

Lead-cooled fast reactor (LFR)

Preamble: For a sake of homogeneity among all the system reports within this Annual Report, this chapter has been intentionally synthesized in a reduced number of pages. The full extended version of the 2019 LFR system report with the complete list of publications can be uploaded on the GIF website.

Main characteristics of the system

The LFR features a fast neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium. It can also be used as a burner of minor actinides, both self-generated and from reprocessing of spent fuel from light water reactors (LWR), and as a burner/breeder with thorium matrices. An important feature of LFR is the enhanced safety that results from the choice of a relatively inert coolant.

The system identified by GIF includes three reference concepts. The options considered are a large system rated at 600 MWe (ELFR EU) intended for central station power generation, a system of intermediate size (BREST 300 Russia), and a small transportable system of 10-100 MWe size (SSTAR US) that features a very long core life. The expected secondary cycle efficiency of each of the LFR reference systems is at or above 42%. These three GIF LFR reference concepts cover the full range of powers. It has therefore the potential to provide wide electricity needs: from remote or isolated sites or to serve as large inter-connected power stations. Important synergies exist among the different LFR systems, so that a co-ordination of the efforts carried out by participating countries is a the key point of LFR development. The typical design parameters of the GIF LFR systems are summarized in **Table LFR.1**.

Table LFR.1 **Key design parameters of GIF LFR concepts**

Parameters	ELFR	BREST	SSTAR
Core power (MWt)	1 500	700	45
Electrical power (MWe)	600	300	20
Primary system type	Pool	Pool	Pool
Core inlet T (°C)	400	420	420
Core outlet T (°C)	480	540	564
Secondary cycle	Superheated steam	Superheated steam	Supercritical CO ₂
Net efficiency (%)	42	42	44
Turbine inlet pressure (bar)	180	180	200
Feed temperature (°C)	335	340	402
Turbine inlet T (°C)	450	505	550

R&D objectives

The System Research Plan (SRP) for the LFR is based on the use of liquid lead as the reference coolant and lead-bismuth as the back-up option. Given the R&D needs for fuels, materials, and corrosion control, the LFR system is expected to require a two-step industrial deployment: demonstration reactors operating at relatively low primary coolant temperature and low power density by 2025; then high-performance reactors by 2040. Following the reformulation of GIF LFR PSSC in 2012 the SRP was completely revised, and an updated final draft is in preparation. The approach taken in the SRP is to consider the research priorities of each member entity, and

to propose a co-ordinated research programme to achieve the objectives of each member while avoiding unnecessary duplication of effort.

The committee notes that there are significant potential commonalities in research and design among these three system thrusts. The plan proposes co-ordinated research along parallel paths leading to one (or more) pilot facilities that can serve the R&D needs of the reference concepts. The needed research activities are identified and described in the SRP. Co-ordinated efforts can be organized in four major areas and formalised as projects: System Integration and Assessment (SIA); lead technology and materials; system and component design and fuel development.

System integration and assessment (SIA) project: The ultimate goal of the SIA project is to ensure the feasibility of the LFR system to meet GIF objectives, taking into account schedule and cost. The LFR SIA activities are to be carried through an iterative process aimed at ensuring that the R&D projects, either individually or jointly, satisfactorily address the GIF criteria of safety, economy, sustainability, proliferation resistance and physical protection.

System and component design project: System design activities are envisioned in the preliminary design of central station and small-scale plants, design of prototypes and demonstration plants, and co-ordination of cross-cutting activities including safety approach, component development, balance-of-plant, etc.

Fuel development project: The LFR fuel development project is a continuing long-term process consisting of tasks designed to meet progressively more ambitious requirements. It includes efforts in the areas of core materials development, fuel fabrication, fuel irradiation and tests aimed at fuel qualification. Strong synergies are existing with the parallel SFR fuel development.

In the near term, one essential goal is to confirm that at least some technical solutions exist so that fuel can be provided in an early time frame suitable for demonstration reactor systems. This “fuel for the Demo” milestone achievement will provide the assurance of the feasibility of a safe and competitive LFR for electricity production.

