**Development of Lead-Cooled fast reactor technologies at ENEA**

**Brasimone Research Centre**

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Abstract – *In the framework of the Generation IV (GEN IV) innovative nuclear system, the ENEA Brasimone R.C. is supporting the technological development of lead-cooled fast reactor as one of the most promising GIF concepts. ENEA is currently involved in several EURATOM (EC funded) projects devoted to heavy liquid metal technological development as well as to materials investigations, modelling and simulations and licensing for Lead Fast Reactor (LFR).*

*Since 2013 ENEA is full member of the Fostering Alfred CONstruction (FALCON) international consortium in partnership with ANSALDO NUCLEARE and RATEN-ICN aiming at the construction and operation of the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) in Romania with the goal to fully demonstrate the LFR technology viability and shortening the time-to-market of LFR fleet.*

*Moreover, in 2022 ENEA and newcleo signed a framework agreement with the intention of exchanges information and knowledge for the development and deployment of LFRs. The main goal of this cooperation is the construction at the ENEA Brasimone site of an electrical prototype of the newcleo LFR-AS-30, named PRECURSOR, to allow studying the thermo-dynamic, mechanical and functional performances of newcleo concept.*

*That said, ENEA Brasimone Research Centre host one of the largest European fleets of experimental facilities aiming at investigating Heavy Liquid Metal (HLM) thermal-hydraulics, coolant chemistry control, corrosion behavior for structural materials, and material properties in HLM environment, as well as at developing corrosion-protective coatings, components, instrumentation, and innovative systems, supported by experiments and numerical tools for modelling and simulations. The aim of this paper is to present an overview of the research activities carried out at the Brasimone Research Centre supporting the technological advancement of lead cooled fast reactor design.*

**Keywords:** HLM, LFR, ENEA, ALFRED, GEN IV, FALCON

I. Introduction

Since 2000, ENEA has been strongly involved in the development of Heavy Liquid Metal (HLMs) cooled nuclear reactor. The main rationale is the reduction of CO2 emission in the energy production designing innovative nuclear reactor that meet the requirements introduced by GEN IV international forum of sustainability, safety, reliability, proliferation resistance, physical protection and economy.

Within this research framework ENEA is involved in several European collaborative project:

* **PASCAL**: under the coordination of ENEA, the PASCAL “Proof of Augmented Safety Conditions in Advanced Liquid–Metal-Cooled Systems” project aims at addressing several topics that have been requested to substantiate the pre-licensing processes that are ongoing in Romania for ALFRED and in Belgium for MYRRHA. The general approach is to perform experimental work, in such a way to provide data that can be directly used to support the safety claims for the two systems, and data that can be used for the validation of the simulation codes and methods that are used in the evaluation or verification of the safety performances.

• **PATRICIA**: under the coordination of SCK●CEN, the “Partitioning and Transmuter Research Initiative in a Collaborative Innovation Action” project will investigate advanced partitioning to efficiently separate the radioactive chemical Americium from spent fuel, and it will study the development of transmutation systems. It will also explore the behaviour of Americium-bearing fuel under irradiation and conduct safety-related research.

• **INNUMAT**: under the coordination of KIT “Innovative structural Material for fission and fusion” aims at developing structural materials for nuclear applications.

* **ANSELMUS**: under the coordination of SCKCEN “Advanced Nuclear Safety Evaluation of Liquid Metal Using Systems” project aims at contributing to the safety assessment of HLM systems, in particular ALFRED and MYRRHA as these are included in the roadmap for the development of advanced systems in Europe.

Hereafter, a general overview of the main activities ongoing/performed at ENEA Brasimone Research Centre (R.C.) including a brief description of activities in the frame of the Falcon Consortium and in the ENEA-newcleo framwork agreement.

II. Flow Induced Vibration (FIV) on grid-spaced fuel bundle.

In the frame of the PASCAL project, a test section (TS) has been developed to study the FIV phenomenon on grid-spaced fuel bundle in flowing Lead. Excessive vibrations must be avoided in components as it can cause failures due to fretting-wear or fatigue and therefore limit the life of the power plant. This research activity stands as a supporting study for the development of ALFRED Reactor. The high density of Lead coupled with the slander shape of the fuel pins, might result in significant FIV, and thus important fluid-structure interaction dynamics could arise. This research activity aims at developing a fluid-structure interaction model. Specifically, the experimental results will be used to validate the STAR-CCM+ CFD code and the Pressure Fluctuation Model which allows to sustain the vibrations in an unsteady Reynolds Averaged Navier-Stokes (RANS) framework.

