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TEST MATRICES DEFINITION FOR THE SIRIO FACILITY IN THE FRAME OF THE H2020-PIACE PROJECT: Pre-test simulation results and conclusions

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Framework

- The HORIZON 2020 Passive IsolAtion CondEnser (PIACE) project, started in 2019, aims at testing the IC passive safety system in a new experimental facility, at SIET premises in Piacenza (Italy). An experimental program is defined to test the applicability of the IC concept for selected reactor technologies: LFR, MYRRHA ADS, PWR, BWR, PHWR.

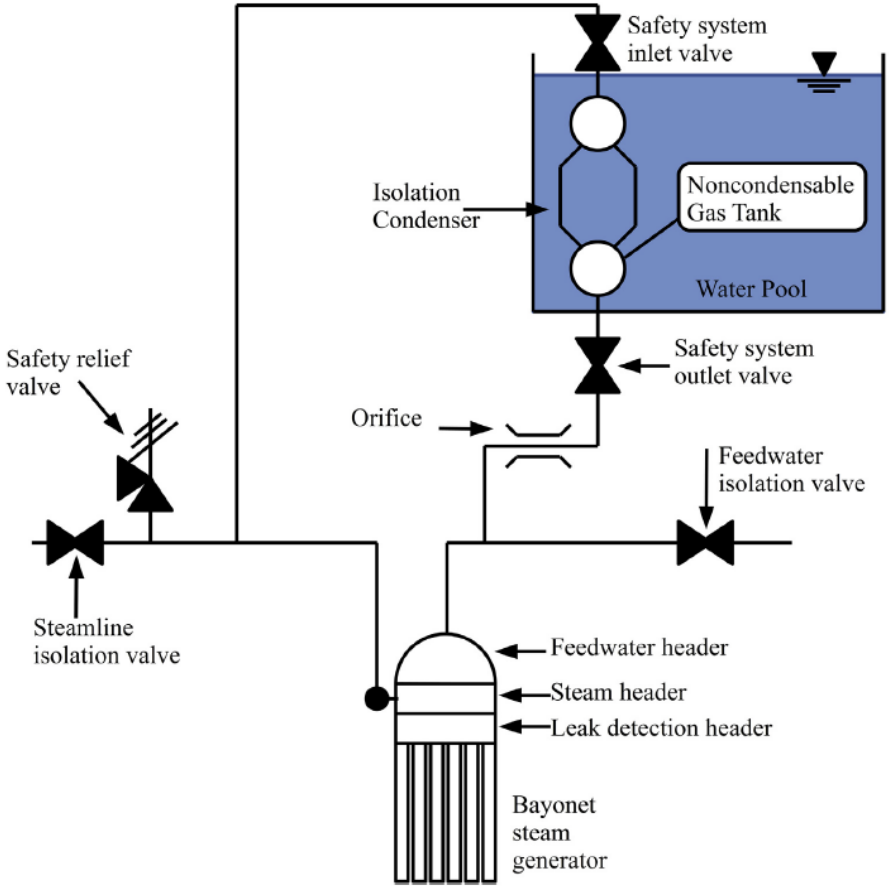
- The project is led by the Italian national research organizations, ENEA and sees the involvement of 10 other research centers, universities and private companies in the nuclear sector

OUTLINE

- Working principle of the Isolation Condenser with non-condensable
- SIRIO facility description
- Scaling from ALFRED DHR
- Pre-test of LFR
- Scaling from ADS DHR
- Pre-test of ADS
- Conclusions

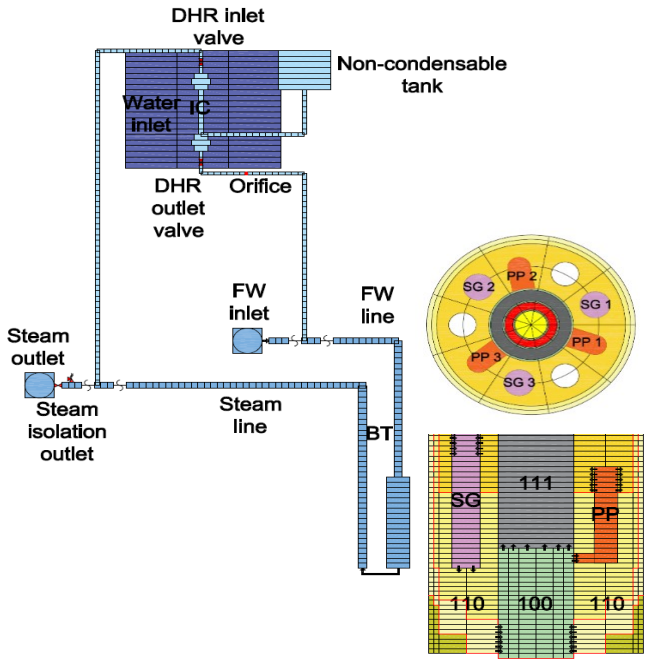
Isolation Condenser with non-condensable

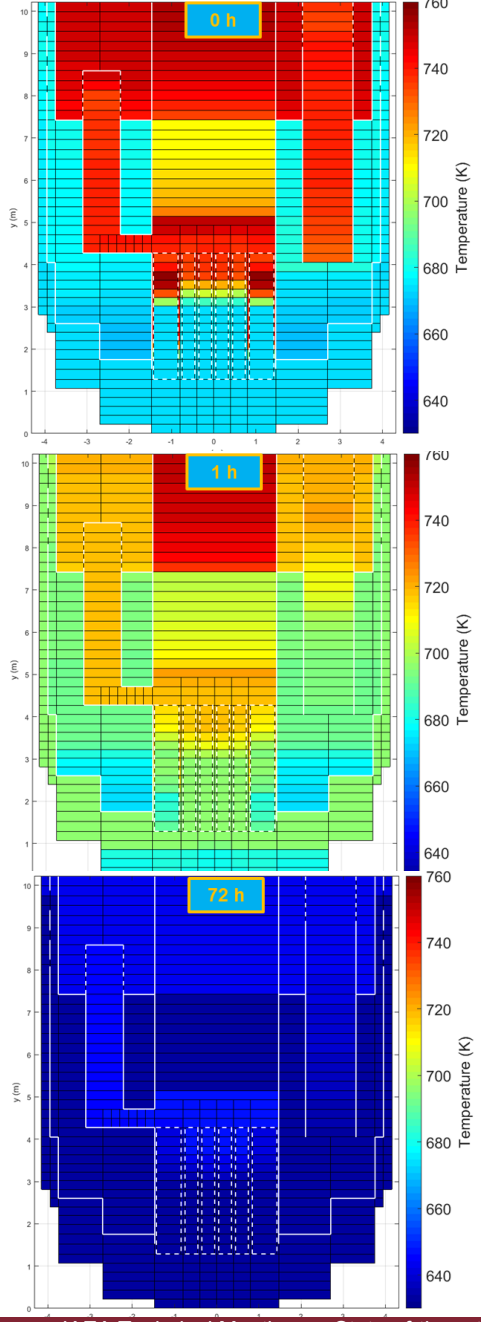
- The ALFRED DHR system consists of two redundant and diversified systems.
- The first one is composed of three loops connected to the three SG in order to reduce the number of components within the RV.
- It is redundant itself, allowing the failure of one of the three loops.

