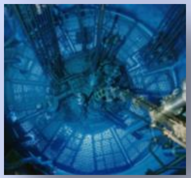
HERACLES

NEUTRONS FOR SCIENCE

HERACLES-CP

Towards the Conversion of High Performance Research Reactors in Europe



From HEU to LEU

Why a new fuel?

HEU MINIMZATION

Nuclear terrorism is one of the most challenging threats to international security, and strong nuclear security measures are the most effective means to prevent terrorists, criminals, or other unauthorized actors from acquiring nuclear materials.

Washington Nuclear Security Summit 2010 Communiqué

We, the leaders, met in La Hague on 24 and 25 March 2014, [...] encourage States to continue to minimise the use of HEU through the conversion of reactor fuel from HEU to LEU, where technically and economically feasible, and in this regard welcome cooperation on technologies facilitating such conversion.

The Hague Nuclear Security Summit 2014 Communiqué

HISTORY OF NON-PROLIFERATION EFFORTS

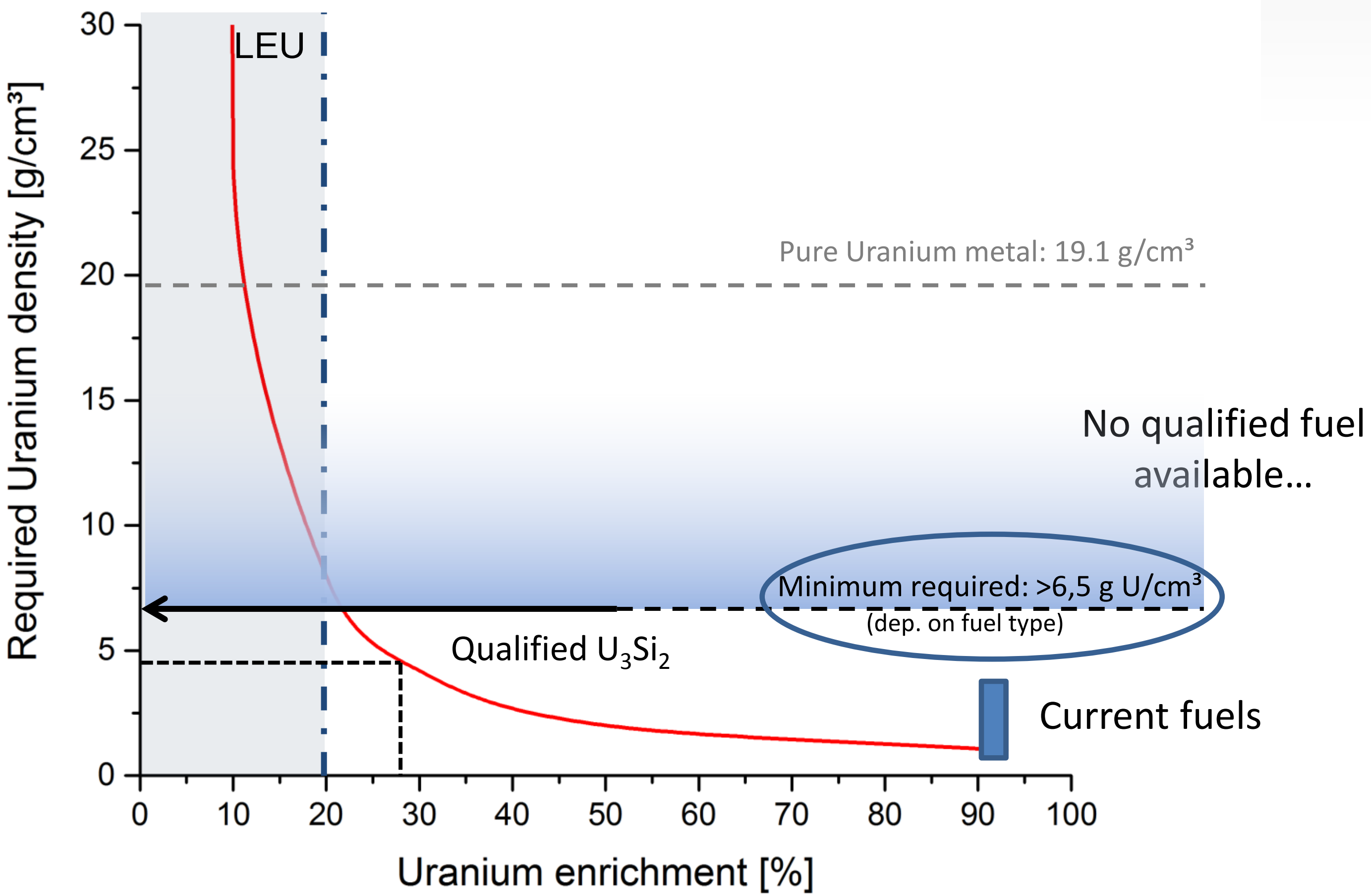
1953: atoms for peace speech of Eisenhower
Late 1970s: concerns raised about nuclear proliferation

1978: U.S. DOE initiated the Reduced Enrichment for Research and Test Reactors (RERTR)
Russian Federation later began activities similar to RERTR with the same objective
Development of high density LEU fuels (e.g. uranium silicide)

1990 – 2000 : implementation of LEU fuel (silicide) where technically feasible (not applicable to HPRR)

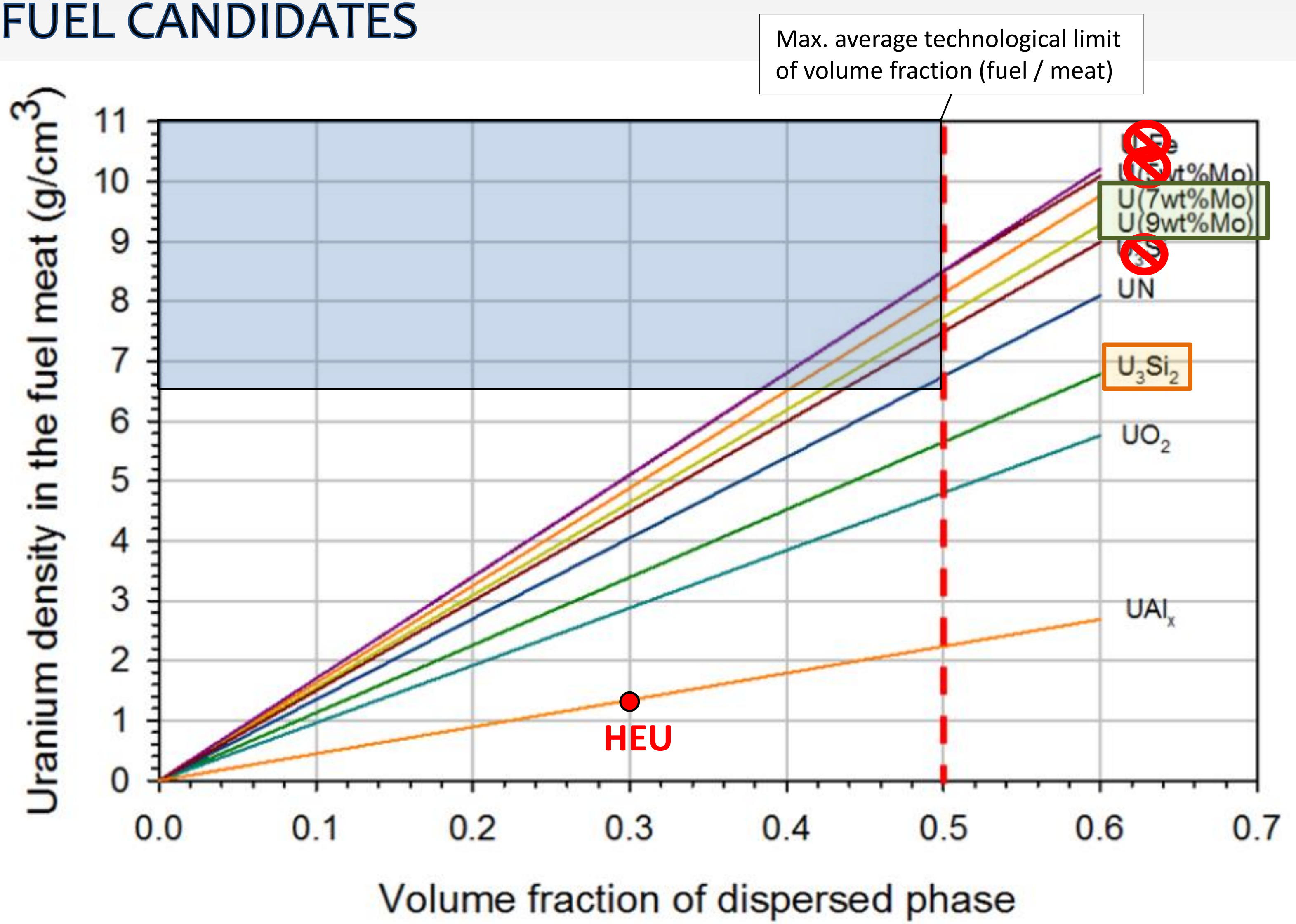
> 1999: Europe addressed high density LEU fuel qualification for High Performance Research Reactors: IRIS, LEONIDAS, ALPS
> 2013: The HERACLES group as a joint European effort

REASONS TO DEVELOP A NEW FUEL



Schematic drawing, no actual data!

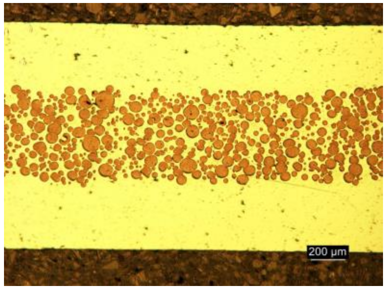
FUEL CANDIDATES



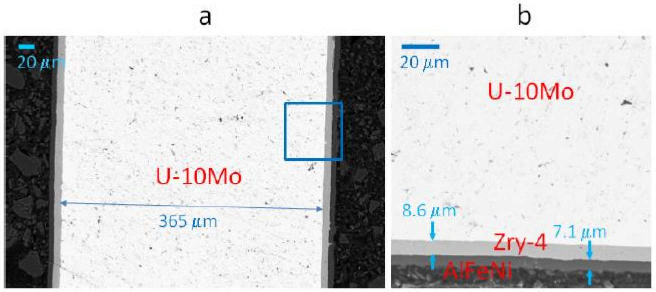
URANIUM MOLYBDENUM ALLOYS

Best candidate high density fuel is U-Mo alloy

- 7-10 wt% Mo added to stabilise high temperature γ-U phase
- Dispersion of 50 vol% results in 8-8.5g U/cm³
- Highest loading with monolithic U(Mo): 16g U/cm³, U-Mo foil between cladding



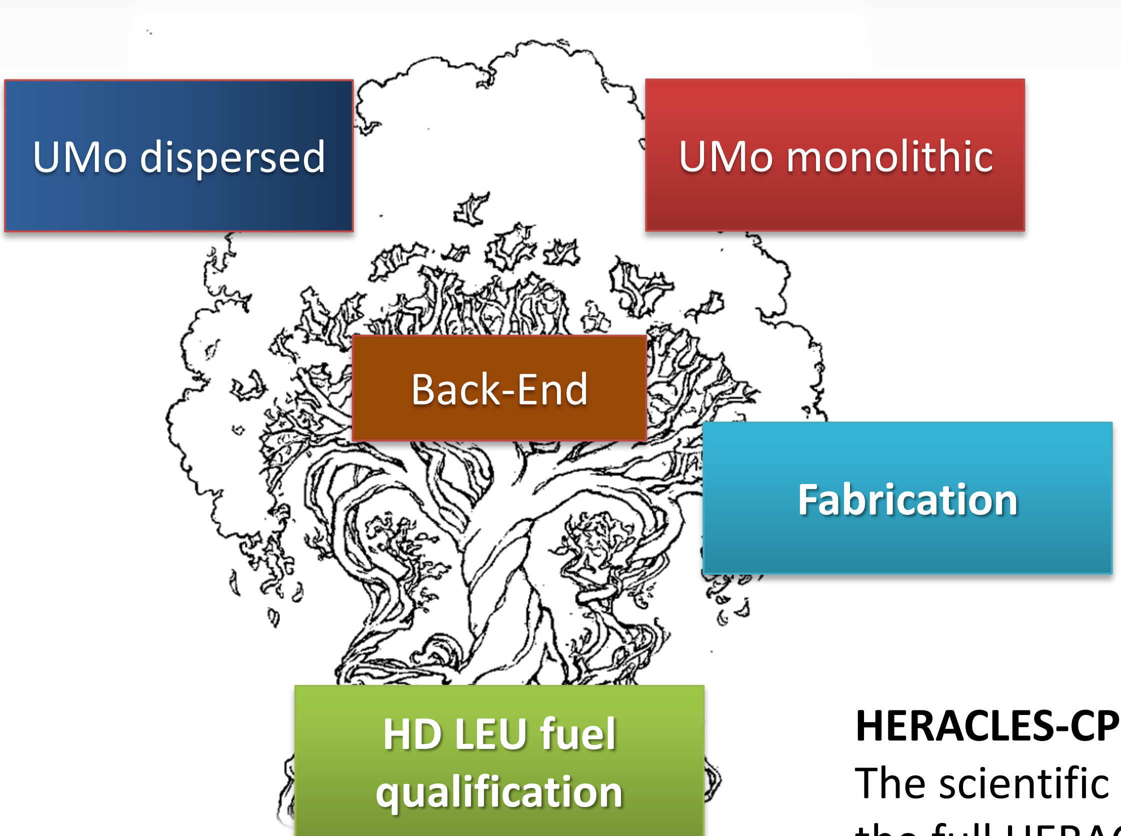
Dispersion fuel



Monolithic fuel

Sources: W. Schmid, *PhD thesis,* Technische Universität München, 2011
A. Leenaers et. al., J. Nucl. Mater., 335 (2004) 39-47

