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

Heavy liquid metal pool thermal-hydraulics: experiments, analysis, technology

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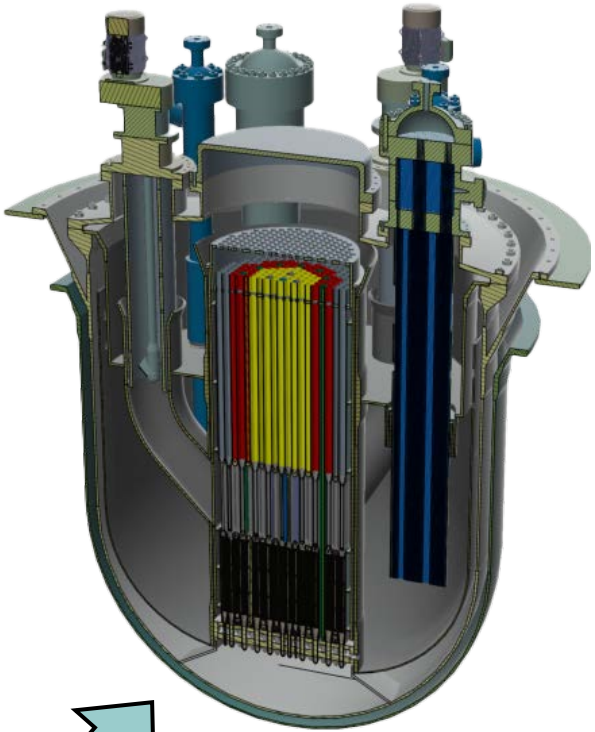
Motivation



Reactor Components

Thermal Hydraulics

Structural Material

Neutronics

Fuel/Advanced Fuel

Instrumentation

Coolant and Cover Gas Chemistry

Towards the LFR Development

Reactor Components

- Fuel assembly (feasibility, structural integrity, support structure from the top or from the bottom of the FA, buoyancy, failed fuel detection).
- Fuel handling machine (reliability, accuracy, shielding, fuel loading procedure).
- Spent fuel element cooling system (active and passive, reliability, behavior with blocked FA).
- Core arrangement integrity (core compaction prevention, radial expansion of core & feed back on reactivity).
- Control and shut-down rods (insertion from the top or from the bottom, reliability, actuation, speed of insertion).
- Inner Vessel Structures (support, replacement, resistance to lead sloshing loads).
- Pump (Pressure head, reliability, inertia, bearings…)
- Steam Generator (Design validation, material selection, component behavior in forced and natural convection, tube rupture/leakage detection, tube rupture mitigation, reliability and performance assessment, replacement).
- Reactor vessel (seismic assessment).
- Decay heat removal systems (Functional design, reliability, material selection, TH behavior)

Towards the LFR Development

Structural Material

- Corrosion in Lead (oxidation, dissolution).
- Embrittlement in Lead (reduction of fracture toughness and ductility, Fatigue, Creep)
- Irradiation effects on materials in Lead (irradiation performance of candidate materials, corrosion in Lead under irradiation, Irradiation embrittlement, irradiation creep, swelling).
- Material for short term deployment (austenitic steel such as AISI 316L and 15-15 Ti, DS stainless steel, ferritic martensitic such as grade 91 steels).
- Coatings development (Al_2O_3, FeCrAl)
- High temperature materials for long term deployment (700-800° C, ODS steels, "MAX" phase materials).
- Main components issues:
  - Fuel Cladding (irradiation effects, compatibility with coolant, material workability, component fabricability, oxide formation thickness, coating compatibility).
  - Material for pump impeller (high relative coolant velocity).
  - SG and HX (oxide formation thickness)
  - Reactor vessel (long lifetime, seismic loads)
  - Seismic isolators (qualification)

Towards the LFR Development

Fuel/Advanced Fuel

- Manufacturing constrains (Pellet specifications - density, grain size, homogeneity, porosity, pellet straightness, pellet mechanical stability, roughness - Clad specifications - wall thickness, wall thickness variation, straightness, toughness, roughness, cleanliness, corrosion resistance, heat treatment)
- Fuel pellets (FP release, fuel restructuring, densification and swelling)
- Fuel cladding (swelling, embrittlement, corrosion -coolant and fuel side-, clad-FP interaction, fatigue, creep)
- Fuel operating conditions and failure margin assessment (normal operation, operational transients, accidental conditions)
- Failed fuel pin behaviour (release of gaseous FP, dissolution of FP in the coolant, loss of fuel particles chemical reaction between fuel and coolant)
- Corium-coolant interaction (Fuel dispersion in coolant, chemical stability of corium)

For the existing fuel can be considered the experience gained in SFR (Phénix, Monju, Superphénix, etc..).
For the new advanced fuels (MA mixed MOX fuel, nitride fuel, carbide fuel) all aspects related to fuel need to be re-assessed.

Towards the LFR Development

Thermal hydraulics

- Phenomena:
  - HLM pool thermal-hydraulics (flow patterns in forced convection, mixing & stratification, surface level oscillations, transition to natural circulation driven flow, natural circulation flow, etc..)
  - Water injection in lead (SGTR accident, rupture of DHR tubes)
  - Fuel Pin - coolant interaction (Flow induced vibrations)
  - FA blockage (Fuel Assembly damage)
  - Gas entrainment (two phase flow)
  - Coolant freezing (flow blockage)

- Modeling:
  - System thermal-hydraulic codes (V&V)
  - STH and neutronics (V&V)
  - CFD and mechanical code coupling (V&V)
  - STH code and CFD code coupling (V&V)

Towards the LFR Development

Thermal hydraulics

- Experiments:
  - Integral tests (including natural circulation and decay heat removal to support the licensing process)
  - Fuel bundle (sub-channel analysis, heat transfer, cross-flow, pressure loss, etc..)
  - Steam Generator (functional tests, SGTR accident)
  - Lead pumps (functional tests)
  - FA cooling system at refueling (performance test)
  - Core cooling with total inlet flow blockage (SGs or downcomer frozen)

Towards the LFR Development

Instrumentation and chemistry control

- Coolant control & purification (oxygen control, oxygen sensor reliability, coolant filtering, lead purification, lead cleaning from components)
- Cover gas control (radiotoxicity assessment of different elements, migration flow path into cover gas, removal and gettering)
- Temperature-level-pressure-flow-neutron flux measurements (improvement of reliability, failure mode investigation, irradiation effects)
- In service Inspection (ultrasound imaging & inspection, transducers development, image reconstruction technologies, sensors for in vessel inspection, sensor for reactor vessel inspection, inspection strategies,)

Towards the LFR Development

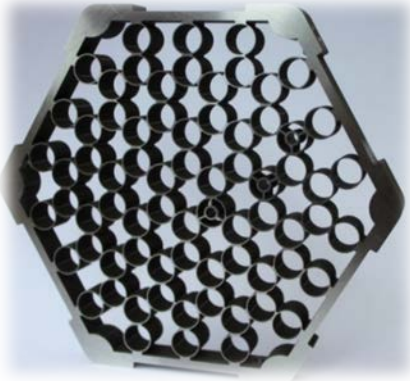
Neutronics and reactor operation/control

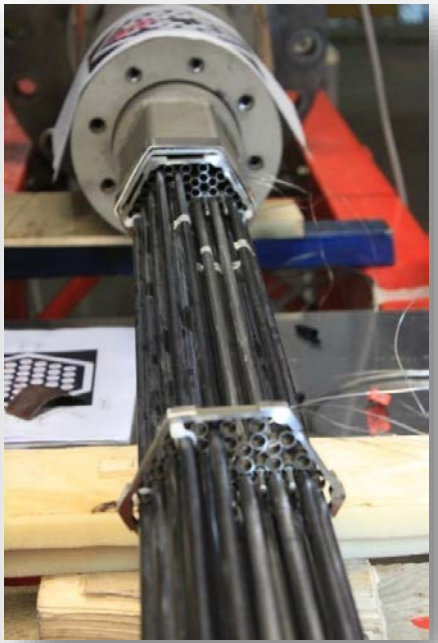
- Validation measurements for nuclear data improvement (MA cross-sections, uncertainty reduction on cross-sections as Pb-MA-^{241}Pu, ^{242}Pu, etc..).
- Determination of flux gradients in fast spectrum.
- Reactivity effects (local-coolant void reactivity worth, density coefficients, Doppler coefficient, dimension coefficients).
- Fuel neutronic performances (fuel utilization, spectrum evolution with burn-up, delayed neutron fraction).
- Absorbers neutronic performances (boron carbide, europium…)
- Neutronic shielding (absorbing materials, moderating materials)
- Reactivity control (control rods).
- Shut down systems (active and passive, additional protection measures).
- Neutron code development (Improvement & extension MCNPX, Deterministic code set-up & validation)
- Neutron code validation experiments (Nuclear data improvement, integral measurements & comparison with calculations)

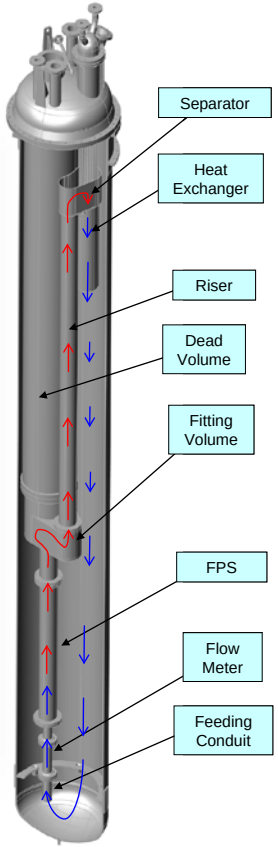
Pool thermal hydraulic experiments

CIRCE pool-type experimental facility

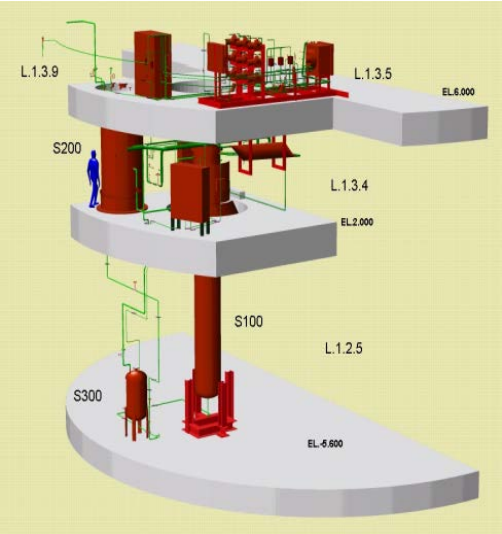
- Integral Experiments (@ 1 MW)
- OCS testing in large pool
- Component qualification
- SGTR Experiments
- SG & Pump Unit Test





