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LEU UMo dispersion fuel :

Past, present, future

The path to fuel qualification and conversion

National Academy of Sciences visit – May 8th, 2015

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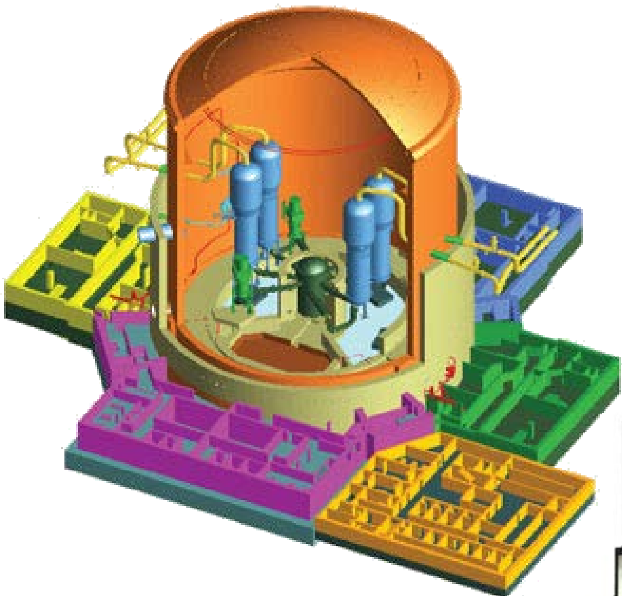
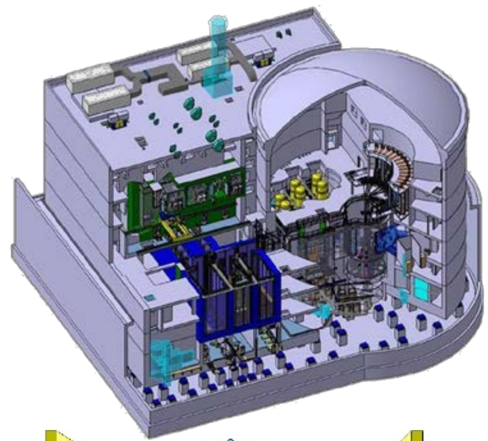
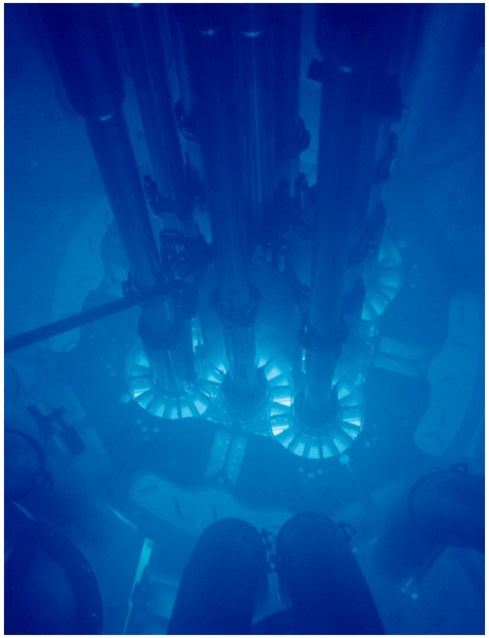
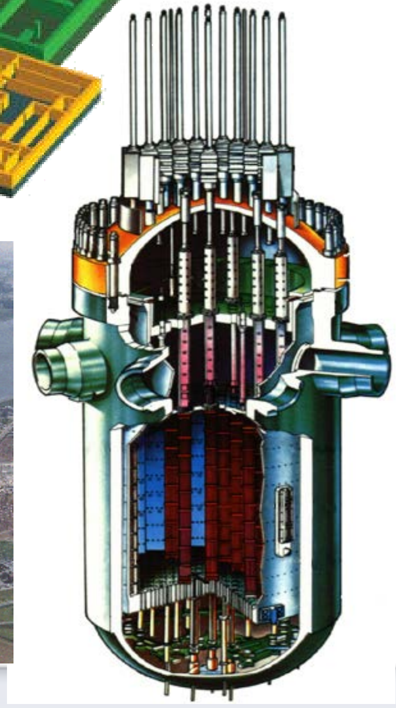
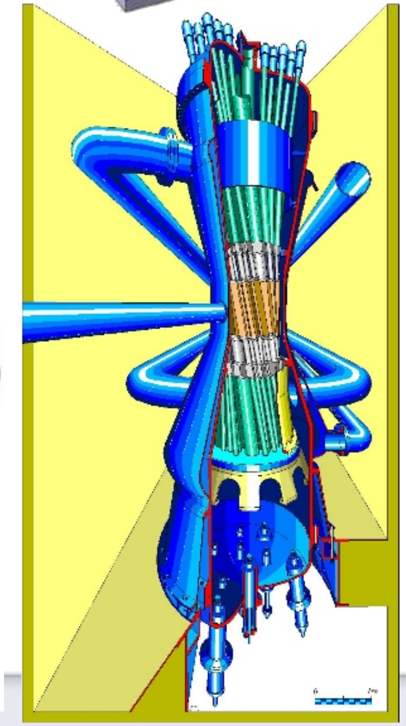
Power reactors vs. research reactors

