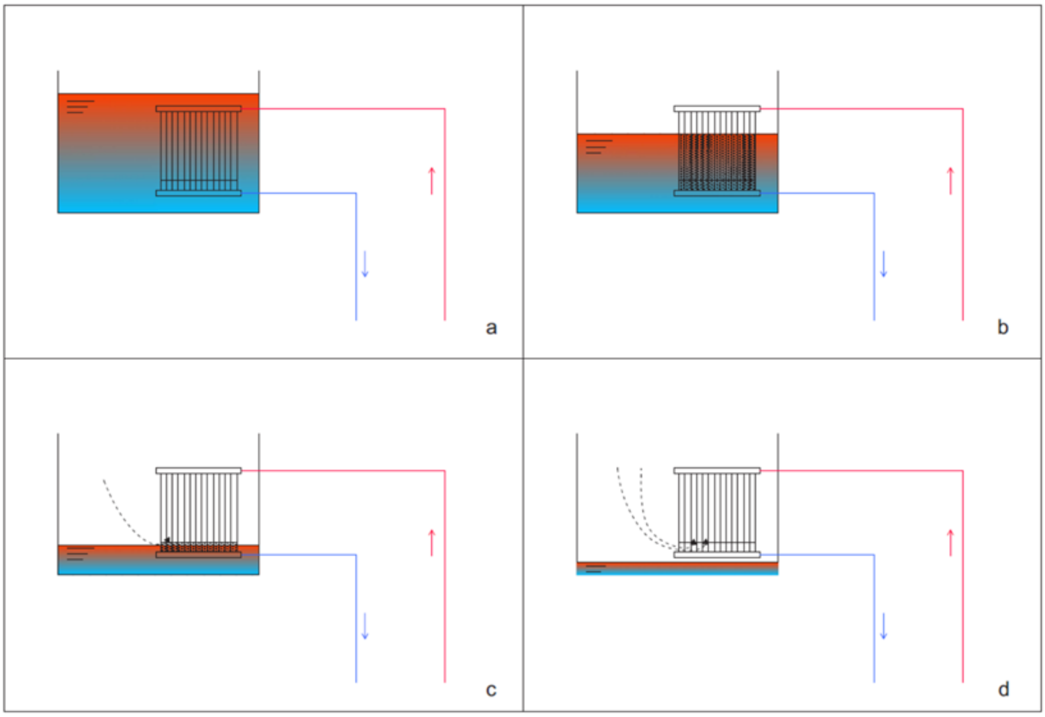

Fig. 6 - PHX operating phases: a) reactor normal operating condition; b) pool boiling condition; c) transition heat transfer condition; d) air only heat sink

The heat transfer coefficient is higher when the PHX operates with water (but for a limited period of time, if no refill is provided), while air allows to remove a lower amount of heat for an unlimited period of time (last phase of the transient). It should be noticed that the heat transfer rate follows the trend of the decay heat generated in the reactor after the shutdown.

The PHX main characteristics are reported in Tab. 2.

Tab. 2- PHX main characteristics

Number of tubes	**3 000**
Water volume	18 m^3
Tube height	5 m
Tube diameter	7/8” BWG 16
Fin height	5.5 mm
Fin thickness	2 mm
Number of fins per tube	4
p/d ratio	1.5

The system is characterized by high availability and reliability since only static components are involved in the DHR system operation.

In order to control temperature and fluid conditions within the secondary DHR circuit, a small flow within the DHR should be guaranteed during reactor normal operating condition. The heat loss through the DHR can be reused for some system application and a too low temperature in the secondary coolant must be anyhow avoided to prevent any lead freezing risk.

Heat transfer coefficients into the pool (Tab. 3) are strongly influenced by its water inventory, and they change during the transient. In the most complex situation, during transition from water to air heat sink, there are:

- convection with liquid water;
- boiling water;
- natural convection with air.

- **Tab. 3 - HTC into the pool (R5 calculation)**

Coolant	Time [s]	HT mechanism	mean HTC [W/(m^2 K)]
Subcooled / Saturated Water	0 - 51000	Convection / Boiling	1500 – 6500
Air	51000 - end	Convection	8.5 – 9.0

3 Preliminary calculation

To evaluate performances of the proposed system, a preliminary analysis, using RELAP5 mod. 3.3 (Ansaldo Nucleare/ENEA modified version), has been carried out. The best-estimate RELAP5 mod. 3.3 code was updated with the aim of reproducing TH systems cooled by heavy liquid metals (Meloni and Nitti, 2010). Examples of preliminary safety analyses performed on liquid metal cooled systems, with the Ansaldo/ENEA modified version, are available in literature (Bandini et al., 2011a, 2011b).

The aim of the present work was to carry out a preliminary TH analysis of the proposed system in order to verify the system capability in the decay heat removal under accidental conditions. In the present analysis, water has been selected as secondary fluid.

Nodalization description

The TH nodalization developed for the present analysis is presented in Fig. 7. The model is composed by 294 control volumes, with 296 junctions and 1511 heat transfer nodes.

