Agenzia Nazionale per le Nuove Tecnologie,
l'Energia e lo Sviluppo Economico Sostenibile

Ministero dello Sviluppo Economico

RICERCA DI SISTEMA ELETTRICO

Thermal-hydraulic analysis of HELENA facility

N. Forgione, J. Fusani, F. Oriolo

Report RdS/2011/48

THERMAL-HYDRAULIC ANALYSIS OF HELENA FACILITY

N. Forgione, J. Fusani, F. Oriolo - UNIPI

Settembre 2011

Report Ricerca di Sistema Elettrico
Accordo di Programma Ministero dello Sviluppo Economico – ENEA
Area: Governo, Gestione e sviluppo del sistema elettrico nazionale
Progetto: Nuovo nucleare da fissione: collaborazioni internazionali e sviluppo competenze in materia nucleare

Responsabile Progetto: Paride Meloni, ENEA

CIRTEN

Consorzio **I**nteruniversitario per la **R**icerca **TE**cnologica **N**ucleare

UNIVERSITA' DI PISA

DIPARTIMENTO DI INGEGNERIA MECCANICA, NUCLEARE E DELLA PRODUZIONE

THERMAL-HYDRAULIC ANALYSIS OF HELENA FACILITY

N. Forgione, J. Fusani, F. Oriolo

CERSE-UNIPI RL 1086/2011

Pisa, Agosto 2011

Lavoro svolto in esecuzione della linea progettuale LP3 punto B1
AdP MSE - ENEA "Ricerca di Sistema Elettrico" - PAR2008-09
Progetto 1.3 – "Nuovo Nucleare da Fissione".

ABSTRACT

The Brasimone ENEA Research Centre has designed a new experimental facility HELENA (HEavy Liquid metal Experimental loop for advanced Nuclear Applications) with the aim to studying and supporting the development of prototype components and the selection of structural materials for future employment in LFR reactors. In particular, the HELENA facility will have as its main objective the qualification of a centrifugal pump, made of corrosion and erosion high resistance material, that can be used in the primary circuit of Gen. IV pilot and demo reactors.

This report is focused on the numerical pre-test analysis performed at the University of Pisa adopting the RELAP5/Mod3.3 system code, modified to allow the use of lead as cooling fluid. A very detailed nodalization is developed in order to take into account every component from the entire circuit: primary and secondary loop.

In the present report, after an accurate description of the experimental facility, the results of simulations are presented. In particular, three different tests have been considered to investigate the thermo-hydraulics behaviour of the facility. Two tests were performed to evaluate a possible start-up and shutdown procedure and another to study the circuit response after an accident scenario.

INDEX

Nomenclature iii

1. Facility description 1

1.1 Primary loop *1*

1.2 Secondary loop *4*

2. Code nodalization 6

3. Obtained results 10

4. Conclusions 16

References 17

Appendix A: Secondary loop nodalization 19

NOMENCLATURE

Roman letters

p	Pitch [m]
D	Diameter [m]
Pe	Peclet number [-]
Nu	Nusselt number [-]

Abbreviations and acronyms

HELENA	HEavy Liquid metal Experimental loop for advanced Nuclear Applications
HX	Heat eXchanger
HS	Heat Source
HLM	Heavy Liquid Metal
LFR	Lead Fast Reactor
TMDPJUN	TiMe DePendent JUNction
HTC	Heat Transfer Coefficient

1. FACILITY DESCRIPTION

The HELENA apparatus was designed at the Brasimone Research Centre of ENEA and mainly consists of two different thermal-hydraulic loops, instrumentation, heaters and coolers. The first loop represents the primary side of the facility and uses molten lead as cooling fluid, while the second loop is employed to work with sub-cooled water at a pressure of 100 bar.

The aim of the facility is to set up a circuit able to qualify and characterize components, systems and procedures relevant for HLM nuclear technologies. For this purpose, it was conceptualized to accommodate different test sections:

- test section for the qualification of high corrosion resistant structural materials (LFR primary pump impeller);
- test section to qualify the isolation valves operating in molten lead;
- heating section for the characterization of forced circulation heat transfer;
- test section for the qualification of the heat exchanger;
- test section for qualification and characterization of the measuring instrumentation, such as flow meters, differential pressure devices, probes for the control of oxygen concentration.

1.1 Primary loop

The primary side of the facility is a HLM rectangular loop which basically consists of two vertical pipes working as riser and downcomer, connected by means of two horizontal branches, that contain test sections for the insertion of components and measurement instruments.

The adopted material is an austenitic stainless steel (AISI 316L) and the total inventory of lead is about 2000 kg; the design temperature and pressure are 450 °C and 10 bar, respectively.

In the middle section of the riser a Heat Source (HS) is installed through appropriate flanges, while the Heat Exchanger (HX) is positioned at the end of the downcomer.

To promote the lead circulation along the loop, a centrifugal pump (PC101) is installed in the low branch of the loop. The performance characteristic curve of this pump was chosen in such a way that, at the nominal value of the lead mass flow rate of 35 kg/s, the pressure head corresponds to the nominal value of about 3 bar.

On the discharge line of the centrifugal pump, a calibrated orifice is inserted in order to introduce a concentrated loss of pressure of about 1.5 bar.

The loop is completed by an expansion vessel, housed on the upper part of the loop, coaxially to the downcomer.

The general 3D layout of the primary loop is depicted in Figure 1, while the main geometrical data characterizing the facility are reported in Table 1.

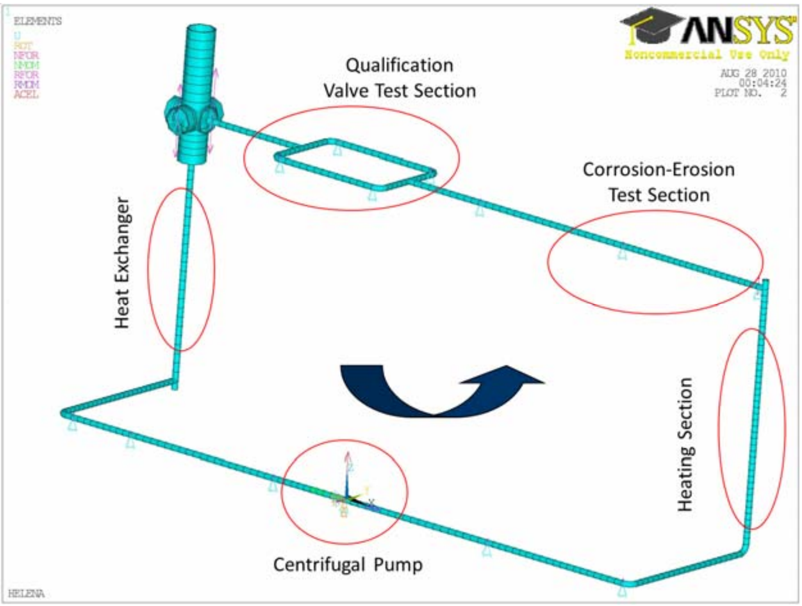

Figure 1. Layout of the primary loop

Pipe Inner Diameter [mm]	62.68
Pipe Thickness [mm]	5.16
Expansion Vessel Height [mm]	1400.00
Expansion Vessel Inner Diameter [mm]	304.86
Heat Exchanger Length [mm]	2000.00

Table 1. Main geometrical data of primary loop

The heater section foreseen for the primary loop of the facility consists of a wire spaced pin bundle arranged in hexagonal geometry supplying a total power of 250 kW. It has been simulated by electrical heaters and built with 19 rods of 6.55 mm diameter arranged on a triangular lattice (pitch-to-diameter ratio of 1.28).

A scheme of the pin bundle designed for the heater section is depicted in Figure 2. Each rod is designed with a wired wrapped spacer, helically wound along the pin axis to enhance the mixing of the coolant between the sub-channels, preventing, at the same time, contact between the fuel pins. A single rod supplies about 13 kW of power corresponding to a wall thermal flux in the order of 1 MW/m^2, reproducing a typical value of LFR systems. The total length of the heater is approximately 3000 mm with an active length of 600 mm.