In the mid-term, it is necessary to confirm the possibility of using advanced minor actinide-bearing fuel at levels representative of the specified equilibrium fuel cycle in order to assure minimization of long-lived nuclear waste and fuel cycle closure. This second goal is therefore to confirm the possibility of achieving higher fuel burn-up compared with that reached in current liquid metal cooled reactors.

In the long term, it is important to confirm the potential for industrial deployment of advanced MA-bearing fuels, and the possibility of using fuels that can withstand high temperatures to exploit the advantage of lead (margin to boiling) to increase plant efficiency for electricity generation and also provide of high-temperature heat production. This “advanced high temperature fuel” milestone achievement will demonstrate the sustainable, multipurpose capability of the LFR technology.

Lead technology and materials project: In the near term it is necessary to maximize the use of available materials thereby limiting material qualification activities only in their new environment. To establish reactor feasibility, it is necessary to provide a technologically viable structural material capable of withstanding the rather corrosive/erosive operating conditions of an LFR. In the mid- and long term, the high boiling point of lead is advantageous for high temperature operations of the reactor, extending the LFR mission towards higher efficiency cycle and hydrogen production. Those missions require the development of new materials both for mechanical components and fuel cladding, or industrial processes to protect existing materials (coatings). These material developments will be time consuming and will be carried out with a flexible schedule depending on investments and technological achievements. Peculiar is the development of a fuel cladding resistant to high neutron doses (increased fuel burn-up) and at high temperature (increased coolant temperature and power density).

Main activities and outcomes

During 2019, the LFR pSSC has been strongly involved in the drafting or revising of several GIF reports that are expected to be issued in 2020:

- *LFR – System Safety Assessment (SSA)*. In collaboration with RSWG, the first SSA draft report was finalized in December 2018 and sent to GIF experts in 2019. The final agreed version of the report will be issued early in 2020.
- *LFR – Safety Design Criteria (SDC)*. Throughout 2019, the LFR pSSC has worked on a revision of the LFR – SDC draft report based on comments received from RSWG members. The report has been updated and finalized. It will be transmitted back to RSWG in early 2020.
- *LFR – PRPP white paper*. A first draft of the PRPP paper has been developed in strong collaboration with PRPPWG. Following a dedicated meeting in December 2019, the document is now under finalization by the LFR pSSC. It is expected to issue it in 2020.

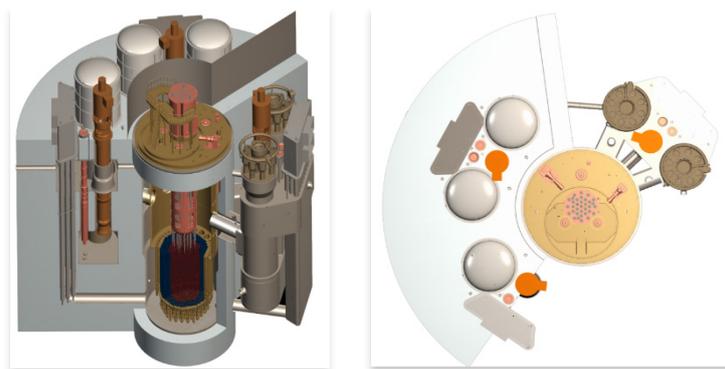
The LFR – pSSC has been also working actively with the GIF Task Force on Research Infrastructures and provided input to the Advanced Manufacturing Task Force (AMME). Finally, the LFR – pSSC was enlarged first in February 2018 by the LFR-MoU signature of USDOE, and then in Oct. 2019 by the signature of INEST (on behalf of the Chinese Academy of Sciences).

Main activities in Russia

The BREST-OD-300 fast neutron lead-cooled reactor (see **Figure LFR 2**) has been developed as the pilot and demonstration prototype of a baseline commercial reactor facility for future nuclear power. The BREST-OD-300 unit is intended for:

- practical confirmation of the key design approaches used in lead-cooled reactor facilities operating as part of a closed nuclear fuel cycle, and the fundamental principles of the inherent safety concept;
- phased justification of reactor component endurance for future commercial lead-cooled reactors;
- electricity generation.