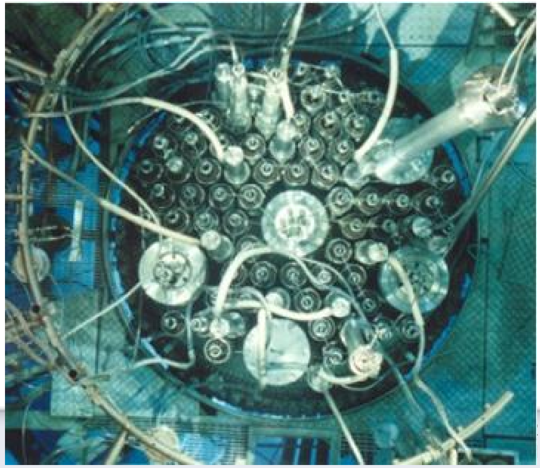










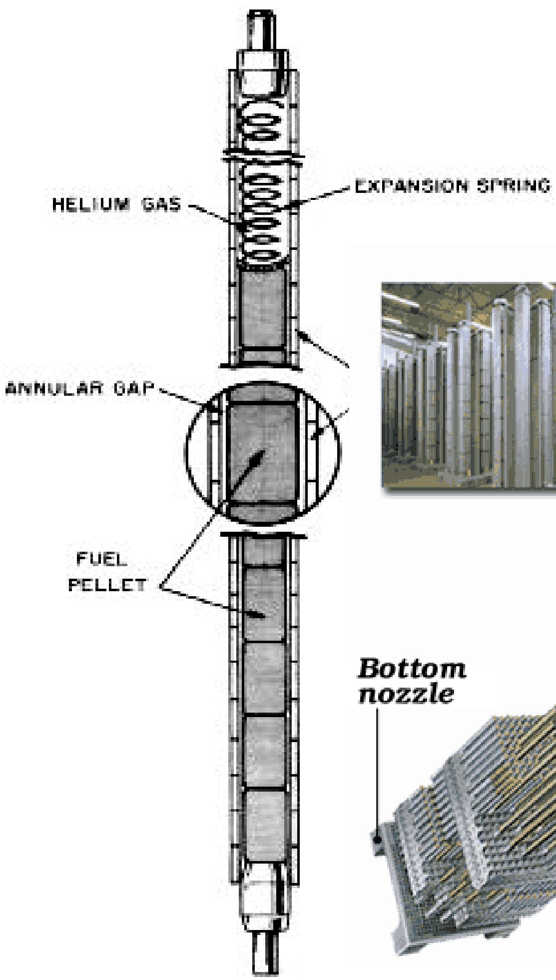


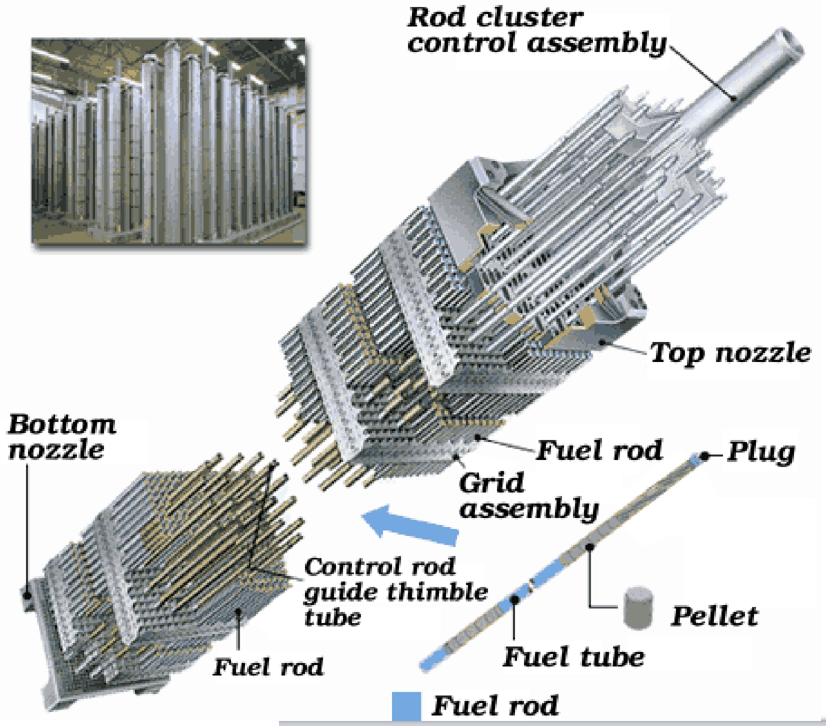
Power reactors vs. research reactors

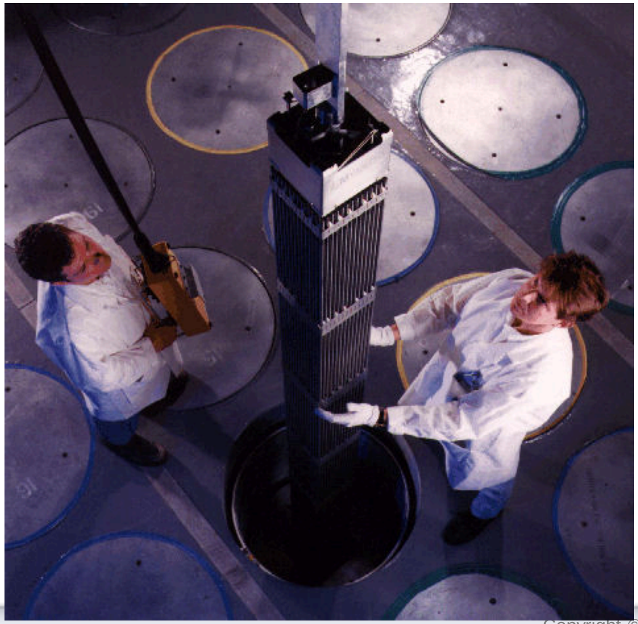
- PWR-BWR-CANDU
- Heat production (steam) for electricity
- Large core with long cycles (12-18 months)
- Reliability
- Low power demand on fuel, but high temp.
  - ~20-50 W/g
  - 1000-1400°C

- Various designs
- Beam tube reactors or materials test reactors
- Compact core with high neutron flux
- Versatility (MTR)
- High power demand on fuel, but low temp.
  - ~2000-2500 W/g
  - 200-250°C

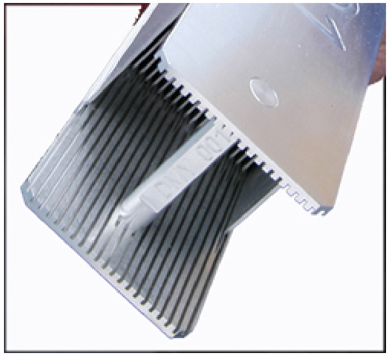
Nuclear fuel (power reactors - PWR)