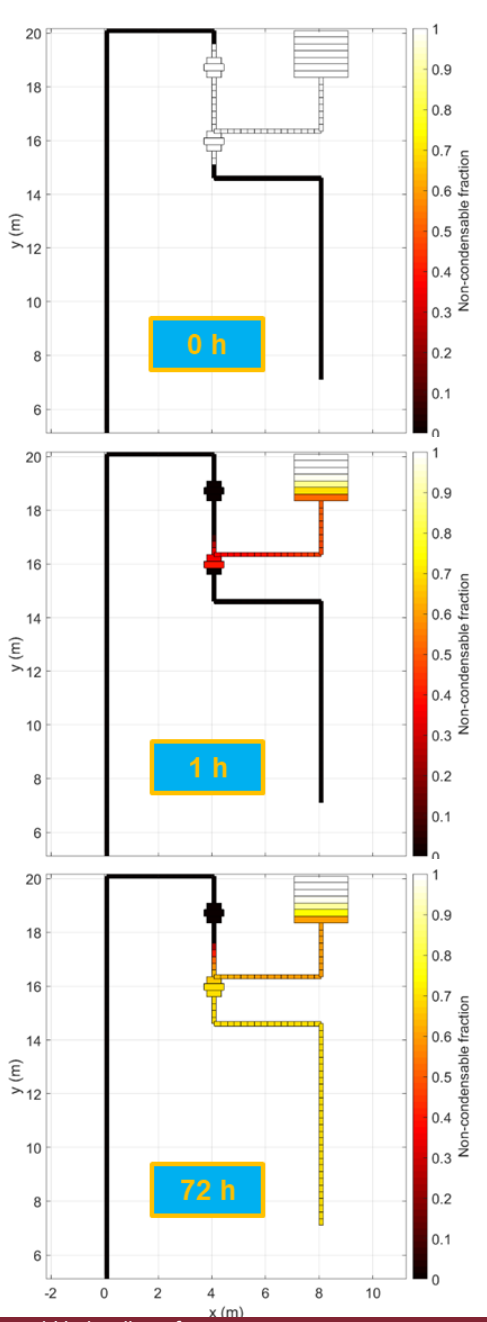


ALFRED reactor Isolation Condenser

Sapienza verified the transient of the system developed by Ansaldo Nucleare as in-kind contribution to FALCON with a focus on non-condensable movement into the secondary circuit using RELAP5-3D (Narcisi et al., 2020)

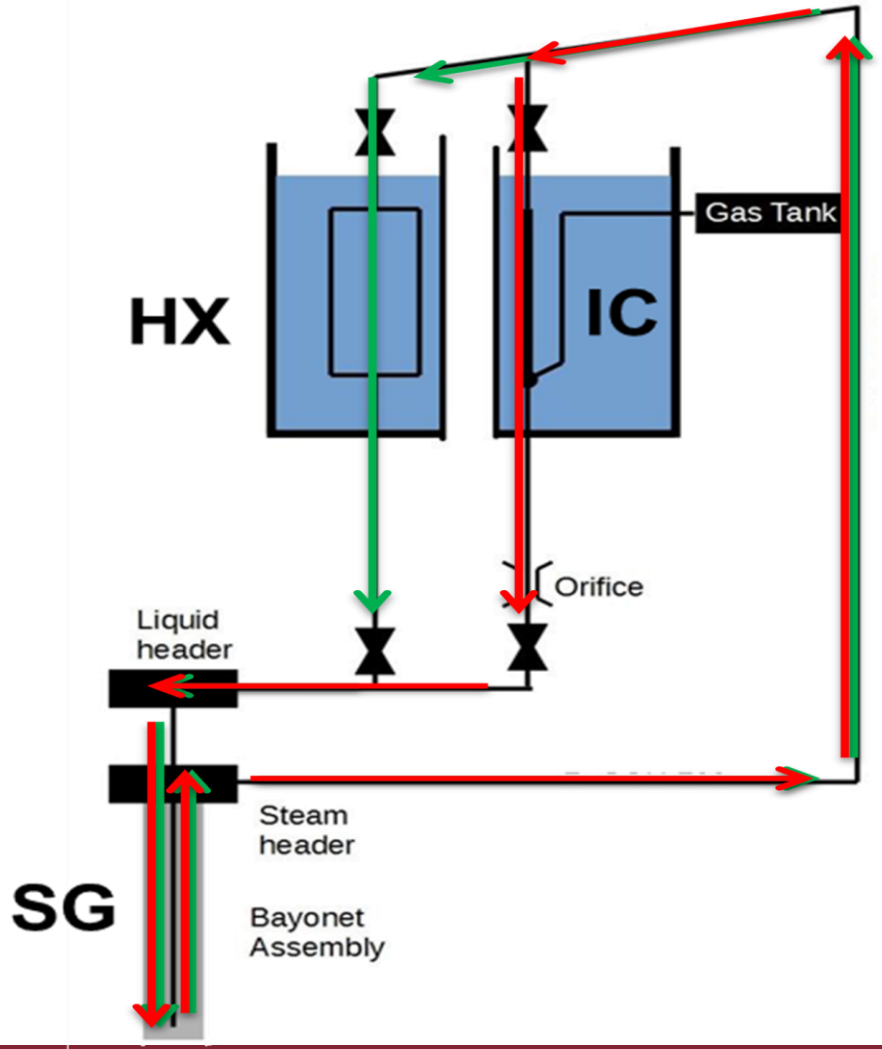






SIRIO: decay power removal system for innovative reactors conceptual scheme

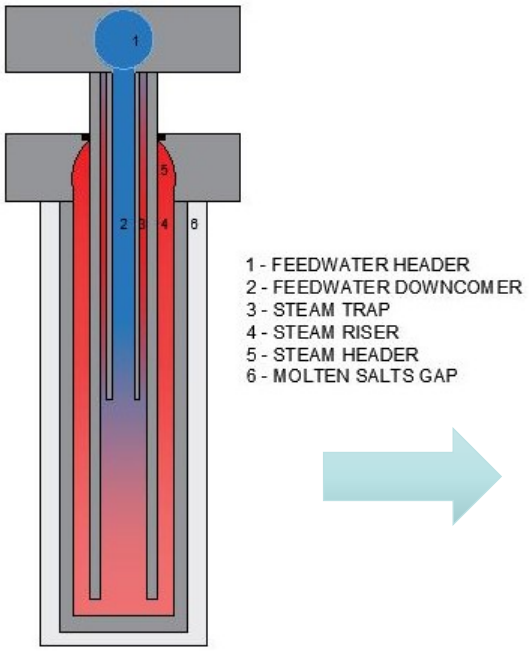
- ✓ The facility "Sistema di rimozione della Potenza di decadimento per Reattori InnOvativi" (SIRIO) was made in an Italian-funded project to simulate the operation of the passive safety system with Non-Condensable (NC) gases planned for ALFRED on a small scale.
- ✓ The facility is not able to simulate the reactor full power, but starts the transient in natural circulation, with the branch where the IC is contained isolated and contains gas (nitrogen) at a lower pressure than the water circuit.



SIRIO test facility: the main components 1/2

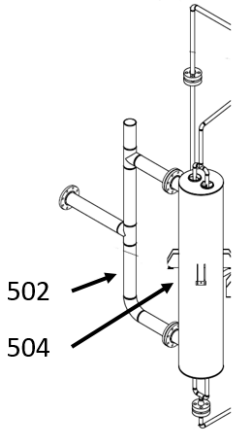
Steam Generator

- ✓ The heat source for both tests is the Bayonet SG
- ✓ The SG is formed by 11 bayonets, each of these is composed of 6 components
- ✓ The Molten Salts (MS) gap transfers the thermal power by natural circulation to the steam riser
- ✓ During the scaling procedure, a choice of scaling factor's deformation about the IC was done

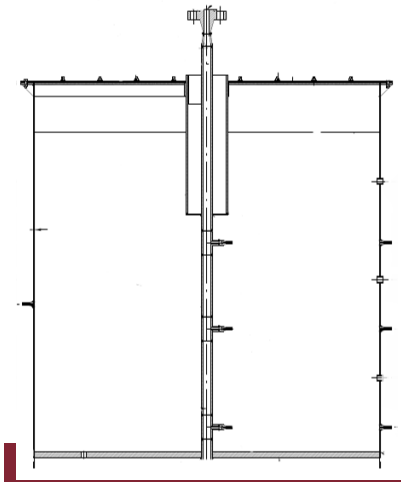


SIRIO test facility: the main components 2/2

Bypass Heat Exchanger



Isolation Condenser Pool



SIRIO Design – Facility Scaling

Facility scaled with reference to the DHR of ALFRED$_{(LEADER)}$ reactor

European project LEADER configuration

- Power: 300 MW
- SGs: 8
- SG tubes: 510
- SG tube type: double wall bayonet
- SG number coaxial pipes: 4
- Tube length: 6 m

