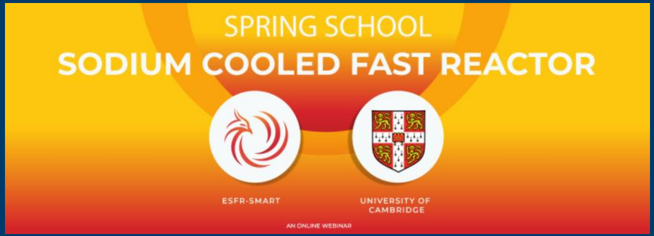
ENEA

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

R&D topics to support LFR projects



ESFR-SMART Spring School

SODIUM FAST REACTOR SAFETY

March 29-31, 2021, online Webinar Session 5-1 OTHER COOLANTS

D. Martelli (ENEA)

Outline

- GEN IV LFR
- Integral test & component qualification
- SGTR experiment
- Coolant Chemistry
- FLOW Blockage experiment
- Coating and material characterization

GEN-IV

Generation IV Systems	*Acronym*
Sodium-Cooled **F**ast **R**eactor	**SFR**
Gas-Cooled **F**ast **R**eactor	**GFR**
Lead-Cooled **F**ast **R**eactor	**LFR**
Molten **S**alt **R**eactor	**MSR**
Super**c**ritical **W**ater-Cooled **R**eactor	**SCWR**
Very-**H**igh-**T**emperature **R**eactor	**VHTR**

Because the capability of fast reactors to meet the sustainability goal and hence to re-position nuclear energy from the present transition-energy role into an inexhaustible source of clean energy

three out of the six systems selected by GIF (GFR, LFR and SFR) are fast reactors and

- for two systems (MSR and SCWR) studies have been carried out recently to explore the possibility of them to become fast reactors.

- For heavy liquid metal coolants (lead-bismuth alloy, lead) **the stored thermal potential energy cannot be converted into kinetic energy.**
- There is **no significant release of energy and hydrogen in an events of coolant contacting with air, water, structural materials.**
- The way to improve the NPP safety and economic performance is to implement reactor facilities with **the lowest stored potential energy**, where the inherent self-protection and passive safety properties are used to the maximal extent.

GEN-IV Lead Fast Reactor

How lead coolant improves the reactor design?

Lead is a low-moderating medium and has a low-absorption cross section

- Fast neutron spectrum: operation as burner of MA and improve resource utilization (Sustainability)
- Long Life Core: unattractive route for the plutonium procurement (Proliferation resistance and physical protection)
- Large fuel pin lattice (opened/closed): enhanced the passive safety (Safety and Reliability)

Lead does not interact vigorously with air or water

- Improve Simplicity and Compactness of the Plant and reduce the risk of plant damage (Economics)
- Increase the protection against acts of terrorism (Proliferation resistance and physical protection)

GEN-IV Lead Fast Reactor

Main advantages and main drawbacks of Lead

Atomic mass	*Absorption cross-section*	*Boiling Point (°C)*	*Chemical Reactivity (w/Air and Water)*	*Risk of Hydrogen formation*	*Heat transfer properties*	*Retention of fission products*	*Density (Kg/m³) @400°C*	*Melting Point (°C)*	*Opacity*	*Compatibility with structural materials*
207	*Low*	*1737*	*Inert*	*No*	*Good*	*High*	*10580* *10580*	*327*	*Yes*	*Corrosive*

Innovation in the nuclear industry is a long and expensive process that requires several years of R&D including both numerical studies and experimental activities

One of the most important tools to develop safety systems are the **Integral Test Facilities** (ITF). They are generally developed for a reference configuration of a reactor or a system to be investigated, and are intimately related to their reference through mathematical scaling relationships.

