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REVIEW ARTICLE **OPEN ACCESS**

Innovation and qualification of LEU research reactor fuels and materials

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Abstract. Two projects within the Euratom Research and Training Programmes 2014–2018 and 2019–2020 are focused on the innovation and qualification of novel nuclear fuels for conversion from highly-enriched uranium to low-enriched uranium (LEU) and for securing the supply chain of EU research reactors into the future. The LEU-FOREvER project is drawing to a close and has made significant progress in developing and demonstrating the uranium-molybdenum fuel system, demonstrating the viability of a high-density uranium-silicide fuel for EU high-performance research reactors (BR2, RHF, FRM-II, JHR). This project has significantly increased the fabrication know-how and fuel performance understanding of the uranium-molybdenum and high-density uranium-silicide dispersion fuel systems. Further, a new, innovative and increased performance design for the LVR-15 research reactor fuel assembly has been engineered and a demonstration is planned in 2022. In the EU-QUALIFY project, which began in 2020, the planning of four demonstration irradiation tests has been nearly completed and fabrication development of the various fuel systems is ongoing, including the establishment of an EU monolithic uranium-molybdenum fabrication capability. It is expected that the results of this project will begin or complete the data gathering necessary for generic fuel qualification of the LEU uranium-molybdenum dispersion and monolithic fuel systems, and the LEU high-density uranium-silicide fuel system.

1 Introduction

Two projects targeting innovation and qualification of LEU research reactor fuels and materials are currently being executed within the Euratom Research and Training Programmes, i.e. the "Low Enriched Uranium Fuels fOR REsEarch Reactors" (LEU-FOREvER) [1,2] and the "EUropean QUALIFication approach for low enriched fuel sYstems for secure production supply of medical isotopes" (EU-QUALIFY) [3]. These projects are complimentary and overlapping (started 3 years apart in 2017 and 2020) and they follow a general framework for fuel qualification planned by the HERACLES consortium to support the worldwide non-proliferation efforts. The HERACLES consortium is comprised of 4 research institutions with respective high performance research reactors: Commissariat á l'énergie atomique et aux énergies alternatives (CEA in France), Institut Laue-Langevin (ILL; France), Technische Universität München (TUM; Germany), SCK CEN (Belgium), and the EU research reactor fuel fabricator Framatome (CERCA; France). The two projects presented herein are consecutive initiatives of HERACLES to further develop research reactor fuels to enable conversion from highly-enriched uranium (HEU) to low-enriched uranium (LEU) specifically for high-performance research reactors (HPRR), for which the physical form and/or demonstrated fuel performance behavior of the classical LEU (4.8 gU/cc) silicide fuel is insufficient for direct use or application. The main route of accomplishing this, e.g. for the European HPRRs given in Table 1, is to increase the uranium loading over the aforementioned 4.8 gU/cc through various means and to demonstrate the behavior of these novels fuels at high-performance conditions through irradiation testing and post-irradiation examinations. Other prime objectives include ensuring the fabrication capabilities are established and qualified, and that all fabrication, irradiation, and PIE data are collected and usable for fuel performance modeling to support LEU qualification and conversion reports. These activities naturally combine to secure the European supply chain of both research reactor services and the global supply of medical isotopes into the foreseeable future. The structure of the HERACLES consortium program with completed, ongoing, and planned irradiation campaigns is shown in Figure 1 and a simplified fabrication route description of the here studied fuel systems is shown in Figure 2.

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Table 1. European HPRRs, operators, and their target fuel system(s) for conversion.

Reactor (primary type)	Operator/Organization	Current fuel system(s) targeted for potential conversion
BR2 – Belgian Reactor 2 (material test reactor)	SCK CEN Mol, Belgium	U_3Si_2 / UMo dispersion
FRM-II – Forschungs-Neutronenquelle Heinz Maier-Leibnitz (neutron source, beam-tube reactor)	Technische Universität München (TUM) Garching bei München, Germany	UMo monolithic
RHF – Réacteur a Haut Flux (neutron source, beam-tube reactor)	Institut Laue-Langevin (ILL) Grenoble, France	U_3Si_2 / UMo dispersion
JHR – Jules Horowitz Reactor (material test reactor) *Note*: Under construction	Commissariat à l'Energie Atomique (CEA) Cadarache, France	U_3Si_2 / UMo dispersion / UMomonolithic[1]

[1] The driver fuel for the first years of nominal operations of JHR will not be High Assay LEU (HALEU; <20 % U-235 enrichment). For the JHR reference fuel after this period, CEA is deeply involved in the international collaborations aiming to develop and qualify the various HALEU fuels, in particular within the HERACLES consortium (high loaded U_3Si_2, UMo dispersion and monolithic fuels) [38,39].