The FIVFPS (Flow Induced Vibration Fuel Pin Simulator) TS is mounted on HELENA (Heavy Liquid Metal Experimental loop for Advanced Nuclear Applications), a multipurpose facility located at the Brasimone R. C..

The TS is a 37-pin (1:1 scale in length) mock-up representative of the ALFRED Fuel Assembly, instrumented with Strain Gauges to measure the maximum pin displacement. The single pin must be representative of the ALFRED pin from a vibrational point of view, therefore its dimensions and wight distribution are the same. The pins have a total length of 1710 mm and an active length of 810 mm. The bundle is characterized by a hexagonal lattice with pitch of 13.6 mm. and a diameter of 10.5 mm. To reproduce the fuel in the active length holed pellets of tungsten carbide have been used. The expected experimental outcomes are the determination of the vibration’s mode and the associated vibration amplitude as function of the mass flow. Due to the environmental and geometrical constrains, strain gauges have been chosen as the best option. As these sensors must withstand a maximum temperature of 500°C and an expected maximum deformation of 300 micron, the KYOWA KHC Encapsuled weldable strain gauges (KHC-20-120-G9-16 C2MV) has been selected. The strain gauges are placed at the maximum position of the first and third eigenfunctions, according to numerical pre-test analysis. To have information about both the amplitude and the direction of the deformation, at each of the two planes a set of three strain gauges, at 120° are welded. An appropriate data acquisition system (DACS) acquires the voltage data output from the SGs at 1 kHz of frequency and reconstruct the oscillation amplitude and frequency of the pin. A total of 24 SGs have been mounted in the TS, 12 SGs at each plane, thus 4 instrumented pins per plane. A study on the maximum error has been carried out considering the possible misplacements in the three directions of the SGs, and the errors in the measuring chain. The total maximum error has been verified to be below the 4%.

III. SGTR and thermal hydraulic experiments

CIRCE [1] (Eutectic Circulation) is a large HLM pool aimed at investigating safety related incidental transient and thermal-hydraulic behaviour of a pool type reactor in normal and abnormal operative conditions. In the frame of the completed MAXSIMA (Methodology, Analysis and eXpreriments for the Safety in MYRRHA Assessment) project, a dedicated TS for Steam Generator Tube Rupture (SGTR) experiments was realized and hosted in the CIRCE main vessel (*Fig. 1*). The water operative conditions at which the SGTR event is initiated are 200°C and 16 bar, relevant for the MYRRHA reactor. The TS has been conceived to perform four tests, investigating HLM-water interaction occurring at two different tube rupture positions (i.e. bottom and middle) of MYRRHA Primary Heat eXchanger (PHX) [2].



*Fig. 1:* *SGTR Test section*

Two tests have been carried out for each rupture configuration, for acquiring feedback on test repeatability. Four full-length portions of the PHX, represented by 31 tubes, have been installed conserving the flowing areas for the tube and shell sides. In the central tube of the bundle in which the test was performed, water evaporating upwards was provided by a pressurized and heated tank upstream CIRCE and discharged in a condenser tank downstream it. Before rupture, LBE flowed downwards shell side of the investigated tube bundle, pushed by a pumping system composed by a centrifugal and jet pumps arranged in series. Both water and LBE pressure, temperature and mass flow rate were regulated for reaching, before rupture, initial conditions in agreement with MYRRHA. The PHX design parameters are: i) 70 g/s of water at 200°C and ii) 16 bar and about 70-80 kg/s of LBE at 350°C under a cover gas at about 1 bar. The tube rupture event is achieved by an external hydraulic jack pulling up the pre-notched tube. This setup allows performing four SGTR tests, one at a time, without the need to remove the component from the pool. The experimental results for middle rupture tests highlighted a maximum pressure of 2.7 bar, both at about 5 s after the start of injection, as consequence of rupture disc activated at such a pressure threshold. Tests with injection at bottom positions reached about 4 bar at 6.5 s after rupture occurrence (rupture disc threshold was 7 bar). Being the water injection performed in the lower part of the pool, sloshing of LBE free level was detected by oscillations measured in the cover gas pressure (*Fig. 2* and *Fig. 3*). Concerning the thermal field, in the middle and bottom scenarios, the lower temperatures reached were about 120 and 140°C, respectively.