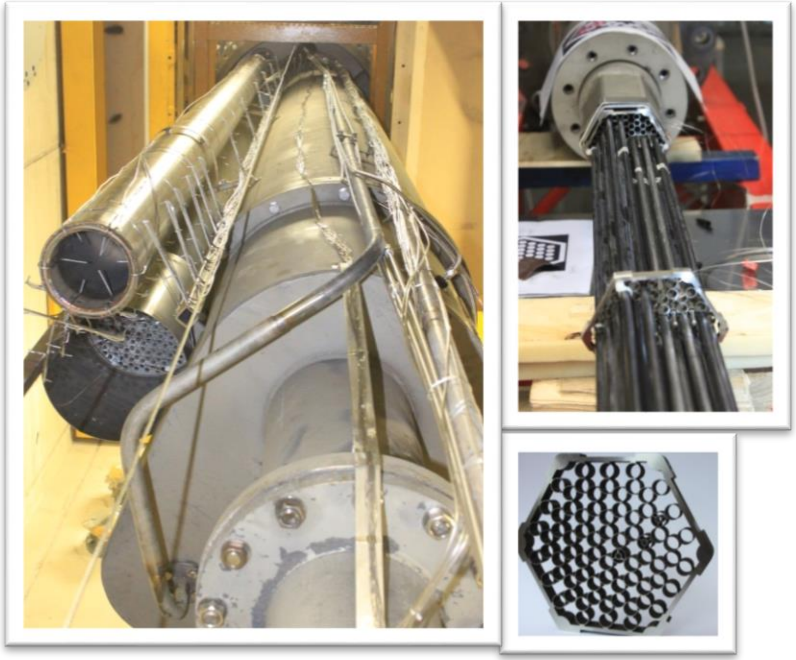
GEN-IV Lead Fast Reactor

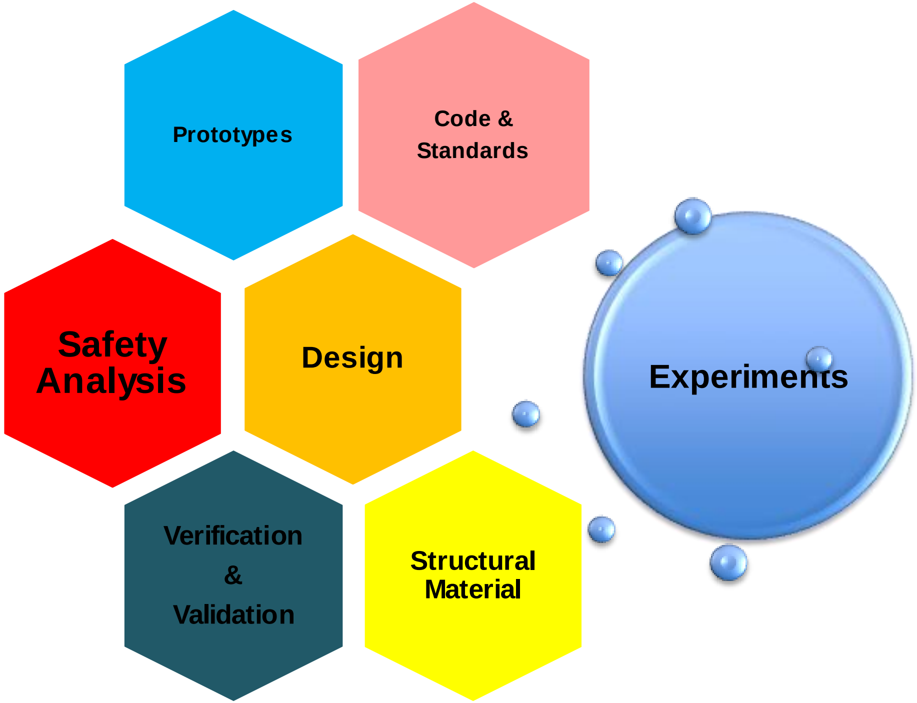
A comprehensive R&D program is necessary because of:

- **The use of a new coolant and associated technology, properties, neutronic characteristics, and compatibility with structural materials of the primary system and of the core.**
- **Innovations which require validation programs of new components and systems (the SG and its integration inside the reactor vessel, the extended stem fuel element, the dip coolers of the safety-related DHR system, pump, OCS, …)**
- **The use of advanced fuels (***at least in a further stage***).**

