EXPERIMENTAL INFRASTRUCTURE IN SUPPORT OF ALFRED LICENSING PROCESS AND OF LEAD FAST REACTOR TECHNOLOGY DEVELOPMENT

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Abstract

The implementation of ALFRED demonstrator is currently in the preparatory phase, with a pre-licensing step started in 2017. In this context, six large facilities were proposed to be built on the Mioveni nuclear platform in support of the licensing process and the future Lead Fast Reactor technology development. The paper presents the concept of this new experimental infrastructure, the main characteristics of the facilities, as well as the progress of the implementation. The first two facilities, ATHENA and ChemLab, are in the construction phase to be completed in December 2023, the other four experimental facilities being approved for funding in the European operational programme POCIDIF, with the operational phase planned for 2026. A preliminary experimental programme, highlighting the main priorities, is also presented.

Keywords: *ALFRED, Lead Fast Reactor, experimental infrastructure, Licensing, POCIDIF*

Introduction

Lead Fast Reactor (LFR) is one of the very promising Generation IV technologies expected to produce major improvement in the sustainability performances of the nuclear power. The development of LFR technology is currently in the demonstration phase. Based on the results of this phase, a First-of-a-Kind will be built and, later, the commercial deployment will be started [1]. The LFR technology demonstrator, named ALFRED (Advanced Lead Fast Reactor European Demonstrator), has a nominal power of 125 MWe and is planned to be implemented in Romania. An international consortium, FALCON (Fostering ALFRED Construction), assumed the responsibility to prepare its implementation. The Mioveni nuclear platform was selected as a reference site for ALFRED based on the existing infrastructure and the proximity of experimental facilities and specialists.

The vision on financing ALFRED implementation is based on a mix of European structural funds, national funds and contribution of the industry. The implementation was structured into four phases: Viability (dedicated to investigate ALFRED feasibility in Romania), Preparatory, Construction, and Operation [2]. The project is currently in the *Preparatory* phase, with the pre-licensing process started in 2017.

In the *Viability* phase important efforts were devoted to identifying experimental needs for licensing process, such as testing and demonstrating the control of all phenomena, qualification of materials, components and equipment, validation and verification of the computer tools, etc. Based on the analysis of the features of the existing LFR experimental facilities, and on their availability, a set of gaps was identified [3]. As a main outcome of these efforts, a group of six new experimental facilities has been identified and defined. These facilities are referred as ″LFR experimental infrastructure″ and will be built on the nuclear platform Mioveni. The facilities will be used both for licensing purpose and to support the development of solutions for the open issues of LFR technology [4].

A coordination centre (named Hub) devoted both to ALFRED and the experimental supporting facilities has been added to them. It is aimed to perform the scientific management, including open access and data storage, processing and sharing. A vision on the facilities sitting on the nuclear platform was elaborated based on the existing networks of utilities and the proximity of ALFRED reference site.

In the same time, considerable efforts have been made to identify the financial resources and to select appropriate funding. Considering the scale of the projects and their relevance to the national climate and energy objectives, the structural funds of Romania were considered the most suitable and applications were prepared for financing.

Two facilities, ATHENA and ChemLab, are currently in the construction phase [4]. The investment is supported mainly by structural funds of POC (Operational Programme Competitiveness), Section Large Experimental Infrastructures through the project ″ALFRED Infrastructure, stage 1, ATHENA and ChemLab″. The project is in the implementation phase being expected to be finalized in December 2023 with the testing of the ATHENA and ChemLab operational phase.

For the other experimental facilities (ELF, HELENA2, HandsON, Meltin'Pot), the financing will be supported by POCIDIF (Operational Program Smart Growth, Digitization and Financial Instruments). The total investment estimated at approximately 104 million Euro was approved by the EC at the end of 2022.

Experimental Infrastructure for ALFRED and LFR

The configuration of ALFRED reactor [1] is presented in Fig.1. A small core is immersed in a large pool with pure lead. Due to the inertness of the lead in relation with water and air, there is no need of intermediate loop. The configuration is very compact having the steam generators inserted directly in the pool. The primary system is very simple compared to the classical reactors without any large pipes susceptible for failure (LOCA accidents).