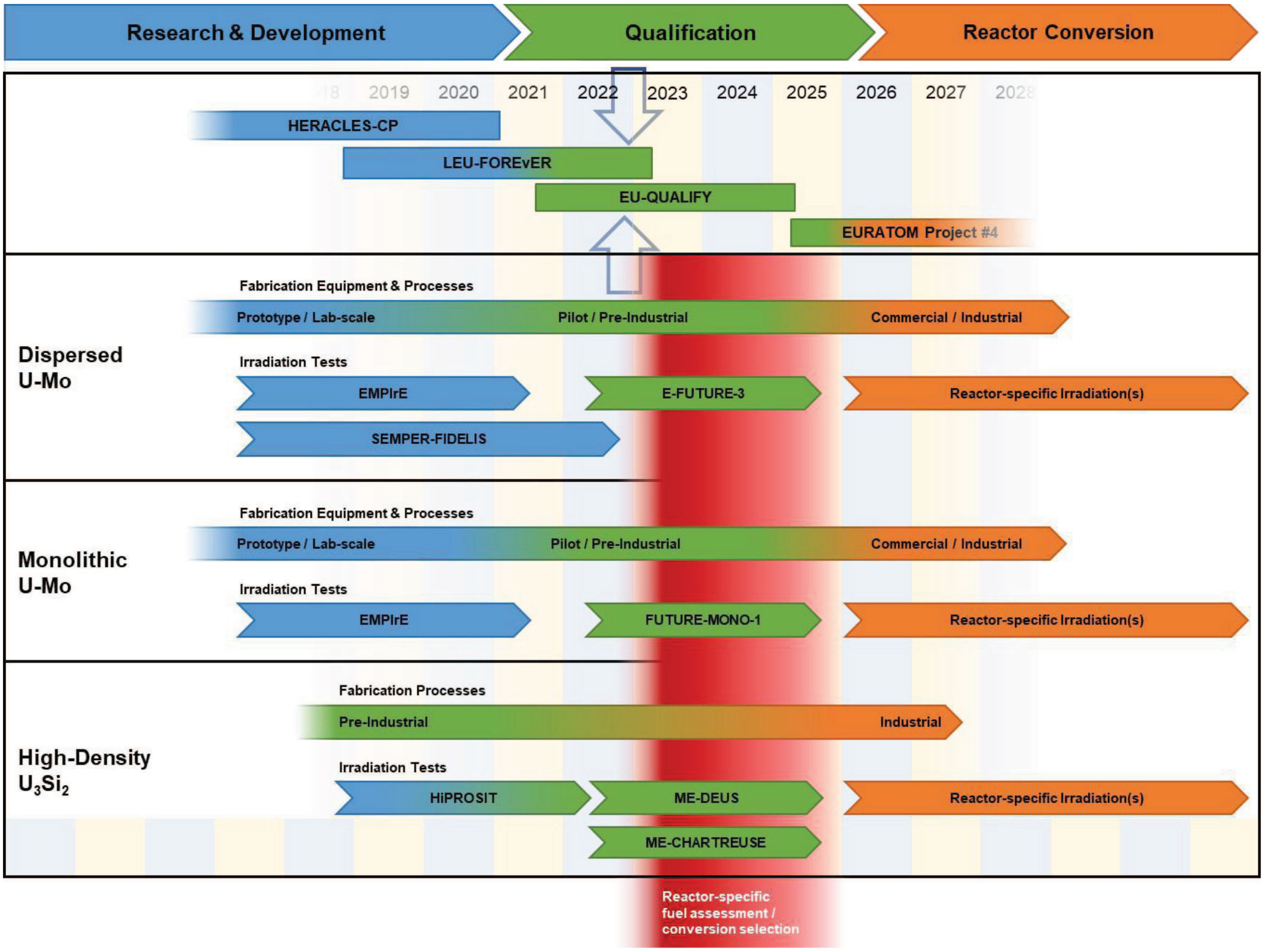


Fig. 1. The HERACLES consortium program with planned irradiation campaigns for advanced research reactor fuels. The LEU-FOREvER and EU-QUALIFY projects are indicated with arrows.

2 Fuel loading and systems

The research reactor (RR) fuel systems that the HERACLES consortia are developing and qualifying have differences in the uranium loading that makes them interesting for different reactor-specific conversion projects. Many LEU conversions are constrained by limited or no geometrical/dimensional changes of the fuel plates and assemblies. In many cases, this leads to the uranium loading being the limiting factor in the choice of a suitable fuel system for the RR conversion. Also, HEU to LEU conversion necessitates countering the neutronic penalty of U-238 to fulfill the reactor-specific fuel performance requirements such as cycle length and the neutron flux.