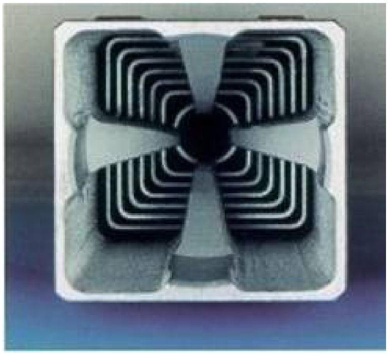


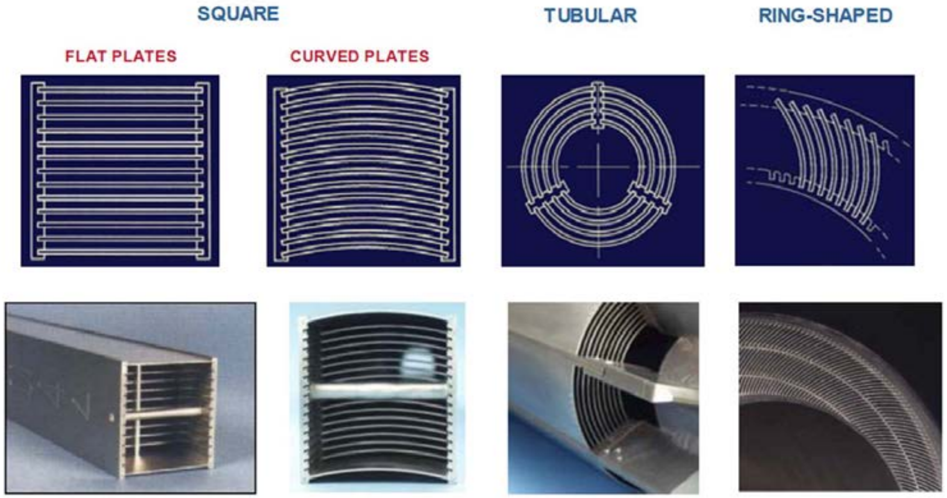


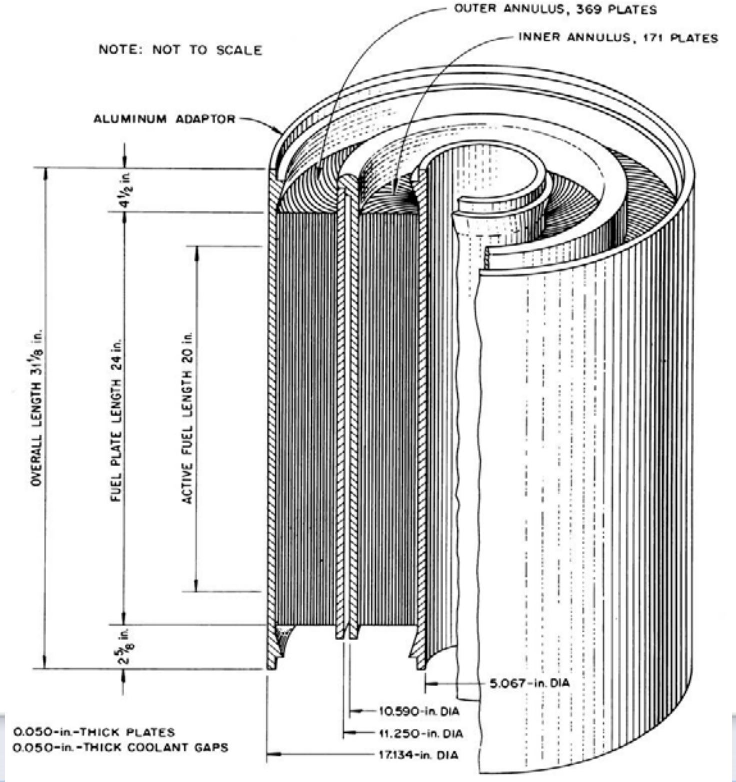


Research reactor fuels (plate-type)









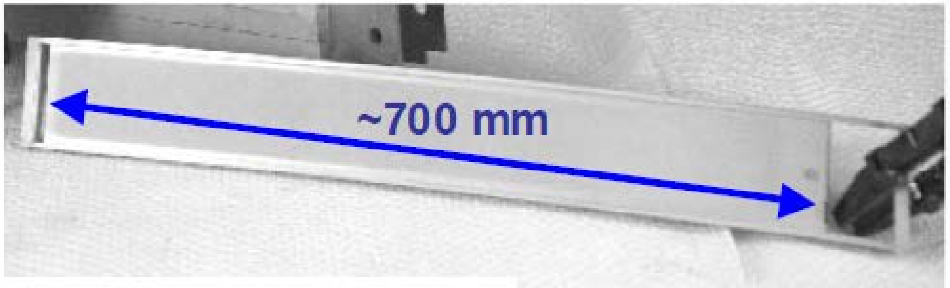
Power reactor vs. research reactor fuel

- Fuel pin
- Ceramic fuel (UO_2-PuO_2)
- Homogeneous (UO_2) or cer-cer (MOX) dispersed
- Zr-based cladding with He-filled fuel-clad gap
- Plenum for fission gas
- Burnup to ~5-7 at%
- Enriched to ~5% ^{5}U

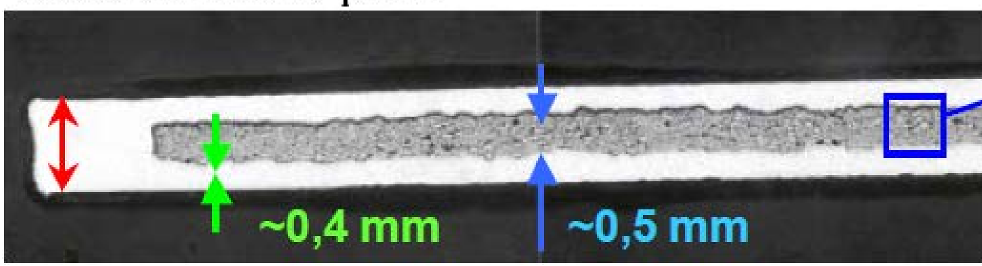
- Fuel plate (or pin)
- 'Metallic' fuel (UAl_x) or oxide (U_3O_8)
- Dispersion in metal (fuel-in-Al) hot rolled
- Al-based cladding with direct fuel contact
- Limited open volume
- Burnup to ~70-80 at%
- **Enriched to ~95% ^{5}U**

