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# Research on the safety of heavy-liquid-metal-cooled reactors

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**Abstract.** Since the fifth edition, dating 1998 to 2002, the Euratom Framework Programmes have supported numerous collaborative projects dealing with the research and development of the heavy liquid metal technology. In this 20+ year’s context of outstanding scoring, LESTO – the latest project recently launched – is taking the baton from PASCAL, about to conclude, with ANSELMUS bridging the gap in between. Both PASCAL and LESTO address (on complementary and synergic topics) key safety-related aspects of the technology, sharing the same foundational approach: advancing on the two pillars of experimental testing and software simulation. The two projects also share the focus on ALFRED and MYRRHA, the two heavy-liquid-metal-cooled reactors included in the strategic roadmap of the European Sustainable Nuclear Industrial Initiative. Thanks to the results generated by the two projects, a significant contribution will be delivered to the substantiation of evidences requested for the licensing of ALFRED and MYRRHA and, in perspective, for that of future heavy-liquid-metal-cooled nuclear systems.

## 1 Introduction

Research in Europe on the heavy liquid metals (HLM) technology for nuclear application dates back to the end of the ‘90s, when national actions triggered collaborative initiatives that materialized thanks to the support of the Euratom Framework Programmes. And regularly, several collaborative projects were proposed and approved under subsequent Framework Programmes, extending not only the knowledge on HLM technology, but also the involvement of European organizations, in fact creating and consolidating a sound European community involving academia, research, industry and, more recently safety authorities.

From a technical point of view, the continuity of the support allowed to address systematically manifold aspects of HLM technology: at first, the fundamental phenomena were explored, understood and mastered through basic research actions; then, more technological aspects were addressed by applied development, up to defining and refining, *inter alia*, engineering practices and operational procedures.

Thanks to this continued and extended work, the European community specializing in HLM technology was enabled to design concepts of nuclear energy systems based on HLM cooling. Initially, accelerator-driven subcritical (ADS) systems were developed, specifically

targeting the possibility of burning minor actinides at industrial scale. Along with the European facility for industrial transmutation (EFIT), specifically meant for that purpose, an experimental reactor (eventually evolved in the multi-purpose hybrid research reactor for high-tech applications – MYRRHA – design) was conceived to demonstrate the ADS concept. Subsequently, concepts of lead-cooled fast reactors (LFRs) for commercial power production were developed, such as the European lead system (ELSY), further evolved in the European LFR (ELFR); also these concepts were paired with a demonstration reactor: the advanced LFR European demonstrator (ALFRED), developed as well in the context of Euratom-supported collaborative research projects and then brought forward by the fostering ALFRED construction European consortium. With ALFRED and MYRRHA selected among the reference concepts by the European Sustainable Nuclear Industrial Initiative – coherently with their priority in time with respect to follow-on systems – the focus of European research projects shifted to these, and reflecting the status of their advancement.

The main challenges regarding the licensing of HLM-cooled systems, such as the lack of nuclear operational experience, the innovative design and safety systems, the validation of new codes developed for their analysis (or of the tools transposed from other technologies), the testing of new materials and the qualification of the coolant chemistry systems, need to be addressed in order to sustain and accelerate the time-to-market of this technology, starting from the ALFRED and MYRRHA precursors.

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The primary activities that have been recently executed and are currently in progress are predominantly co-financed through the European Commission's H2020 and Horizon-EU Euratom Programmes. Among the various initiatives, the ongoing projects include ANSELMUS, INNUMAT, HARMONISE and PUMMA. In this context, and with these elements of focusing and tailoring, projects like PASCAL and LESTO were conceived to address further unique elements.

PASCAL (Proof of Augmented Safety Conditions in Advanced Liquid-metal-cooled systems) was proposed in 2019 and launched in November the next year. It involves 16 European organizations, deploying over 420 person-months effort in the 4 years of duration of the project. This effort, along with the costs of the experiments foreseen, is worth more than 4.6 M€, co-funded by the European Commission with 3.8 M€.

PASCAL is aimed at significantly contributing to the advancement of the safety research on innovative HLM-cooled reactors, with the ambition to generate evidence that is ready-for-use in the discussions between the ALFRED and MYRRHA designers and the respective safety authorities in the pre-licensing phase. The goal of the project is also to set an ambition of relevance and quality to the results, which is reflected in structuring and organizing the proposal. Relevant experiments in representative conditions are planned, and – wherever applicable – accompanied by simulations with the objective of extending their domain of validation and reducing uncertainties.

All the selected activities address the main reference: supporting the justification of resilience to severe accident conditions, aiming to demonstrate the claim that no off-site emergency measures are needed for an HLM-cooled system.

Finally, the project also aims at further strengthening the longstanding collaborations among European organizations, and at strongly supporting the education and training of a new generation of experts, to secure safety culture is preserved.

Following the same footsteps, the LEad fast reactor Safety design and Tools (LESTO) project aims to contribute the framework. The LESTO project is dedicated to expand the experimental evidence that demonstrates the improved resilience of LFRs to severe accidents and their high level of reliability and sustainability, as well as integration with the electrical grid, heat production, and hydrogen generation. Last but not least, LESTO contributes to the establishment of experimental databases for code validation, testing novel materials, and exploring coolant chemistry approaches.