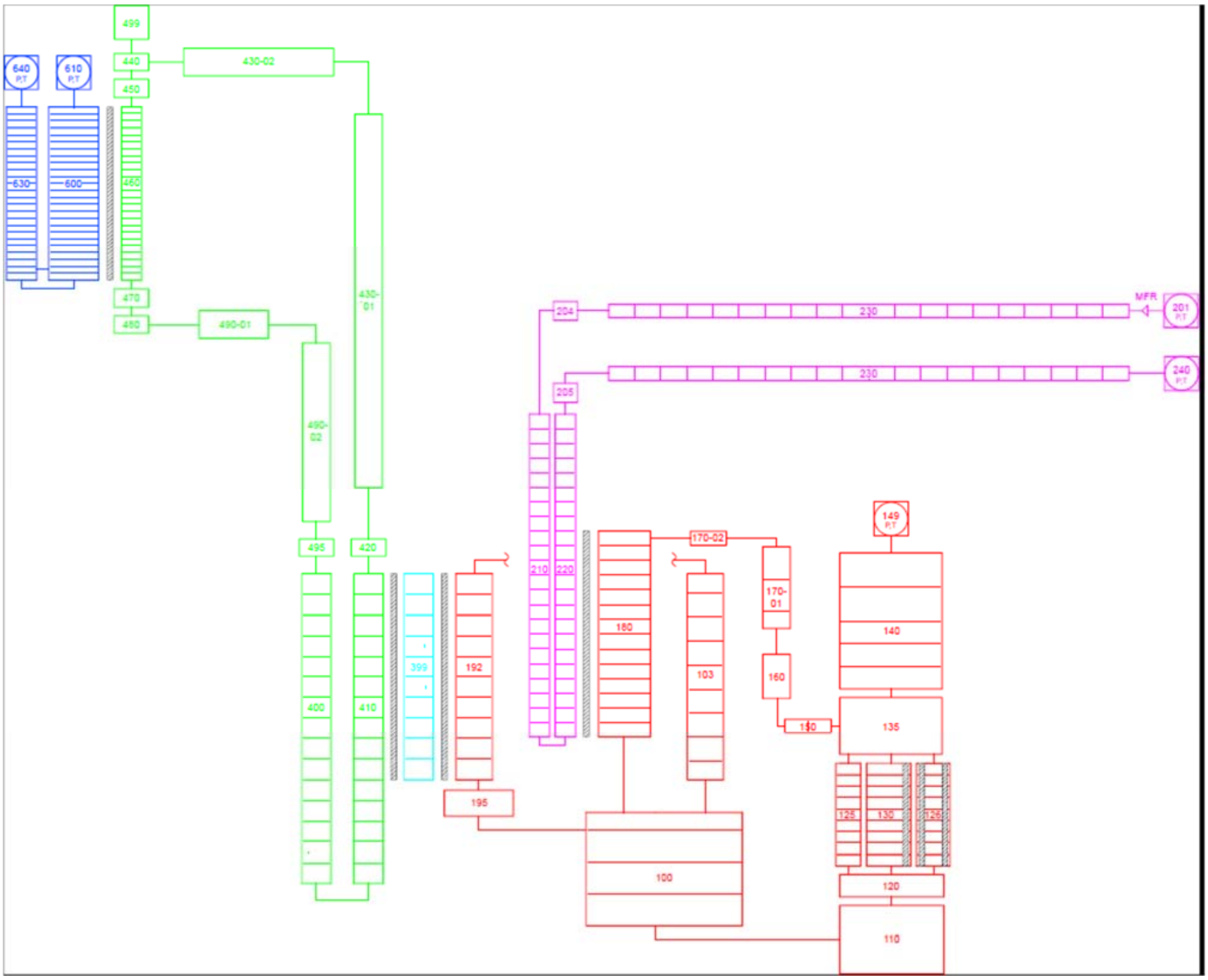

Fig. 7 – RELAP5 TH nodalization

The core is modelled by two different pipes: one for the hottest fuel assemblies and one for others. In addition, three heat structures were considered: the hottest pin, the hottest fuel assembly and all the others.The eight SG loops are collapsed (both primary and secondary circuits) in a single equivalent loop. Regarding the DHR, in order to comply with the single failure criterion, a single model train was adopted, but it must be pointed out that, even if no failure affects the second DHR circuit, it must be isolated in any case, because the simultaneous operation of the two loops would cause lead freezing.

The DHX component is nodalized by three pipes and two heat structures, with the thermal radiation model active. The PHX pool is modelled with two pipes, one for the channels into the fins and another for the water reservoir part; the boundary conditions for this circuit are two time dependent volumes and the mass flow rate is not imposed, but calculated by natural circulation.

The behavior of the proposed DHR system has been investigated by simulating a Loss of Onsite and Offsite Power (LOOP) event. First, a steady state TH analysis, simulating the reactor normal operation, has been performed to provide the initial thermal condition in the whole system. Subsequently, a transient analysis has been carried out to determine the temperature evolution of lead, coolant, and fuel pins (and of other variables) during and after the LOOP event. The analysis duration was properly chosen in order to catch both short and long term aspects, including the transition from water to air cooling condition. The time step used is variable from 5×10^{-4} s in the first phase, to 0.05 s in the last phase.

LOOP transient results

The LOOP causes the SCRAM and the pumps stop. During the short term, the temperatures remain in the admissible range; the maximum clad temperature reaches 820 K.

Referring to the long term phase, the most noteworthy event during DHR operation is the transition from boiling water to air only cooling due to water run out, which happens at about 51000 s. In particular, the most relevant steps of this transition phase are the followings:

1. Pool boiling effective heat transfer surface is progressively reduced because of the water level decreasing. As a consequence of this, a progressive reduction in the heat transfer rate inside the PHX can be noticed.
2. Because of boiling, the water level decreases starting to uncover fins slits. At this point air starts to flow into the PHX taking part in the residual heat removal.
3. Once the PHX heat transfer surface is no longer wetted by boiling water, the overall heat transfer rate quickly decreases halving the exchanged power. This causes an increasing in the average coolants temperatures. Time-histories, presented in Fig. 8, show a relevant increase of the water temperature in the tubes (from 423 K to about 575 K), which does not affect the system functionality (water within tubes is still liquid T_{sub}=10 K). If a local boiling condition were reached, the pressure of the system is maintained around the nominal value by a large pressurizer (pressurized by nitrogen) and, eventually, by a pressurizer safety relief valve (which does not operate in the analyzed transient).
4. Increasing in the secondary coolant average temperatures cause a progressive, even if limited, increase of primary coolant temperature reaching a long term new steady state

condition. The core mass flow rate is marginally affected by the transition and the long term value stabilizes at some 400 kg/s.

Moreover, other aspects have to be taken into account during the analyzed transient. In particular, primary coolant cold temperature has to be constantly above the lead melting point. Before the transition to air only heat removal condition, a minimum temperature value of 608 K, less than 10 K above the lead melting point, has been reached in the primary loop. Therefore, the reduction in the DHR system heat transfer performance allows to greatly delay the possibility of lead melting, shifting the condition before the transition, characterized by the risk of lead freezing, of about three days (Fig. 8).

As shows in the same figure, worth mentioning the pool temperatures trend, as consequence of the transition. In the first phase, the pool boiling regime fixes the pool at saturation temperature. The pool "inlet" temperature is, in this phase, slightly decreasing given that the pressure of the bottom decreases to decrease the level. The outlet pool temperature, starting from the saturation temperature when the pool is filled, rises proportionally to the thermal exchange area of out of the water, and therefore likely to superheat the steam.

After the ingress of the air into the PHX fins, the inlet temperature is settles down to the air temperature (283 K). The small air HTC is the cause of the low outlet temperature of the air, after the transition.

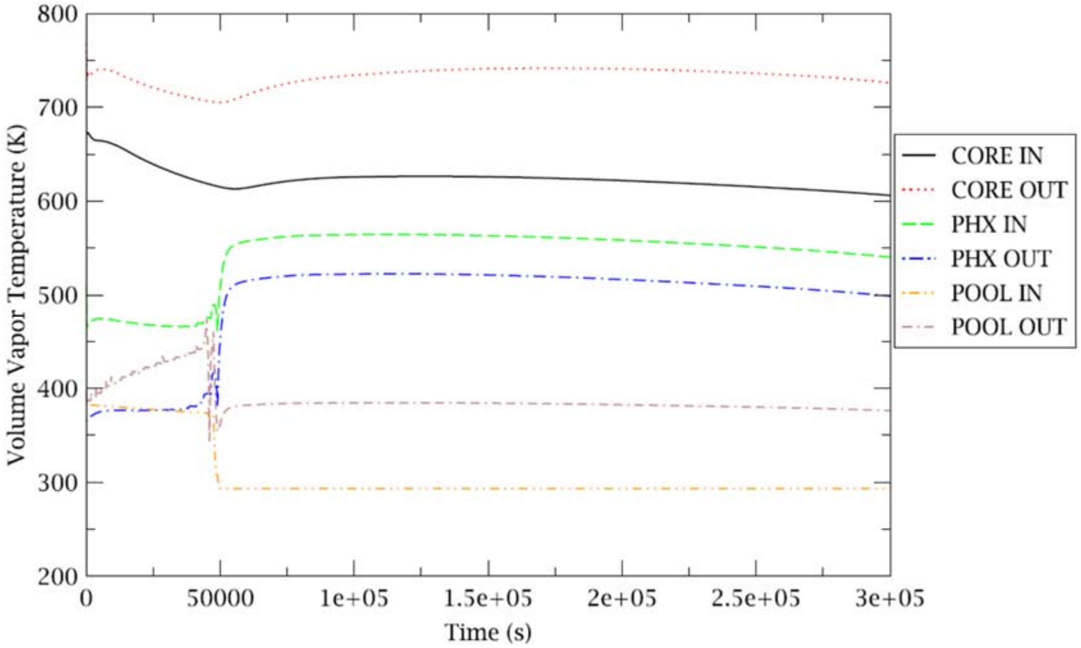

Fig. 8 – Core, PHX and pool inlet and outlet temperature referred to the R5 simulation

The mass flow rate of the two circuits is driven by natural circulation. The results showed in Fig. 9 The core mass flow rate follow the decay heat trend and decreases during the time. It is possible to view a change in the trend only in correspondence of the boiling water to air transition into the pool, but, after few hours, a new pseudo-equilibrium conditions are reached.

