# Implementation of LFR Experimental

# Infrastructures in Romania

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**Abstract**

Romania through RATEN ICN is deeply involved in the development and implementation of the ALFRED demonstrator being the reference site for ALFRED construction. The ALFRED Project aims at the development, up to full demonstration, of the LFR technology, one of the most promising Gen-IV concepts being significantly safe, sustainable, economically competitive, and non-proliferant. The Project will complement the existing centre of excellence on the lead technology located in Italy with a new one in Romania, where the facilities supporting the design and licensing of an LFR and presently missing in Europe are planned to be built. The resulting ALFRED infrastructure will be capable of investigating the key points related to heavy liquid metals up to supporting the technological development and qualification of the LFRs, with the demonstrator itself as distinguishing feature for the qualification of components in a real nuclear environment, whenever the associated materials will be subject to fast spectrum neutron irradiation. Six facilities are under construction or will be built on RATEN ICN site: ATHENA (a large pool for full-scale testing of components, assessment of systems behaviour, etc.), ChemLab (for coolant and cover gas chemistry, auxiliary systems development), HELENA2 (a multipurpose loop for pump, valves, sub/assemblies testing and erosion/corrosion investigations in lead), ELF (a pool for long-running system tests (endurance)), Meltin’Pot (for fuel-(clad-)coolant interaction tests) and Hands-ON (a simulator for assembly manipulation and handling tests). The purpose of the LFR experimental infrastructure is to support not only the ALFRED licensing process (demonstration of the complete control of the phenomena, qualification of the materials, component, equipment, validation and verification, etc.), but also the safe and sustainable operation of future LFRs, to facilitate the creation of skills and competences for the lead technology, and to explore synergies with other fields of application of the heavy liquid metals technology.

## INTRODUCTION

The Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) and the associated experimental facilities planned to be built in Romania are a complex and flexible infrastructure designed to meet the current and future needs associated with the development and deployment of the lead-cooled fast reactor (LFR) technology.

The ALFRED Project aims to support the development of the LFR technology, involving test of structures systems and components, including fuel performance, materials, prototypical equipment, safety features, etc., to demonstrate the sustainability of the concept. Following a careful analysis to identify the most relevant R&D needs, several research facilities have been conceived to provide the scientific ground, complementing the existing ENEA Brasimone centre of excellence on lead technology located in Italy.

The ALFRED infrastructure (including the demonstration reactor) is intended to carry out LFR technology-specific research activities involving thermo-hydraulics, chemical control of oxygen and impurities, materials compatibility, corrosion and erosion, mass transport of impurities within lead and cover gas, testing and qualification of LFR components as well as the validation and verification of computational codes/methodologies.

Thus, six infrastructures, ATHENA, ChemLab, HELENA -2, ELF, Hands-On and Meltin'Pot were designed by ENEA and ANSALDO NUCLEARE on the basis of the analysis of needs and remaining open issues in the field of LFR by clearly defining the purpose, objectives, scope of work, technical characteristics so as to ensure their wide flexibility in addressing both the current problems identified and the new issues generated by the evolution of the technology [1-2].

Moreover, the intrinsic and passive safety characteristics molten lead as coolant appear particularly appropriate to address some critical aspects associated with the development of SMR-AMR concepts [3]; as they offer the possibility of simplifications in the design process that allow both the use of mature technological options and the achievement of a high level of competitiveness.

Thus, in the vision of the FALCON (Fostering Alfred Construction) Consortium, the implementation of the ALFRED Project aims to achieve two major objectives (Figure 1) that will strengthen Romania's position in the nuclear field and will support Europe in reaching the leading position in the field of LFR:

1. Demonstrator of the Generation IV LFR concept;
2. Prototype for a modular reactor based on LFR technology (SMR-LFR) for short-term deployment.



Figure 1 FALCON Consortium vision on LFR development

The ALFRED research infrastructure will support the staged approach of the demonstrator [4-5] (in which the system is initially operated under conditions that can be achieved with current technology (Stage 1), followed by the sequential shift to operating conditions (higher power and temperature) considered for LFR reactors, (Stage 2 and Stage 3), addressing the highest priorities in terms of research and development needs to enable the safe authorization and operation of the reactor in Stage 1. Once this first objective is achieved, the research infrastructure will continue to support the optimization of the demonstrator for later stages, thereby extending the results achieved in the previous stages and thus contributing to sustainability.