ALFRED Staged Approach (Stage 2)

- Power: 200 MW
- SGs: 3
- SG tubes: 880
- SG tube type: single wall bayonet
- SG number coaxial pipes: 3
- Tube length: 6 m

SIRIO configuration

- SG tubes: 11
- SG tube type: single wall bayonet
- SG number coaxial pipes: 3
- Tube length: 6 m

SIRIO geometrical features suitable for ALFRED Stage 2

SIRIO Design – Facility Scaling

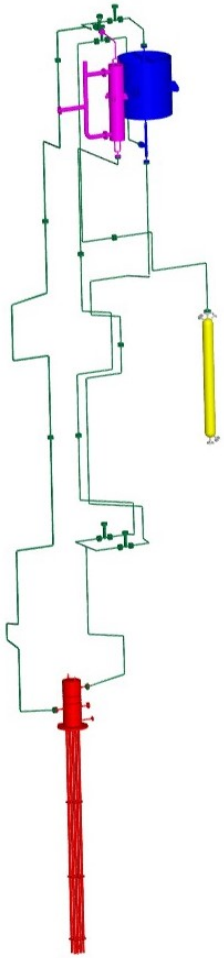
- Reduction of the tube length due to the small number of the IC tubes used.
- Possible impact on natural circulation.
- considering the scope of the experiment and the overall height of the legs (about 15 m), the distortion is considered acceptable.

Parameter	Unit	ALFRED	SIRIO	Ratio
Decay Power	kW	2 625	55	47.72
SG Power per tube	kW	5	5	1
SG Heat Transfer surface	m^2	244.2	5.27	46.37
SG Thermal flux	kW/m^2	10.75	10.44	1.029
Total volume	l	8059	173.4	46.47
Water mass	kg	2 034	37.9	53.66
Power density	kW/l	0.326	0.317	1.028

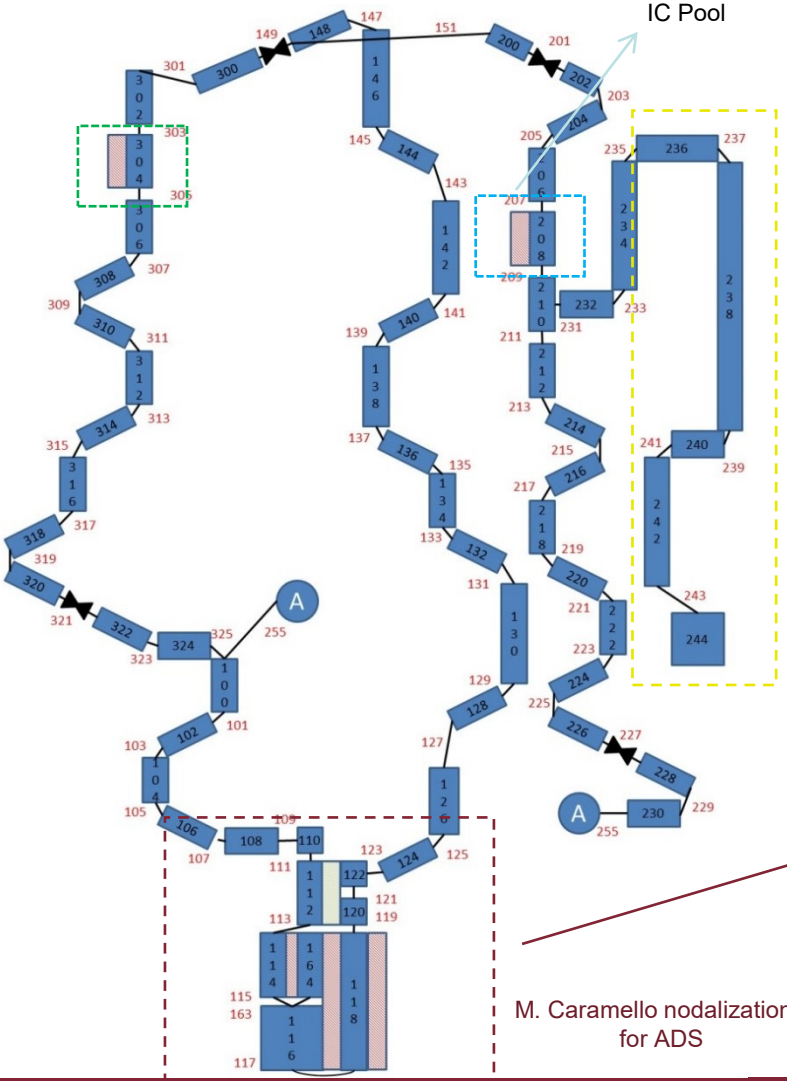
RELAP5 thermal-hydraulic model 1/4

- ✓ Two similar models are used for the LFR and ADS tests
  - ✓ for LFR pre-test RELAP5/MOD3.3 modified by Sapienza is used
  - ✓ for ADS RELAP5-3D is used
- ✓ There are three systems:
  - the primary circuit
  - the IC pool side
  - the bypass HX pool side
- ✓ The model is developed with: sliced approach, length ratio of adjacent nodes into the range of 1÷1.25
- ✓ Each hydrodynamic component respects the construction characteristics of the facility (as-built quote)

RELAP5 thermal-hydraulic model 2/4

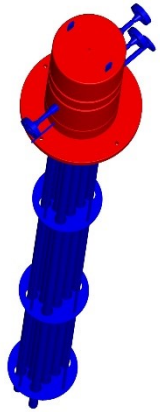


Bypass HX



Gas Tank

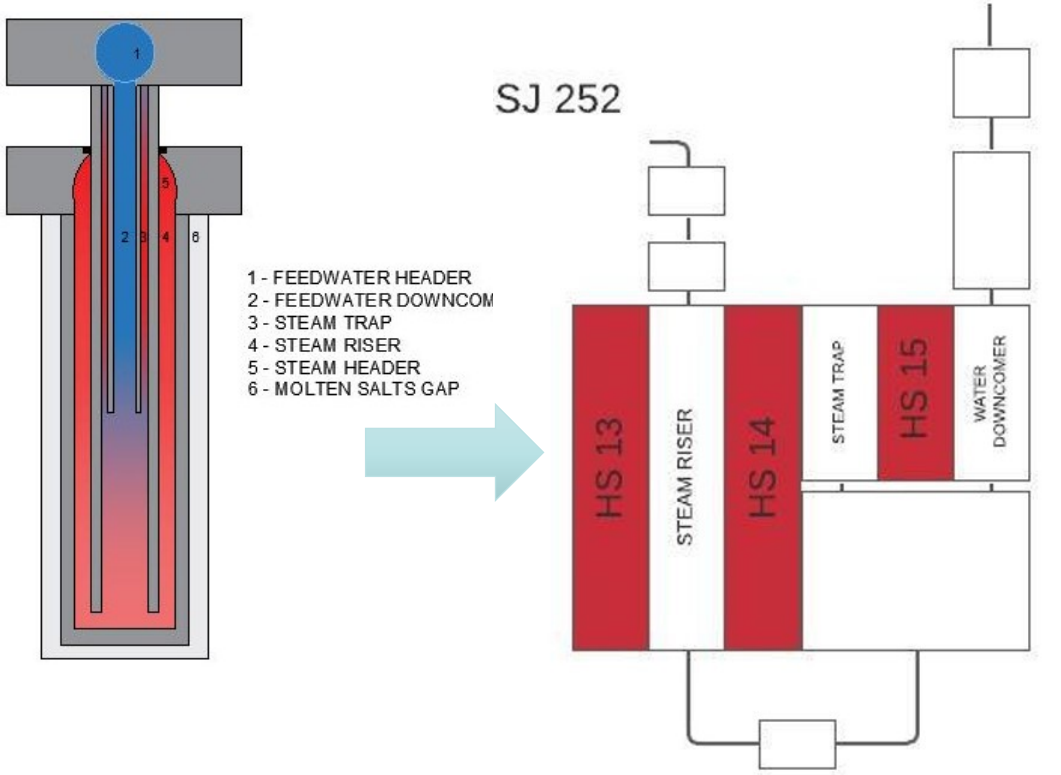
Steam Generator



M. Caramello nodalization for ADS

RELAP5 thermal-hydraulic model 3/4

Steam Generator



✓The SG starts with a junction (SJ 238) from the feedwater line
and ends with a junction with the steam line (SJ 252)

