

# THE H2020 EUROPEAN PROJECT LEU–FOREVER: LEU FUELS FOR MEDIUM AND HIGH POWER RESEARCH REACTORS IN EUROPE

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## ABSTRACT

Global efforts are on the way to minimize the use of highly enriched uranium in research reactors. In the EU, this conversion from high to low enriched uranium has already begun and is currently on its way towards the qualification phase. This concerns both medium and high power research reactors.

Neither for medium nor for high power research reactors are off-the-shelf low enriched uranium fuel elements available. Indeed, introducing a new type of fuel element in a research reactor implies the conservation or improvement of both safety and performance on one-of-a-kind units within specific safety legislation.

The H2020 European LEU-FOREVER Project (2017-2021), associating major actors of the European research reactors field – Framatome, CEA, CVŘ, ILL, NCBJ, SCK·CEN, TechnicAtome, TUM, aims to foster the development of sustainable and innovative low enriched uranium fuel elements for the whole spectrum of European research reactors.

## 1. Introduction

One of the biggest challenges for European research reactors is securing their nuclear fuel supply. Two major factors have been identified in this regard: (i) the ongoing conversion of High Performance Research Reactors (HPRRs) from high to low enriched nuclear fuels (LEU), and (ii) the diversification of fuel sourcing for Medium Power Research Reactors (MPRR) with an original Soviet design. A multi-disciplinary consortium composed of fuel and core designers, nuclear research centre operating research reactor and fuel manufacturers has been set up to tackle both issues in the framework of the H2020 European Project LEU-FOREvER (2017-2021). Key issues and operative solutions for this topic are underlined in the schematic drawing of Figure 1. This project is carried by CEA, CVR, Framatome, ILL, NCBJ, SCK•CEN, TechnicAtome and TUM. These actors are supplemented by an End-User Group (EUG), an advisory body consisting of representatives from potential end-users of the Project results.

Five of the members, AREVA-NP (now Framatome), CEA, ILL, SCK•CEN and TUM, constituting the HERACLES consortium, have been closely involved for almost 20 years in the development of LEU fuels for HPRR conversion. The focus of their common work has been the development of UMo based solutions, both dispersed and monolithic. Within LEU-FOREvER, optimisation of the manufacturing process up to the construction of pilot equipment, modelling of the in-pile behaviour and post-irradiation examinations of European fuels irradiated in the EMPIRE test at the Advanced Test Reactor (ATR) of the Idaho National Lab (INL) are addressed.

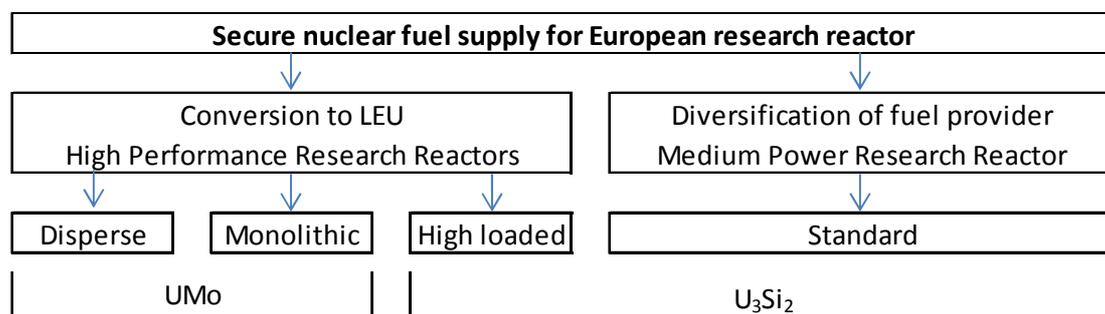


Figure 1: key issues and related nuclear fuel development to secure fuel supply for European research reactors.

As fall-back strategy to UMo based fuels, high loaded  $U_3Si_2$  is considered as second path toward conversion of HPRRs. Within LEU-FOREvER, design and manufacturing of such fuel plates will be optimised and tested in an irradiation experiment under representative high power and burn-up conditions.

For European MPRR, a new fuel assembly will be designed fabricated and irradiated within LEU-FOREvER. The LVR-15 reactor in the Czech Republic (CVR) will serve as a case study, identified in a preliminary analysis carried out by TechnicAtome which resulted in a robust design based on  $U_3Si_2/Al$  fuel plates. To improve economic competitiveness, Framatome will also reinvestigate its manufacturing process to identify optimisation opportunities.

