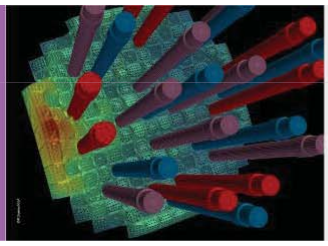


Innovation & Qualification of LEU Research Reactor Fuels & Materials

Jared Wight – SCK CEN
Stéphane Valance – CEA
Stefan Holmström – SCK CEN

Non-proliferation Background

- 1953: **Atoms for Peace** speech of Eisenhower
- Late 1970s: Concerns about nuclear proliferation
- 1978: U.S. DOE initiated the Reduced Enrichment for Research and Test Reactors (**RERTR**), development of high density LEU fuels (e.g. uranium silicide)
- 1990 – 2000 : LEU silicide fuel utilized for LEU conversions where technically feasible
  - 4.8 gU/cc; moderate power/BU (not applicable to HPRRs)
- 1999 - 2013: Europe addresses high density LEU fuel qualification for High Performance Research Reactors: IRIS, LEONIDAS, ALPS
- Since 2013: **The HERACLES group forms as a joint European effort**
- Since 2015: HERACLES-CP
- Since 2017: LEU FOREvER — Euratom Projects
- Since 2020: EU-QUALIFY

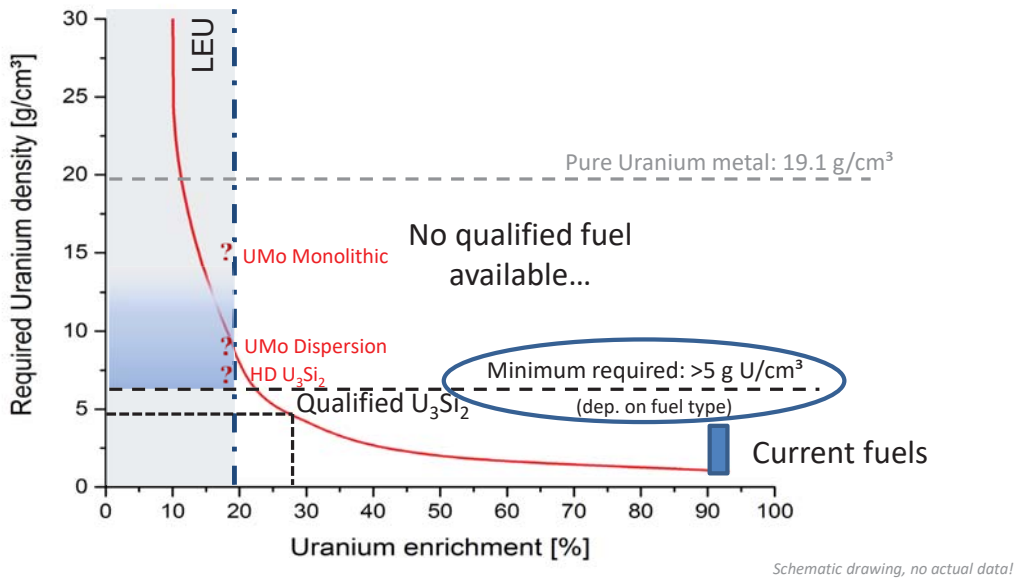
HERACLES Team & Partners

EU's Leading Nuclear Fuel Developers

www.heracles-consortium.eu

HERACLES Partners

LEU Fuel Challenge



Schematic drawing, no actual data!

EURATOM Projects

- Initial fuel development
  - Fabrication development
  - UMo dispersion
    - Irradiation & PIE
  - UMo monolithic

This project has received funding from the Euratom H2020 research and training work programme 2014-2018 under grant agreement No 661935