✓Height and volume are kept constant from the constructive characteristic

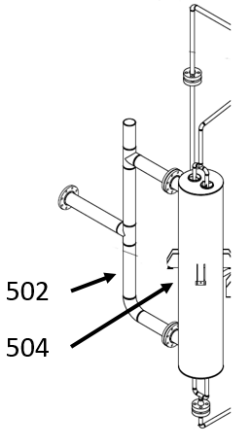
✓The HS 13 is used to impose power and to simulate the steel and molten salt conduction only

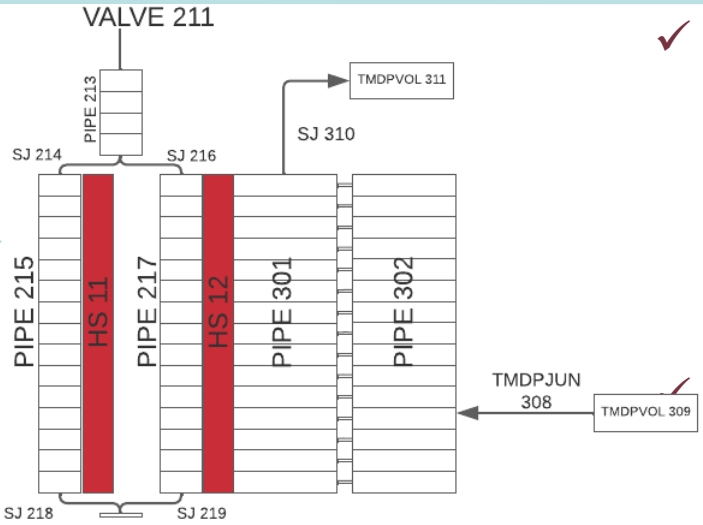
✓The MS simulated is Dynalene-MS2

✓The MS was simulated throught Heat Structures Thermal
Properties tables

RELAP5 thermal-hydraulic model 4/4

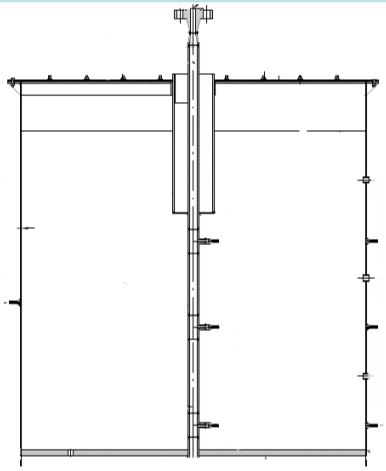
Bypass Heat Exchanger

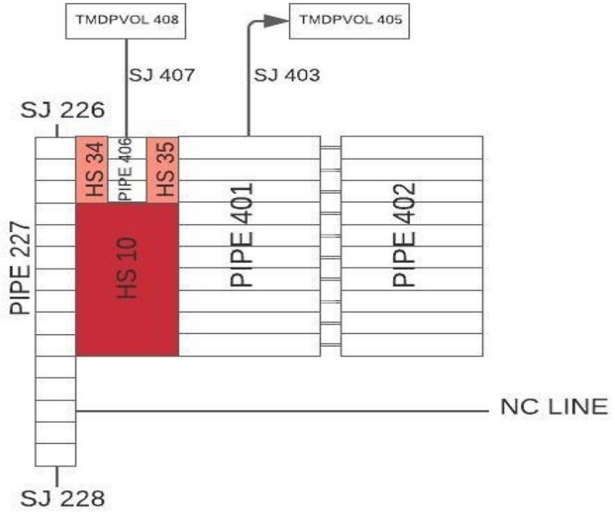




- ✓ The bypass HX pool side modeled with two parallel pipes components connected through multiple junctions
- ✓ Imposed secondary inlet mass flow rate

Isolation Condenser Pool





- ✓ The IC pool side modeled as the bypass HX pool
- ✓ Downward of the IC tube side there is the NC gas line

LFR pre-test

PERSEO IC (R5 mod 3.3 updated by Sapienza vs default R5)

PhW 1 (10000 s → 11260 s)

- First activation of the system
- Good evaluation of the primary MFR
- Discrepancy on the HX power
- Good prediction of slow water consumption within HXP
- Satisfactory simulation of maximum values of HXP level and MFR
- Good agreement in the pressure drops

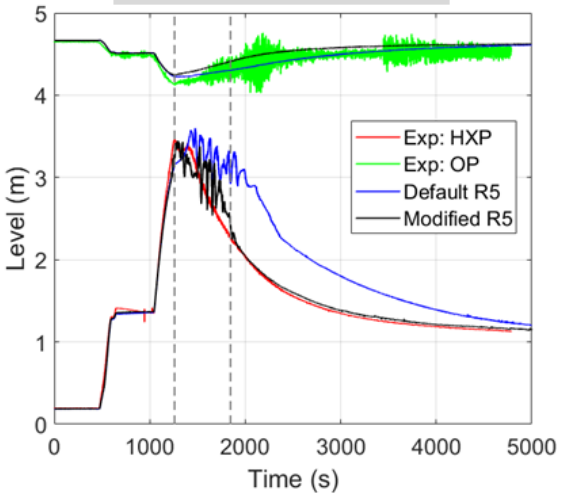
PhW 2 (11260 s → 11845 s)

- Quasi-steady operation
- Good evaluation of the MFR
- Underprediction of the HX power

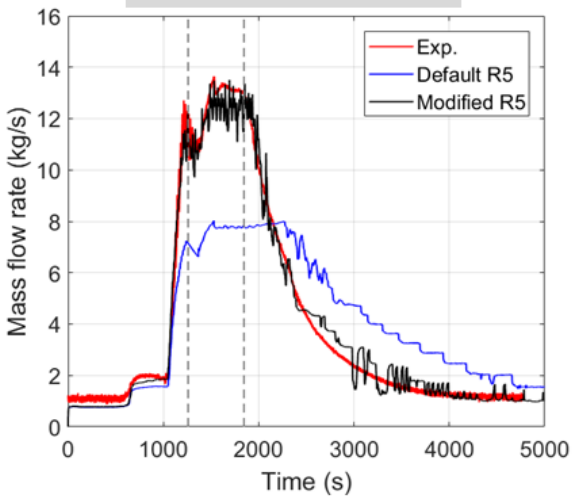
PhW 3 (11845 s → 14784 s)

- Boil off in the HXP with a consequent level reduction and power decrease
- Globally agreement between experiment and simulation
- Typical stepwise change in the MFR and power decrease (due to discretization of nodalization scheme)
- Oscillations related to steam condensation instabilities