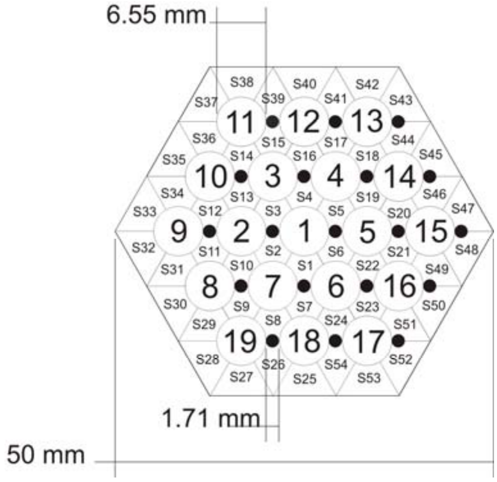

Figure 2. HS pin bundle of the HELENA facility

The rods are built using the technology of coaxial electrical heaters to maintain a uniform distribution of radial heat flux.

The heater section bundle characteristics are reported in Table 2.

Number of Active Pins	19
Diameter [mm]	6.55
Active Length [mm]	600
Total length [mm]	3000
Heat Flux [W/cm^2]	100
Flux Distribution	Uniform
Thermal Power [kW]	250

Table 2. Bundle characteristics

The heat exchanger is a “shell and tube” counter flow type: the secondary fluid consists of water at a pressure of 100 bar. The HX is made of seven coaxial tubes, six of which are disposed in a hexagonal lattice (pitch-to-diameter ratio equal to 1.3), while the remaining tube is positioned in the middle of the HX section. The dimensions of the tubes are reported in Table 3.

Molten lead flows downward inside the pipes, while water flows upwards in the outer region between the tubes and the shell.

Each tube is characterized by a double-wall which creates an annular region (2.5 mm width) filled by stainless steel powder. The aim of the powder gap is to guarantee the thermal flux towards water (due to good thermal conductivity) mitigating, at the same time, the thermal stress on the pipes during operation. Moreover, the powder gap reduces the thermal gradient through the thickness of the pipes; in fact, its thermal resistance is about 35% of the overall one.

	Internal 2.5” S40	Middle 3” S40	Shell 16” S120
Outer Diameter [mm]	73	88.9	446.4
Pipe Thickness [mm]	5.16	5.49	30.9
Inner Diameter [mm]	62.68	77.92	344.6
Length [mm]	2000	2000	2000
Material	AISI 316L	AISI 316L	AISI 316L

Table 3. HELENA HX pipes dimension

1.2 Secondary loop

The secondary side of HELENA facility is a rectangular circuit constituted by two sub-loops, with a common vertical branch. The general layout is depicted in Figure 3.

In loop A , water is heated to reach the required temperature without flowing through loop B. Once the desired conditions are reached, the two loops are connected (by means of adequate valves opening/closing) allowing the water to flow in the heat exchanger located in loop B. This procedure avoids low temperature water flowing directly through the HX, causing undesired solidification of lead in the primary loop.

The design temperature and pressure are 290 °C and 100 bar, respectively. The adopted material is stainless steel (AISI 316L). The main geometrical data are reported in Table 4.

Pipe Inner Diameter [mm]	85.44
Pipe Thickness [mm]	8.08
Pressurizer Height [mm]	1450
Pressurizer Inner Diameter [mm]	736.6
Heat Exchanger Length [mm]	2000
Air Cooler Length [mm]	2000

Table 4. Main geometrical data of secondary loop

The main components of loop A are: an electrical heater housed at the bottom of the pressurized tank and an air cooler and pump, placed in the lower branch, which supplies a water mass flow rate of 4.57 kg/s.

Three motor valves ensure a connection between the two loops and allow the flowing of water through the HX when the cooling fluid reaches the nominal temperature value.

The air cooler removes heat transferred to the HX (250 kW) in order to guarantee a correct energy balance between the primary and secondary loop.

The difference in level (about 1.3 m) between the thermal centre of the HX and the heat sink (air cooler), provides a driving force to fluid circulation in the event of pump breakdown and, consequently, an acceptable heat removal.

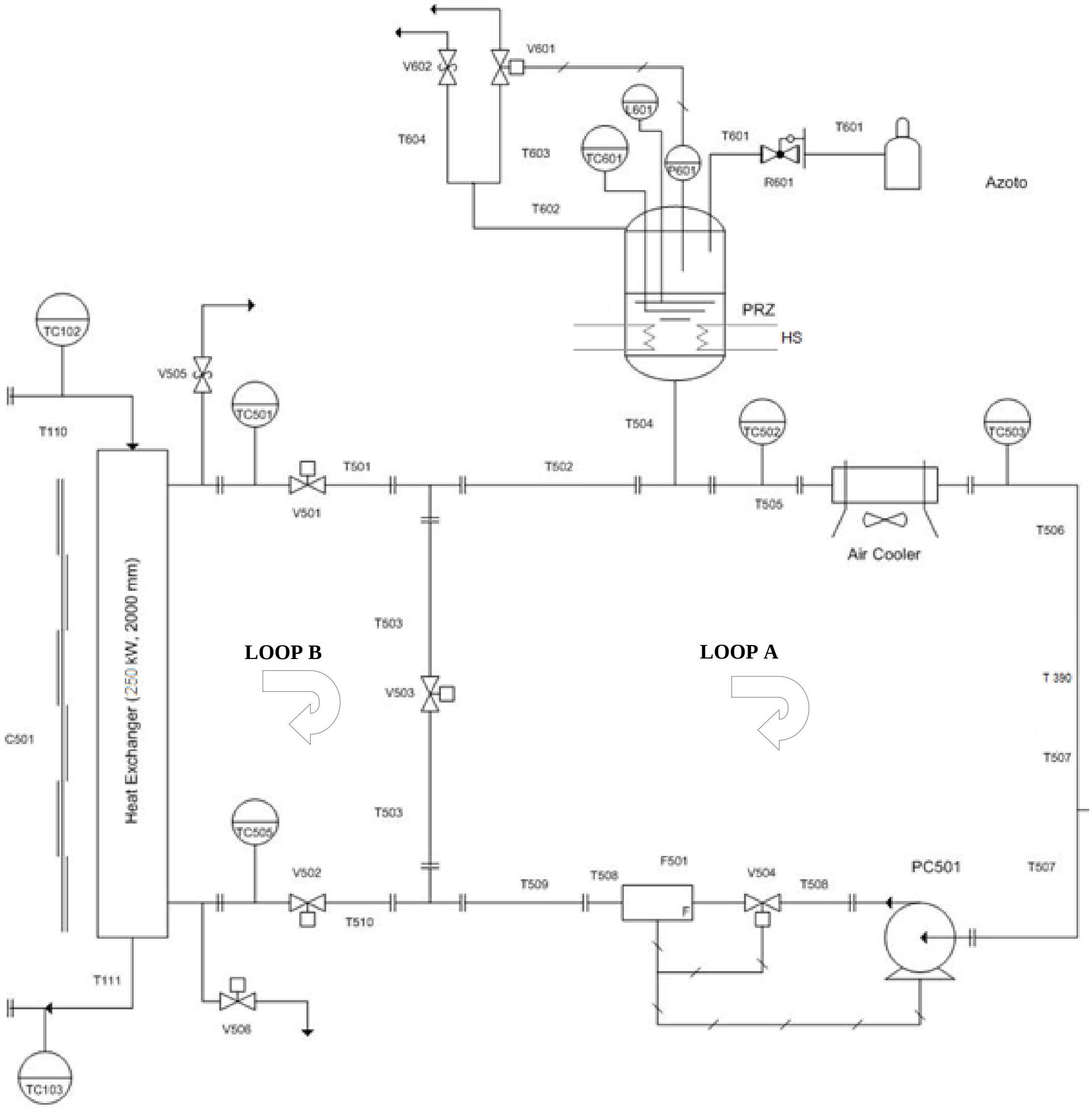

Figure 3. Scheme of secondary loop

2. CODE NODALIZATION

A scheme of the nodalization of both primary and secondary side of the HELENA facility adopted for RELAP5/Mod.3.3 is reported in Figures 4 and 5. It consists of several pipes, branches and single junction components aiming at the simulation of different parts of the loop.

The detailed description of the primary loop nodalization is reported in a previous work [8], while the nodalization set-up for the secondary loop is accurately explained in Appendix A. In the following part of this section only a short description of the RELAP5 nodalization is presented.