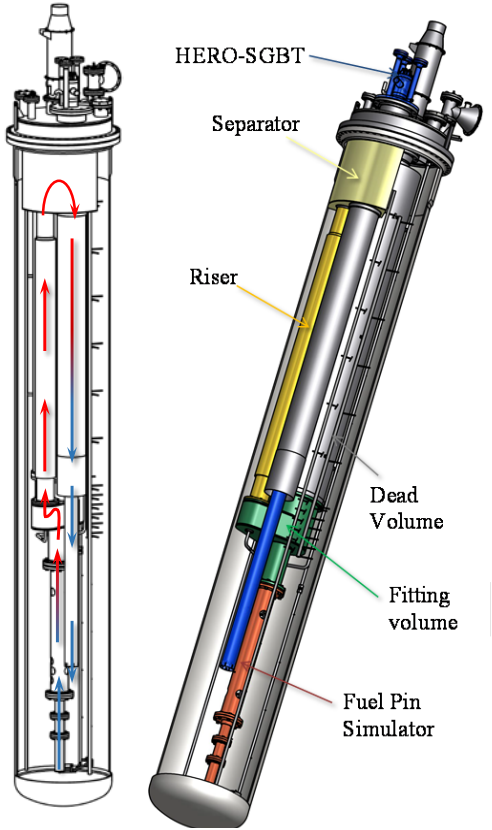


CIRCE pool-type experimental facility

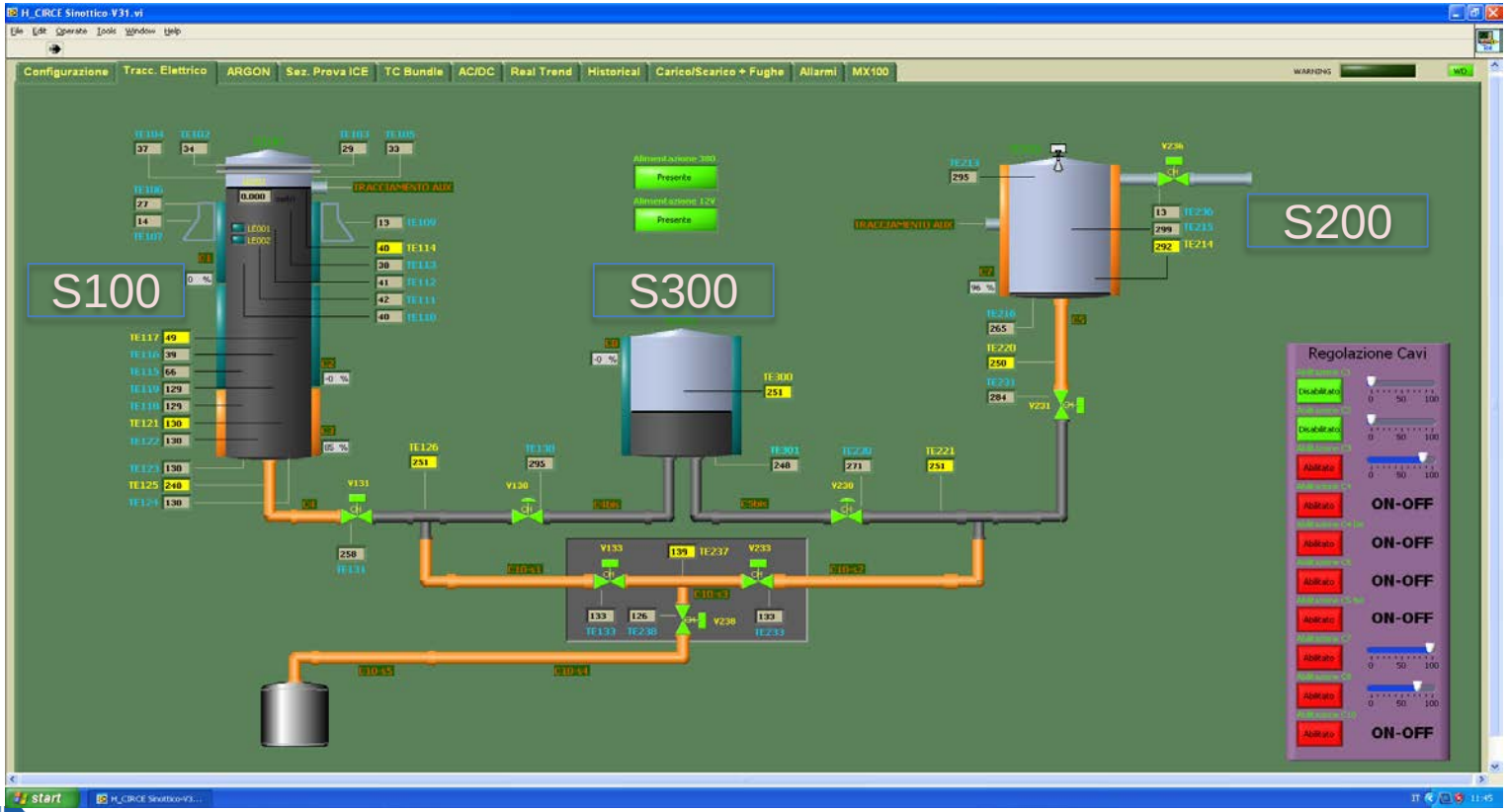


The **CIRCE facility** consists of:

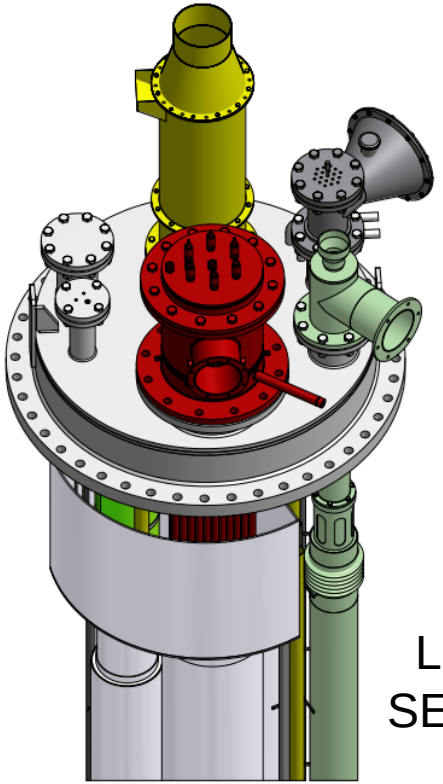
- **S100** cylindrical main vessel, 8.5 m height filled with about 70 tons of Lead-Bismuth Eutectic (LBE) with argon as cover gas
- **S200** storage tank
- **S300** transfer tank