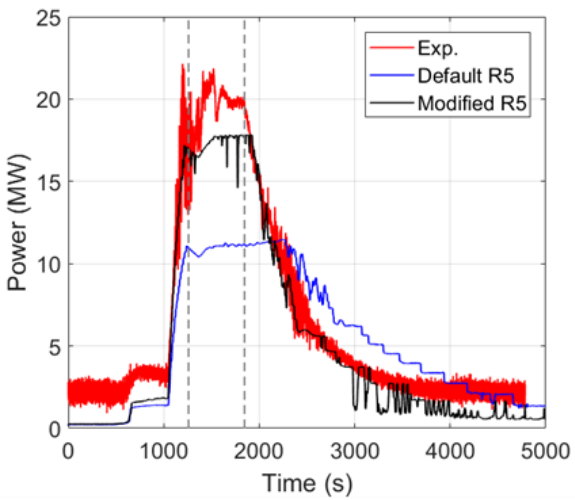
HXP and OP levels



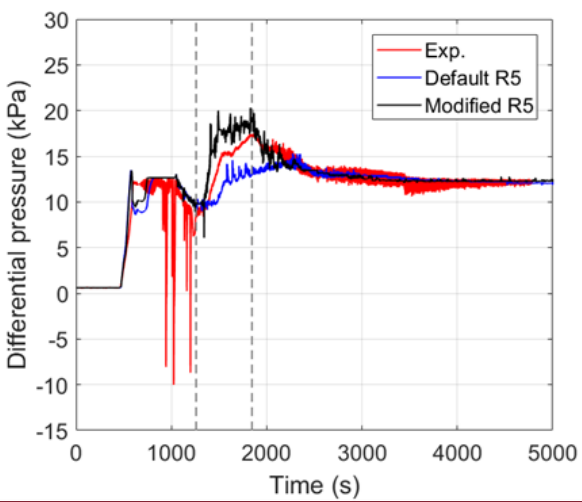
Primary MFR



HX power



HX pressure drop



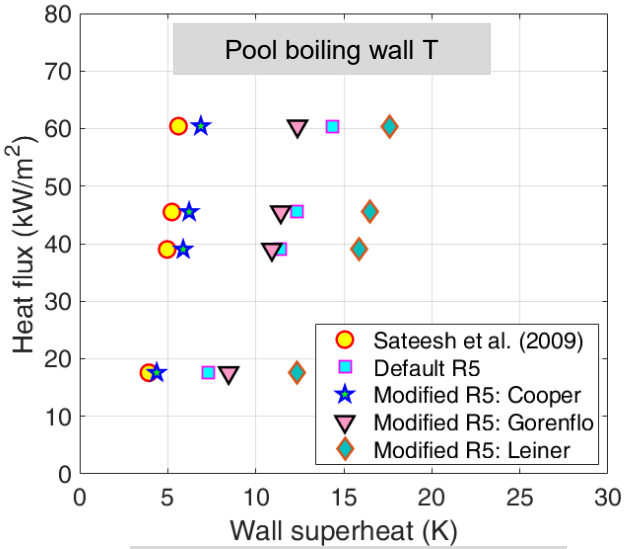
RELAP5/MOD3.3 code modification for liquid metal (and fusion) reactors

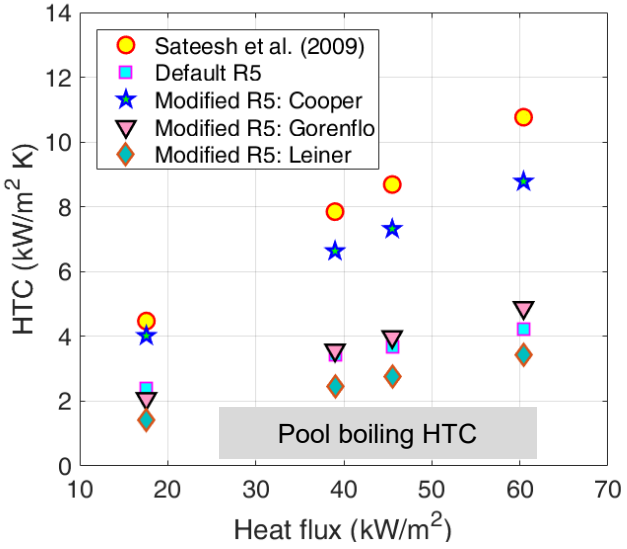
This upgraded version is used for the LFR pre-test due to the additional features:

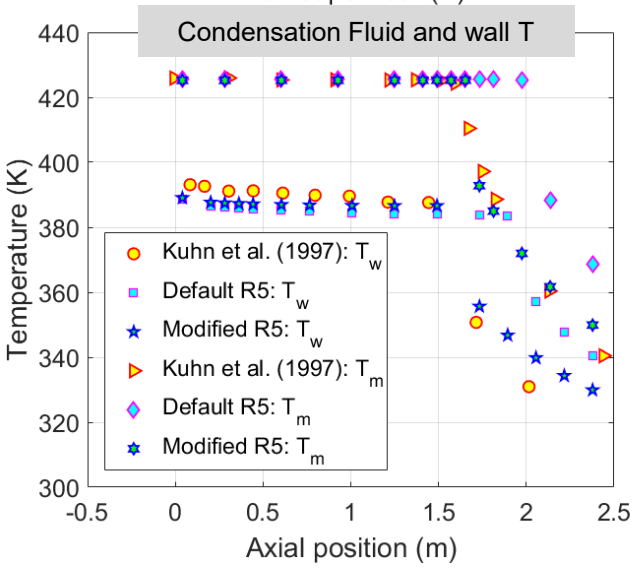
- ✓ Pool boiling and condensation heat transfer for the simulation of passive safety systems as the IC (Narcisi et al., 2021) :
  - ✓ Improvements have regarded the addition of more suitable HTC correlations for pool boiling and for film condensation at low flow rates and high pressures
  - ✓ A new “boundary type” has been added for pool boiling, using Cooper correlation for the evaluation of nucleate boiling HTC
  - ✓ For film condensation (pure steam) in vertical geometry, the original set of correlations has been improved with the most recent release of Shah correlation for turbulent condensation (applicability enlarged to high pressure) and with the addition of Kutateladze correlation for wavy laminar condensation
- ✓ Other features added:
  - ✓ Lead, LBE, LLE, Na and HITEC working fluids with updated properties (in collaboration with UNIPI and ENEA)
  - ✓ Liquid metals heat transfer correlations (HTCs)
  - ✓ New Helical geometries flow maps for HCSGs (dryout specific correlation)
  - ✓ External tubes bank HTCs (Zukauskas)
  - ✓ MHD pressure drop calculation

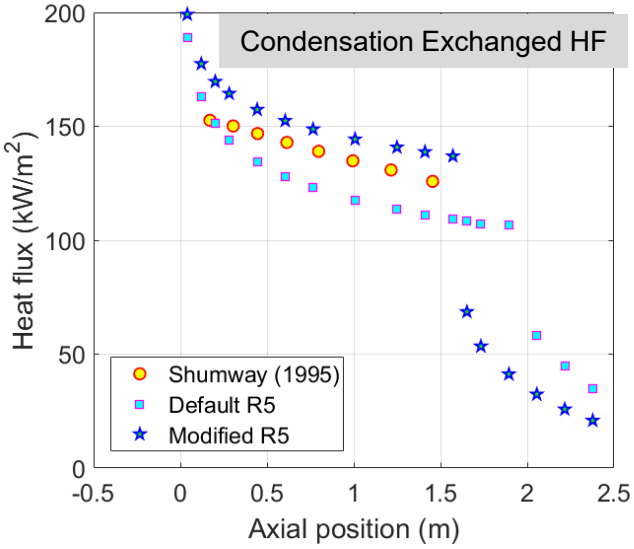
Pool boiling and condensation heat transfer for the simulation of passive safety systems (R5mod3.3 updated by Sapienza)

- SET used to evaluate the effect of the modification in the R5 for passive systems
- The main relevant phenomena considered are:
  - Pool boiling (Sateesh et al.)
  - Condensation, also in laminar wavy condition (Kuhn et al.)