## Romania’s Research, Development and Innovation Agenda on LFR

To fully exploit the ALFRED RI the LFR Research, Development and Innovation Agenda (RDI) in Romania has been defined [6] aiming to address in a systematic and integrated manner all the necessary aspects ensuring the LFR technological progress by involving all actors with expertise in the field: research organizations, industry, utilities, nuclear regulatory body and academia.

The National RDI Agenda defines the activities and programs that will be carried out within the future ALFRED infrastructure in the field of LFR technology based on the requirements and priorities generated by the implementation of this strategic infrastructure.

The RDI Agenda outlines the RDI strategy for LFR in Romania (purpose, objectives and strategic directions of action) and the implementation action plan also leveraging on the activities carried out in the framework of PRO ALFRED project which has received funds from the Romanian Ministry of Education and Research through the contract no. 5/18.09.2019. The performed investigations have been focused on the aspects ensuring the RI sustainability and on identification and prioritization of LFR technology-specific aspects requiring further investigation [7-8], on the definition of the experimental campaigns needed to be carried out in the experimental infrastructures [9-10] with a view to V&V process taking into account the rules of the quality management system, on the research and development trends and early forecasting of future needs in the field of LFR, as well as the role, expertise and contribution of partner organizations in Romania.

The main actors of LFR Agenda implementation are: the FALCON Consortium [11] and the European support organizations which signed a MoA (Figure 2), NUCLEARELECTRICA [12], ROMATOM (Romanian Nuclear Industry) as well as CESINA National Consortium consisting in research organizations and universities involved in the nuclear field.



Figure 2 FALCON Support Organizations

The present as well as the envisaged financial resources needed for LFR technology development are represented by the National Fund for Research (PNCDI), European Cohesion and European Regional Development Funds (ERDF), HORIZON Europe, EURATOM as well as the Ministry of Energy which is financing annually (around 1mil. Euro) the R&D Programme on “Advanced Nuclear Reactors and Fuel Cycles”.

## ALFRED research infrastructure

The identified key issues [8], [13] in the development of LFR requiring further investigation and covered in the Romania’s Research-Development-Innovation Agenda are summarised in the following main categories:

* Studies/analyses/characterization of components materials compatibility with lead and coolant chemistry;
* Investigations into the integrity and coolability of the core, moving components in molten lead (e.g. control and safety rods), instrumentation, maintenance, inspection and repair activities;
* Functionality of steam generators, heat exchangers and experimental campaigns dedicated to demonstrating their safety in operation;
* Thermo-hydraulic systems with liquid metals (processes/phenomena) especially in pool type configurations;
* Reliability of pumps for heavy liquid metals (HLM);
* Advanced fuels and irradiation tests;
* Neutron aspects (validation and verification of computational codes).

The six experimental installations conceived to cover these needs, as well as their role in the research and development activities necessary for the development of LFR technology, are described briefly below.

**ATHENA (**Advanced Thermo-Hydraulics Experiment for Nuclear Application) [14] is an electrically heated experimental pool-type installation aimed at investigating a wide spectrum of LFR technology-specific aspects such as: controlling the chemistry of the coolant in pool-type geometries, analysis/testing of thermohydraulic regimes in large volumes of lead, testing of components and auxiliary systems at large to full- scale (steam generator, heat removal system (DHR), etc.), tests relevant to nuclear safety, such as molten lead – water interaction and SGTR-type accident (steam generator tube rupture), etc.

The facility is designed to operate up to 550 °C and is provided with chemistry control features to cover the real operative conditions of ALFRED and other LFR systems.

The implementation of experimental campaigns in the ATHENA installation will contribute to the development of the experimental database needed in the development of mathematical models and in the verification and validation of computational codes, which is essential in the licensing process of the ALFRED demonstrator.