As it can be seen in Figures 4 and 5, a time dependent volume is included in both the loops to impose pressure at the top of the circuits. The mass flow rate inside the primary loop is ensured by the presence of a pump component (PUMP 10 in Figure 4), which simulates the real behaviour of the centrifugal pump that is expected to be tested and installed.

Water mass flow rate in the secondary side is guaranteed by a time dependent junction component (TMDPJUN 415 in Figure 5), simulating the pump PC501, placed in parallel with the junction at the exit of the component T507; in this aim the exit junction has been given a very large reverse flow form loss coefficient, in order to avoid that during pump operation it could act as a pump bypass. This expedient resulted in a reasonable simulation of actual pump behaviour, without the need to include a true pump component, with related complications and uncertainties in the characteristic curves.

Forced circulation of the working fluid within the secondary circuit is counter-clockwise, while in the primary circuit it was designed in a clockwise direction to allow a counter-current heat transfer in the HX.

A new correlation of Heat Transfer Coefficient (HTC) for fuel bundles was implemented in this code version, in order to have a better accuracy of the HTC inside the HS. The knowledge of the HTC value between the liquid metal and the fuel rods has a great importance in the pin design because of its influence on the temperature of the rods. The effect of the wired wrapped spacer inserted on each pin of the HS bundle was not taken into account and will be investigated in future works.

The new correlation, used for the current pre-test simulations, is the one proposed by Mikityuk [9], valid for both triangular and squared arrangement bundles:

$$Nu = 0.047\left(1 - e^{-3.8(p/D-1)}\right)\left(Pe^{0.77} + 250\right) \tag{1}$$

This correlation is recommended for Peclet numbers in a range of 30-5000 and pitch-to-diameter ratios of 1.1-1.95.

The results obtained with the correlation (1) were compared with the results derived using the Ushakov correlation [10] for the calculation of convective heat transfer coefficient. The equation is written as follows:

$$Nu = 7.55\left(\frac{p}{D}\right) - \frac{20}{\left(p/D\right)^{13}} + \frac{0.041}{\left(p/D\right)^{2}} Pe^{0.56+0.19\,p/D} \tag{2}$$

and has a validity range of 0-4000 for the Peclet number and 1.3-2.0 for the pitch-to-diameter ratio.

Heating components in the facility have been simulated using heating rods, in the primary and secondary loop, positioned in the middle section of PIPE 50 (see Figure 4) and in PIPE 354 (see Figure 5), respectively.

Heat losses have also been introduced in the analysis taking into account the presence of a rock wool layer as insulation material that will be used for each pipe. With this aim, an equivalent HTC has been calculated and used as boundary condition.

This value of outer HTC, combined with an imposed temperature value for the air outside the pipe walls (20 °C), allows a good prediction of heat transfer through each structure of the facility.

The powder gap thermal conductivity, inside the HX tubes, was chosen as 12.5% of the stainless steel theoretical value, in agreement with data obtained from previous experimental tests on a similar HX structure [11].

The HTC assigned on the outside surface of the air cooler (PIPE 370 in Figure 5) was evaluated using the log mean temperature difference (LMTD) assuming the expected values of the outer air temperature and velocity.

Three motor valve components (V501, V502 e V503 in Figure 3) have been used in the nodalization of the secondary loop of HELENA facility because of their realistic behaviour regarding opening and closing procedures. These are controlled by a logical command through which, when the water temperature in the component BRANCH 275 (see Figure 5) reaches the imposed value (290 °C), the opening of V501 and V502 valves and the closing of V503 occurs using an appropriate time sequence (see next section).

Furthermore, another motor valve component (V506 in Figure 3) has been simulated to allow the emptying of water inside the HX, using gravimetric effect, in order to reproduce the real behaviour of the facility during shutdown proceeding.

All the pressure drops inside the circuits have been taken into account inserting an appropriate value of pressure loss coefficient in junctions of the primary and secondary side of the facility.

Pipes have been simulated using 5 cm length volumes throughout the nodalization.