The DHR loop mass flow rate also follows the same trend.

Instead the pool mass flow rate changes obviously has a discontinuity in the transition. The value in the water phase starts from 2.5 kg/s and arrives to 1.5 kg/s at the pool dryout. In the successive air phase, the mass flow rate rises rapidly to 22 kg/s; it remains until the end of the calculation near this value, with a temporal derivative slightly negative, according to a gradual temperatures decrease.

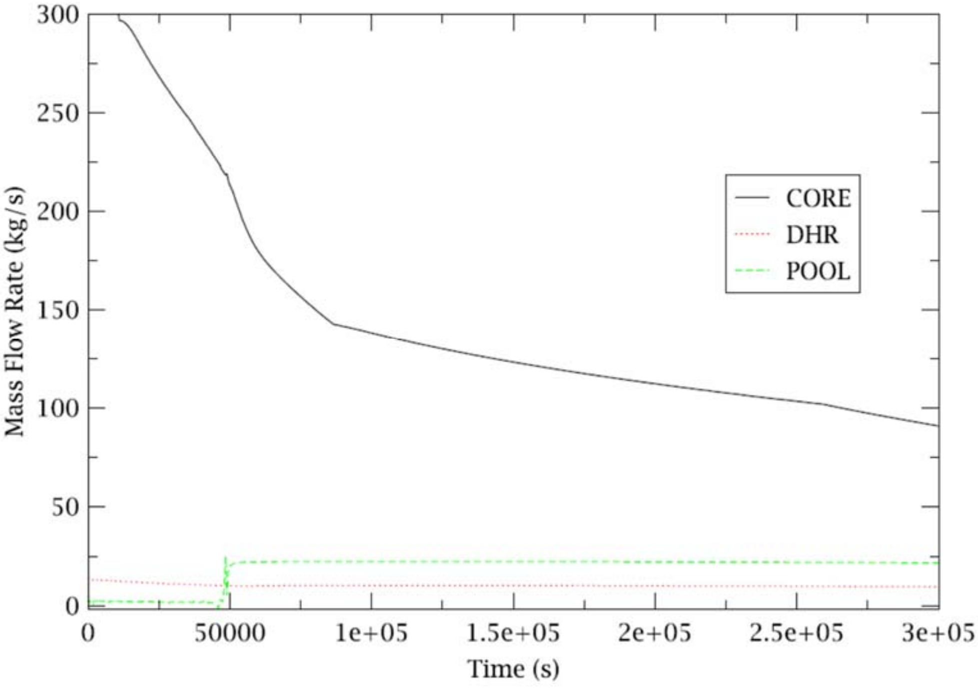

Fig. 9 – Core, DHR and pool mass flow rate

On the other hand, the design of the proposed system could be characterized by some drawbacks; in particular:

1. The DHR operates at high pressure, about 10 MPa, in order to avoid the possibility of water boiling within the secondary loop. This level of pressure has been identified through preliminary calculations carried out for optimizing the DHR system operating condition.
2. During reactor normal operating condition, a very small flow of secondary coolant is continuously maintained in order to limit its temperature. This is especially important in zones characterized by highest temperatures (i.e. within the DHX). This limited secondary flow causes a loss of power of about 0.5% of the reactor nominal thermal power. An

alternative solution, aimed at reducing thermal losses, can be reached by reducing the secondary coolant flow during normal operating condition; this can be obtained with an alternative fluid or increasing the secondary loop operating pressure.

3. An optimization in the PHX design is strongly required in order to limit in all other possible transients the highest secondary coolant temperature (to avoid boiling into secondary loop) and, at the same time, to limit the minimum primary coolant temperature (to avoid lead freezing).Sensitivity analysis

Three parameters was selected, after a simplified PIRT, for a preliminary sensitivity analysis: the emissivity of the finned surfaces of the DHX, the water HTC into the PHX and the lead HTC (both in the DHX and into the core).

The impact of the first parameter, as expected, is a moderate variation of the removed power. This parameter is subject to a possible variation during wear of the components and, for this, is important to know the possible working range. The range analyzed is from 0.5 to 0.9 (Fig. 10).

For emissivity equal to 0.5 the maximum core outlet temperature is 785 K and the correspondent clad temperature (786 K) is few degree above the limit. For this, the acceptable range of emissivity is limited at 0.6 ÷ 0.9,

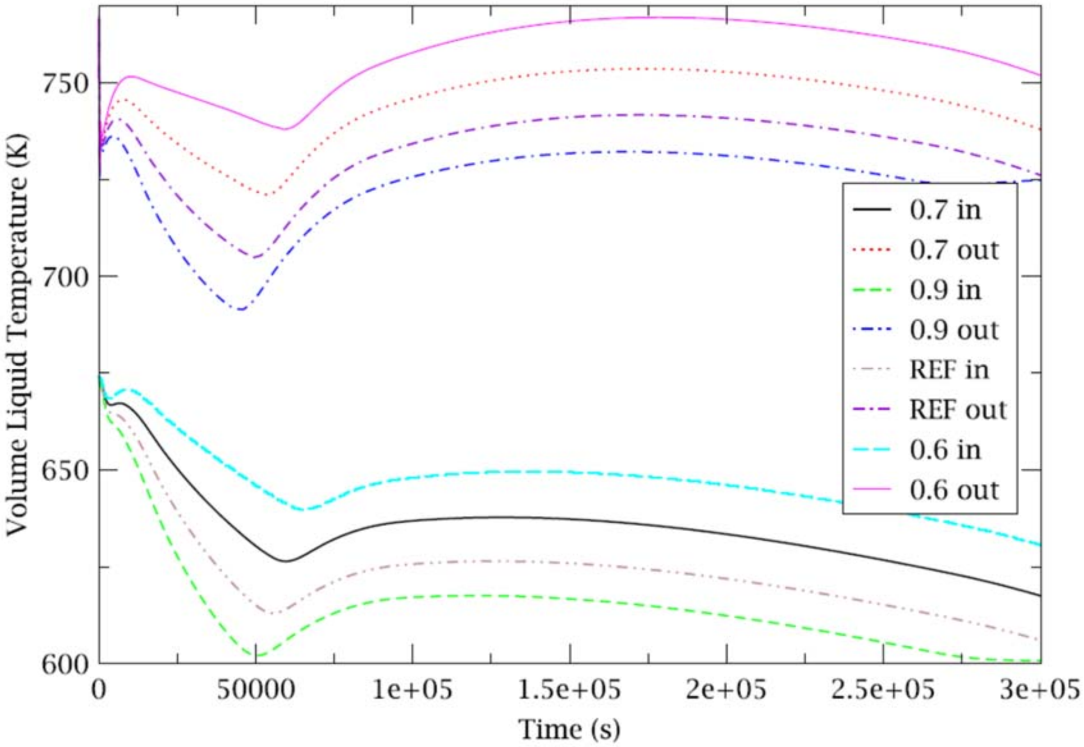

Fig. 10 – DHX emissivity sensitivity

This sensitivity demonstrates that the radiation is the limiting resistance for all the pool boiling phase and, after the transition, the temperature variations becomes almost insensible to the emissivity variations.

