Italian National Agency for New Technologies, Energy and Sustainable Economic Development

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STATE-OF-THE-ART REVIEW OF THE T/H SYSTEM CODES RELAP5 FOR HLM APPLICATIONS

Technical Meeting on State-of-the-art Thermal Hydraulics of Fast Reactors

September 26th , 2022

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Introduction

TH codes

- The aim of TH analysis is to indicate if the analyzed nuclear object with the available safety systems is able to withstand an accident sequence and what the potential consequences of and accident are, along with the related timescale

- The simulation results play a key role in designing, licensing and operating the NPPs. The codes are required because NPPs systems work at a highly sophisticated level that surpasses the capabilities of the human mind and simple, basic theoretical models

- With the increasing quality of data and the models implemented, it is possible to create a more realistic thermal-hydraulic analysis, which uses data from probabilistic codes to choose the most probable accidental scenario

Introduction

TH code V&V

- The thermal-hydraulic codes used for safety analysis need to be adequately subjected to a process called **Verification and Validation (V&V)**
- **Verification**: describes the accuracy of the translation of physical equations to the computer code language
- **Validation**: determines the correctness of the mathematical models, which have to be realistic representation of the systems. Validation is usually performed by comparing the results obtained from the model and experiments
- The validation process shows uncertainties and inaccuracies in models, which need to be taken into account later in the safety analysis process

Verification

Solving the equations right (mathematics)

- Solution uniqueness
- Solution stability
- No physical experiments in verification

Validation

Solving the right equations (science/engineering)

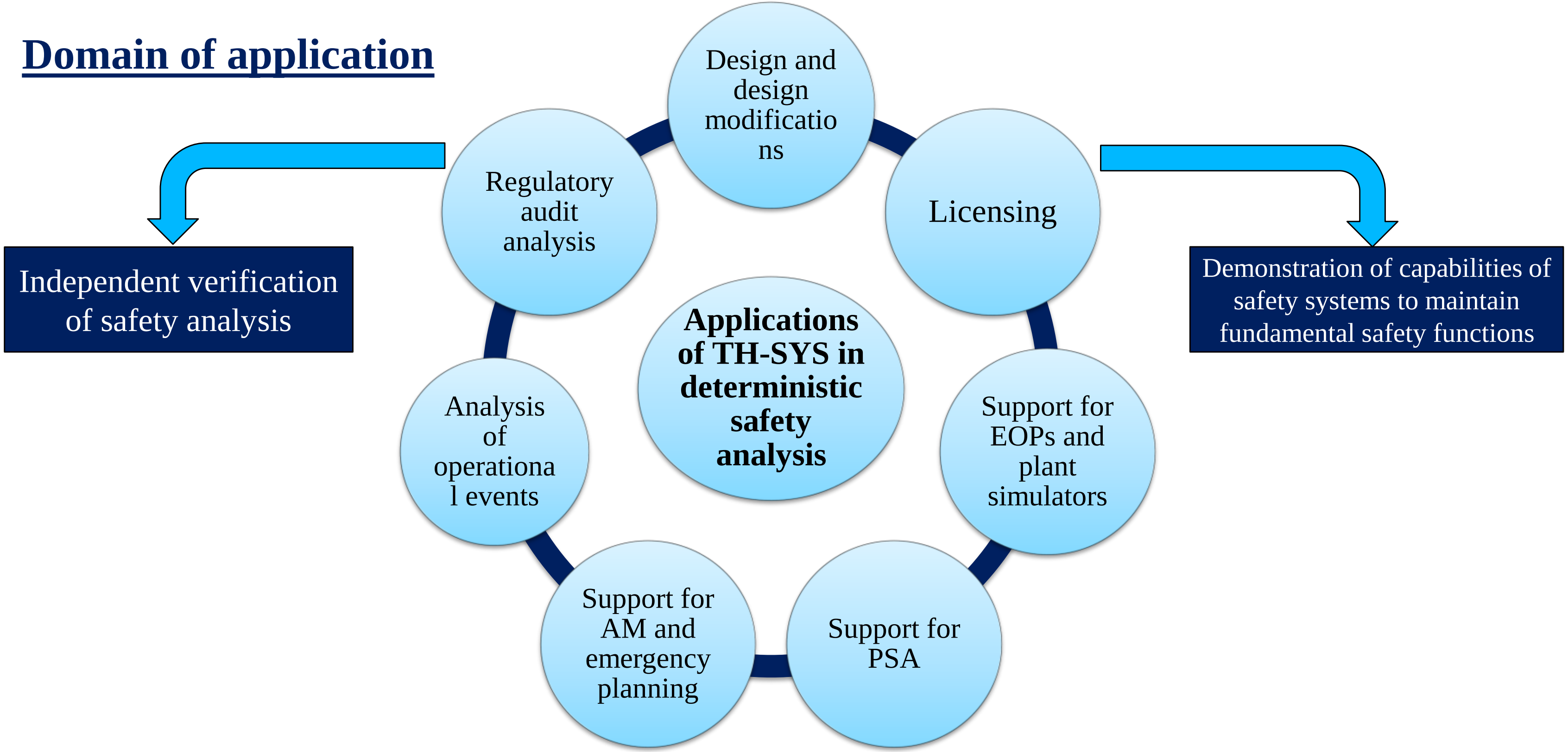
- Support of experimental data for verification

Certification

- Qualification
- Engineering management

Introduction

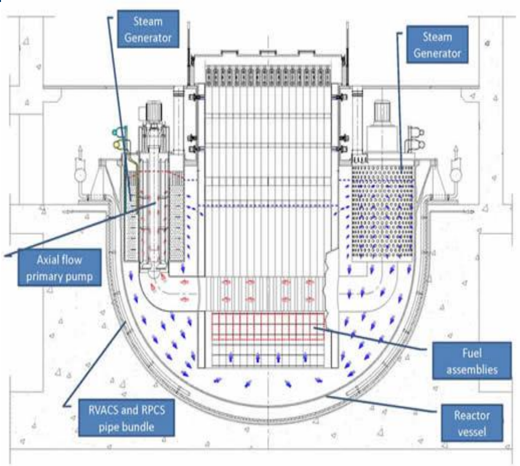
Domain of application



Introduction

HLM reactor system: requirements for TH-SYS code

- **TH-SYS codes are used for LWR**
  - capability to simulate a wide range of working fluids ☺
- **Extensively used and validated for TH analysis of LWR**
  - limited validation for other working fluids ☹



- **Gen IV LFR and ADS concepts development: LBE and Lead for PS**
  - EC framework programme and National projects support their development
  - TH-SYS codes applied for preliminary design, preliminary accident analysis and scoping calculations
  - TH-SYS codes used to support exp. activities (planned and ongoing) and vice-versa
  - Development, verification, validation independent assessment limited

RELAP5 TH-SYS code

RELAP5 SYS-TH code

Reactor Excursion and Leak Analysis Program

- The RELAP5/MOD3.3 code has been developed for **best estimate transient simulation of light water reactor coolant systems during postulated accidents**
- The code models the coupled behavior of the reactor coolant system and the core for loss of coolant accidents and operational transients such as anticipated transient without scram, loss of offsite power, loss of feedwater, and loss of flow
- A generic modelling approach is used that **permits simulating a variety of thermal hydraulic systems**
- Control system and secondary system components are included to permit modelling of plant controls, turbines, condensers, and secondary feedwater systems

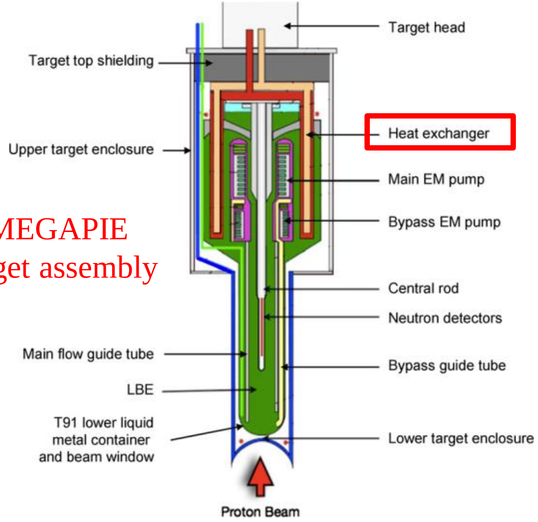
- RELAP5 has been originally developed by the NRC (Nuclear Regulatory Commission). Currently it continues to be developed by private American research organizations:
  - ISS: RELAP/SCDAPSIM mod 3.4 e 4.0 (F95)
  - INL: RELAP 3D ver. 4.0

- Nowadays it is the most widely used thermo-hydraulic code in the nuclear industry

RELAP5 qualification in MEGAPIE

MEGAWatt Pilot Experiment (MEGAPIE), dedicated to the design, manufacturing and testing of a liquid metal spallation target have provided relevant data from the thermal hydraulic measurements, which offered the opportunity to qualify the codes used in the design phase

