# *new*cleo’s Fuel Cycle innovations for SMR-LFR including transport

# of fresh and spent fuels

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**Abstract**

*new*cleo is designing SMR-LFRs fuelled with uranium and plutonium mixed oxide (MOX).

A novel approach is envisioned to better use the fissile nuclear material from the current fuel cycle.

*new*cleo is planning to design, build and operate a state-of-the-art MOX fuel facility versatile and modular in nature with an innovative concept to cope with radiological and nuclear thermal effects in order to consume and re-use plutonium bearing materials either already in separated inventories or to be reprocessed in the future, with a focus on fissile material without an already established and existing recycling scheme.

In view of implementing its long-term vision, *new*cleo will also reinstitute a complete supply chain adapted to Fast Reactors and as a part of it, *new*cleo will develop innovative and adapted transport cask solution and logistics to support all the globally needed shipments.

In summary, *new*cleo is presenting a comprehensive view of a closed fuel cycle encompassing multi-recycling in its LFRs with country specific solutions to operate synergistically with existing nuclear fleets, with the overall goal of moving towards a more sustainable nuclear fuel cycle and thus a reduction in the radiotoxicity and volume of the final waste.

## INTRODUCTION

*new*cleo aims to design, manufacture, license and operate 200 MWe reactors (LFR-AS-200) for the European and international markets, to support the energy transition and secure the long-term supply of sustainable, CO2-free energy.

*new*cleo aims at commissioning a Gen-IV 30 MWe Lead-cooled Fast Reactor (LFR-AS-30), an irradiation reactor fuelled with MOX, manufactured in France in a dedicated fabrication plant which is also the subject of a project supported by *new*cleo. These infrastructures support the development of an innovative, robust and safe technology, integrated into the French nuclear industry.

In addition to the LFR-AS-30, *new*cleo aims at deploying a large fleet of 200 MWe reactors in France, in the UK and internationally. To support this deployment, a MOXLFR fuel fabrication plant with a total capacity of 120 tML/year will gradually be commissioned in France.

*new*cleo aims to bring together all the players in the nuclear industry in France to achieve its objectives of implementing a solution that will contribute to the closure of the fuel cycle and the implementation of new solutions to support the energy transition.

Major investments in cycle facilities will be required to enable the recovery of nuclear materials currently stored and not used in the current fuel cycle (large-scale processing of MOXLWR, processing of spent MOXLFR in particular).

The deployment of Gen-IV LFR reactors is an opportunity for the nuclear industry to prepare for the deployment of innovative and sustainable nuclear systems and processes, without disrupting the current industrial pattern of mono-recycling in 3rd-generation reactors.

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Fig. 1 – newcleo’s long-term vision

## *new*cleo’s LFR reactor

*new*cleo's LFR reactors are lead-cooled fast neutron reactors.

The advantageous physical and chemical properties of lead, combined with additional safety provisions, enable simplification and overall compactness of design, resulting in cost reductions and a high degree of intrinsic safety. Its relative transparency to neutron flux enables fast flux and better nuclear material consumption rates. Operating at near-atmospheric pressure reduces the thickness of forgings and the energy released in the event of vessel failure. The very high boiling temperature is an advantage in terms of safety against the risk of incidents linked to fluid boiling in the core.

The high thermal inertia of the reactor is also an advantage in the event of a malfunction of the heat dissipation systems. Other advantages include fission product retention capacity and intrinsic shielding against ionizing radiation.

Each LFR reactor comprises a core system and a pool-type primary circuit, internally integrating all primary equipment including steam generators and residual heat removal systems.

Lead's high density and good calorific potential lead to a compact design.

Apart from the reactor block, which is specific to the LFR, the standard equipment of a power reactor is present.

The conventional island is standard (turbine, utilities, electrical sources and grid connection).

### LFR’s core

The core of the LFR-AS-30 comprises 37 fuel assemblies, test devices (irradiated material samples), control rods, shutdown systems, probes with instrumentation cables. No reflector or gamma shielding subsystem is required, given the coolant used (lead). Biological neutron protection is offset to avoid impacting the core's neutron performance. The fuel assembly is based on the principles developed for the Sodium-cooled Fast Reactor (SFR), but the parameters (fissile length, pellet diameter, etc.) are optimised for neutronics.