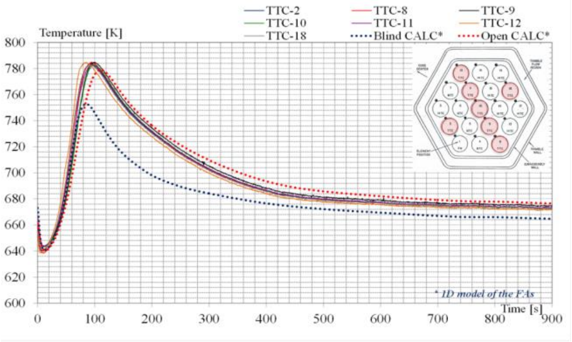
Rolw of Experiments in the R&D of LFR

- **Experiments** play a **crucial role** in the R&D of LFR

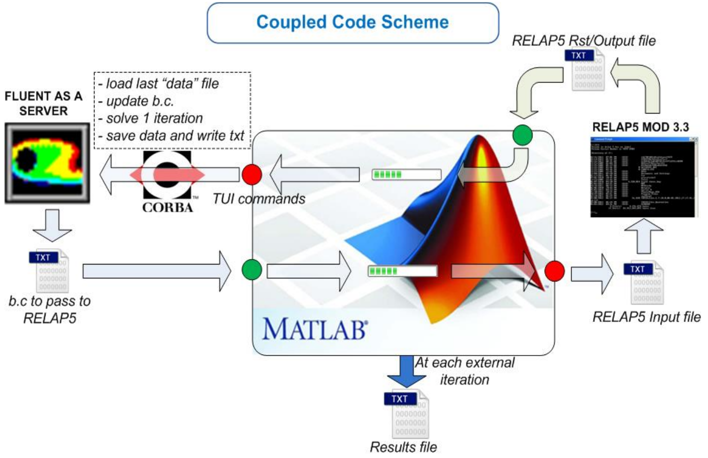


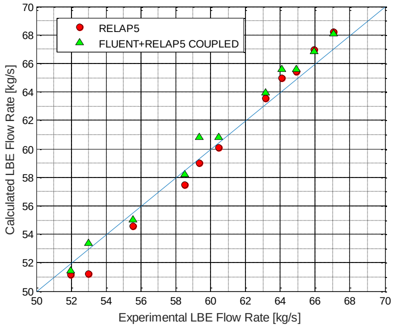


Experimental database for Code Validation



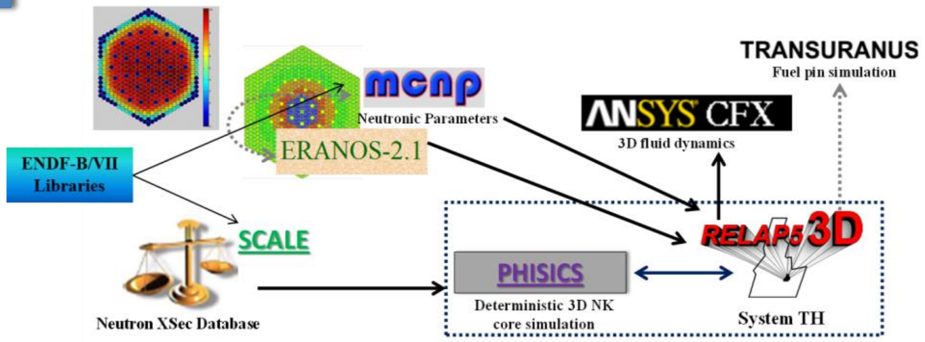
SYSTEM CODE (RELAP5)