JUST A FEW THINGS TO DO…



HERACLES-CP:
The scientific foundation for the full HERACLES program

Image source: Wikia,.com User Razeluxe91, Yggdrasil.jpg

U-Mo dispersion fuel

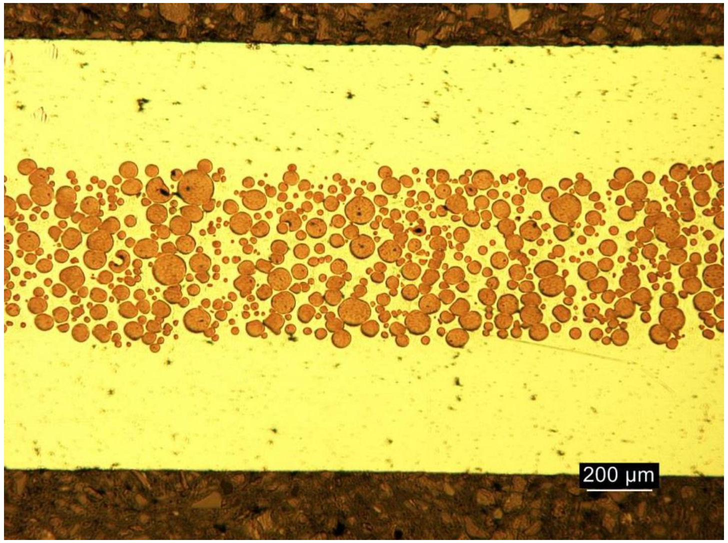
Irradiation behaviour

HISTORY: U-MO DISPERSION FUELS RESEARCH

- **Neutron absorption by Mo requires loading of ≥ 8g/cc.**

- **Initial qualification approach similar to U_3Si_2-Al fuel**
  - Manufacturing process requires powder production
    - Atomisation method developed by ANL/INL and KAERI
  - No vital changes to plate production (high loading)
  - Irradiation testing at gradually increasing power
    - US : RERTR miniplate irradiations
    - CEA : IRIS-1, IRIS-2, FUTURE (first in OSIRIS, then BR2)
    - Russian, Canadian and Korean irradiation tests in different configurations

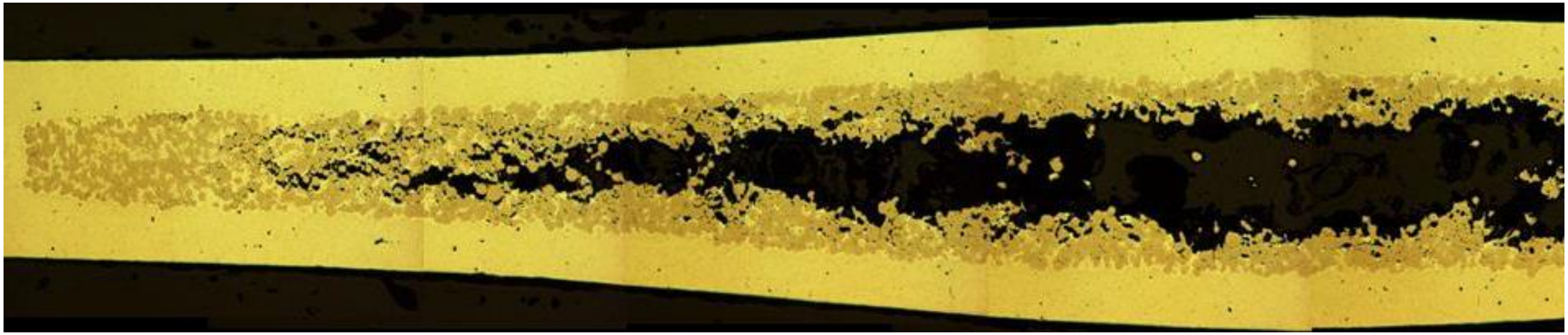
NOT A STRAIGHT-FORWARD SOLUTION



Fresh fuel

Sources: A. Leenaers et al., JNM 335 (2004), pp. 39-47

NOT A STRAIGHT-FORWARD SOLUTION



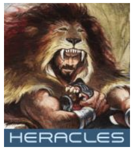
U-Mo undesirable irradiation behaviour

Sources: A. Leenaers et al., JNM 335 (2004), pp. 39-47

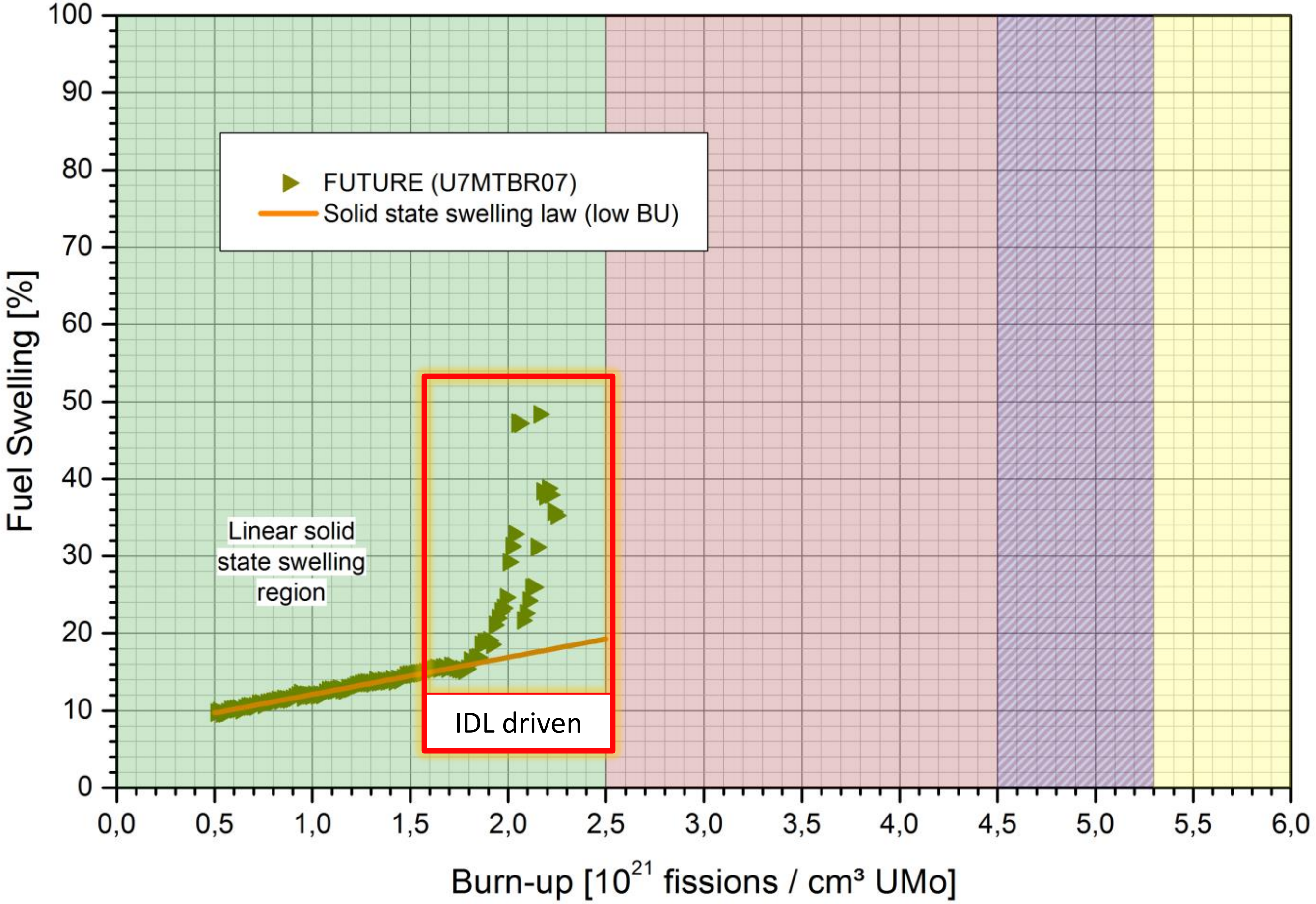
FUEL SWELLING

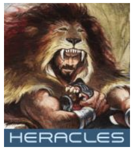
- **Fuel plate swelling is a major aspect of qualification**
  - Narrow cooling gaps between plates close as plate swells
  - Swelling needs to be limited, gradual and predictable
    - Breakaway swelling = uncontrolled and excessive rapid increase in plate thickness, leading to blistering and possibly cladding failure

- **Components of plate swelling**
  - Swelling is an unavoidable consequence of fission
  - Plate = fuel + matrix + cladding, only fuel swells
  - Fuel swelling = solid fission products + fission gases
    - Solid swelling = dissolved fission products or precipitates = linear
    - Gaseous swelling = bubble formation = faster than linear