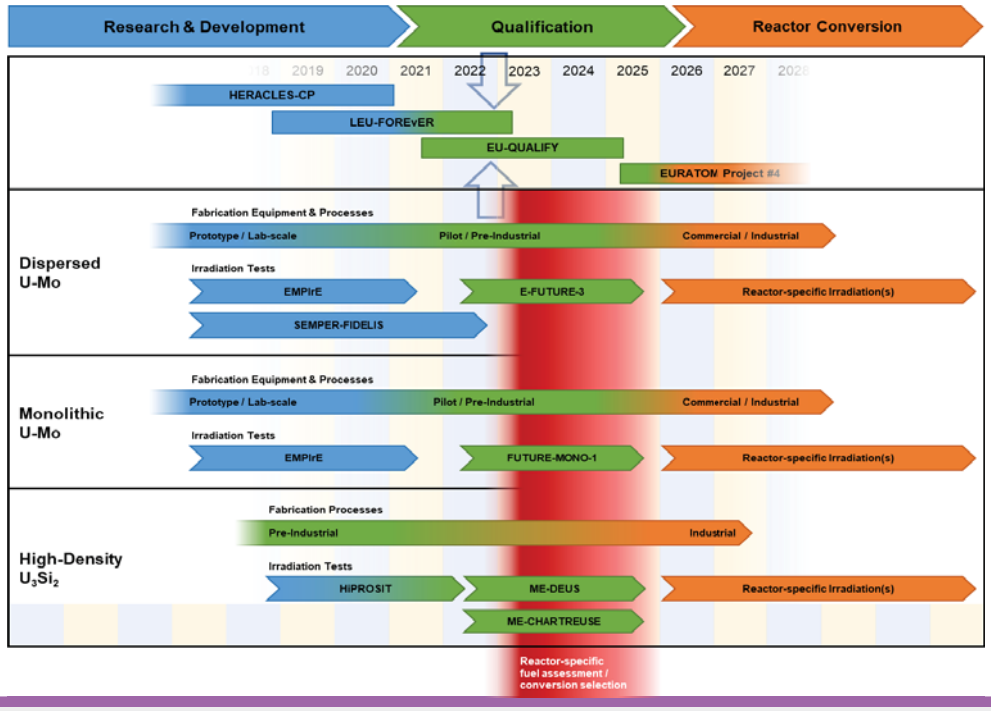
- Further fuel development
  - Fabrication development
  - UMo dispersion
  - UMo monolithic
    - PIE
  - Alternative: U3Si2 dispersion
    - Irradiation & PIE

This project has received funding from the Euratom H2020 research and training work programme 2014-2018 under grant agreement No 754378

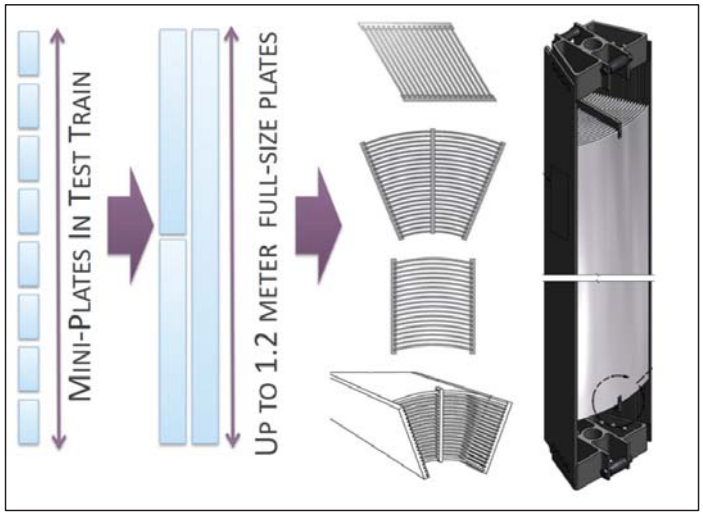
- Initial fuel qualification
  - Fabrication development
  - UMo dispersion
    - Irradiation & PIE
  - UMo monolithic
    - Irradiation & PIE
  - U3Si2 dispersion
    - Irradiation & PIE

This project has received funding from the Euratom H2020 research and training work programme 2018-2019 under grant agreement No 945009