As most HPRRs will also have to operate with a mixed core configuration during conversion and both HPRRs and MPRR are considering or even already using  $U_3Si_2/Al$  fuel plates, strong synergies are found between the two subprojects.

## 2. Objectives

### 2.1. Advance UMo fuel development

UMo based nuclear fuels, monolithic and dispersed, are promising candidates to carry out the conversion of HPRRs. In such a fuel system, the addition of molybdenum to uranium stabilises the body-centred cubic crystal structure of the high-temperature  $\gamma$ -phase of uranium under irradiation. Hence the transition to the low-temperature orthorhombic  $\alpha$ -phase with its strongly anisotropic thermal expansion is prevented with an addition of 7 or 10 wt.% Mo. This stoichiometry has been proven to be the best compromise between achievable uranium density and stabilisation of the phase behaviour.

Despite this inherent quality, significant obstacles were encountered on the way to qualification in the challenging environment of the HPRR regarding density of dispersion fuel, power and burn-up. The very first in-pile tests (IRIS2, FUTURE, IRIS3 0.3%Si) of nuclear fuels with a UMo/Al composition showed an unacceptable swelling under irradiation, in certain cases even leading to plate breakaway, even though these tests were only performed with limited surface power ( $\leq 350 \text{ W.cm}^{-2}$ ) [1] [2] [3]. The failure has been traced back to a UMo/Al Inter-Diffusion Layer (IDL) growing during in-pile irradiation at UMo-Al interfaces and to its unsatisfactory properties under irradiation: poor fission gas retention leads to the formation of large porosities at the interface between this IDL and the matrix, accompanied by low thermal conductivity [4].

The developments performed worldwide over the last fifteen years have successfully limited the IDL growth [5]. The beneficial effect of Si additions to the dispersion UMo fuel, and more recently the coating of UMo particles with a diffusion barrier can be observed in the gradual, controlled swelling up to higher burnups. A dispersion of UMo particles coated by Physical Vapour Deposition (PVD) with a 1  $\mu\text{m}$  thick ZrN layer, dispersed in an Al matrix, is currently the baseline solution for the conversion of most European HPRR.

Concerning the dispersed case, the key tasks of the comprehension phase are undoubtedly the SEMPER FIDELIS irradiation test (BR2, Mol – Belgium) and its sister experiment EMPIrE (ATR, Idaho – USA). These tests aim to fill the data gaps in the understanding of UMo fuel irradiation behaviour and assess a number of fabrication options for the dispersion UMo fuel. Both experiments are scheduled to start in 2017 with Post Irradiation Experiments lasting until 2020. With the progression of the current H2020 HERACLES-CP project (2015-2019) [6], identified additional knowledge and comprehension gaps will now be addressed in the LEU-FOREvER project.

Regarding the monolithic UMo fuel type, the developments and assessments performed in the HERACLES-CP project have made it possible to successfully demonstrate that the fabrication of monolithic UMo plates with the appropriate quality is entirely possible with the processes developed in Europe. Therefore, significant efforts can now be devoted to the next manufacturing steps and to improving the current manufacturing techniques.

Within the frame of the LEU-FOREvER proposal, the developments are threefold:

1. Irradiation temperature is suspected to have an influence on the swelling of UMo/Al based fuel and this influence will be studied using the SEMPER-FIDELIS test. To reach this objective, the fuel meat temperature will be computed using the CEA MAIA code that is dedicated to thermo-mechanical simulations of research reactor;
2. UMo particle coating is necessary to stabilize fuel plate swelling during irradiation. Prototypic equipment was designed for using Physical Vapor Deposition (PVD) at SCK•CEN and Atomic Layer Deposition (ALD) at Argonne National Laboratory (ANL, USA). It has been used for coating powders for the SELENIUM (PVD), SEMPER-FIDELIS (PVD) and EMPIrE tests (PVD & ALD). Within the HERACLES-CP H2020 project, the design of combined pilot equipment for both PVD and ALD is on-going. Its fabrication is a deliverable of the project by the end of May 2019. Within LEU-FOREvER, a combined (PVD and ALD) pilot equipment for coating, designed in the frame of the HERACLES-CP project, will be assessed with special care taken in the safety aspects;
3. Conducting first experiments on the fabrication of graded foils and the production of plates from such foils, albeit with inert material as precursor to monolithic UMo.