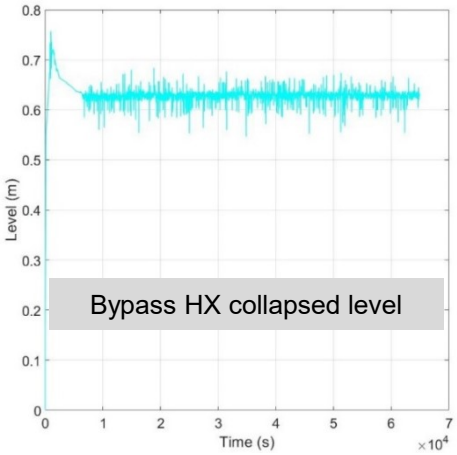


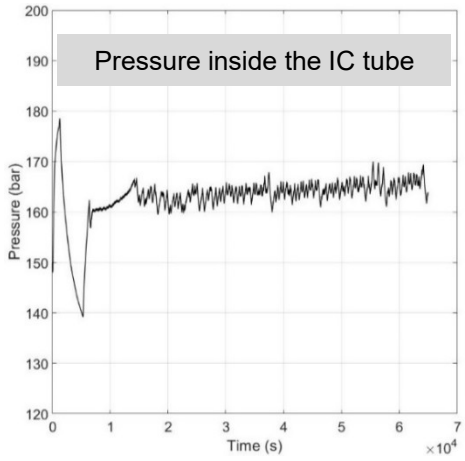


LFR Test: steady state

- ✓ Constant power provided to SG correspondent to the scaled initial decay heat power
- ✓ A regulation of power removed by HX with power supplied is needed
- ✓ There is only one control system, and is for the bypass HX level to maintain the pressure into the primary loop

Test conditions for steady state case	
Power supplied	55 kW
Primary circuit pressure	180 bar
Bypass HX valves (upstream and downstream)	Fully open
IC valves (upstream and downstream)	Fully closed





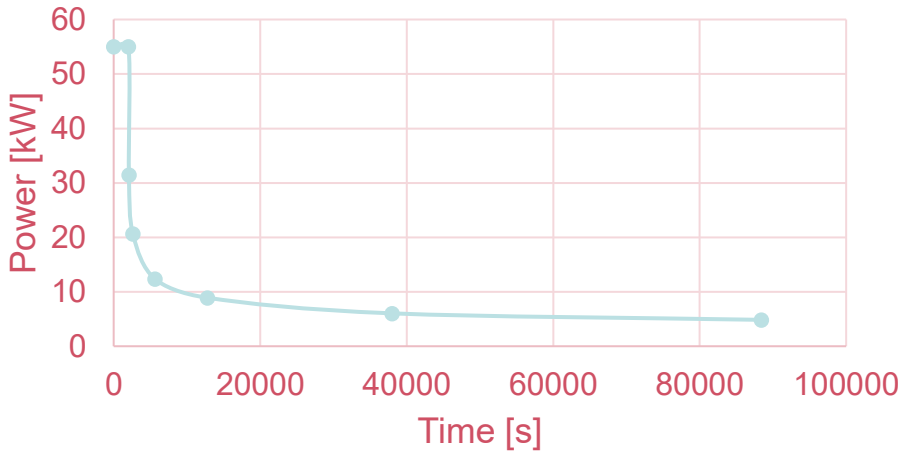
LFR Test: transient phase 1/3

The transient test analyzed is a SBO with Decay Heat (DH) generation imposed directly on the SG:

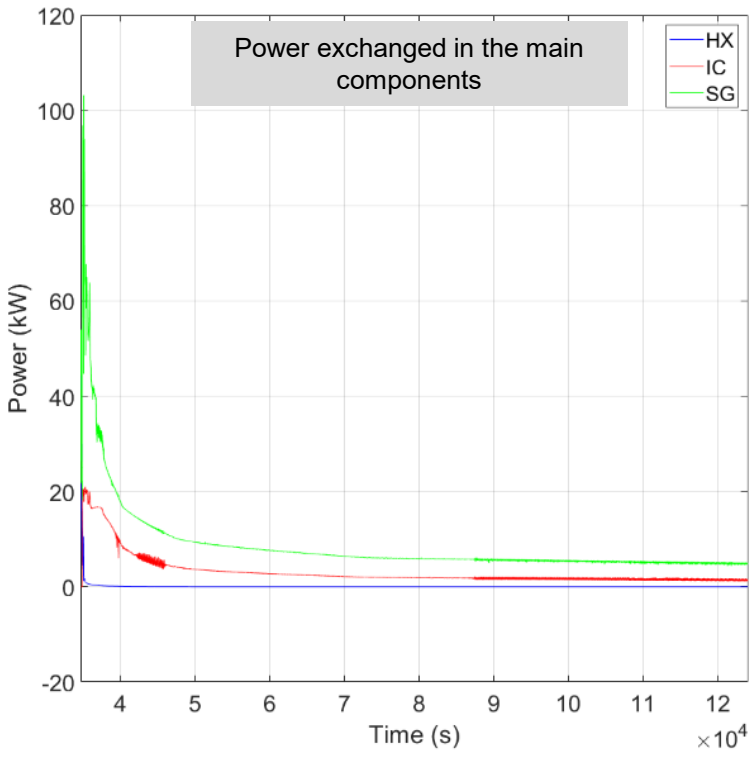
1. Isolation of the bypass HX
2. Reaching the IC pressure opening setpoint
3. Full power provided for 2000 s to account metal structures heat capacity (time based on ALFRED simulations)
4. During this test any control system action is considered, only the decay heat variation imposed

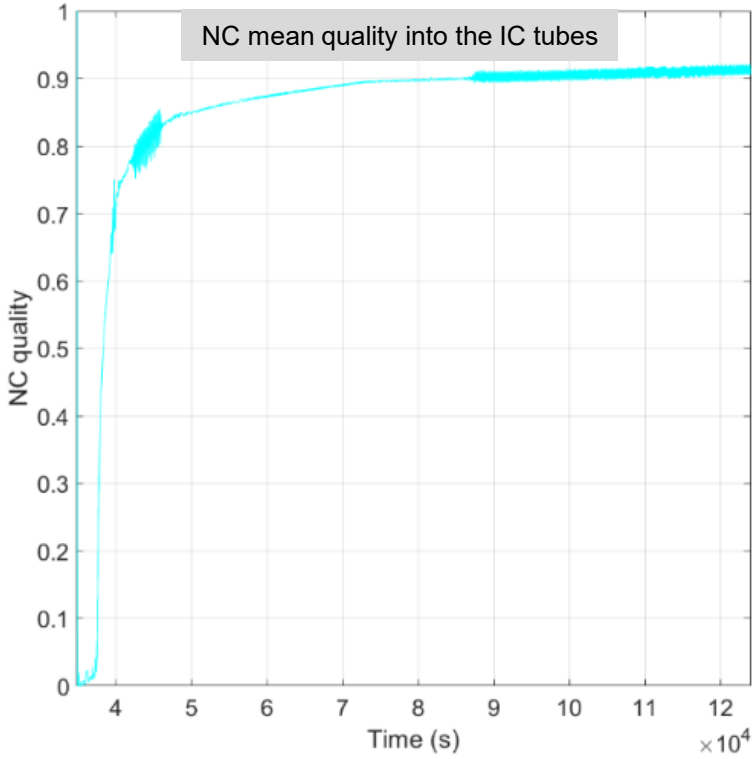
Test conditions for transient case	
Power supplied	Follows a DH trend
IC valve setpoint (upstream valve)	190 bar
IC valve setpoint (downstream valve)	60 s after the upstream valve
Bypass HX valves (upstream and downstream)	Fully closed