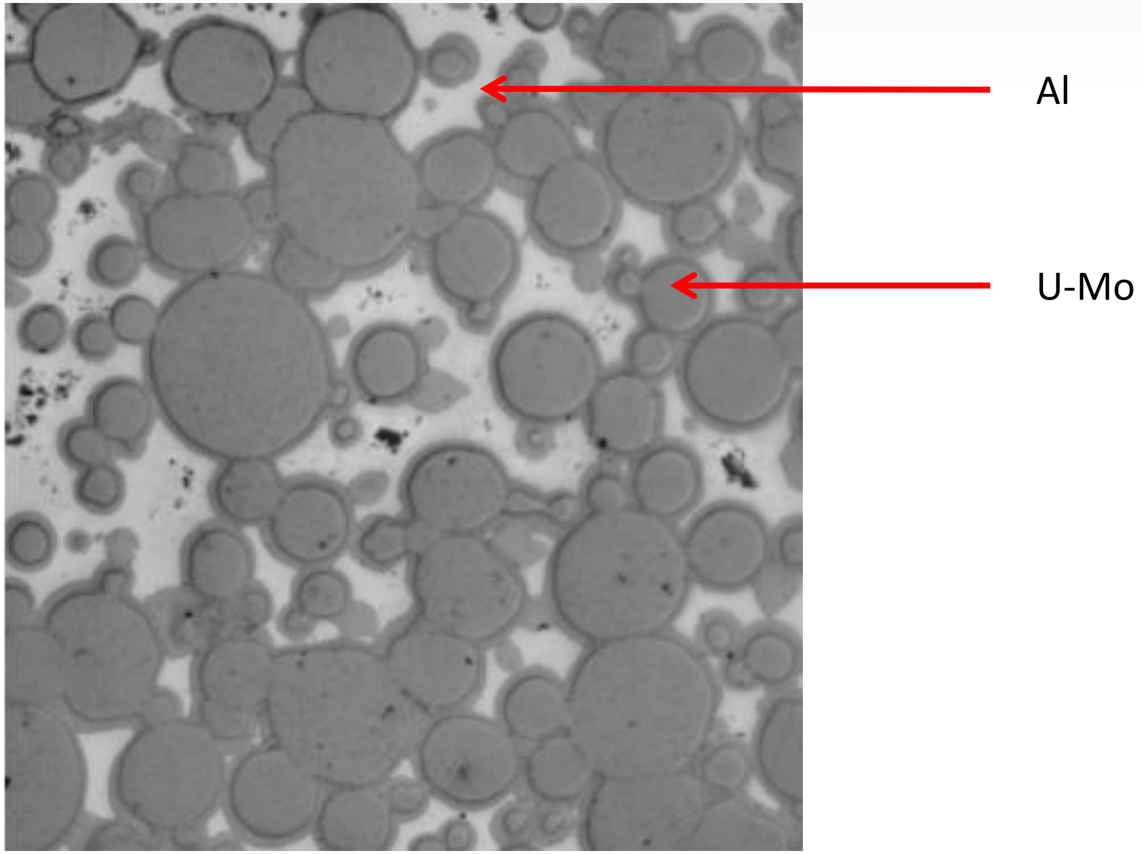


THE U-MO SWELLING PROBLEM





THE INTERACTION LAYER PROBLEM



Sources: RERTR

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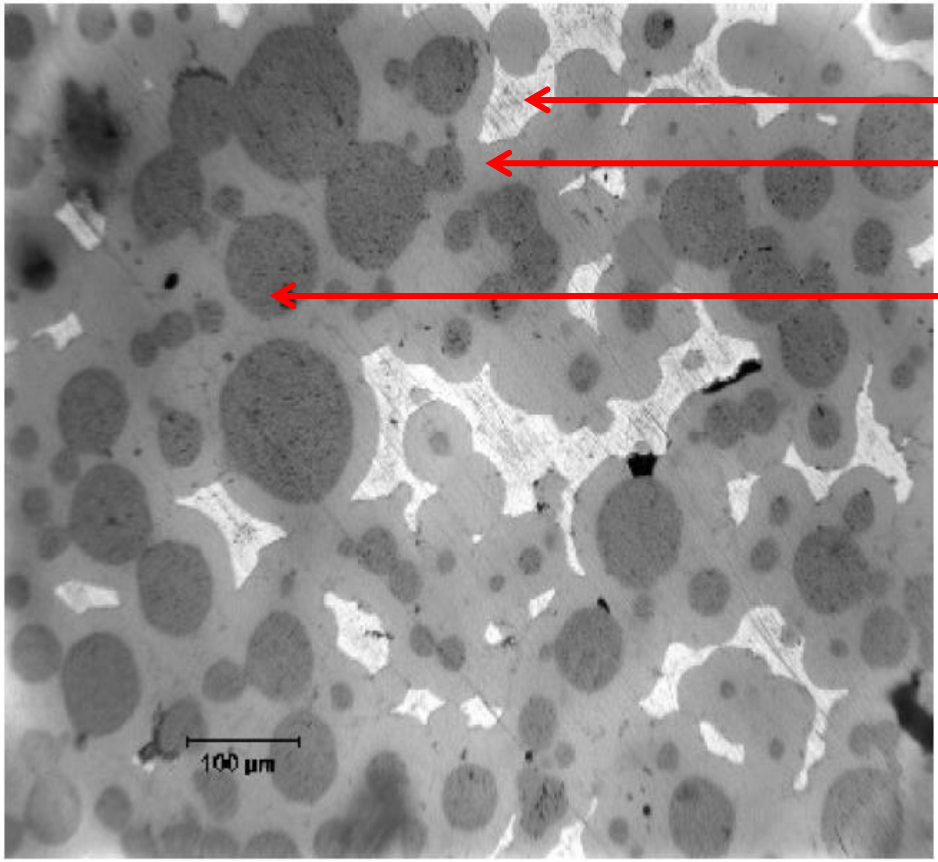

Sources: RERTR

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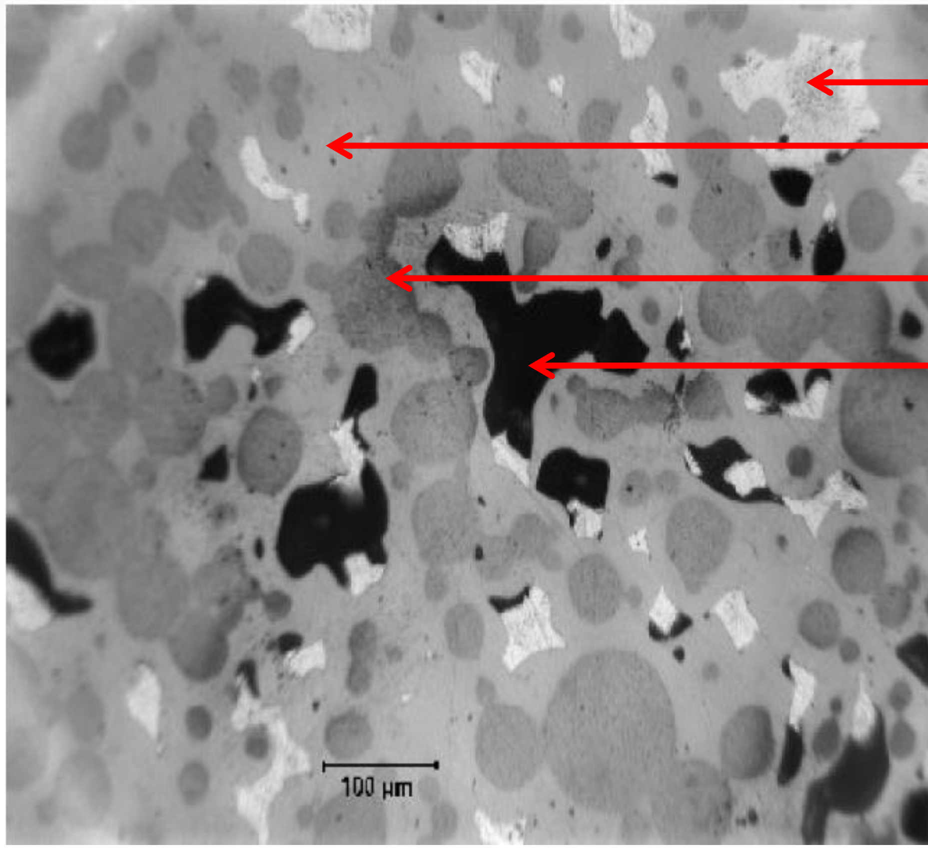
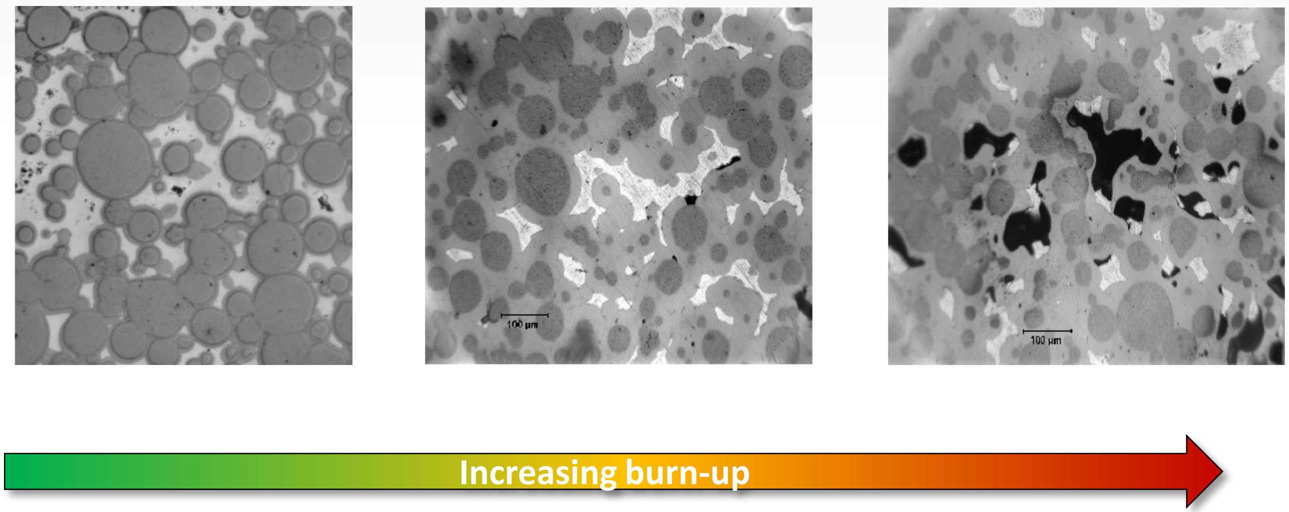


Sources: RERTR

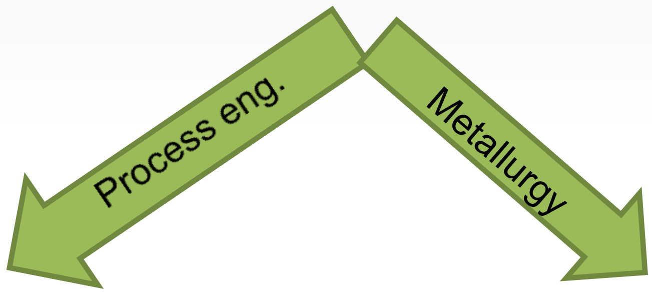
THE INTERACTION LAYER PROBLEM



- Formation of large “pores” related to interaction layer (IL) between U(Mo) and Al matrix
    - IL formation ‘sweeps up’ fission products, creating weak interface
    - IL is amorphous (metallic glass), providing poor host for fission gas

Sources: RERTR

MITIGATION STRATEGIES



- **Coating** of particles / UMo with a diffusion barrier:
- Si, Nb, ZrN, TiN, Zr, Mo…

→ SELENIUM

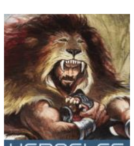
- Adding a further component to the matrix (**Si**) or to the fuel itself
- Matrix cannot be modified infinitely

→ E-FUTURE

THE E-FUTURE TEST

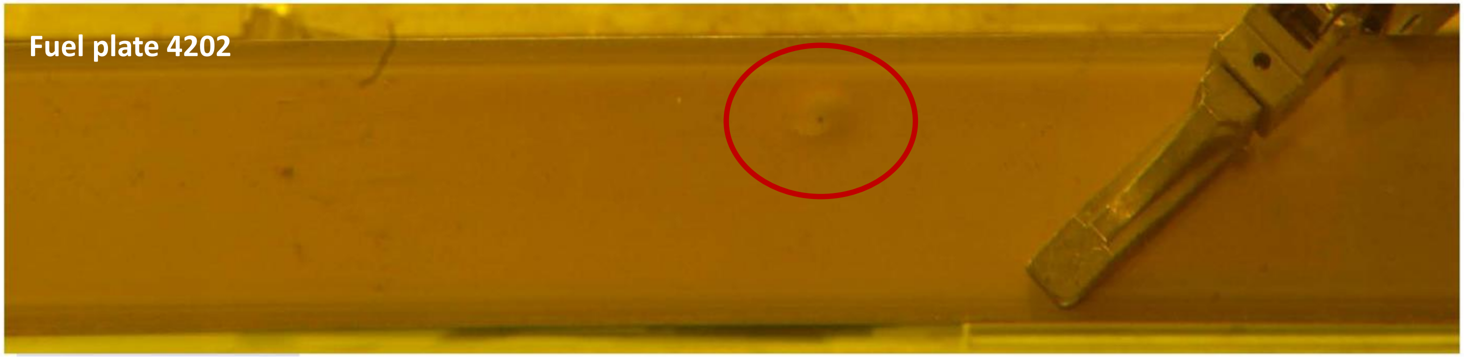
- 2010: First irradiation of the LEONIDAS fuel qualification program
- Irradiation of four flat fuel plates in BR2 (E-FUTURE device)
- U7Mo atomised powder (KAERI) dispersion in Al(Si) matrix
- Density: 8 g/cm^3, enrichment: 19.7 % ^{235}U

Plate Id.	U7MC4111	U7MC4202	U7MC6111	U7MC6301
Fabrication data				
Cladding	AlFeNi	AG3NE	AlFeNi	**AG3NE**
Si % in Al matrix	4%	4%	6%	**6%**
Thermal treatment	425 °C – 2h	475 °C – 2h	425 °C – 2h	**475 °C - 4h**
Irradiation data				
Mean BU (%^{235}U)	48.3	48.1	47.1	**47.5**
Max BU (%^{235}U)	71.3	71.3	68.7	**71.4**
Peak Heat Flux (W.cm^{-2})	**457**	**453**	**465**	**472**



THE E-FUTURE TEST

- All plates show considerable swelling in the high burn-up region
- Pillowing detected

