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

# Investigation and qualification of Nuclear Materials for Gen-IV Lead Fast Reactor

**IAEA Technical Meeting on Advances and Innovations in Fast Reactor Design and Technology**

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# Introduction

- The investigation and qualification of materials to be used in the Generation-IV Lead Fast Reactor (LFR), in operational and accidental conditions, is a critical issue in the development of the Reactor.

- At the Brasimone Research Center, ENEA in partnership with *newcleo*, is working to design, build, and operate Gen-IV Advanced Modular Reactors.

- To rapidly increase the TRL for the desired nuclear applications towards requirements of corrosion resistance, high temperature strength and thermal stability, a strong qualification roadmap is ongoing with the support of the experimental facilities.

# Introduction

To define the operation limits, plan Restart Limits and major accident limits of the structural materials used in the design of the LFR experimental analysis e investigated with the experimental facilities at **ENEA BRASIMONE**:

- **SOLEAD:** to investigate chemistry control in the lead in a big pool in standard operation and accidental scenario with interaction between liquid lead and water vapour/air

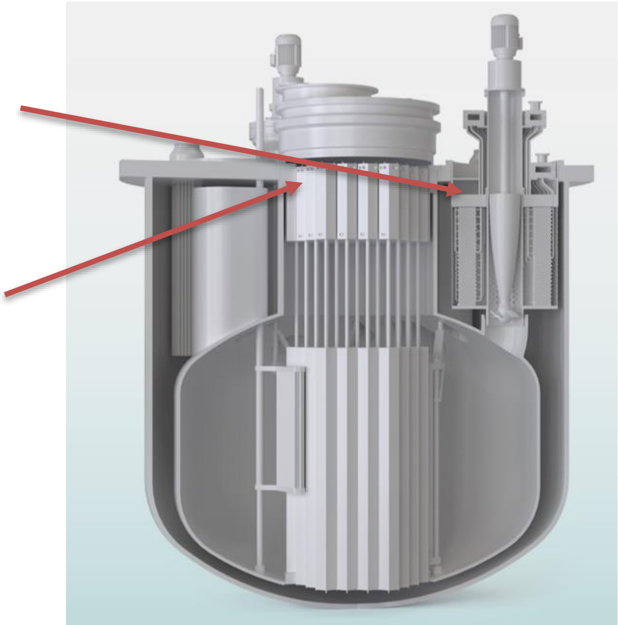
- **CAPSULE**: is used to investigate the corrosion behavior of materials in stagnant conditions with chemistry control in standard operation, transient and accidental conditions
- **CORE-1**: is dedicated to investigating the corrosion and erosion phenomena in flowing lead temperature range between 400° C and 650° C at 1-10m/s with chemistry control

# Chemistry control in Lead in accidental scenario

1) Tests, consisting of water/steam injection inside the liquid lead, were carried out with the scope to support the **safety analysis** concerning the consequences of a leak-before-break in a tube of the **steam generator**.

2) A test, consisting of **water/steam injection inside the cover gas**, was carried out to support the safety analysis concerning the consequences of a steam inlet into the cover gas during the fuel handling.

3) A test, consisting of **injecting air into the cover gas**, was carried out, with the scope to study the kinetics of oxygen diffusion from the cover gas to the liquid lead.



***Newcleo LFR AS:200***

These tests had to provide information about the chemistry of lead and its control.

# SOLEAD Experimental Facility

- **SOLEAD** (Solar tOwer LEAd Demo) experimental facility has used, in collaboration with newcleo, to carry out tests of interest for GEN-IV fast reactors, LFR type.

- The fields of SOLEAD application are: qualification of large size component, tests in natural circulation of the lead coolant, thermo-hydraulics tests in a big pool, material corrosion tests, lead conditioning and chemistry control tests.