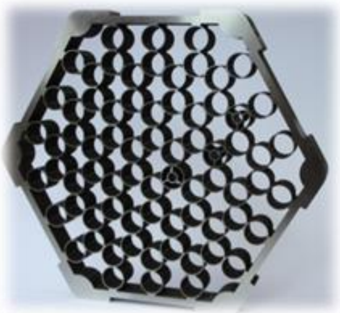
System Code + CFD coupling

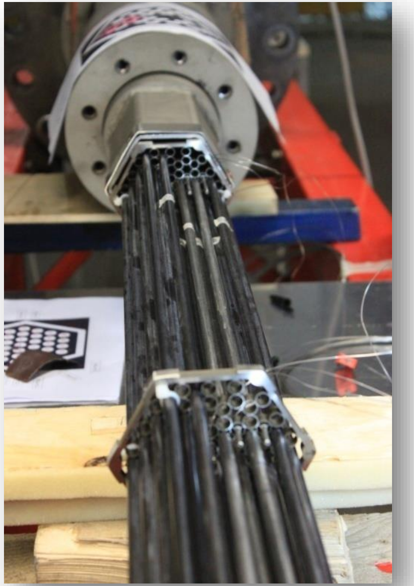
Multi-physics

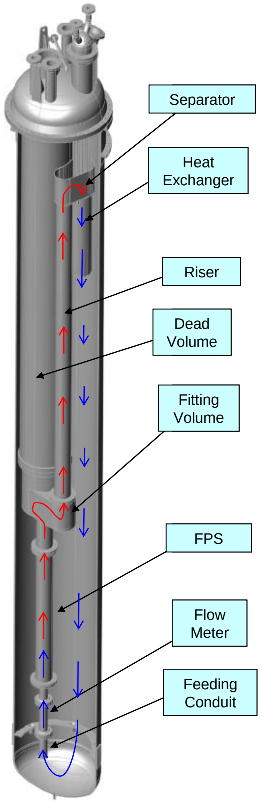


Integral Test & Component qualification

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







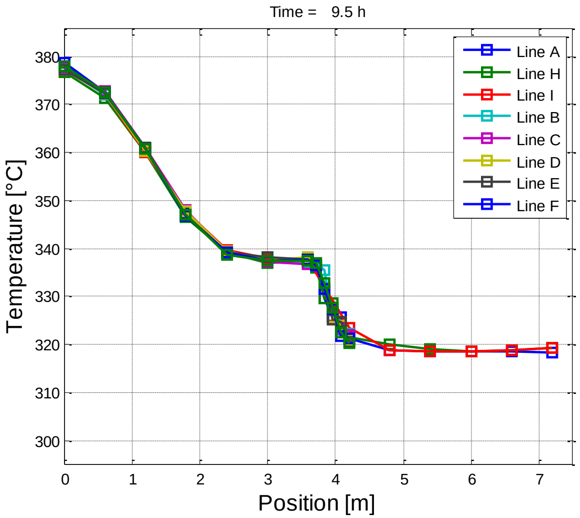
CIRCE experimental outcomes

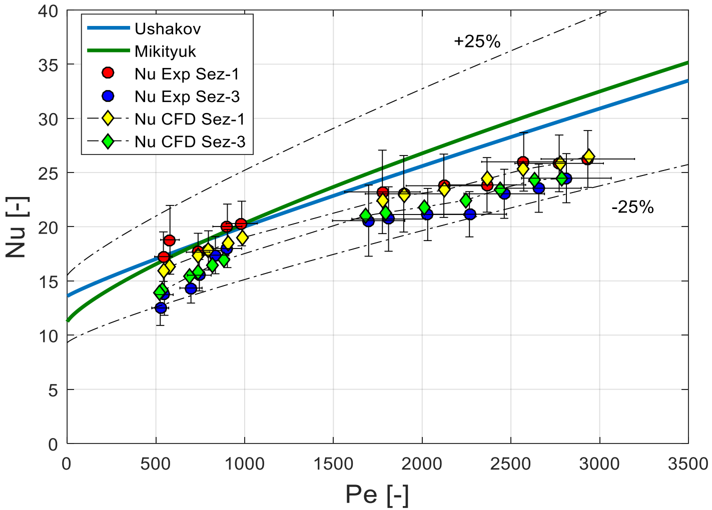
Thermal stratification phenomena

CIRCE **experimental campaign.** Simulation of a LOCA+LOF accident

Heat transfer in fuel pin bundle

CIRCE **experimental campaign for the analysis of** Heat transfer analysis (**Nu vs Pe**)





Component qualification

A new mechanical pump will be tested in CIRCE facility replacing the Gas-lift forced circulation;

Impeller erosion and Hydraulic characteristics will be investigated

- A new prototypical **HCSG** will be tested in CIRCE facility replacing HERO-HX;
- **Qualification of the component** in terms of thermal hydraulics performances

  in **steady state** and **transient abnormal conditions**;

✓ HCGS main advantages:

  - Excellent **heat transfer performances**;
  - **Compact geometry.**

Component qualification

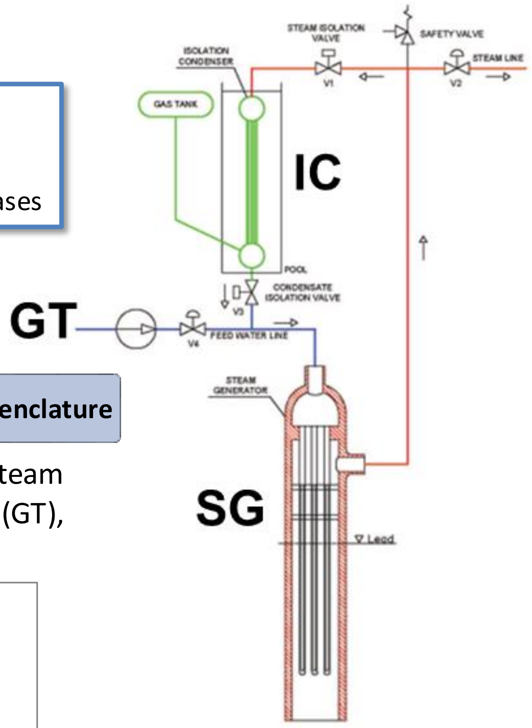
- **SIRIO** (*Sistema di rimozione della potenza di decadimento per reattori nucleari innovativi*) facility has the objective to study and completely characterize a passive **DHRS** and provide the final design on an industrial scale.

Two main functions:

- to guarantee the correct primary system cooling
- to control passively the heat removed from its ultimate heat sink by means of noncondensable gases

The loop operates in **natural circulation regime**, with a water SG inlet temperature in steady state condition of **~335°C** and a pressure of about **180 bar** (up to ~190 bar), in conditions suitable for ALFRED.

No need of any external actions or energy → **Passive system according to the IAEA nomenclature**



- The facility is scaled with reference to the ALFRED reactor and comprises a bayonet-tubes Steam Generator (SG), an Isolation Condenser (IC) set inside a water pool, and a Gas Tank (GT), connected to the lower header of the IC.

The approach follows the "power-to-volume" scaling:

- power density, height and system pressure are kept 1:1
- **ratio** between volumes and masses of the liquid region and gas region are **kept**

Component qualification

Preliminary Test Matrix

On the basis of ALFRED Stage1 and Stage 2 and feedback from WP1

Parameters	Unit	Case 1	Case 2	Case 3
Water Inventory [kg]	[kg]	38	38	38
Primary loop pressure [bar]	[bar]	175	175	170
Primary loop gas pressure [bar]	[bar]	110	130	110
Thermal power supplied during the steady state	[kW]	55	55	27.5
IC Valve 100-PV613 set-point	[bar]	190	190	190
IC Valve 100-PV615 delay	[s]	60	60	60
Orifice diameter	[mm]	5	5	5

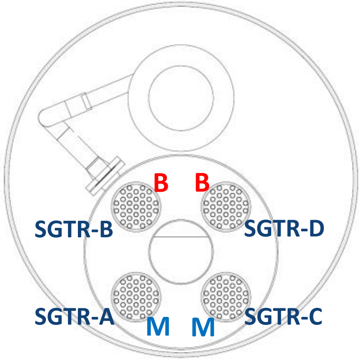
- Development of a numerical model using the thermal-hydraulic system code RELAP5-3D
- Simulation of the facility operation in both steady state and transient regimes
- Analysis of the numerical results achieved from the pre-tests. Assessment of the thermal-hydraulic behavior of the system and comparison with the expected results