The influence of pool water HTC in the heat removal function is showed in Fig. 11. This sensitivity is important because the R5 code is not fully validated at low pressure[1], despite the conditions into the pool is similar, for pressure and temperature to PERSEO facility (Ferri et al., 2005) where the results obtained with RELAP5 are globally similar to the experimental result.

In the range analyzed, the results are acceptable.

The figure shows also that the thermal resistance of the PHX (pool side) becomes dominant in the air phase, where air HTC greatly influence the power removed, while it is negligible in the water phase.

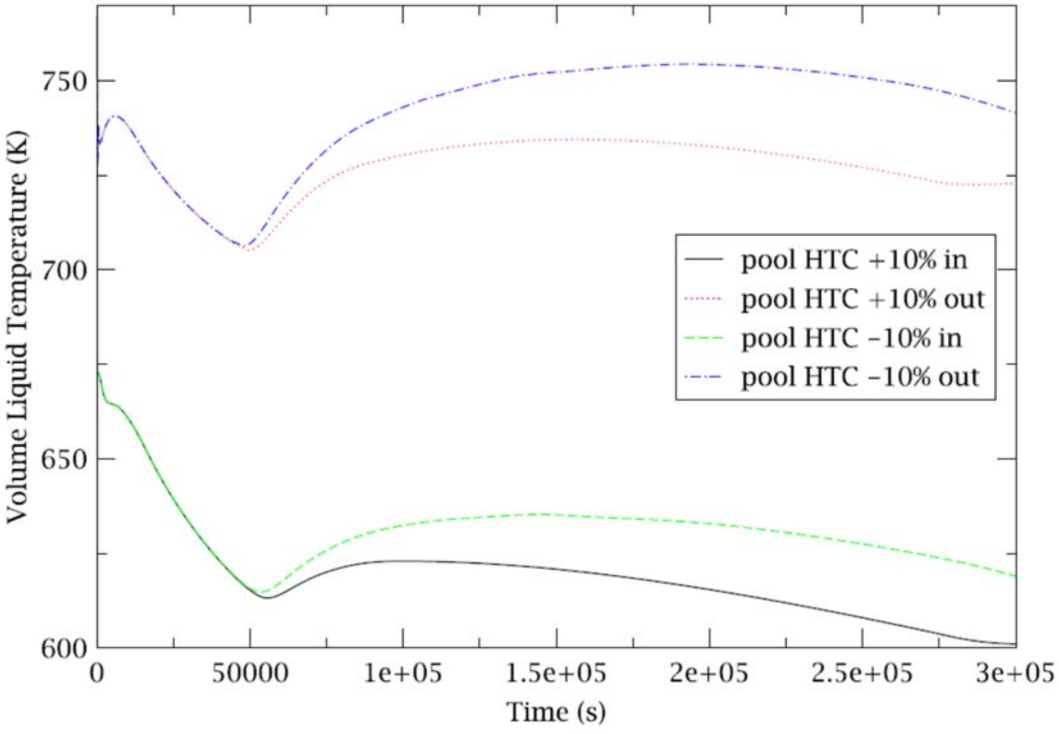

Fig. 11 – pool water HTC sensitivity

The sensitivities of the core inlet and outlet temperatures for the lead HTC variations are reported in Fig. 12. In spite of 40% lead HTC variation, the temperatures and the mass flow rates in the DHR are practically unmodified. The only variation observed is in the clad (and, as consequence, in the fuel) temperatures, where the temperatures rise of few degree.

---

[1] At low pressure, for water, the large density difference between the two phases could be causes a large error in the void fraction evaluation in each time step and consequent numerical oscillations.

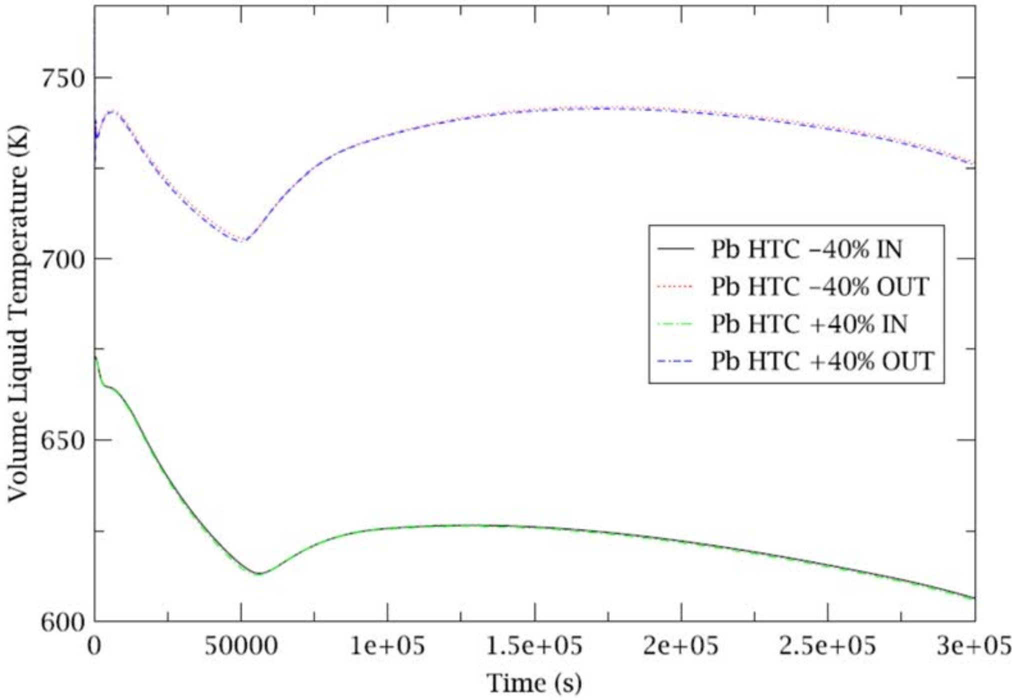

Fig. 12 – lead HTC sensitivity

3.1.1 RELAP5 vs. RELAP5-3D results comparison

The same input, described before, was also used for a RELAP5 3-D® v. 4.2.1 calculation with the aim of comparing the results and evaluating the difference between the two codes.

This analysis conducted, using R5-3D, has been repeated with the new thermos physical properties for lead described in Balestra et al., 2016, This properties are obtained from OECD/NEA, 2015.