The core's compactness means that it can be piloted with control rods (enriched boron) outside the fuel assembly zone. No consumable poisons (other than the B4C in the rods) are required for the operation of *new*cleo's LFRs.

The core of the LFR-AS-200 will be constituted of 120 to 150 fuel assemblies depending on the reactor core management.

### Cooling

The heat transfer medium used is lead. Forced convection circulation is achieved through the action of primary pumps and the input of the amphora-shaped inner vessel, which also serves as a fuel assembly support structure.

The primary pumps required are therefore not particularly specific, and *new*cleo relies on the experience of ENEA and its suppliers for this type of component.

Given the non-reactivity of lead with water, direct exchange is possible, enabling compact steam generator (SG) design. The tube bundle is wound around the axis of the primary pump in order to reduce its size and, consequently, the external dimension of the reactor vessel. This makes the SG an innovative component.

### Materials

The R&D program concerning the behaviour of materials (steels and alloys) with lead at elevated temperatures is a very important research topic in the development of LFRs. At typical fast reactor operating temperatures (more than 500°C), corrosion of structural steels by lead may occur.

Lead corrosion of common structural steels is characterized by different mechanisms:

* oxidation layer
* penetration of lead into the steel,
* dissolution of alloying elements in liquid lead (especially Ni)
* erosion

*new*cleo’s R&D programme, also thanks to the non-nuclear experimental facilities being installed at the ENEA-Brasimone centre in Italy, will focus on these topics.

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Fig. 2 – newcleo’s design: simplification is key

## Fuel cycle

Starting in the early 2030s, *new*cleo's ambition is to contribute to the fuel cycle closure by deploying a Gen-IV LFR-SMR reactor combined with a MOXLFR fuel fabrication plant.

Our program contributes to Europe's decarbonised energy independence, the stabilisation of plutonium stocks and the reduction of the radiotoxicity of final waste.

The nuclear materials currently available in France and Europe, which can only be recycled in fast-neutron reactors, are sufficient for the deployment of *new*cleo's LFR reactors by 2050, without disrupting EDF's current MOX LWR processing / single-recycling scheme.

The diagram of the fuel cycle in France presented below aims to highlight:

* the synergy between a fleet of thermal neutron reactors and a fleet of fast neutron reactors,
* the sustainable balance of the cycle allowing multi-recycling,
* the benefit in the management of nuclear materials by consuming existing stocks,
* the limitation of the radiotoxicity of final waste.

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Fig. 3 – new fuel cycle

### Current situation in France

The current fuel cycle in France, in Fig. 3 in teal arrows, uses mined uranium, which is converted and then enriched to about 5% in 235U.

The UO2 fuel is manufactured to supply EDF's nuclear power plants in France.

Part of the depleted uranium resulting from the enrichment phase is used for the production of MOXLWR fuels.

The UO2 fuel after irradiation in the reactor is reprocessed, thus recovered plutonium, and reprocessed uranium can be recycled.

Besides Fission Fragments and minor actinides are packaged into UC-V (Universal Canister for Vitrified Waste) which are High Level Waste (HLW). The skeleton and hulls of the fuel element are compacted and conditioned into UC-C (Universal Canister for Compacted Waste) which are Long-lived Intermediate Level Waste (ILW).

Plutonium from the reprocessing of UO2 fuels is recycled with depleted uranium in the manufacture of MOXLWR fuel.