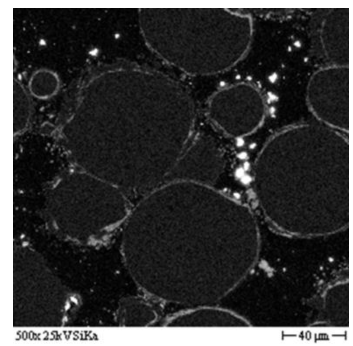


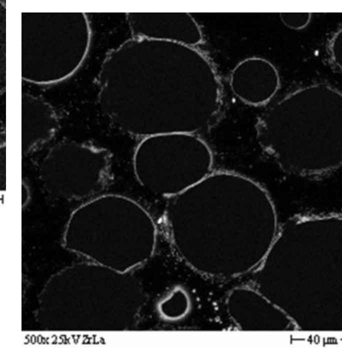
Sources: S. Van den Berghe et. al., J. Nucl. Mater., 430 (2012) 246-258

THE SELENIUM TEST

- 2012 : first-of-a-kind irradiation of coated U(Mo) fuel
- Irradiation of two flat fuel plates in BR2 (E-FUTURE device)
- U7Mo[Si] and U7Mo[ZrN] dispersion in Al matrix
- Density: 8 g/cm^3, enrichment: 19.7 % ^{235}U

Plate Id.	U7MD1231	U7MD1231
	Fabrication data	
Cladding	AG3-NE	**AG3-NE**
Matrix	Al	**Al**
Coating	~600 nm Si	**~1000 nm ZrN**
	Irradiation data	
Max BU (%^{235}U)	70	**70**
Peak Heat Flux (W.cm^{-2})	**470**	**470**



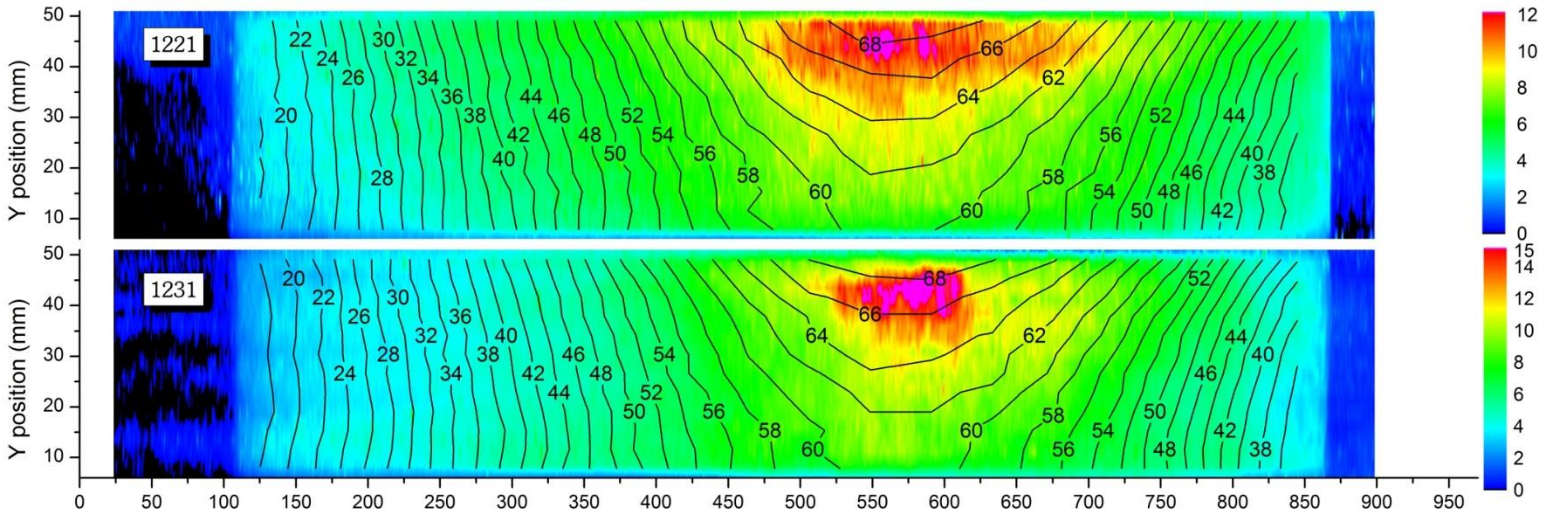


Sources: A. Leenaers et. al., J. Nucl. Mater., 440 (2013) 220-228

THE SELENIUM TEST

- Maximum swelling measured (before oxide correction) :
  - Si coated plate (1221) : ~13%
  - ZrN coated plate (1231) : ~18%

- Expected swelling (based on E-FUTURE) : ~10%



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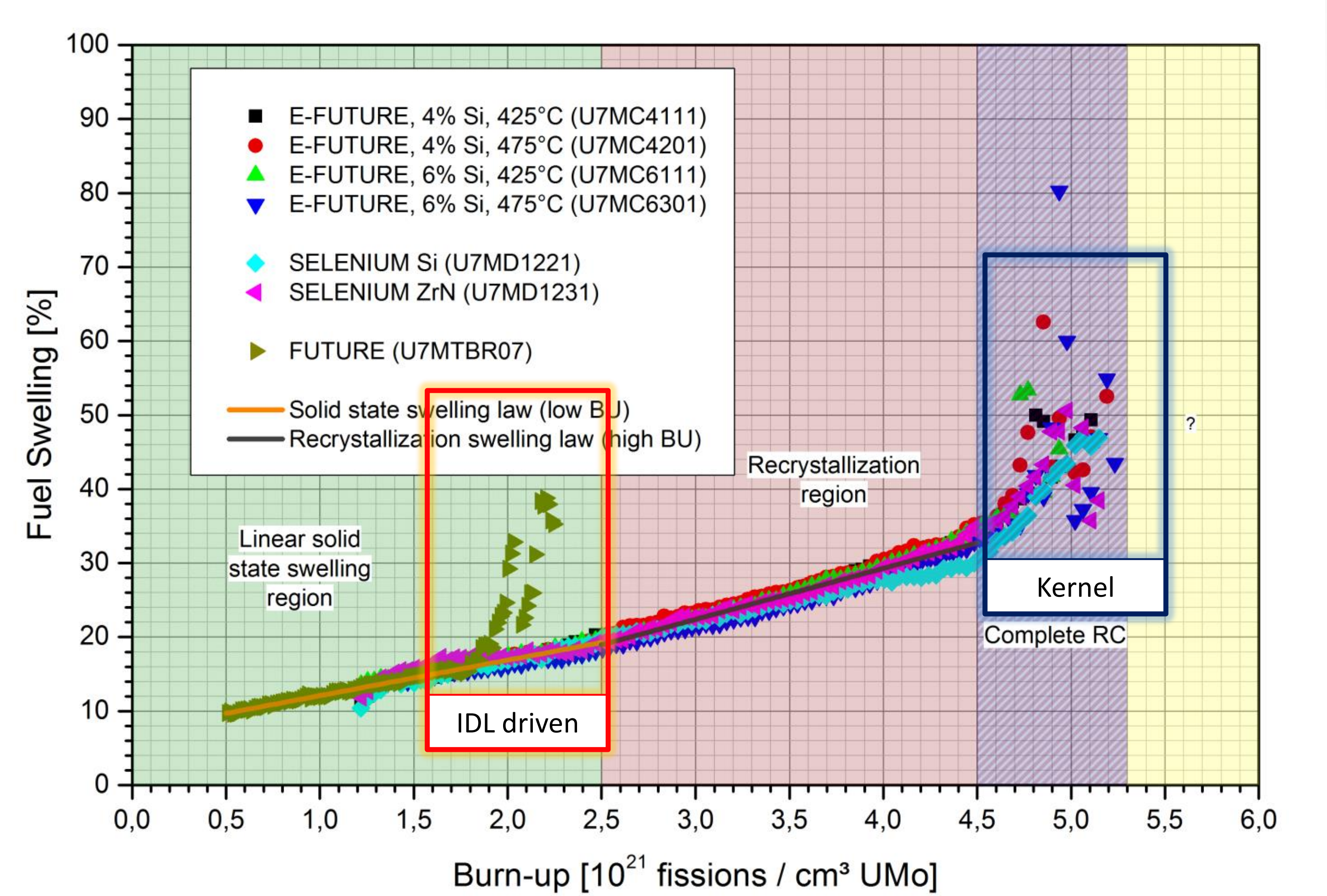
THE U-MO SWELLING PROBLEM II



INTRINSIC KERNEL SWELLING

SELENIUM & E-FUTURE have similar swelling evolution

- No pillowing for SELENIUM, but acceleration visible, independent of Si addition, Si or ZrN coating !
- Only low IL formation

→ The high BU swelling is intrinsic to UMo!

- During recrystallization gradual increase in swelling rate
- Swelling rate becomes faster than matrix can creep → tearing
- Tears accumulate fission gas and cause pillowing

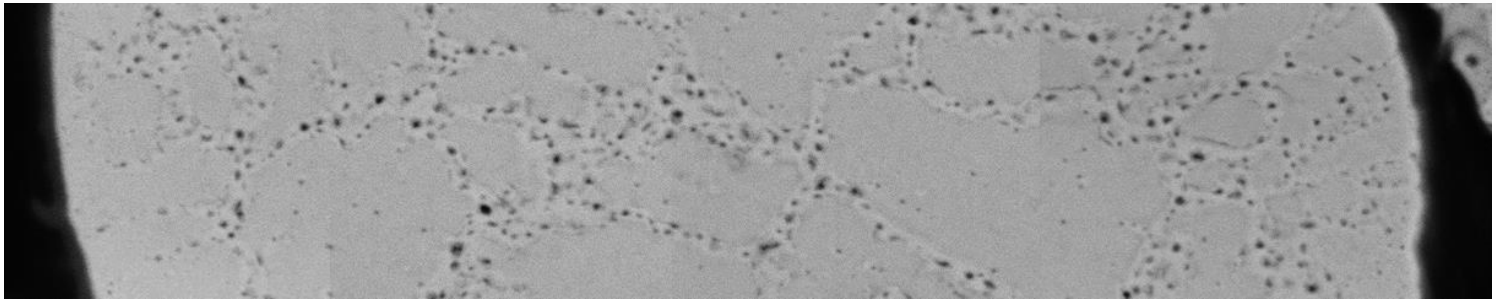
→ Need to engineer fuel system for recrystallization

WP 2

RECRYSTALLIZATION AND BUBBLE FORMATION

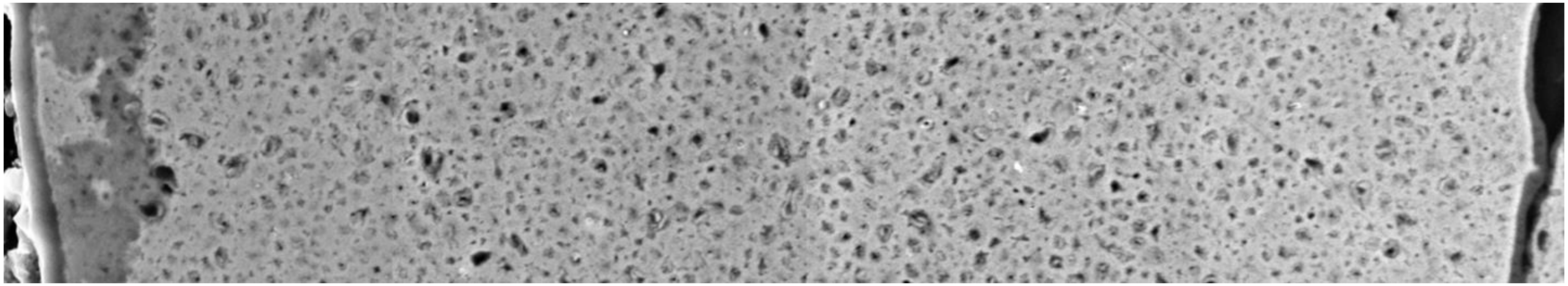
Starts at the cell boundaries (low in Mo content) ~FD 3 × 10^{21} f/cc

3.7×10^{21} f/cm^3



Gradually proceeds towards cell center and is complete ~ FD 4.5 × 10^{21} f/cc

5.2×10^{21} f/cm^3



Consequence of recrystallization is the 'release' of the overpressurized fission gas (nano)bubbles