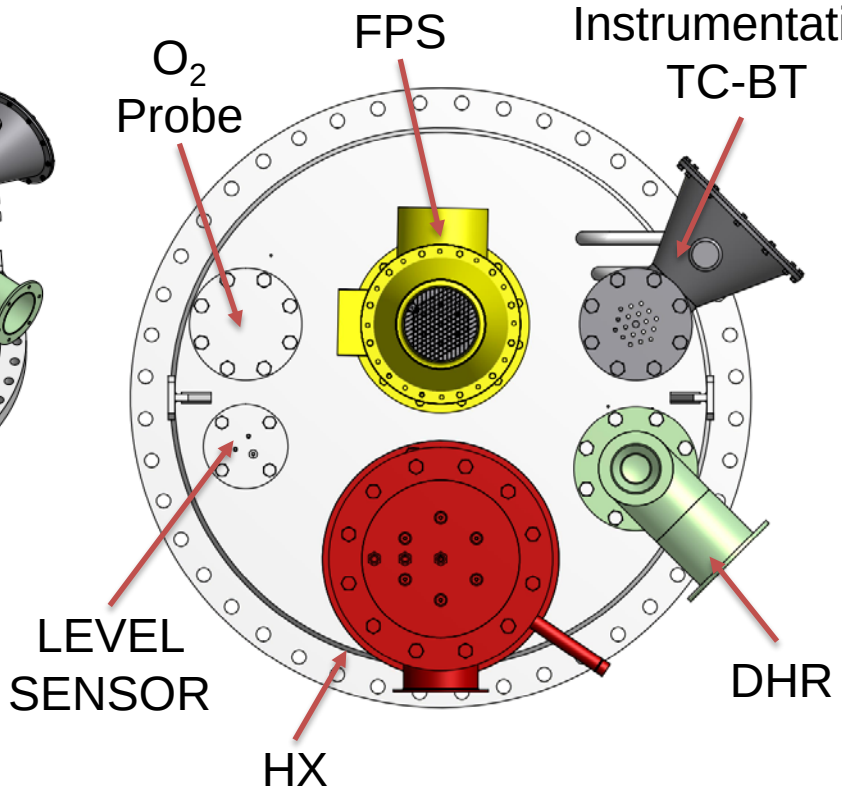


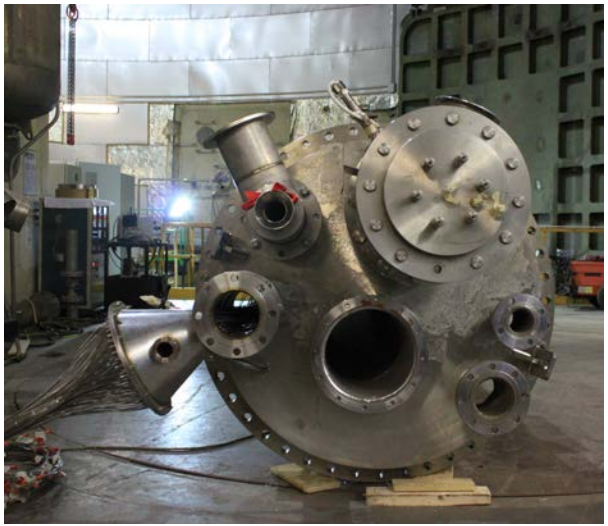
CIRCE Filling & Draining Procedure



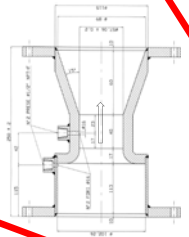
CIRCE TS main flange

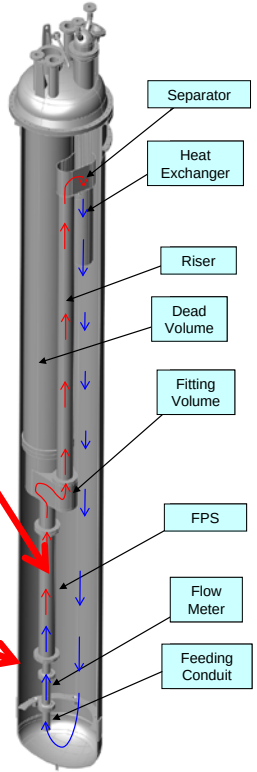


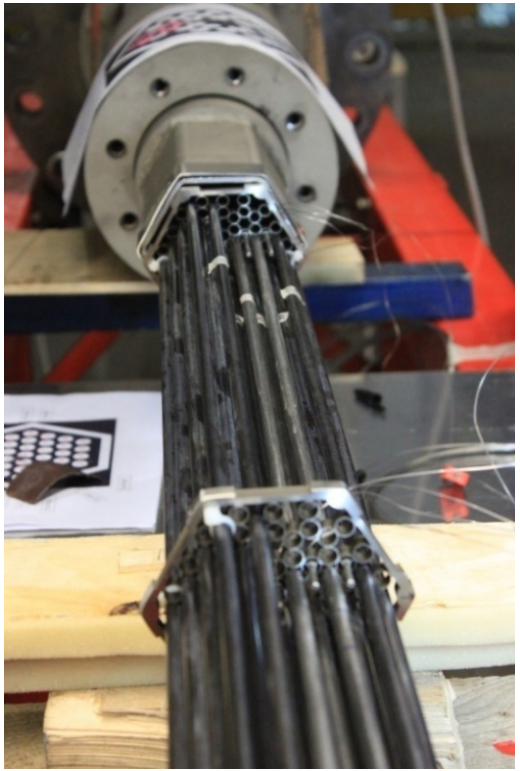




CIRCE FPS



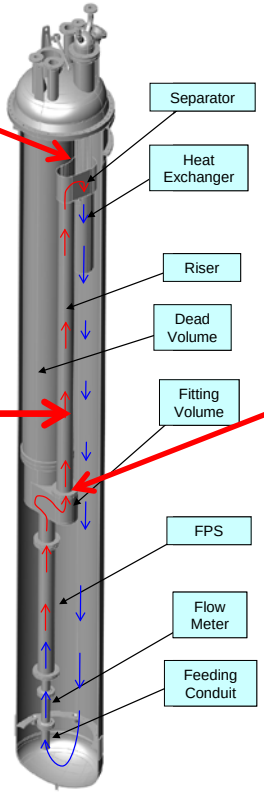


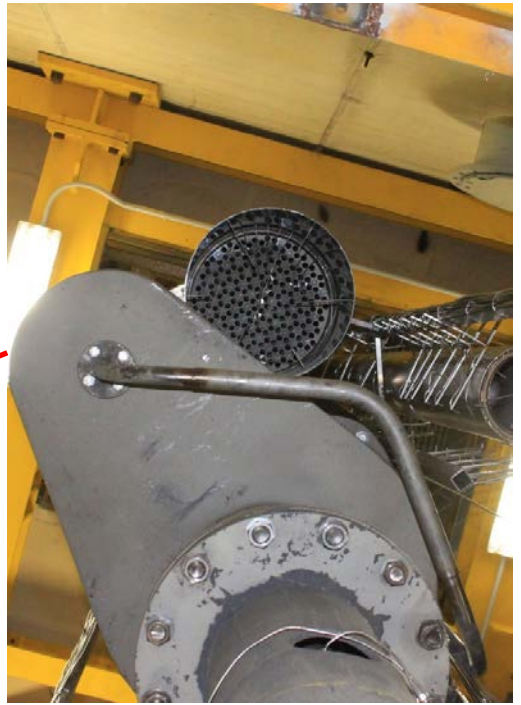


- Assembly: Hexagonal
- d: 8.2 mm
- p/d: 1.8
- L_{act}: 1000 mm
- N_{Pin}: 37
- q": 100 W/cm^2
- Q_{Pin}: 25 kW

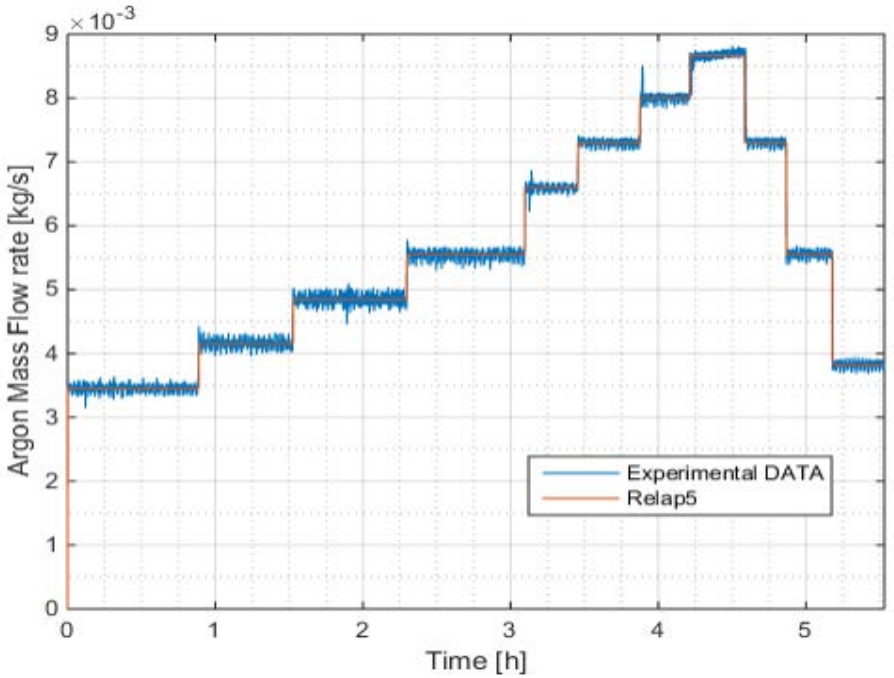
- Thermal Power: 925 kW
- LBE T_{AV}: 300 - 450 °C
- Core ΔT: 100 °C
- Core velocity: 1.0 m/s
- LBE Flow Rate: 55.2 kg/s

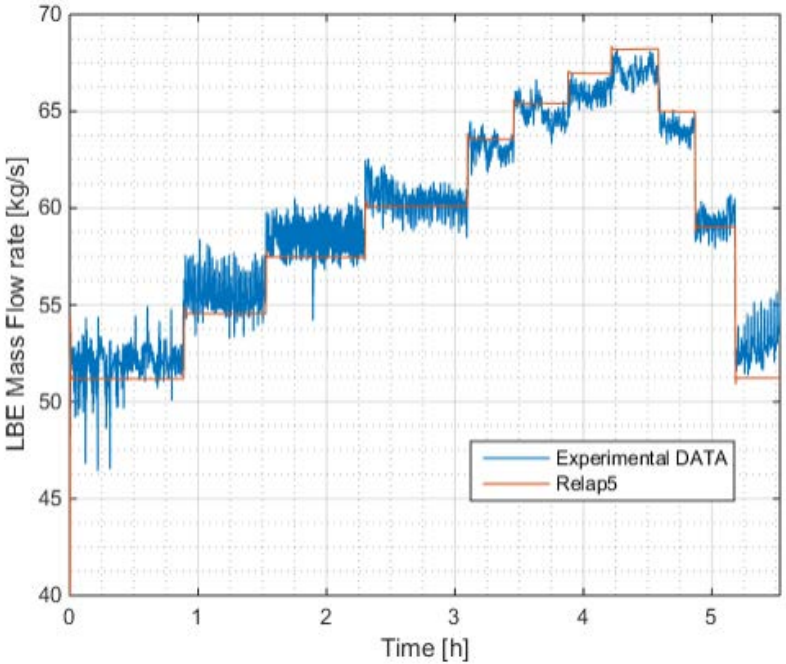
CIRCE-ICE Configuration



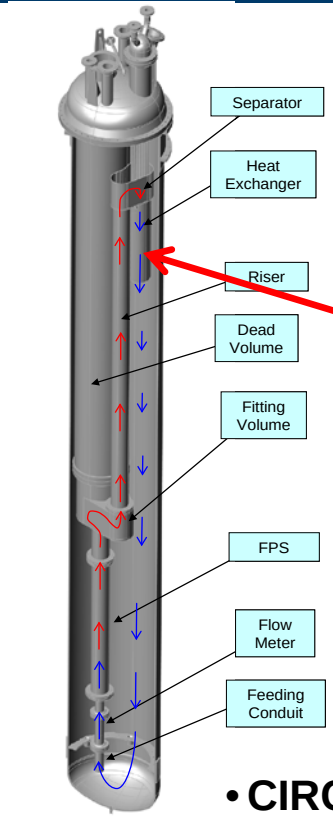


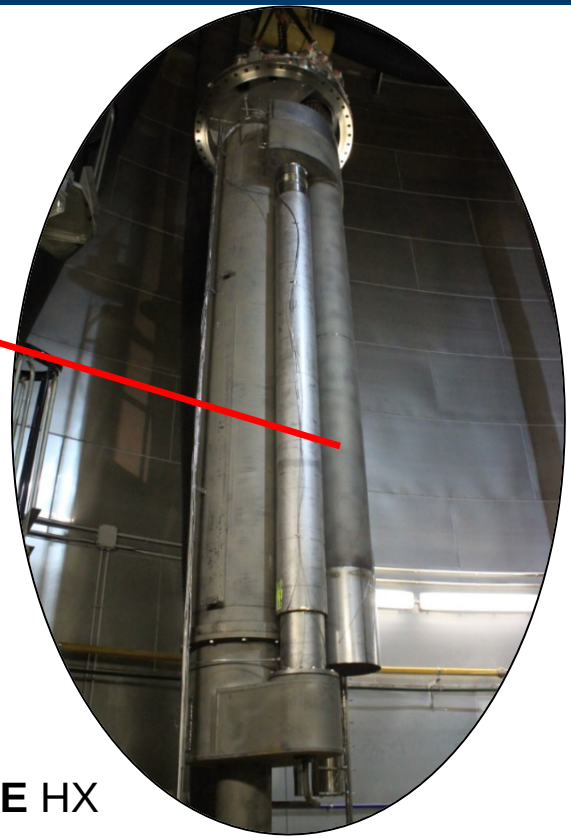
CIRCE-ICE Configuration





CIRCE-ICE HX

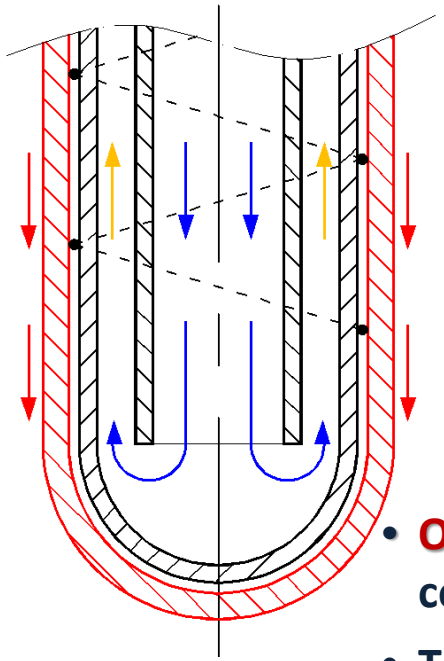




- **CIRCE ICE** HX

HX Bayonet tube concept

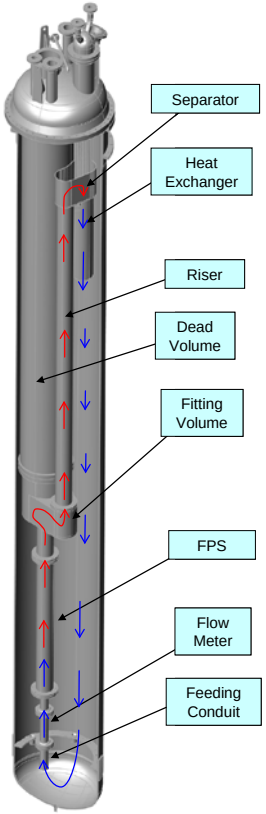
HLM–low pressure boiling water shell heat exchanger

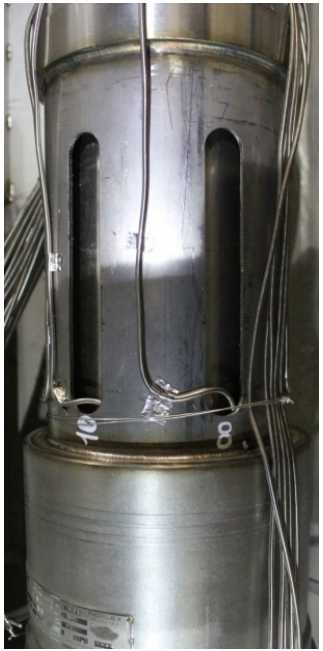


- Assembly : Triangular
- Tubes: double wall “Bayonet” with He Gap
- Material: AISI 316
- Water Pressure: 3.5 bar
- Steam Pressure : 1 bar
- Steam Quality: 0.4
- Flow Rate: 0.7 kg/s