Expected Phenomena	Conceptual Design	Detailed design
Control of the pressure	✓	✓
Migration of non-condensable gases	✓	✓
Power balance	✓	✓
Regeneration inside the bayonet tube	✓	✓
Modulation of the power removed	✓	✓
Long term cooling	✓	✓

Experimental tests suitable for system thermal-hydraulic codes validation

SGTR Experiments

- 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:

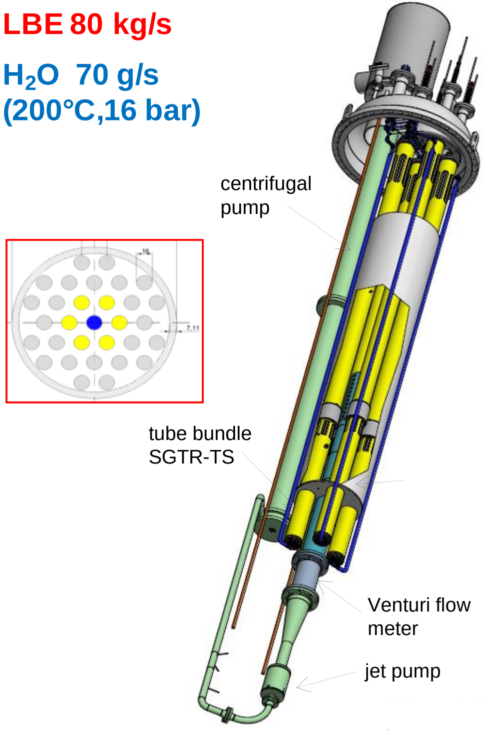
200 TCs (45 in each SGTR-x,) (50 Hz)
H2O ultrasonic flowmeter (15 Hz)
H2O level meter (1 Hz)
8 fast pressure transmitters (1 kHz)
12 bubble tubes (1 Hz / kHz)
30 strain gages (10 kHz)
2 LBE Venturi flow meters (1 Hz)

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

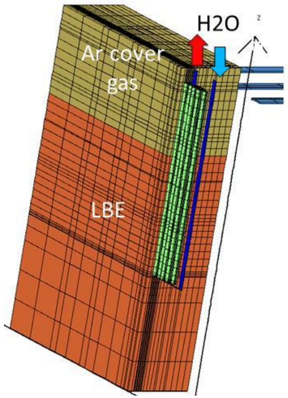
SGTR Experiments

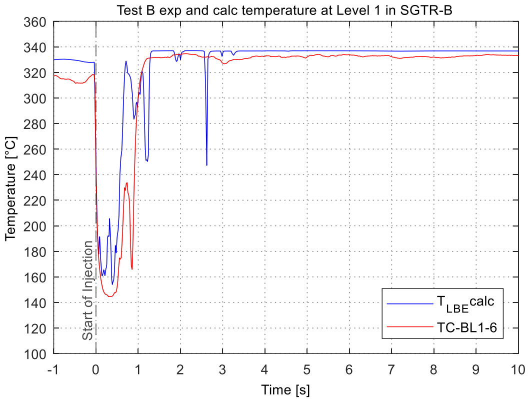
LBE 80 kg/s

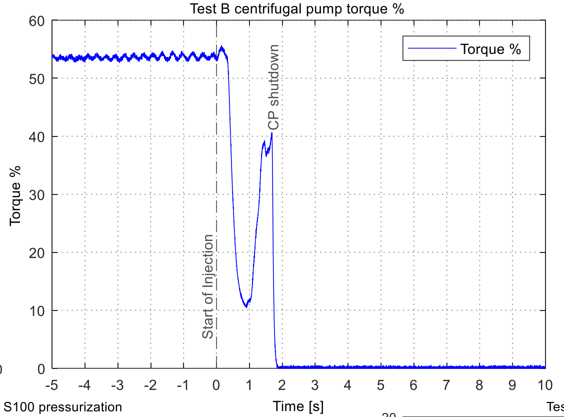
H_2O 70 g/s (200°C,16 bar)