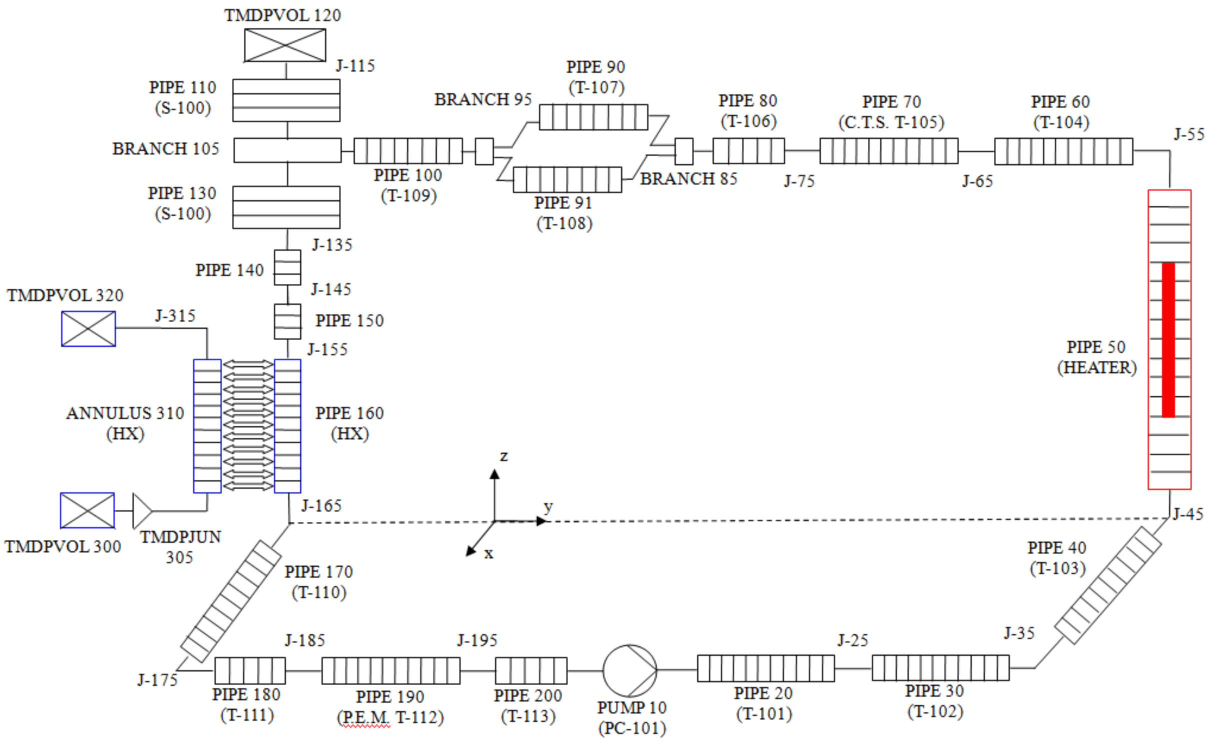

Figure 4. Relap5 nodalization for the primary loop

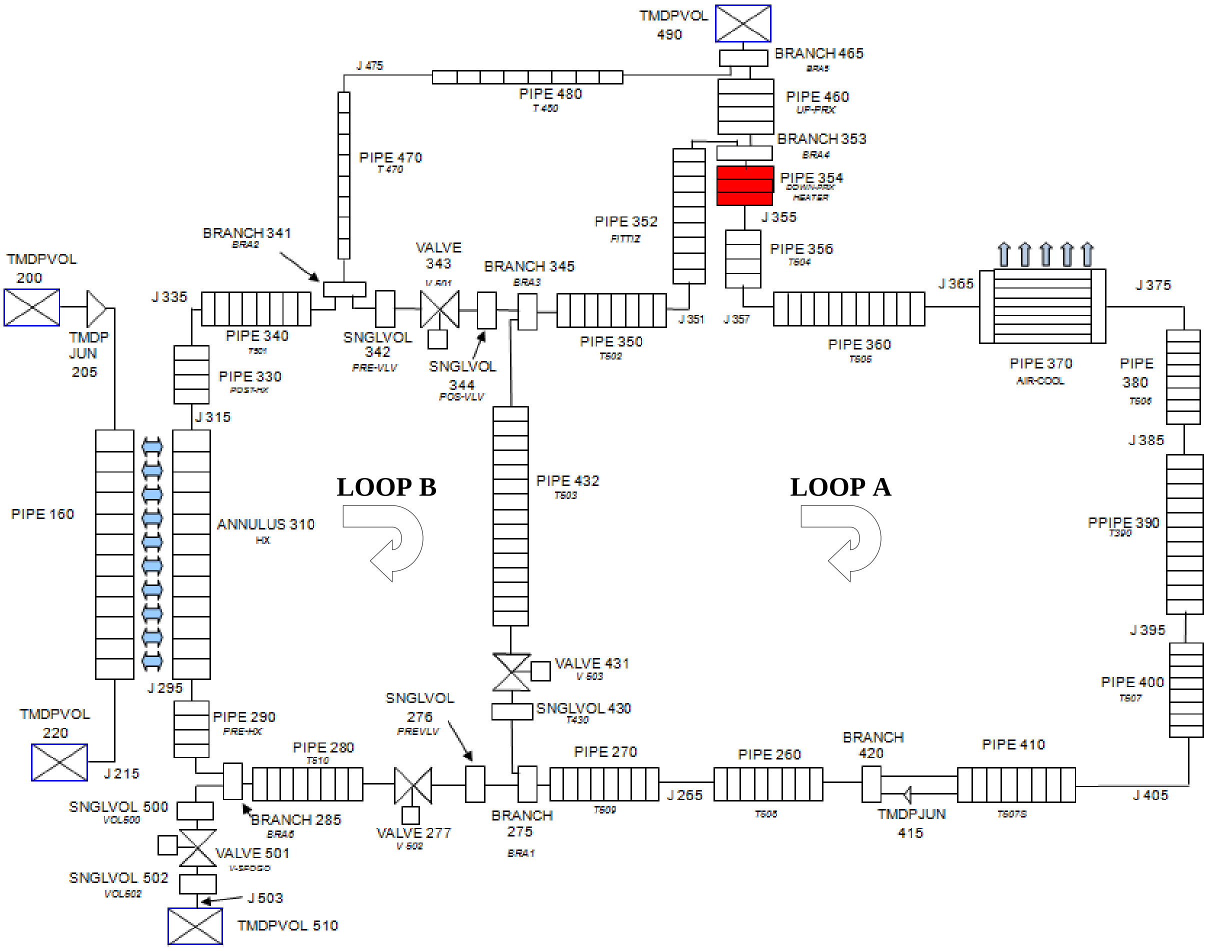

Figure 5. Relap5 nodalization for the secondary loop

3. OBTAINED RESULTS

A detailed analysis of thermal-hydraulic behaviour of HELENA facility during operational and accidental transient was performed.

The aim of these analysis is to provide useful information to set up a reasonable start-up and shutdown test procedure and, at the same time, to verify the response of the circuit after possible accidents that could be encountered during the facility working conditions.

The simulations matrix, shown in Table 5, summarizes the adopted boundary conditions and the main variables that have been monitored in the present work.

Test	Description	Monitoring variables	Conditions
A	Start-up and steady state analysis	• T_{in} and T_{out} in the primary and secondary sides of HX • T_{in} and T_{out} in the HS and in the Air Cooler • Superficial temperature of heating rods • Mass flow rate in the primary and secondary loop • Liquid level in HX	• Heater thermal power in the primary loop: 250 kW • Heater thermal power in the secondary loop: 50 kW • Initial lead temperature: 400 °C • K_{loss} orifice: 30 • Water mass flow rate: 4.57 kg/s • Water temperature: 20 °C
B	Shutdown analysis	• T_{in} and T_{out} in the HS • Mass flow rate in the primary and secondary loop	Steady state conditions: • Thermal power: 250 kW • Mean lead temperature: 445 °C • Water mass flow rate: 4.57 kg/s • Water mean temperature: 290 °C
C	Water pump failure accident	• T_{in} and T_{out} in the HS and in the HX • Mass flow rate in the primary and secondary loop	Steady state conditions: • Thermal power: 250 kW • Mean lead temperature: 445 °C • Water mean temperature: 290 °C

Table 5. Simulations matrix

In Test A, start-up procedure for the entire facility has been proposed, trying to optimize the timing of each parameter, such as power supplied in the HS of the primary circuit or valves opening in secondary loop, in order to avoid problems that could be encountered in the experiments due to the occurrence of undesired low or high fluid temperature values.

In the sequence of the events, the three following phases have been considered:

1. A constant water flow rate was imposed in the first period of the transient through the time-dependent junction 415 increasing linearly in 100 s to reach the nominal value of 4.57 kg/s. Subsequently, a linear increase of thermal power inside the pipe 354 (HS) to the maximal value of 50 kW is provided in 100 s, in order to raise the water temperature from 20 °C to

290 °C. At this stage, the HX is separated from the rest of the secondary circuit through valves V501 and V502 (see Figure 3) until achieving nominal water temperature in loop A. The HX secondary side has been initialized full of non-condensable gas to prevent excessive cooling of the molten lead on the primary side. The air-cooler is thermally insulated from the outside by bulkheads which minimize convective heat transfer.

2. Few instants before water temperature in the secondary loop reached its nominal value, molten lead flow rate in the primary circuit started to circulate, increasing the main pump rotation velocity in 200 s. The primary loop HS heating rods were switched on in 300 s to deliver the nominal thermal power of 250 kW at the same time when the opening/closing of the valves in secondary loop occurred. This condition was chosen in order to avoid an excessive thermal gradient with relative thermo-mechanical stress, in the HX tubes structures as consequence of high value of temperature difference between the primary and secondary working fluids.
3. When water temperature reached the nominal value of 290 °C in the lower branch of the secondary loop, the opening of valves V501 and V502 and the closing of valve V503 take place. The opening phase of the V502 is the longest (1000 s) to prevent an excessive mass flow rate which would cause elevated thermal stress in the HX tubes. Valve V503 had a closing time of 500 s while the opening time of V501 is related to the void fraction inside the HX. The HS of the secondary loop is automatically switched off once nominal temperature value is reached, while the air-cooler reaches steady state conditions after 1200 s.

Test B includes useful possible shutdown procedures to bring the whole facility back to initial conditions. During the first step, the primary loop HS thermal power is switched off in 300 s and the closure of the valves V501 and V502 occurs in 500 s. To avoid heat transfer through the HX when thermal power is null the emptying of the HX secondary side is provided by opening the discharge valve V506, when the water mass flow rate is zero. However, a minimal value of thermal power of about 30 kW is delivered in the HS to avoid lead solidification in the primary circuit (actually there are heater coils placed over the circuit to keep the lead molten).

As it can be observed in Figure 6, the Mikityuk correlation implemented in the RELAP5 code shows good agreement with the Ushakov correlation, although a quite lower HTC value can be observed.

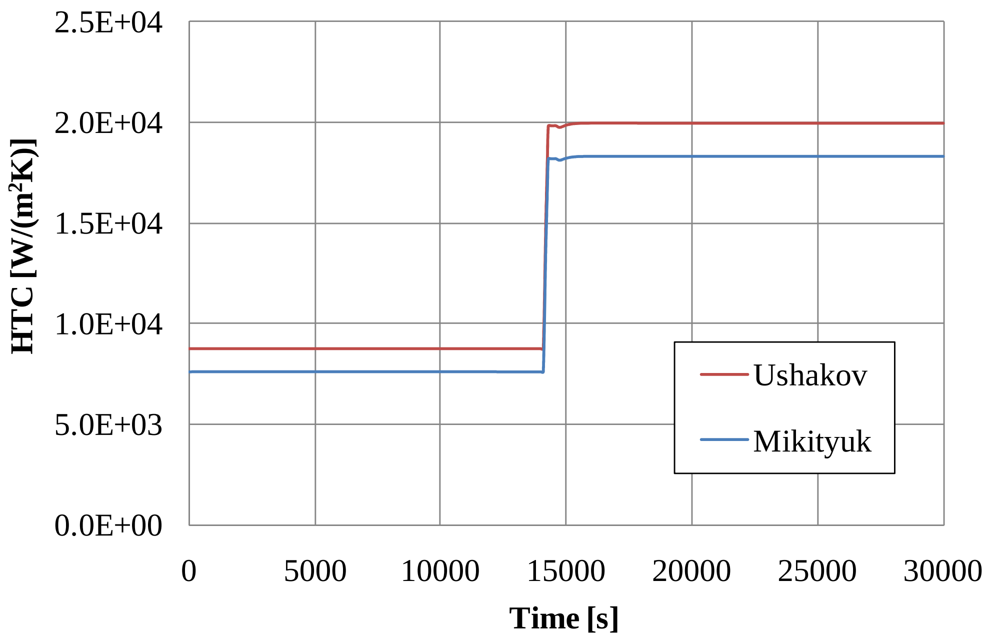

Figure 6. Comparison between HTC values obtained with the two different correlations in the HS of the primary loop (Test A)

The direct consequence of this trend can be seen in Figure 7, which shows the primary circuit HS heating rods surface temperatures. The temperatures obtained using the two correlations are in good agreement and the highest rod temperature does not exceed 530 °C. In the same way, the HS inlet and outlet section lead temperatures calculated with the two correlations proposed match themselves.