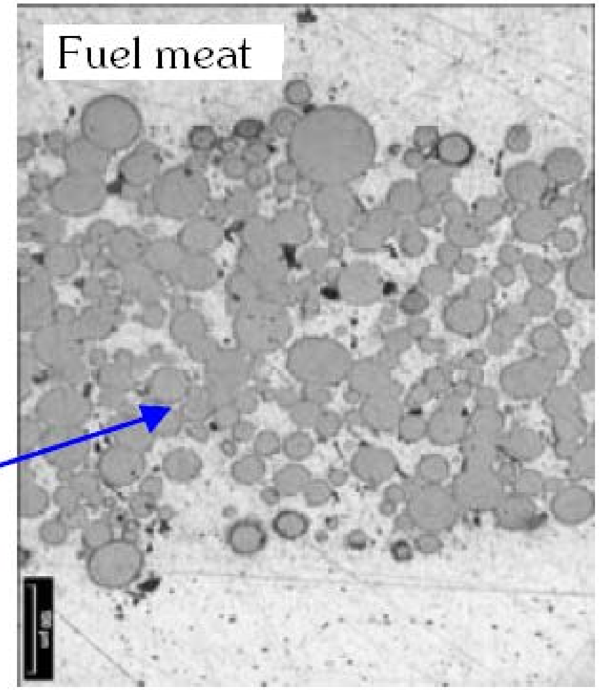
Research reactor fuels (plate type)

