The H2020 european project fuel for research reactors LEU–forever: leu fuels for medium and high power research reactors in Europe

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

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ABSTRACT

The minimization of proliferation risks for research reactors necessitates the reduction of the enrichment of the uranium fuels. 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 –Areva-NP, CEA, Centrum výzkumu Řež, 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 monopoly for the manufacture of fuel for Medium Power Research Reactors (MPRR) with an original Soviet design. A multi-disciplinary consortium composed of fuel/core designers, operators 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.

Five of the members, AREVA NP, 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 at the ATR are addressed.

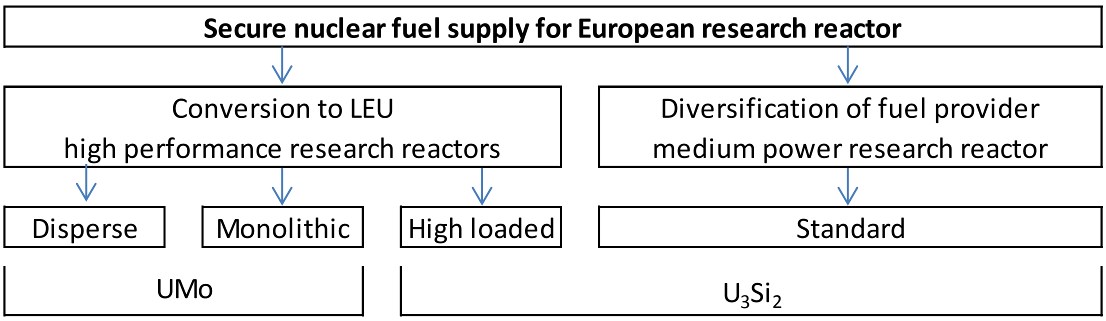

Figure 1: key issues and related nuclear fuel development to secure fuel supply for European research reactors.

An alternative to UMo based fuels, high loaded U_3Si_2, appears also to be a possible path toward conversion of HPRR. Within LEU-FOREvER, design and manufacturing will be optimised and tested in an irradiation experiment under representative high power and burn-up.

For European MPRR, a new mixed core design is under definition to operate with both the original and new fuel elements that will be developed, licensed and qualified 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 flat fuel plates. To improve economic competitiveness, AREVA NP 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 in both 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 HPRR. In such a fuel system, the addition of molybdenum to uranium stabilises the body-centred cubic crystal structure of the high-temperature γ-phase of uranium under irradiation. Hence the transition to the low-temperature orthorhombic α-phase with its strongly anisotropic thermal expansion, is prevented with an addition of 7 or 10 wt.% Mo. These stoechiometries have been proven to be the best compromise between achievable uranium densities 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 under limited surface power (≤350 $W.cm^{-2}$) [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, probable 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 µm 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 PIEs lasting until 2020. With the progression of the current H2020 HERACLES-CP project (2015-2019), 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 dedicated to thermos-mechanical simulations of research reactor ;

2. UMo particle coating is necessary to stabilize fuel plate swelling during irradiation. Prototypic equipment was designed for using PVD (SCK•CEN, Belgium) and ALD (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 HPRR

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 [6]. 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, more plates per assembly.

In an optimised geometry, it would then be possible to increase the quantity of fissile material in the assembly still maintaining the volume fraction of fuel at an acceptable level. One of these options or a combination of both approaches may offer an alternative to UMo based dispersion fuels for conversion.

As the aluminide fuel option is insufficient for achieving conversion with acceptable modifications of the assembly geometry, the best candidate for developing such high loaded fuel is U_3Si_2. Under the NUREG-1313 NRC document [7], U_3Si_2 is qualified as a low power research reactor dispersion fuel at a loading of 4.8 $g_U.cm^{-3}$, which is equivalent to a volume density of 42%. Other developments in the frame of JHR fuel qualification are ongoing to extend the use of U_3Si_2 dispersion fuel to higher powers (i.e. 500 $W.cm^{-2}$) [8] [9] [10].

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 fix the boundary for the use of high loading 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 flat 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 and thereby minimise the risk of proliferation.

2.3. Diversify fuel supply for European MPRR

MPRR with an original Soviet design have a single fuel provider. An alternative to the fuel currently employed will be developed in LEU-FOREvER. However, the assembly will have different characteristics, eg. geometry, fuel composition, uranium loading. The use of such a fuel therefore implies an in-depth analysis of the reactor neutronics, thermo-hydraulics and the design of the MPRR core. In addition to these technical aspects, special care will be taken to develop a solution which is also economically efficient. Here, the direct aim of LEU-FOREvER is the qualification of a well-assessed fuel solution.

For this work, the LVR-15 research reactor will be a case study. First, it is representative of several other MPRR in Europe. Second, it has a very good operational record.

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 coolant flow, operating at a thermal power up to 10 MW. The reactor was put in trial operation in 1989 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 a transformation from 36 % enrichment to 19.7 % in 2009, maintaining its fuel geometry.

The active part of the reactor consists of 28-32 cells containing standard fuel assemblies. 12 fuel assemblies contain control rods (control 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 doping of silicon, 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, 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 2.77 $g.cm^{-3}$ at an enrichment of 19.7%. 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 fuel assembly is 880 mm, the length of the active fuel part is 600 mm. The ^{235}U weight per assembly is approx. 230 g and 263.8 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 Russian origin ;
- Facilitated transition from historical fuel to new fuel, with respect to both technical and regulatory aspects ;
- Improved life cycle cost coupled with extended operating cycles.

Extensive joint investigations to achieve these goals already 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 affected entities:

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

A preliminary dimensioning has already been developped for a LVR-15 fuel alternative based on assemblies with a European design, i.e. with parallel flat plates and U_3Si_2/Al meat. Significant manufacturing and operating experience already exists for this kind of 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. It was verified that even though the total fuel plate heating surfaces are drastically different in both assembly designs, it is still possible to optimise the $_{235}U$ density, moderator volume, plate shapes, etc. Furthermore, it has been verified that the envisaged U_3Si_2/Al fuel plate usage in LVR-15 is covered by NUREG 1313 [7] as suggested by the UO_2/Al fuel operational parameters in Table 4. This will make the qualification phase considerably shorter and cheaper. Finally, it has been verified that control elements are also compatible with the use of flat fuel plates.

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 element based on solid European technology, produced by a European manufacturer. Moreover, efforts will be made to enhance fuel lifecycle costs. As an example, the possible use of burnable poison will be assessed. To do so, the COCONEUT neutronic scheme developed by AREVA-TA will be implemented [11].

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, by the end of 2021 before starting the qualification phase, a robust evaluation of their maturity. 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 all 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 ;
- Neutronic and thermal hydraulic codes at CVR, able to calculate a LVR-15 mixed core, i.e. a mix of Russian and European designs ;
- First-of-a-kind fuel assembly irradiation in LVR-15.

Beyond LEU-FOREvER, it is anticipated that CVR will be able to start the process of regulatory approval for LVR-15 operation with a mixed core beyond 2020:

- Irradiation of another LTA (Lead test assembly) to verify its performance at very high levels of burn-up ;
- Neutronic and thermal hydraulics codes qualification and validation ;
- Full amendment of the safety report to be allowed to operate with a mixed core.

For other reactors, irrespective of whether or not, they are members of LEU-FOREvER, or the end-user group, who are willing to initiate the process, a way forward will be defined. Based on LVR-15 experience and LEU-FOREvER development, these reactors can expect to benefit from an accelerated process for their conversion.

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