MEGAPIE
target assembly

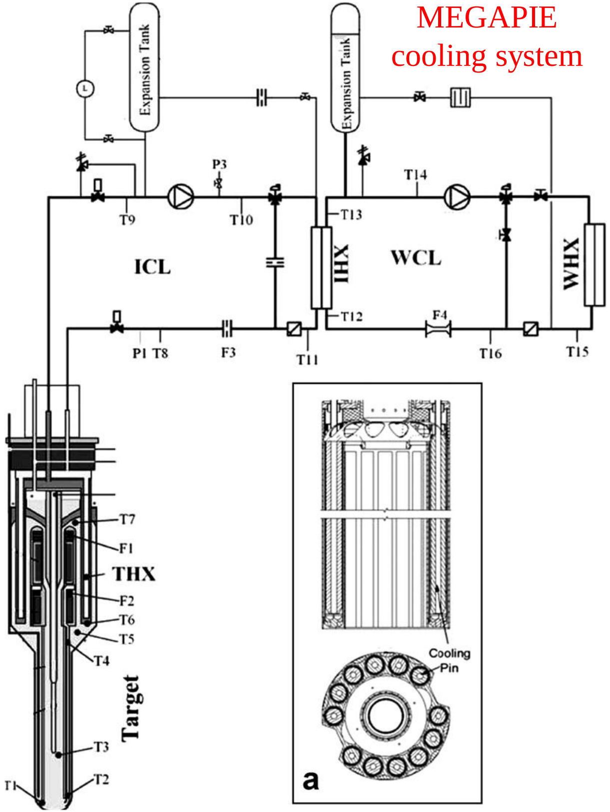


Target cooling system composed by a triple-loop

- The primary LBE loop
- an intermediate cooling loop (ICL) filled with oil (Diphyl THT)
- and a water cooling loop (WCL)

Heated LBE flowed upward through the guide tube to reach the THX where it was cooled and, afterwards, returned to the pump. In the THX the heat was transferred to ICL. The WCL was used to cool the Diphyl oil

MEGAPIE
cooling system



Zanini, L., et al., Experience from the post-test analysis of MEGAPIE, Journal of Nuclear Materials, Volume 415, Issue 3, 31 August 2011, Pages 367-377

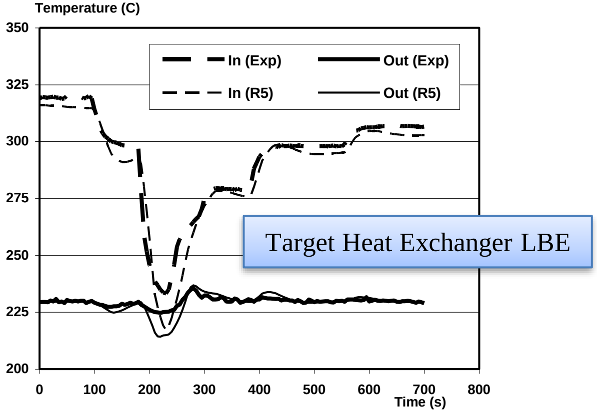
RELAP5 qualification in MEGAPIE

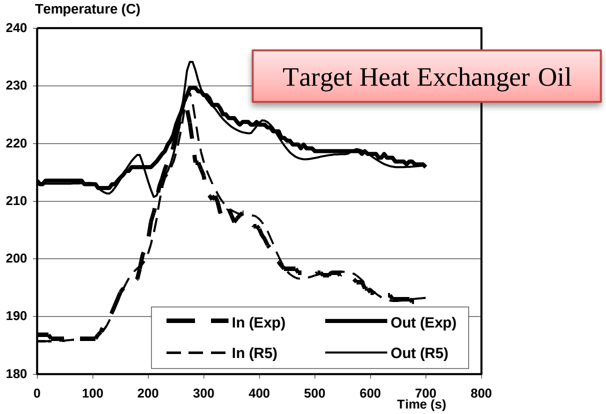
MEGAPIE Target Experiment has provided data on the T/H behavior of the cooling system to support the qualification of RELAP5 mod3.2.2β version for transient and safety analysis of LBE and Lead cooling systems

Gnielinski correlation has been implemented in RELAP5 to correctly predict the thermal exchange in the oil side of THX (LBE-oil Target Heat Exchanger)

Target Power 540.3 kW		Exp.	RELAP5 standard	RELAP Gnielinsky
THX LBE	Mflow (kg/s)*	41.23	imposed	imposed
	T1(inlet) °C	319.6	316.2	316.2
	T2(outlet) °C	229.5	imposed	imposed
THX Oil	Mflow (kg/s)	9.25	imposed	imposed
	T3(inlet) °C*	185.8	175.4	185.3
	T4(outlet) °C	212.9	203.5	212.6
IHX Oil	Mflow (kg/s)	N.A.	2.93	2.72
	T5(inlet) °C	214.4	204.1	212.9
	T6(outlet) °C	112.0	109.4	110.7
IHX Water	Mflow (kg/s)	8.04	imposed	imposed
	T7(inlet) °C	33.8	imposed	imposed
	T8(outlet) °C	49.3	50.3	50.1

Zanini, L., et al., Experience from the post-test analysis of MEGAPIE, Journal of Nuclear Materials, Volume 415, Issue 3, 31 August 2011, Pages 367-377

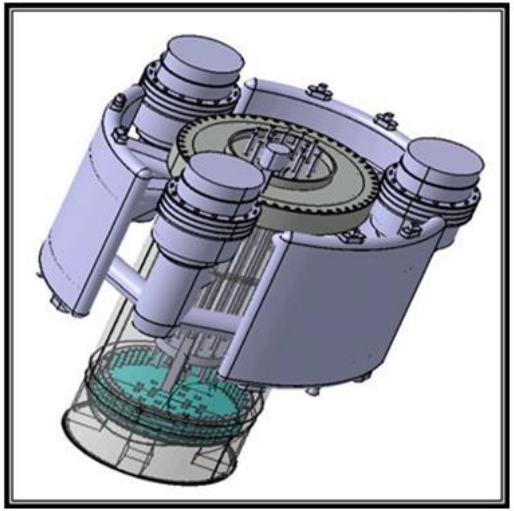


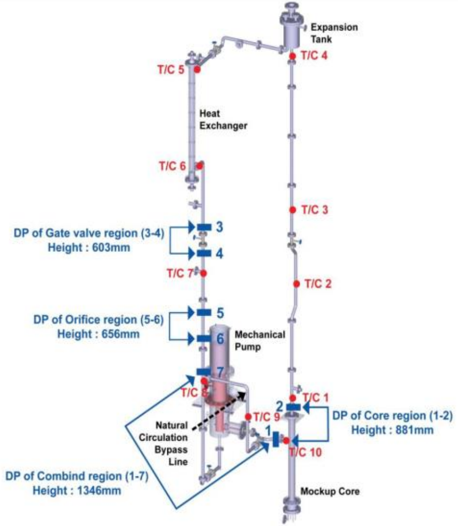


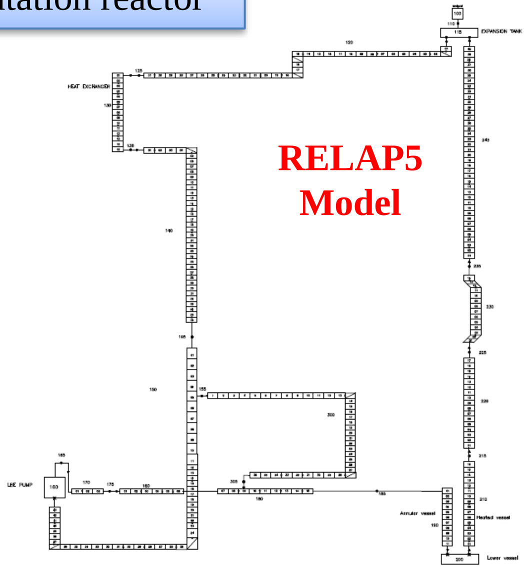
RELAP5 qualification in LACANES benchmark

In the framework of **LACANES OECD/NEA benchmark**, RELAP5 has been used to simulate the T/H behaviour of the **LBE loop HELIOS** both in forced and in natural conditions.

HELIOS loop is a T/H scaled facility of the PEACER-300, an LBE-cooled transmutation reactor







PEACER-300

HELIOS

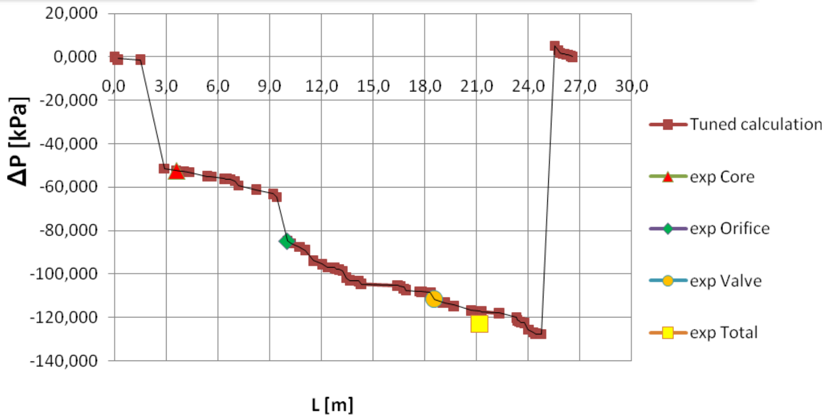
Nitti, F.S.; Meloni, P.; RELAP5 Code Validation in the Framework of the LACANES OECD/NEA Benchmark for HLM Innovative Nuclear System," Proceeding of NUTHOS8

RELAP5 qualification in LACANES benchmark

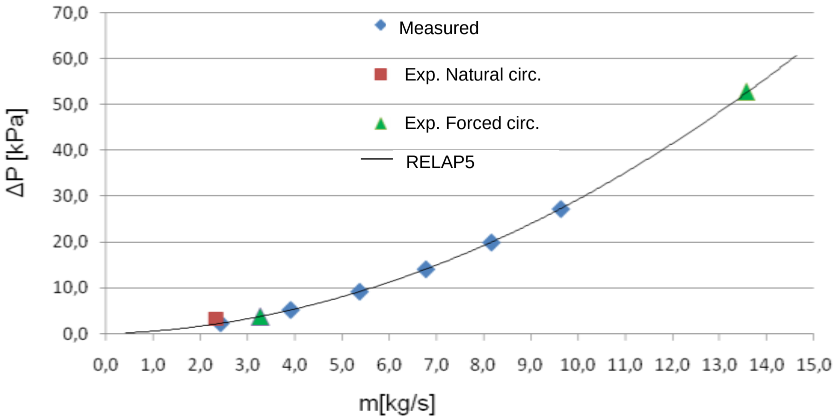
In the first phase of the LACANES benchmark, **two different forced circulation steady states** have been considered in order to assess the distributed and local pressure drops calculated by RELAP5. Lately, an upgraded model has been developed to characterize the **natural circulation** in the loop.