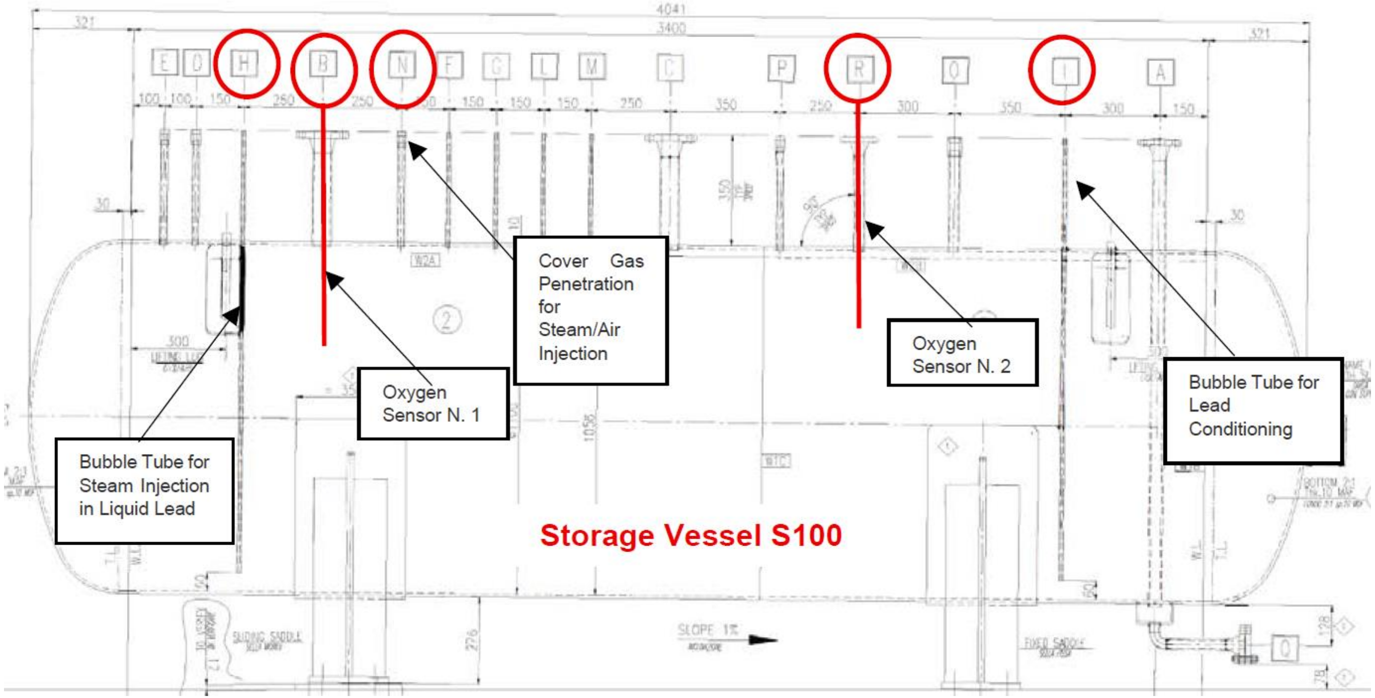
# SOLEAD Application

Main Design parameters of SOLEAD facility

| Data | Value |
|---|---|
| Lead quantity | 37 t |
| Storage vessel capacity | 3640 L |
| Main vessel capacity | 3720 L |
| Maximum temperature of lead conditioning in storage vessel | 500°C |
| Maximum temperature for tests in main vessel | 800°C |
| Lead conditioning by gas mixture | Ar/$H_2$/Air |
| Oxygen concentration measurements by Electrochemical Oxygen Sensors | Max. 3 (in storage vessel) |

# SOLEAD Facility Description

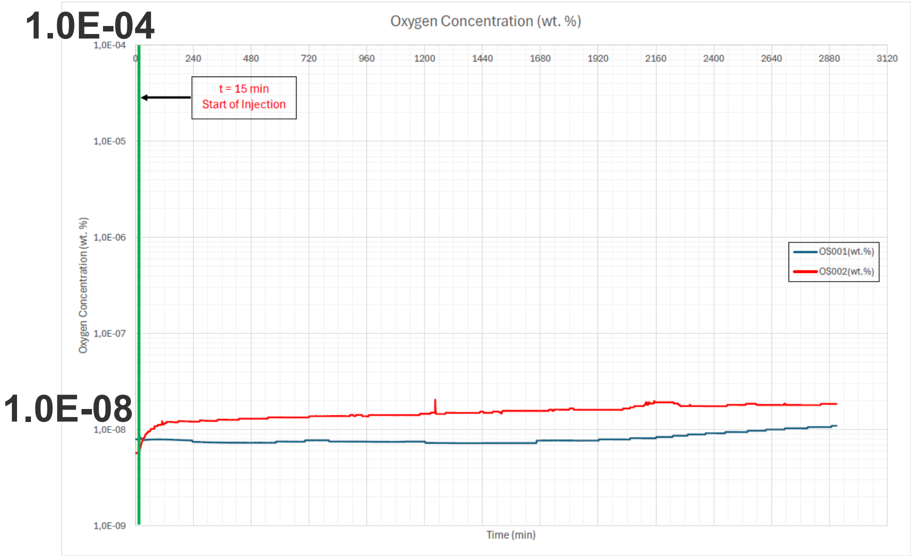
The facility is mainly composed of a main vessel S200, a storage vessel S100 and a gas panel, for the conditioning of the lead and the Ar supply to the cover gas of the vessels. For the tests described in the following, only the storage vessel was used.