Such large pool configuration using a high-density coolant introduces some experimental needs in terms of:

- thermal hydraulics in forced and natural circulation regimes,
- molten lead stratification,
- corrosion and erosion phenomena induced by flowing lead interaction with the structural materials and fuel claddings,
- lead chemistry,
- inspection of components in an opaque environment,
- handling of fuel assemblies, control and safety rods in an environment with high buoyancy,
- retention of the fission products in lead, in case of a release,
- interaction between fuel pellets and lead in case of cladding failure.

Additionally, all the components and equipment should be tested in both normal operation and accidental conditions in order to demonstrate their behaviour. Some demonstration and testing are required to prove the full control of the main phenomena, and to obtain experimental data for the validation and verification of the computer codes used for numerical simulations.

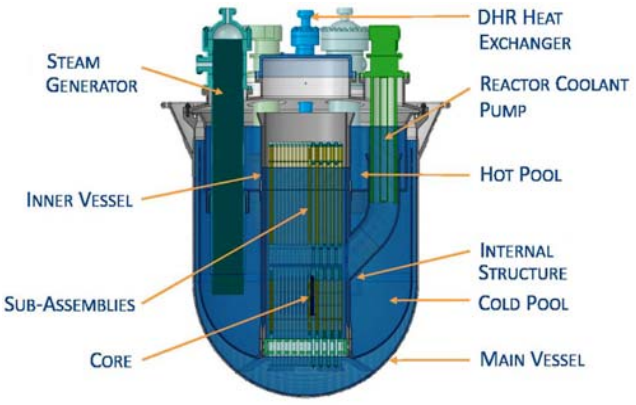


Fig. 1. Schematic view of ALFRED demonstrator

Based on a detailed analysis performed in ARCADIA project [3] with a consistent support of FALCON consortium, a set of six experimental facilities to complete the existing experimental capabilities for LFR was defined:

(1) ATHENA, a large pure lead pool, devoted to testing the main components in different thermal-hydraulic regimes and investigating the chemistry in large pool configuration;
(2) ChemLab, a Chemistry laboratorydirectly coupled with ATHENA facility, to investigate lead and cover gas chemistry;
(3) HELENA2 [5], a loop type facility to test components and equipment in relevant thermal-hydraulic conditions, in particular, the ALFRED hottest fuel assembly;
(4) ELF [6], a large-scale pool-type facility performing electrical stimulation of ALFRED reactor to test the endurance and reliability;
(5) HandsON [7], a pool-type experimental facility, aimed to demonstrate the handling of fuel assemblies;
(6) Meltin'Pot [8], a set of small-scale facilities for the investigation of the severe accident associated phenomena in lead environment.

Considering an optimal approach for the investment and for the operation, ATHENA and ChemLab will be accommodated in a single building. The same approach will be applied to HELENA2 and ELF facilities. Hands'ON will be installed in an existing building on the nuclear platform, whereas the Meltin'Pot will be placed in the hot-cells of the Post-Irradiation Laboratory at RATEN ICN.

The first stage of facilities operation, estimated to be 5 years, will be dominated by the activities necessary for the ALFRED implementation. The next stage, benefitting also by the ALFRED operation, will be devoted to improving performances of the LFR technology by addressing its open issues. The capitalization of the results will be done through their essential contribution to the demonstration of the technical and economic viability of the LFR technology, as well as through the development and testing of innovative materials and components.

ATHENA and ChemLab implementation

ATHENA and ChemLab facilities will be hosted by a building with a surface of 1104 m^2 having 4 floors. An auxiliary building (610 m^2) will serve the facilities as an area for components cleaning, materials storage and mechanical workshop.

ATHENA is a pure lead pool type facility, with a nominal power of 3.75 MW, conceived for a multipurpose activity: (1) investigation of different thermal hydraulics regimes and phenomena; (2) demonstrating the oxygen control at large scale; (3) testing single components or systems on representative scale (Steam Generator and Main Pump); (4) investigate the behavior of materials, coatings, ad components in lead environment in operational conditions.