In Figure 8 the time trend of lead temperatures through the HS both for start-up (Test A) and shutdown (Test B) simulations are depicted. After the first phase of the transient in which lead temperature remains constant because of the lack of forced circulation and thermal power, the temperature rises to a maximum value of 470 °C. The inlet lead temperature shows a little decrease due to the fact that the water flowing inside the secondary side of the HX occurs few seconds later than thermal power delivered to the HS of the primary loop.

At the end of the simulation, lead temperature time trend when the shutdown (Test B) occurs can be seen. Thermal power supplied in this phase maintains temperature values up to the solidification limit.

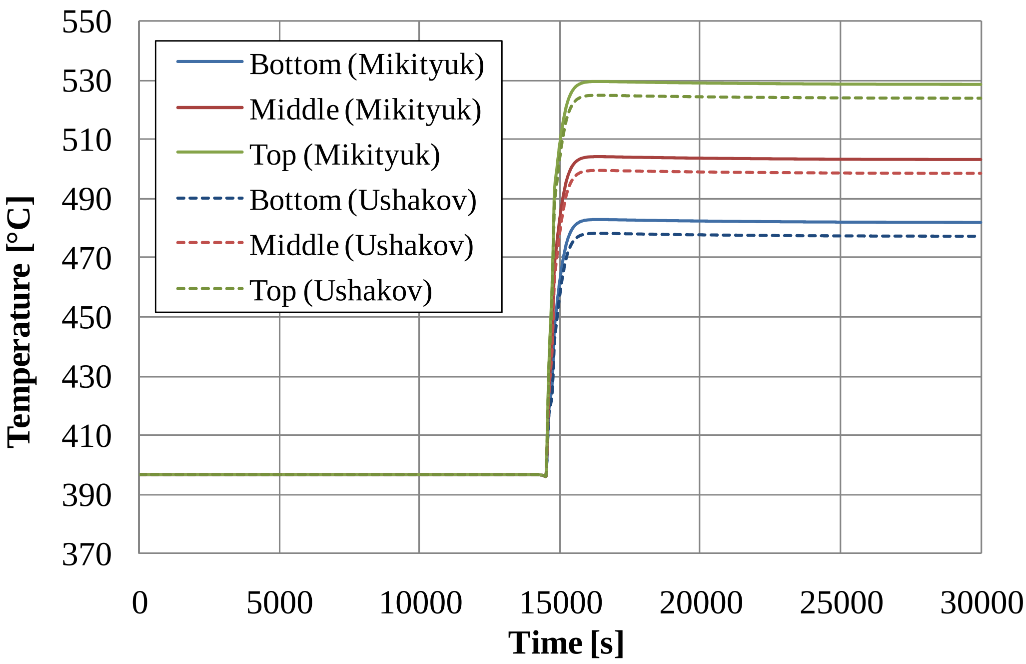

Figure 7. Comparison between wall rod temperatures obtained with the two different correlations in the HS of the primary loop (Test A)

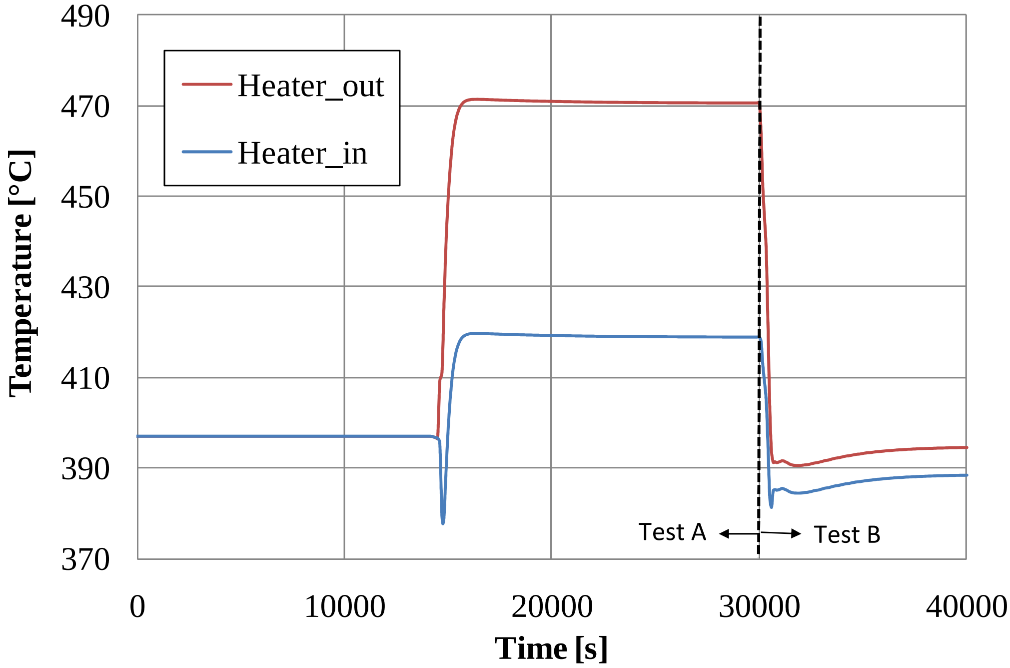

Figure 8. Lead temperatures through the inlet and outlet section of the HS for the start-up and shutdown tests (Test A + Test B)

The temperature time trend inside the Air Cooler is depicted in Figure 9; the increase in water temperature can be noted due to deliver of thermal power up to its nominal value of 290 °C. At the time when valves open, a little fall of temperature takes place, caused by liquid level dropping from the expansion vessel. This water is characterized by a lower temperature than that flowing in the rest of the loop due to the lack of axial conduction in the system code.

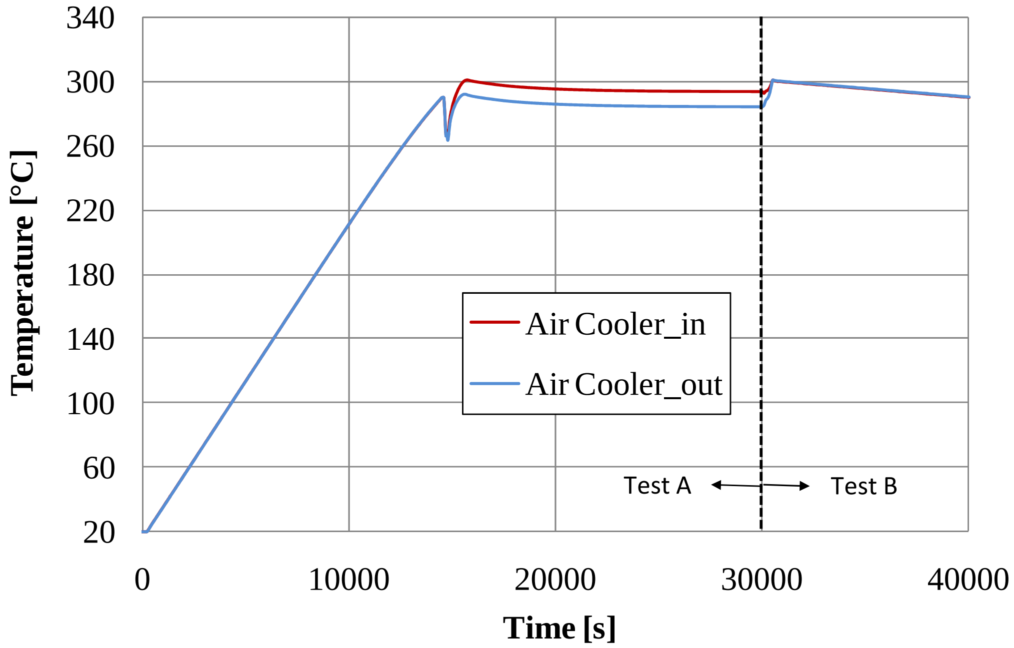

Figure 9. Inlet and outlet water temperature through the air cooler (Test A + Test B)

The mass flow rate of both the working fluids inside the primary and secondary side of the facility are reported in Figure 10. Concerning the water mass flow rate, it starts at the first instant of the transient and remains constant until it reaches the nominal water temperature, when the opening of the valves is provided. At the same time, it decreases in a linear way in the vertical branch to allow the entire water to flow through the HX. The lead mass flow rate is guarantee by the main pump and reaches a steady state value of 32.5 kg/s.