RELAP5 code modified including the physical and thermodynamics properties for Pb, Pb-Bi and for diathermic Oil, as well as implementing new correlations for HLMs. Specific heat transfer correlations were added: convective heat transfer for heavy liquid metals, evaluated according to **Seban-Shimazky (pipe) or Subbotin-Ushakov (tube bundle), and for oil helical path (Gnielinsky)**

Pressure drop in a tuned-calculation Vs experimental data for a mass flow rate of 13.57 kg/s



Core pressure drop Vs mass flow

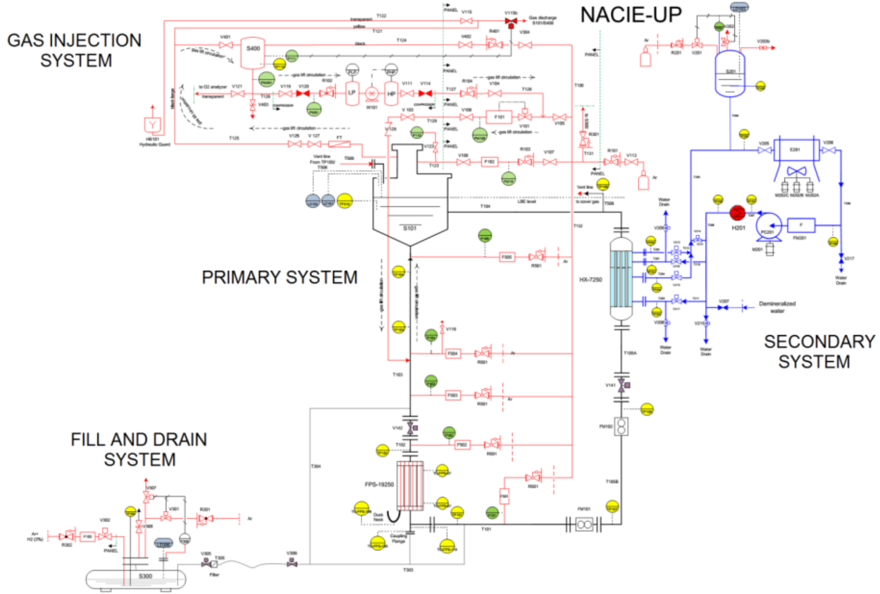


RELAP5 qualification in NACIE-UP loop-type facility

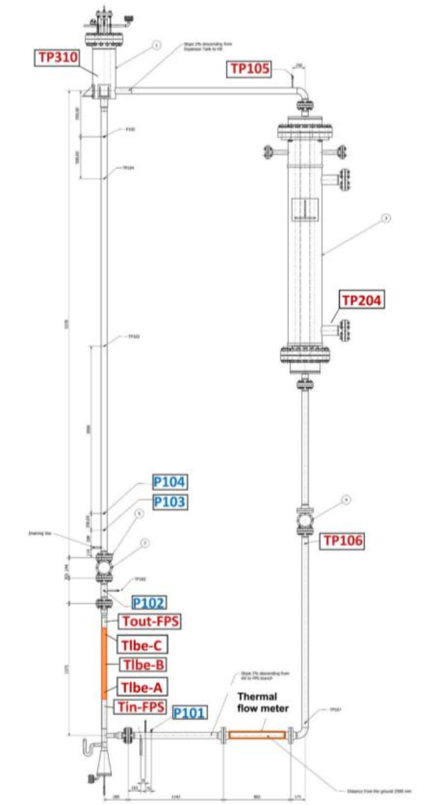
- **Participation** to **SYS-TH code Benchmark** on NACIE-UP
  - ✓ RELAP5-3D analysis – steady state, transient and accidental scenarios
  - ✓ Validation of system code against experimental data

NACIE-UP
LBE facility

NACIE-UP – Natural CIrculation Experiment – UPgraded



RELAP5 qualification in NACIE-UP loop-type facility



Coolants:
- **Primary**: Lead Bismuth Eutectic (LBE)
- **Secondary**: pressurized water (16 bar)

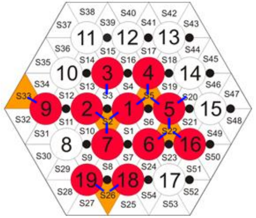
LBE Flow regimes:
- Natural Circulation
- Forced (gas-enhanced) circulation (by Argon)

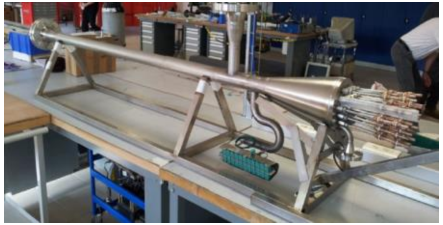
Heat Exchanger

- ❖ Shell-and-tube exchanger
- ❖ 7 pipes LBE side
- ❖ Power duty of 250 kW
- ❖ Low power section with an active length of 300 mm
- ❖ High power section with an active length of 2100 mm

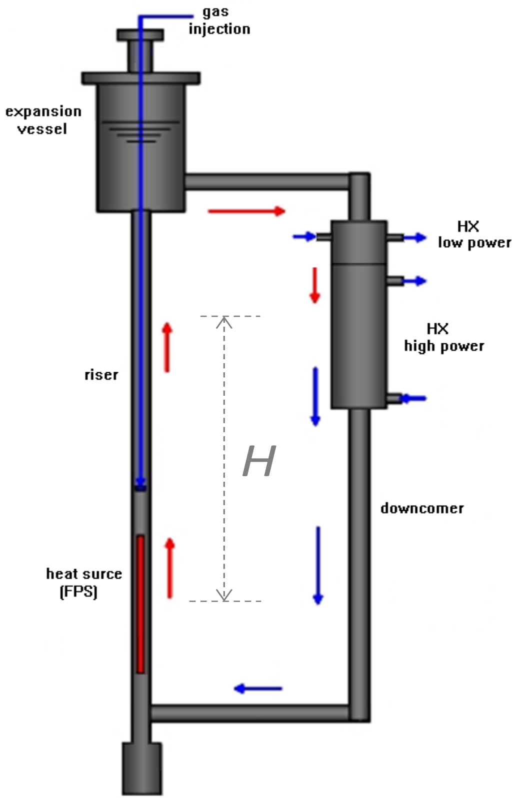
Fuel Pin Simulator – MYRRHA Fuel Assembly

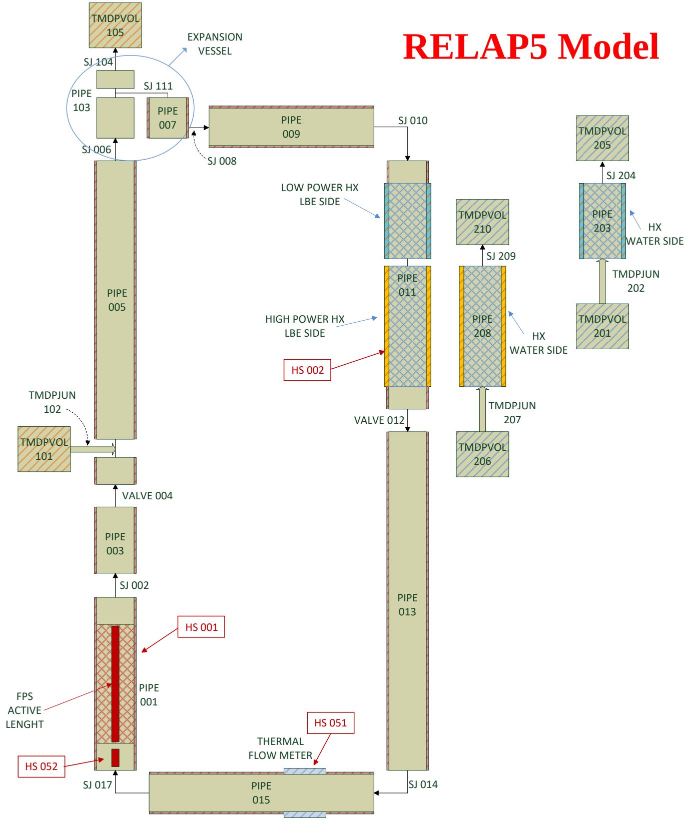
- ❖ 19 pins in hexagonal bundle
- ❖ 235 kW maximum power
- ❖ Total length 2000 mm
- ❖ Active length 600 mm