Decay power imposed



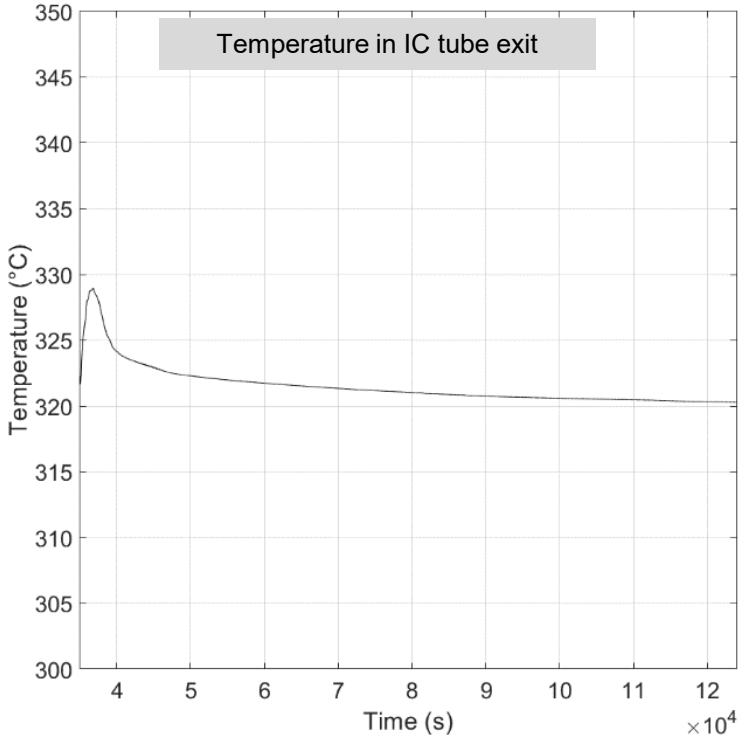
LFR Test: transient phase 2/3

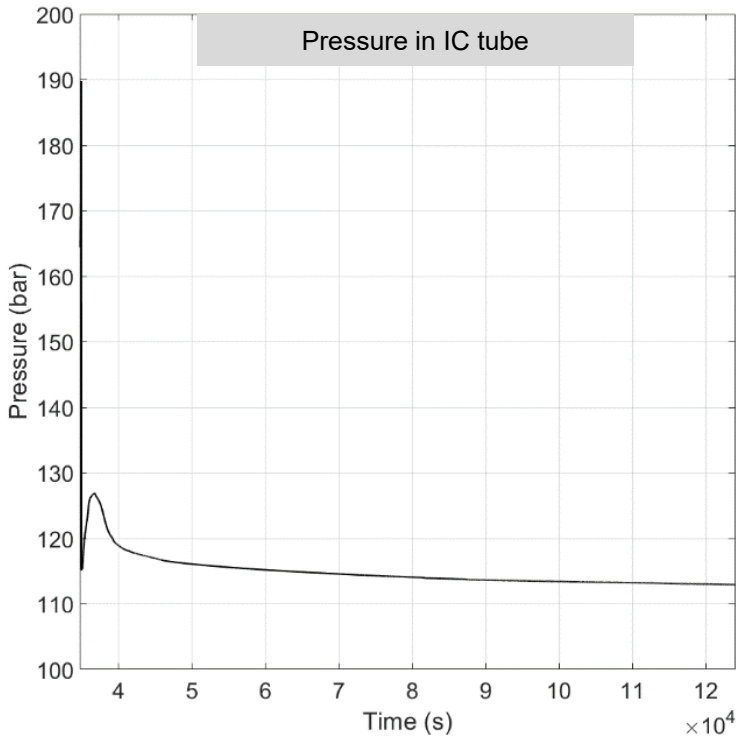




- ✓ The power removed by IC is influenced by the NC quality into the IC tubes
- ✓ The large difference between the SG power and the IC power is mainly due to the heat losses

LFR Test: transient phase 3/3



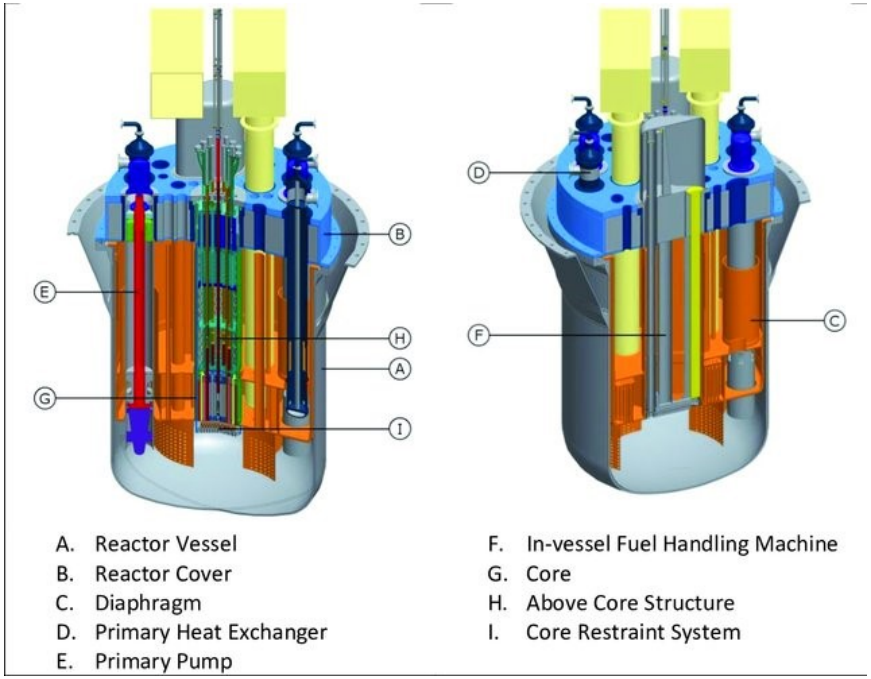


- ✓ Sharp increase in primary circuit pressure up to 190 bar and a long-term stabilization
- ✓ The temperature trend goes down to 593 K
- ✓ After 24h from the DHRS activation, the MS freezing temperature is not reached
- ✓ The passive self-regulation of the power removed is supposed in the pre-test

ADS pre-test

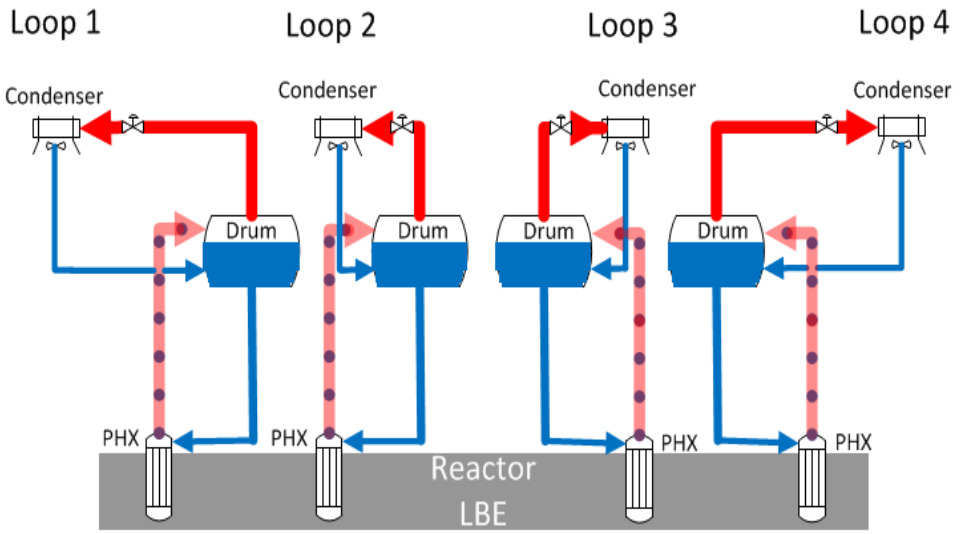
MYRRHA-ADS reactor

- For the demonstration of the IC concept to ADS technology, the MYRRHA-ADS reactor is selected.
- MYRRHA is a Multi-purpose hYbrid Research Reactor for High-tech Applications that is under development at SCK CEN (Belgium).
- MYRRHA is conceived as a pool-type ADS reactor with a proton accelerator linked to a subcritical core fuelled with MOX and cooled by liquid Lead Bismuth Eutectic (LBE), with the chain reaction sustained by the interaction of the proton beam with the LBE spallation target.



MYRRHA ADS cooling circuits

3 loops in cascade, working in forced circulation during normal operation conditions and in natural circulation in decay heat removal conditions.
Each SCS loop is operated with a two-phase water mixture at 16 bars (200° C) with saturated water entering the PHX and exiting with a dynamic flow quality of about 0.3.