HERACLES Roadmap



Fuel Qualification Strategy

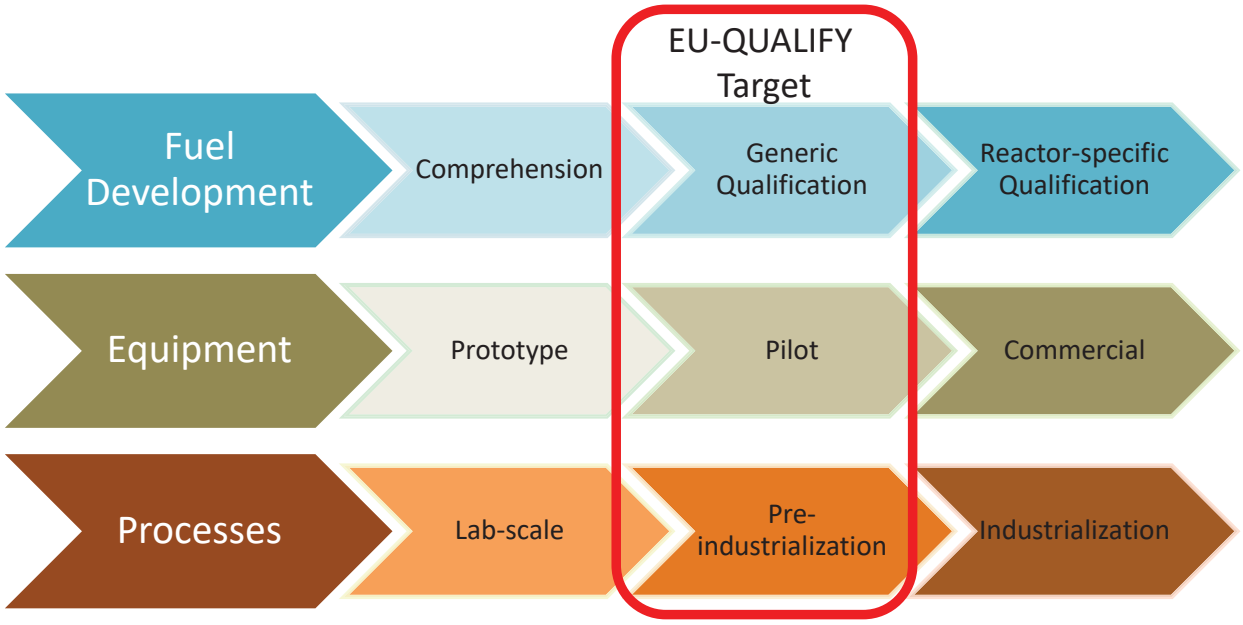


Scale: miniplates -> full-size plates -> assemblies

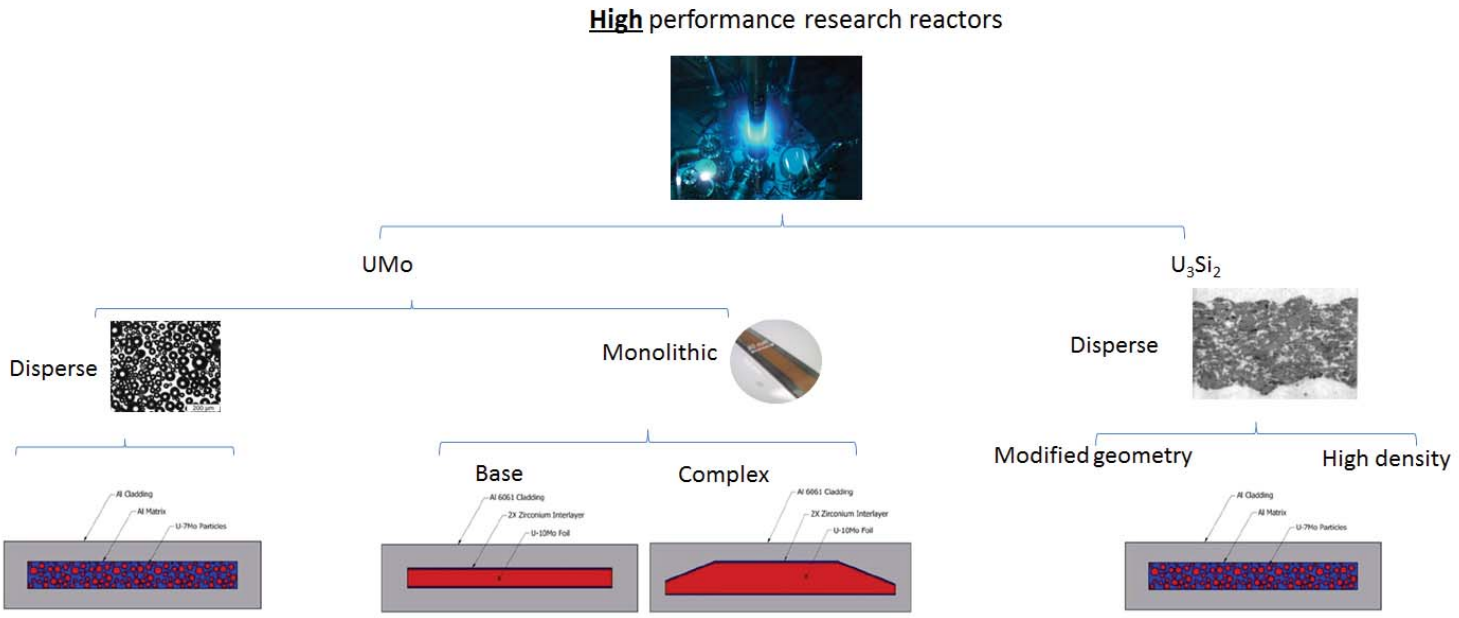
Volume: individual plates to multiple plates in assemblies