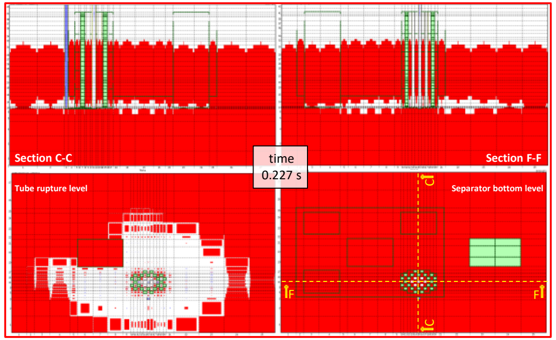
SGTR Experiments

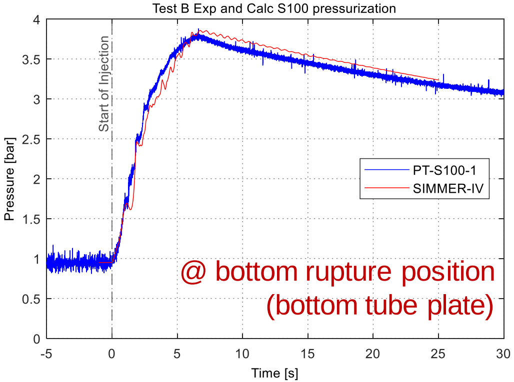


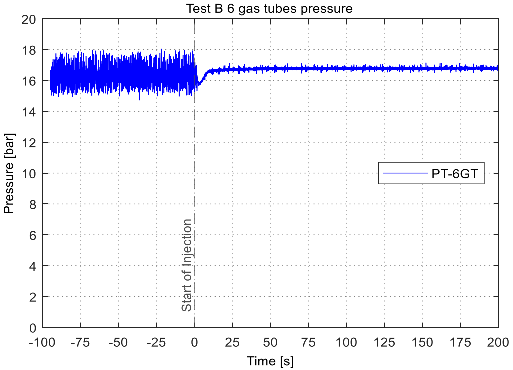




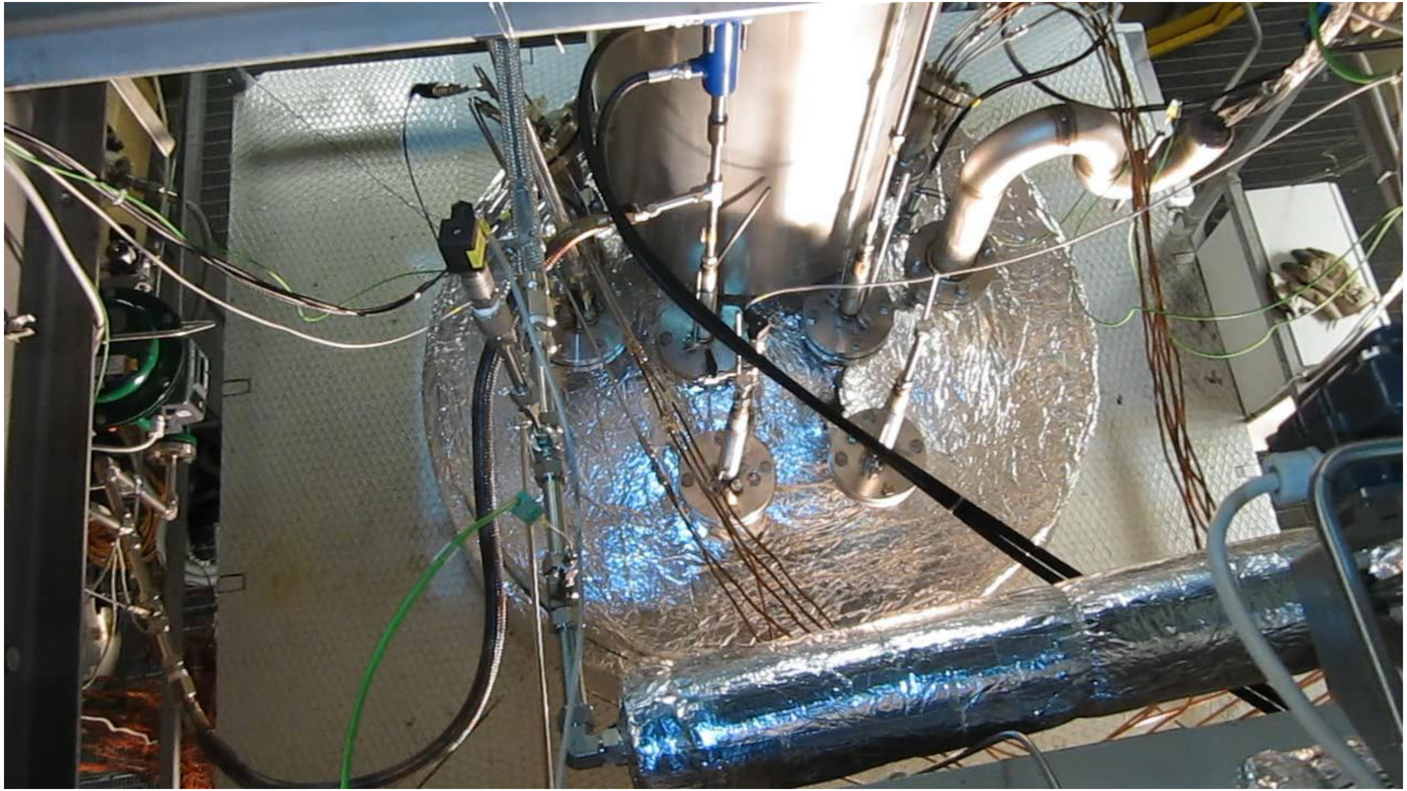
steam from SGTR rupture reached the CP suction before CP shutdown