Figure LFR 2. **BREST-OD-300 reactor**



The baseline principle behind the inherent safety of LFR consists of the preferential use of the favorable inherent neutronic and physicochemical properties of the incorporated fuel, coolant and structural materials, as well as design solutions that allow full realization of these properties to exclude entire classes of severe accidents (uncontrolled power excursions and loss of heat removal). The BREST-OD-300 reactor power level has been selected with regard for the feasibility to use the associated design concepts as a reference for future larger output reactor facilities.

The reactor core design uses mixed uranium-plutonium nitride fuel; low-swelling ferritic-martensitic steel as fuel cladding; and fuel elements contained in shroud-less fuel assemblies. The selected dense nitride fuel, in combination with the lead coolant, makes possible to have complete breeding of fissile material in the reactor core with a constant low reactivity margin, thus preventing any rapid or large neutron-power excursion during reactor operation.

Until now, the dense nitride fuel technology has been implemented in pilot process lines. Technological processes are being improved and industrial production is being created for BREST-OD-300 (i.e. the fuel fabrication and re-fabrication module). To confirm serviceability of the fuel and the structural materials, fuel elements are being tested in BN-600 power reactor and in BOR-60 research reactor. Some of the fuel elements irradiated in BN-600 and BOR-60 have been completed and Post-Irradiation Examination (PIE) has been undertaken. They confirm in principle the fuel serviceability. The maximum burn-up achieved to date is -7.4% heavy atom (h.a.). Results required for fuel code verification have been obtained in these PIEs. The behavior of the fuel elements under irradiation meets, in principle, the pre-test analytical prediction. The obtained data demonstrates the feasibility of safe operation of the BREST fuel elements up to the parameters of the initial stage of operations (fuel burn-up of 6% h.a.).

Full-scale mock-ups have been manufactured for all types of fuel assemblies, reflector and shielding blocks. Hydraulic and vibration tests in water and liquid lead were performed. Data has been obtained which is required for updating reactor core calculations.

Neutronic calculations performed using a certified code have shown that the reactivity margin of the BREST-OD-300 reactor core life is in a range of 0.45-0.68 β_{eff} . This reactivity margin can be ensured with regard for existing experience in fuel fabrication (fabrication accuracy is 1.2% $\delta K/K$), and the neutronic characteristic studies have been conducted, including with nitride fuel, at the BFS bench at IPPE (estimated error is 0.7% $\delta K/K$).

The specific design concepts used in the BREST-OD-300 reactor include an integral layout, absence of shutoff valves in the primary circuit, and use of passive and active-passive safety-related devices and systems. The integral layout, in a combination with the multilayer metal-concrete vessel, excludes accidents from loss of lead coolant. The justification of the metal-concrete vessel strength and serviceability (**Figure LFR 3**) is being performed based on data obtained by testing medium-sized metal-concrete structures (with typical dimensions of up to 7 m). Tests have been conducted to determine the properties of HT concrete grades under working temperatures and irradiation; the chemical inertness of the coolant with respect to concrete has been shown, and calculation procedures have been verified.

Figure LFR3. **Reactor vessel computational model and mock-up**



The BREST-OD-300 has a submerged-type once-through steam generator with a coiled heat exchanger. Silicon-containing austenite steel is used as the material of the heat-exchange tubes. Experiments were conducted to study the dependent failure of tubes caused by the rupture of one tube. The results of the experiments in lead coolant conditions simulating full-scale ones (temperature, pressure) have shown no dependent failure. Serviceability of the assembly for the

heat-exchange tube embedment into the tube sheet (see **Figure LFR 4**) was confirmed based on a thousand cycles of thermally loading a model (heat-up to 540°C, cooling down to 220°C). Studies of the weld and tube metal have not revealed intolerable defects.

Figure LFR 4. **Examination of the assembly for the heat-exchange tube embedment into the tube sheet**



The Main Circulation Pump (MCP) is vertical with an electric drive, axial type. The flow path has been optimized at water and lead test benches. The required head – flow rate characteristic has been obtained to ensure the pump operation in a range from 30 to 100 %. The full-scale MCP lower bearing has been designed and tested for endurance in liquid lead. No damage has been detected based on four intermediate withdrawals of the lower radial bearing's stator and rotor (30% of the design life achieved). A positive serviceability prediction has been formulated.