Maturity: lab-scale fabrication to commercial-scale manufacturing

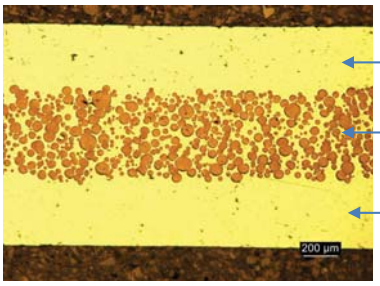
Fuel Qualification Objectives



LEU Fuel System Development for HPRRs



UMo Dispersion Fuel – Overview



BONAPARTE bench for PIE thickness/oxide measurements

UMo fuel

- In 2000 UMo alloy was identified as best candidate high density fuel
  - 7-10 wt% Mo added to stabilise high temperature γ-U phase
  - High U density in alloy: >15 gU/cc
- Development pursued in two paths:
  - U-7wt% Mo dispersion
  - U-10wt% Mo monolithic
- Challenge: U-Al interdiffusion leading to unacceptable swelling behavior

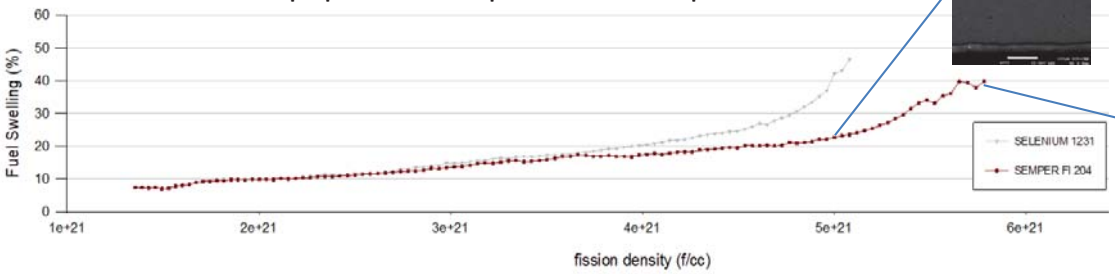
UMo dispersion fuel

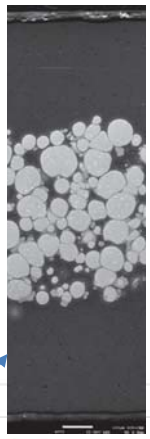
- Dispersion of 50 vol% fuel/Al matrix results in 8-8.5g U/cm³
- Various initial tests identified the unacceptable swelling behavior
- Various modifications tried in SEMPER-FIDELIS experiment