To achieve the objectives of LESTO and expedite the time-to-market LFRs, various industries have been engaged from the outset. This includes Ansaldo Nucleare, the designer of the ALFRED, which serves the European demonstrator for the LFR concept, supported by RATEN-ICN and ENEA. *newcleo*, an innovative start-up, is actively advancing LFR development in Europe with its LFR-AS-30 experimental system and LFR-AS-200 reactor model. Furthermore, SCK CEN is dedicated to initiate the development of small modular reactors (SMRs)

based on LFR technology in Belgium, under a firm mandate from the government. Beside these, important European research institutions (CIEMAT, CRS4, NRG, VKI, KIT, Siet) together with universities (Chalmers, CIRTEN, LTU, KTH, PSI) expert on the field are part of the consortium to support the project with their experimental facilities and to maximize its impact. Among the facilities involved in the project, it is worth to mention ATHENA, a large-scale pool type facility being commissioned in Romania, the CIRCE facility in Italy, and MELECOR for the material testing. With the other research infrastructure in Belgium, Germany and Sweden involved in LESTO, this represents the state of art for the LFR R&D.

## 2 Safety enhancements in HLM-cooled reactors

Assessing and ensuring the safety of HLM reactors is the primary importance and one of the goals of both PASCAL and LESTO projects. The activities undertaken in these projects aim to enhance it by comprehensive studies and experimental activities in different fields: fuel and clad performance; reactor cooling performance; containment strategies; structural and components integrity. By investigating safety systems and mitigation strategies, these projects can contribute the meeting of the needed safety standards and to the rapid deployment of these nuclear reactors in Europe.

### 2.1 Fuel pin system

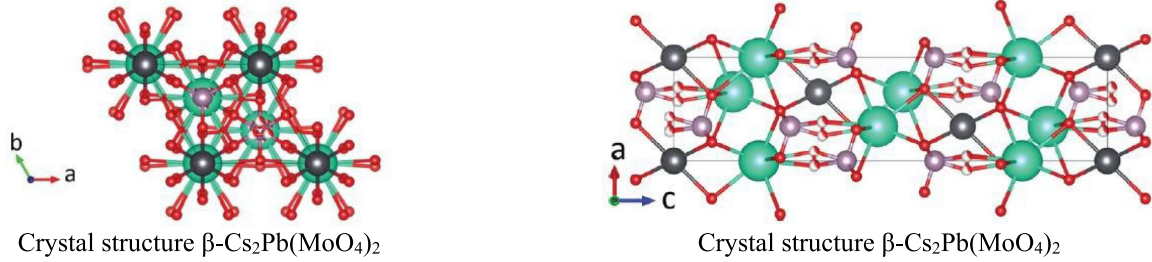
In the framework of the PASCAL project, the interactions between irradiated fuel, coolant and cladding, by coupling experimental and modelling techniques, were investigated.

The first branch of activities focused on studies of interaction between lead/lead bismuth eutectic (LBE) and relevant fission products, selected for their hazardousness in case of release (e.g., caesium, iodine) or long-term radiological impact (such as barium). Experiments and analytical studies (such as in [1–4]) permitted to explore, then extend and refine the basic crystal (see Fig. 1) and thermodynamic data of the resulting compounds, including crystal parameters, phase diagrams, heat capacities.

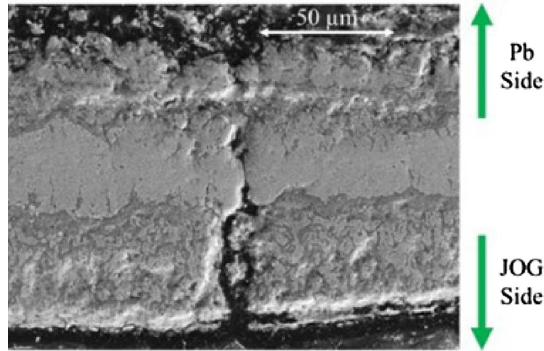
The obtained results also permitted to extend the international databases TAF-ID, the same used, by the CALPHAD method, to perform the analytical studies.

A second branch of studies dealt with the experimental and analytical investigation of the interaction mechanisms between the species of the joint oxide-gas (JOG, i.e., the compound made of some fission products and oxygen which, migrating towards the periphery of the fuel pellet by the thermal gradient, during irradiation form a solid layer filling the gap between the fuel and the cladding), the lead or LBE coolant, and possibly the cladding [5].

In the first part of the experiments, the actual JOG was simulated by sim-JOGs made with representative compositions of the main JOG species. The studies permitted to appreciate the stability of the JOG in retaining critical elements, generally stably bound in the JOG,



**Fig. 1.** Crystal structures of lead-caesium-molybdenum compounds (courtesy of TU Delft).



**Fig. 2.** Synergistic effect of JOG and HLM in the corrosion of the cladding steel at high temperatures (courtesy of Chalmers).

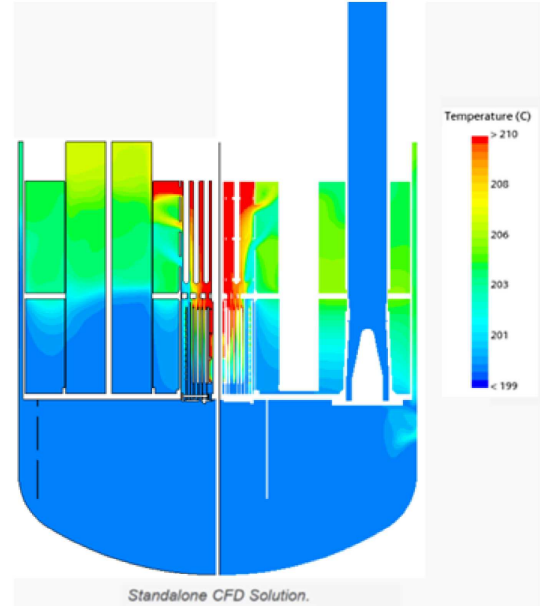
against a potential dissolution effect exerted by HLMs, with or without the aid of cladding elements. The tests involving the cladding were also used to acquire new data about the synergistic corrosion effects observed on the cladding at high temperature, due to the JOG (inner side) and HLM (outer side), as represented in Figure 2.