Radiation safety for the reactor facility conditions is based on data obtained as the result of out-of-pile and in-pile experiments using lead. Experiments have been completed and dependences have been determined to justify the release and transport of activation and fission products from the coolant at different temperatures (up to 680°C). The results of the radiation safety analysis have confirmed the implementation of target indicators, including no need for evacuation and resettlement of the public outside the site during anticipated operational occurrences with multiple failures (e.g. loss of power supply with scram failure, full reactivity insertion). The calculation results show that the FP released from the reactor for the first day is not more than $4.3 \cdot 10^8$ Bq (i.e. does not exceed the reference level for the allowable daily release during normal operation) in anticipated operational occurrences accompanied by multiple failures for a scenario with full reactivity insertion. The probability of core damage at the NPP with the BREST-OD-300 does not exceed $8.6 \cdot 10^{-9}$ 1/year, which makes it possible to ensure the acceptable level of safety for such type of nuclear power based reactor.

The reactor facility detailed design was developed subject to the fundamental requirements set forth in Russia's nuclear regulatory documents. The entire set of standards and regulatory documents, which take into account the peculiarities of lead-cooled reactors, are being developed in parallel with the detailed design and R&D performance. At the present time, the federal standards and rules have been updated based on the comments received and have been sent to Rostekhnadzor. Studies show that the BREST-OD-300 concepts can be used in large commercial reactor facilities while ensuring their competitiveness. The BREST-OD-300 unit design received a positive conclusion of the Glavgosexpertiza and currently is in the process of licensing with Rostekhnadzor.

Main activities in Japan

Fundamental experimental and theoretical studies for the LFR have been carried out by the Tokyo Institute of Technology. Experimental studies on chemical control and material compatibility of heavy liquid metal coolants (HLMs) have been performed. Chemical compatibility of structural concrete materials with the HLMs is important topic for the

development of LFRs, especially in the case of a coolant leakage accident. The chemical compatibility of various cement materials with liquid Pb and Pb-Bi was investigated by means of corrosion tests at 773 K. The coupon specimens made of Portland cement having different water/cement ratio were prepared and immersed into Pb and Pb-Bi at a static condition for 250 hours. After the tests, the chemical interaction between the cement specimens and the liquid metals was analysed. The results indicated that the chemical interaction between the HLMCs and the cement was limited (only small chemical interaction and mass transfer). These chemical behaviors were reasonable (cement materials are thermodynamically stable in the HLMCs at this temperature) and these results indicated the potential of the structural concrete as a coolant boundary.

In a theoretical study, innovative LFR concepts have been studied. The use of lead-alloy can provide for good neutron economy in fast reactors. The study on a new concept of a breed-and-burn reactor has been started utilizing the attractive features of lead-alloy. The new concept of this reactor is based on a conventional reactor design. The reactor needs only natural uranium or depleted uranium for fuel once they come into an equilibrium condition. It is possible to achieve high burn-up of fuel without the movement of the burn-up region in the core in the equilibrium condition.

Main activities in Euratom

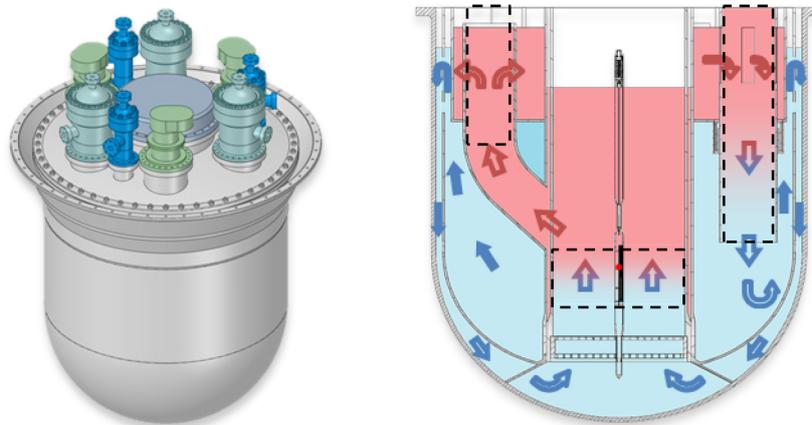
In June 2019, the European Commission (EC) co-organized the FISA 2019 and EURADWASTE '19 conferences in Pitesti (Romania) with the Ministry of Research and Innovation of Romania and the Institute for Nuclear Research (RATEN-ICN). The conference gathered some 500 stakeholders, presenting progress and key achievements of around 90 projects which are or have been carried out as part of the 7th and Horizon 2020 Euratom Research and Training Framework Programmes (FP). In that frame, a side workshop organized by the FALCON consortium on the ALFRED infrastructure attracted a significant number of participants stimulating the discussion of the state of R&D of heavy liquid metal technology and a road map for the LFR demonstrator in Europe.