⇒ Increased swelling rate

Sources: A. Leenaers, PhD thesis 2014, University of Ghent – SCK•CEN

INTRINSIC KERNEL SWELLING MITIGATION

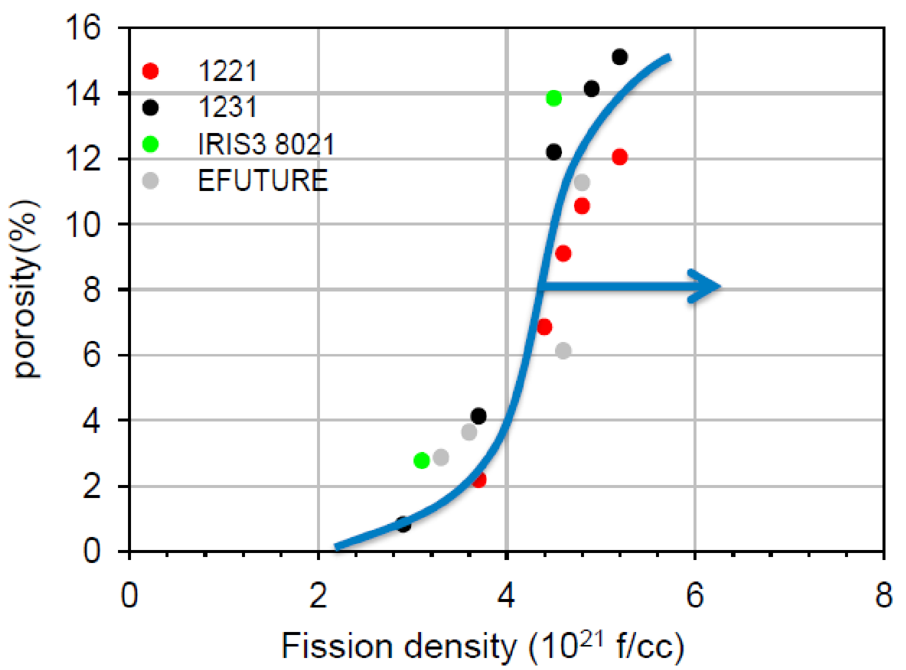
Recrystallisation region:

2.5 – 5.0 × 10^{21} fiss/cm³ UMo

Solutions:

- Increase Mo content
- Heat treatment to homogenize Mo and increase grain size

Delay in RC delays bubble formation and therefore reduces the swelling rate



WP 2

Sources: A. Leenaers et al.,to be published

MITIGATION STRATEGY

- The Fuel Developer Expert Group concludes that 2 issues need to be addressed to conclude the comprehension phase :
  - High burnup swelling rate of UMo (restructuring)
  - UMo-matrix interaction layer (IL) formation

- Both phenomena are unavoidable consequences of the fission process and the physico-chemical properties of the UMo-Al system

- Mitigation strategies :
  - Swelling (restructuring) : annealing for Mo homogenization + grain growth (limiting GB)
  - IL formation : Si addition, ZrN coating

- Next step : SEMPER FIDELIS and EMPIrE irradiations

SEMPER FIDELIS → **HERACLES-CP**

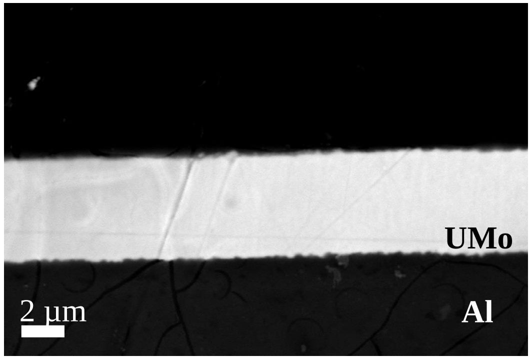
WP 6

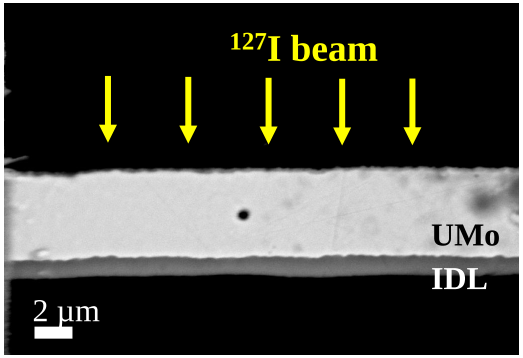
U-Mo fuel

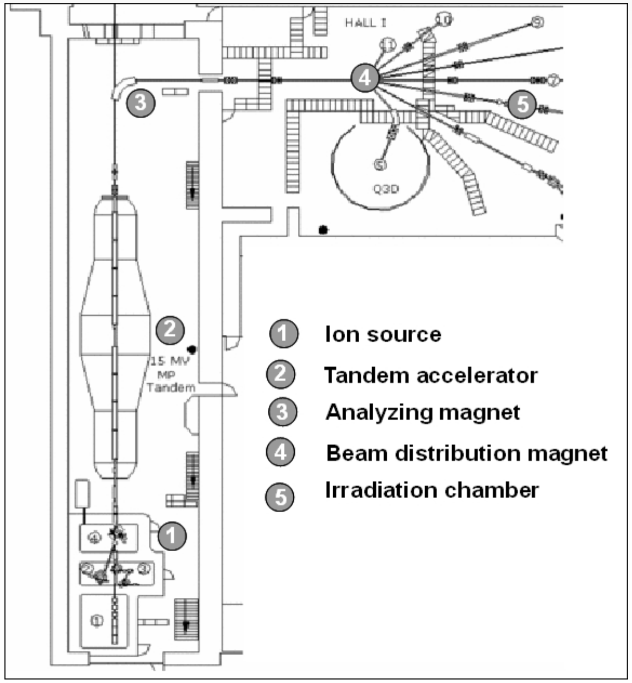
Irradiation testing

HEAVY IONS IRRADIATION TESTING

- Irradiation of layer systems with ^{127}I @ 80 MeV at Maier-Leibnitz Laboratory (MLL, TUM)
- Reproduces the relevant effects for the creation of an IDL
- Very short irradiation time (only some hours)
- No additional radioactivity







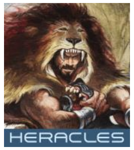
WP 5

Sources: T. Zweifel, *PhD thesis*, Technische Universität München, 2014

SEMPER FIDELIS

- Subsize- or full-size experiment? Will be decided on first TC meeting. FDEG proposal: Full-size.
- Coating or Al-Si ?
  - Eliminate IL formation? Coating required!
  - Reduction of swelling rate allows fuel system to accommodate IL formation in Al-Si matrix → Cheaper fuel system, better for back-end
- First use of UMo powder created by AREVA-CERCA
- Effect of the heat treatment?
  - HT delays recrystallization sufficiently to reduce swelling at high BU?
- Fission rate versus fission density dependences
- Parameterization of recrystallization (with/without HT)

WP 6



EMPIRE

- Sister experiment of SEMPER FIDELIS. Not in scope of HERACLES-CP, but very important complementary experiment! Performed with US DoE.
- Deposition method for coating?
    - Differences between ALD and PVD? Effect of AlN interlayer?
- C2TWP method for monolithic fuel (if not in SEMPER FIDELIS, i.e. if SF not sub-size)
- Fission rate versus fission density dependences
- Parameterization of recrystallization (with/without heat treatment)
- Benchmark effect of fuel variables (kernel size distribution, Mo content, loading, …)

Cycles 1 and 2 — Left Test Train stays in for 2 cycles

	1	2
A	U10Mo/ZrN/ALD/STD/no Heat	ZrN/ALD/MOD/Heat
	ZrN/ALD/STD/no Heat	ZrN/ALD/STD/ Heat
B	U10Mo/ZrN/ALD/STD/no Heat	ZrN/ALD/MOD/ Heat
	ZrN/ALD/STD/no Heat	ZrN/ALD/STD/ Heat
C	ZrN/PVD/MOD/no Heat	ZrN/PVD/MOD/Heat
	ZrN/PVD/MOD/Heat/CERCA pow	ZrN-AlN/ALD/STD/Heat
D	ZrN/PVD/MOD/no Heat	ZrN/PVD/MOD/Heat
	ZrN/PVD/MOD/Heat/CERCA pow	ZrN-AlN/ALD/STD/Heat

Cycle 1 — Right Test Train removed after 1 cycle

	1	2
A	Mono Co-Rolled	Mono Co-Rolled
	ZrN/ALD/STD/no Heat	ZrN/ALD/STD/ Heat
B	U10Mo/ZrN/ALD/STD/no Heat	ZrN/ALD/MOD/ Heat
	ZrN/ALD/STD/no Heat	ZrN/ALD/STD/ Heat
C	ZrN/PVD/MOD/no Heat	ZrN/PVD/MOD/Heat
	ZrN/PVD/MOD/Heat/CERCA pow	ZrN-AlN/ALD/STD/Heat
D	ZrN/PVD/MOD/no Heat	ZrN/PVD/MOD/Heat
	ZrN/ALD/MOD/no Heat	ZrN-AlN/ALD/STD/Heat

Cycle 2 — Right Test Train - New loading for 1 cycle irradiation

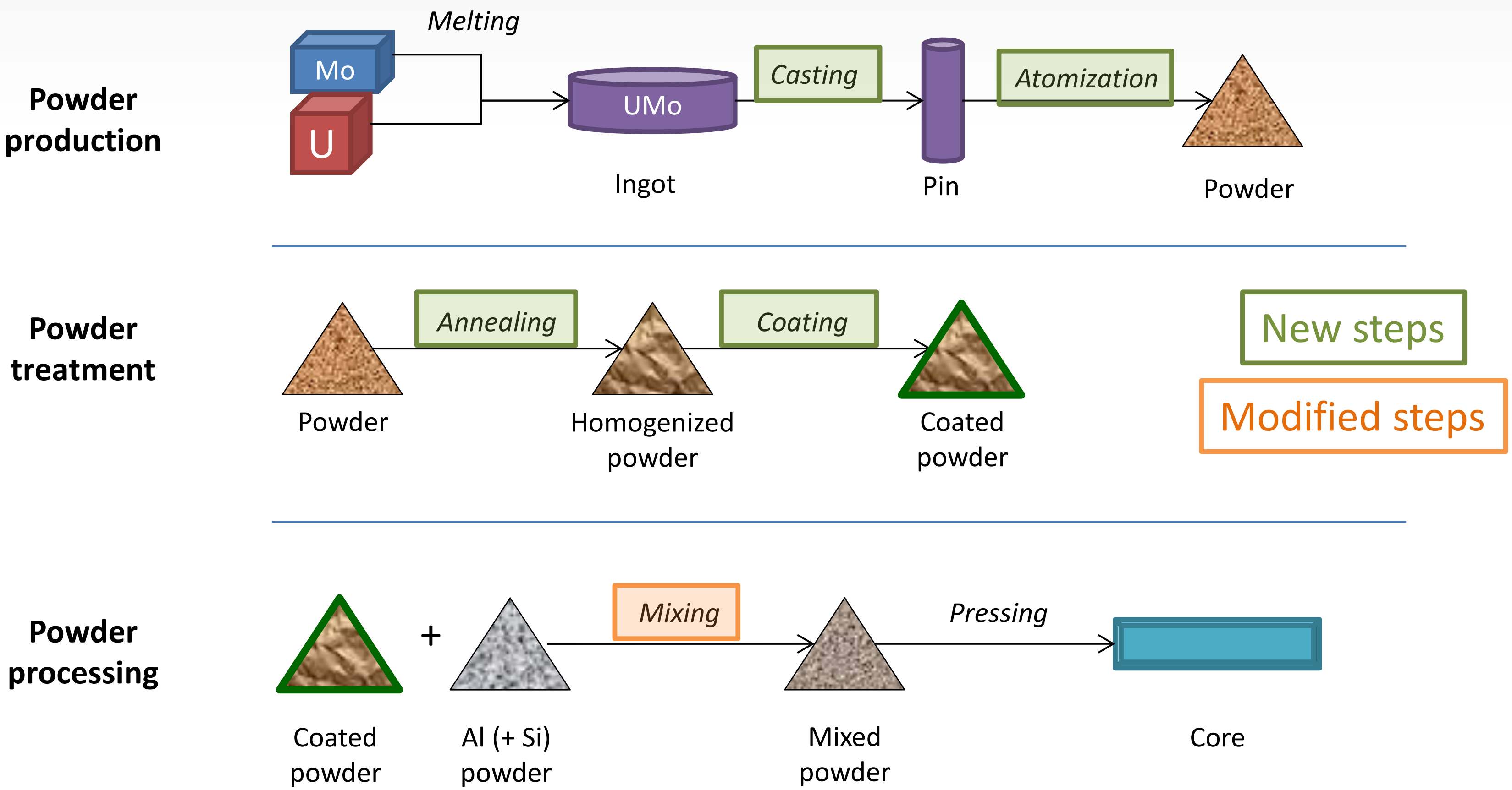
	1	2
A	Mono PVD	Mono PVD
	ZrN/ALD/MOD/no Heat	ZrN/ALD/MOD/Heat
B	U10Mo/ZrN/ALD/STD/Heat	***ZrN/PVD/MOD/Heat***
	ZrN/ALD/MOD/no Heat	***ZrN/ALD/MOD/ Heat***
C	***ZrN/ALD/STD/no Heat***	***ZrN/ALD/STD/ Heat***
	ZrN/PVD/MOD/no Heat	***ZrN-AlN /ALD/STD/Heat***
D	***ZrN/ALD/STD/no Heat***	***ZrN/ALD/STD/ Heat***
	U10Mo/ZrN/ALD/STD/Heat	***ZrN/PVD/MOD/Heat***