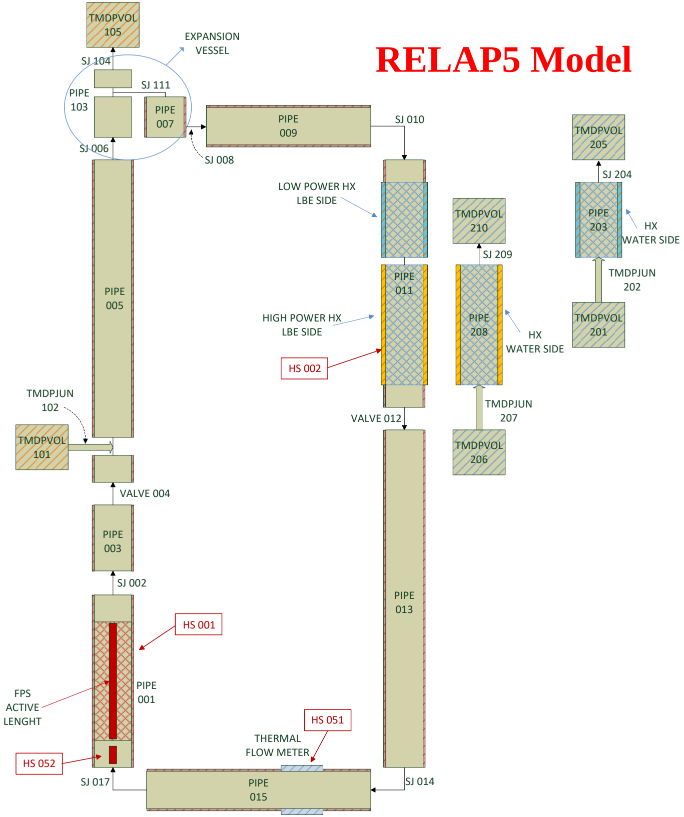


RELAP5 qualification in NACIE-UP loop-type facility





RELAP5 qualification in NACIE-UP loop-type facility



Hydrodynamic model

TMDPVOL 101 and TMDPJUN 102 **simulate the argon injection system** while TMDPVOL 105 assures the outlet of the gas;

TMDPVOL 201 and TMDPJUN fix the **water inlet conditions requested in the low power section of the heat exchanger**; the time dependent volume 205 represents the outlet of the water,

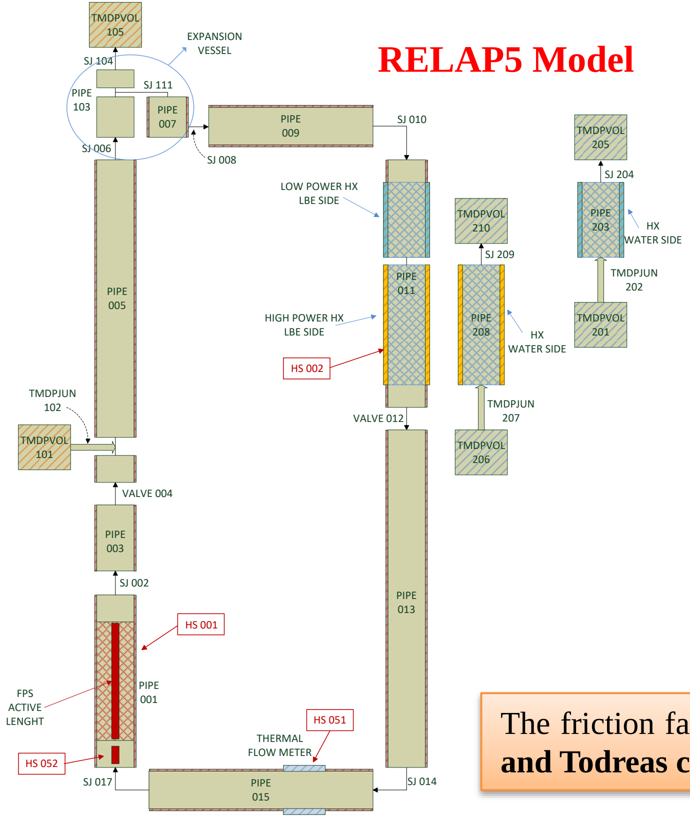
At the same way, TMDPVOL 206, TMDPJUN 207 and TMDPVOL 210 manage **the water flow in the high power section of the HX**.

All the components (i.e. FPS, HX, expansion tank, piping) hydrodinamically reproduced

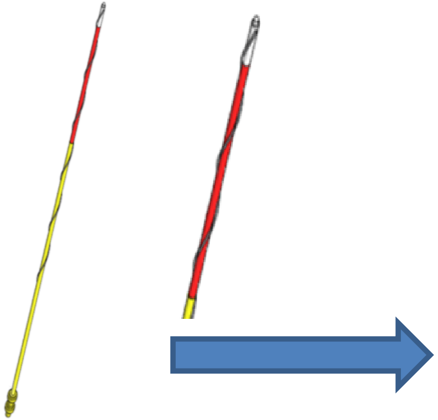
Cell sizing set in order to match the correct instrumentation positions

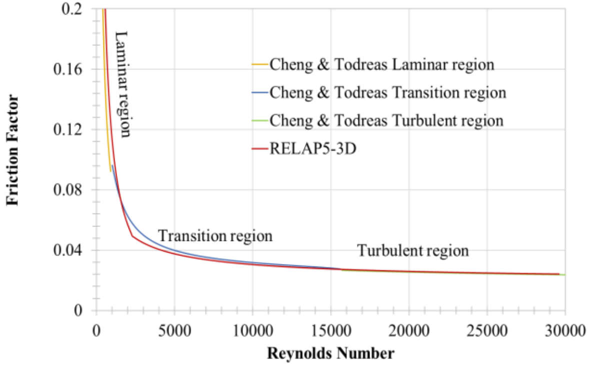
RELAP5 qualification in NACIE-UP loop-type facility

RELAP5 Model



RELAP5-3D have the possibility to insert only two correlations (one for laminar zone and one for turbulent). The difference is the transition zone: in R5-3D a linear interpolation from the laminar friction evaluated with Re=2200 and the turbulent friction with Re=3000 is imposed. For this few differences from Cheng and Todreas correlations and the implemented friction factor in Figure 12 are presents.

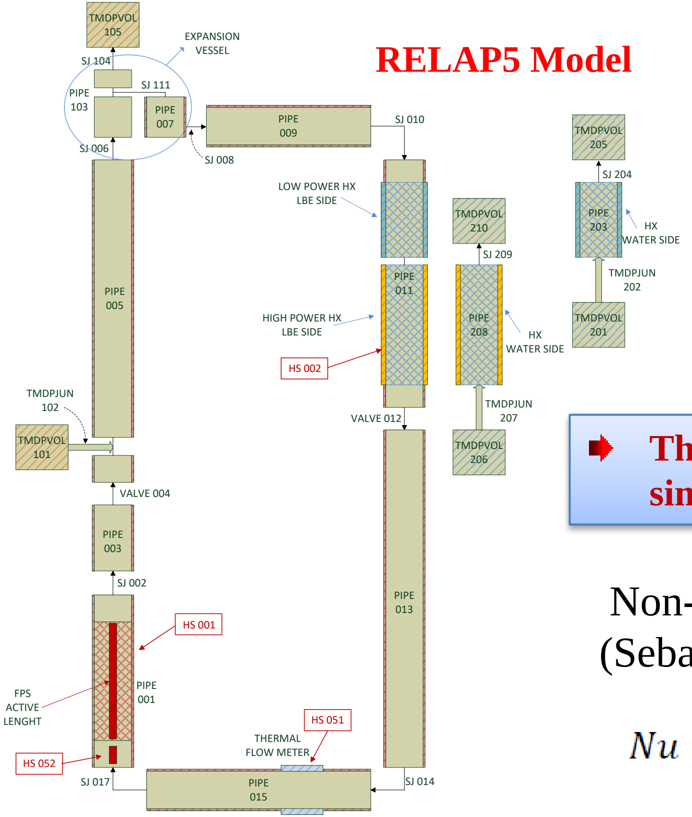




The friction factor for the wire-wrapped rod bundle has been evaluated with the **Detailed Cheng and Todreas correlation** *(S.K.Chen et al. / Nuclear Engineering and Design 267 (2014) 109-131)*

RELAP5 qualification in NACIE-UP loop-type facility

RELAP5 Model



Thermal coupling

The thermal coupling has been simulated with the heat structures:

- Between the pins of the FPS and the LBE in the primary side
- Between the LBE of the primary side and the water in the secondary system
- Between the primary system and the external environment

The 19 pins of the FPS and the seven pipes of the HX have been simulated with a single equivalent heat structure respectively

Non-bundle geometry
(Seban and Shimazaki)