**ChemLab** (Lead Chemistry Laboratory) [14] is an advanced laboratory devoted to heavy liquid metals chemistry aiming the studies of materials and coatings compatibility with HLMs in various temperatures and environmental conditions representative for LFRs as well as the development and qualification of oxygen monitoring and control systems and components envisaged to fulfil the oxygen content requirements in the ALFRED reactor. The facility consists of a series of small reaction capsules provided with instrumentation where materials, probes and devices can be immersed in an HLM bath with controlled temperature and oxygen content. The laboratory also includes a number of instruments such as light optical microscopy, scanning electron microscopy, X-ray diffraction and fluorescence and inductively coupled plasma-mass spectroscopy, for advanced analysis of material samples before and after exposure to the HLM.

**HELENA2** (Heavy Liquid Metal Experimental Loop for Advanced Nuclear Applications) experimental facility is designed for testing and qualification of components such as the fuel assembly, control and shutdown devices and any other sub-assemblies, at large-to-full-scale in the representative condition of LFRs as well as for corrosion experiments in flowing lead. The facility can also test the consequences of flow blockages through dedicated experiments. In addition, experiments will be carried out to measure the flow induced vibrations and impact on the structural integrity of the FA, as well as deformation tests for different configurations, both in natural and forced circulation. The purpose of these tests is to determine the temperature range in which the FA operation is safe even if a loss of the cooling capacity of the FA occurs due to its deformation.

**ELF** (Electric Long-running Facility) is a pool type installation with pure lead, operated under natural or forced circulation. The endurance tests to be performed in ELF aim at demonstrating the long-term operability of the ALFRED reactor as well as the reliability of its systems and components. To this end, the installation will operate for a relevant time interval under forced circulation (FC) conditions demonstrating the long-term operation of the primary system of the ALFRED reactor (consisting in 3 symmetrical bayonet-type steam generators positioned inside the main vessel, the heat removal system consisting of three heat exchangers submerged in the coolant and positioned symmetrically and 3 vertical circulation pumps) while the active core will be simulated by electrical heating core simulator; all the operational parameters will be the same as for ALFRED. Moreover, ELF will be used as a simulator in the training process of the future operators of ALFRED.

**Meltin'Pot** is an experimental facility designed to investigate the phenomena associated with severe accidents and fuel/coolant interaction in fast neutrons nuclear systems cooled by lead.

The facility consists in 4 installations (small pool type) dedicated to investigations concerning: the interaction between fuel and the cooling agent, the dispersion/relocation of fuel during a severe accident, the dispersion/retention of the fission products, and the dispersion/retention of polonium. The installation shall have adequate instrumentation for monitoring and data acquisition, as well as associated laboratory analysis equipment.

**Hands-ON** is an experimental installation reproducing a portion of the primary system, to test and qualify the reliability of the handling machines and procedures. The installation will contain a portion of the active core simulated on a real scale containing FAs and simulated control-command systems. The installation will demonstrate fuel handling capabilities (loading, unloading, FA relocation). Simulation will be performed in the air in a first stage and then in molten lead. This approach is intended to decouple phenomena of a mechanical nature from those related to the thermo-hydraulics of molten lead. Tests on the insertion and extraction of deformed FAs will be also carried out. All the tests envisaged to be performed will allow overcome the uncertainties related to the handling of irradiated fuel by reproducing the conditions foreseen by the operators during ALFRED operation.

The current status of ALFRED RI implementation is presented in Table 1.

TABLE 1. STATUS OF ALFRED RESEARCH INFRASTRUCTURE

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Facility | Conceptualdesign | Feasibilitystudy | Funding application | Contracting construction |
| ATHENA | yes | yes | yes | yes |
| ChemLab | yes | yes | yes | yes |
| HELENA-2 | yes | yes | 2022 | - |
| ELF | yes | yes | 2022 | - |
| Hands-ON | 2022 | - | - | - |
| Meltin’Pot | 2022 | - | - | - |

## experimental campaigns in support of lfr technology development

### ATHENA Experimental Campaigns

The experimental activities on ATHENA will be carried out during its years of operation, including through the refurbishment of the facility with respect to its basic configuration. Planned experimental activities will also be dictated by the experimental evidence that will be collected during the first activities.

#### Characterization of control rods

Tests have been proposed in the ATHENA facility to characterise the control rods (CRs) by checking the functioning, performance and reliability of the control mechanisms (Table 2). The impact of seismic movements on the system will also be characterized by the application of an external force to simulate the seismic load on the control rod tube. The tests will be performed at different lead temperatures (400°C, 480°C), with/without pumps in operation.