PT-S100-1_PT-S100-2_clean

*Fig. 2:* *SGTR-A: pressure in S100 cover gas.*

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*Fig. 3:* *SGTR-A:* *temperatures measured by TCs 1-6 Level 4.*

These values were measured in inner and outer position of TCs, at levels near tube rupture, for a period lasting about 1 s at the beginning of injection phase. After the minimum, temperature recovery (higher than 250°C) was registered in both TCs locations at the end of injection, about 6 s after rupture occurrence. In such a configuration the cooling effect did not represent an issue for the bundle. Moreover, a wider tube array cannot be affected by freezing phenomenon. The six tubes, composing the first rank of each bundle, surrounding the fed central tube were pressurized at about 16 bar, for acquiring feedback on tube rupture propagation. All the tests showed a final pressure in these tubes equal to the initial one, highlighting the absence of ruptures and leakage due to SGTR event. The high-quality data acquired have been used for transient analysis and code development and validation [3] for applications in water-HLM interaction scenario in a large pool facility.

In the frame of the PATRICIA project, a TS named Thermalhydraulic HElical Tubes Innovative System (THETIS) is under construction as new TS to be installed in the CIRCE facility. The new TS will include a vertical mechanical pump for primary coolant circulation and a new prototypical helical coil steam generator (HCSG). This steam generator concept turns out to be very promising for nuclear power plants since the helical geometry is very compact and it assures high power removed, taking up a minimum amount of space. Accordingly, with the aims of the project, the experimental tests in CIRCE-THETIS will focus on i) investigating the thermal-hydraulic behavior of the system in steady-state operation (forced circulation regime) during operational and accidental transients (postulated scenarios) and in a natural circulation regime considering as heat sink the HCSG (acting as a decay heat removal system) and the reactor vessel auxiliary cooling system in stand-alone or coupled operation and ii) characterizing the performance of the HCSG.

IV. Development and characterization of innovative materials

Materials are one the main research topic to be addressed in the frame of LFR development. Indeed, materials in LFR system are exposed to harsh conditions due to the presence of the molten lead which is particular aggressive towards conventional steels used for structural applications (e.g. austenitic stainless steels and ferritic/martensitic steels). Molten lead acts as a chemical solvent for steels leading to solution of alloying elements (Fe, Cr and Ni) and to severe corrosion effects [4]. The addition of sufficient amount of oxygen in the molten lead is reckoned to be beneficial in the protection of the steels against solution-based corrosion thanks to formation a Fe-based oxide layer which acts as protective barrier [4]. However, this approach seems to be effective only up to a certain temperature limit (around 480°C in molten lead) and severe corrosion is usually observed at higher temperature. This represents a limitation for the employment of conventional steels at high temperature, particularly for the fuel cladding pin structures whose hot spots is around 530-550°C. In addition, fuel cladding pin structures are also exposed to neutron irradiation and creep effect.

Presently, ENEA participates to the cross-cutting project INNUMAT (Horizon Europe, GA 101061241) focused on the development and characterization of innovative materials for Gen IV fission reactors and fusion reactor [5]. Among the various materials under optimization in the project for Gen IV, ENEA coordinates the track on alumina coating development for the protection of 15-15Ti AIM1 fuel cladding structures in LFRs. Indeed, alumina layer deposited on 15-15Ti is presently considered as the candidate functional material for the protection of fuel cladding pins [6]. In recent years, alumina coating by PLD (Pulsed Laser Deposition) developed by X-Nano (Milan, formerly IIT) in collaboration with ENEA demonstrated to be promising for the application. The process allows to deposit at room temperature amorphous coating with metal-like properties with the advantage to not modify the cold-worked structure of AIM1 [7]. Moreover, corrosion tests showed that PLD alumina coating is chemically inert in molten lead with low dissolved oxygen concentration and resistant to recrystallization at 550°C, and irradiation tests under heavy ions at high dpa showed that the coating possess good resistance to delamination and cracking [8]. In INNUMAT project, a new series of coating for 15-15Ti substrate will be optimized by X-Nano to resist to corrosion and recrystallization also to higher temperature (> 600°C). The characterization of the coating performed by ENEA in Brasimone will be an essential part of the project: corrosion tests at high temperature in molten lead (≥ 600°C) will be carried out under oxygen control as well as fatigue and creep tests on coated pressurized tubes at different temperatures. Moreover, in the frame of INNUMAT project, irradiation campaigns on new optimized coatings will be performed with heavy ions but also with neutrons inside BR2 reactor (Belgium), with different damage levels and with post-exposure characterization in hot cell.

