

# Lead-cooled Fast Reactor Status & Perspectives

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# Outline

- Why Lead-cooled Fast Reactor
- R&D Ongoing
- International Context





# **The «ideal» Nuclear Power Plant**

Fission Nuclear Power Plants of a new type are being developed for a short-term deployment (beyond 2030) to replace the current fleet and better integrate future hybrid energy systems: smaller, more flexible, economically competitive, able to produce more than purely electricity.





The fission process used in nuclear reactors produces a **number of isotopes that can be toxic to human lives and the environment**.

Since the start of the large scale deployment of nuclear energy, **disposal** of the long lived isotopes has been an issue that has had a priority in most nuclear countries.





### Reactor and Fuel Cycle Options to Implement P&T

#### The **P&T** objectives can be summarized as:

- □ Minimization of waste mass sent to a repository,
- Reduction of the potential source of radiotoxicity
- □ Reduction of the heat load in the repository

#### Strategies making use of P&T can be gathered into three categories:

- Sustainable development of nuclear energy and waste minimization (Pu as a resource)
- □ Reduction of MA inventory
- Reduction of TRU inventory as unloaded from LWRs

# Fast neutron spectrum reactors are the most adapted technology and offer flexible options for implementation.



#### NUCLEAR MATERIALS INVENTORY (TONS) NEEDED TO PRODUCE 100TWH

		1) Present scenario	2) Near term scenario	3) Long term scenario (after 2040)		
		Light water reactors	Lead –cooled fast reactors without Minor Actinides recycling.	Lead –cooled fast reactors with Minor Actinides recycling.		
Natural Uranium		2100	10,8** or a, b, c	10,44** or a, b, c, d		
Unused	Depleted Uranium from the enrichment facility.	1900 (a)	_	_		
uranium,	Uranium from the spent fuel.	184 (b)	_	_		
net generated Pu,	Pu	2,6* (c)	Negligible	Negligible		
Nuclear waste	Minor Actinides (Np,Am,Cm)	0,38 (d)	0,36	Negligible		
	Fission fragments	13	10,43	10,43		
•* It is possible to reduce the plutonium inventory with increased production of Minor Actinides.						

•\*\* Reprocessing losses not included





Recycle of all actinides in spent LWR fuel in fast reactors provides a significant reduction in the time required for radiotoxicity to decrease to that of the original natural uranium ore used for the LWR fuel (i.e., man-made impact is eliminated). From 250,000 years down to about 400 years with 0.1% actinide loss to wastes



## Lead-cooled Fast Reactor

### Main advantages and main drawbacks of Lead

Atomic mass	Absorption cross- section	Boiling Point (°C)	Chemical Reactivity (w/Air and Water)	Risk of Hydrogen formation	Heat transfer properties	Retention of fission products	Density (Kg/m³) @400°C	Melting Point (°C)	Opacity	Compatibility with structural materials
207	Low	1737	Inert	No	Good	High	10580 10580	327	Yes	Corrosive



## Lead-cooled Fast Reactor

#### How lead coolant improves the reactor design?

Lead is a low-moderating medium and has a low-absorption cross section

- > Fast neutron spectrum: operation as burner of MA and improve resource utilization (Sustainability)
- Long Life Core: unattractive route for the plutonium procurement (Proliferation resistance and physical protection)
- Large fuel pin lattice (opened/closed): enhanced the passive safety (Safety and Reliability)

#### Lead does not interact vigorously with air or water

- Improve Simplicity and Compactness of the Plant and reduce the risk of plant damage (Economics)
- Increase the protection against acts of terrorism (Proliferation resistance and physical protection)



## Lead-cooled Fast Reactor

#### How lead coolant improves the reactor design?

Lead has a high boiling temperature, high shielding capability and very low vapor pressure

- Un-pressurized primary system (Safety and Reliability, Economics)
- Enhancements in passive safety (Safety and Reliability)

### Lead has a high heat transfer, specific heat, and thermal expansion coefficients

Decay heat removal by natural circulation (Safety and Reliability)

### Lead has a density close to that of fuel, and retains fission products

- Reduce the risk of re-criticality and vessel damage in the case of core melt (Safety and Reliability)
- No need of off-site emergency response (Safety and Reliability)



# A comprehensive R&D program is necessary because of:

- The use of a new coolant and associated technology, properties, neutronic characteristics, and compatibility with structural materials of the primary system and of the core.
- Innovations which require validation programs of new components and systems (the SG and its integration inside the reactor vessel, the extended stem fuel element, the dip coolers of the safety-related DHR system, pump, OCS, ...)
- The use of advanced fuels (at least in a further stage).