Names in bold italic are duplicate plates

Dispersion & monolithic fuel

Fuel production

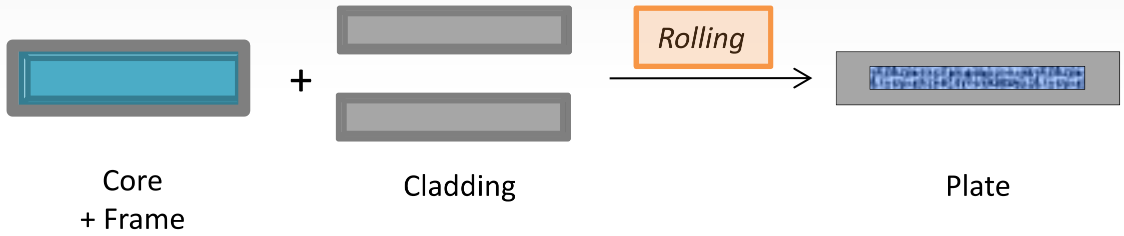
DISPERSION FUEL PRODUCTION



DISPERSION FUEL PRODUCTION II

Modified steps

Plate rolling

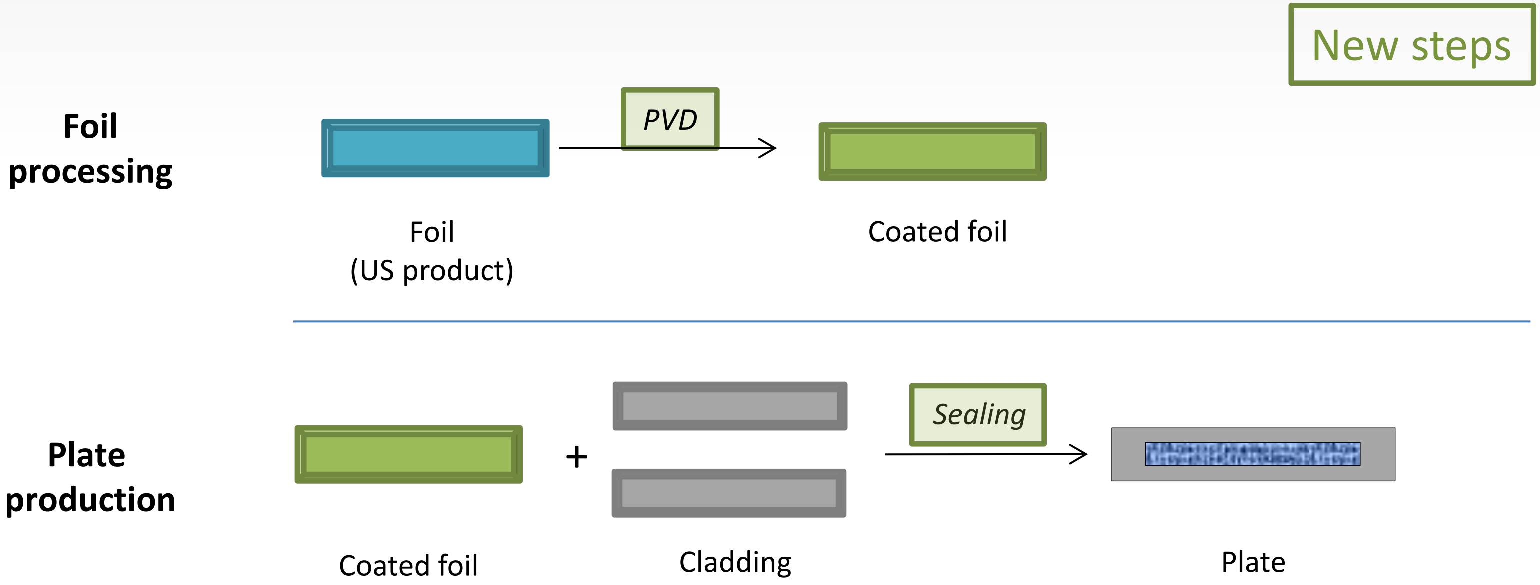


- 4 new and 2 significantly modified process steps compared to current fuels
- Prototype equipment available for each step, but needs to be better understood
- Yield and quality improvements required for industrial-scale production

WP 3

WP 4

MONOLITHIC FUEL PRODUCTION



- All new processes
  - PVD coating of bare foils
  - C2TWP plate production
- U-Mo foils produced in USA

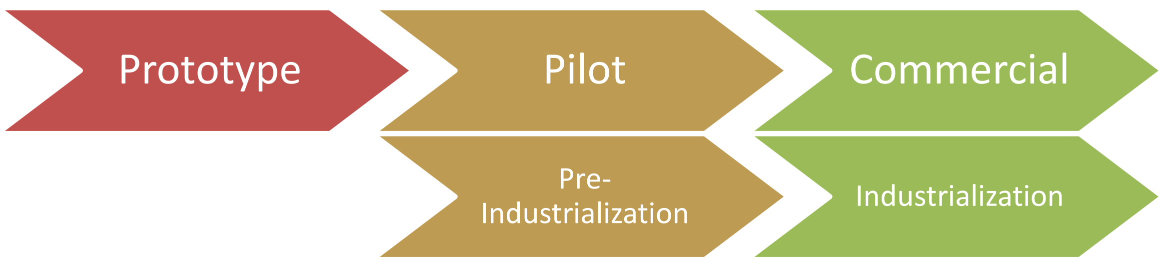
DEVELOPMENT PLAN

3 fabrication equipment development stages to minimize scaling risks:

- Prototype: 1% of final production capacity
- Pilot: 10% of final capacity
- Commercial: 100% of final capacity

Equipment:

Processes:



PROTOTYPES

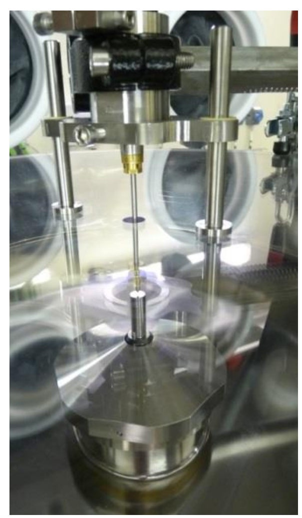
Prototype

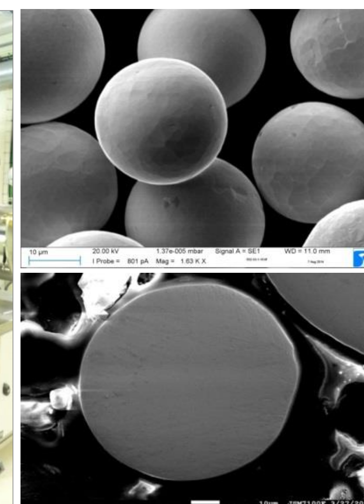
- Necessary equipment
  - Induction furnace
  - Atomizer
  - Powder annealing
  - Powder coating
  - Foil coating
  - C2TWP

HERACLES-CP: Deeper understanding of technique for upscaling / development of pilot equipment

WP 3

- Status:
  - All projects completed
  - All operational





Sources: R. Schenk, PhD thesis, to be published, Technische Universität München, 2015

PILOT EQUIPMENT

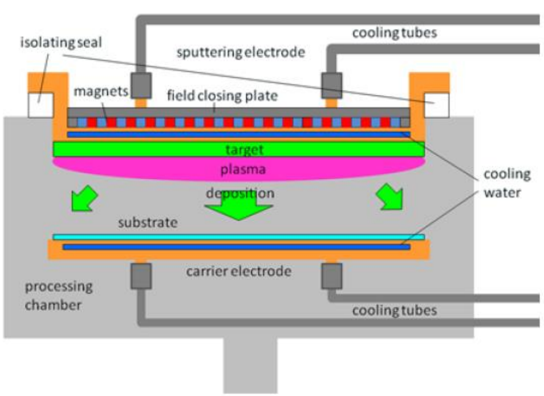
Pilot

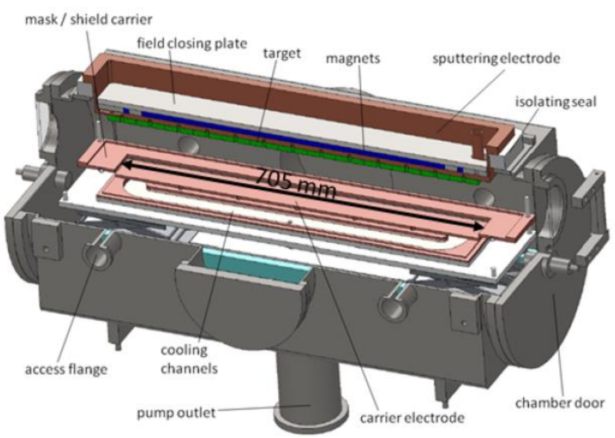
- Necessary equipment:
  - Arc furnace
  - Induction furnace
  - Atomizer
  - Powder annealing
  - Powder coating
  - Foil coating
  - Foil grading

HERACLES-CP: Development of important equipment

WP 3

- Status:
  - Current projects
  - Ongoing work





Sources: W. Schmid, *PhD thesis,* Technische Universität München, 2011

PROCESS PRE-INDUSTRIALIZATION

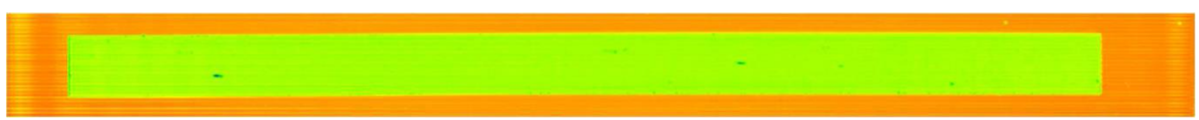
Pre-Industrialization

- R&D studies
  - Plate production modeling
  - Powder homogenization
  - Monolithic flat
  - Monolithic with grading

HERACLES-CP: Tackle two major non-conformance problems

WP 4

- Status:
  - Current projects
  - Ongoing work



Sources: B. Stepnik et. Al., RRFM 2014

COMMERCIAL EQUIPMENT & INDUSTRIALIZATION

Commercial

Industrialization

- Equipment and process industrialization
- No contributions inside HERACLES-CP
- Development after 2019

HERACLES

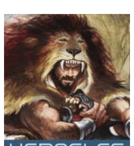
The consortium

REACTOR CONVERSION

- Belgium, France and Germany are committed to the conversion of their HPRRs

- LEONIDAS (2010 – 2014) coordinated European efforts on UMo dispersed technology
- ALPS (2008 – 2013) coordinated European efforts on UMo monolithic technology

- HERACLES since 2013 integrates European efforts for the qualification of high density LEU research reactor fuel(s)



LEONIDAS, ALPS & HERACLES

PAST

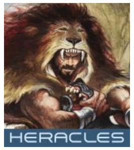
ALPS

+

LEONIDAS

LEONIDAS, ALPS & HERACLES

FUTURE



TECHNISCHE UNIVERSITÄT MÜNCHEN (TUM)

Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II)	
Operator:	Technische Universität München (TUM)
Location:	Garching bei München, Germany
Dedication:	Neutron source / beam tube reactor
Start-up:	2004
Power and flux:	20 MW, 8.0×10^{14} neutrons/s cm²
Fuel:	U_3Si_2 dispersed in Al, 3.0 g U/cm³ 8,1 kg U, 93% enriched, single fuel element
Cycles:	4 cycles p.a., 60 days each (240 days total)
Moderation:	H_2O cooled, D_2O reflected
Key facts:	25 scientific instruments; Dedicated sources for cold, hot and fission neutrons, ultra cold neutron source in construction; Irradiation capabilities at 12 positions; Silicon doping facility; ^{99}Mo production facility in construction; Fission neutron cancer therapy station

AREVA-NP (CERCA)