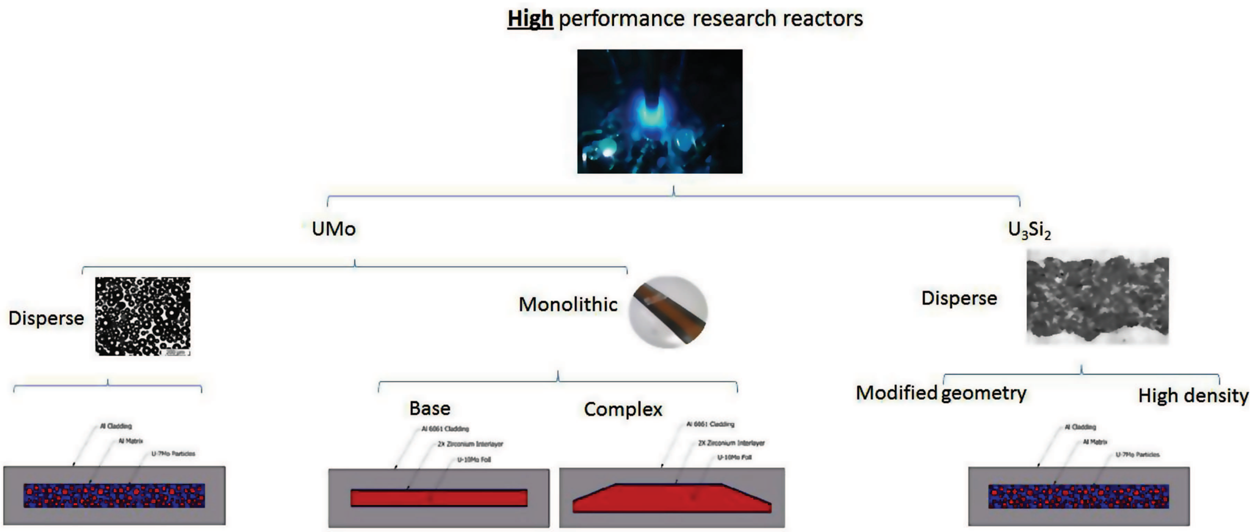


Fig. 2. Fuel system fabrication routes studied in LEU-FOREvER and EU-QUALIFY.

Naturally, the reactor design itself will limit the available meat dimensions, e.g. the maximum fuel zone thickness, obtainable without affecting safety parameters in the existing fuel core design. A higher loading or density increases the flexibility to find a suitable design option (e.g. increasing total uranium in the same volume/fuel core thickness) and can accommodate a larger range in suitable meat thicknesses (in relation to the classical 4.8 gU/cc U_3Si_2) [4,5] with the same surface loading or gain in surface loading at a constant meat thickness. It should be noted that many factors interplay in the selection of a suitable reactor-specific conversion alternative. The following paragraphs outline the three (3) key fuel systems being pursued for qualification.

2.1 High-loaded U_3Si_2 dispersion fuel

The experience and fabrication status of the LEU 4.8 gU/cc loading U_3Si_2 fuel system is explained in greater detail in [4] and this fuel is widely used in research reactors throughout the world. This fuel type is a roll-bonded dispersion fuel core, with U_3Si_2 fuel dispersed in a pure aluminium matrix. The silicide fuel at 4.8 gU/cc loading is fully qualified and this fuel has been manufactured by Framatome since the1980s, with a well-established manufacturing process, thus with high manufacturing and technology readiness level. However, the U_3Si_2 high-loaded or high-density (HD) fuel development, e.g. 5.3 → 5.6 gU/cc at higher power conditions, for specific RR needs revision regarding quality criteria, optimized fabrication processes, and actions for reducing cost and fabrication time in order to increase the security of supply of suitable LEU fuel for the low and medium power research reactors [5–7,32,33].

2.2 UMo dispersion fuel

The UMo-based fuel systems have a rather high intrinsic density of about 16 gU/cc in UMo. When used in the typical aluminium matrix dispersion fuel, with a fabrication-based limit of about 50 volume percent, the achievable fuel meat loading is ∼8 gU/cc in the fuel meat. The UMo dispersion fuel behavior has been studied in the irradiation experiments such as FUTURE, IRIS, E-FUTURE, and SELENIUM, [8–12], and most recently in the LEU-FOREvER project irradiation named: SEMPER FIDELIS [13,14] (all irradiated in BR2). The current state-of-the-art development is targeting the reduction of the detrimental swelling of UMo-Al fuel plates at high power and high burnup by heat treatment, ZrN PVD coating of the UMo particles [15], and adding a small amount of silicon in the matrix. Further development will continue in the EU-QUALIFY project, through the execution of the E-FUTURE-III experiment, planned for irradiation in BR2.

2.3 UMo monolithic fuel

The UMo monolithic fuel is currently the fuel system that is closest to producing fission densities for HEU to LEU conversion of the very high-power research reactors, e.g., FRM-II and the ATR reactor in the US. The U.S. Department of Energy's United States High-Performance Research Reactor (USHPRR) Conversion Project has investigated low-enriched uranium (LEU) since 1978 as an alternative to highly enriched uranium. Due to the high loading and good fabrication performance, U-10Mo was chosen as the most promising LEU fuel for the conversion of all USHPRRs [9,18–20,23–27].

The fabrication of the UMo monolithic fuel with a U loading of ∼16 gU/cc is significantly different from the dispersion UMo and silicide fuel systems [21]. Monolithic fuel foils are a solid alloy clad in aluminium [22]. The USHPRR fabrication process of the monolithic fuel foil and plate requires multiple complex thermo-mechanical processes including casting, homogenization, hot/cold rolling, annealing, and hot isostatic pressing.

This fuel pate type has the highest possible uranium density of all current state-of-the-art options. The monolithic plate bonding method developed at CERCA, i.e. C2TWP [16] will be further developed to encompass full-size plates. The development of the EU process and capability was first demonstrated in the "European Mini-Plate Irradiation Experiment" (EMPIrE) which was irradiated in the ATR and evaluated in the LEU-FOREvER project and will continue in the EU-QUALIFY project, in the form of the FUTURE-MONO-1 experiment (planned for irradiation in BR2).

3 Fuel performance development and qualification

Fuel development and qualification projects for research reactor fuel have been conducted in the EU and abroad for many decades. These projects have had a similar process including:

- identification of suitable candidate fuel(s).
  - Typically through preliminary/simple neutronic and fabrication studies.
  - Typically through optimizations/improvements to existing fuel systems.
- Fabrication development and demonstration.
- Irradiation testing.
- Post-irradiation examinations (PIE).