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# **Safety Analysis**

![](_page_12_Picture_1.jpeg)

Fuel Assembly characterization in transient conditions including flow blockage

![](_page_12_Picture_3.jpeg)

LFR Integral Tests including SGTR

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# **Integral Test & Component Qualification**

- Integral Test Experiments
- OCS testing in large pool
- Component qualification
- SGTR Experiments
- SG & Pump Unit Test

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# Performance

- HTC measurements
- OCS testing in loop
- Component qualification
- Instrumentation Test

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# **Separate Effect Experiments**

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- Code Validation
- Component & Instrumentation qualification

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# **Material Characterization**

- Corrosion test in flowing lead
- OCS testing in loop
- Component qualification
- Instrumentation Test
- Pump Unit Test

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![](_page_16_Picture_7.jpeg)

![](_page_16_Picture_8.jpeg)

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РБ	Ale Pa
magnetite	e alle a
spinel	
T91	10 µm

![](_page_16_Figure_11.jpeg)

# **Coating Development**

### Pulsed Laser Deposition Nanoceramic Coatings (IIT & ENEA)

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![](_page_17_Picture_3.jpeg)

coating

1515Ti

#### 1 µm Al2O3 coating no buffer layer

![](_page_17_Picture_5.jpeg)

Corrosion tests in static Pb: 550°C -1000 h - 10<sup>-8</sup>/10<sup>-9</sup> wt.% O 1 μm Al2O3 coating

18

# **Coolant Chemistry**

![](_page_18_Picture_1.jpeg)

capsules (small & large)

![](_page_18_Picture_3.jpeg)

Stagnant Test up to 750°C

capsules for HLM chemistry (oxygen sensor testing, deoxygenation with gas) & corrosion tests of materials in Pb alloys

![](_page_18_Picture_6.jpeg)

gas control system (Ar-H<sub>2</sub> injection)

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# **Modelling & Simulations**

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![](_page_19_Figure_2.jpeg)

![](_page_19_Figure_3.jpeg)

SYSTEM CODE (RELAP5)

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Multi-physics

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System Code + CFD coupling

# LMC nuclear submarines

- Russian research into naval reactors began in the early 1950s. Two options were considered from the early stages of development.
  - The first approach used a water-cooled, water-moderated design (PWR) developed at the Kurchatov Institute in Moscow under the leadership of A. Alexandrov.
  - The second approach used a lead-bismuth cooled reactor design (also known as an LMC reactor) developed at the Institute of Physics and Power Engineering (IPPE) in Obninsk under the leadership of A. Leipunsky.
- The ALPHA class (NATO terminology) LYRA class (USSR terminology) LMC nuclear submarines were very efficient and established the world underwater speed record (design was for 40+ knots).
- This was possible thanks to the use of a titanium alloy hull. The use of titanium alloy allowed the hull walls to be thinner and reduced overall weight.

![](_page_20_Picture_6.jpeg)

# LMC nuclear submarines

## Lessons learned

- Coolant purification
- Oxygen control
- Prevent slug formation
- Cleaning of the system by Hydrogen injection
- Freezing
- Formation of Polonium
- $^{209}$ Bi + n  $\rightarrow ^{210}$ Bi ( $\beta$  ; 5 days)  $\rightarrow ^{210}$ Po ( $\alpha$ , 138 days)
- However, no known problems of radiation in nuclear submarines

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## Lessons learned

• Many-year observations by Navy personnel allowed them to reach the following conclusion:

The radiation and sanitary conditions and morbidity of the crew at NSs with LBC cooled reactors do not differ from those of the crew at NSs with water-cooled reactors. They also do not differ from morbidity of the on-shore service personnel whose work is not directly related to radiation"

- A low concentration of Po in the coolant and the formation of a thermodynamically proof chemical compound of Po with lead (lead-polonide), decrease 210Po volatility by nine orders of magnitude in comparison with a sole metal polonium.
- The good retention properties of lead are essential in preventing the release of Po outside the primary system.
- Primary system cleaning was successfully performed through Hydrogen injection