The main component of ATHENA consists of the Main Vessel (MV), a large size cylinder (D = 3.2m, H = 10m) filled with pure lead and operated at specific conditions, p = 2 MPa and T = 450°C. A schematic view of MV is presented in Fig. 2. The MV has a volume of 80,000 L able to host individual components at the real scale such as the Steam Generator (SG) presented also in Fig 2.

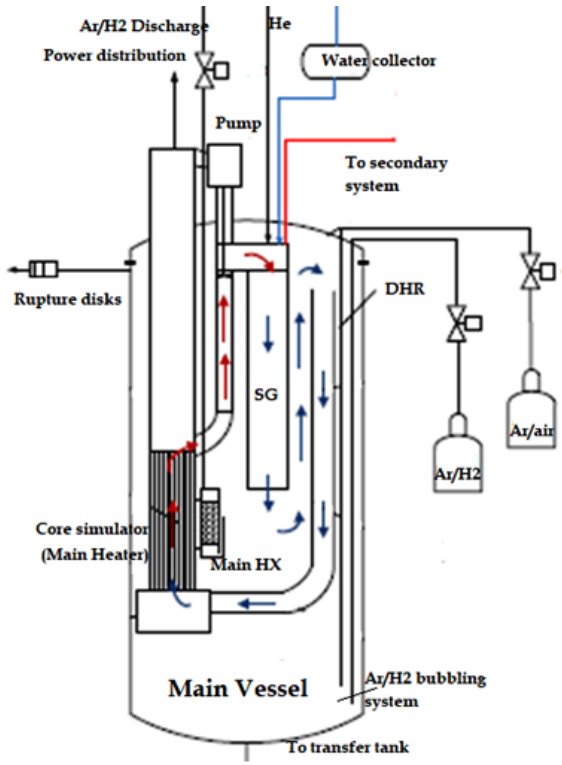


Fig. 2. Schematic view of ATHENA Main Vessel

A separate tank is used to melt the lead, and a filter section is added in the melting tank in order to introduce pure lead in the MV. Another tank is used to store the lead from the MV. Between the MV and the storage tank, there is a transfer tank. The internal structures consist of the suction pipe (equipped with a flow meter), an ascending pipe (containing the main pump), a distributor connecting the ascending pipe to the exchanger, and a space that houses the heater and instrumentation cables.

ATHENA includes a chemical control system of the primary agent to obtain and maintain an optimal level of oxygen concentration, and a lead purification system. It involves the removal of oxygen in excess before it enters the MV and the removal of the corrosion products that may appear.

The secondary cooling system is a closed loop, using demineralized water under pressure. It is coupled to the primary system via the main heat exchanger (2.21 MWt). It consists of a jacket and a tubular beam with counter-current circulation, through which heat transfer takes place between the hot fluid (molten lead) and the cold one (water). The primary agent, pure molten lead, enters the mantle at the upper part of the exchanger, and the water circulates through the tubular beam made of tubular elements with double walls, bayonet type (Fig. 3).

The cooling system consists of a centrifugal pump, electric heating elements, a feed water collector, coolers with air, a pressurizer, as well as fittings and connecting pipes. The pressurizer is a tank located in the highest part of the circuit, partially filled with water, partially with gas under pressure (Ar or He used as cover gas).

The blanket gas maintains the pressure of 12 bars in the secondary circuit. The pressurizer plays both the role of an expansion vessel and that of a water tank for the start-up period. Probes and Argon/Hydrogen bubbling systems are installed in the main vessel and in the storage tank, to monitor and control the contents of dissolved Oxygen.