Compagnie pour l'Etude et la Réalisation de Combustibles Atomiques		
Operator:	AREVA	
Location:	Romans, France	
Dedication:	Fuel element fabricator	
Start-up:	1957	
Power and flux:	-	
Fuel:	-	
Cycles:	-	
Moderation:	-	
Key facts:	150 people, 40 M€ turnover Production and R&D workshops LEU and HEU handling capacity ISO 9001, ISO 14001 certifications	

SCK●CEN

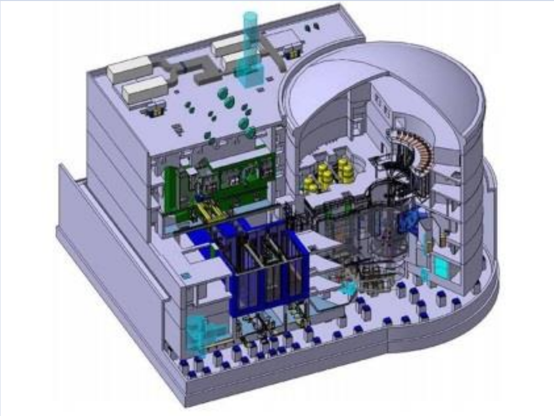
Belgian Reactor 2 (BR2)	
Operator:	Studiecentrum voor Kernenergie / Centre d'Etude de l'Energie Nucleaire (SCK●CEN)
Location:	Mol, Belgium
Dedication:	Material test reactor
Start-up:	1963
Power and flux:	50 - 80 MW, 10^{15} neutrons/s cm^2
Fuel:	UAl_x dispersed in Al, 1.3 g U/cm^3, 93% enriched Variable core configuration (400g U per fuel element)
Cycles:	5 (1 cycle is 21-28 days)
Moderation:	Light water cooled, Be and H_2O moderator
Key facts:	• The safety of nuclear reactors, plant lifetime evaluations and ageing of components • The safety of nuclear fuels, the increase of their burn-up and MOX fuels • The development of new fuels with reduced risk of proliferation of nuclear weapon technology • The evolution and assessment of safety problems • Production activities related to medical and industrial applications (Production of radioisotopes and neutron transmutation doped silicon)

INSTITUT LAUE-LANGEVIN (ILL)

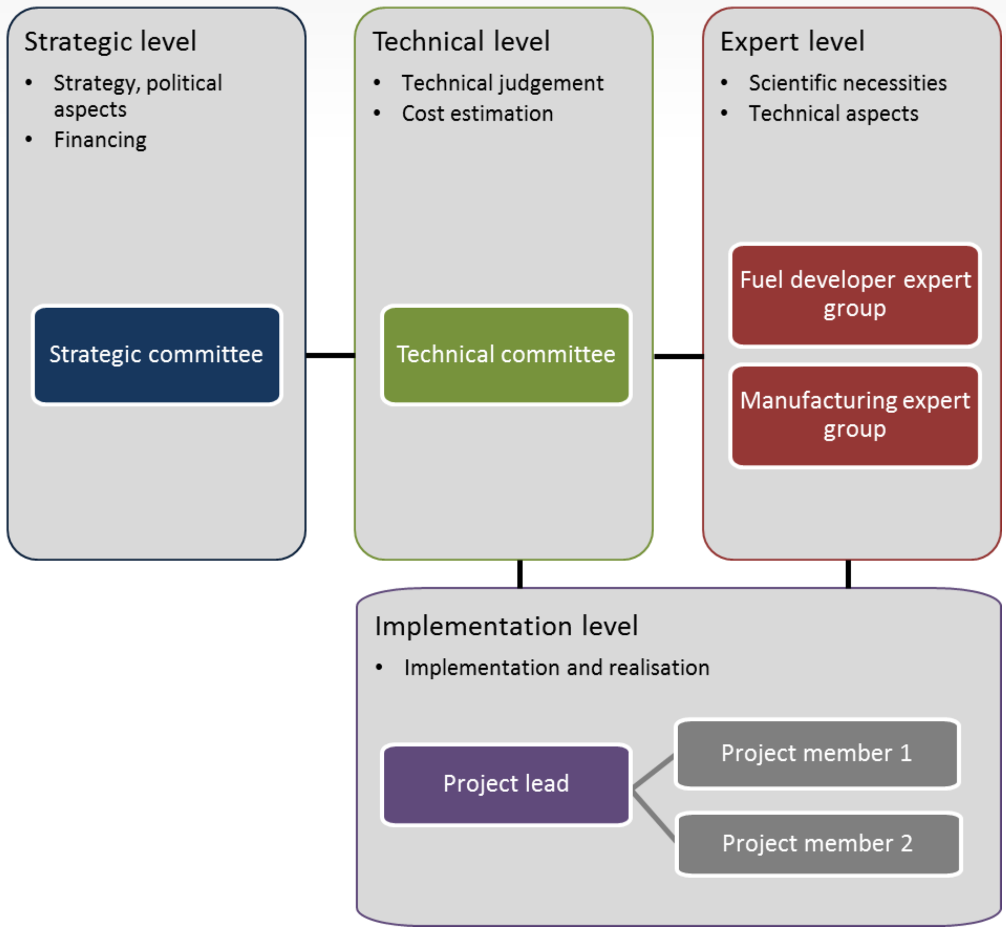
Réacteur a Haut Flux (RHF)		
Operator:	Institut Laue-Langevin (ILL)	
Location:	Grenoble, France	
Dedication:	Neutron source / beam tube reactor	
Start-up:	1969	
Power and flux:	58.3 MW, 1.5×10^{15} neutrons/s cm^2	
Fuel:	UAl_x dispersed in Al, 1.1 g U/cm^3 8.658 kg U, 93% enriched, single fuel element	
Cycles:	4 cycles p.a., 50 days each (200 days total)	
Moderation:	Heavy Water (D_2O)	
Key facts:	40+ scientific instruments	

COMMISSARIAT À L'ENERGIE ATOMIQUE (CEA)

Jules Horowitz Reactor (JHR)	
Operator:	Commissariat à l'Energie Atomique (CEA)
Location:	Cadarache, France
Dedication:	Material test reactor
Start-up:	*Under construction*
Power and flux:	100 MW, 5.5×10^{14} neutrons/s cm² (thermal), 1×10^{14} neutrons/s cm² (fast)
Fuel:	U_3Si_2 dispersed in Al, 34-37 fuel assemblies 4.8 gU/cm³
Cycles:	To be defined: between 25.7 and 35 days
Moderation:	H_2O moderator, Be reflector
Key facts:	• ^{99}Mo production (25% of the European basis demand, 50% of the European demand in case of specific demand) • Nuclear fuel/materials testing: O Hot cell examination equipments: Gamma and X-ray tomographies, NDE multipurpose bench O Support laboratories : Fission product, Chemistry, Activation laboratories O Underwater NDE benches : gamma scanning and tomography, X-ray tomography, neutronography