# Steam Injection in Liquid Lead

- The tests aimed to study if interactions occur when **steam is injected into liquid lead** and if these interactions, causing the dissociation of the water, can increase the oxygen dissolved in the liquid metal bath.
- Different quantities of steam have been injected inside the liquid lead: the minimum amount (**40 g**) of injected water has an oxygen content sufficient to increase its concentration inside the liquid lead from $10^{-8}$ wt% to $10^{-4}$ wt%.

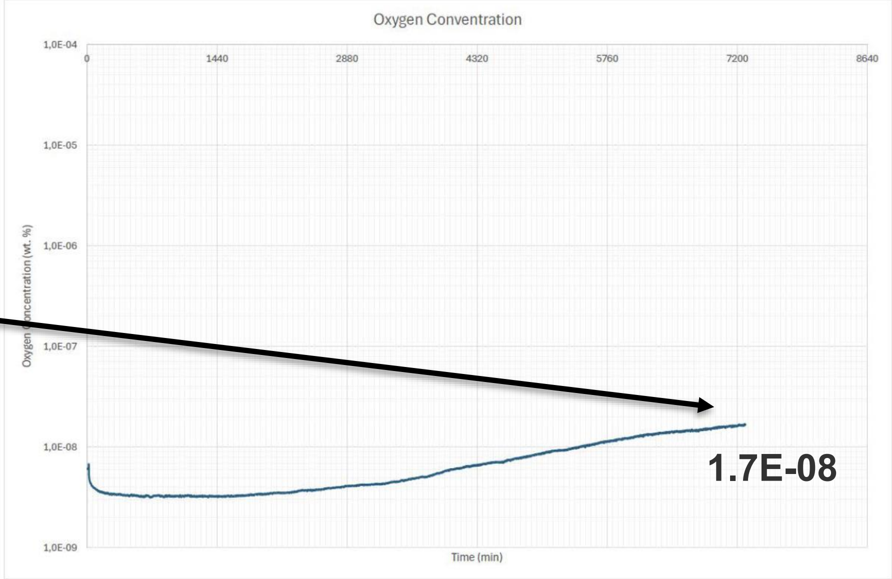
- The initial test conditions are the following:
  - Lead temperature: 480 ± 2 °C
  - Oxygen content in Pb: ~ $10^{-8}$wt. %
- The Figure shows the oxygen concentration measured by the 2 Oxygen Sensors in Pb.
- The measured concentration is far from $10^{-4}$ wt%, value close to oxygen saturation in liquid lead at 480°C.



# Steam Injection in Cover Gas

- The test aimed to study if interactions occur between **steam injected into the cover gas** and the lead free surface and **if these interactions can cause the dissociation of the water molecules**, with production of oxygen and hydrogen, and diffusion of oxygen into the lead bulk.
- The quantity of water that has been injected inside the cover gas is **100 g**. The initial test conditions are the same of the previous tests.

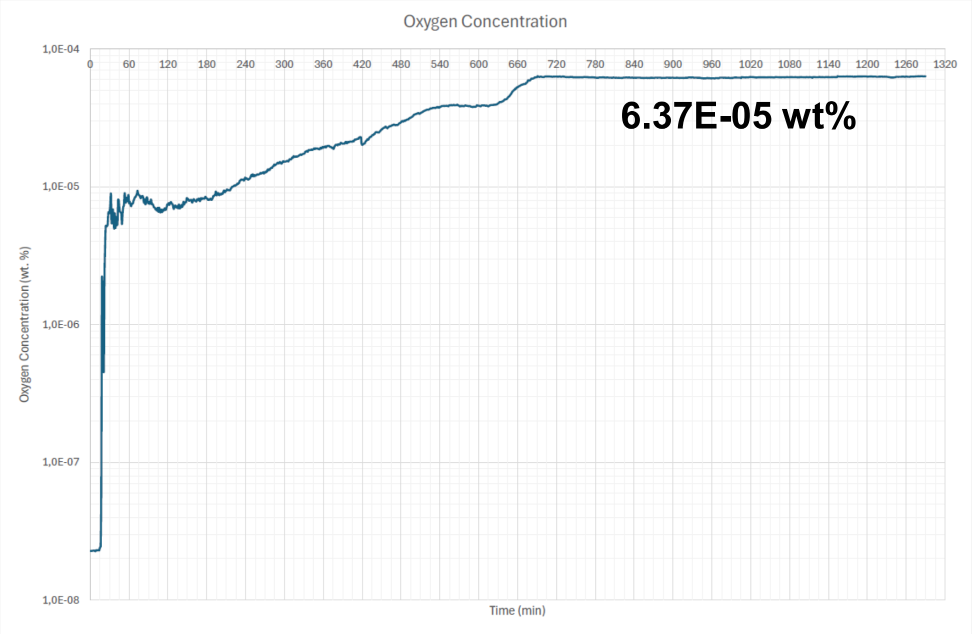
- The Figure shows the oxygen concentration measured by OS001, during the test.
- After the initial transient, the oxygen concentration measured remains approximately constant for a little over a day and then starts to increase, reaching the maximum value, at the end of the test, of approx. 1.7E-08 wt. %.