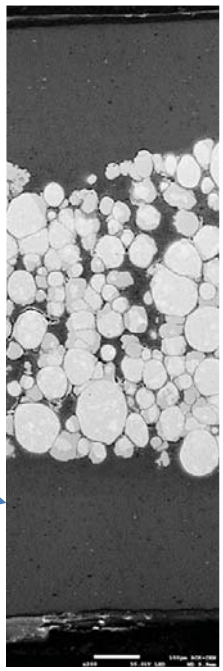
UMo Dispersion Fuel – Status

Results of LEU-FOREvER

- PIE/comprehension of SEMPER-FIDELIS experiment results
  - HERACLES identified optimizations for acceptable fuel performance at high power and high burnup
    - Heat treatment of the atomized powder
    - ZrN coating of the powder
    - Addition of 5% Si to the matrix
  - Optimizations demonstrated with commercial-scale fabrication equipment and pre-industrial processes







UMo Dispersion Fuel - Objectives

Objectives of EU-QUALIFY

- E-FUTURE-III test
  - Fabricate 4 UMo dispersion fuel plates
  - Irradiate flat plates in FUTURE-5 basket
  - Perform NDE PIE

FUTURE-5 basket loaded with fuel plates

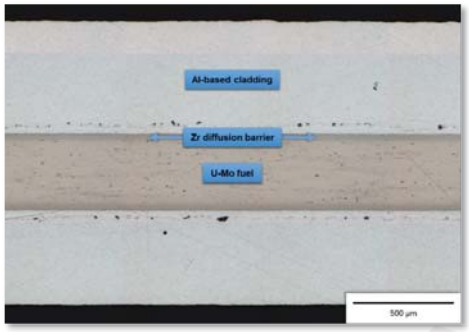
FUTURE-5 fuel plates

EU-QUALIFY Objectives	
Fuel Development	• Establish fuel performance database • Increase data set with E-FUTURE-III test
Equipment	• Establish/implement pilot scale equipment: atomizer, heat treatment, and powder coater
Processes	• Demonstrate all processes at pre-industrial with E-FUTURE-III test

UMo Monolithic Fuel – Overview & Status

UMo monolithic fuel

- Highest possible uranium density of all fuel candidates: **up to 15.5 gU/cm³**
- Consists of a metallic U-Mo foil, coated with a Zr diffusion barrier, clad between aluminum
- Acceptable irradiation behavior demonstrated in various irradiation tests performed by US DOE
- Challenge: fabrication equipment/processes considerably different to existing dispersion fuel systems



LEU-FOREvER Results

- PIE of EMPIrE mini-plate irradiation test (US DOE funded)
  - Demonstrated acceptability of EU fabrication process

framatome

UMo Monolithic Fuel - Objectives

Objectives of EU-QUALIFY

- FUTURE-MONO-1 test
  - Fabricate 2-4 UMo monolithic fuel plates
  - Irradiate flat plates in FUTURE-5 basket
  - Perform NDE PIE

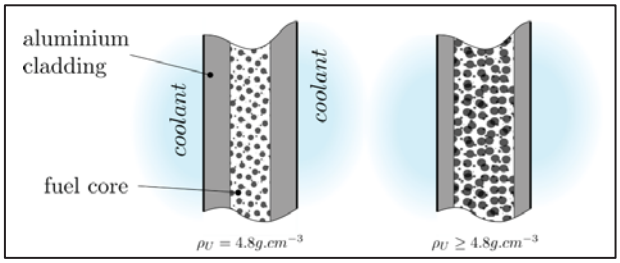
Post-irradiation underwater visual inspection of a FUTURE-5 fuel plate

EU-QUALIFY Objectives	
Fuel Development	• Establish a fuel performance database • Increase data set with FUTURE-MONO-1 test
Equipment	• Establish pilot scale equipment: casting, foil rolling and foil coating
Processes	• Demonstrate all processes at pre-industrial scale with FUTURE-MONO-1 test