Tab. 4summarizes the results from the RELAP5 mod3.3 and the RELAP5-3D steady state analyses, showing an overall good matching between the two sets of results.

The main difference between R5-3D and R5 mod3.3 results is in the average lead HTC. Because of this, the primary loop simulated with R5-3D shows higher temperatures than those calculated with R5 mod3.3; differences of about 4-5 K and 16 K have been identified for the lead and for the fuel respectively.

Two different correlations for the convective heat transfer in liquid metals are used in the two TH codes. In particular, the R5 mod3.3 (Ansaldo/ENEA modified version) HTC evaluation is based on the Ushakov correlation (rod bundle geometries for liquid metals) (Ushakov et al., 2007), while in R-3D the Westinghouse correlation (Kazimi and Carelli, 1976) is used. In Fig. 13 HTCs vs Reynolds number, evaluated by some correlations available in the literature, are compared under conditions similar to those present in the core of the ALFRED reactor.

Tab. 4 – Comparison between RELAP5 and RELAP5-3D steady state results

PARAMETER	UNIT	RELAP5	RELAP5-3D	RELAP5-3D[2]
Reactor thermal power	MW	300	300	300
Average FA flow rate	kg/s	147.8	148.1	147.9
Hottest FA flow rate	kg/s	174.7	174.8	174.7
Core inlet lead temperature	K	673	678	677
Average FA outlet lead temperature	K	754	758	757
Hottest FA outlet lead temperature	K	762	765	764
Upper plenum lead temperature	K	753	756	756
Average pin max clad temperature	K	774	790	794
Hottest pin max clad temperature	K	782	798	803
Average pin max fuel temperature	K	1826	1842	1848
Hottest pin max fuel temperature	K	2078	2092	2098

[1] With OECD/NEA, 2015 thermophysical properties for lead

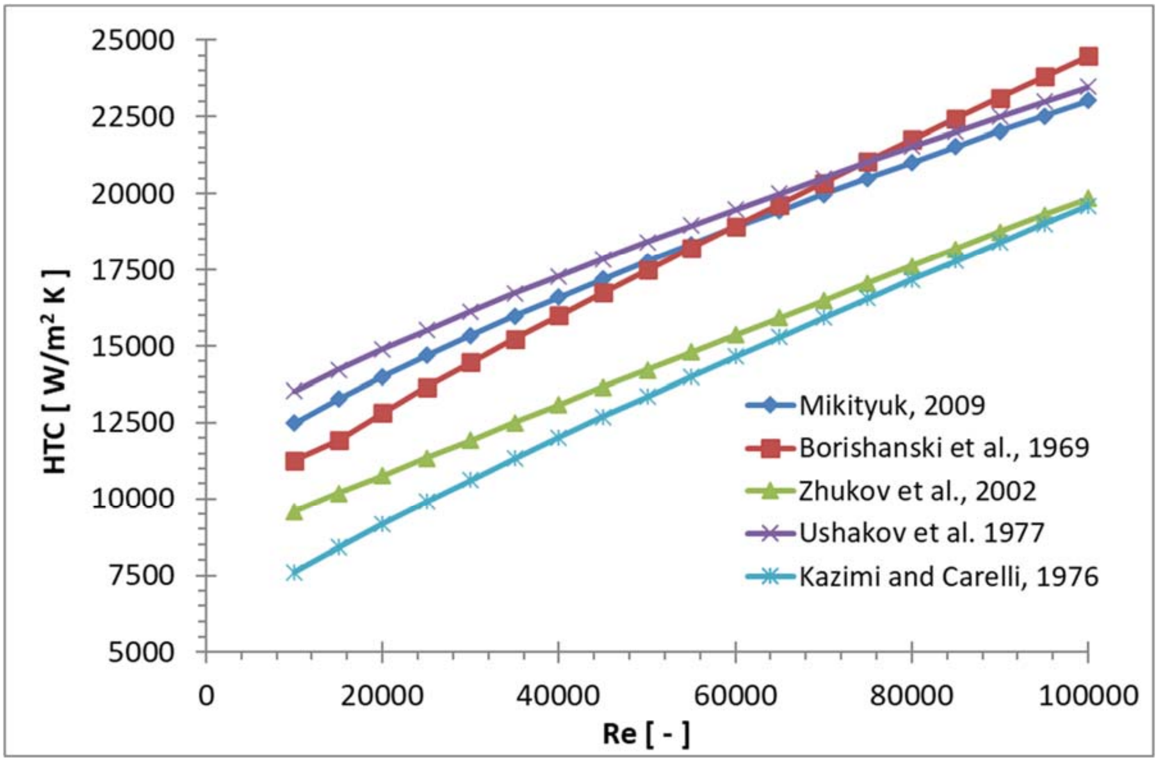

Fig. 13 – HTC vs Re for lead, p/d=1.3, T=440°C

Todreas and Kazimi, 1993, showed that HTCs evaluated by the Westinghouse correlation are in good agreement with experimental data at p/d equal to 1.15; for p/d = 1.3, the Nusselt number results to be underestimated.

In the present analysis, focused on lead natural circulation, an important thermodynamic parameter that could strongly affect the results is the density variation with the temperature. In particular, in the analyzed condition, the absolute density values are very similar while the derivatives of the density in function of the temperature are characterized by a higher difference. In Fig. 14 the lead density trends in function of the temperature, for RELAP5-3D, RELAP5 mod3.3 and reference data (OECD/NEA, 2007and OECD/NEA, 2015) are shown.