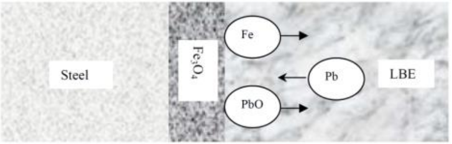


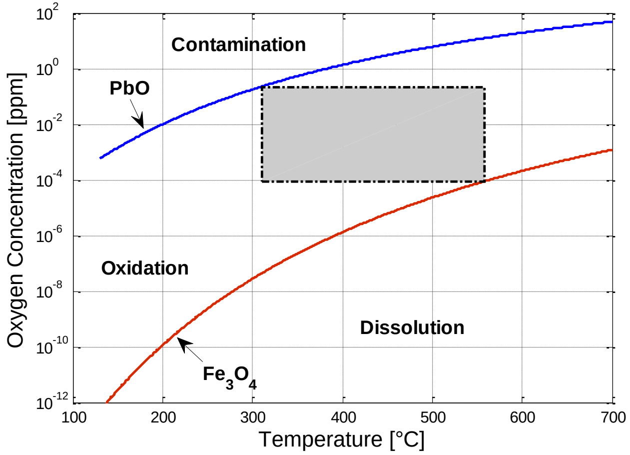
SGTR Experiments



Coolant chemistry

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





air ingress and Pt wire

ceramic adhesive at YSZ-SS junction

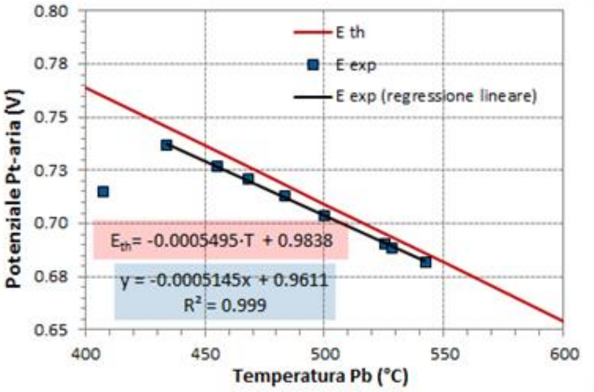
YPSZ tube

Pt-air sensor L= 850 mm
T=400-550°C

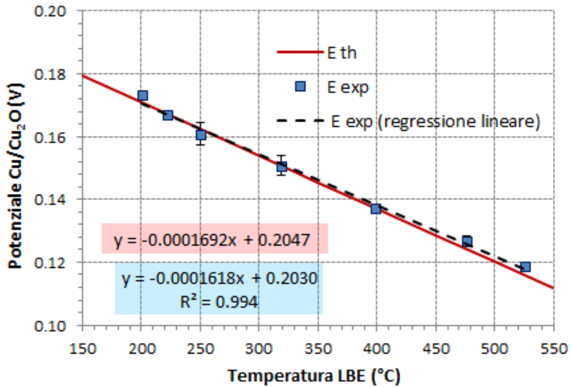
Min. reading T ≈ 430°C

Cu/Cu2O sensor
L= 600 mm
T=200-400°C

Min. reading T ≈ 200°C



oxygen-saturated Pb



oxygen-saturated LBE

Coolant chemistry RACHEL Lab

(Reaction and Advanced CHEmistry of Lead)

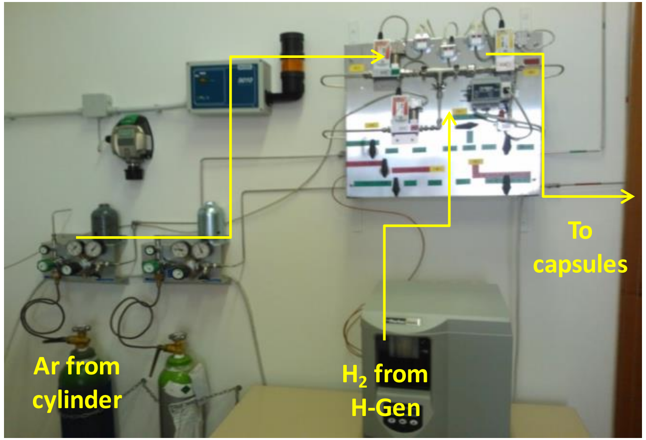
capsules (small & large)

oxygen sensors

specimen

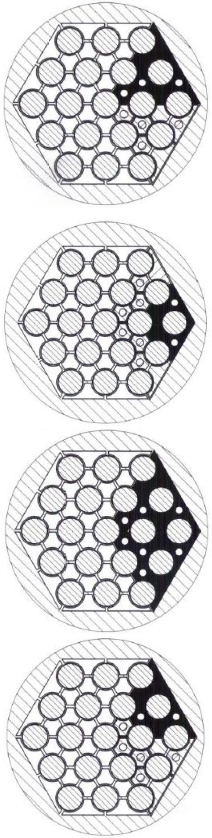
capsules for HLM chemistry (oxygen sensor testing, deoxygenation with gas) & corrosion tests of materials in Pb alloys (Pb, Pb-Bi and Pb-Li)