High-loaded U_3Si_2 – Overview & Status

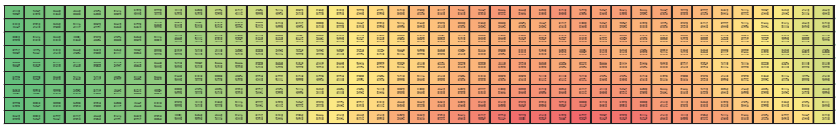
High density/loaded U_3Si_2

- Demonstrated fabrication technology and existing infrastructure at 4.8 gU/cc
- Increase volume of fuel to ~50% in fuel meat
- Change to fuel design may be necessary such as a slightly thicker fuel plate
- Challenge: ensure acceptable fuel performance at higher loading and thinner cladding



LEU-FOREvER Results

- Irradiation & PIE of HiPROSIT test
  - Demonstrated fabrication capability
    - Thicker fuel meat at 4.8 gU/cc
    - Thinner cladding and higher density at 5.3 – 5.6 gU/cc
  - Demonstrated acceptable fuel behavior at high power and high burnup conditions for all candidates

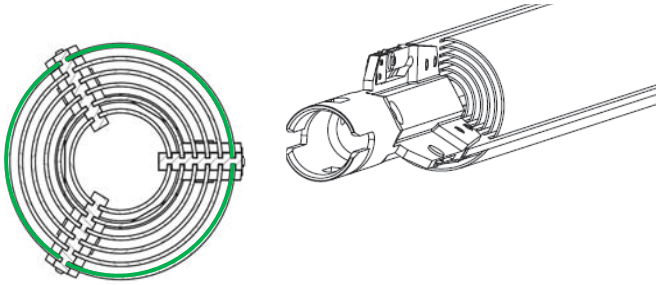


HiPROSIT plate
Post-irradiation neutronics analysis
peak heat fluxes

High-loaded U_3Si_2 – Objectives

Objectives of EU-QUALIFY

- ME-DEUS test
  - Fabricate 3 high density U_3Si_2 (5.3 gU/cc) formed/curved fuel plates
  - Assemble into outer ring of a mixed BR2 fuel element
  - Irradiate at high power and moderate BU
- ME-CHARTREUSE test
  - Fabricate 3 thick meat U_3Si_2 (4.8 gU/cc) formed/curved fuel plates
  - Assemble into outer ring of a mixed BR2 fuel element
  - Irradiate at high power and moderate BU



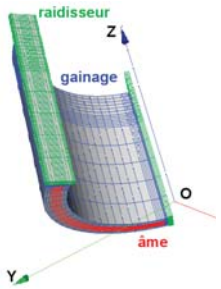
BR2 Mixed Element

LEU silicide plates in green

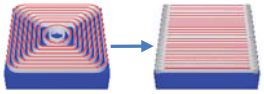
EU-QUALIFY Objectives	
Fuel Development	• Establish a fuel performance database • Increase data set with examination HiPROSIT test • Increase data set with ME-DEUS and ME-CHARTREUSE tests
Equipment	• None necessary All equipment currently at commercial-scale
Processes	• Demonstrate all processes at pre-industrial scale with ME-DEUS and ME-CHARTREUSE tests

Conclusions

- **LEU-FOREvER project was highly successful**
  - Increased comprehension of UMo dispersion fuel system and identified design for qualification through SEMPER-FIDELIS PIE
  - Demonstrated the EU fabrication process for the UMo monolithic fuel system through PIE of EMPIrE
  - Demonstrated high loaded/density U3Si2 fuel system at high power and high burnup enabling an alternative solution for some LEU conversions
  - Demonstrated a new design for LVR-15 fuel assembly (medium-power reactor) to increase EU security of fuel supply through fabrication and irradiation
  - Increased EU fuel performance modeling capabilities through the MAIA code
- **EU-QUALIFY project has high expectations**
  - Demonstrate final design of the UMo dispersion fuel system in multiple FUTURE-5 plates through the irradiation and PIE of EF3 to initiate generic fuel qualification
  - Demonstrate design of the UMo monolithic fuel system in multiple FUTURE-5 plates through the irradiation and PIE of FM1 to initiate generic qualification
  - Demonstrate high loaded/density U_3Si_2 formed/curved plates in MEs for generic qualification



MAIA code mesh for curved MTR fuel plate


LVR-15 current to new FA

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754378

SCK CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL

This project has received funding from the Euratom H2020 research and training work programme 2018-2019 under grant agreement No 945009