TABLE 2. EXPERIMENTAL TEST MATRIX TO VERIFY THE ALFRED CRS MECHANISM

|  |  |  |
| --- | --- | --- |
| Test type | Scope | Parameters |
| 1. Testing control rod mechanisms.Normal operation. | Verification of the operation, performances and reliability. | Insertion/extraction times; relative position of the middle and high absorbing portion of the CR and the active region in the fuel assembly. |
| 2. Testing control rod mechanisms.Seismic load applied. | Verification of the operation, deformations, performances and reliability. | Investigation of correct insertion/ extraction in case of external seismic load applied;Deformation and failures occurring in case of insertion/ extraction under the effect of external seismic load applied. |

#### Characterization of the main components of the reactor coolant system (RCS)

The experimental campaign for the characterization of the steam generators (SG) and reactor coolant pump (RCP) proposed for the ALFRED reactor, is mainly focused on the validation of their performances related to pressure losses and the capability to be operated at different power levels and flow rate under both normal and transient/accidental conditions.

Transition from forced to natural circulation (in case of Protected Loss of Flow Accident -PLOFA) will be also performed to fully characterize the core simulator (CS), and the pump coast down addressing pump pressure losses when stopped. A general test matrix is presented in Table 3.

TABLE 3. EXPERIMENTAL TEST MATRIX FOR THE CHARACTERIZATION OF THE ALFRED SG, DHRS, RCP, CS

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Unit | Test 1 | Test 2 |
| Lead inlet temp. | °C | 390 | 400 |
| Lead outlet temp. | °C | 430 | 480 |
| Lead mass flow | kg/s | 189 | 189 |
| Water inlet temp. | °C | 110 | 110 |
| Water outlet temp. | °C | 160 | 160 |
| Water mass flow | kg/s | 5.24 | 10.34 |
| Water Pressure | Bar | 175 | 175 |
| Power removed | MW | 1.12 | 2.21 |
| PLOFA (7% of power) | - | YES | YES |
| Duration (steady-state) | h | 100-500 | 100-500 |
| Duration (after PLOFA) | h | 500-1000 | 500-1000 |

In the ATHENA facility all these features, together with associated performances will be tested, addressing their viability and supporting the related licensing process, both with a technological qualification and numerical tools validation.

#### Steam Generator Tube Rupture (SGTR) Experiment

The Steam Generators are located inside the reactor vessel and the interaction between the secondary side coolant (water) and lead might occur. As consequence, the leak of pressurized water in the primary system (e.g., steam generator tube rupture) would represent a notable off-normal event for both the design and the preliminary safety analysis of LFRs. The scope of SGTR experimental investigation that will be performed in a devoted test section of ATHENA is twofold: to understand the phenomena involved in the accident scenario, and to study how to prevent or mitigate the consequences of the event.

Considering that this type of event could affect the geometry and the structural integrity of the plant, as a consequence of various phenomena and processes as vessel pressurization, pressure wave propagation, possible domino effect, sloshing effects, slug/plug formation, etc., appropriate instrumentation will be installed to acquire and monitor the transient. Moreover, the experimental data will be used for the V&V process of models and computer codes.

The experiments will also support the licensing process of ALFRED, addressing the performance of the safety systems designed and installed to avoid an overdesign pressurization of the main vessel in case of a SGTR event (e.g. rupture disks or flow limiters on the feed water line and/or steam line).

To reach the main objectives of SGTR experiments, a general test matrix (Table 4) has been proposed.

TABLE 4. TEST MATRIX FOR THE SGTR EXPERIMENT [9]

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Parameter | Unit | Test 1 | Test 2 | Test 3 | Test 4 |
| Position of rupture | [-] | middle | lower | middle | lower |
| Lead temperature | °C | 400 | 400 | 480 | 480 |
| Lead mass flow | kg/s | 189 | 189 | 189 | 189 |
| Water temperature | °C | 335/450 | 335/450 | 335/450 | 335/450 |
| Water pressure | bar | 175 | 175 | 175 | 175 |
| Water mass flow | g/s | 50 | 50 | tbd | tbd |

### ChemLab Experimental Campaigns

The main tests to be performed in CHEMLAB are addressing the coolant chemistry and the interaction of the liquid metal with the structural materials and related protection means (e.g., coatings).