# Air Injection in Cover Gas

- The aim of the test was to study if **interactions** occur between **air injected** into the **cover gas** and the lead **free surface** and the **kinetics of oxygen diffusion** inside the lead. The initial test conditions are the same of the previous tests. The quantity of air that has been injected inside the cover gas is **120 NL** (same atomic oxygen content of 40g of water).

- In this test, the oxygen concentration measured by OS001 shows a sharp increase. Then, the increase becomes less pronounced and, after approximately 675 min from the start of injection, the oxygen concentration remains approx. constant, reaching a maximum value of 6.37E-05 wt%, close to saturation. The arrest of the oxygen concentration growth is due to the decrease of the cover gas pressure and, as consequence, its lower oxygen content.



# Test Results – Chemestry control in lead

- The results showed that the **steam injection**, both in the lead and cover gas, has had a negligible impact on the coolant chemistry control.

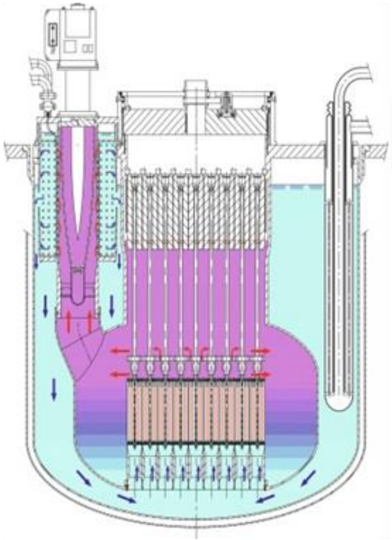
- The inlet of **air in the cover gas** has had a quick effect on the oxygen content inside the liquid lead; this fact leads to suppose that the operations of the facility could be compromised if countermeasures are not taken.

# Materials Characterization in Lead

- Structural materials behaviour in lead are analysed at operational, accidental and transient conditions.
- Different product type of the alloy is investigated for each condition: forged bar, seamless pipe, laminated plate, and welded joint.

| Component | Acc. Max Temp. (0) (°C) | Max. Rad. damage (dpa) | Material (early stages with $C_O$ = $10^{-6}$-$10^{-8}$ w%) |
|---|---|---|---|
| **Fuel cladding** | 530/750 | 100 | 15-15Ti 20% CW (AIM1) |
| **FA Structures** | 500/750 | 100 | 15-15Ti 20% CW (AIM1) |
| **Internal structures** | 500/700 | <2 | AISI 316LN (ASTM) |
| **Steam Generator** | 500/700 | 0.01 | AISI 316LN (ASTM) |

## Newcleo LFR: AS-200



| | |
|---|---|
| Power | 480 MWth |
| Core coolant | Pure lead |
| Core coolant temperature | inlet 420°C, outlet 530°C |
| Layout | Pool-type |
| Circulation | Forced: 6 pumps |
| Spectrum | Fast |
| Fuel form | Extended-stem fuel assembly |
| Fuel | MOX |
| Secondary side fluid | Water |
| Steam generators | 6 spiral-tube SG |
| Design life | 60 years |
| Lifetime capacity factor | 94% |

# Materials Characterization in stagnat Lead

The material characterisation is performed with 36 standardized modular capsule to carry out the experiments adopting the same device and procedures.

**CAPSULES** have been in operation since December 2023.
The facility is used to test various kinds of steel, both bare and coated, in stagnant lead under an oxygen-controlled concentration, essentially between 10^-8 and 10^-6 wt%; a temperature range of 450-750 °C is also employed.