With regard to Euratom R&D projects, the already-running main projects related to LFR technology and Gen-IV fuels are GEMMA, M4F, INSPYRE and the LFR SMR INERI project (involving JRC and US DOE). A new project named PIACE has started related to the passive safety freezing prevention in LFRs. The project has had its kickoff meeting at the ENEA research lab in Brasimone and is presently under execution, expecting some experimental results to be delivered within 2020.

At the end of 2018 MYRRHA defined its road map for implementation of LBE technology for an ADS system. Belgium allocated EUR 558 M for the period 2019-2038 as follows:

- EUR 287 million for phase 1: building MINERVA (linear accelerator up to 100 MeV, 4 mA + proton target facility /PTF/) in the period 2019-2026;
- EUR 115 million for phase 2 and 3: phase 2 being the design and R&D of the second section of accelerator up to 600 MeV and phase 3 for further design and licensing activities related to LBE-cooled subcritical reactor, both to be carried out in the period 2019-2026;
- EUR 156 million for operation and experiments of the MINERVA for the period 2027-2038.

For the ALFRED project (LFR European demonstrator), the FALCON consortium made important steps during the period 2018-2019. First, a main step of the design review was completed, and a new system configuration was defined, consisting of three steam generators (SG) using single wall bayonet tubes, three dedicated dip coolers for the second decay heat removal (DHR) system, and three primary pumps (PP). Additional changes have been made in the primary system configuration by the definition of a hot and cold pool and a special arrangement of the primary flow path to completely eliminate the thermal stratification on the vessel (for forced and natural circulation conditions). The new configuration and its main characteristics are presented in the following **Figure LFR.5**. The DHR-1 is constituted by Isolation Condensers connected to steam generators (three units) and equipped with the anti-freezing system which is investigated in the PIACE project. A similar system is used for the DHR-2 system connected to a dip cooler using double-wall bayonet tubes.

Figure LFR 5. **ALFRED primary system flow-path configuration and external view**

The FALCON consortium enlarged the community and extended the ALFRED project with the signature of several Memorandum of Agreements with partners willing to support in-kind the technical activities related to ALFRED development. The FALCON consortium also reached an important decision with regard to ALFRED operation and licensing: it was decided to approach both the operation and licensing using a step-wise approach to better face the known limits concerning materials in a representative environment. The idea is to follow a staged approach characterized by a constant primary mass flow and increasing power levels resulting in an increase of the maximum lead temperature:

- 1st stage (low temperature): Use of proven technology, proven materials, oxygen control, low T° , and Hot Fuel Assembly (FA) for in-core qualification of dedicated coatings for cladding;
- 2nd stage (medium temperature): Requires FA replacement, but uses the same SGs and PPs, and Hot FA for in-core qualification at higher temperature;
- 3rd stage (high temperature): Replacement of the main components for improved performance, representative of First-Of-A-Kind (FOAK) conditions for LFR deployment.

Consequently each stage is used to qualify the operation that will be carried out in the following stage. Each stage of the operation will need to be separately licensed but, using the confidence gained in the previous stage, the licensing process is expected to be a continuous process. The following table provides the main parameters of the envisaged staged approach:

Table LFR 2. **ALFRED staged approach main parameters**

Normal operation – full power	Units	Stage 1	Stage 2	Stage 3
Thermal power	(MW)	100	200	300
Core inlet temperature	($^{\circ}$ C)	390	400	400
Core outlet temperature	($^{\circ}$ C)	430	480	520
Pump head	(MPa)	0.15	0.15	0.15

During 2019, the Romanian government awarded RATEN-ICN (the Romanian research lab) funding of EUR 2.5 million in the frame of a project dedicated to “Preparatory activities for ALFRED infrastructure development in Romania”. The project will last 15 months from September 2019 to November 2020. RATEN-ICN also responded to a call for proposals from the Romanian government with a project “ALFRED – step 1, experimental research support infrastructure: ATHENA (Lead pool-type facility) and ChemLab (Lead chemistry laboratory)”.