Fuel performance analysis is also of interest in the LESTO project, specifically the accuracy of the fuel performance codes (FPCs) estimation of the quality and amount of fission products. Improvements are planned in the cross sections employed by the FPCs, by identifying the discrepancies and their underlying causes. The findings of a benchmark between different codes will be utilized to create a surrogate model for integration into FPCs. In parallel, a coupled neutron and thermal analysis of the ALFRED reference design will be conducted to evaluate power profiles, thermal profiles, criticality safety parameters, neutron fluxes, and displacements per atom (dpa) maps.

## 2.2 Reactor coolant system

The impact of off-nominal conditions on the overall performance of an HLM-cooled reactor is of primary importance and is a relevant part of the research activities of the PASCAL and LESTO projects.

The asymmetric operation of the reactor coolant system as due to the single failure of a circulation pump or heat exchanger, or heat removal through deformed fuel bundles in the core has been investigated in the former.



**Fig. 3.** Example of standalone CFD analysis of a single pump failure event in a HLM pool (courtesy of NRG).

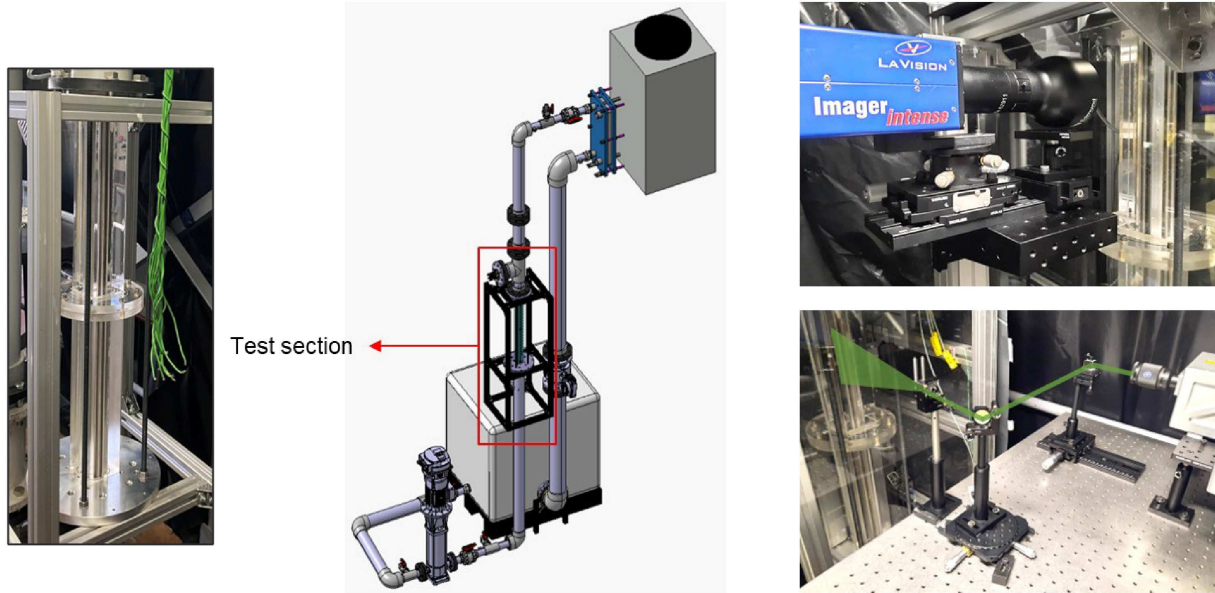
For the asymmetric operation of the reactor coolant system, new experiments were performed in the E-SCAPE facility of SCK CEN, simulating the failure of one bank of major equipment [6]. The heavy instrumentation of the facility provided detailed information on the new flow and thermal regimes set by the asymmetric conditions upon different single failures. These data also permitted to establish best practices for capturing local phenomena – as determined by asymmetric conditions – when simulating large pool systems by CFD codes alone (Fig. 3) or coupled with system codes.

For the study of heat removal in deformed fuel bundles, a new facility – AUPINEL – was designed and realized at VKI (Fig. 4), implementing a transparent test section, laser and a high-speed resolution camera for particle image velocimetry (PIV) measurements, along with more traditional pressure and temperature measurements.

All this data will be used to validate turbulence correlations or models for use in sub channel or CFD codes, respectively.

A goal of the LESTO project as well is to design and evaluate inherently safe and passive systems that can prevent or mitigate accidental scenarios. While





**Fig. 4.** Overview of the AUPINEL facility (left), and detail of the equipment for PIV measurement (right) (courtesy of VKI).

performing the necessary tests, experimental data will be generated and will support the necessary validation process of numerical tools for LFR analysis.

In particular, the following topics will be analysed.

**In-vessel long-term accident management.** A passive DHR system is designed to remove the maximum decay power using water phase transition. With power reducing during time, the cooling may turn excessive, additional steam condenses and pressure in DHR system reduces. In LFR, if the saturation temperature goes below the lead freezing temperature, lead may solidify on the surface of the DHRs, preventing its correct/safe operation. To mitigate the risk of overcooling the liquid metal, non-condensable gas can be introduced into the system to passively manage the power transfer to the ultimate heat sink.