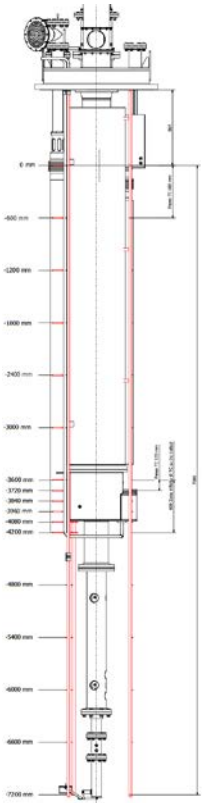
- **Outer tubes leakage could be detected** from depressurization of the common gas plenum.
- The **two outer tubes are mechanically and thermally decoupled.**

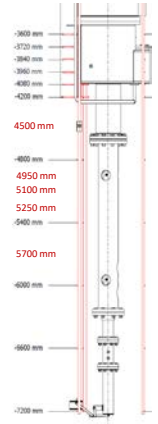
CIRCE-ICE DHR

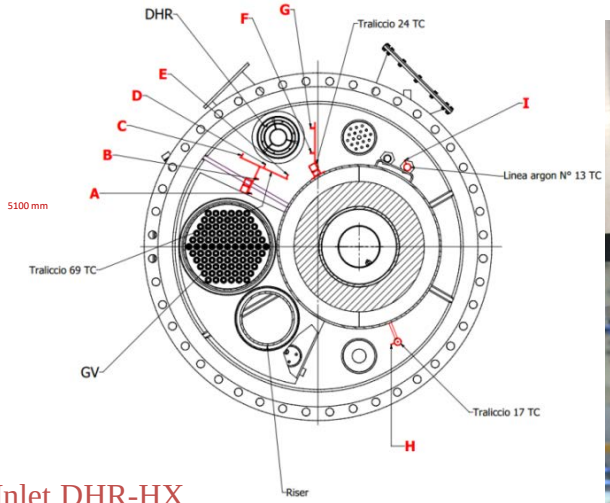




CIRCE Pool Instrumentation







- 6 TC Inlet DHR-HX
- 6 TC Outlet DHR-HX
- 3 TC Inlet SG
- 9 TC into the SG's subchannels
- 6 TC Outlet SG
- 119 TCs distribute in 17 vertical positions
- 3 TC at the riser Inlet
- 3 TC at the riser Outlet

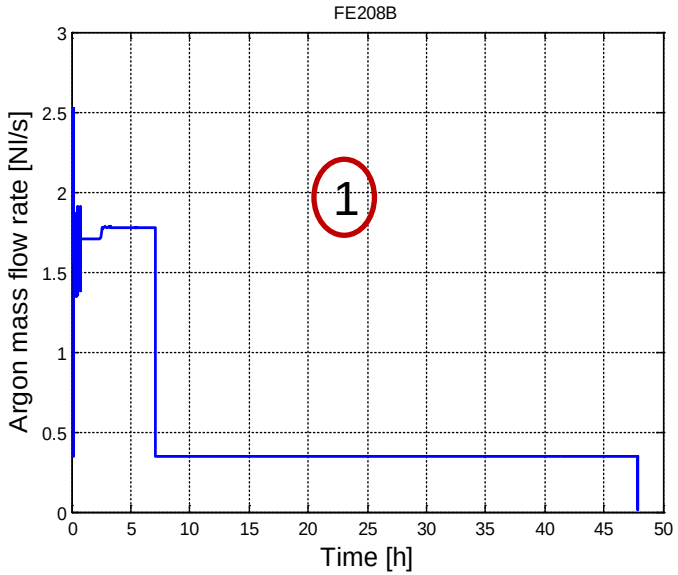
CIRCE-ICE Experimental Campaign

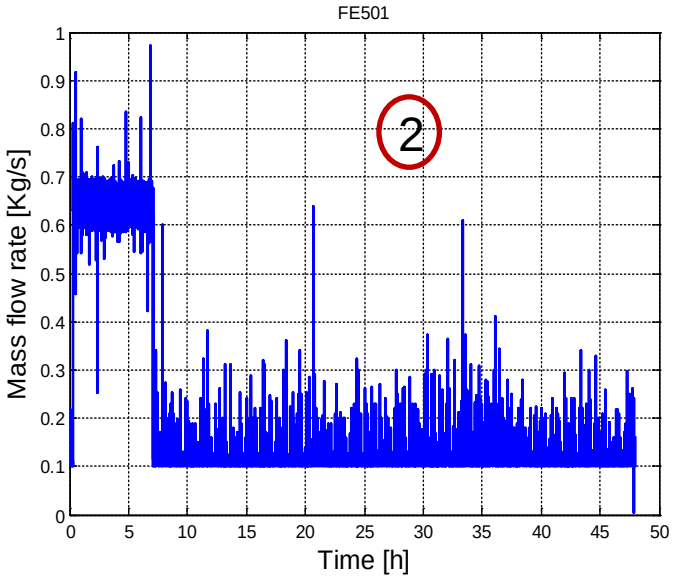
- Characterize the phenomena of mixed convection and stratification in a liquid metal pool
- Under nominal condition (full power, forced circulation promoted by gas lift), a main flow path exists along the test section, which directly connects the HS with the HX.
- The **DHR** adopted ***air*** as secondary fluid, and it was be designed for a thermal duty of **40 kW** (about ***5%*** of the nominal power)

Transition from nominal condition to natural circulation was run *CUTTING OFF THE MAIN HX AND STARTING THE DHR HEAT EXCHANGER*, allowing to evaluate the manifestation of secondary flow paths, involving DHR and downcomer, uncoupled from the primary flow path.

- **Study *PLOHS + LOF accident* (*station blackout*) that in a LFR consists of:**
  - ✓**Loss of all primary pumps and secondary circuits**
  - ✓ **Reactor scram**
  - ✓**Decay heat removed in natural circulation by emergency systems (DHR-HXs).**

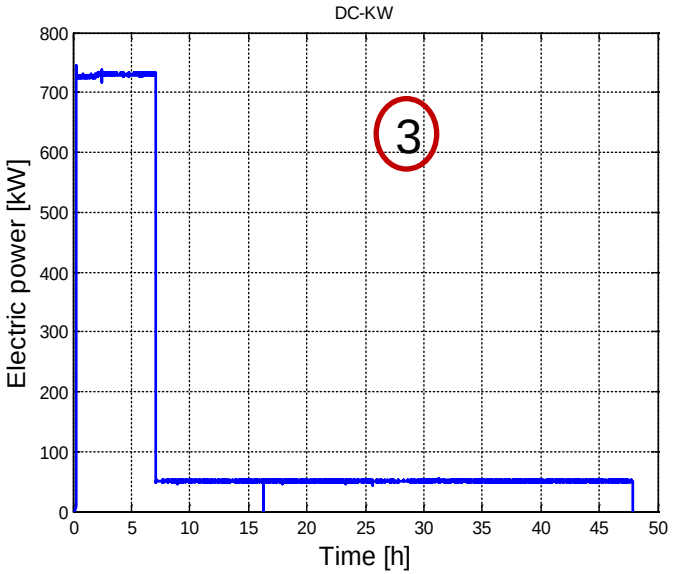
Experiment Description (CIRCE-ICE)

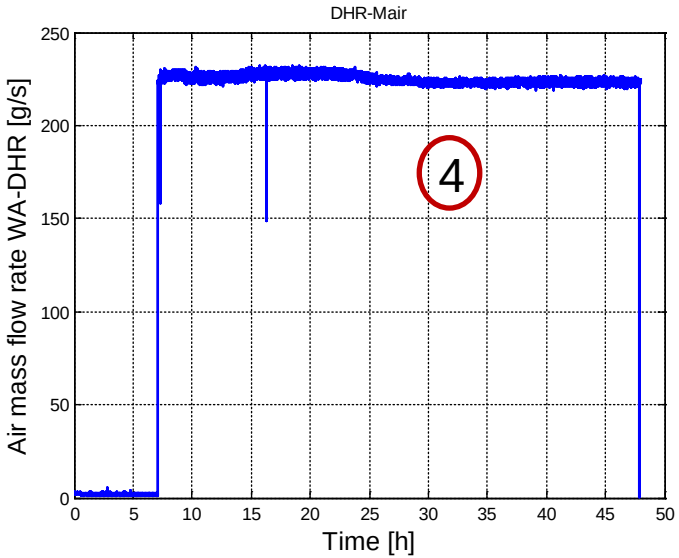




1. Loss of primary pumps → Stop Ar injection
2. Loss of primary circuit → Stop HX feedwater injection

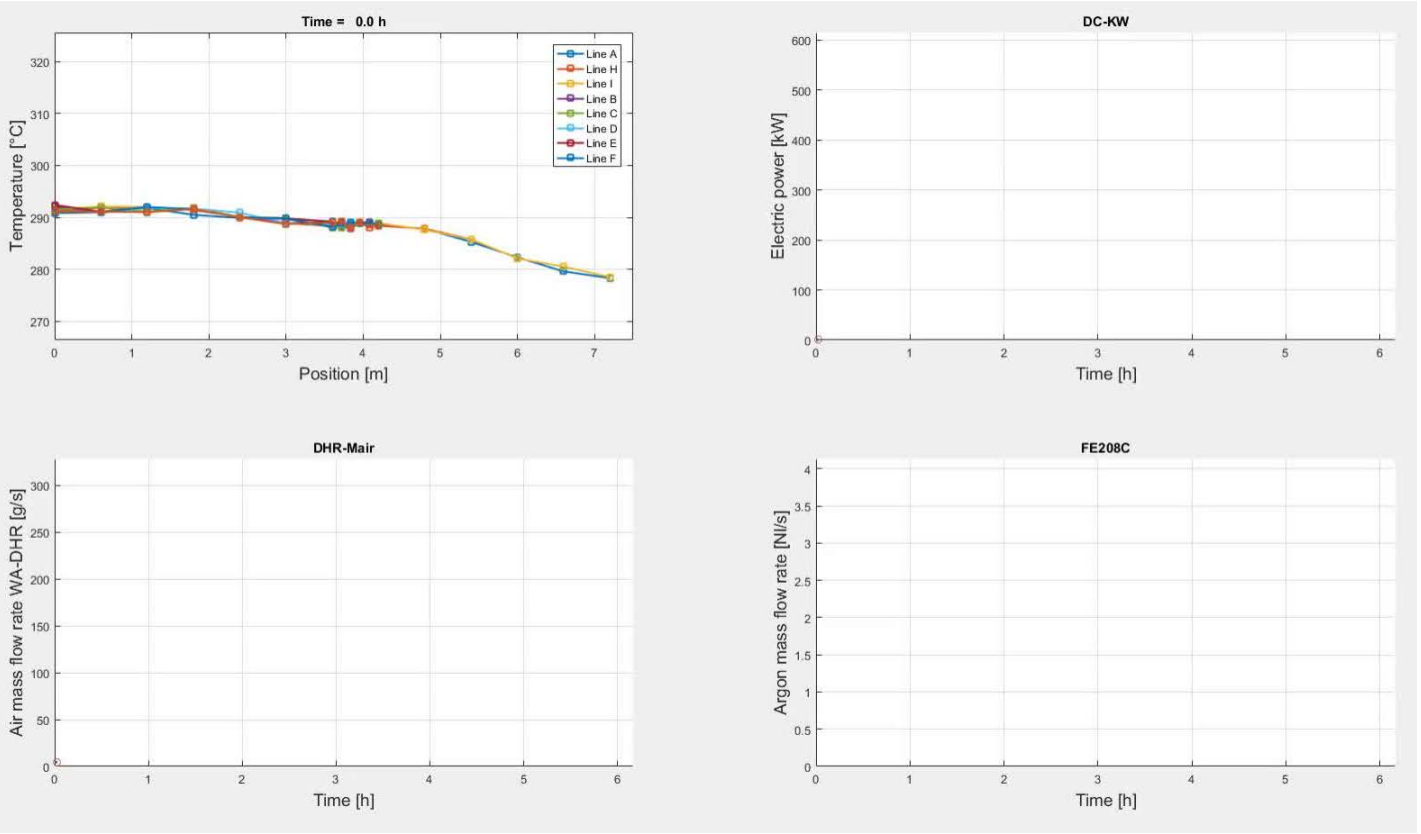
Experiment Description (CIRCE-ICE)