A budget of EUR 133.9 million has been allocated in the 2019-2020 Euratom Fission Call for H2020 project proposals. Several project proposals were submitted in domains related to LFRs. The selected projects are expected to start by mid-2020. Finally, the SESAME Euratom collaborative project was finalized in 2019 with a workshop and the issue of a book dedicated to thermal-hydraulics aspects of liquid metals.

Main activities in Korea

In Korea, the LFR R&D has been redirected towards marine propulsion and space power development, by taking advantage of the excellent safety, very long refueling intervals and economic potential of LFR. Since the first Korean study begun in 1996 at Seoul National University (SNU), a new university consortium named Micro Nuclear Energy Research and Verification Arena (MINERVA) was formed to carry out a four-year conceptual design development of a non-refueling marine propulsion reactor cooled by LBE, in support of the Ministry of Science, Information and Technology (MSIT). The Ulsan National Institute of Science and Technology (UNIST) leads the MINERVA consortium with the participation of SNU, the Korea Advanced Institute of Science and Technology (KAIST), Kyunghee University, Ulsan University, KEPCO International Nuclear Graduate School (KINGS) and Moojin-Keeyeon Company. The Korean LFR Program has presently two main objectives:

- micro-modular reactors for marine propulsion, including ice breakers for opening the Northern Sea Route (NSR) that will cut CO₂ emission up to 40% for civilian vessels between Europe and Northeast Asian countries (including ROK). It is envisaged to expand it to container ships and bulk carriers, in support of the International Maritime Organization (IMO) resolution to ameliorate climate change.
- a technology development requirement for sustainable power generation using energy produced during nuclear waste transmutation has been reformulated towards increased safety.

To meet the first goal, a non-refueling micro-modular reactor called MicroUranus has been designed by MINERVA consortium based on URANUS as the reference. MicroUranus has innovative features including a compact core with the help of pony pumps and inherent natural circulation while keeping the reactor core life up to 40 years covering the entire life cycle of icebreakers and container ships without refueling. The power rating of MicroUranus is being optimized in the range between 15 MWe and 30 MWe. In order to assure the reliability of reactor systems overcoming aging phenomena including corrosion, Functionally Graded Composite (FGC) materials are envisioned to be used. As part of this material development, a group of researchers designed a FGC tube pilgering process using three-dimensional finite element analysis (FEA).

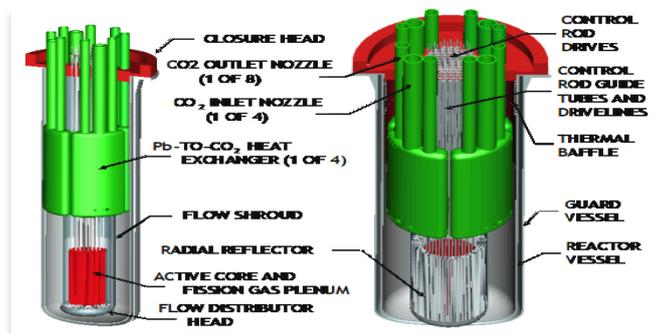
To meet the second goal, the Korean first LFR-based burner PEACER (Proliferation-resistant Environment-friendly Accident-tolerant Continual energy Economical Reactor) has been developed to transmute long-lived wastes into short-lived low-intermediate level wastes. In 2008, the Korean Ministry of Science and Technology (MOST) selected the SFR as the technology for long-lived waste transmutation. Recently, LFR R&D for transmutation in Korea has turned its direction towards an ADS-driven Th-based transmutation system designated as TORIA (Thorium-Optimized Radioisotope Incineration Arena) by a consortium led by SungKyunKwan University with the participation of Seoul National University and UNIST. For both objectives, large-scale test loops are employed for materials and thermo-hydraulic testing and model benchmarking. Korea's first large-scale LFR test facility, HELIOS, has been moved from SNU to UNIST where MINERVA is led. At SNU, a URANUS mock-up, designated as PILLAR (Pool-type Integral Leading test facility for lead-alloy-cooled small modular Reactor), has been designed, built and operated since 2018.