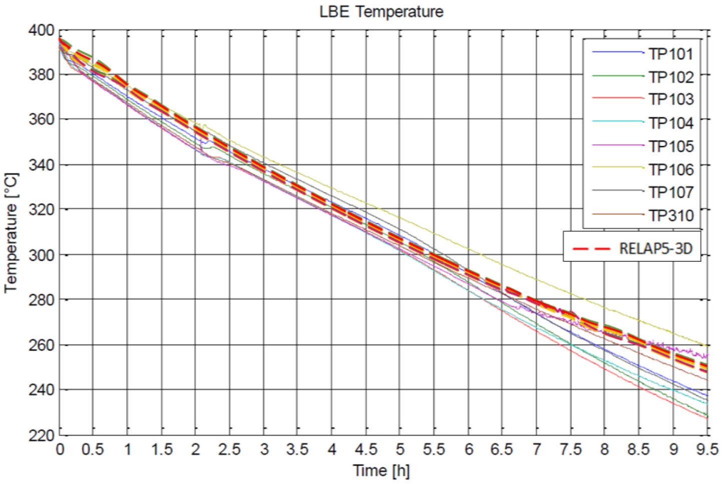
$$Nu = 5 + 0.025Pe^{0.8}$$

Bundle geometry
(Kazimi and Carelli)

$$Nu = 4.0 + 0.33\left(\frac{p}{d}\right)^{3.8}\left(\frac{Pe}{100}\right)^{0.86} + 0.16\left(\frac{p}{d}\right)^{5}$$

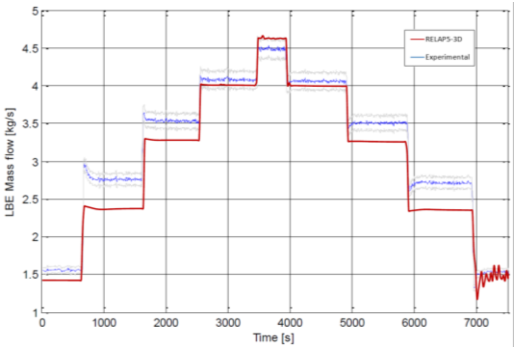
RELAP5 qualification in NACIE-UP loop-type facility

Preliminary Test 1 – Heat Losses



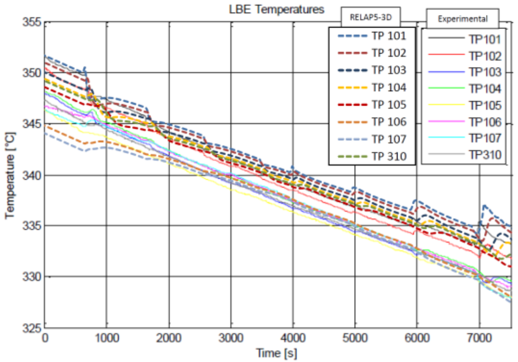
The test ends when the LBE temperature decreases up to 250°C. The cooling time is very close to the experimental value of 9.5 h

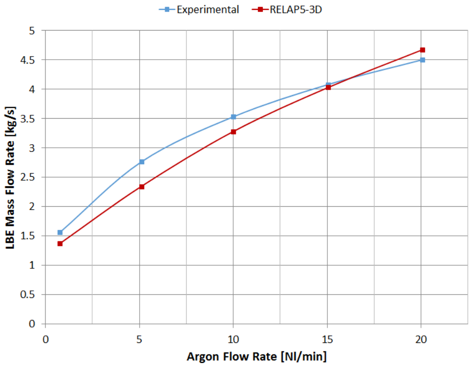
Preliminary Test 2 – Isothermal transition



At high mass flow rates the agreement with the experimental values is better than lower flow rates.

Pressure drops calibration



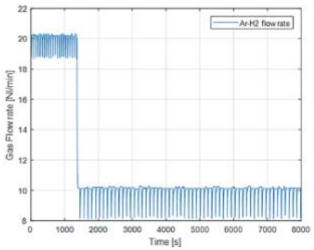
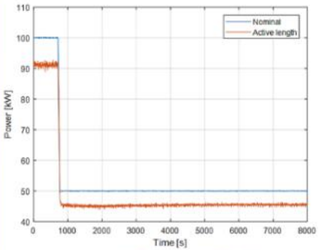
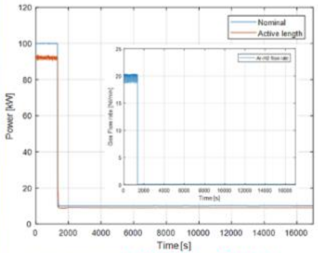


RELAP5 qualification in NACIE-UP loop-type facility

TEST MATRIX

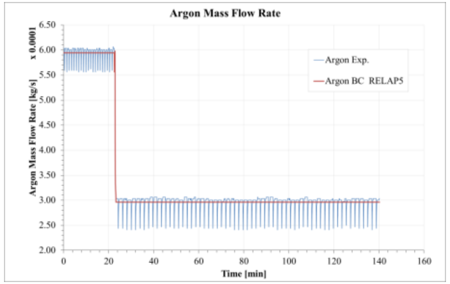
The experimental campaign consisted in three transients (operative and accidental) relevant for HLM nuclear systems

Forgione N., et al.; Post-test simulations for the NACIE-UP benchmark by STH codes, Nuclear Engineering and Design 353 (2019) 110279

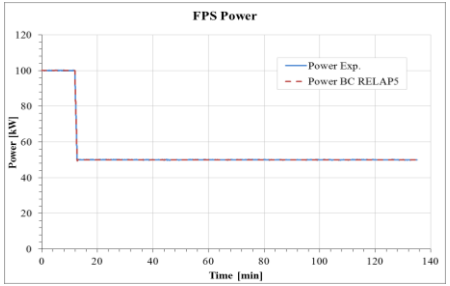
Test 1	Test 2	Test 3
Gas-lift transition	*Power transition*	*PLOFA*
		
• FPS power 50 kW • $\dot{m}_{gas}$ = 20 Nl/min → 10 Nl/min • $\dot{m}_{H_2O}$ = 10 m³/h • $T_{in,\,H_2O}$ = 170°C	• FPS power 100 kW → 50 kW • $\dot{m}_{gas}$ = 18 Nl/min • $\dot{m}_{H_2O}$ = 6.6 m³/h • $T_{in,\,H_2O}$ = 170°C	• FPS power 100 kW → 10 kW • $\dot{m}_{gas}$ = 20 Nl/min → 0 Nl/min • $\dot{m}_{H_2O}$ = 10 m³/h • $T_{in,\,H_2O}$ = 170°C