V Safety assessment of HLM systems

The Phenomena Identification and Ranking Technique (PIRT) [9] is a systematic way of eliciting and gathering knowledge from a panel of selected experts on a specific subject. The approach is aimed at ranking the importance of the information as a combination of level of knowledge and impact on identified figures of merit, to support design and licensing processes towards the prioritization of studies and experiments.

In the ANSELMUS framework a PIRT will be performed for the ALFRED and MYRRHA designs via a thorough analysis exploiting experience accumulated in past national and European projects and, whenever necessary, state-of -the-art simulations in support, so to investigate the phenomena underlying the plant response to challenging design basis events and hypothetical beyond design basis events.

ENEA participates in the panel both as expert and as ALFRED core designer and lead-related technology developer, moreover it is supervising activities leading to the selection of the reference postulated initiating events, and ensuing transients, and the simulations to support the ranking by the panel.

Referring to the ANSELMUS task aimed at investigating the fuel assembly safety, ENEA Brasimone R. C. is designing a new test section (DFPS, Deformed Fuel Pin Simulator) to assess the effect on the pin deformation on temperature field in the fuel pin bundle of the ALFRED Fuel Assembly in flowing Lead conditions. Results of the pre-tests numerical simulations showed that with 2 mm max bending at z=300mm there is more than 70°C of overheating in the surrounding pins at z=500mm and more than 50°C at z=300mm [10] in nominal conditions, therefore the choice is perfectly coherent and the configuration is highly perturbed by the modified geometry.

The DFPS test section will be instrumented by bulk and wall thermocouples (*TC*) to allow a complete mapping of the temperature field. The bended pins 2, 13 and 16 will not be instrumented to allow rotation by Swagelok connectors. Two monitoring sections have been selected in the active region: in the middle (plane A, 300 mm from the beginning of the active region) and close to the outlet of the active region at (plane B, z=500 mm). Moreover, a differential pressure transducer will measure the pressure drop across the bundle for code validation.

A notional scheme of the thermocouples in the monitoring sections is shown in *Fig. 3*. A complete test matrix with flow rates up to 20 kg/s representative of the ALFRED pin bundle, will be carried out.

VI. R&D partnership activities

Europe has supported collaborative research and innovation actions on LFR technology during the past years, also with relevant economical investments [11]. Different projects have been launched as ELSY (European Lead SYstem), which aimed to define a conceptual design of LFR and the consequent LEADER (Lead-cooled European Advanced Demonstration Reactor) project that results in the first design of the Advanced Lead Fast Reactor European Demonstrator (ALFRED) [12].

Immagine che contiene diagramma

Descrizione generata automaticamente

*Fig. 4: Notional scheme of the location of the TC in the generic monitoring section (z=300 mm, 500 mm).*

The mission to manage the R&D strategic needs and to secure the necessary funding for siting, licensing and constructing ALFRED has been carried out by the FALCON international consortium established in 2013. Main partners of the consortium are Ansaldo Nucleare, RATEN-ICN and ENEA together with other European Organizations [13].

The first step to support the development of ALFRED project is to enlarge the research infrastructure dedicated to the study of the lead technology. ATHENA (Advanced Thermonuclear-Hydraulics Experiment for Nuclear Application) is one of the most important research infrastructures of ALFRED. A consortium, including Ansaldo Nucleare and Reinvent Energy (Romania), has been realized for the construction of ATHENA facility. ENEA and SRS (Italy) support the consortium for the conceptual and executive design. The facility will be located at RATEN-ICN research center, near Pitesti (Romania) [14]. ATHENA is a 2.21 MW pool type multipurpose facility, representative of LFR technology. It is composed of a big pool having a diameter of about 3 m and a height of 10 m, filled with liquid lead [15]. The main components installed inside the pool are the following:

* a core simulator, composed of 127 pins electrically powered, simulating the fuel pins of the reactor;
* a vertical axial mechanical pump working in pure lead;
* a heat exchanger having a shell and tubes structure, with a tube bundle composed of bayonet tubes, working in counter current, with the primary fluid (lead) flowing in the shell side and the secondary fluid (water) flowing in the tube side.

ENEA's expertise and achievements in the field have garnered global recognition, resulting in prestigious partnerships and collaborations, such as with the Westinghouse Electric Company. ENEA plays a crucial role in shaping the research plan for the construction of the Westinghouse LFR, contributing to the design of experimental facilities, and providing operational support based on its extensive decades-long experience.