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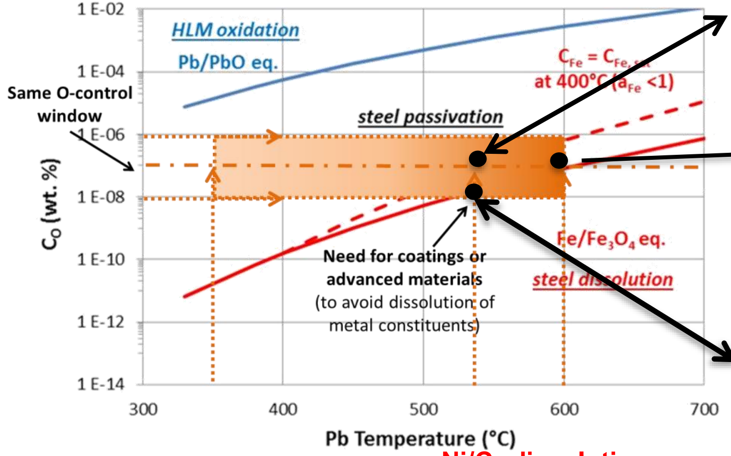
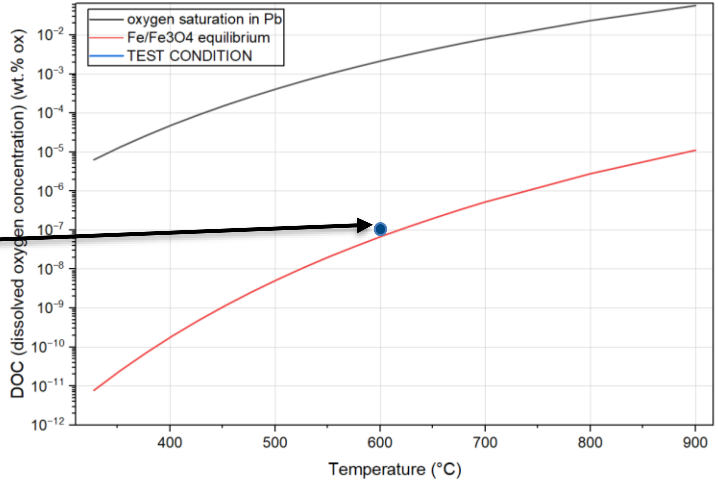
# Material Characterization in Lead-accidental scenario

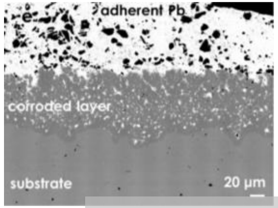
**Screening tests on 316L (N)** have been performed in CAPSULE at 500°C and 600°C with oxygen concentration slightly above the passivating one: 10-7wt.%. **Exceeding the operational limits** helps to see any difference in the materials' behaviour.




**Oxidation + Ni/Cr dissolution (γ Fe → α Fe), Pb penetration**


**316L steel in flowing LBE, 550°C, high $C_O$, 7500 h.**



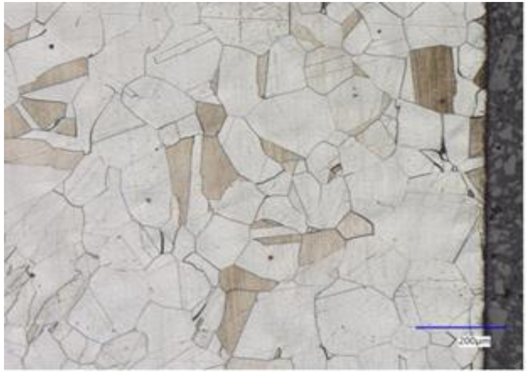

**F. García Ferré (2017)**

**Ni/Cr dissolution (γ Fe → α Fe), Pb penetration, no oxidation**

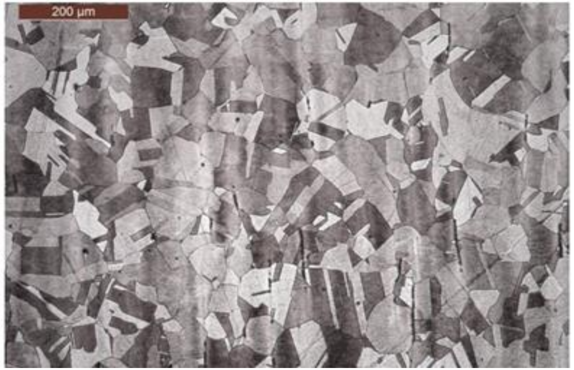
# Material Characterization in Lead –316L Characterization