Main activities in United States

Work on LFR concepts and technology in the United States has been carried out since 1997. In addition to reactor conceptual design, past activities included work on lead corrosion and thermal-hydraulic testing, and the development and testing of advanced materials suitable for use in lead or LBE environments. While current LFR activities in the United States are limited, past and ongoing efforts at national laboratories, universities and the industrial sector

demonstrate continued interest in LFR technology. With regard to reactor design concepts, of particular relevance is the past development of the Small, Secure Transportable Autonomous Reactor (SSTAR) shown in **Figure LFR 6**, carried out by Argonne National Laboratory (ANL), Lawrence Livermore National Laboratory (LLNL) and other organizations over an extended period of time. SSTAR is a small modular reactor (SMR) that can supply 20 MWe/45 MWt with a reactor system that is transportable and sealed. Some notable features include reliance on natural circulation for both operational and shutdown heat removal; a very long core life (15-30 years) with whole reactor or cassette refueling; and an innovative supercritical CO₂ Brayton cycle power conversion system. This concept represents one of the three reference designs of the GIF LFR pSSC. Even if this concept is no longer under development, it is still retained as a reference system by the pSSC to represent the small/very small size category for LFRs.

Figure LFR 6. **ALFRED Small, Secure Transportable Autonomous Reactor (SSTAR) view**



Past national laboratory efforts related to the LFR, in addition to the SSTAR reactor design efforts, include lead and lead-alloy performance and material compatibility studies activities at Los Alamos National Laboratory (LANL) with the Delta Loop. This facility has since been discontinued.

Current national laboratory activities include conceptual design, advanced material development and performance research, and instrumentation for monitoring steam generator status, principally conducted as industry-government partnerships under the USDOE GAIN (Gateway for Accelerated Innovation in Nuclear) program, at Oak Ridge National Laboratory (ORNL) and the Pacific Northwest national Laboratory (PNNL) in association with industry participants Westinghouse, Hydromine and Columbia Basin Consulting Group (CBCG). In the US industrial sector, current LFR reactor initiatives include the three companies mentioned above. Westinghouse Corporation maintains an ongoing initiative to design and commercialize a new advanced LFR system. Hydromine, Inc. is developing a new LFR reactor concept identified as LFR-AS-200 (Amphora-Shaped) in the 200 MWe size range as well as a family of smaller (microreactor) systems, and CBCG is developing a new conceptual design for a LBE reactor concept.

The Westinghouse LFR aims at economic competitiveness, even in the most challenging global markets, through a simple and robust design, passive safety and life cycle requirements embedded in the design from the early design phase. It is a 950 MWt (~450 MWe) reactor, being developed starting with a lower-power prototype unit for technology demonstration. It utilizes a hybrid, micro-channel type heat exchangers to reduce vessel size/weight, and a thermal energy storage system to provide load following with minimum variations in-core thermal power. Additionally, it features a supercritical CO₂ power conversion system with air as the ultimate heat sink. The prototype unit will use oxide fuel and a pure lead coolant maintained at temperatures below 550°C. Advanced fuels and higher temperatures will be implemented after the prototype demonstration phase.

Hydromine's LFR-AS-200 concept is a compact 200 MWe LFR in which a high degree of compactness (<1 m³ primary system volume/MWe output) is achieved by elimination of components and other design optimizations utilizing the favorable characteristics of pure lead

as a coolant. This compactness metric is estimated to be from 2 to 5 times lower than other metal-cooled fast reactors previously designed or in current design stages. In addition to this 200 MWe concept, Hydromine also envisions a family of very small (micro) reactors (5-20 MWe) known as the LFR-TR-X family with similar compactness and simplification of design. In these designs, control and shutdown rods are located outside the core, and the reactors are able to operate continuously for 15 years without refueling. The LFR-5 could be deployed in the near term, owing to its lower operating temperatures and use of qualified materials.