#### Coolant chemistry experiments

Considering that the oxygen concentration (CO) should be between 10-6 and 10-8 % wt. to reduce the chance of PbO formation even in case of local heterogeneities and potential deviations, the tests devoted to coolant chemistry assessment aim to support process optimisation of oxygen control systems, process optimization of impurity control as well as the reliability and accuracy of the associated instrumentation (including oxygen sensors, impurities monitoring techniques).

Moreover, as the LFR programmes foresee the future increase of reactors operating temperatures beyond 550 °C aiming to enhance the thermodynamic efficiency and to allow side energy production efficient processes (hydrogen production, desalinization, etc.), the experiments will be performed for lead temperatures in the range 400-750°C.

In line with these goals, general test matrixes have been set up to address the following aspects [9]:

1. Design and testing of oxygen sensors for large pools (Table 5);
2. Lead conditioning in small, medium and large pools (Table 6);
3. Testing of potentiometric oxygen sensorsfor the liquid metal phase (accuracy, minimum temperature for the sensor reading, time of response);
4. Study of the efficiency of oxygen getters(e.g. Zr, Ti, Mg and Ta) in the conditioning of the liquid lead to a low oxygen level (Table 7);
5. Filtering and cold trap experiments (preliminary test in CHEMLAB concerning the thermal stability in lead of the proposed material for the filters while the final assessment will take place on the external loop for the oxygen control in ELF facility).

TABLE 5. OXYGEN SENSOR TESTING IN CHEMLAB

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Lead Temp.[°C] | Pressure[bar] | Length[mm] | Reference Electrolyte | Duration[h] |
| 400-750 | 1 - 20 | 1000/3000/6000/9000 | Pt/air or other | 300 - 500 |

TABLE 6. LEAD CONDITIONING TESTS IN CHEMLAB

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Lead Temp.[°C] | Lead volume[lt] | Oxygen content[wt%] | Conditioning | Cycles[**#**] |
| 400-750 | 5/20/100/1000 | 10-4-10-8 | Ar/H2/O2 injection | 10 |

TABLE 7. GETTER TESTING IN CHEMLAB

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Getter | Lead Temp.[°C] | Lead volume[lt] | Oxygen content[wt%] | Conditioning | Cycles[**#**] |
| Zr/Ti/Mg/Ta | 400-750 | 20 -100 | 10-4-10-8 | O2 injection | 20-50 |

Oxygen sensors longer than 1000 mm will be tested in ATHENA while the endurance tests will be performed in ELF facility.

#### Corrosion in stagnant lead

The main concern connected with the use of lead as coolant is the chemical compatibility between the lead and structural materials. Several steel alloying elements (e.g. Ni, Cr) are soluble in liquid metal, thereby exposing structural material to dissolution-based corrosion phenomena at the interface between molten lead and steel surface. The factors influencing corrosion are the composition of material, oxygen content in lead, flow velocity and temperature. The experiments planned in ChemLab are intended to extend material applicability in lead beyond 550°C also covering accidental conditions.

Therefore, the corrosion tests in stagnant lead for the selected materials (AISI316L, AISI316LN, 15-15Ti (AIM1), AISI300 series) will be performed for various temperatures in the range 400-650 °C, different oxygen concentrations (10-4 -10-8 wt %) and exposure time (1000 – 3000 h) for both raw and coated samples.

#### Mechanical testing in lead

The mechanical tests identified as priority are referring to slow strain rate tensile (SSRT), creep-rupture, fretting and erosion and will be performed with the oxygen control of the molten lead, the temperatures values and the oxygen concentrations being representative for LFR technology. The experiments will allow assessing the strength, the ductility performances while also providing information about liquid lead embrittlement. Moreover, the erosion tests will support the selection of the pump impeller material while the fretting experiments will offer important information about the impact of flow induced vibration on FA fuel rod- grid interaction. Test matrixes have been set up for each type of mechanical experiment, an example (for fretting tests for both PLD coated and raw samples) being detailed in Table 8.