SIRIO facility has been scaled from the ALFRED DHR system, several modifications were proposed considering a new scaling analysis and adaptations of the IC to the MYRRHA DHR1 system because the two reactors are different

Scaling procedure for ADS

Two different options for modified SIRIO operation conditions were proposed and supported by pre-test simulations using RELAP5-3D©

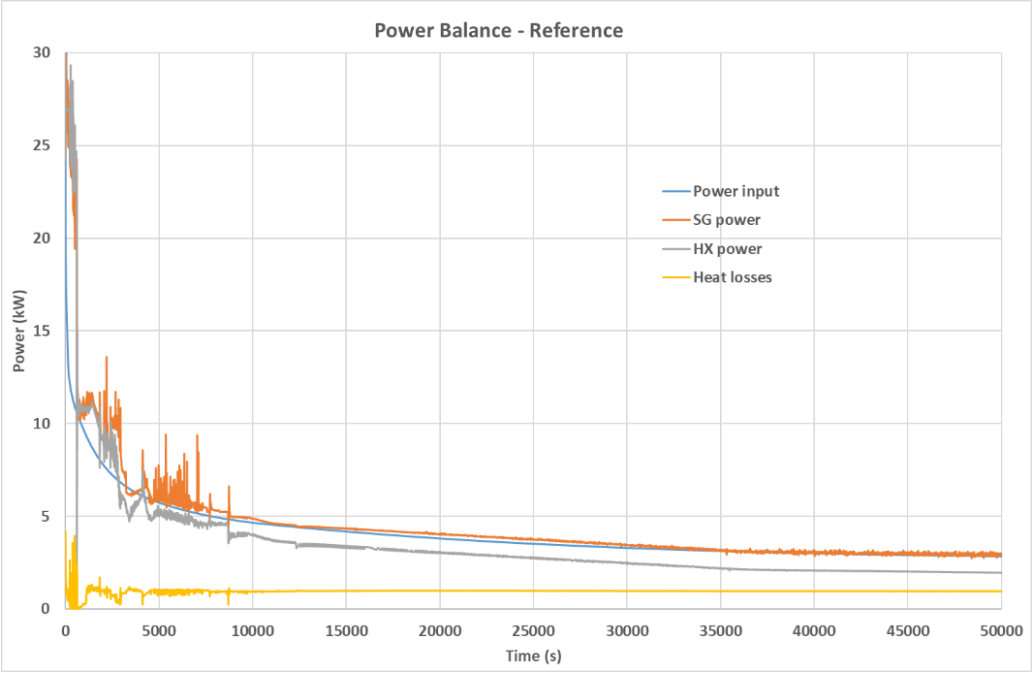
Parameter	Unit	MYRRHA	Option 1	Ratio	Option 2	Ratio
Power	kW	1925	28.3	68.0	3.25	592.3
Power per tube	kW	2.57	2.57	1.0	0.30	8.7
SG Heat Transfer surface	m^2	182.50	5.27	34.6	5.27	34.6
Thermal flux	kW/m^2	10.55	5.55	1.9	5.55	1.9
Total volume	l	65000.0	110.3	589.3	110.31	589.3
Water mass	kg	30000.0	37.9	791.7	50.70	591.7
Power density	kW/l	0.03	0.26	0.12	0.03	1.0
Specific power	W/kg	64.17	746.84	0.09	64.10	1.0

The results of the pre-test simulation for the option 1 requires minimum modifications of the SIRIO facility and then was selected for the pre-test

ADS LOOP transient simulation in SIRIO

The transient proposed in the test matrix is the Loss Of Off-site Power (LOOP).
The transient conditions were run for more than 15 hours.

With the IC concept implemented, stable conditions are observed after a certain time, characterized by a very low water pressure (~9.4 bar for the reference case) and temperature (~175°C for the reference case) whereas without the IC, the pressure stabilize around 2 bar (120°C).



These results show the advantage and the effectiveness of the IC to maintain the molten salt temperature (~176°C) stable with enough margins above the LBE melting temperature (125°C).

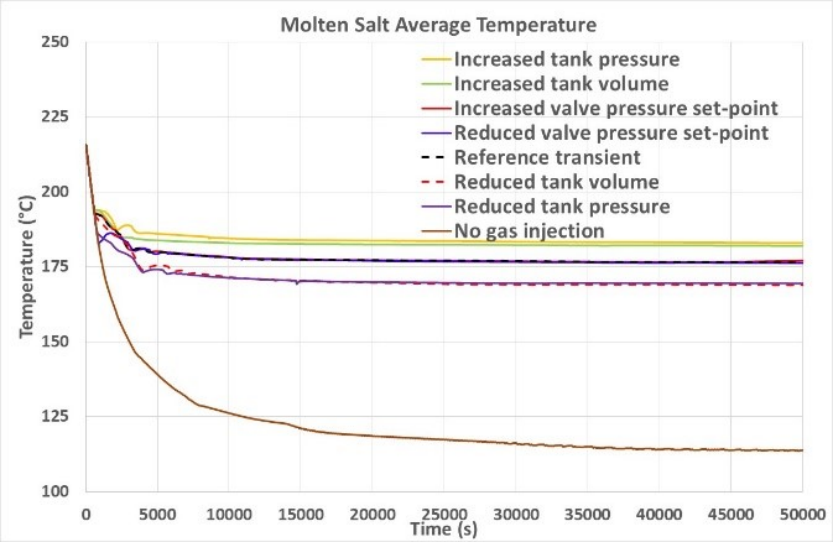
ADS LOOP transient simulation in SIRIO – sensitivity analysis

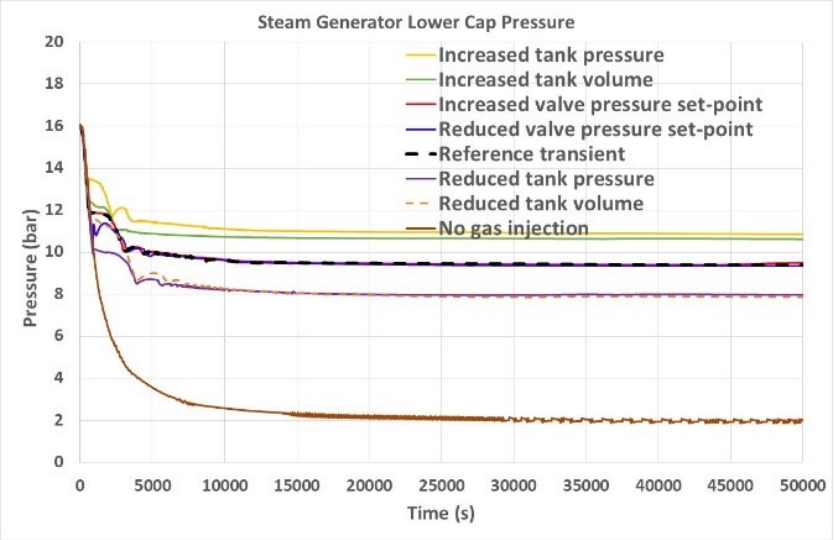
Sensitivity studies are also performed to highlight the key parameters that affect the facility with respect to MYRRHA conditions such as:

— Sensitivity on nitrogen tank volume (2.5 m³ – 10m³);

— Sensitivity on nitrogen tank pressure (12 bar ± 2 bar);

— Sensitivity on nitrogen injection trigger pressure (10 bar ± 2 bar);





Conclusions

- The IC concept developed to delay the freezing of lead during long term decay heat conditions in the ALFRED reactor was proposed to be tested in the SIRIO facility within the HORIZON 2020 PIACE European programme.
- The project was also a good opportunity to test this concept for other technologies and objectives such as PWR, BWR, PHWR and ADS.
- ✓ The pre-test calculations carried out for the first planned ALFRED tests are able to show that the SIRIO IC with the NC gas self-regulates the power removed from the SG, with a reduced changes in the temperature behavior in the primary circuit avoiding a possible lead freezing.
- ✓ The influence of heat losses could be significant, and an apposite detailed characterization is planned.
- The implementation of the IC concept in the MYRRHA ADS DHR1 required modifications of the SIRIO layout and operation conditions, even without fully respecting the scalability rules.
- The pre-test simulations showed that the adapted concept to MYRRHA ADS proves to be efficient to prevent with sufficient margins LBE freezing in the PHX.

THANKS FOR YOUR ATTENTION

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SIRIO data acquisition