Within the framework of the PIACE Euratom H2020 project, the SIRIO facility [7], pictured in Figure 5, served as a platform for evaluating the impact of non-condensable gas injection across various DHR configurations.

However, the outcomes of the testing campaign were affected by gaps identified in the facility's design and anticipated performance such as:

- lack of flow measurement, which makes it more difficult to analyse the experimental results;
- missing information of the gas across the steam generator;
- insufficient unstable power delivery.

One of the goals is then to address the shortcomings identified and enhance the quality of the data collected. This will involve measuring previously overlooked quantities and characterizing the components in terms of their heat transfer capabilities and pressure drops. The objective is to expand the dataset from the SIRIO facility by conducting a sensitivity analysis on critical testing parameters. Unlike the PIACE project, these tests will be conducted

only with the Lead Fast Reactor (LFR) configuration of the facility.

The following steps will be undertaken:

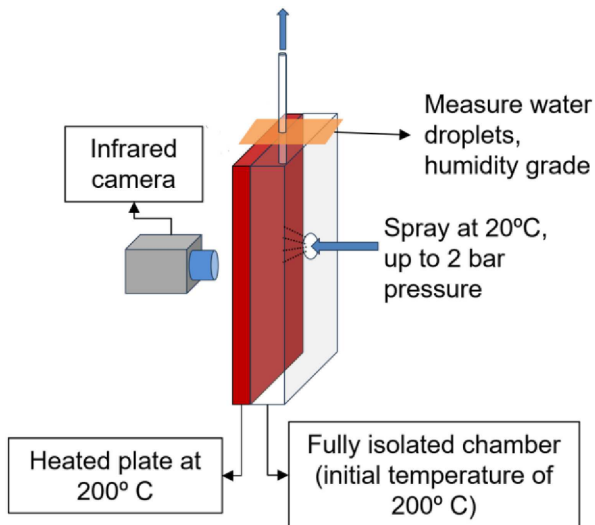
- modification of the SIRIO facility;
- commissioning tests, with evaluation of the facility's performances following the modifications;
- characterization tests, to accurately characterize the steam generator, IC, and bypass heat exchanger;
- sensitivity tests, with a dedicated campaign in LFR conditions to evaluate the impact of injecting non-condensable gases into the IC during a power reduction transient.

Pre-tests and intermediate analyses are planned to identify any newly discovered gaps and to guide the remainder of the testing campaign by highlighting areas that require further investigation.

**Ex-vessel long-term accident management.** A new facility – HERMES (Fig. 6), Heated Enclosed RVACS Measurements to Evaluate Spray cooling performance – will be deployed aiming at characterizing the heat transfer (multiphase flow, mass balance, phase change phenomena) of different water injection systems in an environment representative of an enclosed insulated Reactor Vessel Auxiliary Cooling Systems (RVACS) for pool-type reactors. The goal is to evaluate multiple concepts of RVACS water injection, including water jet injection, water spray, and water atomization. These methods aim to effectively remove decay heat from the system, particularly in the upper section of the vessel, thereby facilitating enhanced heat redistribution through natural convection within the pool. The experiments will evaluate proof of concept of passive water injection RVACS systems and will be used as benchmark for numerical modelling. The specific test matrix will be determined based on the requirements of LFR designers. Given the constraints associated with operating at lower temperatures anticipated for LFR



**Fig. 5.** Conceptual scheme (left) and components (right) of the SIRIO facility (courtesy of SIET).



**Fig. 6.** Conceptual scheme of the HERMES facility (courtesy of VKI).

applications, the study will prioritize a conceptual analysis of the different water injection methods rather than a detailed examination of their implementation. At the end, the data collected will undergo post-processing to refine the simulation tools utilized in the design analysis of the RVACS system. This process will encompass not only the reporting of relevant quantities along with their uncertainties but also the documentation of initial and boundary conditions, facilitating an accurate correlation between experimental results and numerical models.

### 2.3 Containment and radiological safety

Relative to the containment of radioactive contaminants, studies have been performed in PASCAL on the mechanisms of formation and transport of aerosols, and on the

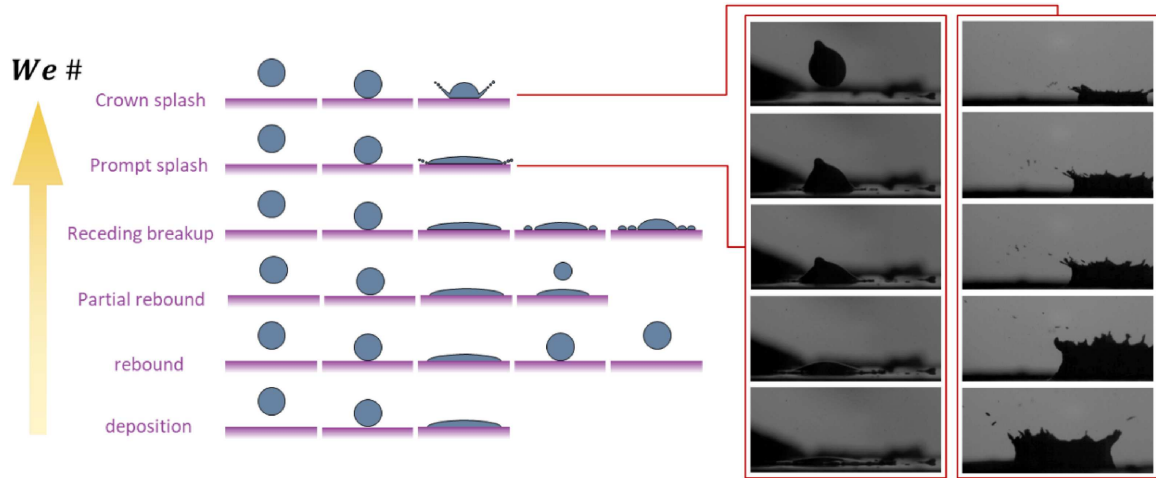
volatilization of radiotoxic species from HLMs and their condensation on cold surfaces, such as those in the reactor building.