### Possible improvements in the current fuel cycle in France

We can make the following observations about the current cycle in France (Fig. 3):

* 1. Supply of mining uranium is of external origin. The stability of this foreign resource needs to be guaranteed
  2. Enrichment step of the mining uranium generated a significant amount of depleted uranium (several 100,000 t. at ~0.3% 235U)
  3. Reprocessed uranium (Rep U) (UNGG and LWR) has been recycled in a very limited way. A large stock of Rep U is, therefore, unused
  4. Quantity of plutonium produced by the reprocessing of UO2 fuels has been greater than the quantity recycled into MOXLWR, generating an aging surplus stock. As plutonium ages, content of americium increases
  5. Part of the spent UOX fuels have not been reprocessed, thus generating a stock of spent fuel awaiting treatment and saturating the storage pool capacities
  6. Irradiated MOXLWR fuels have not been routinely reprocessed to recycle the valuable nuclear materials. Reprocessing campaigns were carried out, which confirmed the suitability of the PUREX process to treat MOX fuel, but also that the design needs to be defined according to the fuel characteristics
  7. Plutonium from the reprocessing of spent fuel MOXLWR has degraded isotopic characteristics for recycling into thermal neutron reactors
  8. MOXLWR fuel manufacturing process has generated scraps that has not been recycled
  9. French experience in the field of fast reactors with Superphénix, which resulted in a shutdown decision, leaves fresh and spent SFR fuels waiting for treatment

### *new*cleo: completion in the fuel cycle closure

The diagram in Fig. 3 emphasises, in orange arrows, the integration of *new*cleo's activity into the fuel cycle.

*new*cleo's business plan schedules the commissioning of a modular and flexible MOXLFR fuel manufacturing plant in 2029 and the gradual deployment of a fleet of 200MWe LFR reactors in France from 2032.

MOXLFR fuels will be manufactured from:

**Uranium**

Uranium can be depleted or from reprocessing (RepU).

*new*cleo’s vision frees from the mining dependence of Uranium from foreign countries, contribute to consume stockpiles that are passive or have no outlet, and therefore provides a solution to points 1, 2 and 3 above.

**Plutonium**

Plutonium is consumed in significant quantities (up to 35%), and LFR reactors accept a wider spectrum of isotopic carriers.

Plutonium from irradiated MOXLWR contains a low quantity of fissile isotopes (<60%), which makes it more difficult to recycle in LWRs without coupling it with enriched uranium.

Conversely, the even and odd isotopes of plutonium are fissile in fast reactors, making it possible to consume plutonium from irradiated MOXLWR reactors without enriching the uranium.

Aged plutonium is consumable in LFR reactors and therefore an americium content of over 3.5% is acceptable. This rate remains incompatible with the current cycle based on the MOXLWR fuel fabrication plant and the LWR reactor fleet.

*new*cleo provides a solution to points 4, 5, 6 and 7.

Additionally, through the flexibility of its MOXLFR fuel manufacturing process, *new*cleo provides a solution to points 8 and 9. These topics are developed in Chapter 4 "Focus on the fuel fabrication facility".

This inventory of these nuclear materials consumable in *new*cleo LFR reactors guarantees the operation of *new*cleo's reactors for at least 40 years assuming 12 GWe installed, allowing the resorption of the actual passive stockpiles.

### Spent fuels reprocessing capacities

In order to deploy Generation IV, to stabilise Pu stocks and to ensure energy independence, French reprocessing capacity will have to take into account the recycling of the above-mentioned spent fuels, in particular will need investment for:

* **A MOXLWR fuel reprocessing unit**

allowing the recycling of recoverable material (plutonium) in LFR reactors. The French government has announced its decision to continue reprocessing until the end of the century and to agree for a new unit to deal with reprocessing needs. The plutonium from the reprocessing of MOXLWR fuel can be recycled into *new*cleo's LFR reactors and the MOXLWR fuel stockpile will thus be absorbed.

* **A MOXFNR fuel reprocessing unit,**

allowing the recycling of recoverable material (plutonium) from FNR spent fuels, once the recoverable material (plutonium) from spent MOXLWR will have been consumed. *new*cleo will then have closed the FNR second cycle, recycling the material from MOXLFR fuels, or even from other FNR reactors. France will have to be equipped with this reprocessing unit in a longer term (2060-2070). This period will be used to make the necessary R&D to adjust and industrialise an adapted treatment process.