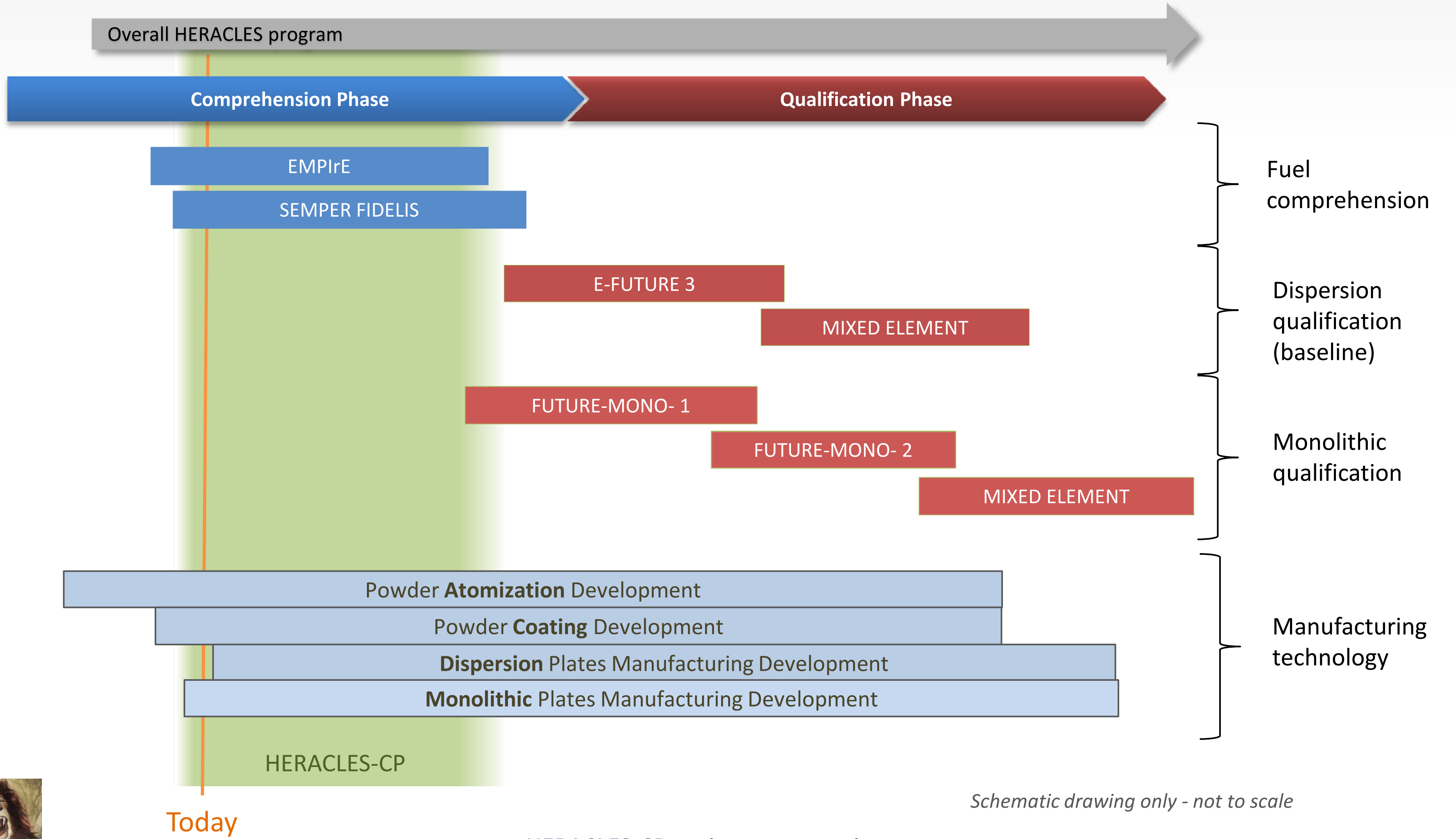
MANAGEMENT STRUCTURE



Where HERACLES-CP belongs

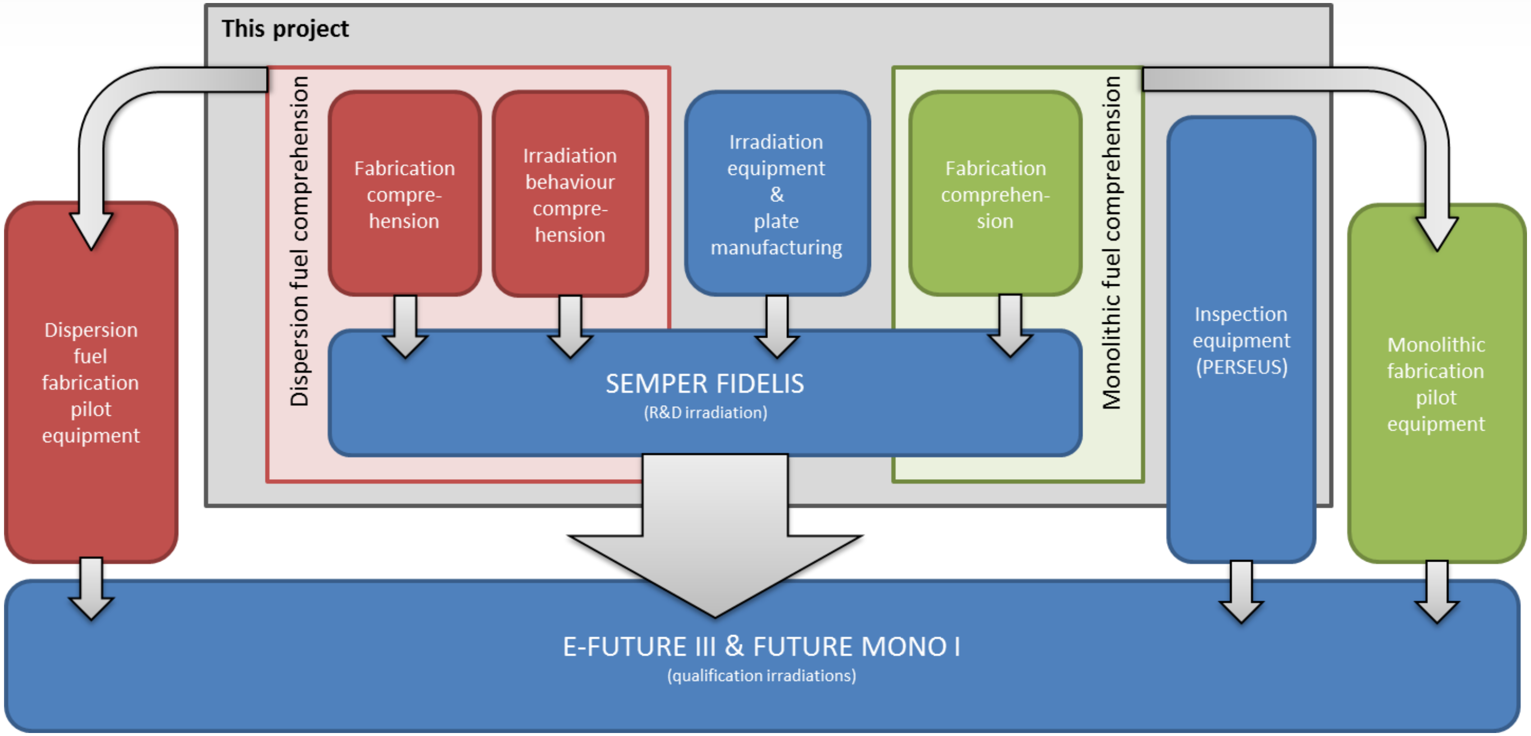
Framework

COMPLETE HERACLES ROADMAP



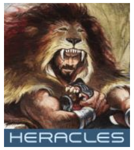
Schematic drawing only - not to scale

HERACLES-CP PROJECT OVERVIEW



WORK PACKAGES IN HERACLES-CP

- WP1: Management
- WP2: Comprehension phase
- WP3: Production technology
- WP4: Powder and plate manufacturing
- WP5: Heavy ion irradiations
- WP6: SEMPER FIDELIS
- WP7: PERSEUS



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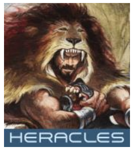
2.1 SF test matrix definition
2.2 Comprehension phase report



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- WP5: Heavy ion irradiations
- WP6: SEMPER FIDELIS
- WP7: PERSEUS

3.1 Pin casting comprehension
3.2 Atomization compr.
3.3 Furnace pilot
3.4 UMo foil coating

WORK PACKAGES IN HERACLES-CP

- WP1: Management
- WP2: Comprehension phase
- WP3: Production technology
- WP4: Powder and plate manufacturing
- WP5: Heavy ion irradiations
- WP6: SEMPER FIDELIS
- WP7: PERSEUS

4.1 Dispersed plate modelling
4.2 Monolithic comprehension
4.3 SF manufacturing
4.4 Uranium transport study
4.5 Heat treatment furnace

WORK PACKAGES IN HERACLES-CP

- WP1: Management
- WP2: Comprehension phase
- WP3: Production technology
- WP4: Powder and plate manufacturing
- WP5: Heavy ion irradiations
- WP6: SEMPER FIDELIS
- WP7: PERSEUS

5.1 IDL generation
5.2 Diffusion barrier thickness
5.3 ZrN barrier break down
5.4 Supporting irradiations

WORK PACKAGES IN HERACLES-CP

- WP1: Management
- WP2: Comprehension phase
- WP3: Production technology
- WP4: Powder and plate manufacturing
- WP5: Heavy ion irradiations
- WP6: SEMPER FIDELIS
- WP7: PERSEUS

6.1 Fresh fuel characterization
6.2 Irradiation device
6.3 Neutronic calculations
6.4 Irradiation
6.5 Cooling, transport, PIEs
6.6 Waste

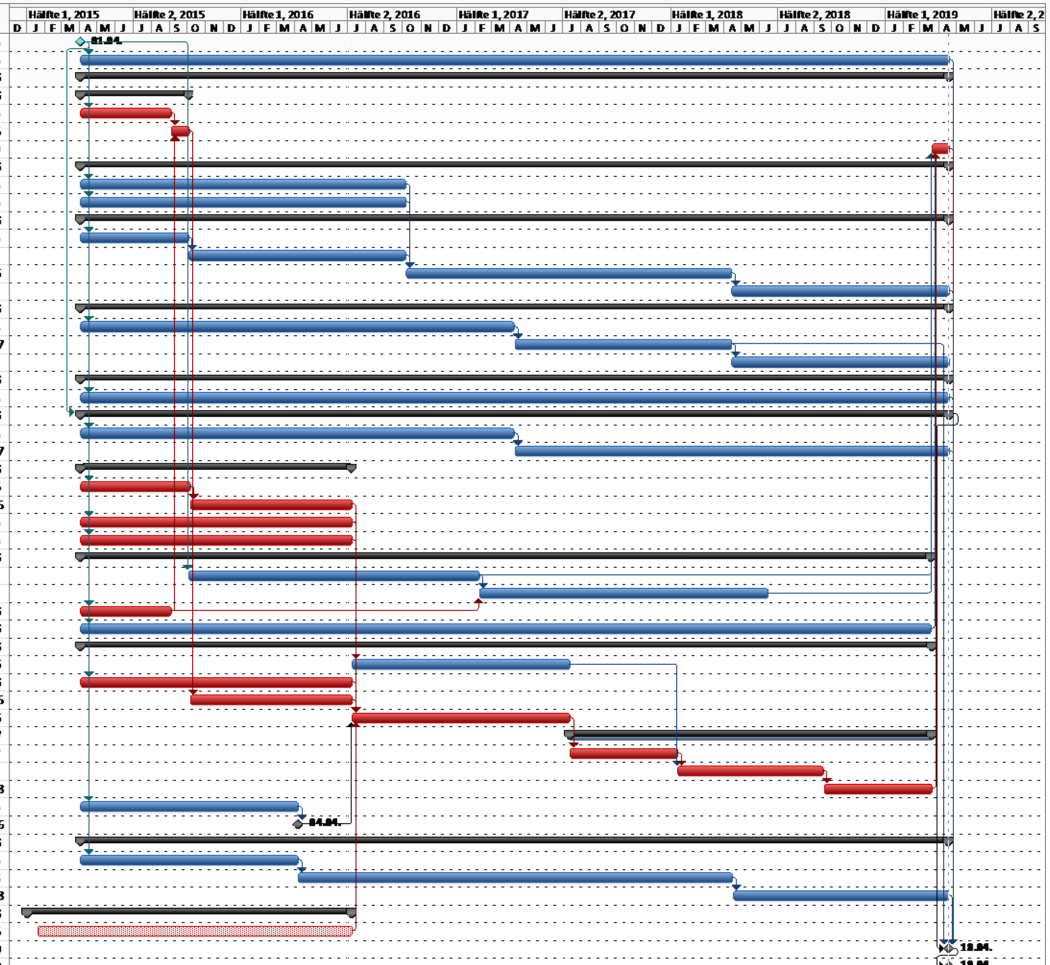
WORK PACKAGES IN HERACLES-CP

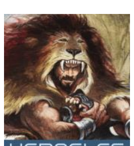
- WP1: Management
- WP2: Comprehension phase
- WP3: Production technology
- WP4: Powder and plate manufacturing
- WP5: Heavy ion irradiations
- WP6: SEMPER FIDELIS
- WP7: PERSEUS

7.1 Prototype
7.2 Advanced device
7.3 BR2 set-up

HERACLES-CP ROADMAP

Nr.	Vorgangsname	Dauer	Anfang
1	Project start	0 Monate	Mi 01.04.15
2	**WP1: Management**	48 Monate	Mi 01.04.15
3	**WP2: Dispersed fuel comprehension**	**48,05 Mon**	**Mi 01.04.15**
4	2.1 Evaluation of first part & test matrix defini	**6,05 Monat**	**Mi 01.04.15**
5	Evaluation of comprehension phase	5,05 Monat	Mi 01.04.15
6	Test matrix definition	1 Monat	Do 03.09.15
7	2.2 Evaluation of comprehension phase	1 Monat	Mi 20.03.19
8	**WP3: Production technology**	**48 Monate**	**Mi 01.04.15**
9	3.1 UMo pin casting comprehension study	18 Monate	Mi 01.04.15
10	3.2 UMo pin atomization comprehension stud	18 Monate	Mi 01.04.15
11	**3.3 Induction furnace pilot developments**	**48 Monate**	**Mi 01.04.15**
12	Safety assessment	6 Monate	Mi 01.04.15
13	Design	12 Monate	Fr 02.10.15
14	Manufacturing	18 Monate	Do 06.10.16
15	Qualification	12 Monate	Fr 13.04.18
16	**3.4 UMo foil coating developments**	**48 Monate**	**Mi 01.04.15**
17	Development	24 Monate	Mi 01.04.15
18	Validation	12 Monate	Mo 10.04.17
19	Reporting	12 Monate	Fr 13.04.18
20	**WP4: Powder and plate manufacturing**	**48 Monate**	**Mi 01.04.15**
21	4.1 Dispersed UMo plate modelling	48 Monate	Mi 01.04.15
22	**4.2 Monolithic comprehension phase**	**48 Monate**	**Mi 01.04.15**
23	Foil quality study	24 Monate	Mi 01.04.15
24	Plate quality study	24 Monate	Mo 10.04.17
25	**4.3 SEMPER FIDELIS manufacturing**	**15,05 Mon**	**Mi 01.04.15**
26	Dispersion fuel preparation	6 Monate	Do 02.04.15
27	Dispersion plate manufacturing	9 Monate	Mo 05.10.15
28	Monolithic plate manufacturing	15,05 Mon	Mi 01.04.15
29	4.4 Uranium transport study	15,05 Mon	Mi 01.04.15
30	**WP5: Heavy ion irraditions**	**47 Monate**	**Mi 01.04.15**
31	5.1 IDL generation	16 Monate	Fr 02.10.15
32	5.3 ZrN barrier break-down	16 Monate	Di 07.02.17
33	5.2 Diffusion barrier thickness	5,05 Monat	Mi 01.04.15
34	5.4 Supporting irradiations	47 Monate	Mi 01.04.15
35	**WP6: SEMPER FIDELIS in-pile irradiation**	**47,05 Mon**	**Mi 01.04.15**
36	6.1 Fresh fuel characterisation	12 Monate	Do 07.07.16
37	6.2 Manufacturing of the irradiation device	15 Monate	Do 02.04.15
38	6.3 Neutronic calculations	9 Monate	Mo 05.10.15
39	6.4 Irradiation	12 Monate	Do 07.07.16
40	6.5 Cooling, transport and PIEs	**20 Monate**	**Mi 12.07.17**
41	Cooling	6 Monate	Mi 12.07.17
42	Non-destructive PIEs	8 Monate	Fr 12.01.18
43	Basic destructive PIEs	6 Monate	Mo 17.09.18
44	6.6 Waste contract	12 Monate	Mi 01.04.15
45	Agreement to take over plate remnants	0 Monate	Mo 04.04.16
46	**WP7: PERSEUS device**	**48 Monate**	**Mi 01.04.15**
47	7.1 Prototype	12 Monate	Mi 01.04.15
48	7.2 Advanced device	24 Monate	Mi 06.04.16
49	7.3 BR2 steup	11,95 Mon	Mo 16.04.18
50	**External factors**	**17,95 Mon**	**Do 01.01.15**
51	BR2 Refurbishment	17,95 Mon	Do 01.01.15
52	Project completed	0 Monate	Do 18.04.19
53	*QUALIFICATION PHASE (placeholder)*	0 Monate	Do 18.04.19





Summary

Conclusions

HERACLES-CP

- ✓ Developing a new, safe, high-density fuel for high performance research reactors (HPRR)
- ✓ Addressing one of the last proliferation concerns in the civil nuclear fuel cycle in order to implement this new fuel as soon as possible in the European HPRR (as far as technically and economically feasible)

- ✓ Deep scientific understanding of UMo irradiation behaviour: Preparing the qualification
- ✓ R&D for fuel production techniques, increasing capacity up to 10× from prototype

- ✓ International consortium encompassing all European HPRRs und fuel manufacturers
- ✓ Intense collaboration with complementary programs in USA, Russia and Korea

- ✓ Research & Innovation project
- ✓ NFRP 8: „High density uranium fuel and targets for the production of medical radioisotopes“
- ✓ Running 4 years, from 6/2015 to 5/2019