Three different 316L(N) alloy product types are investigated, all in a solution annealed conditions (RCC-MRx designation, RPS SECTION III, TOME 2 ):

- **RM332-4** forged bar
- **RM334-1** seamless pipe
- **RM333-1** laminated plate



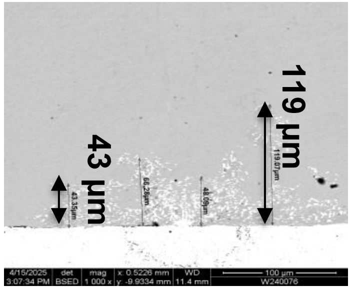
**RM332-4** forged bar




**RM333-1** laminated plate

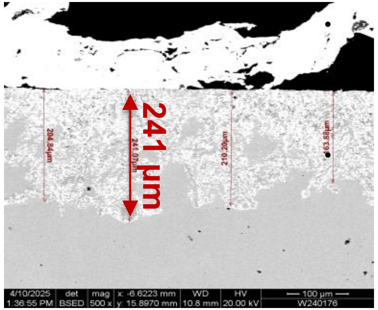
# Screening Test in Stagnant Lead - 500h 600°C 1e-7 wt.%

## RM 333-1 laminated plate




Deep localized corrosion and lead penetration (up to 119 µm)

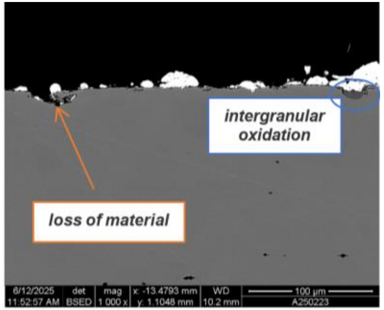
## RM 332-4 Forged bar




Deep localized corrosion and lead penetration (up to 241 µm)

Most of the analysed surface not corroded

## RM 334-1 seamless pipe

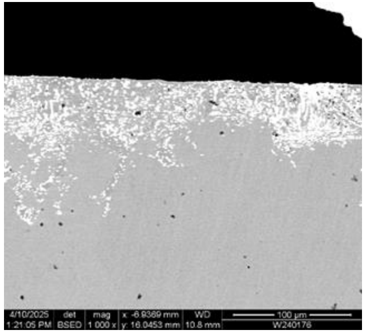


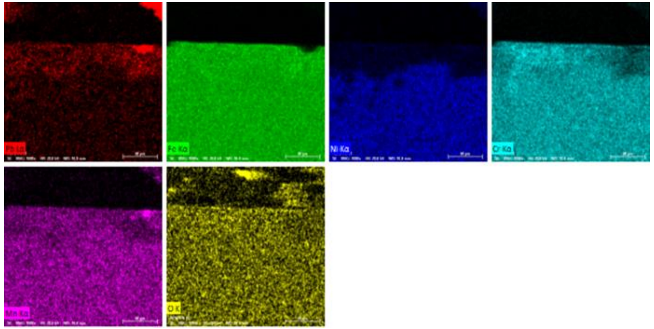

Lead penetration (spots)

Unselective leaching (loss of material)

Internal oxidation

Corrosion layer up to ~ 20 µm





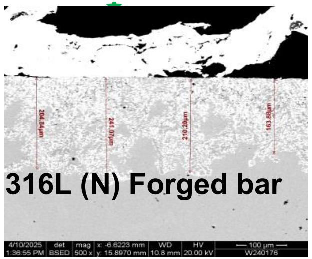
**Worst cases** for the condition 600°C, 1e-7wt.% are shown for different products:

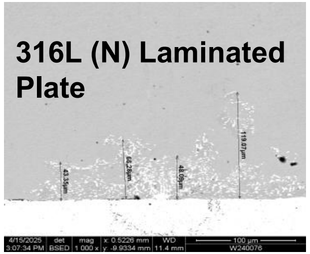
- Corrosion by selective and/or unselective dissolution, coupled with Pb penetration, observed in all products,
- **Worst** behaviour in **forged** part (max 241 µm dissolution depth), **best** in seamless **tube**
- **Preliminary results, to be confirmed**