Depending on the complexity of the change, fuel development is normally a feedback loop, where information obtained from the various development steps is normally fed back to the beginning to continue to optimize the fuel design until a suitable fuel can be demonstrated to be:

(1) acceptable for meeting reactor-specific fuel performance requirements,
(2) stable, predictable, and safe (including at reactor-specific safety requirements),
(3) affordable, such that the reactor can sustainably obtain and dispose of the fuel.

The transition from development to qualification is often marked by the irradiation and examination of various fuel plates that are similar or identical after the design has been chosen. This may also be followed by irradiation in fuel assemblies with multiple fuel plates. The typical progression of an MTR experiment to build upon the previous knowledge or experience to reduce the likelihood of an unintended event during irradiation (e.g. fission product release) includes the following steps:

- Step 1: identify/document previous relevant fuel performance or perform a mini-test
  - Document existing fuel performance from relevant development, qualification, or reactor operation
  - Perform an irradiation test with mini plates
- Step 2: perform an initial full-size fuel plate irradiation at moderate fuel performance conditions
  - Moderate heat flux: 250–350 W/cm^2
  - Moderate U-235 burnup: 40–50% U-235 burnup
- Step 3: perform a fuel plate irradiation (e.g. FUTURE device) at high-performance conditions
  - High heat flux: 400–500 W/cm^2
  - High U-235 burnup: 65–80% U-235 burnup
- Step 4: perform a fuel assembly irradiation at typical performance conditions
  - Typical conditions for the specific reactor.

Irradiation testing and subsequent PIE can have significant costs and time durations. It is, therefore, necessary to adequately plan these projects based on existing data, previous experience, and expert judgment. Two international expert groups have been established within the framework of the HERACLES group to enable this review and planning: the Fuel Development Expert Group (FDEG) and the Fuel Manufacturing Expert Group (FMEG). The FDEG provides expert opinions and recommendations on fuel performance-related issues and potential design changes, while the FMEG provides this type of information on fabrication processes and equipment. They work together to identify fuel design improvements (e.g. materials, composition, fabrication processes, and equipment) in the feedback loop of development and qualification. The FDEG group also leads the establishment of fuel performance databases and fuel qualification reports.

3.1 Irradiation testing

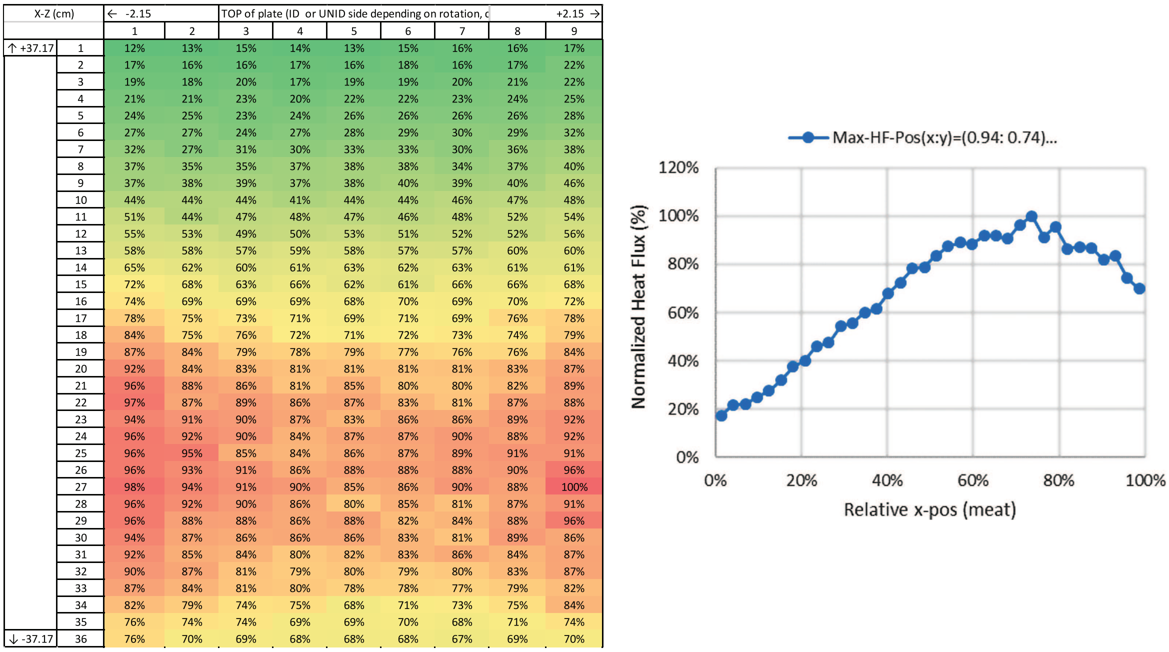
Irradiation testing includes extensive neutronics calculations to ensure the appropriate experiment conditions are obtained and verified. At SCK CEN, the MCNP software, which utilizes Monte Carlo methods to estimate the particle interactions during an irradiation cycle is used for pre-and post-irradiation calculations. The pre-irradiation neutronics is based on an *assumed BR2 reactor core* and the post-neutronics on the *actual BR2 reactor core* and BR2 power and control rod histories. The neutronic calculations are conducted to evaluate essential exposure statistics, usually determined at beginning of cycle (BOC), 3 days into the irradiation (3D), and at the end of cycle (EOC). The main parameters estimated and verified are:

- peak and average heat flux (W/cm^2), "target" values with the pre-irradiation neutronics, and 'acquired' results with the post-irradiation neutronic calculations over the plate "meat" section.
- Peak and average U-235 burnup (%), target and acquired.
- Peak and average Fission distribution (e.g. fissions/cc meat), target and acquired.