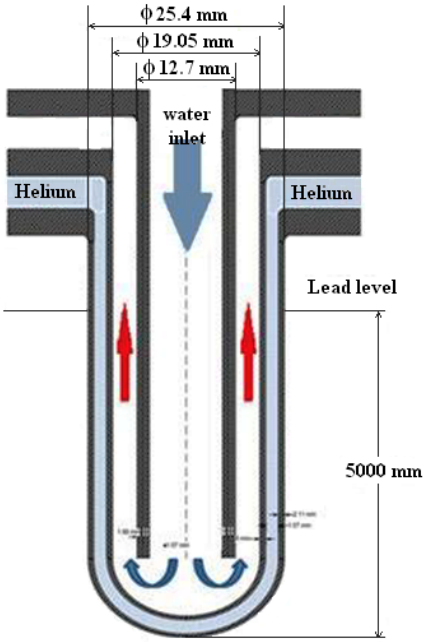


Fig. 3. Heat exchanger (HX), bayonet type

ChemLab laboratory is dedicated to: (1) supporting the implementation and development of the control and monitoring of the lead chemical regime for long-term operation; (2) investigating the interaction of liquid metal with structural materials.

ChemLab consists of two components, namely:
(1) the experimental laboratory dedicated to the investigation of oxygen control, solubility of chemical elements and corrosion of structural materials,
(2) structural analysis laboratory to characterize the interaction of structural materials with liquid lead and evaluate the quantities of impurities released in liquid lead.

The experimental laboratory includes:

- 10 large capsules for experiments on the efficiency of O_2 getters (containers for retaining O_2), investigation of various oxygen sensors as well as long-term corrosion aspects (> 8000 h),
- one small size pool-type installation equipped with O_2 control and monitoring systems devoted to the investigation of various equipment and instruments used for control and monitoring in molten lead (in the temperature range (400°C - 550°C),
- auxiliary equipment and components (furnace with the retort; technical balance; high impedance voltmeter; glove box; 2 hoods with movable arm (500 m^3/h) for capsules, H_2 generator; gas cylinders for Argon and Argon/H_2; a stock of crucibles and tubes for corrosion tests; band saw (cutting ingots).

The structural analysis laboratory will host specific equipment for the characterization of base materials and coatings: optical and confocal microscope, scanning electron microscope (SEM) coupled with EDS, X-ray diffractometer equipped for solids and powders surface analysis, X-ray fluorescence spectrometer (XRF), optical emission spectrometer coupled with plasma induction (ICP-OES).

The two facilities are under implementation process in the frame of ″ALFRED Infrastructure, Stage 1, ATHENA and ChemLab″ project supported by European structural funds POC (Operational Programme Competitiveness), Section Large Experimental Infrastructures.

The total investment is of 22 million Euro, out of which 20 mil Euro are supported by the structural funds. The finalization of the project is planned for December 2023. Due to some delays in the construction phase, the commissioning tests will probably be shifted in the first part of 2024, and the first experiments could be started in the second part of 2024.

ELF, HELENA2, HandsON and Meltin'Pot facilities implementation

Conceptual designs for ELF, HELENA2, HandsON, and Meltin'Pot facilities have been developed in the frame of the national project PRO-ALFRED (2019-2020) supported by Ministry of Research and Innovation through Sub-Program 5.5 – ″Research, development and innovation program for IV Generation reactors – ALFRED″. The same project included producing of a feasibility study for ELF and HELENA2 facilities.

In 2022, a new programme of structural funds, POCIDIF (Operational Program Smart Growth, Digitization and Financial Instruments), has been launched. This programme was found suitable to support the construction of ELF, HELENA2, HandsON, and Meltin'Pot experimental facilities. The application, embodied in ″4ALFRED″ project, was approved both at national and European level. The total investment is about 100 mil. Euro, and covers the implementation of the above mentioned four facilities, logistics for Hub (servers for data management), as well as the research activities associated to these facilities.

The construction of the four experimental facilities is planned to be finalised by the end of 2026. The last year of ″4ALFRED″ project (2027) will be dedicated to demonstrate the experimental performances and run experimental tests.

HELENA-2 is an experimental loop-type installation for investigating thermohydraulic phenomena and for testing the LFR technology components. The facility is dedicated to the performance tests, investigations, as well as to demonstrate the complete control of the physical and chemical processes taking place in pure lead in natural or forced circulation. The main purpose is to test, via an electrically heated fuel pin simulator, the nuclear fuel assembly for ALFRED reactor at a relevant scale, in the maximum load conditions (heat flux, turbulence regime).