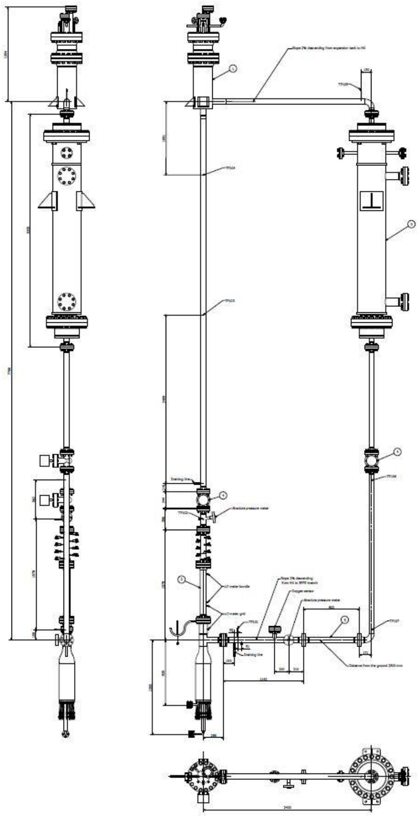
gas control system (Ar-H_2 injection)



Flow Blockage experiment in NACIE Loop

Parameter	BFPS	ALFRED FA
d_{pin}[mm]	10	10.5
p/d	1.4	1.32
Power [kW]	250	-
Pin power [kW]	13	-
Wall heat Flux [MW/m^2]	0.7	0.7-1
Subch velocity [m/s]	0.8	1.1
Npin	19	127
Lactive [mm]	600	600
L_{plenum} [mm]	500	500

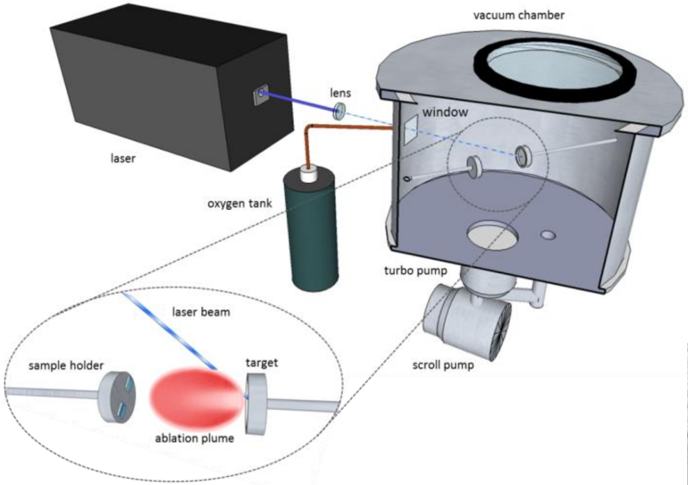


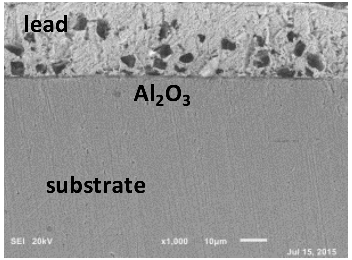


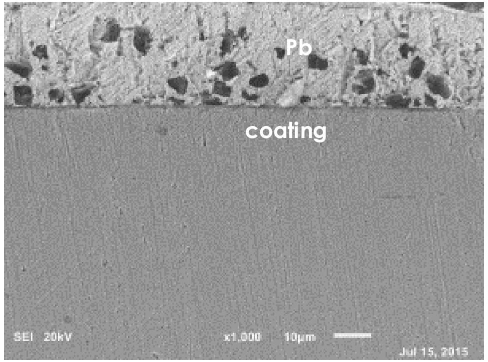
- 8 pull tab ‘rods’ will be pulled or pushed to fix the blockage configuration
- 4 blockage configurations are feasible
- Facility is filled for the experiment with fixed blockage configuration

Coating Development

Pulsed Laser Deposition Nanoceramic Coatings (IIT & ENEA)







1 µm Al2O3 coating
no buffer layer

Corrosion tests in static Pb:
550°C -1000 h - $10^{-8}/10^{-9}$ wt.% O 1 µm Al2O3 coating

- ✓ high quality coatings
- ✓ custom process: bottom-up approach
- ✓ process at room temperature

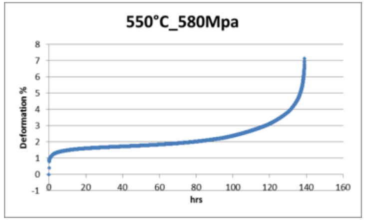
Material characterization

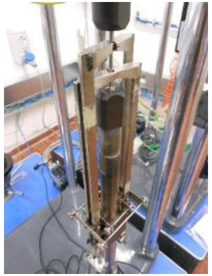
- Corrosion test in flowing lead
- OCS testing in loop
- Component qualification

Material characterization

- CREEP & SSRT test in lead a@550°C in very low Oxygen content environment (10^-8)
- Optimization of the thermomechanical treatments (SEM and hardness measurements to tune Grain Size and solubilization of carbides)
- Tensile tests (improvement of high temperature properties)
- Creep tests
- Impact tests (Charpy ISO-V and KLST)
- SANS (Small Angle Neutron Scattering) measurements to correlate the distribution of the precipitates to the improvement in terms of high temperature mechanical properties

Creep Machines





Creep fatigue

Fretting tests in lead alloy

Daniele Martelli
daniele.martelli@enea.it