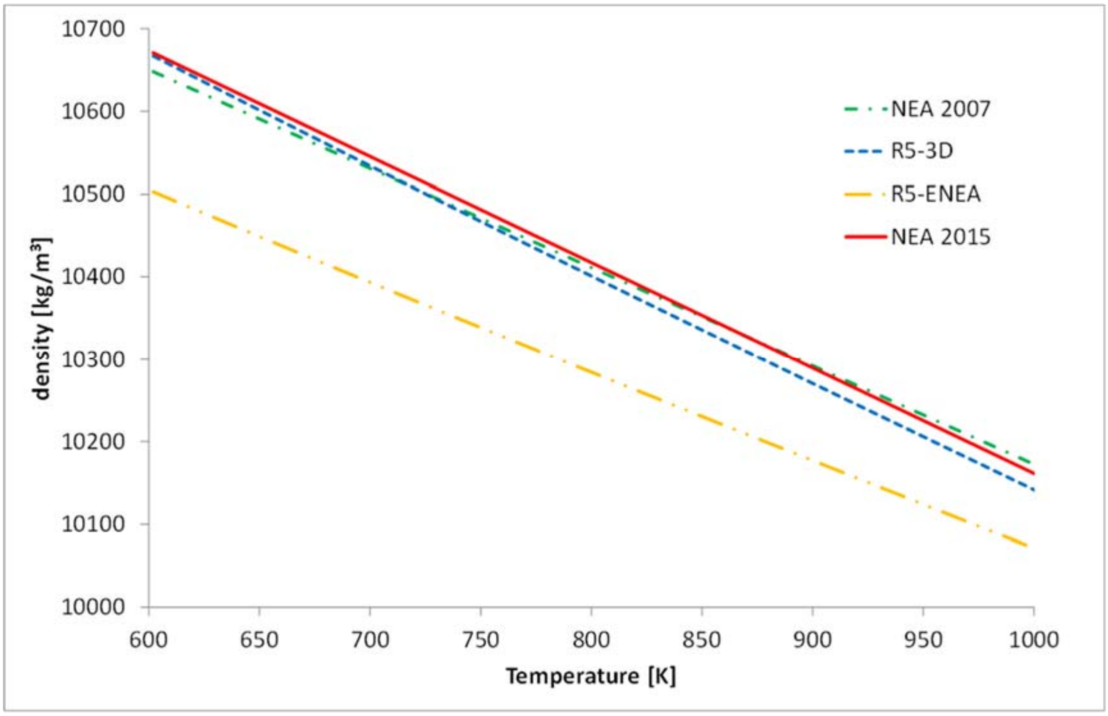

Fig. 14 – Lead density in R5 and R5-3D vs OECD/NEA, 2007 and OECD/NEA, 2015

The thermal expansion coefficient α and the density variation $\Delta\rho$ of RELAP5-3D, RELAP5 mod3.3 and OECD/NEA data are presented in Tab. 5. The ratio between RELAP5-3D and RELAP5 mod3.3 density variation is about 1.22. This is considered one of the main causes for the difference in the mass flow rate in natural circulation, as shown in Fig. 15.

Tab. 5 – Comparison of RELAP5, RELAP5-3D and references density derivative data

	OECD/NEA, 2007	OECD/NEA, 2015	R5-3D	R5-ENEA
$\alpha = -\frac{1}{\bar{\rho}}\frac{\partial \rho}{\partial T}$ $\left[K^{-1}\right]$	1.161 10^{-4}	1.257 10^{-4}	1.266 10^{-4}	1.048 10^{-4}
$\Delta\rho = -\int_{673K}^{753K} \rho\,\alpha\,dT$ $\left[kg\,m^{-3}\right]$	95.55	102.36	107.02	88.05

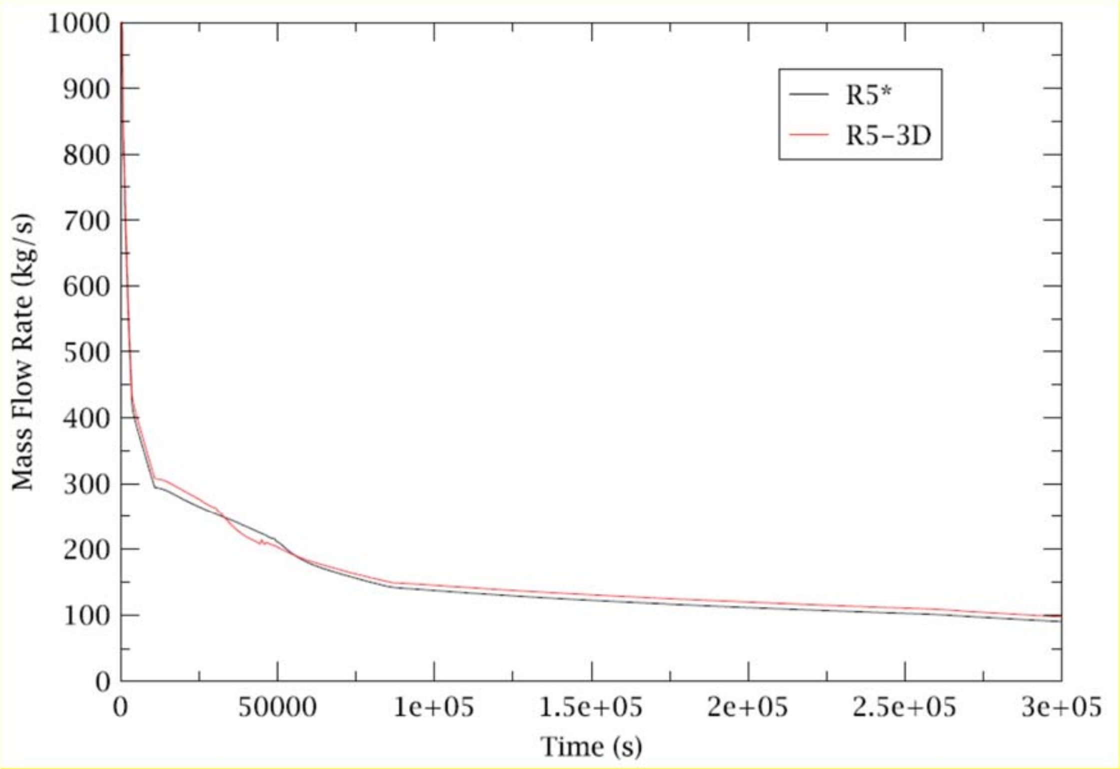

Fig. 15 - R5 and R5-3D core mass flow rate

The system behavior obtained in the two analyses, carried out during a LOOP transient, is similar.

The main differences from R5 to R5-3D concern with the change of heat transfer mode, in particular in the transition phase from nucleate boiling to air only heat removal, into the PHX.

The R5-3D results with the new properties are similar respect to original R5-3D.

The difference on the lead-side heat transfer performance (Fig. 16) is caused by the different correlations implemented in the two codes; this implies a slight variation in fuel and clad temperatures but, as evaluated in the specific sensitivity analysis, this is not particularly influent in the transient behavior.

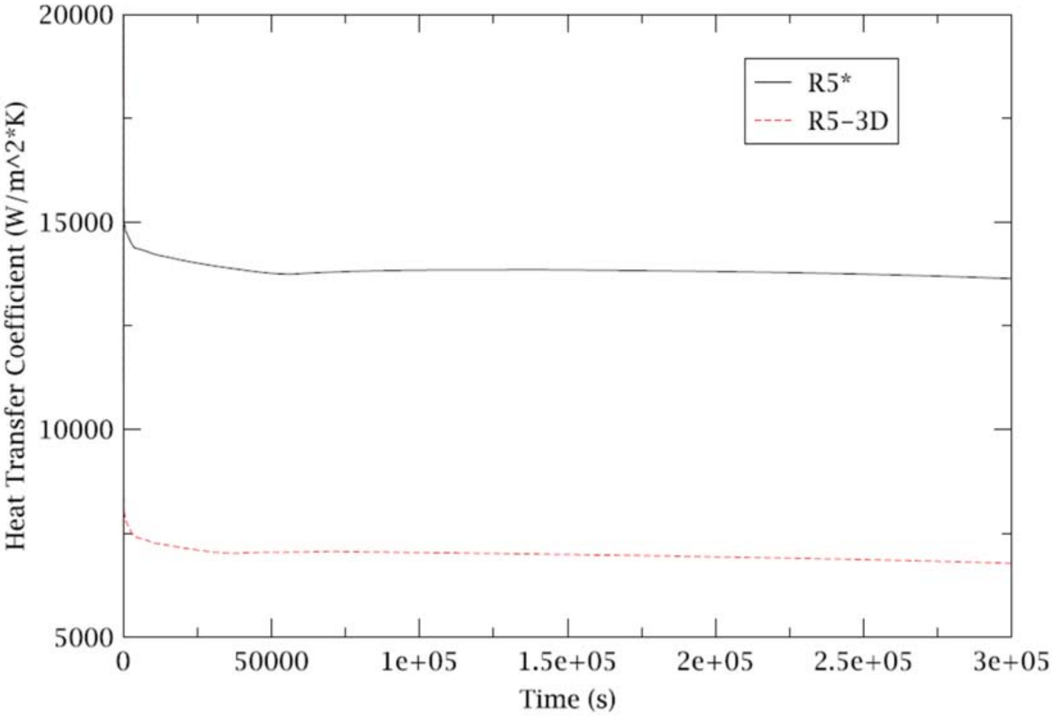

Fig. 16 – R5 and R5 3D average heat transfer coefficient in the core

In Fig. 17 a comparison between inlet and outlet core temperatures evaluated with R5 and R5-3D is shown. It is clearly visible the difference in the timing of the two transients, in particular with regard to the occurrence of the transition from boiling water to air only condition. Because of this, also the minimum temperature of the primary coolant at this time results to be different in the two simulations: the value obtained from the R5-3D calculation is more than 20 K higher than the temperature resulting from the R5 simulation, where this last value is only 10 K above the lead melting temperature.