An example of a heat flux distribution, here normalized by the maximum for visualization purposes, is shown in Figure 3 with a typical FUTURE plate calculation mesh.

3.2 Post-irradiation examinations

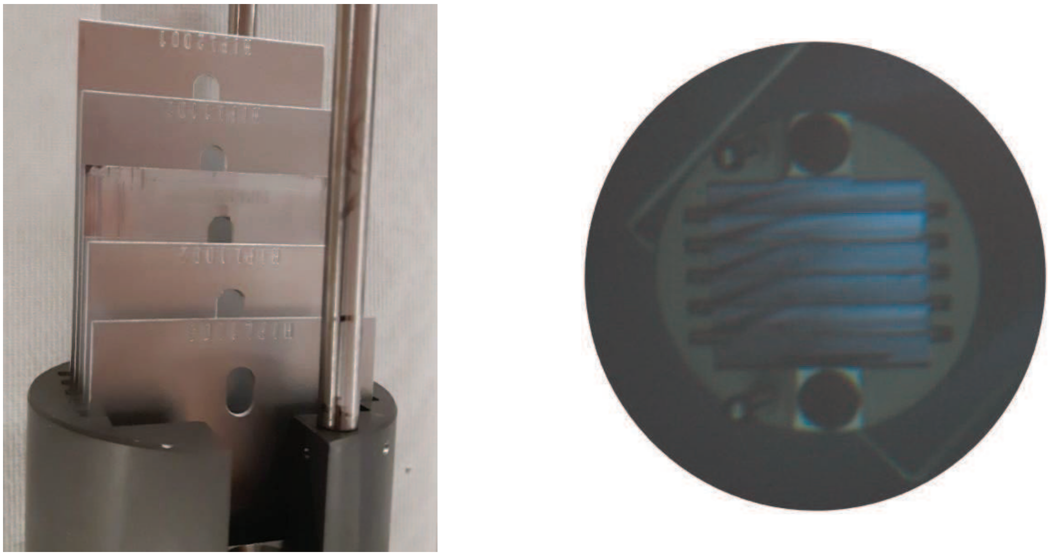
Post-irradiation examinations are conducted in two phases: non-destructive exams (NDE) and destructive



X-Z (cm)		← -2.15		TOP of plate (ID or UNID side depending on rotation, c				+2.15 →
		1	2	3	4	5	6	7	8	9
↑ +37.17	1	12%	13%	15%	14%	13%	15%	16%	16%	17%
	2	17%	16%	16%	17%	16%	18%	16%	17%	22%
	3	19%	18%	20%	17%	19%	19%	20%	21%	22%
	4	21%	21%	23%	20%	22%	22%	23%	24%	25%
	5	24%	25%	23%	24%	26%	26%	26%	26%	28%
	6	27%	27%	24%	27%	28%	29%	30%	29%	32%
	7	32%	27%	31%	30%	33%	33%	30%	36%	38%
	8	37%	35%	35%	37%	38%	38%	34%	37%	40%
	9	37%	38%	39%	37%	38%	40%	39%	40%	46%
	10	44%	44%	44%	41%	44%	44%	46%	47%	48%
	11	51%	44%	47%	48%	47%	46%	48%	52%	54%
	12	55%	53%	49%	50%	53%	51%	52%	52%	56%
	13	58%	58%	57%	59%	58%	57%	57%	60%	60%
	14	65%	62%	60%	61%	63%	62%	63%	61%	61%
	15	72%	68%	63%	66%	62%	61%	66%	66%	68%
	16	74%	69%	69%	69%	68%	70%	69%	70%	72%
	17	78%	75%	73%	71%	69%	71%	69%	76%	78%
	18	84%	75%	76%	72%	71%	72%	73%	74%	79%
	19	87%	84%	79%	78%	79%	77%	76%	76%	84%
	20	92%	84%	83%	81%	81%	81%	81%	83%	87%
	21	96%	88%	86%	81%	85%	80%	80%	82%	89%
	22	97%	87%	89%	86%	87%	83%	81%	87%	88%
	23	94%	91%	90%	87%	83%	86%	86%	89%	92%
	24	96%	92%	90%	84%	87%	87%	90%	88%	92%
	25	96%	95%	85%	84%	86%	87%	89%	91%	91%
	26	96%	93%	91%	86%	88%	88%	88%	90%	96%
	27	98%	94%	91%	90%	85%	86%	90%	88%	100%
	28	96%	92%	90%	86%	80%	85%	81%	87%	91%
	29	96%	88%	88%	86%	88%	82%	84%	88%	96%
	30	94%	87%	86%	86%	86%	83%	81%	89%	86%
	31	92%	85%	84%	80%	82%	83%	86%	84%	87%
	32	90%	87%	81%	79%	80%	79%	80%	83%	87%
	33	87%	84%	81%	80%	78%	78%	77%	79%	82%
	34	82%	79%	74%	75%	68%	71%	73%	75%	84%
	35	76%	74%	74%	69%	69%	70%	68%	71%	74%
↓ -37.17	36	76%	70%	69%	68%	68%	68%	67%	69%	70%

A B

Fig. 3. (A) Example of calculated BR2 heat flux distribution at BOC (normalized, full plate) and (B) length distribution at the maximum location.