CBCG is taking an integrated approach to clean energy production by developing a nuclear plant design with load-following capabilities as an integrated grid-scale battery concept. Both the nuclear plant and the grid-battery are new designs by CBCG – when paired as an integrated facility, demand load-fluctuations are accommodated by the battery, while the nuclear plant remains at baseload operations. The nuclear plant uses LBE coolant with operation in a fast reactor spectrum. Initial efforts are focusing on licensing and regulatory requirements. As part of its ongoing research, CBCG is developing a Polonium mitigation system to reduce containment building requirements and off-site release potentials by eliminating the principal radiological release hazard associated with this technology.

Main activities in China

In February, 2019, INEST, the Chinese Academy of Sciences (CAS) was appointed as the Chinese representative for the Lead-cooled Fast Reactor (LFR) program in the Generation IV International Forum by the Ministry of Science and Technology of China. In this role, INEST co-ordinates the GIF LFR activity framework of domestic organizations inside China. On 18 October 2019, INEST signed the LFR memorandum of understanding (MoU) on behalf of China during.

The Chinese government has provided continuous national support to develop lead-based reactor technology since 1986, by the CAS, the Minister of Science and Technology, the NSF. Following the last 30 years of research on lead-based reactors, the China LEAd-based Reactor (CLEAR) was selected as the reference reactor for both ADS and fast reactor systems, and the program is being carried out by the INEST/FDS Team, CAS. The activities on CLEAR are reactor design, reactor safety assessment, design and analysis software development, lead-bismuth experiment loop, key technologies and components R&D activities are being carried out.

Several “13th Five-Year” plans by the government related to lead-based reactor have been published. The CLEAR-M project aiming to construct a small modular energy supply system has been launched. The engineering design for the first prototype mini-reactor CLEAR-M10a with power of 10 MWth was carried out. To promote the engineering and commercial application of CLEAR-M, the China Industry Innovation Alliance of Lead-based Reactor (CIIALER) and the International Co-operative Alliance for Small LEAd-based Fast Reactors (CASLER), both led by INEST, were established and supported by over 100 companies, and a related industrial park began to be built.

For an ADS system, several concepts and related technologies are under assessment. For example, the detailed conceptual design of CLEAR-I with the final goal of MA transmutation having an operational capability of subcritical and critical dual-mode operation has been finished. An innovative ADS concept system as an advanced external neutron source driven traveling-wave reactor for energy production, CLEAR-A, was proposed. The CiADS project aiming at building a 10 MWth subcritical experimental LBE-cooled reactor coupled with accelerator was approved, and preliminary engineering design is underway. The project was conducted by the collaboration of CAS and other industrial organizations.

In order to support the China LEAd-based Reactor projects as well as validate and test the key components and integrated operating technology of lead-based reactors, three integrated test facilities have been built and commissioned since 2017, including the lead-based engineering validation reactor CLEAR-S (see **Figure 12 LFR.7**), the lead-based zero power critical/subcritical reactor CLEAR-0 coupled with HINEG neutron generator for reactor nuclear design validation, and the lead-based virtual reactor CLEAR-V. In 2019, a loss-of-flow benchmarking test based on the pool-type CLEAR-S facility was prepared, and is planned to be conducted in 2020.

Figure LFR 7. **Lead-based Engineering Validation Reactor CLEAR-S**

In recent years, several other organizations started paying greater attention to LFR development. China General Nuclear Power Group (CGN) is carrying out CLFR reactor conceptual design and related research. China National Nuclear Corporation (CNNC) is developing LFR technologies such as core neutronics characteristics testing. The State Power Investment Corporation (SPIC) is focusing on the 100 MWe BLESS reactor conceptual design. Several universities, such as Xi'an Jiaotong University (XJUT), the University of Sciences and Technology of China (USTC), are carrying out fundamental LFR technologies R&D, including materials testing, thermal-hydraulic analysis, safety analysis, etc., to support LFR development in China.

In December 2019, the domestic co-ordination meeting of GIF LFR was held in INEST. Representatives from more than ten Chinese organizations who were involved in LFR R&D attended this meeting. The domestic LFR joint working group was proposed and INEST was suggested as the lead of the working group to co-ordinate the participation and co-operation of related organizations and activities in China.

**Alessandro Alemberti**

*Chair of the LFR SSC
and all Contributors*