Since the two transients have been simulated using the same geometrical model, the results of the simulation are affected by the codes differences. The geometry used guarantees, in the R5 simulation, a steady state condition in the pool, characterized by stagnant water, at the beginning; the same does not occur in the R5-3D simulation. This is caused by the thermo-physical properties of water, slightly different from those of R5, which generates in the R5-3D simulation a very low velocity in the pool volume junctions; because of this, that steady sate simulation starts from a different condition and this causes a decrease of the pool level at the starting of the transient. If in a real applications the water in the pool should be effectively maintained in a stagnant condition, the R5 simulation and the corresponding results (including temperature and timing) are more realistic then those evaluated by the R5-3D code.

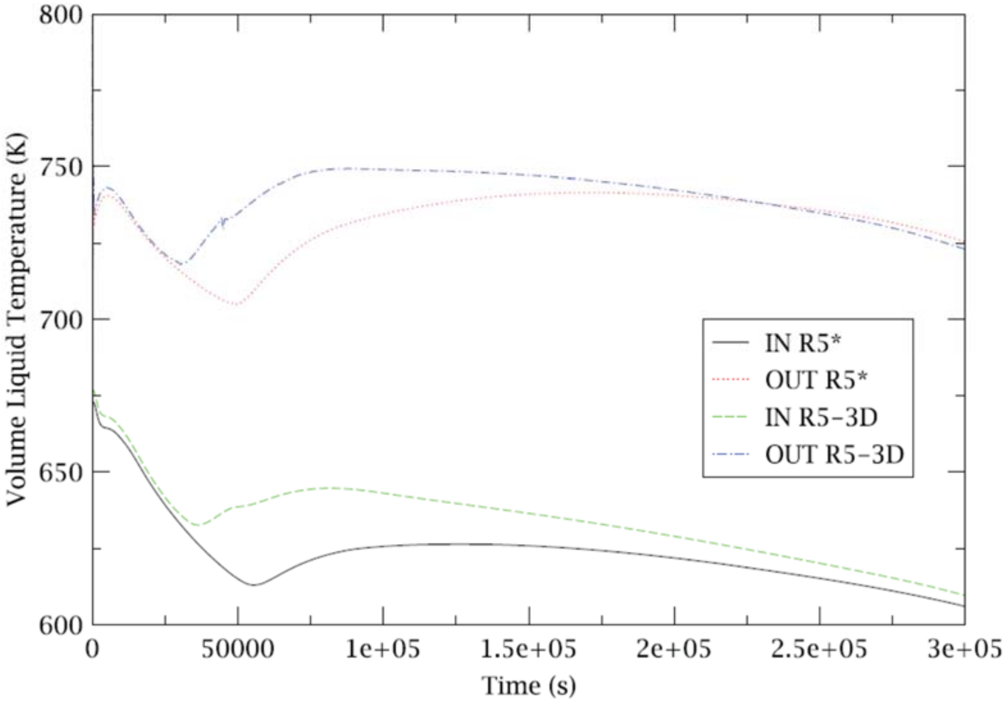

Fig. 17 – R5 and R5-3D core inlet and outlet temperatures

4 Conclusions

The proposed radiation-based system, if compared with standard DHRs, presents considerable advantages:

1. Being the irradiation the limiting heat transfer mechanism in DHX in the first phase, the power exchanged is strongly affected by the hot fluid temperature and, as consequence, the pool design has to be carried out in order to have enough water to delay the air-only condition, while the lead freezing is initially prevented by the bayonet heat exchanger.

   Since decay heat decreases with time following an exponential trend, the characteristic behavior of the proposed system makes it especially suitable to accomplish the decay heat removal function.

   In particular, its special self-adapting features allow it to automatically follow the decay heat trend:

   a. the lead freezing is avoided by the characteristics of the radiation based bayonet tubes for short term coupled with the PHX for the long term cooling;
   b. the system is characterized by a theoretically never ending operation, since it exploits the atmospheric air as heat sink, especially when the decay heat power is reduced, for more than 3 days without any action.

2. The absence of a physical contact between the two systems allows to guarantee the independence between the temperatures of the two fluids. The capability of maintaining a hot temperature at lead side (500 °C) and a cooler one at water side (280 °C) makes possible to achieve two advantages at the same time: lead freezing might be prevented and pressure in the secondary system can be maintained at limited values with water in liquid phase.
3. Fluid leakages from either the primary or the secondary sides, inside the DHX, can be easily detected by an on-line pressure measurement in the vacuum annulus.
4. The presence of the vacuum annulus provides the system with a very high safety degree. The physical separation between primary and secondary fluids is guaranteed from both the inner wall of the external tube and the outer wall of the intermediate tube. The likelihood event of mutual fluid contamination is, for this reason, very much lower than in other DHRs.
5. The final heat sink, after the complete vaporization of the water in the pool, is guaranteed with an air flow moving through the pool by natural circulation, allowing the system with a potentially unlimited autonomy.

Both RELAP5-3D and RELAP5 mod3.3 are capable to study the LOOP transient, providing similar results, with the differences discussed.

For RELAP5-3D, a new set of convective heat transfer correlations for the liquid metals could be adopted to better reproduce the actual state of the art, in addition to the new thermos physical properties for lead implemented.

The basic sensitivity analysis performed shows the practicability of the concept. The acceptable range of the parameters analyzed sufficiently large to proceed for a detailed analysis for a better verification of the concept.

The importance of the emissivity during the pool boiling phase and the air HTC into the pool are demonstrated by the sensitivity.

A special diathermic oil can be an alternative fluid, with the reduction of the pressure on the DHR circuit (from 10 MPa to about 1 MPa), but a qualification of the oil is required.

This system, proposed for the diversification of the DHR in the LFRs, is also applicable in other pool-type liquid metal fast reactors (in particular, for sodium reactors, the application is aided by a relatively low melting temperature).

Acknowledgement

Authors wish to thank the ENEA UTFISSM Technical Unit and ANSALDO for providing the RELAP5 mod 3.3 modified version with lead thermodynamic properties implemented.