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# LMC nuclear submarines

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![](_page_23_Picture_3.jpeg)

# **ALFRED** Layout

![](_page_24_Figure_1.jpeg)

Internal Structure: no safety related, ensure pools separation and flow recirculation

![](_page_24_Picture_3.jpeg)

**Reactivity control**: Two diverse and redundant systems, control and shut-down rods

![](_page_24_Figure_5.jpeg)

Fuel assemblies: MOX fuel, grid-spaced, hexagonal, wrapped, extended stem

**Inner Vessel**: safety-related, removable for out-of-vessel inspection

![](_page_24_Figure_8.jpeg)

lead during refueling operations

# LFR Technology: China

- CLEAR series LFR developed by International Academy of Neutron Science (IANS)
  - CLEAR-M: Small modular transportable reactor with 10MWe
  - CLEAR-400: Small modular LFR with 400MWth
  - CLEAR-A: 1GeV/10mA proton accelerate coupled with 100 MW<sub>th</sub> LFR
- Validation platform for CLEAR
  - NIRVANA: Verification Platforms were built to support LFR engineering verification
  - CLEAR-M0: pool-type integration verification facility, >5MWth, started commissioning and core outlet temp. reaches 550°C

![](_page_25_Picture_8.jpeg)

![](_page_25_Picture_9.jpeg)

![](_page_25_Picture_10.jpeg)

![](_page_25_Picture_11.jpeg)

NIRVANA

## LFR Technology: China

- CiADS Led by CAS-IMP: the environmental impact assessment for the first phase of accelerator has been approved in 2022
- LFR fundamental research is more active, especially primarily conducted by universities (Xi' an Jiaotong University., Lanzhou University., Shanghai Jiao Tong University, etc.)
- Nuclear power enterprises (CNNC, CGN, SPIC) were invested to the LFR conceptual design and validation activities in recently years

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LFR experimental platforms by CNNC

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![](_page_26_Figure_7.jpeg)

Long-Life full natural circulation SLFR **by SPIC** 

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![](_page_26_Figure_10.jpeg)

SARAX code for LFR by Xi'an Jiaotong Univ.

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Lead-water interaction

experiment

by Shanghai Jiaotong Univ.

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Offshore Floating LFR by Lanzhou Univ.

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LFR demonstrator developed by the FALCON consortium together with European research organization and industries.

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ATHENA, almost completed - the first step of ALFRED experimental infrastructure

- 2.21 MW Core simulator
- Full height bayonet tube heat exchanger
- Main Vessel hosting 800 tons of lead

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#### Italy

- Investing in LFR research since the 2000s.
- Discontinued national research program in 2018.
- But continued to support industrial research and Euratom projects.
- Now showing renewed interest in nuclear technologies.
- Very open to international collaboration.

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#### Romania

- RATEN-ICN center involved in European projects on LFR since about 2010.
- Declared interest in hosting the first LFR demonstrator (ALFRED) in 2011.
- Joined the FALCON consortium in 2013.
- Embedded ALFRED and the associated research infrastructure in multiple national strategy documents.
- Financing the largest experimental lead facility in Europe (ATHENA).
- Investment of additional €100 million over the next 4-5 years.

![](_page_28_Picture_16.jpeg)

### Belgium

- Traditionally focused on ADS LBE cooled solutions.
- In 2022, LFR selected as the best technologies to meet national targets.
- Investment of 100 M€ over 4 years.
- SCK CEN is in charge of the research and demonstration activities.
- Experience in licensing process with FANC/Bel-V.
- Managing a fleet of experimental HLM-based infrastructures.
- Experience with MOX fuel.

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Partnership between nuclear national labs and industry leaders standing on a solid experience from the past and a shared vision for the future (MOU signed in Nov. 2023)

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![](_page_30_Picture_1.jpeg)

### SEALER-55 (Swedish Advanced Lead Reactor)

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Item	Value
Power	140 MWth/55 MWe
Lead coolant mass flow	7400 kg/s
Lead inventory	800 tons
Core inlet/outlet temperature	420°C/550°C
Height	5.5 m
Diameter	4.8 m
Fuel	Uranium nitride (UN)
Fuel residence time	25 years

![](_page_30_Picture_5.jpeg)

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- UN powder to be produced by direct ammonolysis of enriched UF<sub>6</sub> – minimizes process steps and residual impurities.
- KTH has successfully shown that uranium ammonium fluoride compounds can be synthesized by reacting gaseous UF<sub>6</sub> with NH<sub>3</sub> at 200°C

![](_page_30_Picture_9.jpeg)

- Raising the temperature to 800°C in a tantalum lined furnace under flow of NH3, UN2 is obtained.
- Denitriding UN<sub>2</sub> at 1100°C in the same furnace under flow of Ar resulted in stoichiometric UN powder with 3% UO<sub>2</sub> impurity.