As regards Test C, the response of the facility to the pump failure accident is reported in Figures 10 and 11. The difference in temperature and height between the HX and the air cooler are able to establish an acceptable mass flow rate from natural circulation (1.6 kg/s).This phenomenon takes place because the thermal resistances located in the outer side of air cooler tubes is dominant with respect to the others thermal resistance present between primary and secondary side of the HX.

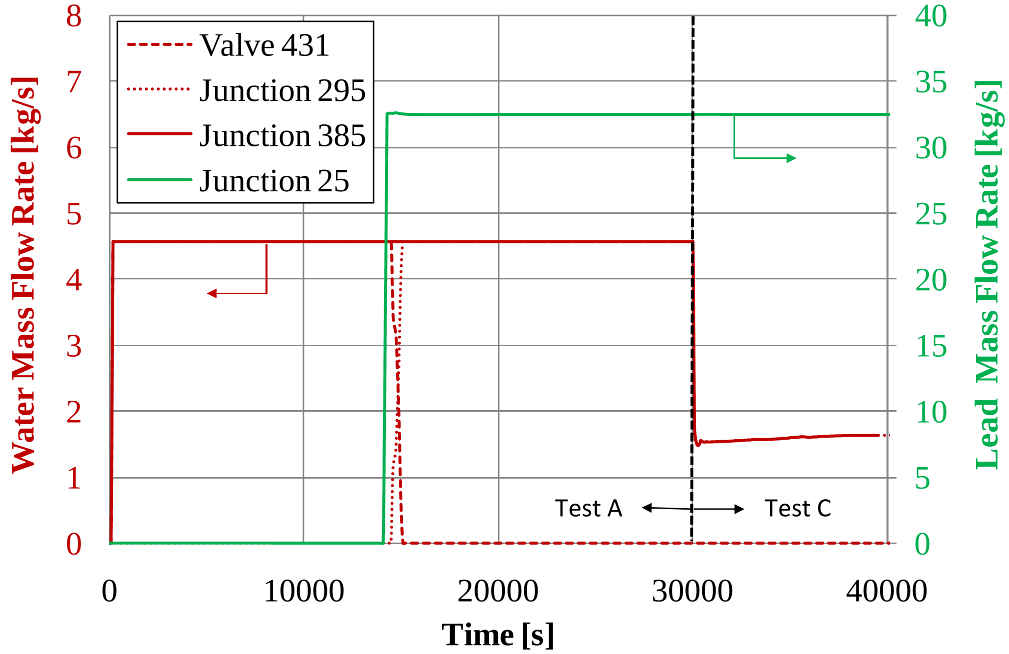

Figure 10. Mass flow rate in the primary and secondary side of HELENA facility (Test A + Test C)

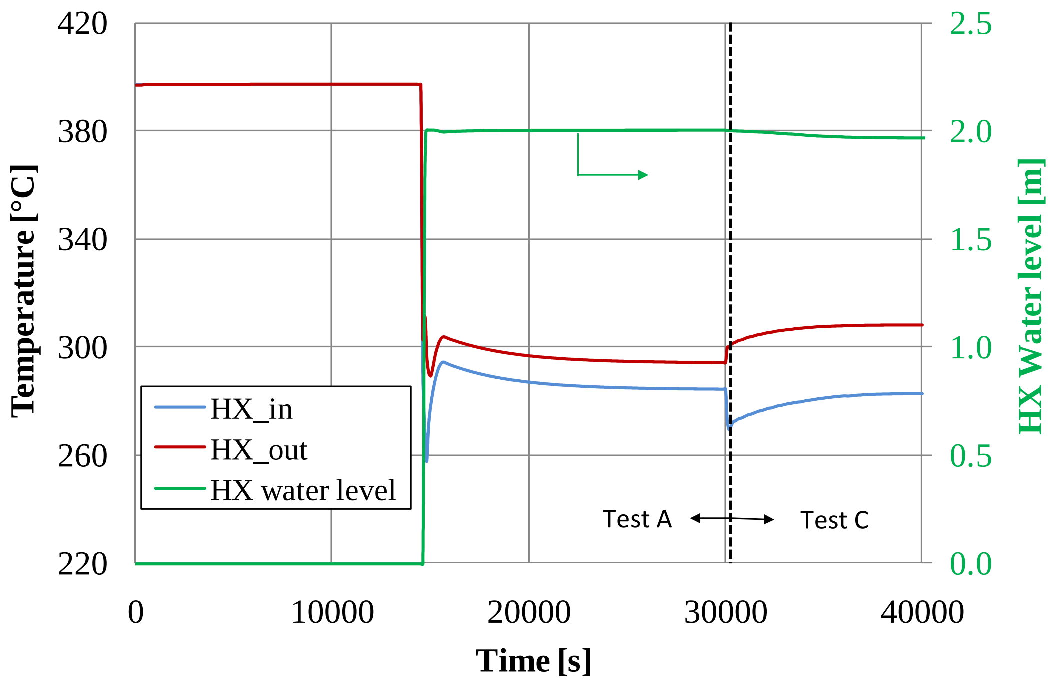

Figure 11. Time trend of the water level and of inlet and outlet temperature through the secondary side of HX (Test A + Test C)

4. CONCLUSIONS

The results obtained in the prediction by the RELAP5 code of start-up and steady state scenarios, such as shutdown simulation for the HELENA facility give important information about the thermal-hydraulic behaviour of both the primary and secondary circuits for what concerns lead temperature in the HS and water temperature in the HX, the lead flow rate inside the primary loop and the cooling capability of the air-cooler.

Two different tests have been performed to simulate a possible start-up and shutdown procedure for the entire facility, which can be useful to set up a future experimental campaign.

The use of the Mikityuk correlation has led to obtain lead temperature values in line with the ones obtained with the Ushakov correlation already tested in previous work [11].

Furthermore, Test C has put in evidence the generation of buoyancy forces in the secondary loop when the pump failure accident took place, allowing, consequently, the removal of thermal power in the secondary loop of the HELENA facility also in natural circulation regime.

REFERENCES

[1] http://www.gen-4.org

[2] GIF, 2002, "A Technology Roadmap for Generation IV Nuclear Energy Systems", issues by the U.S. DOE Nuclear Energy Research advisory Committee and the Generation IV International Forum, Washington DC, USA, 2002.

[3] M. Carta, G. Gherardi, S. Buono, L. Cinotti, "The Italian R&D and Industrial Program for an Accelerator Driven System Experimental Plant", IAEA-TCM on Core Physics and Engineering Aspect of Emerging Nuclear Energy System for Energy Generation and Transmutation, ANL, Argonne, USA, 28th November-1st December 2000.

[4] L. Cinotti et al., "The eXperimental Accelerator Driven System (XADS) Designs in the EURATOM" 5th Framework Program – *Journal of Nuclear Materials*, Vol. 335, pp. 148-155, 2004.

[5] C. Fazio, A. Alamo, A. Almazouzi, D. Gomez-Briceno, F. Gröschel, F. Rölofs, P. Turroni, J.U. Knebel, "Assessment of Reference structural materials, heavy liquid metal technology and thermal-hydraulics for European Waste Transmutation ADS", *Proceedings of GLOBAL*, Tsukuba, Japan, 9th-13th October, 2005.