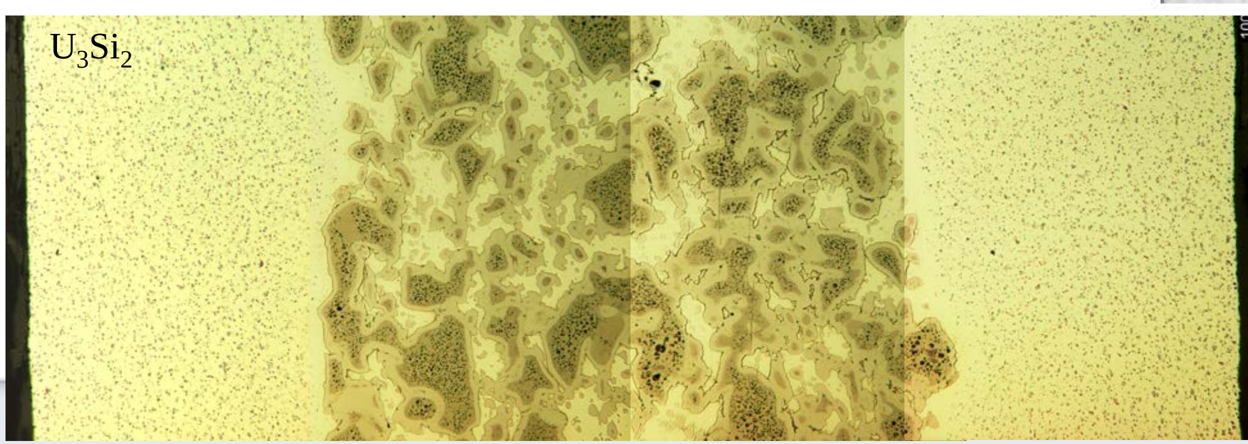
Fuel plate

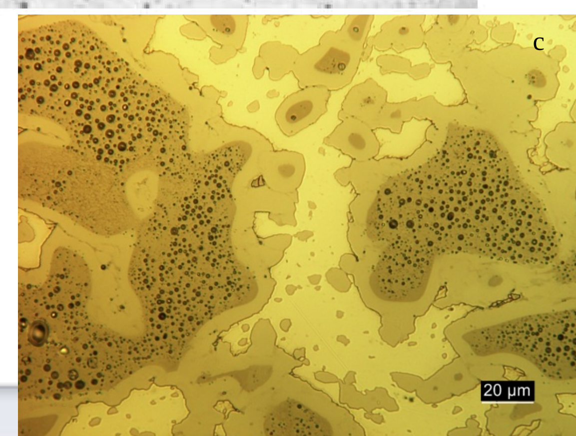


Cross section of plate

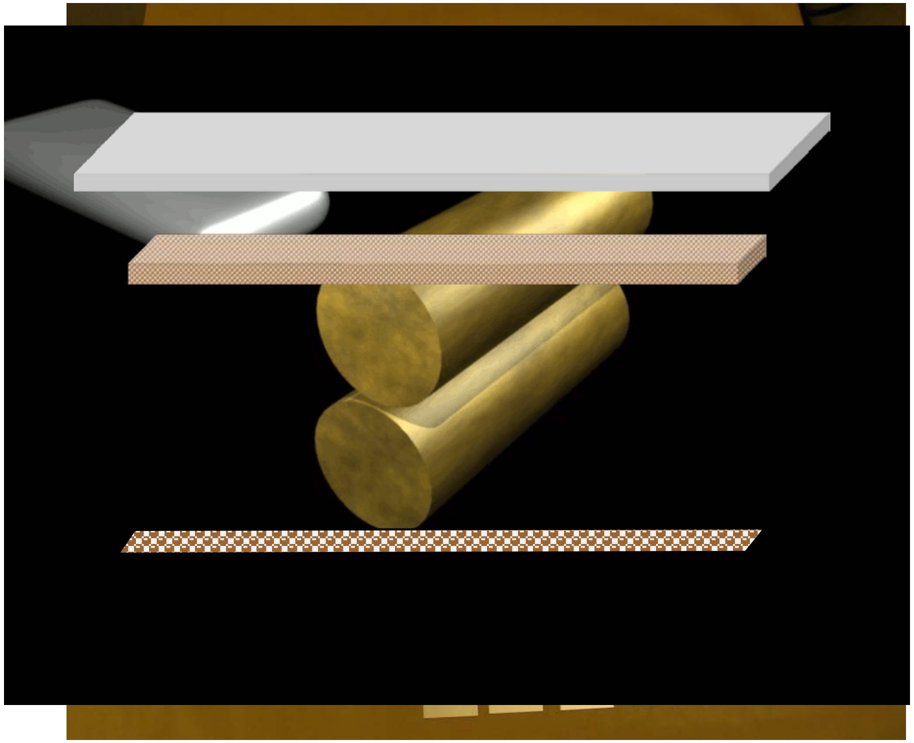








Schematic fuel plate fabrication



1. An Al frame is placed on the bottom part of the cladding
2. The meat (mix of matrix Al and U compound powders) is pressed in a compact
3. The compact is positioned in the frame and the top part of the cladding is placed
4. After welding of the assembly, the plate is manufactured by hot and cold rolling

Reduction of enrichment

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- 1978 : Reduced Enrichment for Research and Test Reactors (RERTR) created by US-DOE to eliminate civil use of HEU because of proliferation risks