*Fig. 5: 3D model of ATHENA main vessel (pool)*

In 2022, ENEA Brasimone also established a significant partnership with newcleo, an international private start-up with locations in Italy, the UK, and France. The objective of this collaboration is to develop a prototype of a small modular LFR reactor by the early 2030s. ENEA is actively involved in supporting the design of critical reactor components and has agreed to host several research and development facilities for newcleo’s program at Brasimone.

Notably, newcleo plans to construct the Precursor at Brasimone in 2026. This electrically-heated demonstrator will showcase the design of the LFR design with a capacity of 30 MWe, and provide a full-scale environment for testing the most innovative solutions and components in a reactor-like setting. Founded in 2021, newcleo 's primary objective is to advance the development of two reactor designs: LFR-AS-30 and LFR-AS-200, boasting capacities of 30 MW and 200 MW, respectively. These small modular reactors (SMRs) offered by newcleo introduce ground-breaking solutions that are protected by multiple patents. The innovative nature of these designs necessitates an extensive and comprehensive research and development (R&D) program to validate the technology's safety, reliability, and maturity. The main fields in which the research of newcleo and its partners proceed are:

* structural materials and coatings;
* fuel and fuel integrity;
* primary coolant behaviour and chemistry;
* core integrity;
* primary system integrity;
* instrumentation and control (I&C);
* reactor physics / neutronics;
* components handling systems;
* in-service inspection (ISI) and repair;
* balance of plant;
* plant operation and accident response.

At the ENEA Brasimone research centre newcleo will construct and operate different facilities to accomplish its goals, supported by the experience gained by ENEA.

First in time to be constructed in the early months of 2024 is CAPSULE, a facility to test various kinds of steel, bare and coated, in stagnant lead under oxygen-controlled concentration, essentially between 10-8 - 10-6 wt %; temperatures span between 450 - 750 °C.

To follow CORE, a loop-type corrosion facility in which various kinds of steel, bare and coated, will be tested in fluent lead under oxygen-controlled concentration. The facility will be designed to withstand temperature in the corrosion test section up to 650 °C and velocity of 1 m/s, while in the erosion test section up to 520 °C and 10 m/s. It will also be used to test the effectiveness of cold traps and mechanical filters.

A versatile and multipurpose loop facility will be constructed, called OTHELLO. In this facility the design of the main component will be tested, with focus on a Fuel Pin Bundle and the Steam Generator, with a maximum power of 1.5 MW. OTHELLO will serve to validate thermal-hydraulic codes, to test the components in safety relevant conditions (e.g. inter-pin flow blockage in the pin or flow induced vibration).

In a conceptual phase is also MANUT, a 10 MW “cold” facility to test the fuel hanging and handling systems as well as the rotating plugs operation during refueling campaign.

Peak of the newcleo research program in Brasimone will be the construction and operation of the PRECURSOR: a 10 MW pool-type integral test facility with an electrical resistors bundle, and three Steam Generators at a thermal reduced scale, and the associated turbine-generator set. It will be used to test the global behaviour of the plant in stationary and transient mode, the inset of lead flow both in hot and cold plenum and of possible stagnant zones, the effectiveness of the DHR system, and test various mechanisms as the control rods.

VII. Conclusion and future works

To overcome the challenging transition period between the experimental HLM facilities and the commercial deployment of LFR technology, the construction of a “first of a kind” lead cooled demonstrator is recognized as an essential step within the European context.

On of the main objective is to bridge the existing gap between fundamental research and market entry, a phase often hampered by insufficient investment. ENEA is actively engaged in this endeavor.

According to the present overview, a first prioritization of R&D needs is here outlined, even if not fully exhaustive, which takes into account also the actual worldwide level ofknowledge on LFR technology.

The R&D needs for the further development of LFRs include the following:

* the development and characterization of oxygen control systems suitable for lead conditioning in large pool systems;
* development of structural materials and coatings compatible with lead environment;
* fuel assembly thermal-hydraulics characterization and tests on deformed bundles and on flow blockage condition for safety assessment;
* FIV test;
* Realization of experimental data base for code verification and validation (V&V).

The experiments mentioned above shall serve to support the deterministic approach to the license of the LFR reactor and, in parallel, to make available an experimental database for code validation.

As a conclusive remarks, ENEA efforts for the future experiment will be dedicated in designing experimental campaign taking into account the necessity of speed-up the licensing process, as well as improving the design support of LFR

Acknowledgments

The research activity presented in this document has been carried out within the PATRICIA, PASCAL, INNUMAT and ANSELMUS project. These projects has received funding from the Euratom research under grant agreement number 945077, 945341, 101061241 and 101061185 respectively.

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