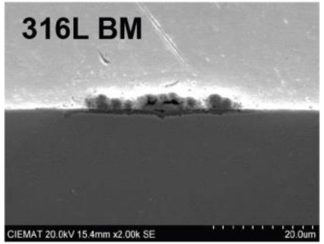
# Literature review on AISI 316 at 480-600°C Pb exposures

The experimental data are in agreement with the literature data at the same operative conditions; the effect of the manufacturing process has to be investigated:

***newcleo*, 600°C, $10^{-7}$ %wt. Ox:**

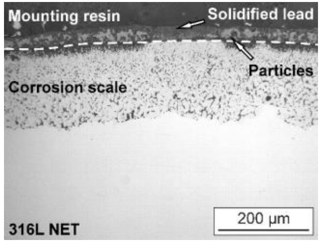



CIEMAT[1]- static Pb, 480°C, 2000h, $10^{-7}$ %wt. Ox.

- Fe-Cr oxidation on both austenitic steels
- No Pb penetration
- No significant elemental dissolution

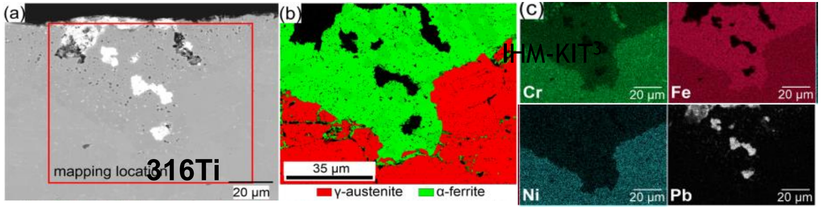



ENEA[2]- static Pb, **550°C**, 1000h, $2*10^{-7}$ %wt. Ox. LOM imaging

- Passivation not occur
- Pb penetration & el. Dissolution and ferritization (100-150 µm)

Summarized assessment of 316Ti after exposures at 600 °C and 700 °C.

| | 600 °C | |
|---|---|---|
| | 1000 h | 2000 h |
| Protective oxide layer | x | x |
| Inward-growing oxidation | x | x |
| Selective dissolution | ~45 µm | ~200 µm |
| Liquid lead penetration | ~30 µm | ~200 µm |




KIT-IHM[3] static lead, 600°C, $2 \times 10^{-7}$ wt% Ox.

[1]Bassini et al. GEMMA conference 2023
[2]Bassini et al. Deliverable 4.2 GEMMA
[3]Purwitasari et al., 2025

# Material Characterization: accidental and accidental conditions

- The next step is the testing in **accidental conditions** just on the material type that showed the **worst** resistance in the screening tests.
- **Accidental, transient and cumulative/integral durations of accidents, transients** and accidents throughout the anticipated lifetime of the relevant components and systems are studied. Three different temperatures are selected to simulate the behaviour of the materials, exceeding:
  - **Operational limit** (Design Basic Condition (DBC)-1, 550°C, corrosion layer under 144 µm in 1,000 hours with an oxygen content of $10^{-7}$ wt.%)
  - **Plant Restart limit** (DBC-2 &3, 650°C, $10^{-2} > f > 10^{-4}$ $y^{-1}$)
  - **Major Accident limit** (DBC-4 & DEC-A, 750°C, corrosion runaway threshold, $f > 10^{-4}$ $y^{-1}$)

Two exposure durations - **100 h and 500 h** - are selected at **each temperature** to simulate both a single accident (lasting more than 72 hours) and the cumulative effect of multiple accidents. During these tests, the oxygen concentration is maintained near the lead **oxide equilibrium ($10^{-4}$ wt.%)** and below the magnetite formation threshold ($10^{-8}$ wt.%, ensuring no passivation).

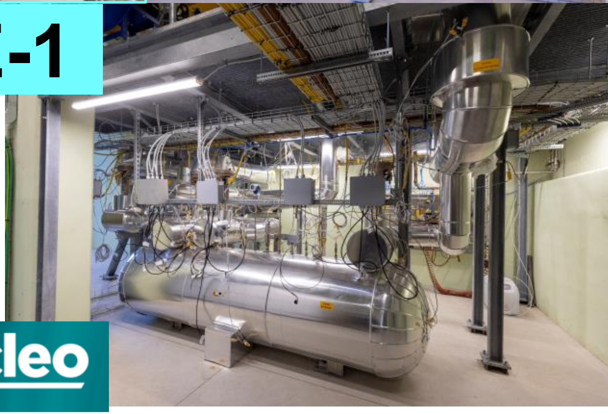
Subsequent tests under **normal operating conditions** are conducted by varying temperature (440°C and 480°C), oxygen content ($10^{-8}$ wt.% - $10^{-5}$ wt.%), and exposure time (500 - 8000 hours). A sensitivity analysis is performed to evaluate the effects of time, oxygen content, and temperature on corrosion and passivation layer development, using SEM and EDS analyses on cross-sections of the tested samples.