  - Reactor performances maintained, but LEU (<20% ^{235}U)
    - Higher fuel loading (more fuel per cm^3)
    - Higher fuel density (fuel compound with more U-atoms/cm^3)
  - Fuel development
    - U_3Si_2 (d=12g/cm^3, 4.8gU/cc load) improves on “classic” UAl_x (d=4.3g/cm^3, 1.3gU/cc load) allowing conversion of many RR
    - Further increase required → scoping high density U-compounds

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Research Reactor fuel : scoping

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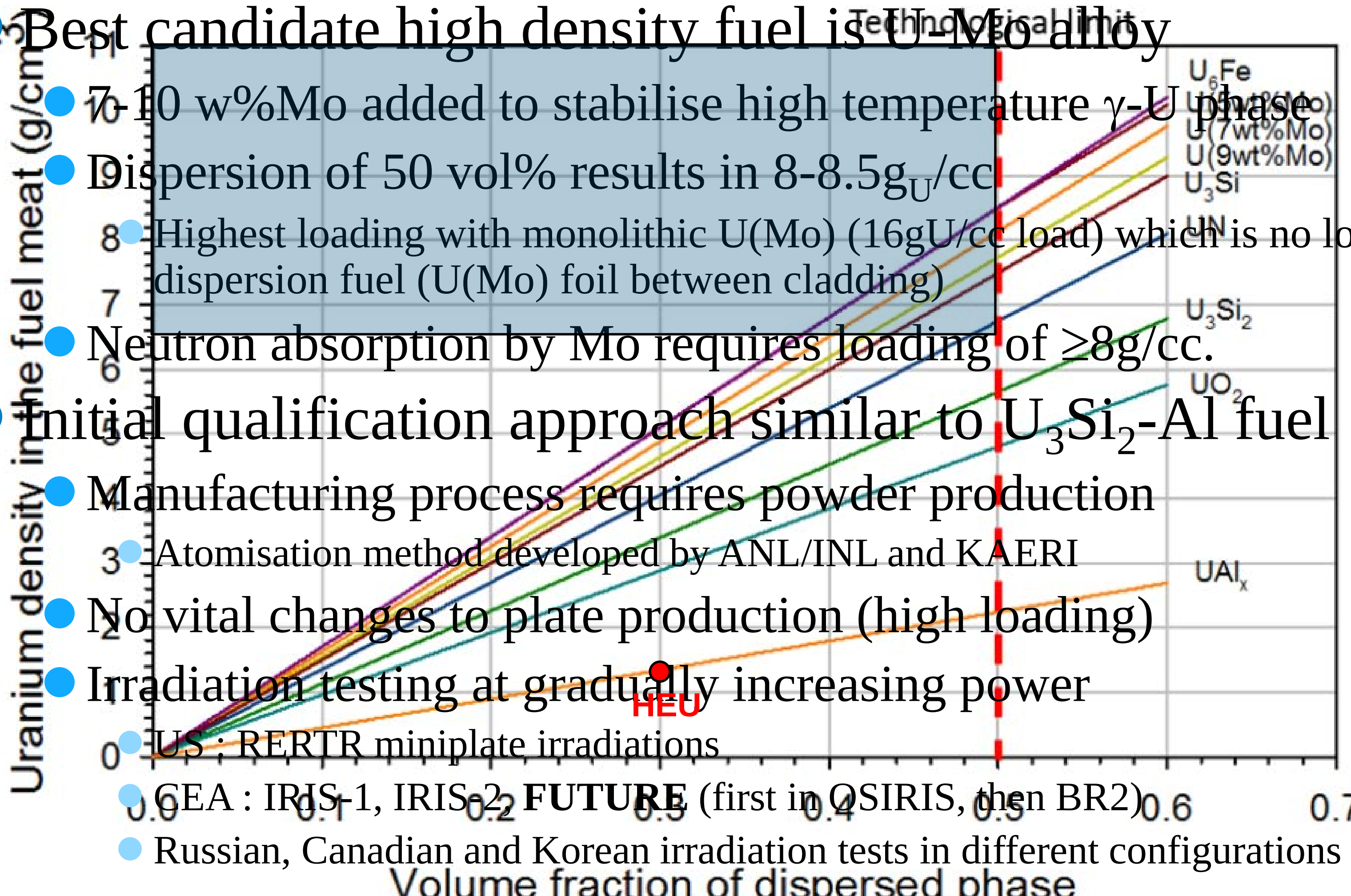

