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

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INTRODUCTION:

ENEA is one of the leading national and international research centres dedicated to the study and development of technologies in the field of fourth-generation fission reactors (Generation-IV LFR). At the Brasimone Research Center, ENEA, in partnership with *new*cleo, is working to design, build, and operate Gen-IV Advanced Modular Reactors [1]. A close, crucial collaboration to fully exploit the skills on both sides and swiftly develop, design, install and operate non-nuclear experimental facilities, including PRECURSOR, a prototype of a lead-cooled reactor capable of reproducing all aspects of its operation, will be installed at ENEA Brasimone for this purpose.

OVERVIEW:

The investigation and qualification of materials to be used, able to operate at high temperature with chemistry control, is a critical issue in the operation of the Lead Fast Reactor. To rapidly increase the TRL for the desired nuclear applications towards requirements of corrosion resistance, high temperature strength, thermal stability and irradiation tolerance, which are not met by current structural materials, a strong qualification roadmap is ongoing with the support of the experimental facilities CAPSULE and CORE-1. CAPSULE is constituted by a set of 18 modules used to investigate corrosion phenomena in stagnant liquid lead in the temperature range 450°C-750°C with chemistry control. CORE 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. To improve the performance of the material at high temperatures superficial coating based on alumina is under investigation and qualification. The main roadmap and status of the activities are summarized.

1. CHEMISTRY CONTROL IN THE LEAD FAST REACTOR

SOLEAD (Solar tOwer LEAd Demo) experimental facility (see FIGURE 1) has been designed to be interfaced with Concentrated Solar Power (CSP) air-based tower systems [2]. However, the facility was used to carry out tests of interest for GEN-IV fast reactors, LFR type. Moreover, the facility SOLEAD can be used for the qualification of components of large size, having interest for LFRs, to carry out tests in natural or forced circulation of the lead coolant, for thermo-hydraulics tests in a big pool, for material corrosion tests, for lead conditioning and chemistry control tests. Tests have been carried out using the SOLEAD facility, with the scope to study the interactions between liquid lead and water vapour/air. The tests have foreseen water vapor injection directly into the liquid lead, by bubble tube, or in the cover gas. A test, consisting of injecting air into the cover gas, was also carried out, with the scope to study the kinetics of oxygen diffusion from the cover gas to the liquid lead. 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. A schematic drawing of the facility is shown in FIGURE 2. The main characteristics of the facility are shown in the following TABLE 1.

TABLE 1. SOLEAD experimental facility – Main characteristics

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 mixtures	Ar/H_2/Air
oxygen concentration measurements by Electrochemical Oxygen Sensors	Max. 3 (in storage vessel)

The test, consisting of water/steam injection inside the liquid lead, had the scope to support the safety analysis concerning the consequences of a leak-before-break in a tube of the steam generator, while the test consisting of water/steam injection inside the cover gas had the scope to support the safety analysis concerning the consequences of a steam inlet into the cover gas during the fuel assembly handling. These two tests, together with the test foreseeing the injection of air into the cover gas, has also provide information about the chemistry of lead and its control. For these tests, only the storage vessel and the gas panel have been used.

The results showed that the steam injection, both in the lead and cover gas, had a negligible impact on the coolant chemistry control. On the other hand, the ingress of air in the cover gas had a quick effect on the coolant chemistry; this fact leads to suppose that the operations of the facility could be compromised if countermeasures are not taken.

FIGURE 1. SOLEAD Facility

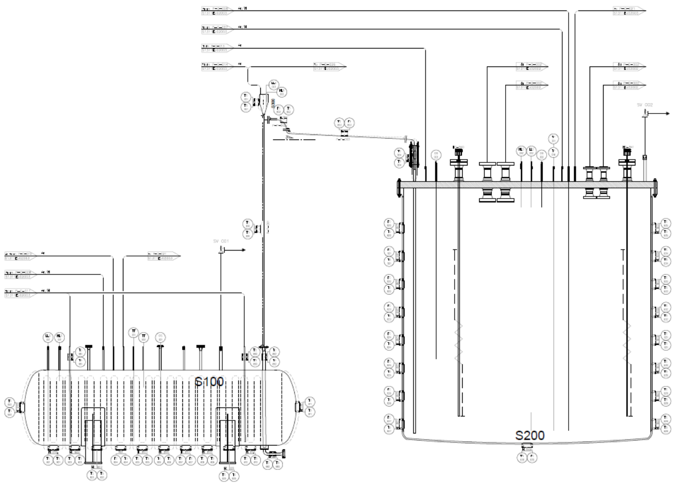

FIGURE 2. SOLEAD Facility – Schematic Drawing

2. CORROSION CHARACTERISATION OF MATERIALS FOR LEAD FAST REACTOR

Material selection for the reactor's structural components is critical to its qualification process. Out-of-core components - both replaceable and non-replaceable - must undergo a rigorous selection process to ensure they meet strict requirements for thermo-mechanical properties, resistance to liquid lead-induced corrosion and embrittlement, and irradiation tolerance.