3. Reactor scram (power reduced to DH conditions) → Decreasing FPS Power
4. DHR system activation → Starting air blower

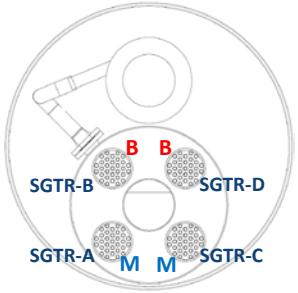
Pool thermal Stratification

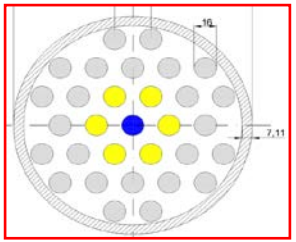


SGTR Experiments

SGTR Experiments in the CIRCE pool

- 4 SGTR runs (pressure wave propagation, cover gas pressurization, domino effect, vapour flow path, safety guard devices, impurities formation, LBE particulate discharge)
- 4 tube bundles (SGTR-A,-B,-C and -D) 31 tubes, full scale portions of the PHX tube bundle





Water injection in **LBE**

T_{H2O} = 200°C P_{H2O} = 16 bar

T_{LBE} = 350°C P_{COVER} = 1 bar

2 rupture positions **B** and **M**:
Bottom **B** (SGTR-B and -D)
Middle **M** (SGTR-A and -C)

Highly instrumented TS:

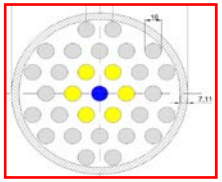
200 TCs (45 in each SGTR-x,) (50 Hz)
H2O ultrasonic flowmeter (15 Hz)
H2O level meter (1 Hz)
8 fast pressure transmitters (1 kHz)
12 bubble tubes (1 Hz / kHz)
30 strain gages (10 kHz)
2 LBE Venturi flow meters (1 Hz)

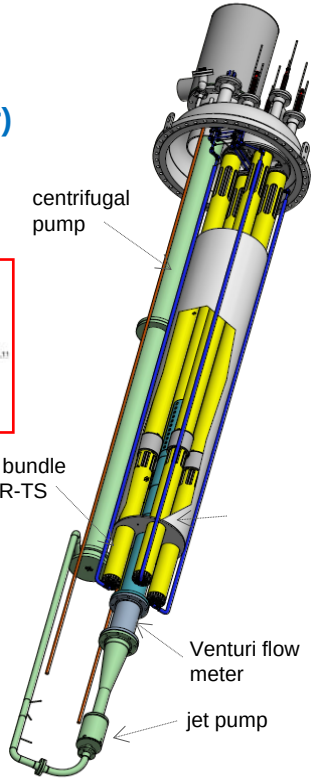
Test matrix	Test #1 SGTR-A	Test #2 SGTR-C	Test #3 SGTR-B	Test #4 SGTR-D
LBE temperature [°C]	350	350	350	350
LBE cover gas pressure [bar]	0.05	0.05	0.05	0.05
LBE flow rate (kg/s)	60-65	75	80	75
Water temperature [°C]	182	190	192	195
Water pressure [bar]	16.3	17	16.5	16.9
Water flow rate (g/s)	65	74	73	72
Centrifugal pump head [bar]	2	2.2	3.1	2.7
Rupture position	Middle	Middle	Bottom	Bottom
Rupture occurrence in right position (by TC analysis)	Yes	Yes	Yes	Yes
Injection time [s]	5	5	5	5
Max water mass flow rate [g/s]	120	130	130	135
Max CIRCE pressurization [bar]	2.6	2.7	3.6	3.7
Rupture disc activation	Yes	Yes	No	No
LBE in 3/4 inch discharge line	No	No	Yes	Yes

SGTR Experiments in the CIRCE pool

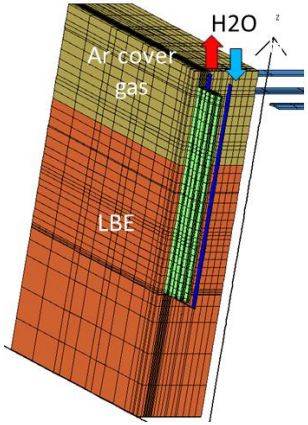
LBE 80 kg/s

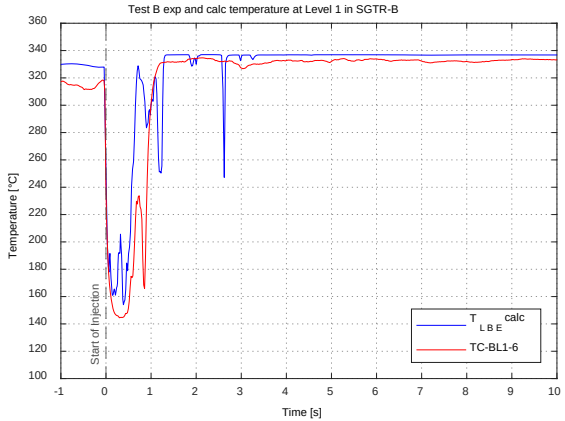
H_2O 70 g/s
(200°C,16 bar)

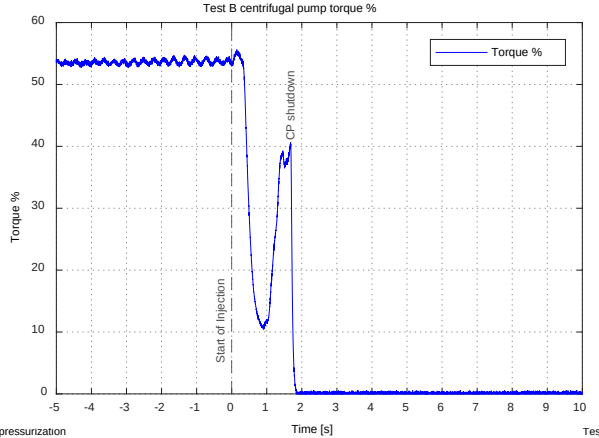




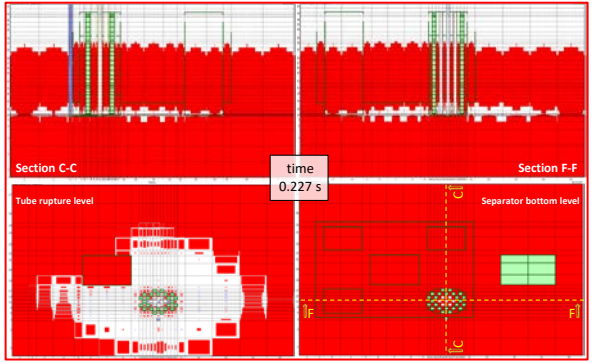
SGTR Experiments in the CIRCE pool

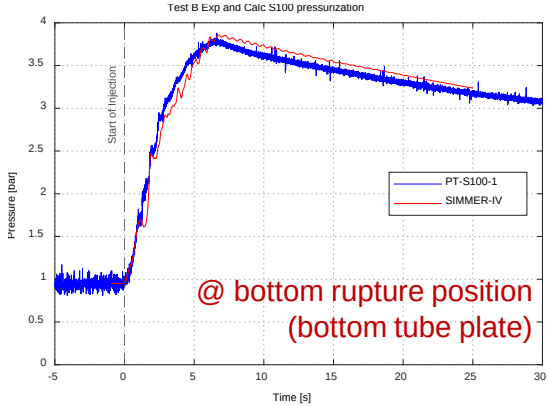




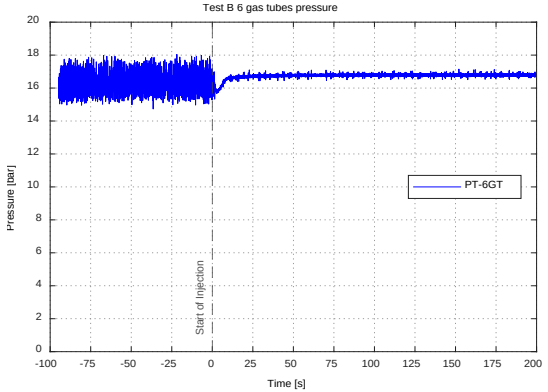


steam from SGTR rupture reached the CP suction before CP shutdown

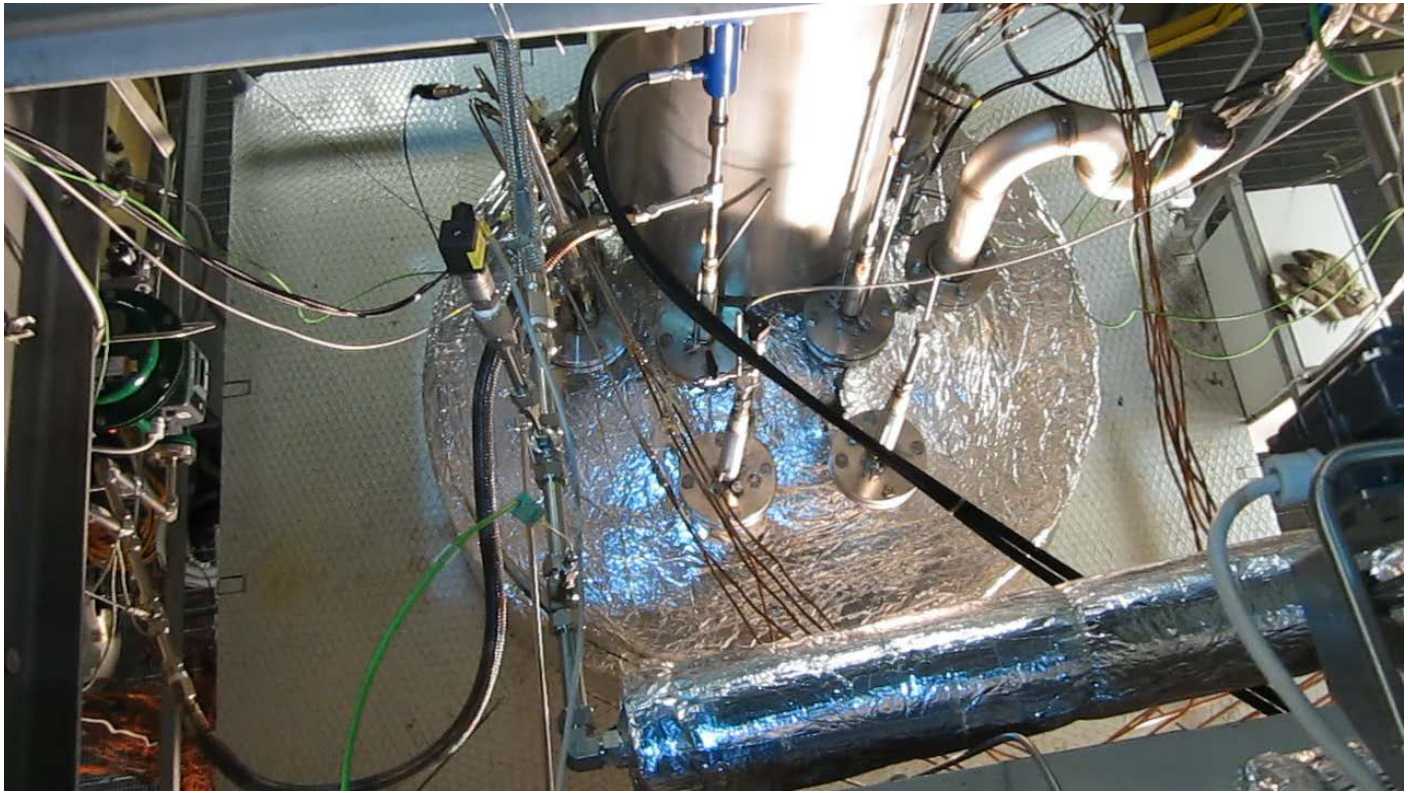




@ bottom rupture position (bottom tube plate)