The formation of HLM aerosols was experimentally investigated (Fig. 7) by dropping HLM droplets of different sizes onto solid steel and liquid HLM surfaces, from different heights. By high-speed cameras, and particle analysers such as an Optical Particle Counter (OPC) and a Scanning Mobility Particle Sizer (SMPS), the size distribution of the produced particles was constructed, and correlations derived.

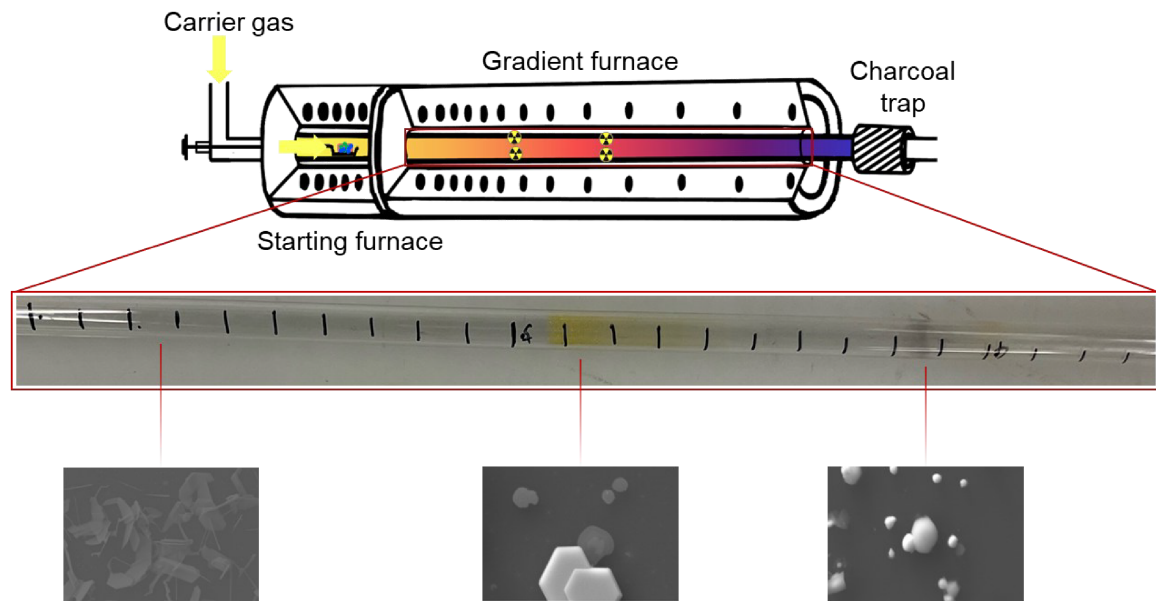
The so derived particle distributions were input to containment codes, to appreciate the effect of aerosol releases, should these occur inside the reactor building. An extensive study was performed, using 0D and 3D models, to appreciate the impact of model parameters on the resulting concentration of aerosols in the building atmosphere as a function of time. The parameters investigated included the total mass of released aerosols, the release rate and duration, the initial aerosol size distribution, the agglomeration and deposition phenomena, size and shape of the containment building as well as flow patterns in the containment (only for 3D models). The comparison between the models allowed to appreciate the observables that are impacted by the choice of the model and simulation parameters, and the trend of deviation between the results obtained in different conditions, so to inform not only about the phenomena to focus on, for the validation of the models, but also regarding the simulation assumptions allowing to analyse problems of interest under conservative conditions.

Regarding the volatilization of radiotoxic species, LBE samples doped with iodine, caesium and tellurium – activated by irradiation – were prepared, which were evaporated in thermal columns for thermosublimatography, so to obtain, on the column walls, deposition of species according to their sublimation temperature (Fig. 8).

The results of the analysis of the deposited species (as in [8]) allowed not only to confirm the distribution



**Fig. 7.** Theoretical (left) and experimental (right) aerosol formation mechanisms (courtesy of SCK CEN).



**Fig. 8.** Principle of thermosublimatography for the speciation of evaporated species (courtesy of PSI).

of the volatilized elements among the different species, but also to clarify whether their formation takes place in the liquid or gas phase. Transpiration experiments, performed in parallel with the thermosublimatography ones, allowed observing the linear behaviour of the logarithm of the Henry constant versus the inverse of temperature to broader ranges than those available in literature, and thereby to confirm or retrieve a new measure of the Henry constant itself. All these elements provided new, relevant input data, including improved models, for the prediction of fission product release from HLMs.

Important achievements are also planned in the LESTO project by the implementation of numerical modelling of fission products release from coolant, with the aim of developing numerical models to predict release and transport of fission products from the source to and in the reactor hall. Approaches based on machine learning, which can accelerate the chemical calculations, will be used and,

for the given system of interest, a surrogate model of the expected chemistry will be produced. In parallel, to further enhance computational efficiency, reduced order modelling approaches with the reactive transport simulation will also be developed. Machine learning techniques will also be used to accelerate sensitivity analysis.