[6] H.A. Abderrahima, P. Kupschusa, E. Malambua, Ph. Benoita, K. Van Tichelen, B. Ariena, F. Vermeerscha, P. D'hondta, Y. Jongenb, S. Ternierb, D. Vandeplassche, MYRRHA: A multipurpose accelerator driven system for research & development, *Nuclear Instruments and Methods in Physics Research* A, vol. 463, pp. 487-494, 2001.

[7] M. Tarantino, "Progettazione concettuale dell'impianto a metallo liquido pesante HELENA per la qualifica di componenti per sistemi LFR", Report ENEA NNFISS-LP3-010, September, 2011.

[8] N. Forgione, F. Oriolo, S. Palazzo, "RELAP 5 Pre-test Analysis on the HELENA Facility for Operational Transients", CIRTEN-UNIPI RL 1076/2010, Pisa, September 2010.

[9] K. Mikityuk, "Heat Transfer to Liquid Metal: Review of Data and Correlations for Tube Bundles", *Nuclear Engineering and Design*, Vol. 239, pp. 680-687, 2009.

[10] W. Pfrang, D. Struwe, "Assessment of correlations for heat transfer to the coolant for heavy liquid metal cooled core designs", Report Forschungszentrum Karlsruhe (FZK) – Institut für Reaktorsicherheit, FZKA 7352, 2007.

[11] G. Coccoluto, P. Gaggini, V. Labanti, M. Tarantino, W. Ambrosini, N. Forgione, A. Napoli, F. Oriolo, “Heavy Liquid Metal Natural Circulation in a One – Dimensional Loop”, *Proceedings of 17th International Conference on Nuclear Engineering, ICONE 17* – 75813, Brussels (Belgium), July 2009.

Appendix A:

Secondary loop nodalization

Secondary loop nodalization

The RELAP5 secondary loop nodalization, set up to study the thermal-hydraulics behavior of the operational transients of HELENA facility, is reported in Figure 5. Hereafter, the nodalization is explained in detail starting with the SNGLVOL 276 (in a clockwise direction).

Stainless steel AISI 304 is taken into account as structural material for the design of all the components of this loop, which have also a superficial roughness value of $3.2\cdot10^{-5}$ m and an external insulation of mineral rock-wool that gives an equivalent convective heat transfer coefficient, between the outside pipe walls and the external environment, of about 0.7 W/(m^2 K).

The initial water pressure inside the loop is 100 bar, while for the initial temperature values of 670.15 K and 293.15 K were imposed for the sub-loop B and a value of for the sub-loop A respectively, including the shared line (SNGLVOL 430, VALVE 431 and PIPE 432).

SINGLE VOLUME 276

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd} = 0.08544$ m

$A_{c\text{-}s} = 5.7334\text{e-}3$ m^2

$L = 0.025$ m (horizontal)

VALVE 277

It connects the outlet section of *snglvol* 276 with the inlet section of *pipe* 280, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The main purpose of this valve is to connect/disconnect the loop A from the loop B.

The opening of the valve is set so that when the temperature in the loop A reaches 563.15 K its opens. The time needed to completely open the valve is set equal to 1000 seconds.

The pressure loss coefficient considered in this *valve* is 1.0 both for forward and reversed flow.

PIPE 280

This component is initially filled with the non-condensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd} = 0.08544$ m

$A_{c\text{-}s} = 5.7334\text{e-}3$ m^2

$L = 1.0$ m (horizontal)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

BRANCH 285

It is a volume with three "internal" *junction* . The first *junction* (J-1) connects the outlet section of *pipe* 280 with the inlet section of *branch* 285, with a flow area that is taken equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow. The second *junction* (J-2) connects the *branch* 285 with the inlet section of *pipe* 290, with a flow area that is taken equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow. The third *junction* (J-3) connects *branch* 285 with the inlet section of *snglvol* 500, with a flow area that is taken equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow.

This component is initially filled with the non-condensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd} = 0.08544$ m

$A_{c\text{-}s} = 5.7334\text{e-}3$ m^2

$L = 0.025$ m (horizontal)

SINGLE VOLUME 500

This component is initially filled with the noncondensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd} = 0.08544$ m

$A_{c\text{-}s} = 5.7334\text{e-}3$ m^2

$L = 0.05$ m (vertical downward)

VALVE 501

It connects the outlet section of *snglvol* 500 with the inlet section of *snglvol* 502, with a flow area that is taken equal to the minimum flow area of the adjoining volumes (see Figure 5).

The main purpose of this valve is to act as a drain valve when the water from the loop B need to be empty at the end of an experimental test series.

SINGLE VOLUME 502

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.05 m (vertical downward)

TIME DEPENDENT VOLUME 510

It is totally filled with water that has a pressure of 100 bar during all the simulated transients.

The main geometrical parameters of this component located in the left side of the secondary loop (see Figure 5), are:

$A_{c\text{-}s}$ = 100.0 m^2

L = 1.0 m (horizontal)

PIPE 290

This component is initially filled with the non-condensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the left side of the secondary loop (see Figure 3), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.2 m (vertical, upward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 295

It connects the outlet section of *pipe* 290 with the inlet section of *annulus* 310, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 3). The pressure loss coefficient considered in this *junction* is 0.29 both for forward and reversed flow.

ANNULUS 310

This *annulus* represents the secondary side of the heat exchanger (HX). In particular, the water flows upward through the outer side of the coaxial pipes of HX, while the liquid lead circulates inside the pipes in counter-current direction.

This component is initially filled with the non-condensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the left side of the secondary loop (see Figure 5), are:

D_{hyd} = 0.06555 m

D_i = 0.3446 m

$A_{c\text{-}s}$ = 0.049815 m^2

L = 2.0 m (vertical, upward)

The pipe thickness used for the associated thermal structure is equal to 0.0309 m.

SINGLE JUNCTION 315

It connects the outlet section of *annulus* 310 with the inlet section of *pipe* 330, with a flow area that is taken equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.28 both for forward and reversed flow.

PIPE 330

This component is initially filled with the non-condensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the left side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.25 m (vertical, upward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 335

It connects the outlet section of *pipe* 330 with the inlet section of *pipe* 340, with a flow area that is taken equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow.

PIPE 340

This component is initially filled with the noncondensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 1.0 m (horizontal)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

BRANCH 341

It is a volume with three “internal” *junction* . The first *junction* (J-1) connects the outlet section of *pipe* 340 with the inlet section of *branch* 341, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow. The second *junction* (J-2) connects the outlet section of *branch* 341 with the inlet section of *snglvol 342*, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow. The third *junction* (J-3) connects the inlet section *branch* 341 with the inlet section of *pipe* 470, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow. This component is initially filled with the non-condensable gas (argon); after the opening of the valves, the gas will be replaced by water.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.05 m (vertical upward)

SINGLE VOLUME 342

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.025 m (horizontal)

VALVE 343

It connects the outlet section of *snglvol* 342 with the inlet section of *sngvol* 344, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The main purpose of this valve is to connect/disconnect the loop A with the loop B.

The opening of the valve is set so that when the void fraction of the pipe 340 reaches 0.1% its opens. The time needed to completely open the valve is set equal to 100 seconds.

The pressure loss coefficient considered in this *valve* is 1.0 both for forward and reversed flow.

SINGLE VOLUME 344

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.025 m (horizontal)

BRANCH 345

It is a volume with three "internal" *junction* . The first *junction* (J-1) connects the outlet section of *snglvol* 344 with the inlet section of *branch* 345, with a flow equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow. The second *junction* (J-2) connects the outlet section of *branch* 345 with the inlet section of *pipe 350*, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow. The third *junction* (J-3) connects the outlet section of *pipe* 432 with the inlet section of *branch 345*, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow.

The main geometrical parameters of this component, located in the left side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.05 m (horizontal)

PIPE 350

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 1.0 m (horizontal)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 351

It connects the outlet section of *pipe* 350 with the inlet section of *pipe* 352, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow.