## **2.2. Demonstrate high loaded $U_3Si_2$ solution for HP RR**

The High Performance Research Reactors currently operating in Western Europe (RHF, BR2, FRM II) are fuelled with HEU either in an aluminide ( $UAl_x$ ) or silicide ( $U_3Si_2$ ) compounds dispersed in a pure Al matrix [7]. Lowering enrichment at constant  $^{235}U$  content involves a significant raise of the uranium surface density of the plate. A correlate of this uranium density increase is an increased parasitic absorption due to the higher amount of  $^{238}U$  in the core. This absorption needs to be overcome in order to maintain cycle length and neutron flux.

Within a given dispersion fuel system, two options are available to increase the fissile phase content:

- increase the volume fraction of fissile compound in the meat for a dispersion fuel;
- modify the geometry of the fuel assembly and/or fuel plates to accommodate more fuel meat volume, e.g. using thicker plates, larger plates or more plates per assembly.

In an optimised geometry, it would then be possible to increase the quantity of fissile material in the fuel assembly while maintaining the volume fraction of fuel at an acceptable level. One of these options or a combination of both approaches is necessary to create a viable fall-back option or for some cases may be even alternative to UMo based dispersion fuels for conversion.

As the aluminide fuel option is insufficient for achieving conversion with acceptable modifications of the fuel assembly geometry, the best candidate for developing such high loaded fuel is  $U_3Si_2$ . Under the NUREG-1313 Nuclear Regulatory Commission (NRC) document [8],  $U_3Si_2$  is qualified as a low power research reactor dispersion fuel at a loading of  $4.8 \text{ g}_U \cdot \text{cm}^{-3}$ , which is equivalent to a volume density of 42%. Other developments in the frame of Jules Horowitz Reactor (JHR) fuel qualification are ongoing to extend the use of  $U_3Si_2$  dispersion fuel to higher powers (i.e.  $500 \text{ W} \cdot \text{cm}^{-2}$ ) [9] [10] [11].

Within the LEU-FOREVER project, manufacturing developments and an irradiation for this high loaded  $U_3Si_2$  are planned. The manufacturing developments will permit to ascertain the manufacturability of such geometry modified fuels, and to set the boundary for the use of high loaded  $U_3Si_2$  fuels. The High Performance research Reactors Optimized Silicide Irradiation Test (HiPROSIT) experiment will then evaluate the behaviour under irradiation of such modified fuels. This test irradiation of 6 full size fuel plates will permit to assess different approaches to increase the loading of  $U_3Si_2$  fuel: increased density, increased meat thickness and a combination of both. These developments maximise the conversion probability.

### **2.3. Diversify fuel supply for European MPRR**

MPRR with an original Soviet design currently can have only a single fuel provider. An alternative to the fuel currently employed will be developed in LEU-FOREVER. Due to some differences between the manufacturing design, the detailed shape and characteristics of the new fuel assemblies, compliant with all the interfaces of the fuel assembly (geometry, performances, safety), will be different. The design of such a fuel therefore implies an in-depth analysis of the reactor and core from neutronics, thermo-hydraulics and overall design point of. In addition to these technical aspects, special care will be taken to develop a solution which is above all globally economically efficient. Thanks to the choice of a proven technology for the fuel element, the potential complementary qualification will only be at fuel assembly level.

For the design of a new fuel assembly, the LVR-15 research reactor will be the most detailed case study. Nevertheless, a first assessment of the BRR core, with a very different current fuel assembly will also be carrying out. .

The research reactor LVR-15 serves as a neutron source for basic and applied research, as well as for the practical needs of industry and irradiation for the production of radiopharmaceuticals.

LVR-15 is a pool-type light water research reactor, placed in a stainless steel vessel covered with the shielding lid and primary coolant, operating at a thermal power up to 10 MW. The reactor was put in trial operation in 1989 (first criticality occurred in 1957) after substantial refurbishing, and has been operating in continuous operation since 1995. In the framework of the Russian-American Global Threat Reduction Initiative (GTRI), the reactor underwent in 2009 a transformation from 36 wt%  $^{235}U$  enrichment to 19.7 wt%, maintaining its global fuel external geometry.

The active part of the reactor consists of 28-32 cells containing standard fuel assemblies. 12 fuel assemblies contain control rods (controlled assemblies); the 4 cells in the centre of the core contain channels for irradiation of samples. Located on the periphery of the core are the active channels of experimental loops, as well as a rotary channel for the silicon doping , a tube post and vertical irradiation channels. The remaining cells are equipped with a beryllium reflector or water displacers.