![](_page_30_Picture_12.jpeg)

#### **Corrosion tolerant steel**

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![](_page_30_Picture_15.jpeg)

vrevene \* 7 m/s

No visible

corrosion-erosio

- Potential show-stopper for commercialisation of lead-cooled reactors: corrosion of stainless steels
- Blykalla's solution: aluminium alloyed steels:
  - Fe-10Cr-4Al-RE (RE = Zr, Ti, Nb, Y)
- Alumina forming austenitic steels (AFA)
- Alumina forming martensitic steels (AFM)
- Form 100 nm thin, ductile and protective alumina film on surfaces exposed to lead with low oxygen content.
- Fe-10Cr-4Al-RE successfully tested at 550°C for 2 years & 850°C for ten weeks.

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![](_page_31_Figure_1.jpeg)

#### **REACTOR DESIGN:**

Small Modular Lead-cooled Fast Reactors

newcleo is working to design, build, and operate Advanced Modular Reactors exploiting fission

#### FUEL MANUFACTURING: **Mixed Uranium Plutonium Oxide**

MOX and Fast Reactors allow the fuel cycle closure, using what today goes to waste as fuel

![](_page_31_Figure_7.jpeg)

# Fuel: MOX

- · A clean solution to the issue of costly and long-lived nuclear waste disposal, using depleted uranium and plutonium, that todav have little use
- The long-term strategy will eliminate the need to mine new uranium, enable energy independence, reduce the volume headed to geological repository
- · Spent fuel will be reprocessed multiple times reducing byproducts: less than 1t of fission fragments from one year's generation by a 1GWe newcleo LFR vs. 199t that goes to waste from conventional reactors

![](_page_31_Picture_12.jpeg)

CAPSULES operational since December 2023

Facility to test various kinds of steel, bare and coated, in stagnant lead under oxygen-controlled concentration, essentially between 10-5 - 10-5 wt %; temperatures span between 450 - 750 °C

![](_page_31_Picture_15.jpeg)

CORE operational in March 2024

Loop-type facility to test various kinds of steel, bare and coated, in fluent lead under oxygen-controlled concentration, essentially between 10.6 and 10.6 wt %; temperature in the corrosion test section 650 °C and velocity 1 m/s; in the erosion test section the temperature is 520 °C and the velocity 10 m/s. It will also be used to test the effectiveness of cold traps and mechanical filters

CAPSULES operational since December 2023	Several tanks filled with O2-controlled lead and Argon, and with immersed specimens: corrosion of structural materials in molten lead	¢	Procurement in progress	Test section at existing ENEA NACIE loop facility: lead cross flow heat transfer
CORE 200 kW operational in March 2024	New loop-type test facility for corrosion/erosion testing of structural materials in molten lead		CIRCE-SGTR with UniPi pending definition of detailed objectives and scope	One or more test sections at existing ENEA- CIRCE: thermal-hydraulics and fluid-structure- interaction phenomena involved in Steam Generator Tube Rupture (SGTR) scenarios in LFR
OTHELLO 2 MW conceptual design in progress	New thermal-hydraulics loop test facility: components performance testing, validation experiments		CIRCE-XXX pending confirmation of availability	Campaigns at existing ENEA CIRCE: endurance tests on axial flow pump bushings, control rods insertion/handling, components insertion/extraction circulation transients
PRECURSOR 10 MW pending definition of detailed objectives and scope	New pool-type large-scale test facility: broad-scope investigations on LFR system transient behaviour, component testing/qualification, etc.	4	DIP COOLER at PoliTo detailed design in progress	New test facility mimicking dip cooler based Decay Heat Removal system: performance and start-up issues
MANUT pending definition of detailed objectives and scope	Mechanical-type test facility: fuel handling systems and mechanisms (including rotating plugs) in air	9	ATHENA-XXX at RATEN-ICN pending confirmation of availability	Campaigns at existing pool-type ATHENA test facility with new test sections to be designed: thermal-hydraulics, lead chemistry control in large pools, SGTR tests with full-length tubes
CHEM-LAB	Chemical laboratory to support lead technology related investigations	4	MATERIALS LAB Environmental Park Turin pending continuation of availability	Material laboratory, mechanical testing on structural materials