The main challenge of HELENA-2 facility is to design a loop configuration able to reproduce ALFRED demonstrator conditions in order to test the behaviour of fuel assembly and control rods in both operational and accidental conditions.

The fuel pin simulator requirements and design will be developed during the execution of the project, accounting for the design of ALFRED demonstrator at HELENA-2 development. The nuclear operating conditions (thermal power released by each fuel element) will be ensured by electric heating. The operating temperature range, as well as the power range, is characteristic of the operational and accidental regimes of ALFRED reactor. The most important results envisioned to be obtained are presented in the section devoted to the experimental programme.

ELF (Electrical Long-running Facility) is an experimental pure lead pool installation, operated in natural or forced circulation mode, intended for endurance tests for the operation of components, equipment and systems developed for the ALFRED demonstration reactor, as well as for measuring the reliability characteristics.

The purpose of the ELF experimental installation is to perform all endurance tests to demonstrate the long-term functionality at designed operational parameters of the main equipment and systems of ALFRED reactor, including the transient analysis of the ALFRED multi-loop primary system configuration.

The main challenge is related to the size of the facility, which needs to reproduce the thermal-hydraulic conditions of the ALFRED demonstrator and to eliminate the scale effect existing in small and medium size experimental facilities. ELF will be the largest experimental facility for LFR technology in the world, providing valuable data for licensing.

A second challenge arises from the operational conditions targeting long-running system tests (endurance tests) for a large variety of components and equipment of the ALFRED demonstrator.

The temperature ranges, liquid lead flow rates and the oxygen contents are specific to the LFR technology. The results will support the demonstration of the reliable functionality of all the components and systems for long time periods, and will be used both for ALFRED licensing process and for the improvement of the components/ systems' performances. The most important results planned to be obtained are presented in the section devoted to the experimental programme.

HandsON facility is aimed to demonstrate the full capabilities for fuel handling in lead. The demonstration is crucial in the ALFRED demonstrator authorization process. A specific configuration of a portion of the reactor core, comprising 1:1 scale mock-up assemblies representative of the fuel, absorber and dummy assemblies of ALFRED reactor will be designed to prove their extraction from the molten lead (opaque) and moving to other locations or outside the core.

The main challenge is to develop and demonstrate the performance of handling fuel assemblies (FA) and safety rods/control rods (SR/CR) in the opaque environment (liquid lead).

The tests will be performed in air (in the first stage) then in molten lead (in the second stage). The mock-up assemblies will reproduce the dimensions and the details coming from he design of the ALFRED demonstrator at the time of project development.

Meltin'Pot is an experimental installation dedicated to experiments on the deposition and transfer of fission products (FPs) and other species potentially deriving from neutron irradiation of lead and structures, as well as the investigation of the interaction mechanism of the nuclear fuel entered into contact with molten lead and the associated transport/retention phenomena.

The Meltin'Pot facility consists of four experimental modules that operate independently of each other:

- (MP-Module 1) fuel-coolant interaction
- (MP-Module 2) fuel dispersion/relocation
- (MP-Module 3) FPs retention/dispersion
- (MP-Module 4) Polonium retention/dispersion

The modules will be designed to be hosted inside dedicated hot cells (among those existing in the Post Irradiation Examination Laboratory at RATEN ICN) or to be operated in a laboratory glove box, located in a non-nuclear area [9].

All modules will operate with nuclear-grade lead to investigate the severe accidents main phenomena such as the fragmentation and dispersion of the fuel, deposition and transfer of FPs. The target is to obtain experimental data needed to be used in the qualification of simulation tools for severe accidents and also for the correct understanding of phenomena and development of reports for the regulator. The operating conditions will cover the ALFRED reactor applicable operating modes.

The experimental results will be used to define possible paths for the evolution of the accidental situations. Most of the obtained knowledge will be incorporated into models and computer codes to simulate the accidents.