Currently, the reactor uses Russian IRT-4M sandwich-type fuel assemblies mainly composed of concentric square tubes [12], manufactured by NZCHK in Novosibirsk. The meat is composed of a dispersion of  $UO_2$  and aluminium powders. The Uranium loading in the meat is  $3 \text{ g.cm}^{-3}$  at an enrichment of 19.7 wt%  $^{235}U$  [13]. The assemblies have the form

of six or eight concentric square tubes. The central tube of the six-tube fuel assemblies can be equipped with a control rod channel. The inlet and outlet parts of the fuel assembly as well as the fuel cladding are made of aluminium. The length of the active fuel part is 600 mm. The  $^{235}\text{U}$  weight per assembly is around 260 g and 300 g, depending on the number of tubes in the assembly. The development of a fuel alternative for MPRRs by the LEU-FOREvER project will bring several enhancements for the operators of these reactors:

- Much greater ease of use, on a routine basis, of European origin fuel in reactors of Soviet origin ;
- Easy transition from historical fuel to new fuel, with respect to both technical and regulatory aspects ;
- Potential improvement of life cycle cost coupled with extended operating cycles.

First joint investigations to achieve these goals began in 2014 and will move forward considerably thanks to the developments carried out in LEU-FOREvER. To maximize the success probability of these efforts, the LEU-FOREvER consortium brings together a multidisciplinary team involving representatives of all involved entities:

- Reactor operators, i.e. CVR ;
- Fuel designers, to optimise both fuel “meat” and fuel “assemblies” i.e. TechnicAtome and Framatome ;
- Research reactor designers with all the relevant core design experience and calculation codes i.e. TechnicAtome.

A preliminary dimensioning has already been developed for a LVR-15 fuel alternative based on assemblies with a European design, i.e. with parallel flat plates and  $\text{U}_3\text{Si}_2/\text{Al}$  meat. Significant manufacturing and operating experience already exists for this kind of fuel assembly in Europe, as the OSIRIS material testing reactor has been fuelled with assemblies of the same geometry and almost the same fuel composition.

Indeed, preliminary drawings have been made for both standard and control fuel elements, making it possible to verify the feasibility of moving from one type to the other. Even if it is still possible to optimize the  $^{235}\text{U}$  density, moderator volume, plate shapes, etc. Furthermore, it will be verified that the envisaged  $\text{U}_3\text{Si}_2/\text{Al}$  fuel plate usage in LVR-15 is covered by NUREG-1313 [8] regarding the fuel operational parameters. This will make the qualification phase considerably shorter and cheaper.

By implementing an innovative methodology for fuel assembly design such as the design-to-cost methodology and by involving all relevant parties from designer to manufacturer and to reactor operator, LEU-FOREvER aims to design and produce an economically attractive alternative fuel assembly based on proven European technology, produced by a European manufacturer.

### **3. Conclusion**

An ambitious work program has been proposed within LEU-FOREvER to provide solutions to HPRRs for their conversion. Developments are pursued in three directions (dispersed

UMo, monolithic UMo and high loaded  $U_3Si_2$ ) to obtain a robust evaluation of their maturity, by the end of 2021 and before starting the qualification phase. Indeed in addition to the manufacturing studies undertaken for these three concepts, each of these solutions will have been tested under in-pile irradiation in three different tests: SEMPER FIDELIS for dispersed UMo within the frame of HERACLES CP, EMPIrE for monolithic UMo supported by the HERACLES group and finally HiPROSIT for high loaded  $U_3Si_2$  thanks to LEU-FOREvER.

For MPRR, LEU-FOREvER will open up the possibility of an alternative nuclear fuel supply to other European MPRR and thus enhance their sustainability. Indeed, on completion of this project, the following should be available:

- A summary report based on “Research reactor licensing and the research reactor fuel manufacturing licensing framework based on MARIA reactor conversion experience” ;
- A hydraulic test loop for new fuel assembly pressure drop test ;
- First-of-a-kind fuel assembly irradiation in LVR-15.

A way forward will be defined for other reactors, which are willing to initiate the process, irrespective of their participation in LEU-FOREvER, or in the end-user group. Based on LVR-15 experience and LEU-FOREvER development, these reactors will benefit from an accelerated process for their conversion.

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