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![](_page_32_Figure_1.jpeg)

![](_page_32_Picture_2.jpeg)

# LFR Technology: Japan

- Fundamental research for LFR in Science Tokyo
  - Design study of innovative LFR
  - Corrosion resistance of FeCrAl steel in flowing LBE
- ADS development study in Japan Atomic Energy Agency
  - ADS concept study
  - CFD analysis
  - LBE corrosion study by OLLOCHI

![](_page_33_Picture_8.jpeg)

# LFR Technology: Korea

## MicroURANUS R&D

- I. Design Development
- II. Materials Development
  - I. AFATi
  - II. Bimetallic Tubes

### **III.** Applications

- I. LFR Fuel Cladding
- II. Steam Generators
- III. Condensers for Load Follow Operation

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![](_page_34_Picture_11.jpeg)

## LFR Technology: Russia

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### **BREST-OD-300: design basis**

- <u>Compliance with the requirements of regulatory</u> <u>documentation</u>;
- Integral layout with a multilayer metal-concrete vessel without shut-off valves in the coolant circulation circuit;
- <u>Reservation</u> of normal operation and safety systems;
- Passive protective and localizing safety systems are widely used
- <u>Lead coolant</u> with high boiling point, radiation-resistant, low activation, not entering into violent interaction with water and air in case of circuit depressurization
- <u>Mixed nitride fuel</u> with high density and thermal conductivity, allows ensuring full reproduction of fuel in the core (core reproduction ratio ~ 1.05) and compensation of reactivity at fuel burnout.

## LFR Technology: Russia

### Construction status at PDEC site (December 2023) Mounting of the BREST-OD-300 reactor began

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![](_page_36_Picture_3.jpeg)

The lower tier of the enclosing structure was immersed in the reactor shaft (December 2023)

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![](_page_36_Picture_6.jpeg)

Mounting of a steel base plate, weight 165 tons (December 2023)

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Construction of electricity transmission lines began: installation of supports and installation of wires (end of December 2023)

## LFR Technology: Russia

"Proryv" project: practical demonstration of all elements of the closed nuclear fuel cycle (CNFC) at the Pilot Demonstrational Energy Complex (PDEC)

![](_page_37_Picture_2.jpeg)

Full Generation-IV technology of the Leadcooled Fast Reactor and the CNFC will be demonstrated on the PDEC site

Construction and commissioning of the Reprocessing module

![](_page_37_Picture_6.jpeg)

# LFR Technology: USA

### Nuclear Energy University Projects

- Simultaneous Corrosion/Irradiation Testing in Lead and LBE -Massachusetts Institute of Technology (MIT)
  - Status: Completed triple-beam (He/Fe<sup>3+</sup>/protons) irradiation testing of Fe-25Ni-16Cr-5Al-1Nb, FeCrAl, and Fe-20Cr. Post-test analysis is being finalized. Final report is in preparation.
- Development of Versatile Liquid Metal Testing Facility for Lead-cooled Fast Reactor Technology - University of Pittsburgh
  - Status: NEUP project completed. The new testing facility was installed at the University of Pittsburgh. Further collaborative research (ULV sensor testing, SAM code development) is on-going in collaboration with ANL and WEC.

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# LFR Technology: USA

- Technology Commercialization Fund projects
  - SAS4A/SASSYS-1 Improvements for Lead Fast Reactors Argonne National Laboratory/WEC
    - *Status*: Project completed. Performed the required testing for the recently developed oxide fuel model (OFUEL). Extended the SAS user interface to facilitate mechanistic source term analysis.
  - Enhancement of PyARC for Westinghouse LFR Design and Modeling Argonne National Laboratory/WEC
    - Status: Major reorganization and improvement to NUBOW-3D (core deformation) code to streamline coupling with DASSH (sub-channel thermal hydraulics) and PERSENT (perturbation theory). Initial demonstration on the Westinghouse LFR.

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