This process will consider among other things:

* The management of the used fuel from its unloading from the reactor and its reprocessing, including its storage under conditions that guarantee its non-degradation, and taking into account the presence of lead, thermal power and radiological characteristics.
* The isotopic, chemical (presence of trace of lead), radiological and thermal characteristics of the used LFR fuels in the reprocessing process.
* Safety and criticality requirements, but also the need to limit the radiotoxicity of the final waste. In this regard, additional process steps may be necessary in order to separate certain minor actinides, or even certain long-lived fission fragments (99Tc, 135Cs, 129I…).
* Multi-recycling.

In a stable state, when the pending nuclear materials will have been recycled into LFR reactors, and the reprocessing capacities will be operational, a symbiotic balance will be established between the operation of the thermal neutron reactor fleet and the operation and recycling in fast neutron reactors.

This balance takes into account the multi-recycling of plutonium, with which the operation of LFR reactors is compatible.

## Focus on the fuel fabrication facility

The Fuel Plant will be designed, built and operated to feed the LFRs reactors.

The fuel design will be based on solid ceramic pellets in stainless-steel pins in hexagonal Fuel Assemblies.

Following a 1-year conceptual design phase, *new*cleo launched the preliminary design phase in spring 2024 for its MOXLFR fuel fabrication plant.

The *new*cleo MOXLFR fuel fabrication project is based on the following principles:

* High level of nuclear and operational safety, security and physical protection,
* High level of automation and robotization for optimum protection of workers and the environment,

Modular design and sequential implementation to accommodate the anticipated expansion needs of this type of fuel for Fast Reactors:

* Modular pilot line with expandable capacity up to 40 tML/year by 2030
* Two capacity extensions of 40 tML/year each, in 2039 and 2042
* A proven manufacturing process based on those used by previous European plants
* Ability to process plutonium batches of varying quality by blending and homogenisation
* A virtuous production process designed to recycle scraps
* Low generation of technological waste, well controlled and measured by the use of modern, appropriate technologies

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Fig. 4 – newcleo’s fuel fabrication plant

## Shipping casks

*new*cleo has identified its fuel transport needs and launched a specific project as follows:

* Route 1: Lease and slight modification of existing 3rd party packages for the LFR-AS-30.
* Route 2: Build new *new*cleo packages for fleet of LFR-AS-200 reactors.

*new*cleo will enter in a commercial arrangement with an owner of a MOX package whereby *new*cleo would lease packages.

The 3rd party supplier would be responsible for all design, engineering, testing, licensing and manufacturing aspects associated with keeping the package in circulation for *new*cleo.

The 3rd party supplier would be responsible for ensuring that the package is licensed, relicensed and maintained as asked by all regulatory authorities where *new*cleo MOX fuel would be transported.

For the LFR-AS-200, *new*cleo will initiate a project to design, license and manufacture a fleet of MOX transport packages specific to our MOX fuel.

*new*cleo will own the design, the intellectual property and preferably the packages.

*new*cleo would be responsible for ensuring that the package is licensed by all regulatory authorities where *new*cleo MOX would be transported. Calculation, design, tests, and further maintenance should be subcontracted.

A route for used LFR fuels is currently under consideration, it will be defined in the same spirit as fresh fuel route 1 or route 2.



Fig. 5 – MOXLFR transportation scheme

## CONCLUSION

Starting in the early 2030s, newcleo's ambition is to contribute to the fuel cycle closure by deploying a Gen-IV LFR-SMR Fast Neutron Reactor combined with a MOXLFR fuel fabrication plant.

Our program contributes to Europe's decarbonised energy independence, the stabilisation of plutonium stocks and the reduction of the radiotoxicity of final waste.

The paper is presenting the main features of newcleo LFR-SMR and the R&D program initiated to validate both the material (steel and alloys) behaviour in lead environment and the performances of the main components (Steam generator-pumps…).

The second part of the paper show how the newcleo solution contributes to the fuel cycle closure in the French context in a symbiotic way with existing nuclear power and reprocessing plants.

The fuel supply of the LFR-SMR power plant will be performed in a newcleo fast reactor MOX fuel plant with a capacity adapted with the assumption on the LFR reactor deployment in Europe and beyond..

New casks are needed for the transportation of the LFR-200MWe MOX fresh fuels to anticipate this need newcleo will initiate a project for the design, licence and manufacturing of this fleet of transportation casks

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