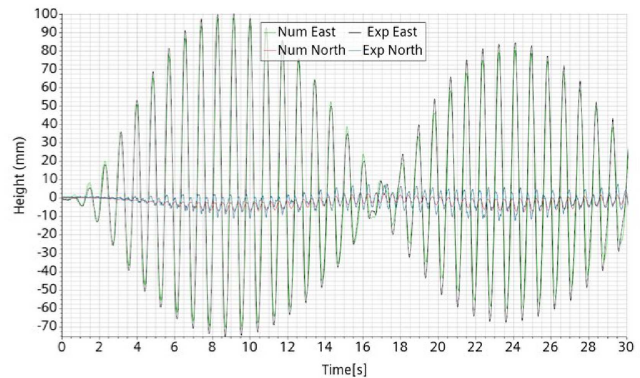
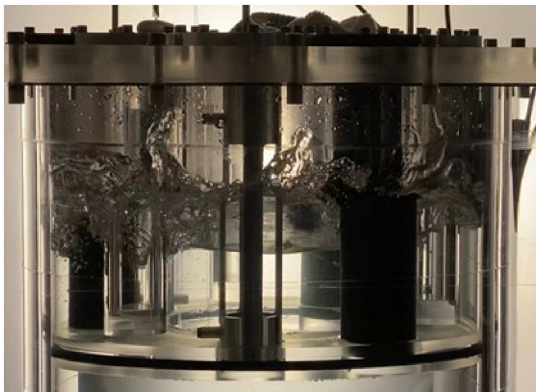
### 3 Integrity and resistance of reactor components

Experimental analysis of phenomena potentially undermining the resistance of key components, such as the fuel cladding tubes, the reactor internals and the reactor vessel, as well as on the investigation of technical feasibility of inspection of the integrity of the reactor vessel at elevated temperatures (i.e., above those typical of other





**Fig. 9.** View of the HELENA loop (left) and drawing of the FIV test section installed in it (right) (courtesy of ENEA).



**Fig. 10.** Picture taken during a sloshing experiment (left) and comparison between simulated and measured wave amplitudes (right) (courtesy of VKI and CRS4, respectively).

reactor systems) have been performed in the framework of the PASCAL project.

Regarding the integrity of the fuel cladding tubes, a new test section was designed and realized for the execution of flow-induced vibration (FIV) experiments. The HELENA loop, at ENEA, was selected for this (Fig. 9), being able to realize forced convection at flow regimes representative of a real fuel bundle. The test section – not heated to only focus on FIV – was instrumented with strain gauges to permit measurement of the deformation of the rods in the bundle, and an algorithm was developed to convert such strains into deformation modes of the corresponding rods. The experiments were developed to both retrieve data (amplitude and frequency) to inform subsequent studies of rod integrity against fretting wear, and to calibrate engineering correlations for vibrational frequency and maximum amplitude, which currently exist only for bundles subject to water flow.

Similarly, to the FIV case, studies were conducted to investigate the effects of seismic actions on the integrity of primary system components and of the reactor vessel, particularly those due to the sloshing of the lead inside of the pool of a HLM-cooled reactor. Analyses started on simple pool models (bare cylinders partially filled with liquid), which evolved then to realistic mock-ups of reactor configurations, i.e., where all internals were replicated, at scale. All test sections were installed on the SHAKESPEARE shaking table at VKI, and both recorded by high-speed cameras and instrumented internally, to retrieve quantitative data on the liquid sloshing at the free level (see left frame of Fig. 10). The experiments were then numerically reproduced by CFD analyses (see right frame of Fig. 10), so to calibrate the simulation models and to derive the forces exerted on the mock-up structures and, by extrapolation, anticipated in real reactors [9].

Feasibility and calibration experiments were also performed regarding the detection of notches in a steel block,



**Fig. 11.** Ultrasonic sensor installed on the calibration block for tests in air (left), and experimental setup mounted in the LBE vessel (right) (courtesy of KTU). 1 – calibration block; 2 – ultrasonic transducer; 3 – wedge; 4 – temperature sensor.

in conditions mimicking the integrity inspection of the reactor vessel from its outer (i.e., non-wetted) surface. A first set of experiments were done in air, inside of an oven (see left frame of Fig. 11), to measure and register the degradation of the signal-to-noise ratio as a function of the steel and ultrasonic transducer temperature, thereby to confirm the transposability of this test to more realistic conditions. Then, final tests were prepared inside a vessel, where the calibration block could have been partly exposed (on the notched surface) to liquid LBE (see right frame of Fig. 11), and executed with the ultrasonic sensor heated to 200°C. Several tests were done, cycling in temperature, to investigate possible hysteresis effects on the transducer, as well as potential degradation effects due to the heating/cooling of the surface (and notch on it) exposed to LBE. The results confirmed the capability of ultrasonic transducers in detecting possible cracks on the surface exposed to LBE at the requested operating temperature, hence the feasibility of inspecting the integrity of the vessel in an LBE-cooled reactor.

LESTO project aims to assess the technical viability of the LFR systems as well. Monitoring the condition of the components in the challenging environment of liquid metal, as well as assessing the capabilities to control the coolant parameters during the operation of the plant, assures indeed a reliable and safe operation of the plant.

Material testing and coolant chemistry management studies are planned, specifically aiming at:

- assessing the reliability of the oxygen sensor and oxygen control system in a large-scale, pool-type lead facility;
- testing a coolant purification system for a pool-type LFR;
- validating the approach for corrosion protection in lead at high temperatures;
- examining flow-induced erosion and fretting effects;
- developing numerical models to forecast the release and transport of fission products from the source.