- Best candidate high density fuel is U-Mo alloy
  - 7-10 w%Mo added to stabilise high temperature γ-U phase
  - Dispersion of 50 vol% results in 8-8.5g_U/cc
    - Highest loading with monolithic U(Mo) (16gU/cc load) which is no longer a dispersion fuel (U(Mo) foil between cladding)
  - Neutron absorption 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

Objective

- Conversion of the EU HPRR (including BR2) to LEU requires a qualified fuel system, including
  - Qualified manufacturing route (BR2: CERCA)
  - **Qualified behaviour of fuel in boundary conditions of reactor operation (BR2: 470W/cm², BU>80%)**
  - Industrially available back-end option (BR2: reprocessing)
- It also requires that this fuel system
  - Has an economically sustainable fuel cycle cost
  - Is capable of achieving acceptable reactor performances
  - Can pass the safety requirements of the regulator

UMo dispersion fuel development

- What unexpected challenges were encountered in the UMo dispersion fuel qualification process and why ?
- What have we learned from the past and how do we consider we can still engineer the fuel behaviour ?
- What is the current status and the roadmap ?

The "FUTURE" Irradiation Test

- 2003 : start of European high power **U(Mo)** fuel qualification (CEA-JHR)
- Irradiation of two flat fuel plates in BR2 (FUTURE device)
- U7Mo atomised powder (KAERI) dispersion in pure Al matrix
- Density: 8.5 g/cm^3 , Enrichment: 19.7 % ^{235}U

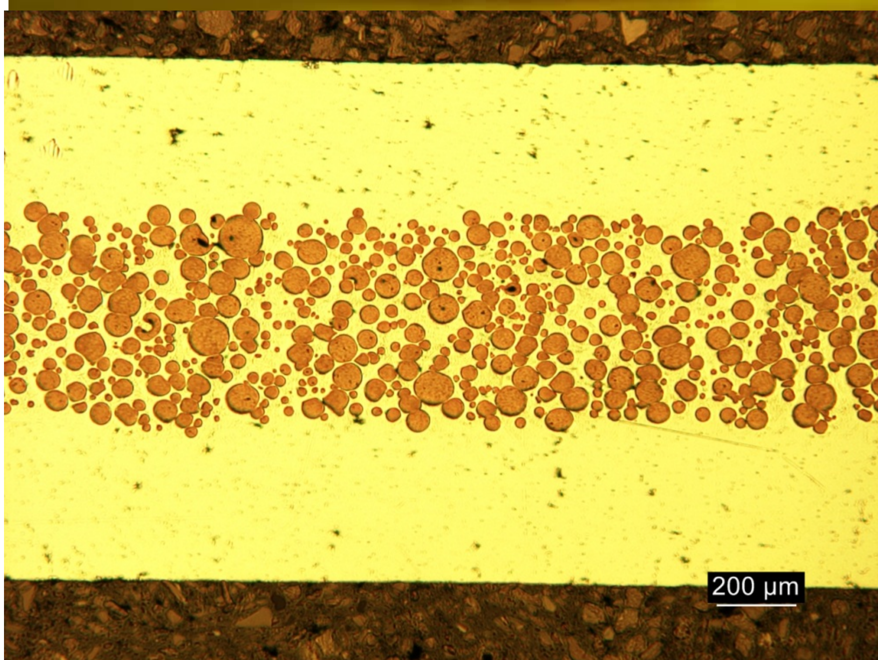

Plate Id.	**U7MC4111**
	Fabrication data
Cladding	AG3NE
Matrix	Al
	Irradiation data
Max BU (%^{235}U)	33
Peak Heat Flux (W.cm^{-2})	353