PIPE 352

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 1.7 m (vertical upward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

BRANCH 353

This volume represents the inlet part of the expansion vessel. It includes three “internal” *junctions*, which connect it to the downward region of the loop. The first *junction* (J-1) connects the outlet section of *pipe* 352 with the inlet section of *branch* 353, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow. The second *junction* (J-2) connects the *branch* 353 with the inlet section of the *heater* 354, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is zero both for forward and reversed flow. The third *junction* (J-3) connects *branch* 353 with the inlet section of *pipe* 460, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is zero both for forward and reversed flow.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd} = 0.762$ m

$A_{c\text{-}s} = 0.5984734$ m^2

$L = 0.05$ m (horizontal)

PIPE 354

This *pipe* represents the heating section of the loop and the lower part of the expansion vessel component. The thermal power is generated by ten cylindrical rods disposed in a square rod array having an active length of 0.65 m.

The main geometrical parameters of this component, located in the right side of the secondary loop (see Figure 5), are:

$D_{hyd} = 0.762$ m

$D_{\text{heating rod}} = 0.003$ m

$A_{c\text{-}s} = 0.5984734$ m^2

$L = 0.65$ m (vertical downward)

The pipe thickness used for the associated thermal structure is equal to 0.0127 m.

SINGLE JUNCTION 355

It connects the outlet section of *pipe* 354 with the inlet section of *pipe* 356, with a flow area that is taken equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.8 both for forward and reversed flow.

PIPE 356

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 1.0 m (vertical downward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 357

It connects the outlet section of *pipe* 356 with the inlet section of *pipe* 360, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow.

PIPE 360

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 1.05 m (horizontal)

The pipe thickness used for the associated thermal structure is 0.00808 m.

SINGLE JUNCTION 365

It connects the outlet section of *pipe* 360 with the inlet section of *air-cooler* 370, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.6 both for forward and reversed flow.

PIPE (air-cooler) 370

This component simulates the behavior of a possible air-cooler. It was simulated by taking 64 finned parallel pipes connected by two collectors. The air-cooler is a cross-flow air/water with forced air having a nominal velocity of about 10 m/s.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

D_{hyd} = 0.01388 m

D_i =0.01388 m

$A_{c\text{-}s}$ = 0.00968386 m^2

L = 2.0 m

The pipe thickness used for the associated thermal structure is equal to 0.00277 m (thickness of the single tube).

SINGLE JUNCTION 375

It connects the outlet section of *pipe* 370 with the inlet section of *pipe* 380, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.95 both for forward and reversed flow.

PIPE 380

The main geometrical parameters of this component, located in right side of the secondary loop (see Figure 5), are:

D_i = D_{hyd} = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.75 m (vertical downward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 385

It connects the outlet section of *pipe* 380 with the inlet section of *pipe* 390, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow.

PIPE 390

The main geometrical parameters of this component, located in right side of the secondary loop (see Figure 5), are:

D_i = D_{hyd} = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 1.0 m (vertical downward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 395

It connects the outlet section of *pipe* 390 with the inlet section of *pipe* 400, with a flow area that is taken equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow.

PIPE 400

The main geometrical parameters of this component, located in right side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.8 m (vertical downward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 405

It connects the outlet section of *pipe* 400 with the inlet section of *pipe* 410, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow.

PIPE 410

The main geometrical parameters of this component, located in lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.7 m (horizontal)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

TIME DEPENDENT JUNCTION 415

It connects the outlet section of *pipe* 410 with the inlet section of *branch* 420, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). Its main purpose is to impose the mass flow rate according to the criteria summarized in the following table.

Time [s]	Mass flow rate [kg/s]
0.0	0.0
100.0	0.0
200.0	4.57
1.0e6	4.57

BRANCH 420

It is a volume with two "internal" *junctions*. The first *junction* (J-1) connects the outlet section of *pipe* 410 with the inlet section of *branch* 420, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 3.1 or forward flow and 1.0e7 for reversed flow. The high value of the reversed flow pressure loss coefficient avoid that it could act as a pump bypass (tmpdjun 415) during pump operation, but allow the presence of natural circulation if the pump accidentally stop.

The second *junction* (J-2) connects the *branch* 420 with the inlet section of *pipe 260*, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow.

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd} = 0.08544$ m

$A_{c\text{-}s} = 5.7334\text{e-}3$ m^2

$L = 0.05$ m (horizontal)

PIPE 260

This *pipe* represents the section of the loop in which two different mass flow meters are expected to be installed.

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd} = 0.08544$ m

$A_{c\text{-}s} = 5.7334\text{e-}3$ m^2

$L = 4.5$m (horizontal)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

SINGLE JUNCTION 265

It connects the outlet section of *pipe* 260 with the inlet section of *pipe* 270, with a flow area that is taken equal to the minimum flow area of the adjoining volumes (see Figure 5). The pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow.

PIPE 270

The main geometrical parameters of this component, located in the lower side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 1.25 m (horizontal)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

BRANCH 275

It is a volume with three "internal" *junctions*. The first *junction* (J-1) connects the outlet section of *pipe* 270 with the inlet section of *branch* 275 with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is zero both for forward and reversed flow. The second *junction* (J-2) connects the outlet section of *branch* 275 with the inlet section of *snglvol* 430, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 1.0 both for forward and reversed flow because of the presence of T-junction. The third *junction* (J-3) connects the outlet section of *branch* 275 with the inlet section of *snglvol* 276 with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow.

The main geometrical parameters of this component (see Figure 5) are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.025 m (horizontal)

SINGLE VOLUME 430

The main geometrical parameters of this component, located in the middle side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 0.05 m (vertical upward))

VALVE 431

It connects the outlet section of *snglvol* 430 with the inlet section of *pipe* 432, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5). The main purpose is to connect/disconnect the loop A with the loop A.

The opening of the valve is set so that when the temperature in the loop A reaches 563.15 K its closes. The time needed to completely close the valve is set equal to 500 seconds.

PIPE 432

The main geometrical parameters of this component, located in the middle side of the secondary loop (see Figure 5), are:

D_i = D_{hyd} = 0.08544 m

$A_{c\text{-}s}$ = 5.7334e-3 m^2

L = 2.45 m (vertical upward)

The pipe thickness used for the associated thermal structure is equal to 0.00808 m.

PIPE 460

It represents the upper part of the expansion vessel that is only partially filled with water, in order to contain the variation of fluid volume during the transient. In particular, with the secondary fluid at rest, around 33% of its volume is filled with lead and the remaining 77% with argon.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

D_i = D_{hyd} = 0.762 m

$A_{c\text{-}s}$ = 0.5984734 m^2

L = 0.75 m (vertical, upward)

BRANCH 465

It is a volume with three “internal” *junction*s. The first *junction* (J-1) connects the outlet section of *pipe* 460 with the inlet section of *branch* 465, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.5 both for forward and reversed flow. The second *junction* (J-2) connects the outlet section of *pipe* 480 with the inlet section of *branch 465*, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow. The third *junction* (J-3) connects the outlet section of *branch* 465 with the inlet section of *tmpdvol 490*, with a flow area equal to the minimum flow area of the adjoining volumes; the pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.762m

$A_{c\text{-}s}$ = 0.5984734 m^2

L = 0.05 m (vertical)

PIPE 470

This pipe, together with the pipe 480, connect the upper side of the Loop B directly with the expansion vessel.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 3), are:

$D_i = D_{hyd}$ = 0.02431 m

$A_{c\text{-}s}$ = 4.64415e-4 m^2

L = 2.50 m (vertical upward)

The pipe thickness used for the associated thermal structure is equal to 0.00455 m.

SINGLE JUNCTION 475

It connects the outlet section of *pipe* 470 with the inlet section of *pipe* 480, with a flow area equal to the minimum flow area of the adjoining volumes (see Figure 5).

The pressure loss coefficient considered in this *junction* is 0.0 both for forward and reversed flow.

PIPE 480

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$D_i = D_{hyd}$ = 0.02431 m

$A_{c\text{-}s}$ = 4.64415e-4 m^2

L = 1.10 m (horizontal)

The pipe thickness used for the associated thermal structure is equal to 0.00455 m.

TIME DEPENDENT VOLUME 490

It is totally filled with argon that has a pressure of 100 bar during all the simulated transients.

The main geometrical parameters of this component, located in the upper side of the secondary loop (see Figure 5), are:

$A_{c\text{-}s}$ = 100.0 m^2

L = 1.0 m (horizontal)