SGTR Experiments in the CIRCE pool

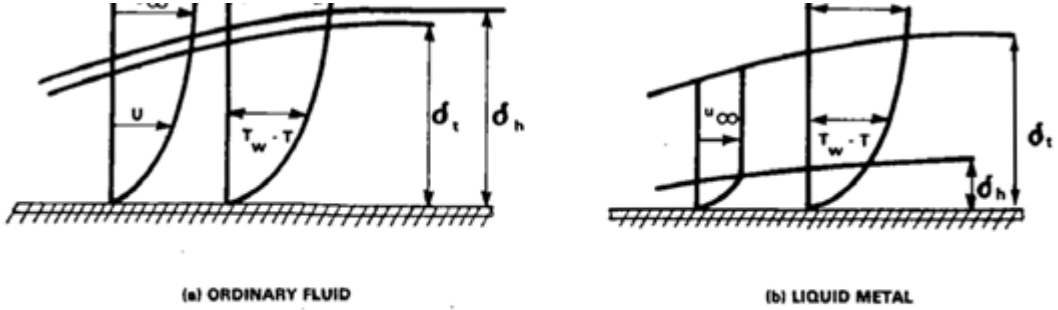


Heat transfer experiments in Pool configuration

Heat Transfer in LEAD

Liquid metals have Prandtl numbers that are **lower than the unity**, as can be seen in the following table

Coolant	Prandtl number	
Water	6.82 (21 °C,1bar)	1.06 (PWR)
Liquid metals	0.004 – 0.04	



Comparison of thermal (δ_t) and hydrodynamic (δ_h) boundary layers for ordinary fluids vs liquid metals.

Due to the large thermal and small viscous diffusivity (low Prandtl number) the momentum and temperature fields are non-similar, so that the turbulent heat flux models based on the Reynolds analogy cannot be applied to liquid metals.

Indeed, in a liquid metal, **the thickness of the thermal boundary layer is significantly larger than the thickness of the hydrodynamic boundary layer**.

Heat Transfer in LEAD

- For calculation of the heat transfer from the fuel rod surfaces to the coolant **correlations are necessary**

1961	Friedland et al.	Hg
1961	Friedland et al.	Hg
1963	Borishanskii and Firsova	Na
1964	Borishanskii and Firsova	Na
1964	Maresca and Dwyer	Hg
1965	Nimmo and Dwyer	Hg
1967	Kalish and Dwyer	NaK*1
1967	Zhukov et al.	Hg
1967	Zhukov et al.	Hg
1967	Zhukov et al.	Hg
1967	Zhukov et al.	Hg
1967	Zhukov et al.	Hg
1969	Hlavac et al.	Hg
1969	Borishanskii et al.	Na
1969	Borishanskii et al.	Na
1969	Borishanskii et al.	Na
1969	Borishanskii et al.	n.a.
1969	Borishanskii et al.	n.a.
1969	Borishanskii et al.	n.a.
1971	Subbotin et al.	Na
1972	Gräber and Rieger	NaK*2
1972	Gräber and Rieger	NaK*2
1972	Gräber and Rieger	NaK*2

The value of h (or HTC) is dependent by many factors:

1. The geometrical shape of the channel
2. The flow rate of the coolant
3. The heat flux
4. The system temperature

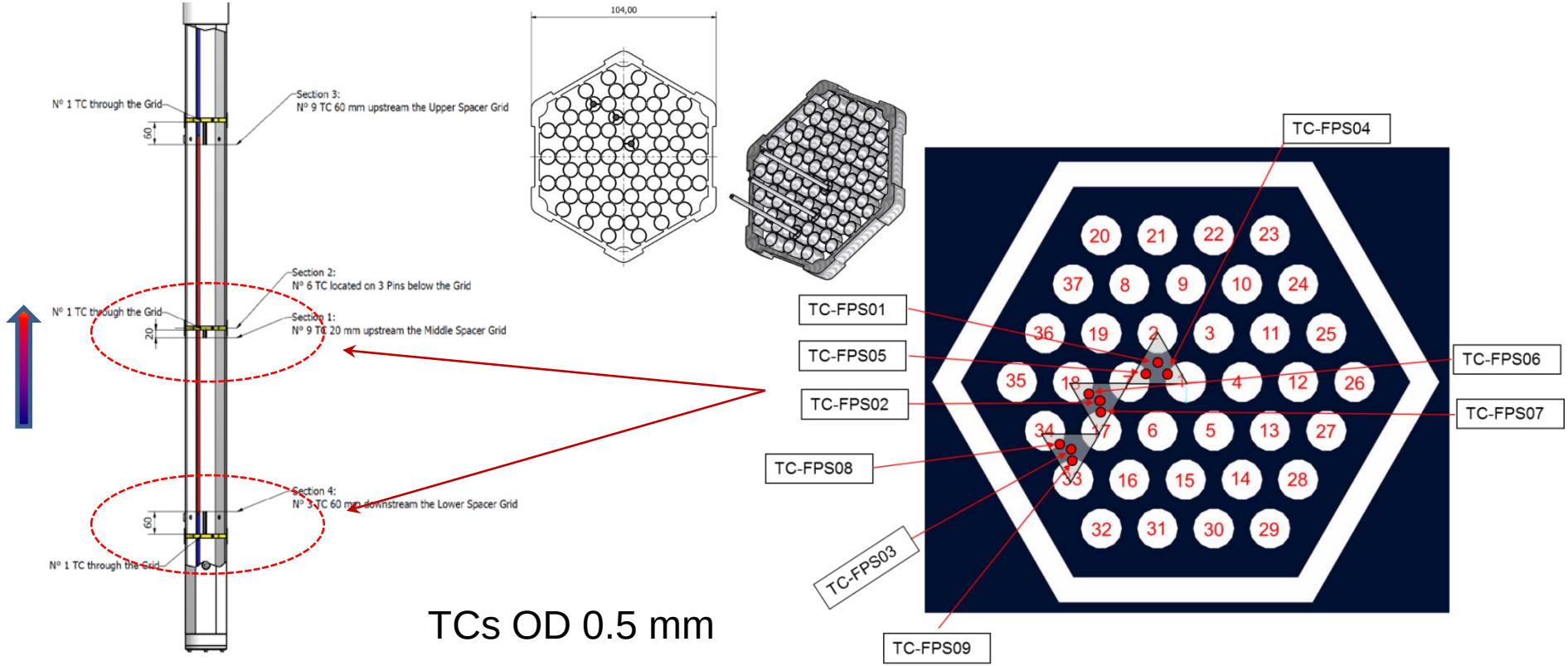
The correlations for the HTC include the dependence from Nusselt number which is generally a function of Reynolds number and Prandtl number.

Nu = f(Re, Pr) **Convection/Conduction** $Nu = a + b \cdot Pe^{c}$

Re = (De w ρ) / μ Inertia force / Viscous force

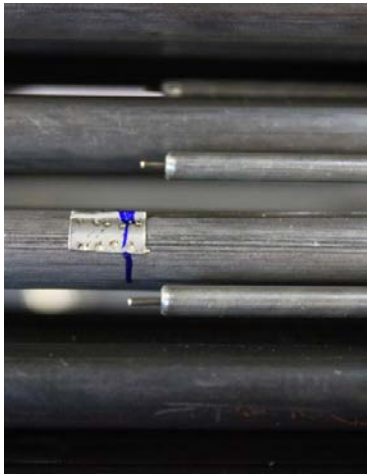
Pr = ν/α= (cp μ) / k Diffusion of momentum /Diffusion of heat

FPS Instrumentation



TCs OD 0.5 mm

FPS Instrumentation



Heat transfer Experimental tests

Name	LBE Mass flow rate [kg/s]	Argon Mass flow rate [Nl/s]	FPS Electrical Power [kW]	*ΔT* (outlet-inlet) FPS [°C]	*ΔT* (clad-bulk) Mikityuk [°C]	*ΔT* (clad-bulk) Ushakov [°C]
1-FC	70	5.00	800	80	35.0	36.0
2-FC	65	4.40	760	80	37.0	39.0
3-FC	60	3.00	700	80	39.5	41.0
4-FC	55	2.40	640	80	41.6	43.5
5-FC	50	1.60	580	80	43.5	45.7
6-FC	45	1.45	525	80	45.4	47.8
7-FC	40	1.41	465	80	47.0	49.5

Name	LBE Mass flow rate [kg/s]	FPS Electrical Power [kW]	*ΔT* (outlet-inlet) FPS [°C]
1-NC	25	600	165
2-NC	23	500	151
3-NC	21	400	133
4-NC	19	300	109
5-NC	14	200	102
6-NC	12	100	58