Preliminary experimental programme

A preliminary experimental programme associated to the experimental infrastructure has been developed. The first part will be implemented in ATHENA and ChemLab facilities starting from 2024, while the second part, planned to start in 2026, is linked to ELF, HELENA2, HandsON, and Meltin'Pot facilities.

The experimental activities to be performed in ATHENA facility and the dedicated laboratory (ChemLab) will support the ALFRED safety demonstration program. A Test Matrix was developed to define the experimental campaigns. Some refurbishment activities (referring the original test section of ATHENA) were considered for progressive adaptation to the foreseen activities. The Test Matrix is presented in Table 1 (activities planned on short-term, first 5 years) and Table 2 (activities planned on longer term, after the first 5 years).

The high priority activities considered are: (i) development and characterization of Oxygen sensors suitable for large pool, (ii) experiments on lead conditioning in large pool systems, (iii) corrosion assessment in lead and experiments to address mechanical properties degradation in lead.

Concerning the main components and systems behaviour investigations, the highest priority is assigned to the ATHENA experiments, in which Steam Generator (SG), Deep Coolers (DCs), Reactor Circulation Pump (RCP) and Core Simulator (CS) will be characterized.

Table 1. Test Matrix for ATHENA and ChemLab, activities planned for the first 5 years

Topic	R&D Need	Identified experimental activities
Material Studies and Coolant Chemistry	Coolant Chemistry and Corrosion in Lead	Testing of Oxygen Sensors for Large Pool
		Lead Conditioning in Large Pools
	Impeller Pump Materials	Erosion Test in Lead
Thermal-Hydraulics	Heavy Liquid Metal Pool Thermal-Hydraulics Assessment	Test on Reactor Cooling System Performance and Transient Behaviour
	Fuel Assembly Thermal- Hydraulics	Transition from Forced to Natural Circulation and Mixed Convection
HLM Pump and Corrosion/Erosion Studies	Reactor Coolant Pump Performance and Material Assessment	Performance and Material Assessment
Heat Exchanger (HX) Functionality and Safety Experimental Studies	Heat Exchanger Qualification	HX Performance Assessment

Table 2. Test Matrix for ATHENA and ChemLab facilities, activities planned for longer-term

Topic	**R&D Need**	**Identified experimental activities**
Heat Exchanger Functionality and Safety Experimental Studies	Lead-Water Interaction and Steam Generator Tube Rupture (SGTR) Event	SGTR experiments
	Auxiliary Nuclear System Qualification	Decay Heat Removal (DHR) tests Isolation Condenser-DHR tests Dip-Coolers tests
Studies of Core Integrity	Control Rods Qualification	Control Rod Mechanisms and Components Tests

Steady state and transient tests will be performed aiming at investigating pool thermal-hydraulics. An experimental database will be made available for code Verification and Validation (V&V).

In a later stage, Isolation Condenser Decay Heat Removal (IC-DHR) will be tested with a partial refurbishment of ATHENA; then experiments on large scale Steam Generator Tube Rupture (SGTR) or Control Rods (CRs) characterization will be performed with a full refurbishment of the facility.

For the other four facilities (HELENA2, ELF, HandsON, Meltin'Pot), the most important activities to be included in the preliminary experimental programme are presented in Table 3 (HELENA and ELF) and Table 4 (HandsOn and Meltin'Pot), respectively.

Concerning the core integrity studies, the highest priority is the fuel assembly characterization and, subsequently, the deformed bundle test, which will require HELENA2 refurbishment. Flow-Induced Vibration (FIV) and Flow Blockage tests will be planned in a second stage.

For ELF facility, the highest-priority test is represented by the full characterization of the external loop for the coolant chemistry monitoring and control in large pool. Such experiment is of paramount importance for the final design of ALFRED demonstration reactor.

Experiments on fuel-coolant interaction, fuel dispersion and relocation, Fission Products (FPs) retention and Polonium retention are considered to have high priority because of the lack of data in these fields.