References

- Alemberti A., Carlsson J., Malambu E., Orden A., Struwe D., Agostini P., Monti S., 2011, European lead fast reactor – ELSY, Nucl. Eng. Des. 241 (9), 3470–3480.
- Alemberti A., 2012a, ALFRED The EUROPEAN Lead Fast Reactor Demonstrator, The 5th Annual International Conference on Sustainable Development through Nuclear Research and Education, 16 - 18 May 2012, Pitesti, Romania
- Alemberti A., 2012b, ELFR-DEMO: ALFRED system configuration, Presented at the Int. Workshop on Innovative Nuclear Reactors Cooled by Heavy Liquid Metals: Status and Perspectives. Pisa, April 17th–20th, 2012.
- Alemberti, D. De Bruyn, G. Grasso, L. Mansani, D. Mattioli, F. Roelofs, 2013, The European Lead Fast Reactor Strategy and the Roadmap for the Demonstrator ALFRED, Int. Conf. on FAST REACTORS AND RELATED FUEL CYCLES: Safe Technologies and Sustainable Scenarios - FR13, 4–7 March 2013, Paris, France
- Balestra P., Giannetti F., Caruso G., Alfonsi A., 2016. New RELAP5-3D Lead and LBE Thermophysical Properties Implementation for Safety Analysis of Gen IV Reactors, Science and Technology of Nuclear Installations, Vol. 2016, Article ID 1687946, 15 pages (http://dx.doi.org/10.1155/2016/1687946)
- Bandini G. et al., 2011a, Analysis of Integral Circulation and Decay Heat Removal Experiments in the Lead-Bismuth CIRCE Facility with the RELAP5 codes, 14th International Topical Meeting on Reactor Thermal-hydraulics (NURETH-14), Toronto, Ontario, Canada, September 25-30, 2011.
- Bandini G., Meloni P., Polidori M., 2011b, Thermal-hydraulics analyses of ELSY lead fast reactor with open square core option, Nucl. Eng. Des. 241 (4), 1165–1171.
- Borishanskii, V. M., Gotovski, M. A., Firsova, É. V., 1969. Heat transfer to liquid metals in longitudinally wetted bundles of rods, Soviet Atomic Energy 27, 1347-1350; translated from Atomnaya Énergiya 27 (6), 1969, 549-552.
- De Santis A., Nobili M., Vitale Di Maio D., Naviglio A., Giannetti F., 2012, Innovative radiation-based decay heat removal system, XXX UIT Heat Transfer Conference Bologna, June 25-27, 2012.

- De Santis A., Vitale Di Maio D., Caruso G., Manni F., 2013, Innovative radiation-based direct heat exchanger (DHX) for liquid metal cooled reactors, Nucl. Eng. Des. 263, 164– 171.
- Ferri R., Achilli A., Cattadori G., Bianchi F., Meloni P., 2005, Design, experiments and Relap5 code calculations for the PERSEO facility, Nucl. Eng. Des. 235, 1201–1214
- Hung T.C., Dhir V.K., Chang J.C., Wang S.K., 2011, CFD modeling and thermal-hydraulic analysis for the passive decay heat removal of a sodium-cooled fast reactor, Nucl. Eng. Des. 241, 425–432.
- Hyun-Sik Park , Ki-Yong Choi, Seok Cho, Sung-Jae Yi, Choon-Kyung Park, Moon-Ki Chung, 2008, Experimental study on the natural circulation of a passive residual heat removal system for an integral reactor following a safety related event, Ann. Nucl. Energy 35, 2249–2258.
- Jae-Hyuk E., Seyun K., Sang-Ji K., Seong-O K., 2007, Feasibility Study of a Passive DHR System with Heat Transfer Enhancement Mechanism in a Lead-Cooled Fast Reactor, Nucl. Technol. 160 (2), 216-232
- John Arul A., Senthil Kumar C., Athmalingam S., Om Pal Singh, Suryaprakasa Rao K., 2006, Reliability analysis of safety grade decay heat removal system of Indian prototype fast breeder reactor, Ann. Nucl. Energy 33, 180–188.
- Kazimi, M. S., Carelli, M. D., 1976. Clinch River Breeder Reactor Plant Heat Transfer Correlation for Analysis of CRBRP Assemblies, Westinghouse, CRBRP-ARD-0034.
- Krepper E., Beyer M., 2010, Experimental and numerical investigations of natural circulation phenomena in passive safety systems for decay heat removal in large pools, Nucl. Eng. Des. 240, 3170–3177.
- L. Burgazzi, G. Bianchini, A. Cervone, M. Polidori, F. Giannetti, D. Vitale Di Maio, T. Murgia, L. Ferroni, A. Naviglio 2012, Confronto e valutazione della risposta di sistemi attivi e passivi in reattori innovativi a fronte di sequenze incidentali significative ai fini della sicurezza, ENEA report ADPFISS-LP1-004 (http://hdl.handle.net/10840/4766), September 2013.
- Meloni P., Nitti S., RELAP5 Code Validation in the Framework of the LACANES OECD/NEA Benchmark for HLM Innovative Nuclear System, The 8th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-8), N8P0106, Shanghai, China, October 10-14, 2010.
- Mikityuk, K., 2009. Heat transfer to liquid metal: Review of data and correlations for tube bundles, Nucl. Eng. Des. 239 (4), 680-687.
- OECD/NEA Nuclear Science Committee, 2007, Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies, ISBN

978-92-64-99002-9 (available on-line at https://www.oecd-nea.org/science/reports/2007/nea6195-handbook.html)

- OECD/NEA Nuclear Science Committee, 2015, Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies, (available on-line at https://www.oecd-nea.org/science/pubs/2015/7268-lead-bismuth-2015.pdf)
- Parthasarathy U., Sundararajan T., Balaji C., Velusamy K., Chellapandi P., Chetal S.C., 2012, Decay heat removal in pool type fast reactor using passive systems, Nucl. Eng. Des. 250, 480–499.
- Risk and Safety Working Group (RSWG), 2011. An Integrated Safety Assessment Methodology (ISAM) for Generation IV Nuclear System. GIF/RSWG/ISAM Report (available on-line at https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/gif_rsgw_2010_2_isamrev1_finalforeg17june2011.pdf)
- Sajith Mathews T., Ramakrishnan M., Parthasarathy U., John Arul A., Senthil Kumar C., 2008, Functional reliability analysis of Safety Grade Decay Heat Removal System of Indian 500MWe PFBR, Nucl. Eng. Des. 238, 2369–2376.
- Todreas, N.E., Kazimi M.S., 1993. "NUCLEAR SYSTEMS I - Thermal Hydraulic Fundamentals", Taylor & Francis, ISBN 0-89116-935-0
- Ushakov, P.A., Zhukov, A.V., Matyukhin, M.M., 1977. Heat transfer to liquid metals in regular arrays of fuel elements, High Temperature 15, 868–873; translated from Teplofizika Vysokikh Temperatur 15 (1977), 1027–1033.
- Vitale Di Maio D., Naviglio A., Giannetti F., Manni F., 2012, An innovative pool with a passive heat removal system, Energy 45, 296-303.
- Zhukov A.V., Kuzina Yu.A., Sorokin A.P., Leonov V.N., Smirnov V.P., Sila-Novitskii A.G., 2002. An experimental study of heat transfer in the core of a BREST-OD-300 reactor with lead cooling on models. Therm. Eng. 49 (3), 175–184.