To accomplish these goals, several aspects are considered.

**Coolant chemistry control & purification.** The development of oxygen sensors for a deep lead pool configuration is foreseen, for delivery and testing in the

ATHENA facility, for the important oxygen level control. The initial approach for managing them involves the implementation in ATHENA of a cover gas oxygen control method, recognized as the most feasible and efficient technique for regulating oxygen in an LFR configuration. The performance of the oxygen control system will be assessed based on its accuracy in oxygen management and its capability for oxygen reduction. In relation to the coolant purification system, experience from various lead loops within the European Union indicates that periodic skimming of the coolant surface is necessary. When impurities are introduced into the coolant, they generally react with dissolved oxygen to produce oxides such as PbO. The behaviour of these oxides, whether they are transported with the flow or accumulate at the surface, depends on local concentrations and coolant flow rates. If surface agglomerates contain oxides that are stable at the expected nominal oxygen concentration, they may not be easily reduced using hydrogen-containing cover gas. Consequently, mechanical methods will be essential for their removal. A survey to identify potential skimming techniques will be performed, followed by a design and feasibility study for an appropriate system in the SEFACE facility.

#### **LFR materials in lead at high temperatures.**

While LFRs have the potential for operation at elevated temperatures, the maximum operating temperature is constrained by the corrosion resistance of the fuel cladding and structural materials. The goal is to explore the corrosion resistance of LFR materials featuring various coatings in non-isothermal flowing lead (Pb) at high temperatures. Different coated materials, such as FeCrAl-coated and Alumina PLD-coated 15-15Ti, along with Alumina-forming austenitic (AFA) steel will be tested from 650°C up to 1000 °C for parametrized exposure times. The findings will enhance our understanding of the corrosion behaviour of LFR materials under transient conditions. Oxidation kinetics will be also investigated, in particular for uncoated LFR materials at temperatures below 500°C, which will inform the development of oxygen control systems, particularly regarding the oxygen consumption rate, as well as to contribute thermal-hydraulic analysis aimed at predicting oxide layer thickness.



**Flow induced erosion and fretting.** Studies concerning grit-rod fretting phenomena (GTRF) will be performed, since there is a notable deficiency in research involving advanced materials and conventional materials with coatings. This will be performed acquiring tribological data on AFA and 316L/15-15Ti, both in their original state and after undergoing peroxidation in a liquid Pb environment. This data will be instrumental in the development of predictive models for the design of reactor components. Testing will be conducted within a temperature range from 480°C to 650°C, while varying the amplitudes of relative movements, loads, and test durations. The experiments will also include a benchmark test to facilitate a comparison of the tribological data obtained from two testing facilities. Additional tests will be performed to evaluate the corrosion-erosion phenomena at the surface of steels, which occur at high flow velocities in combination with high temperatures, and to gain a set of experimental data for the development of numerical models on flow accelerated corrosion and erosion at high temperature.

## 4 Sustainability and integration with energy network

Other important aspects for the deployment of HLM systems are the sustainability of the fuel cycle, the integration of the plants into a network, which is evolving toward a larger use of intermittent energy sources and the possibility to use the characteristics of these systems to processes not related to the production of electric energy. These needs are therefore considered in the framework of the LESTO project.

**Safety and security of the fuel cycle.** Investigation of both the front and back ends of the fuel cycle and assessment of the performance of Mixed Oxide (MOX) fuel during irradiation will be performed, drawing on European expertise in MOX fuel. In detail, it will be considered:

- the availability of fuel for LFR on the market, specifically focusing on MOX fuel containing plutonium in the range of 20% to 30% by weight;
- the identification of the expected critical issues concerning transport from production sites to LFR potential sites;
- the application of a realistic scenario to a reference country with limited or no access to MOX fuel, aiming to operate a fast critical reactor. The examination will include the initial operation of the fast reactor using High-Assay Low-Enriched Uranium (HALEU) fuel, followed by a transition to MOX produced from self-generated irradiated fuel after decay period and reprocessing. This analysis will also evaluate the reactivity safety parameters of the reactor as it evolves through various fuel scenarios (HALEU, HALEU+MOX, and 100% MOX), including the time required to achieve a full transition to 100% MOX;
- the fuel backend strategies, following the output data of the above-mentioned analyses, performing inventory

calculations also for non-fuel components within the reactors (including activated and contaminated materials). This will include an assessment of intermediate and low-level radioactive waste (ILW and LLW) in terms of both quantity and quality, as well as an evaluation of potential recycling and clearance options, whether through direct handling or remote operation. A comprehensive back-end strategy for ALFRED and Lead Fast Reactors will be developed, including recycling, clearance, and spent fuel irradiation to minimize nuclear waste.

**Safety and integrability.** Focusing on the utilization of energy from LFR systems for the generation of hydrogen or other energy carriers, the relevant safety considerations will be explored and incorporated into the energy platform in conjunction with renewable energy sources (RES). Analysed topics will include:

- hydrogen production or other energy vectors, by identifying potential secondary products that can be obtained from an LFR while also considering the associated safety aspects. A review from LFR perspective on suitable energy vectors production will be performed considering open research, EURATOM projects, IAEA publications as well as the Swedish initiative ANITA. Regarding hydrogen production, a review of "NP-T-4.2 - Hydrogen Production Using Nuclear Energy" will be performed, as well as an evaluation of its applicability to LFR technology. Industrial partners will also provide useful insights from their technical experience;
- advanced balance of plants (BoPs) and integration with RES; starting from the potential secondary applications defined above, through thermodynamic performance software, the BoP design of ALFRED will be adapted to include the steam extractions required. In order to assess the flexibility of the LFR cogeneration, operational transients will be analysed through a dynamic model of the LFR plant (nuclear core, balance of plant and cogeneration systems), including load-following and load-following by cogeneration. The results will highlight useful information on the operational range of the systems and requirements for control strategies. In addition, functional safety evaluations for LFR polygeneration will be evaluated, with preliminary categorization of the initiator events related to the safety and their impact on the plant safety performances.