*new*cleo 's qualification programme is designed to systematically identify and assess materials for the construction of the LFR for safety demonstration purposes. This strategy will implement a comprehensive testing framework to evaluate structural materials under representative operating conditions of LFR-AS-30 reactor, including high temperatures and exposure to corrosive lead. The programme will focus on materials such as stainless steels 304L, 316L(N). Co- extrusion solutions are also studied for the different environment H_2O/Pb. The assessment will determine each material's behaviour over the reactor’s expected operational lifetime.

316L(N) is the candidate material for several out-of-core components in LFR (reactor vessel, steam generator, decay heat removal system) according to previous studies (ALFRED, Westinghouse) due to the high mechanical resistance at high temperatures [3], creep strength [4] ,good ductility, good manufacturability (forging, weldability) and low susceptibility to liquid metal embrittlement [6]. It has also an enhanced resistance to sensitization compared to standard 316L.

Several studies show the passivation of this material in liquid lead up to 480°C in an oxygen-controlled environment [5] [6]. Coating technologies, such as alumina-based coating deposited by weld overlay, PLD, detonation spray or packed cementation processes are under examination for enhancing the corrosion resistance of non-replaceable components, such as vessel, at temperatures higher than 480°C (*new*cleo’s Phase II).

The 316L(N) steel sub-components can be supplied in accordance with the RPS (Reference Procurement Specification) of the RCC-MRx code [7]. The bulk material 316L(N) is already standardized in RCC-MRx, but it should be characterized in liquid lead according to the recommendations of paragraph SDG 2321 of RCC-MRx code.

The current tests are designed to assess the resistance of core and out-of-core materials when exposed to static or flowing liquid lead under Phase I normal operating conditions (nominal temperatures of 440°C and 480°C), as well as under incidental and accidental conditions (550°C, 650°C, and 750°C).

Indeed, the investigation of 316L(N) alloy covers the characterization of the different product types of the alloy (i.e. RM332-1 forged, RM334-1 seamless pipe, RM333-1 laminated plated all in a solution annealed conditions) both in static and fluent lead in the facilities CAPSULE and CORE.

For the test in **stagnant lead,** the aim is to appreciate any differences, if any, on the behaviour of the different product types, to be tested in accidental and normal conditions, and preliminarily assessing the safety margins for the design. For this reason, **screening tests** have been performed in CAPSULE at 500°C and 600°C with oxygen concentration lower than the passivating one. Exceeding the operational limits helps to see any difference in the materials’ behaviour.

First results on screening tests show a passivation on both laminated and forged types after 500h and an oxygen content 10^{-8} wt.%. A thin passivating oxide layer (< 1 μm) is observed through EDS maps on a significant fraction of the surface analysed.

After 500h at 600°C and 10^{-7} wt.%, localized dissolution and lead penetration have been observed, with a maximum penetration depth of 120 μm. The majority of the surface has been protected by a passivating oxide layer.

The next step is the testing in **incidental and accidental conditions** just on the material type that showed the worst resistance in the screening tests (conservative approach). Incidental, transient and cumulative/integral durations of incidents, 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 (DBC-1, 550°C, corrosion layer under 144 μm in 1,000 hours with an oxygen content of 10^{-7} wt.% [8], f >10^{-2} y^{-1})
- Plant Restart limit (DBC-2 &3, 650°C [8], 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 incident (lasting more than 72 hours) and the cumulative effect of multiple incidents. 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.

For **fluent lead testing** in the CORE facility, a preliminary 4000-hour test is conducted on 316L(N) forged bars at 480°C with an oxygen concentration of 10^{-6} wt.%, aiming to investigate corrosion mechanisms driven by convective mass transfer. In parallel, a static capsule test under identical conditions is performed to assess the effect of flowing lead (~1 m/s) compared to stagnant lead. Additionally, reactor shutdown conditions are simulated by subjecting samples to abrupt cooling from 480°C to 370°C every 1000 hours, to evaluate thermal cycling effects.

All these tests aim at reproducing in a controlled environment all possible phenomena that will occur in the reactor and exclusively assess the corrosion resistance of these materials. The ultimate goal is to define the kinetic laws of materials in order to justify their behaviour from a safety perspective and to predict their long-term corrosion behaviour, as it is not currently possible to conduct tests over several decade. Tests on the mechanical behaviour in lead and the combined effect of corrosion/irradiation are planned, in order to have a complete characterisation.

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