TABLE 8. FRETTING TEST IN LEAD

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Lead Temperature[°C] | Oxygen Content[wt%] | Load[N] | Slip Amplitude[mm] | Frequency[Hz] | Coating[-] |
| 400 | 10-6-10-8 | 50-150 | 0.1-0.2 | 10-30 | No/PLD |
| 480 | 10-6-10-8 | 50-150 | 0.1-0.2 | 10-30 | No/PLD |
| 550 | 10-6-10-8 | 50-150 | 0.1-0.2 | 10-30 | No/PLD |
| 650 | 10-6-10-8 | 50-150 | 0.1-0.2 | 10-30 | No/PLD |

### HELENA-2 Experimental Campaigns

The RDI Agenda also foresee a series of tests to be performed in HELENA-2 facility which has as one of the main goals to experimentally assess the reliability of the design of the ALFRED fuel assembly to demonstrate of the design choices. The tests will allow performing ALFRED FA characterization, flow blockage and flow induced vibration experiments as well as investigations regarding the impact of the deformed FA on the thermal field into the fuel bundle.

#### ALFRED FA characterization

For this purpose, a Fuel Pin Simulator (FPS) [4-5] reproducing the ALFRED FA will be installed in a test section and provided with a large number of thermocouples allowing the measurement of the heat transfer coefficient in various sub-channels as well as the temperature distribution. The lead flow rate will vary from the nominal value to value typical of natural circulation, the test matrix limiting conditions being shown in Table 9.

TABLE 9. LIMITING CONDITIONS FOR THE ALFRED FA CHARACTERIZATION

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Lead Flow Rate[kg/s] | FPS power[kW] | Feed water[kg/s] | Feed water Tin[°C] | Duration[h] |
| 72 | 1360 | 6.90 | 330 | 20-100 |
| 10 | 95 | 6.00 | 345 | 500-1000 |

It should be mentioned that the investigation of the transition from forced to natural circulation (PLOFA case) in HELENA-2 will address the conditions of ALFRED reactor - Stage 3 meaning a FPS power value of 1.36 MW and 72 kg/s flow rate (in pump forced circulation) to the 7% of the nominal power, i.e. 95 kW.

#### Flow blockage experiment

The flow blockage experiments will support the licensing process of the ALFRED FA as well as the verification and validation of CFD and system thermal-hydraulics codes used in the design and safety assessment of FAs for LFR. Two types of flow blockage experiments are considered: external, when the power will be fixed to the half of the maximum power, i.e. 680 kW, while the flow rate will be varied from 72 kg/s down to 36 kg/s and internal blockage, respectively.

The internal blockage experiments will be performed in a dedicated test section in HELENA-2 where various blockage configurations will be investigated (central blockage, corner blockage, 1 sector blockage and 2 sectors blockage, etc.). A general test matrix is presented in Table 10.

TABLE 10. TEST MATRIX FOR THE INTERNAL FLOW BLOCKAGE EXPERIMENT IN HELENA-2

|  |  |  |
| --- | --- | --- |
| Blockage type | Lead Flow Rate[kg/s] | FPS power[kW] |
| central | 36-72 | 680 |
| corner | 36-72 | 680 |
| 1 sector  | 36-72 | 680 |
| 2 sectors | 36-72 | 680 |

A final test is envisaged to be carried out at full power (1.36 MW) and full nominal mass flow rate (72 kg/s) at the different degrees of blockage from the lighter (central blockage) to the most severe (2 sector blockage).

#### Flow induced vibration

One of the key issues in designing fuel assemblies for innovative fast reactor cooled by heavy liquid metals is the correct evaluation and design of spacer grids against flow induced vibration (FIV). The simulation and experimental data being scarce, a FIV experiment for a not-heated fuel assembly with 61-pins will be designed (so that all the geometrical and materials features to be relevant for ALFRED FA), instrumented and installed in HELENA-2. The mock-up will be instrumented with internal accelerometers and/or strain gauges to measure pins vibration and displacement while the mass flow rate will vary from 5 kg/s to 72 kg/s in steps; thus, the experiments will investigate the impact on the FIV of the grid design, number and position.

#### Deformed FA investigation

To address the FA coolability in the related sub-channels induced by pin deformation, a deformed grid spaced rod bundle representing a part of the planned ALFRED FA will be installed in a test section; various types of deformation will be investigated based on prior numerical simulations under both forced and natural circulation (NC). The test matrix proposed in Table 11 will be applied for each type of deformation increasing the risk of fuel pin cladding failure.