Experimental Results

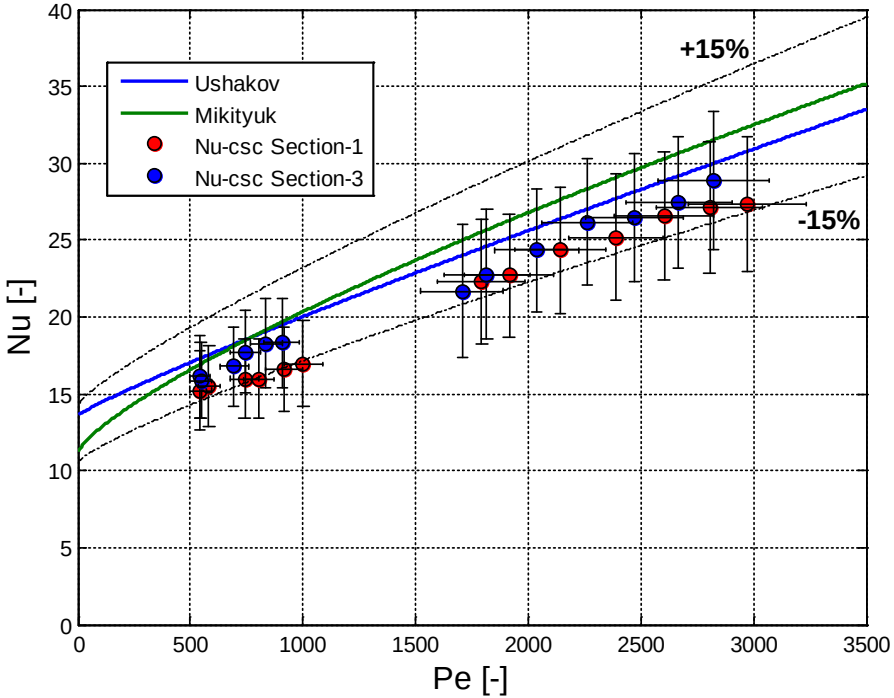
Name	Re	$\langle\sigma_X\rangle$	$\left\langle\frac{\sigma_X}{X}\right\rangle$	Pe	$\langle\sigma_X\rangle$	$\left\langle\frac{\sigma_X}{X}\right\rangle$	Nu	$\langle\sigma_X\rangle$	$\left\langle\frac{\sigma_X}{X}\right\rangle$
1-FC	$1.4\ 10^5$	$7.1\ 10^3$	5.3%	**2971**	260	9%	**27.3**	4.4	16.1%
2-FC	$1.3\ 10^5$	$6.7\ 10^3$	5.3%	**2805**	234	8%	**27.1**	4.3	15.9%
3-FC	$1.1\ 10^5$	$6.8\ 10^3$	5.9%	**2603**	219	8%	**26.6**	4.2	15.8%
4-FC	$1.1\ 10^5$	$5.7\ 10^3$	5.4%	**2388**	211	9%	**25.2**	4.1	16.3%
5-FC	$9.3\ 10^4$	$5.7\ 10^3$	6.1%	**2144**	200	9%	**24.4**	4.1	16.8%
6-FC	$8.1\ 10^4$	$6.2\ 10^3$	7.7%	**1916**	199	10%	**22.7**	4.0	17.6%
7-FC	$7.4\ 10^4$	$6.2\ 10^3$	8.3%	**1794**	194	11%	**22.3**	4.1	18.4%
1-NC	$5.5\ 10^4$	$2.9\ 10^3$	5.2%	**1001**	87	9%	**16.9**	2.8	16.5%
2-NC	$5.1\ 10^4$	$2.7\ 10^3$	5.3%	**917**	81	9%	**16.6**	2.7	16.4%
3-NC	$4.9\ 10^4$	$2.6\ 10^3$	5.2%	**803**	70	9%	**15.9**	2.6	16.3%
4-NC	$4.4\ 10^4$	$2.3\ 10^3$	5.3%	**742**	65	9%	**15.9**	2.6	16.4%
5-NC	$2.9\ 10^4$	$1.6\ 10^3$	5.3%	**583**	51	9%	**15.5**	2.6	17.0%
6-NC	$2.5\ 10^4$	$1.3\ 10^3$	5.3%	**543**	48	9%	**15.2**	2.6	17.3%

$$Nu = 7.55\cdot(p/d) - 20\cdot(p/d) - 0.041\cdot(p/d)^{-2}\cdot Pe^{(0.56+0.19\cdot p/d)}$$

valid for $1.2 \le p/d \le 2$ and for $1 \le Pe \le 4000$

$$Nu = 0.047\cdot\left(1-e^{-3.8\cdot(x-1)}\right)\left(Pe^{0.77}+250\right)$$

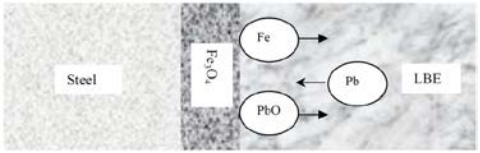
valid for $1.1 \le p/d \le 1.95$ adn for $30 \le Pe \le 5000$

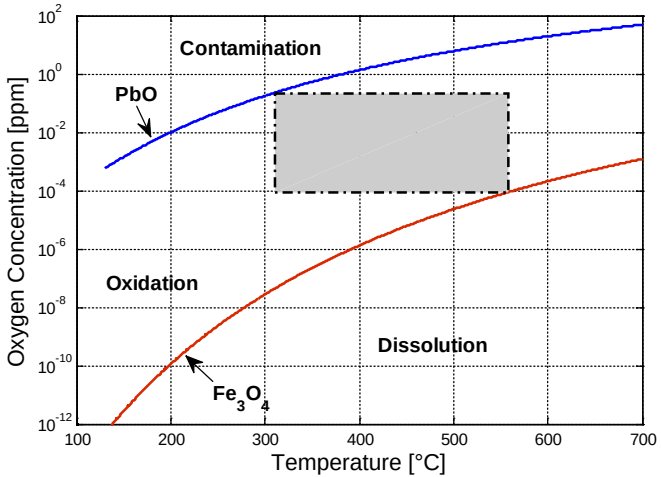


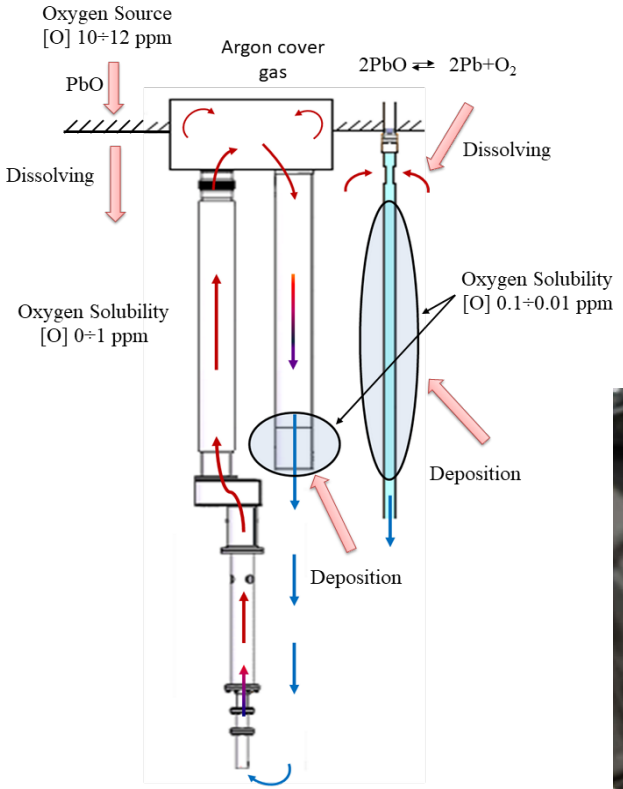
Coolant Chemistry

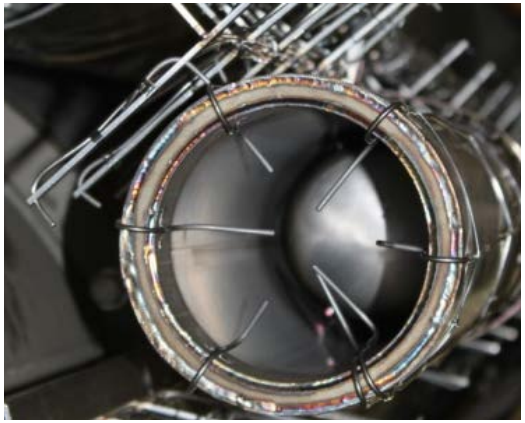
Coolant chemistry

Lead reducing iron oxide film and iron reforming oxide formation (self-healing protective oxide film)