# Material Characterization in Flowing Lead

**CORE-1**

**Loop-type** facility to test various kinds of steel, bare and coated, in fluent lead under oxygen-controlled concentration, essentially between **$10^{-8}$ and $10^{-6}$ wt %;** temperature in the corrosion test section **650 °C** and velocity **1 m/s**; in the erosion test section the temperature is 520 °C and the velocity 10 m/s. It will also be used to test the effectiveness of cold traps and mechanical filters


CORE-1



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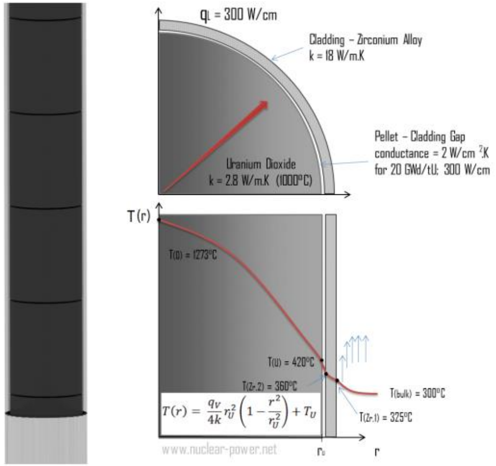
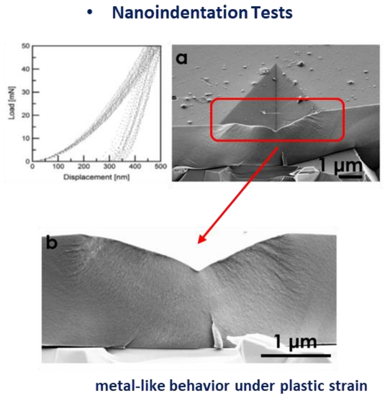
# Coating Technologies

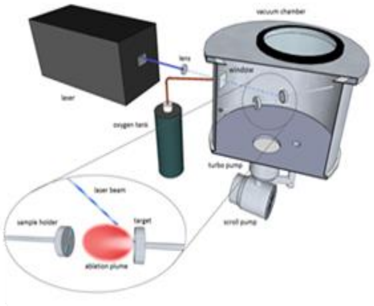


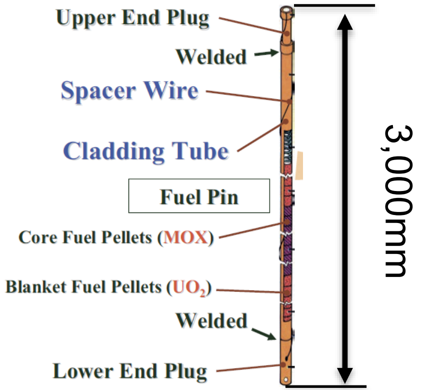

- ❑ Alumina-based coating manufacturing by Pulsed Laser Deposition (PLD) technology was selected as one of the most promising for Fuel cladding coating manufacturing thanks to the metal-like behaviour under plastic strain
- ❑ 1:1 scale PLD facility was designed and will be installed in 2026-2027 in **ENEA Brasimone** to validate the process at an industrial scale




The facility will be able to:

- ❑ Manufacture the coating on pipes characterised by a length of 3,000mm, and a diameter in the range between 6 and 13mm
- ❑ Manufacture the coating on 1000 pipes per year.



# Conclusion

- Experimental characterization of chemistry control in lead in standard operation and in accidental scenario are ongoing in SOLEAD facility, the facility will be upgraded in 2026-2028 to integrate the Remote Handling system and analyze full-scale operational scenario;
- Structural material characterization tests exceeding the operational limits in stagnant and flowing lead are ongoing: Design Basis Conditions, Design Extension Condition, transient and cumulative/integral durations of accidents and transients of the relevant components and systems are studied;
- A database for the analysis of corrosion rate, lead penetration in the materials with different manufacturing processes, surface status, and welding techniques is under development starting from the data available in the literature and European projects (MATTER, GEMMA, CONNECT – NM);
- Coating technologies R&D is ongoing to increase the TRL of the technology available at laboratory scale and demonstrate in 2026-2027 the applicability at industrial scale of PLD technique.

# Thank you for the attention!

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