TABLE 11. TEST MATRIX FOR THE ALFRED DEFORMED FA

|  |  |  |  |
| --- | --- | --- | --- |
| Lead Flow Rate[kg/s] | FPS power[kW] | T inlet[°C] | Duration[h] |
| 72 | 430 | 400 | 50-100 |
| 36 | 215 | 400 | 50-100 |
| 10 (NC) | 30 | >400 | 100-500 |

### ELF Experimental Campaigns

A large series of experiments will be performed in ELF facility to support the licensing of ALFRED through a configuration representative of the reactor coolant system, by assessing performances of components in the long run, while investigating corrosion effects on steel structures, coolant and cover gas chemistry as well as main components robustness and reliability.

#### Long run tests in ELF

ELF has been conceived to operate endurance and reliability tests under forced circulation conditions aiming at demonstrating the long-term operability of a lead cooled system. During the tests which are representative for ALFRED Stage 2 and Stage 3 operation, the lead pool as well as the core thermal-hydraulics will be investigated and the main components (e.g., SGs, DHRs, RCPs) will be tested for a relevant time period. The test matrix set up for long run tests is presented in Table 12.

TABLE 12. TEST MATRIX FOR LONG RUN EXPERIMENTS

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Unit | Test 1 | Test 2 |
| Flow regime | -- | FC | FC |
| CS Thermal power | MW | 6.6 | 10 |
| Lead flow rate | kg/s | 572.46 | 572.46 |
| CS inlet temperature | °C | 400 | 400 |
| CS outlet temperature | °C | 480 | 520 |
| Feedwater flow rate | kg/s | 4.24 | 6.42 |
| Feedwater temperature | °C | 335 | 335 |
| Steam temperature | °C | 450 | 450 |
| Water pressure | bar | 180 | 180 |
| Time |  h | 8000 | 8000 |

#### Integral tests

The integral tests represent a key point in the R&D activities dedicated to the development of LFRs. ELF is the most suitable facility to run the integral tests, thanks to its relevant dimensions and the representativeness of the components with respect to the ones of ALFRED.

The envisaged tests aim to gather experience on facility operation as well as to develop the database needed to support the validation and verification of the computer codes used in the design and safety assessment of LFRs.

In this context, the integral tests campaigns and the associated test matrixes have been designed [9, 10] to address the operation of the ELF facility in different conditions: steady state normal operation, operational transients as well as postulated accidental scenarios. During the experiments, the HLM pool thermal-hydraulics and the core thermal hydraulics will be investigated, as well as the main components (e.g. RCPs, SGs, DHRs) will be tested.

### HANDS ON Test Campaigns

The main objective is to demonstrate the fuel handling capabilities of the ALFRED machine as well as to validate the fuel transfer to the spent fuel pool procedure, addressing viability, reliability and robustness of the proposed design solutions. Tests considering deformed FAs (DA) are also foreseen [2] [9] and they are included in the test matrix for remote manipulation (Table 13).

The following parameters are considered and acquired during the tests: FA and cask temperature, FA strains and deformation induced by operations as well as the load and strains in case of a deformed FA.

TABLE 13. TEST MATRIX FOR REMOTE MANIPULATION IN HANDS-ON

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Unit | Test 1 | Test 2 | Test 3 |
| Component |  | FA | DA | Deformed FA |
| Temperature range | °C | 390-420 | 390-420 | 390-420 |
| Power | kW | 140-160  | - | 140-160 |
| Cycles | # | 10-20 | 10-20 | 10-20 |

Moreover, accidental scenarios for which the cask is blocked in various positions are also simulated to address the FA cooling during these events.

### MELTIN’POT Test Campaigns

The Romania RDI Agenda includes also the experiments to be performed in MELTIN’POT facilities that will support both the design of accident management provisions and the validation of the software analysis tools used in the simulation of the complex phenomena associated to severe accidents.

The tests are devoted to fuel-coolant interaction, fuel dispersion and relocation in the coolant resulting from a severe accidental scenario, retention of fission products in lead and/or migration in the cover gas and the dispersion/ retention of Polonium isotopes in lead.

The main boundary conditions for each type of investigation have been defined [9], an example being provided in Table 14.