A *B*

Fig. 4. (A) FUTURE-5 basket with plates, (B) fuel plates in the in-pile section (IPS) [5].

exams (DE). The NDE is performed to identify any abnormal conditions on the outside of the irradiated fuel plate, quantify the fuel swelling, and verify post-irradiation neutronics analysis results. The exams may include:

- when the BR2 FUTURE-5 basket is used, inter-cycle observations can be performed where both sides of each fuel plate (see Fig. 4) are examined underwater from video recordings of the plates being pulled out of the basket. The underwater observations after each cycle verify the absence of abnormal indications, oxidation, excessive swelling, and buckling and that the plates remain fairly flat.
- Detailed photography of the surface of both sides of each plate can be obtained to review any defects or discolorations that may lead to further investigation.
- High-precision (+/−1 µm) profilometry and oxide thickness measurements of each plate with the SCK CEN Bench for non-destructive analysis of plate and

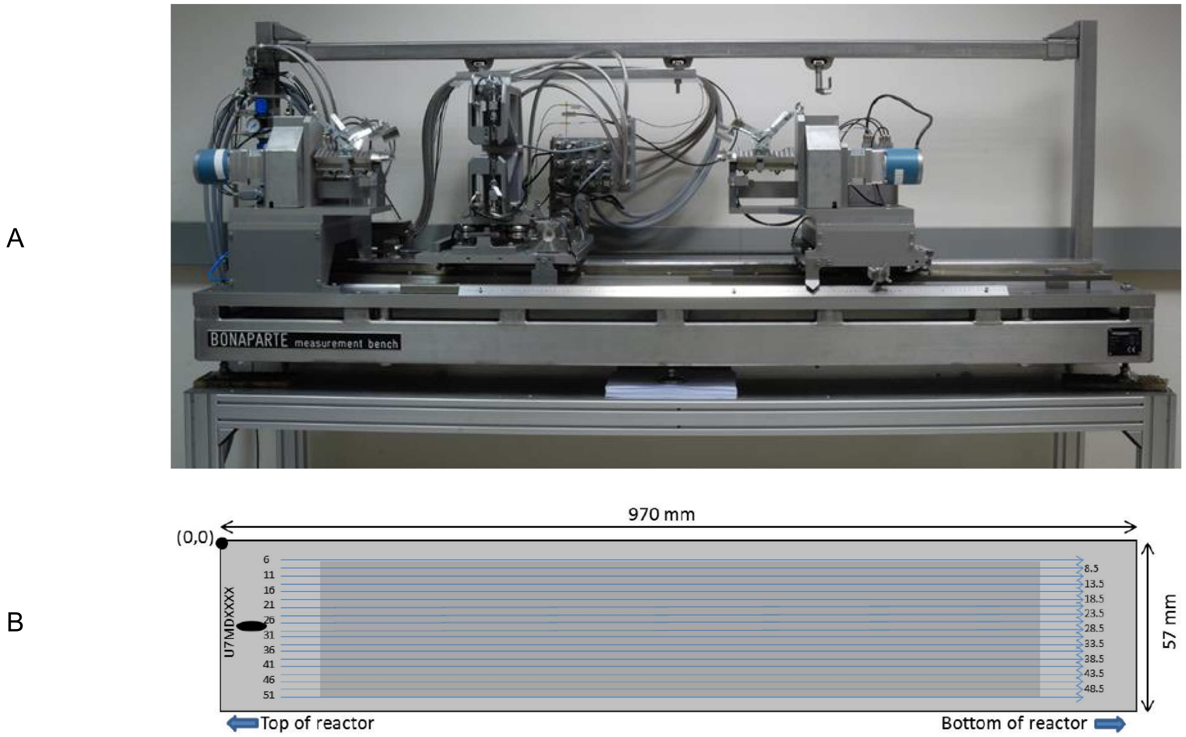


Fig. 5. (A) The BONAPARTE measuring device. (B) Coordinate system adopted for the BONAPARTE measurement results for a typical FUTURE plate.

- rod-type fuel elements (BONAPARTE) measurement device (see Fig. 5). This data is used to perform detailed fuel swelling calculations. The oxide layer composition can vary on a fuel plate depending on the cladding type and the pH of the reactor. The RR plates that are tested in BR2 typically result in the formation of a multi-layered aluminium oxide that is mostly a boehmite layer [AlO(OH)] [37].
- Gamma scanning to determine the relative axial and transverse fuel-burnup profiles and fission product relocation to aid in evaluating the performance of the irradiated fuel plates.

After NDE, a non-destructive examination PIE report is issued and is used for updating the plan for destructive examinations (DE), including locations for performing the cutting of samples. The DE aims to evaluate fuel composition, fuel swelling, interaction layers, oxide growth, interdiffusion, impurities, and other relevant observations, and chemical burnup analysis for further confirmation of post-irradiation U-235 burnup analyses.

The general approach is to have representative samples from the top (T), middle (M), and bottom (B) of the plate or high, medium, and low burnup locations for examination in both the longitudinal and transverse directions. After samples are prepared, the examinations may include the following measurement/evaluation techniques:

- Scanning Electron Microscopy (SEM)
- Electron Probe Micro Analyzer (EPMA)
- Focused Ion Beam (FIB)/Transmission Electron Microscope (TEM)
- Radiochemistry burnup analysis.