RELAP5 Boundary conditions

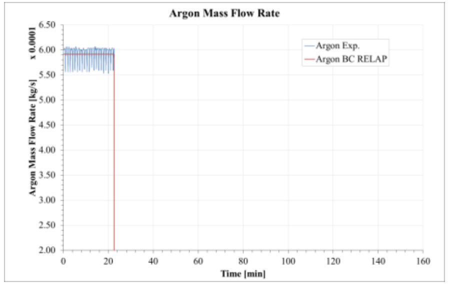
Gas Injection Transition



Power Transition

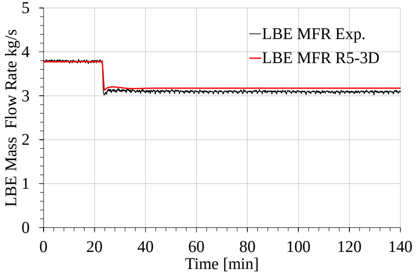


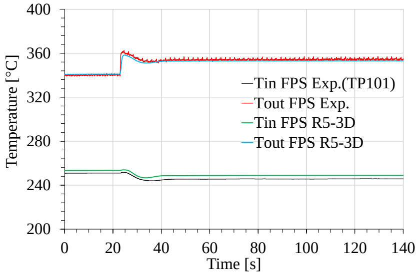
PLOFA

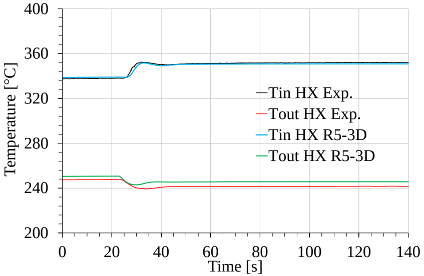


RELAP5 qualification in NACIE-UP loop-type facility

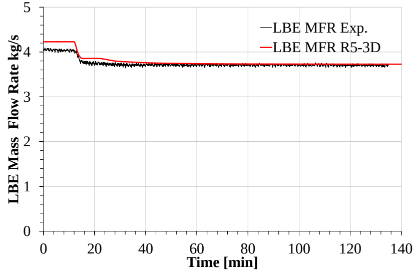
Gas flow transition

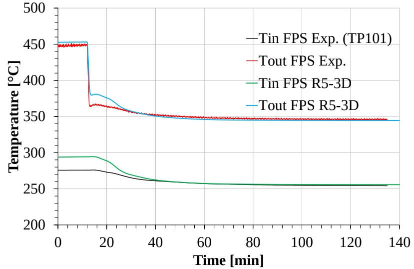


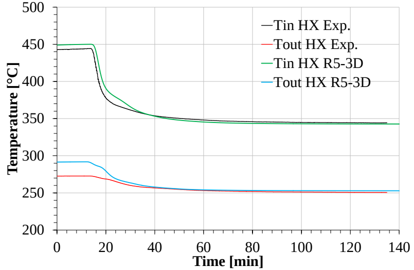




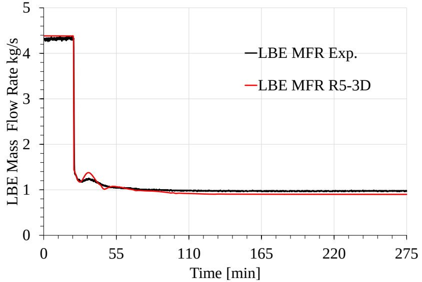
Power transition

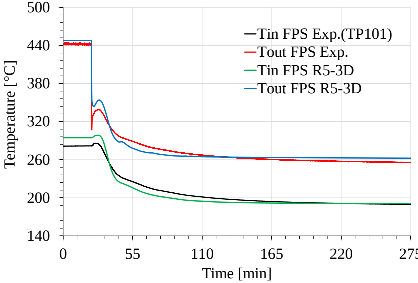


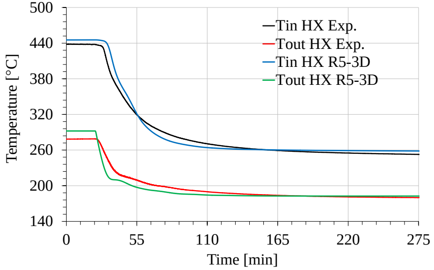




PLOFA

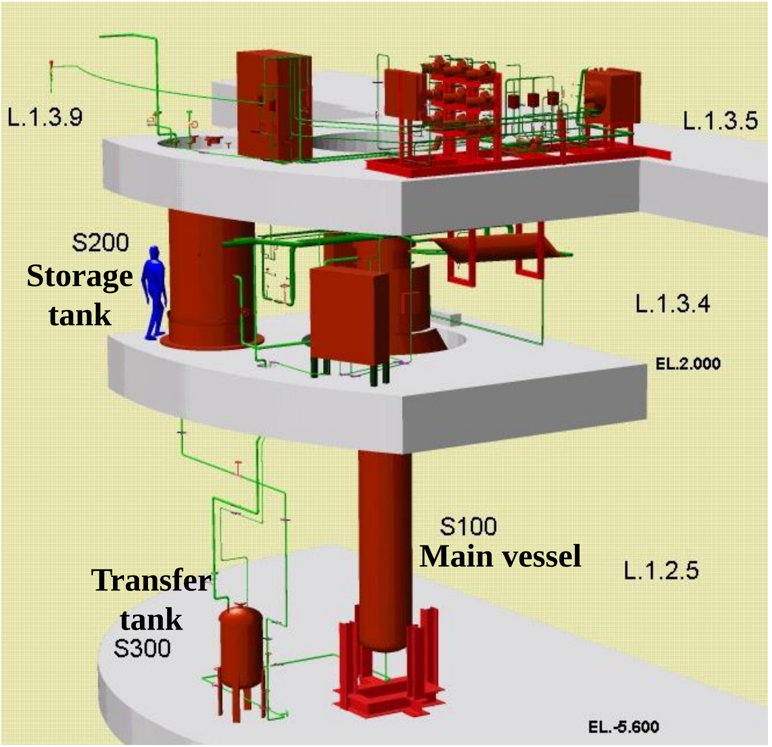






RELAP5 qualification in CIRCE-HERO pool-type facility

CIRCE facility



Facility Components

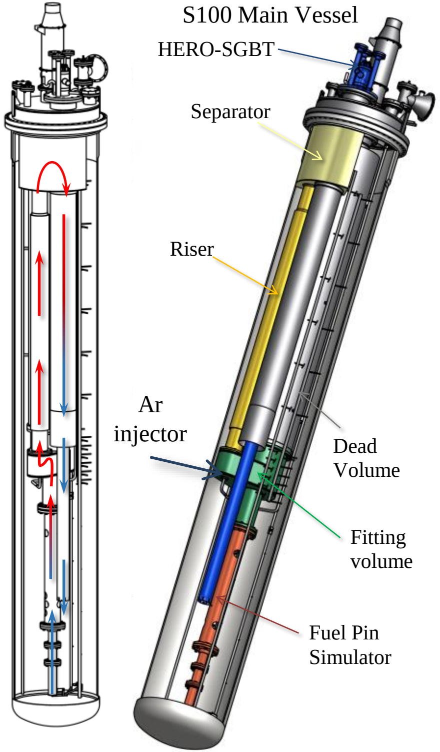
- Main Vessel (S100)
- Storage Tank (S200)
- Transfer Tank (S300)
- Ancillary systems

Coolants

- **Primary**: Lead Bismuth Eutectic
- **Secondary**: pressurized water (up to 172 bar)

LBE Flow Regimes

- Natural Circulation
- Forced (gas-enhanced) circulation (by Argon)



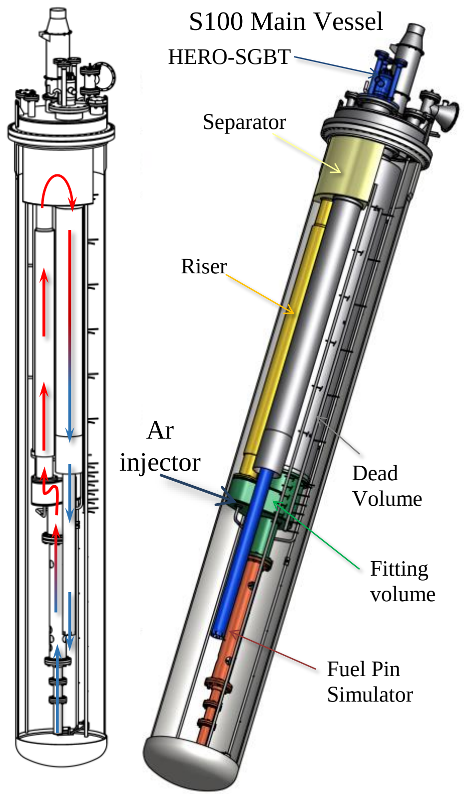
RELAP5 qualification in CIRCE-HERO pool-type facility

Primary System

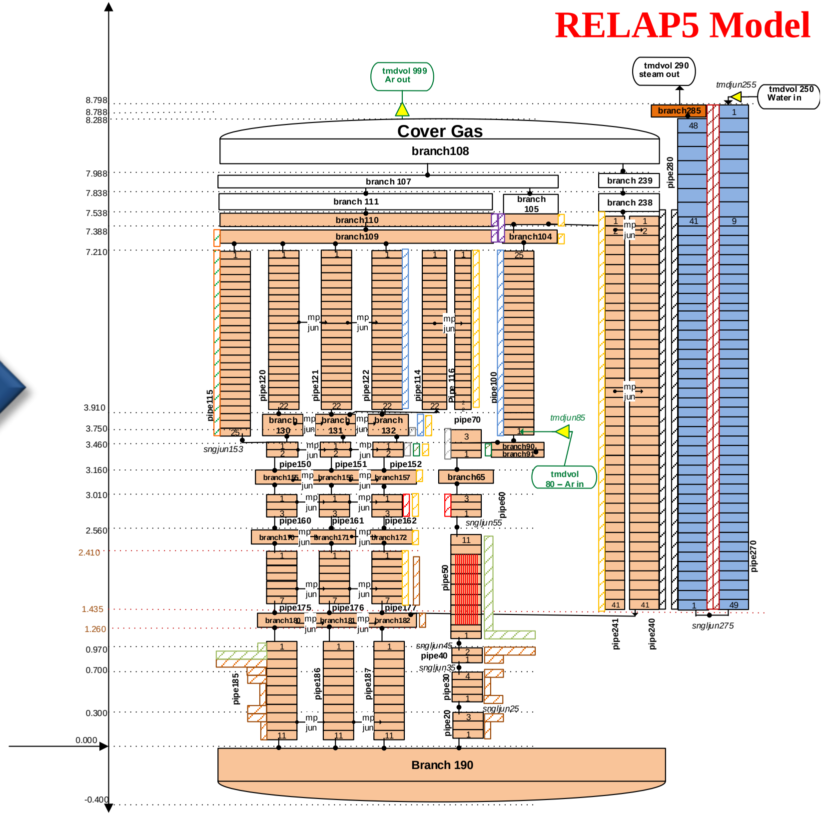





RELAP5 qualification in CIRCE-HERO pool-type facility

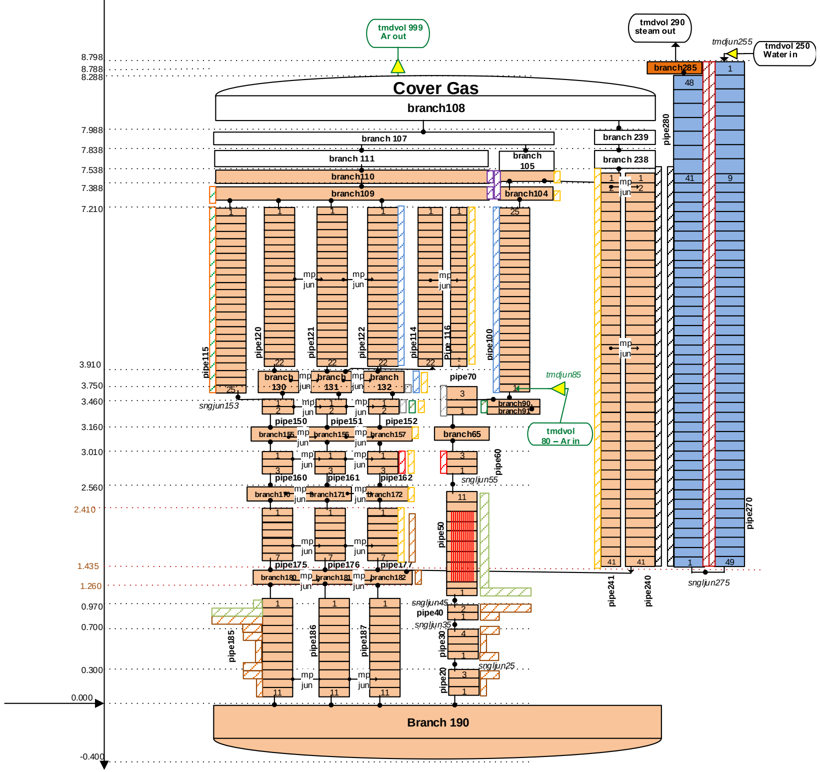


RELAP5 Model



RELAP5 qualification in CIRCE-HERO pool-type facility

RELAP5 Model



- Model divided into **three main parts**: the pool zone, the main circulation zone (including the FRSB, the riser and the LBE side of HERO test section), and the secondary system, i.e. the water side of the HERO test section