## 5 Numerical modelling and validation

The implementation and verification of full-scale models in CFD and thermal-hydraulics system codes for large facilities is a crucial step in developing a reliable set of tools to facilitate the advancement and implementation of the LFR technology. With this in mind, the LESTO project has planned several actions to assess and improve the general status of simulations tools by:

- conducting a comprehensive evaluation of the current numerical tools focused on the thermal-hydraulics characteristics of LFRs;
- executing pre-test analyses of large-scale Steam Generator Tube Rupture (SGTR) events at the CIRCE-HERO facility, which encompasses the establishment of the test matrix and measurement techniques, followed by experimental investigations and post-test validation of the numerical models;
- carrying out pre-test analyses of large-scale pool systems, particularly at the ATHENA facility, which will involve both steady-state and transient experiments alongside numerical modelling, culminating in the validation of these numerical methods.

In particular, the focus will be on the following topics.

**Numerical tools Assessment for LFRs.** This is an important point since numerical tools are frequently seen with scepticism in the design and licensing of nuclear reactors, primarily due to concerns regarding their reliability. This initiative seeks to evaluate the current state of available computational tools, identify appropriate codes, and assess potential gaps in modelling related to LFR technology. The analysis will concentrate specifically on the physics associated with LESTO to focus the efforts.

**Pre-test analysis of large-scale SGTR events.** This involves the CIRCE facility [10], a large pool infrastructure operating with LBE in the range of 200–500°C, 90 tons of LBE, 10 meter deep, with an inner diameter of more than 1 m. The facility will be used to characterize relevant phenomena for SGTR events, such as

- pressurization in the cover gas and into the melt;
- sloshing;
- wave propagation;
- dumping and mechanical loads on immersed metallic structures;
- steam trapping.

Several tests will be performed assuming different sizes of the injection system, different depths for injection, different water/steam flow rates, and different injection orientations. A devoted instrumentation will be set-up (e.g., fast pressure transducers, strain gauges, array of thermocouples) to catch and monitor the above-mentioned phenomena. The aim is to provide a data set, usable for validation of numerical tools adopted for simulating such phenomena.

The following steps will be followed:

- definition of the test matrix, to decide the set-up of the injection system/device, the instrumentation, the procedure for testing;
- pre-test activities, to support the definition of safeguard devices and design parameters, with sensitivity analyses of relevant parameters and geometrical configurations, and to select the more suitable instrumentation and position for the CIRCE test section;
- experimental investigation, carrying out the tests;
- preparation of the experimental data, boundary and initial conditions for the post-test and validation.

**Pre-test analysis of large-scale pool system.** Taking advantage of the ATHENA facility [11], a large pool-type (same height as ALFRED but a smaller diameter), essential components will be tested in scale, allowing the validation of numerical tools in a real-size environment reducing the scaling effect issues often encountered in scaled-down facilities.

To support the experimental campaign within this project, the actions will include:

- a steady-state experimental and numerical analysis of the facility, in forced and natural convection, to provide thermal-hydraulic description of the main components;
- pre-test activities for Protected Loss of Flow Accident (PLOFA) scenario;
- experimental investigations of the PLOFA event, with two categories of tests, one in normal, realistic conditions and one as a slowed-down version of them; the first will give information for a realistic scenario in close-to-real scale, the second will allow the study of the transition from the forced to the natural convection.

**Post-test analysis of large-scale facility transients.** The valuable data collected in CIRCE and ATHENA will be set up for validation activities for CFD and system codes. It will involve almost all the partners in the consortium, allowing a comprehensive validation campaign of the tools for LFR applications and will be instrumental in the building up of a representative database for LFR pool thermal-hydraulic for validation of numerical approaches for large pools both in steady state and transient conditions.

## 6 Conclusion

Thanks to the strong commitment and solid expertise of manyfold-European organisations, PASCAL and LESTO will provide a significant contribution to the advancement of the R&D – and notably the safety-related one – on the HLM technology.

Remarkable results, including from first-of-a-kind tests, have been already achieved by PASCAL, approaching its conclusion, that have extended and consolidated the knowledge bases requested to substantiate the safety demonstration, hence the licensing, of ALFRED and MYRRHA.

The additional results that will be brought forward by LESTO will further strengthen the technological bases required not only for ALFRED and MYRRHA, but also by a future generation of commercial LFRs, reducing the gap to their deployment and thereby contributing to the materialization of a future energy scenario, ensuring the carbon neutrality and security of supply objectives set for Europe could be met.

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### Conflicts of interest

The authors have nothing to disclose.

### Data availability statement

This article has no associated data generated and/or analysed.

### Author contribution statement

Both Simone Gianfelici and Giacomo Grasso contributed to this paper with project administration (each for the project he coordinates, i.e., Simone Gianfelici for LESTO; Giacomo Grasso for PASCAL), and in the writing – original draft, review & editing, of the paper.

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