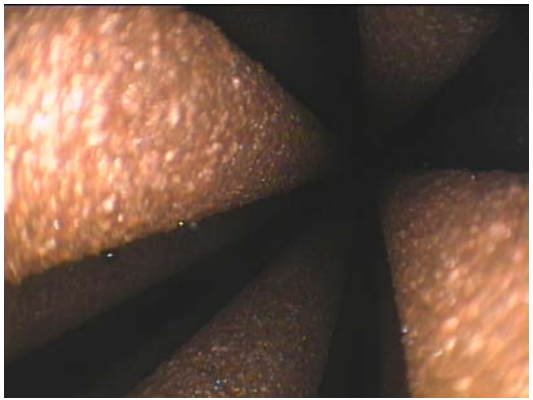


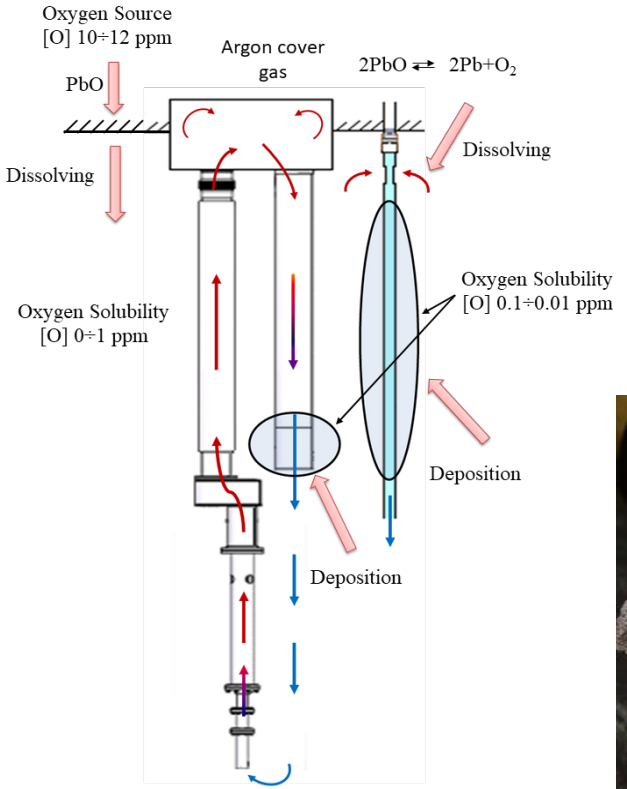






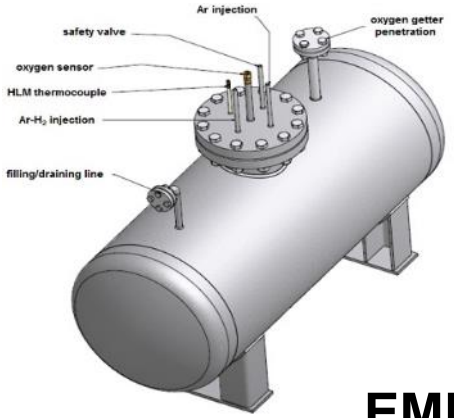
Coolant chemistry



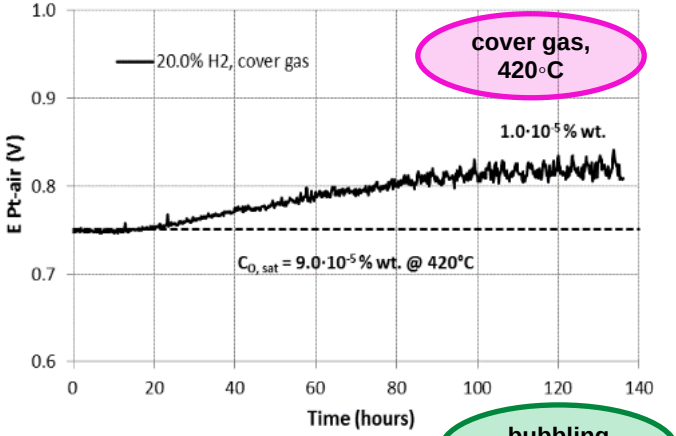


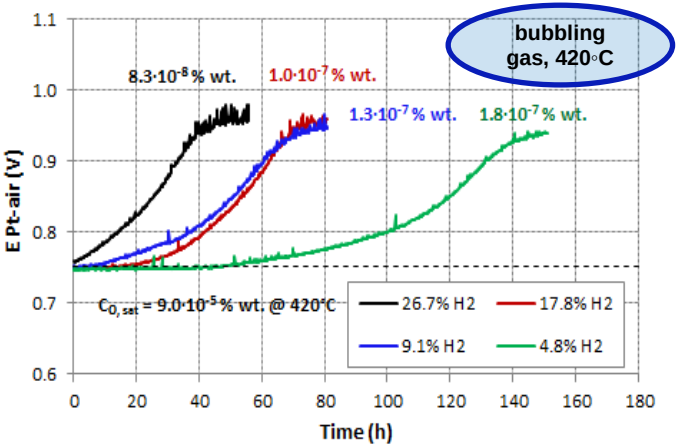
HELENA Storage Tank

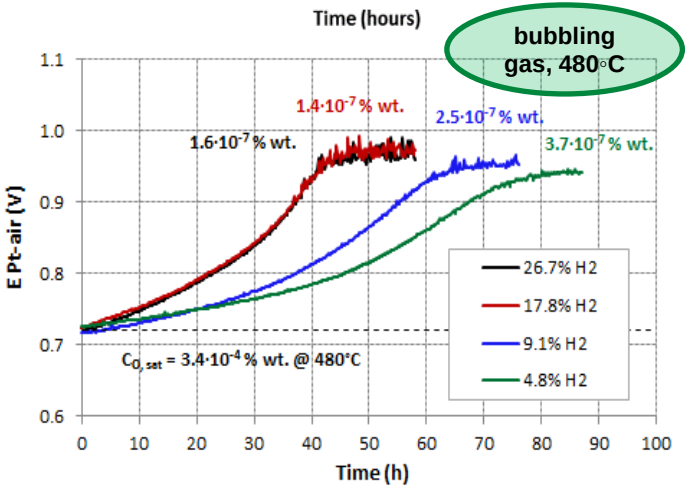
≈ 285 L Pb, gas control system implemented



EMF ↑, C_O ↓

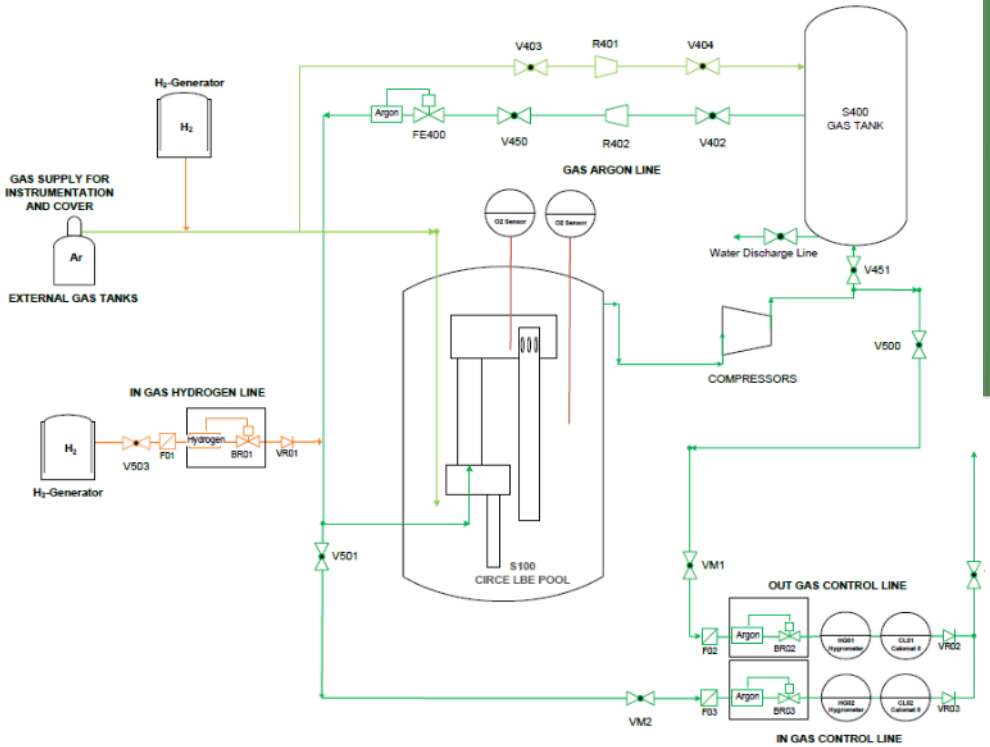


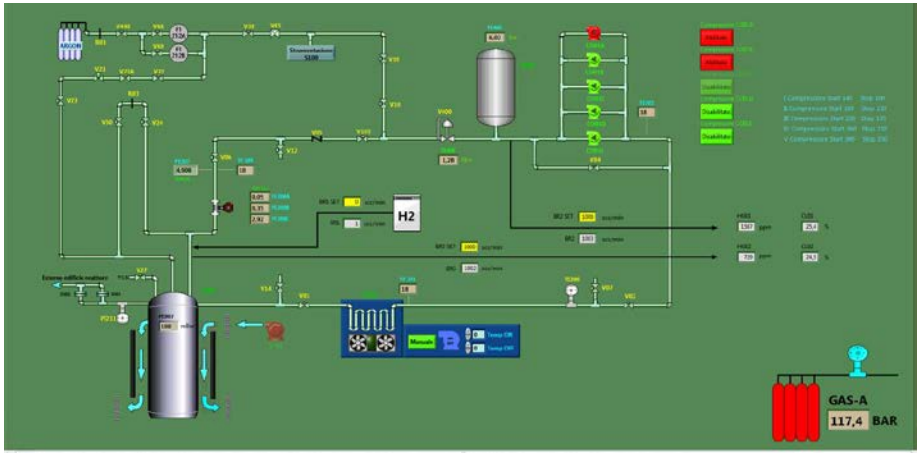




higher deoxygenation efficiency for higher T_{HLM}, H_2 %, and HLM mixing (i.e. bubbling).

CIRCE Experiments (with OCS)





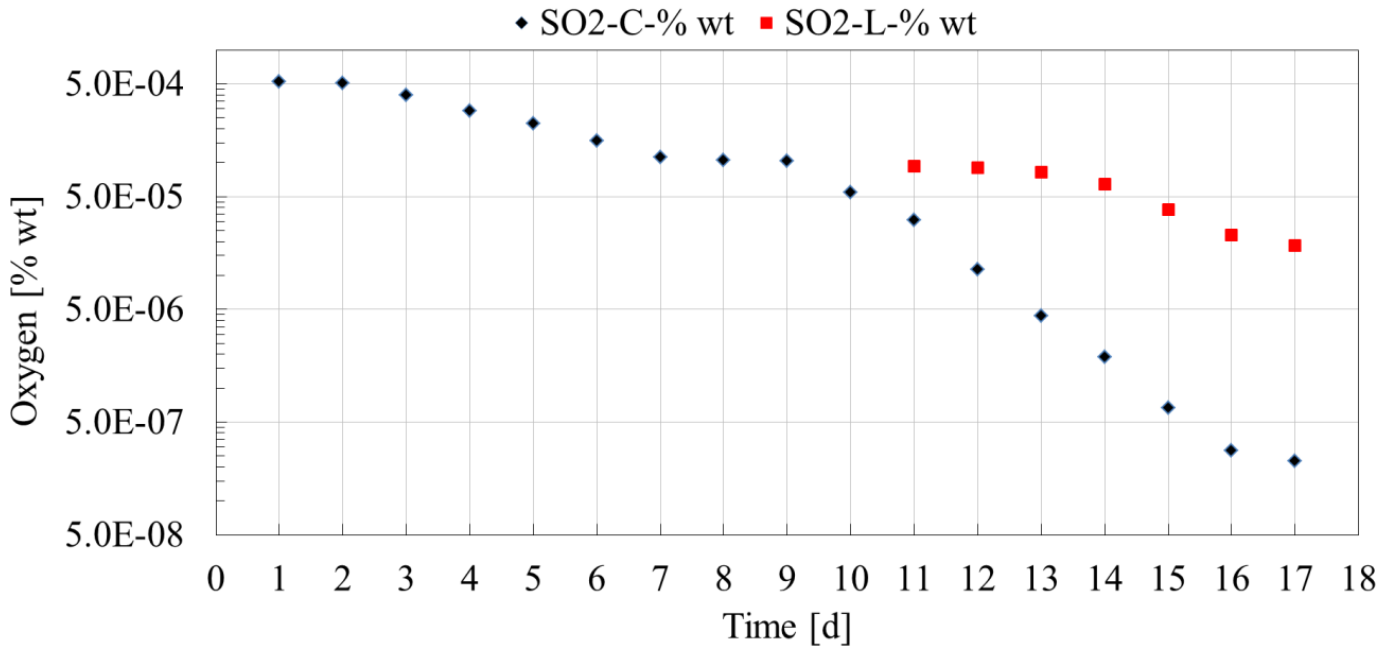
- **OS in hot pool & cold pool**
- **Ar+H2 (30%) multiple injection**
- **Ar+H2 (30%) gas lift**
- **H2 in cover gas recovery**
- **Pool @ uniform T (465°C)**

CIRCE Experiments (with OCS)

Oxygen sensors installed in the CIRCE vessel. In the hot (left) and cold (right) pool

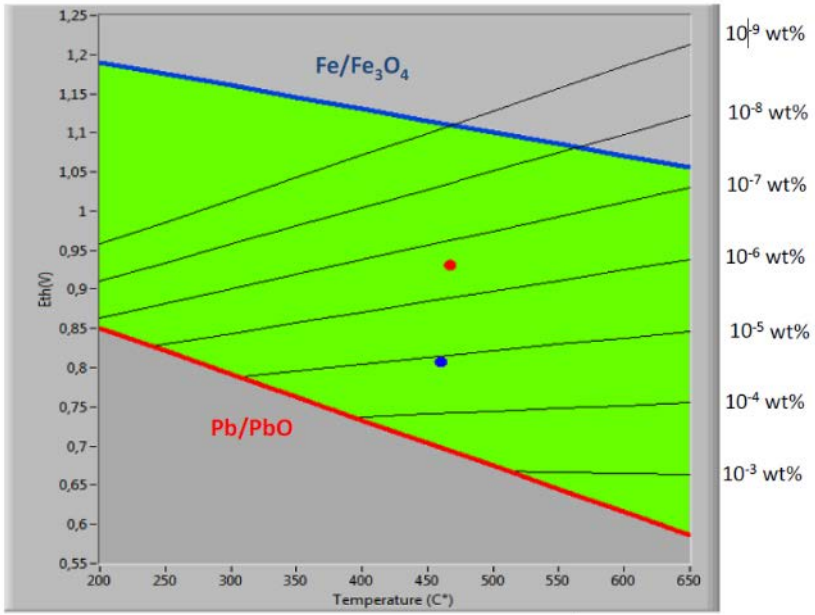
Hydrogen generators connected to argon injection line (left) and to bubble tubes (right)

CIRCE Experiments (with OCS)



Daily average value of oxygen concentration measured by the two sensors (black: SO2-C, hot pool; red: SO2-L, cold pool).

CIRCE Experiments (with OCS)



Instant values measured by the two sensors at day 18 (red dot: SO2-C, hot pool; blue dot: SO2-L, cold pool)

CIRCE Experiments (with OCS)

View of the hot pool after draining.
No lead-oxide are observed.

Free level view in CIRCE facility. No lead-oxides floating are observed in the hot pool