4 Project-specific innovations

4.1 LEU-FOREvER project

Within the Euratom-funded LEU-FOREvER project, further development of all three fuel systems shown in Figure 2 has been achieved. Most of this project has been executed, and it is expected to be fully completed in late 2022. The fuel performance understanding and the fabrication equipment and processes of the UMo dispersion fuel system [8,10] have significantly matured during the project. The increased fuel performance understanding was primarily based on the FDEG review of the SEMPER-FIDELIS [28] experiment that was irradiated in ATR and examined in the previous Euratom project: HERACLES-CP [29].

A significant achievement was made in the demonstration of an alternative high-density fuel system: U_3Si_2 [5]. This was achieved through the successful irradiation of four (4) high-density/high-loaded (4.8–5.6 gU/cc) silicide fuel plates in the BR2 reactor, which subsequently received non-destructive PIE [14] to confirm the acceptable fuel performance at high heat flux (peak heat flux: 450 W/cm^2) and high U-235 burnup (peak U-235 burnup: 80%). This successful demonstration of fuel plates at representative high-performance conditions has opened

Table 2. LEU-FOREvER targeted fabrication technologies and verification experiments for specific fuel systems and gained verification of specific objectives.

Fuel system & technology	LEU-FOREvER experiment	*Gained* improvement/verification	References
HD U_3Si_2 fabrication	HiPROSIT	Fabrication demonstration of high-loading and high-density silicide fuel in full-size plates (4.8–5.6 gU/cc)	[32,33]
HD U_3Si_2 general fuel performance	HiPROSIT	Irradiation & PIE confirmation of high loading and HD silicide fuel behavior (4.8–5.6 gU/cc)	
		Development of the fuel performance modeling to include HD silicide	[5,11]
UMo dispersion fabrication	SEMPER-FIDELIS	Fabrication demonstration of fuel powder heat treatment process	
		Fabrication demonstration of the new design of a fuel particle coating device	
		Fabrication demonstration of UMo dispersion in full-size plates	[9,10,15]
UMo dispersed general fuel performance	SEMPER-FIDELIS	Confirmation of atomized, heat-treated, ZrN-coated U7Mo fuel with and without Si added to the pure Al matrix at high power and high burnup through analysis of PIE results and modeling	[5,10,13,14,17,31,34]
UMo monolithic fabrication	EMPIrE	Fabrication demonstration of the PVD Zr coating process and equipment on representative-size foils	
		Fabrication demonstration of the C2TWP EU cladding process on mini plates	[21]
UMo monolithic general fuel performance	EMPIrE	PIE confirmation of the PVD-coated U10Mo monolithic fuel with C2TWP process at moderate-high power and moderate-high burnup	[22]
U_3Si_2	4EVERTEST	Demonstration of a substitution element for European Reactor with original Russian design	[35,36]

a credible alternative pathway for LEU conversion of high-performance research reactors still using HEU.

Other notable accomplishments in the project include the further development of the equipment and processes of the monolithic UMo fuel system and the successful design, fabrication, and irradiation of a new fuel assembly design for the LVR-15 medium power research reactor. The confirmation of the monolithic UMo fuel system fabrication was demonstrated in a US Department of Energy-funded irradiation experiment called EMPIrE, with mini-plates tested in the ATR reactor (USA) [9]. The PIE of these monolithic plates was included in the scope for this LEU-FOREvER project, and these results are positive and sufficient to enable further irradiation testing in the next project. The new fuel assembly for LVR-15 [30] demonstrates an alternative fuel form and an alternative fuel supplier based in the EU for a medium power research reactor (the LVR-15 is a light water tank-type research reactor at the research organization Centrum Výzkumu Řež (CVŘ) in the Czech Republic). This demonstration enables a path of independence for historical research reactors which may currently be dependent on non-EU fuel fabricators for fuel supply by demonstrating that an EU-based fuel supplier can provide an alternative fuel design that can strengthen the reliability of fuel supply for EU-based research reactors.

Table 3. Fabrication technologies and the expected innovation outcomes from EU-QUALIFY targeted fuel systems. MRL = Manufacturing readiness level, TRL = Technology Readiness Level.

Fuel system & technology	EU-QUALIFY experiment	*Expected* innovations
HD U_3Si_2 fabrication	ME-DEUS, ME-CHARTREUSE	Increased TRL/MRL Fabrication demonstration of HD silicide fuel in full-size formed fuel plates swaged into an assembly (4.8–5.3 gU/cc)
HD U_3Si_2 general fuel performance	ME-DEUS, ME-CHARTREUSE	Irradiation & PIE demonstration of HD silicide fuel in full-size formed fuel plates swaged into an assembly (4.8–5.3 gU/cc) at high power and high burnup Development of the fuel performance modeling to include HD silicide assemblies
UMo dispersion fabrication	E-FUTURE-III	Increased TRL/MRL Fabrication demonstration of atomized powder fuel powder heat treatment process Fabrication demonstration of the new design of a fuel particle coating device with fuel powder
UMo dispersed general fuel performance	E-FUTURE-III	Irradiation & PIE confirmation of multiple plates of atomized, heat-treated, ZrN-coated U7Mo fuel with and without Si added to the pure Al matrix at high power and high burnup
UMo Monolithic fabrication	FUTURE-MONO-1	Increased TRL/MRL Fabrication demonstration of the EU LEU U10Mo foil rolling capability Fabrication demonstration of the PVD Zr coating process and equipment on full-size foils Fabrication demonstration of the C2TWP EU cladding process on full-size plates
UMo monolithic general fuel performance	FUTURE-MONO-1	Irradiation & PIE confirmation of the PVD coated U10Mo monolithic fuel with C2TWP process at high power and high burnup

Table 2 summarizes the innovations obtained from the irradiation tests conducted or examined within the project; namely: SEMPER-FIDELIS (in BR2), EMPIrE (in ATR), HIPROSIT (in BR2), and 4EVERTEST (in LVR-15).