- RELAP5/Mod3.3, modified by ENEA with the implementation of the properties of Pb, Pb-Bi and three relevant heat transfer correlations for HLM: Seban-Shimazaki, Ushakov and Mikityuk
  - Non-bundle geometry (Seban and Shimazaki):

$$Nu = 5 + 0.025Pe^{0.8}$$

  - Bundle geometry (Ushakov):

$$Nu = 7.55\frac{p}{d} - 20\left(\frac{p}{d}\right)^{-13} + \frac{3.67}{90\left(\frac{p}{d}\right)^{2}}Pe^{\left(0.56+0.19\frac{p}{d}\right)}$$

CIRCE-HERO tests

- **Steady state condition**
  - H2O subcooled inlet @ 335° C
  - H2O outlet pressure @ 172 bar
  - Feedwater 0.27-0.29 kg/s
  - LBE SG inlet @ 480° C
  - LBE mass flow rate 34-37 kg/s
- **Transient Test 1 PLOFA (SE-TEST1):**
  - FPS power decrease by decay heat curve*
  - gas lift @ 0 in 10 sec
  - Feedwater kg/s at 30% after 2 sec (DHR)
- **Transient Test 2 PLOFA (SE-TEST2):**
  - FPS power decrease by decay heat curve*
  - gas lift @ 0 in 10 sec
  - Feedwater kg/s at 0% after 2 sec (no DHR)
- **Transient Test 3 PLOFA (SE-TEST3):**
  - FPS power decrease by decay heat curve*
  - gas lift decrease by table (pump flywheel)**
  - Feedwater kg/s at 30% after 2 sec (DHR)

Reference for benchmark

****Pump flywheels (simulated by Ar injection)**

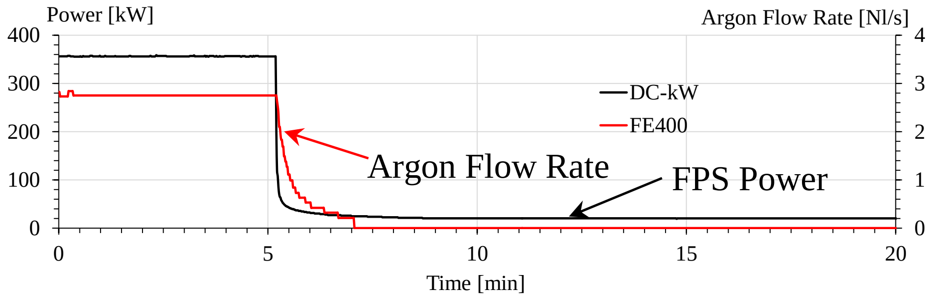
Time (s)	Ar injection [%]
0	100%
1	90%
2	83%
3	77%
4	71%
5	67%
10	50%
20	33%
30	25%
50	17%
100	9%
150	5%
200	2%
300	0%
1000	0%

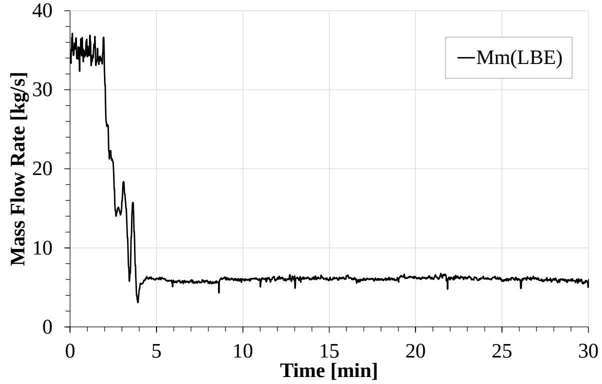
***FPS Power BC**

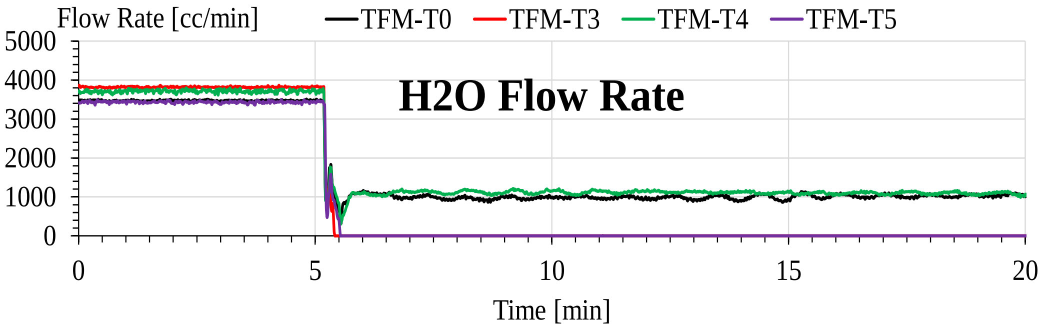
Time (s)	FPS Power [%]
0	100%
1	25%
2	22%
3.5	19%
5	17%
7.5	15%
10	14%
15	12%
22.5	10%
30	9%
40	8%
50	8%
60	7%
90	6%
120	6%
180	6%
240	5%
300	5%
360	5%
420	5%
480	5%
540	5%
600	5%
660	5%
720	5%
780	5%
840	5%
900	5%
1000	5%

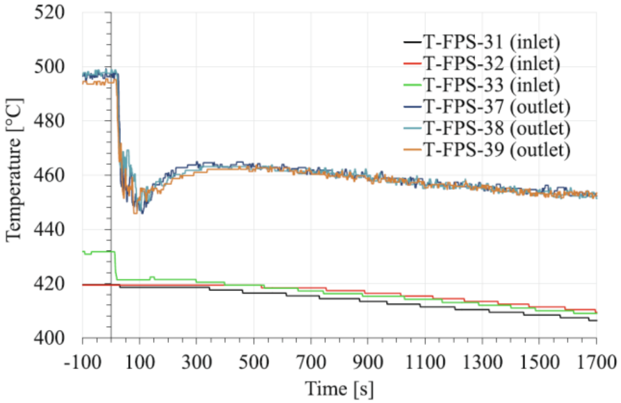
CIRCE-HERO tests

PLOFA EXPERIMENT SE-TEST3









CIRCE-HERO tests

STEADY STATE RESULTS

The **imposed boundary conditions have been implemented in the model** and the steady state results achieved are compared with experimental data

QUANTITY	UNIT	Exp	Calc
Core thermal power	kW	356	356.0 *(0.0%)*
HERO power exchanged	kW	--	351.6 *(--)*
Pool vessel heat losses	kW	--	37.3 *(--)*
Feeding conduit and riser – pool heat exchange	kW	--	18.7 *(--)*
Pool cover gas	MPa(g)	0.014	0.02 *(42.9%)*
Secondary system steam line pressure	MPa(g)	17.1	17.2 *(0.6%)*
LBE FPS inlet	°C	419.6/419.4/431.7	419.6 *(0.1°C)*
LBE FPS outlet	°C	495.5/497.8/495.2	493.2 *(-3.0°C)*
LBE HERO inlet	°C	470.3/485.3/485.3	489.4 *(4.1°C)*
LBE HERO outlet	°C	395.7/413.4/400.9	417.4 *(14.0°C)*
Secondary side DWBT SG inlet (manifold zone)	°C	336.7	336.0 *(-0.7°C)*
Secondary side DWBT SG outlet (steam line zone)	°C	356.7/357.8/354.7	365.3 *(8.9°C)*
Ar injection	nl/s	2.75	2.72 *(-1.1%)*
Primary system (venturi)	kg/s	33.3	33.6 *(0.9%)*
FW total	kg/s	--	0.308 *(--)*