Table 3. Experimental activities to be performed in HELENA2 and ELF

Topic	**Identified experimental activities**
HELENA-2	Demonstration of flow control in loop configuration, including the investigation of forced and natural circulation, in forced and mixed convection
	Evaluation of the flow conditions at the entrance and exit of the fuel assembly, as well as from the flow subchannels
	Investigation of the coolant thermal profile in relevant components
	Evaluation of the heat transfer coefficients and hot-spots identification
	Characterizing pressure losses and flow induced vibration in ALFRED Fuel Assembly
	Characterization of cladding and structural materials in the corrosion and erosion regime
ELF	Reliability and performance demonstration of the primary pumps, the steam generators, the DHR systems of ALFRED reactor
	Characterization of cladding and structural materials behaviour in flowing lead and relevant conditions of the components and equipment of ALFRED reactor
	Demonstration of the technological performances of the coolant chemistry control system in pool configuration, including the filtration system capabilities
	Demonstration of the control of all physical and chemical phenomena in large pool molten lead configuration, including the stratification effect, natural circulation, and other transient conditions
	Asymmetric transient analysis
	Provide experimental data for code validation aiming at supporting the design and safety assessment of ALFRED design
	Assessment of start-up procedures
	Technological assessment of large size components, systems and equipment in forced and natural circulation regime

Table 4. Experimental activities to be performed in HandsON and Meltin'Pot

Topic	**Identified experimental activities**
HandsON	Large scale testing and technological assessment of the fuel assemblies' maneuverability, in the actual geometry of the core, in air (stage 1) and in molten lead (stage 2)
	Demonstration of loading/unloading/repositioning control of fuel assemblies for LFR technology
	Demonstration of the functionality and reliability of the fuel handling machine head and of the ballast section of the fuel assembly structure
	Demonstration of the functionality and reliability of the transfer system with associated transfer cask and assessment of their coolability
Meltin'Pot	Assessment of FPs migration/retention phenomena in molten lead and cover gas
	Assessment of FPs deposition on structures, filtering performances and cleaning of surfaces
	Assessment of FPs chemical interaction with molten lead, addressing formed species, and production fractions
	Assessment on Polonium retention in molten lead, migration in cover gas, stripping by water/steam, gaseous effluents
	Assessment of fuel fragments and molten lead interaction; fuel fragments buoyancy in molten lead as function of temperature and burn-up
	Assessment of fuel chemical interaction with molten lead, addressing formed species, and production fractions

Conclusions

Important ongoing efforts are dedicated to the preparatory phase of ALFRED demonstrator implementation process. ALFRED project is currently in the preparation phase, including the pre-licensing activities aimed to create good conditions for the authorization phase. The pre-licensing phase has been started in 2017.

A crucial activity is oriented towards the improvement and enlarging of experimental facilities for LFR, to support an extensive demonstration and authorization program for ALFRED. In this context, six new facilities were proposed to be built on the Mioveni nuclear platform: ATHENA, ChemLab, HELENA-2, ELF, Hands-ON, and Meltin'Pot.

ATHENA and ChemLab are currently in the construction phase, supported by a project funded by European structural funds (22 million Euro), and will become operational at the beginning of 2024.

The other 4 facilities are approved for financing through POCIDIF structural funds programme and are going to be built in the period 2023-2026.

The main outcomes of new experimental infrastructure implementation will consist in the following:

- large-scale testing of prototypic components and operating procedures in representative conditions;
- characterization, qualification and calibration of solutions regarding the HLMs chemistry and materials science;
- long-term (endurance) experiments, to characterize the components and systems performances;
- electric simulator of the ALFRED primary system, for testing the nuclear fuel assembly at a relevant scale, in the conditions of maximum load;
- a representative part of the ALFRED core, simulated by mock-up assemblies, able to demonstrate the capability of fuel handling for all designed cases;
- characterization of the fresh/irradiated fuels and radioactive elements behaviour upon interaction with lead in postulated accidental conditions.

The paper presents the main characteristics of the planned facilities and the progress in their implementation. The main activities of the experimental programme and their preliminary prioritization were specified, considering the needs for ALFRED implementation preparatory phase.

Important findings will be obtained by the new experimental infrastructure operation, consisting of crucial results both for ALFRED reactor licensing process and demonstration of innovative solutions for the future LFR systems.

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