4.2 EU-QUALIFY project

The recently started EU-QUALIFY project, funded by Euratom, builds on the experience acquired in HERACLES-CP, LEU-FOREvER, and the collaborative actions with the US across all three fuel systems. This project has completed the project planning phase and is well into the preparations to begin 3 different irradiations; one for each of the fuel systems. As the name of the project implies, the scope of this project is to begin the generic qualification of the high-density silicide and both UMo fuel systems.

The high density and highly loaded U_3Si_2 fuel qualification will be moving forward with the fabrication demonstration of full-size plates that are formed and swaged into full-size fuel assemblies. To enable this experiment, a BR2 driver fuel element design will be utilized where the outer ring of 3 fuel plates will be replaced by the LEU U_3Si_2 fuel plates. Two such assemblies will be produced: one with a fuel core consisting of U_3Si_2 4.8 gU/cc with thick meat and one with a 5.3 gU/cc fuel core. Both will be irradiated at high power (450–470 W/cm^2) and relatively high burnup (>60% U-235 burnup). These “mixed elements” (LEU fuel plates mixed together with the standard BR2 HEU driver fuel) will be tested as ME-DEUS and ME-CHARTREUSE at BR2 starting in 2023. Following irradiation and initial visual observations, the LEU plates will be disassembled/removed from the mixed element and then typical non-destructive PIE will follow in 2024.

The qualification of the UMo dispersion fuel system will begin with the irradiation of 4 nearly identical

Table 4. Summary of current state-of-the-art and next development steps for the fuel systems studied in this paper.

Fuel system	Uranium loading	Current status (LEU-FOREvER)	Next steps in EU QUALIFY
U_3Si_2 (standard) fuel	4.8 gU/cc	Readily used in research reactors	Verification in mixed elements *with thick meat* at high power (ME-CHARTREUSE)
U_3Si_2 HD fuel	5.3–5.6 gU/cc	Four (4) full-scale plates successfully tested in relevant irradiation conditions	Verification in mixed elements experiments with 5.3 gU/cc (ME-DEUS)
UMo dispersion fuel	~8 gU/cc	One (1) full-scale plate successfully tested in relevant irradiation conditions	Verification with four (4) full-scale plates (EF3 experiment)
UMo monolithic fuel	~16 gU/cc	Mini-plates successfully irradiation tested	Verification in full-scale plates (FM1 experiment)

plates: U7Mo heat-treated powder coated with ZrN. Two plates will be a pure aluminium matrix and 2 will include a 5% silicon addition. It was observed in SEMPER-FIDELIS that at the micro-scale, there is marked improvement by including the silicon. This test, the E-FUTURE-III (EF3) experiment, will put the silicon side-by-side with plates without silicon to determine if the addition of the material is necessary and warranted. Fabrication will mostly be performed at CERCA, utilizing commercial-scale equipment and processes. Due to timing constraints with fabrication scale-up, the ZrN powder will be coated with a commercial-scale system at SCK CEN. This experiment is planned to begin in 2023 and non-destructive examinations will follow in 2024.

The qualification for the UMo monolithic fuel system with EU fabrication technology will commence with the FUTURE-MONO-1 (FM1) experiment. This experiment is still in the planning stages but will include 2–4 monolithic fuel LEU plates designed prototypic to the LEU design of the FRM-II reactor. Significant investments in equipment by TUM at CERCA will enable the fabrication to mostly be performed at CERCA, utilizing commercial-scale equipment and processes. Only the Zr coating of the foils for FM1 is expected to be coated on a commercial-scale system at TUM. This experiment is planned to begin in 2023 and non-destructive examinations will follow in 2024.

In addition to the fabrication studies leading up to these experiments, the EU-QUALIFY project also includes innovative efforts to establish a fuel performance database and to further enhance the capability of the fuel performance modeling. These activities are also important for a generic fuel qualification and to enable the reactor-specific fuel qualifications.

Table 3 summarizes the innovations *expected* from the irradiation tests conducted or examined within the project; namely: ME-DEUS/ME-CHARTREUSE, E-FUTURE-III, and FUTURE-MONO-1.

5 Conclusions

Several milestones in developing suitable alternative fuels for research reactor LEU conversions have been accomplished to date and several more are expected to be accomplished in the ongoing actions. A short summary of the current European state-of-the-art of innovative research reactor fuel development is given in Table 4. It is envisaged that the dispersion silicide and UMo fuel systems will reach a technological readiness level sufficient to support further reactor-specific irradiation campaigns (see Fig. 1) with the ultimate objective of reactor conversions. The challenges that potentially remain for the monolithic fuel system (currently the least developed in Europe) after EU-QUALIFY are expected to be further tackled through bilateral TUM/CERCA activities and the HERACLES consortium is hopeful for continued financial support through a potentially new European project.

Conflict of interests

The authors declare that they have no competing interests to report.

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Data availability statement

The data reported has been deposited in a data repository in accordance with the regulations of the project partner's organization.

Author contribution statement

The main authors were Stefan Holmström and Jared Wight. Stéphane Valance provided a detailed review.

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