Temp. LBE at the FPS inlet equal to the exp. measurements

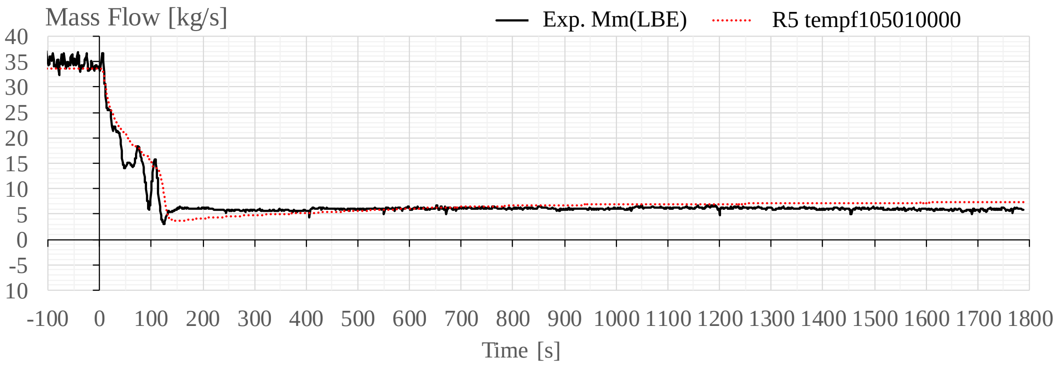
Temp. LBE at the FPS outlet 3°C lower than the exp. measures, which is considered acceptable and justifiable by LBE fluid proprieties uncertainty and the accuracy in measuring the LBE mass flow rate

Temp. LBE at HERO inlet +4.1°C than the exp. value, due to the effect of energy removed by the air cooling system operated in the dead volume

Temp. LBE at HERO outlet +14.0°C than the exp. value, which is the average value between the 3 thermocouples having a relevant scattering between the maximum and the minimum values

CIRCE-HERO numerical benchmark

Transient Results



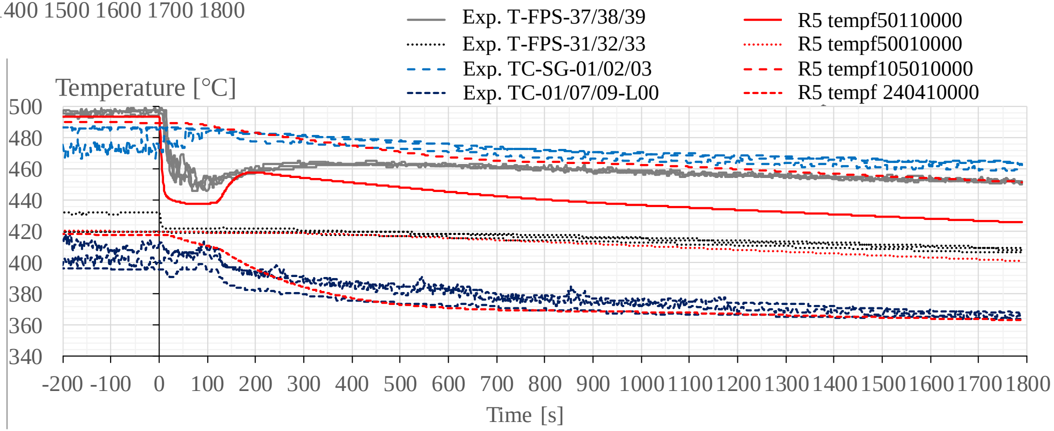
LBE Mass Flow Rate

Experimental mass flow rate predicted reasonably by the code. Differences are easily connected with the real layout and behavior of the gas injection line of the facility reproduced in a simplified way in the code nodalization. In long term, the natural circulation is stabilized.

LBE coolant temperatures @ FPS inlet and outlet, @ HERO inlet and outlet

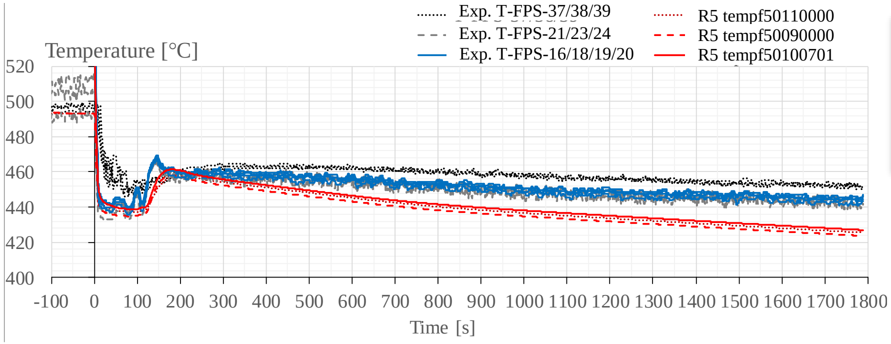
FPS inlet and HERO inlet/outlet LBE temperatures are equivalent to the experimental data time trends.

LBE temperature downstream the heated part drops smoother than in the simulation, maybe due to a more effective thermal coupling between the coolant flowing in the rising channel and the pool temperature.



CIRCE-HERO numerical benchmark

Transient Results

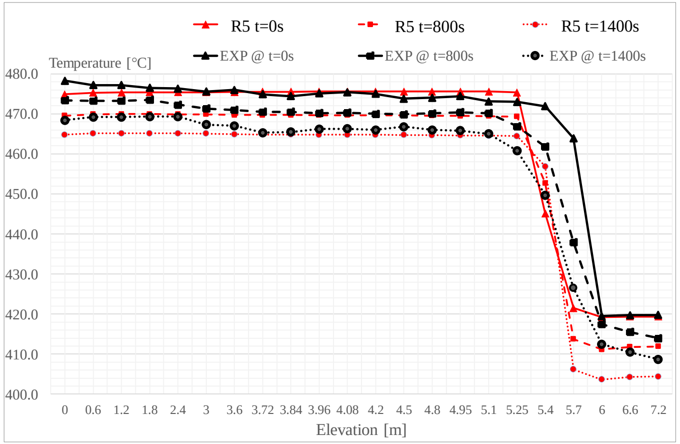


Steam coolant temperature at BT outlet

The temperature increase of the water steam in HERO secondary side is over-predicted by the code

LBE coolant temperatures @ pool Line A

The temperature profile in the pool is reasonably predicted by the code



Lorusso, P., et al.; Total Loss of Flow Benchmark in CIRCE-HERO integral test facility, Nuclear Engineering and Design 376 (2021) 111086

Conclusions

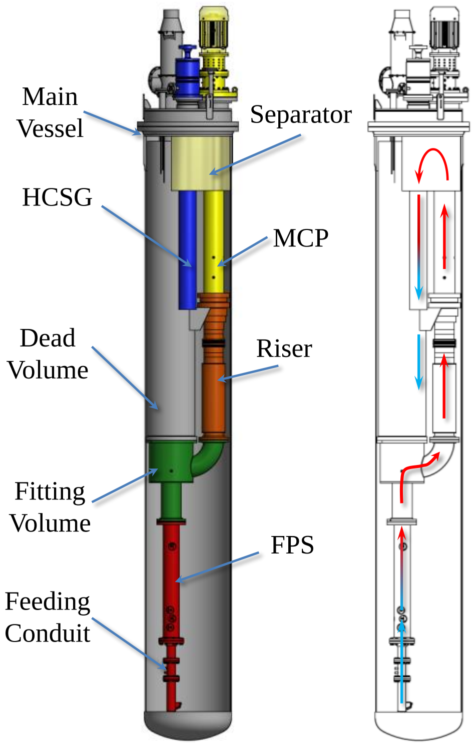
Several projects have been financed by the European Commission in Euratom programs for the study and design of HLM-cooled reactors. In order to **improve the validation matrices of RELAP5 in relation to Gen-IV related HLM-cooled systems**, several experimental data coming from different HLM-cooled facilities have been used.

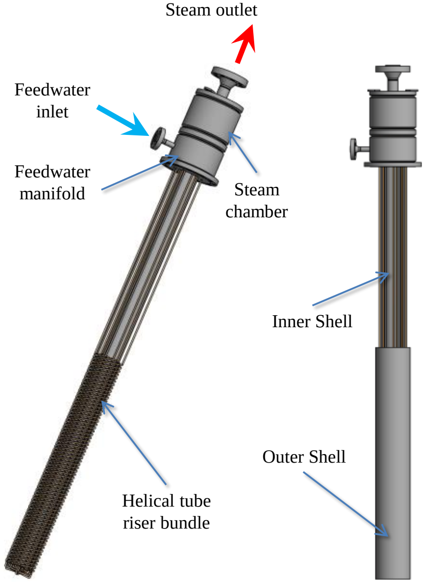
The code underwent to modifications involving the implementation of suitable correlations generating the reference physical and thermodynamic properties for Lead and LBE fluids. Similarly, some specific heat transfer correlations for liquid metals have been added and tested.

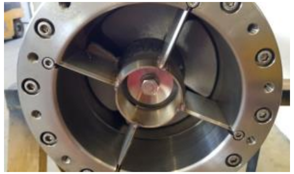
- The results of the simulation showed an adequate capability of the codes to reproduce the relevant phenomena involved during the experiment.
- RELAP5 proved to be accurate in predicting the trend of the main parameters during the transient, even if the in case of sudden transitions (i.e.; PLOFA).

- Activities highlighted that the planning and the execution of further experiments fully devoted for the code V&V process is fundamental for the further development of numerical tools.

Ongoing activities







- Refurbishment of the CIRCE facility with a new test section:
  - Installation of an axial centrifugal pump designed ad-hoc for HLMs
  - SGBT replaced with a helical tube bundle SG
- New configuration in support of one of the last up-dated solutions of the ALFRED SG

- **Primary coolant**: LBE
- **Secondary coolant**: H_2O

LBE Flow regimes:
- Forced Circulation
- Natural Circulation

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