TABLE 14. TEST MATRIX FOR DISPERSION/RETENTIONS OF FISSION PRODUCTS EXPERIMENTS

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Parameter | Unit | Test 1 | Test 2 | Test 3 | Test 4 |
| Temperature range | °C | 400-600 | 600-750 | 400-600 | 600-750 |
| Isotopes Injection | -- | Stable isotopes | Stable isotopes | Radionuclides | Radionuclides |

## Conclusion

The implementation of LFR infrastructure in Romania will allow:

* Deliver outstanding results on materials technology and innovation through the development of fully qualified solutions for HLM environments (e.g., new materials, new coatings, etc.);
* To qualify prototypical components and systems for application in the energy sector;
* To provide top-level R&D services to external users (including training for very qualified personnel requested by industry);
* To provide the European scientific community with a unique infrastructure to achieve the excellence in mastering the HLM technology (Open Access) through various joint programming activities that are proposed in the field of energy;
* ALFRED Demonstrator to be a game-changer for nuclear industry and Europe as a key facility for testing and qualifying in a relevant environment new structural materials and nuclear fuels, components and systems;
* ALFRED to be a prototype for a modular reactor based on LFR technology (SMR-LFR) for short-term deployment due to its SMR-oriented design which represents a vehicle for increased safety, sustainability and competitiveness relaying on technical options with high readiness level;
* ALFRED's technological infrastructure, being by its nature open to transversal collaboration with other energy sectors, is able to support the development of additional complementary technologies such as Renewable energy sources adopting liquid metals for energy storage or fusion technologies.
* Safety authorities, technical safety organizations, research organizations, academia, industry and utilities to improve their knowledge, competences and skills in a comprehensive and well-structured framework for education and training on all operational aspects of LFR.

References

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Catalogue of Facilities in Support of LMFNS, Overview of experimental facilities in support of Lead/LBE-cooled Fast Reactors (LFR) (2020), <https://nucleus.iaea.org/sites/lmfns/Pages/overviewlfr.aspx>.
2. LORUSSO, P., CARAMELLO, M., ALFRED experimental installation: conceptual design requirements, internal report ALFRED-PRO-REP-001, PRO-ALFRED project, November, 2019.
3. G. Grasso, M. Frignani, A. Alemberti, M. Tarantino, M. Constantin, I. Turcu, Lead Fast Reactor Technology: a promising option for SMR application, IAEA-TECDOC-1972.
4. A. Alemberti, M. Caramello, M. Frignani, G. Grasso, F. Merli, G. Morresi, M. Tarantino, ALFRED reactor coolant system design, Nuclear Engineering and Design 370 (2020).
5. M. Frignani, A. Alemberti, M. Tarantino, G. Grasso, ALFRED staged approach, ICAPP 2019–International Congress on Advances in Nuclear Power Plants, France, Juan-lespins – 2019, May 12–15.
6. GUGIU, D. et al., L 4.6 – Agenda de cercetare- dezvoltare-inovare pentru LFR în România, internal report, PRO-ALFRED project, November, 2020.
7. FIRPO, G., TARANTINO, M., ALFRED Infrastructure: Guidelines for Long-Term Sustainability, internal report ALFRED-PRO-REP-003, PRO-ALFRED project, November, 2019.
8. FIRPO, G. et al., ALFRED High Priority R&D Needs, International Conference on Fast Reactors and Related Fuel Cycles: Sustainable Clean Energy for the Future (FR22), 19-22 April, 2022, Paper No. 345.
9. LORUSSO, P. et al., Identification of the R&D Priorities and of the Experimental Campaigns, internal report ALFRED-PRO-REP-009, PRO-ALFRED project, July, 2020.
10. LORUSSO, P. et al., Conceptual Projects of the Experimental Facilities HELENA2 and ELF, internal report ALFRED-PRO-REP-005, PRO-ALFRED project, November 2020.
11. Consortium established to build Alfred - World Nuclear News (world-nuclear-news.org), accessed March 2022
12. https://world-nuclear-news.org/Articles/Nuclearelectrica-to-cooperate-in-development-of-ALFRED
13. <https://www.gen-4.org/gif/jcms/c_177507/lfr-gif-2020-annual-report>
14. <https://www.world-nuclear-news.org/Articles/Contract-for-Romanian-lead-cooled-reactor-research> facility, 23 November 2021.