After second cycle (40 FPD's): observation of swelling of fuel plates in the hot spot. The irradiation was stopped and fuel plates retrieved

Fuel plate swelling

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- Fuel plate swelling is a major aspect of qualification
  - Narrow cooling gaps between plates close as plate swells
  - Swelling needs to be <u>limited, gradual and predictable</u>
    - 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
- Accurate plate swelling measurements are needed !

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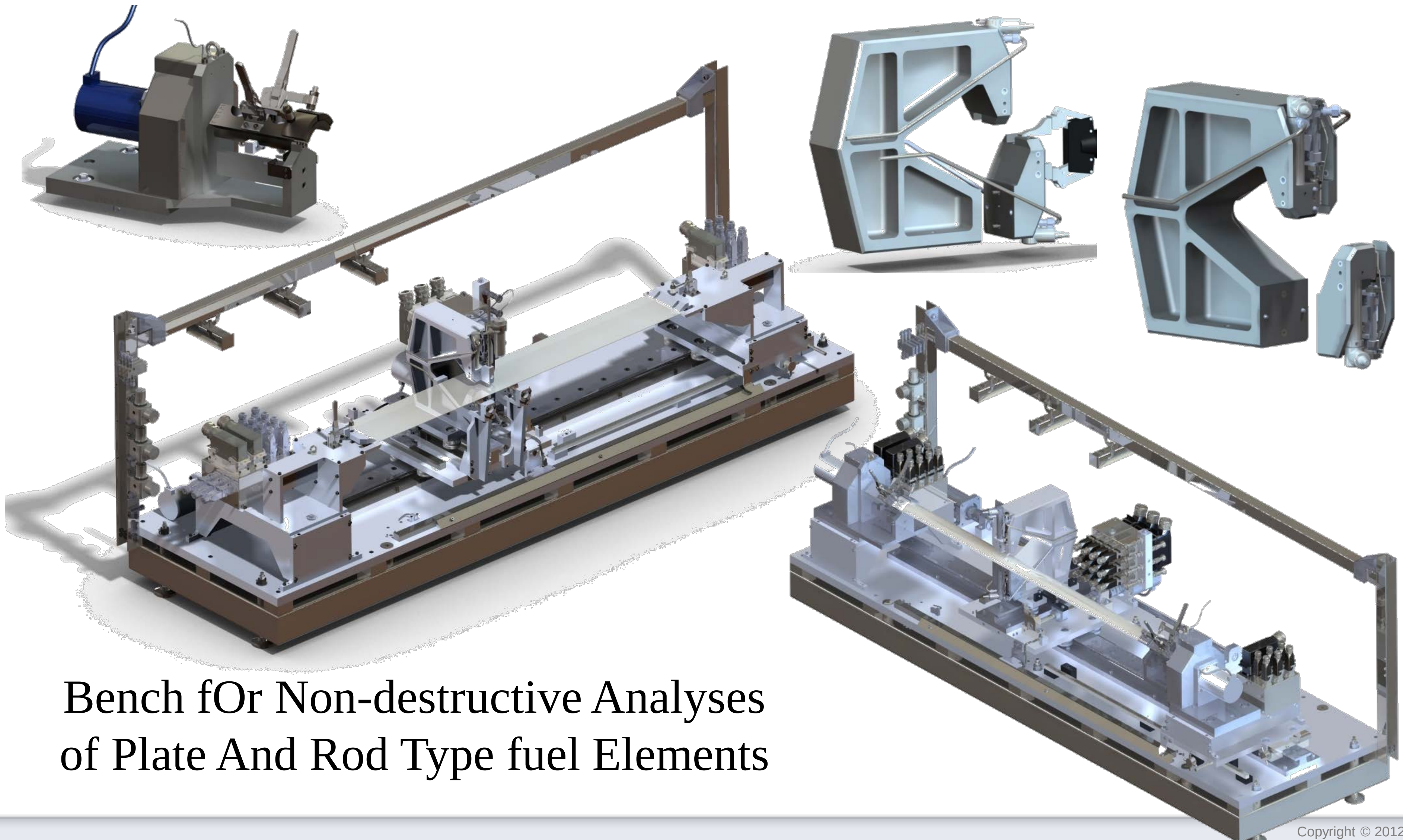

Bench fOr Non-destructive Analyses of Plate And Rod Type fuel Elements

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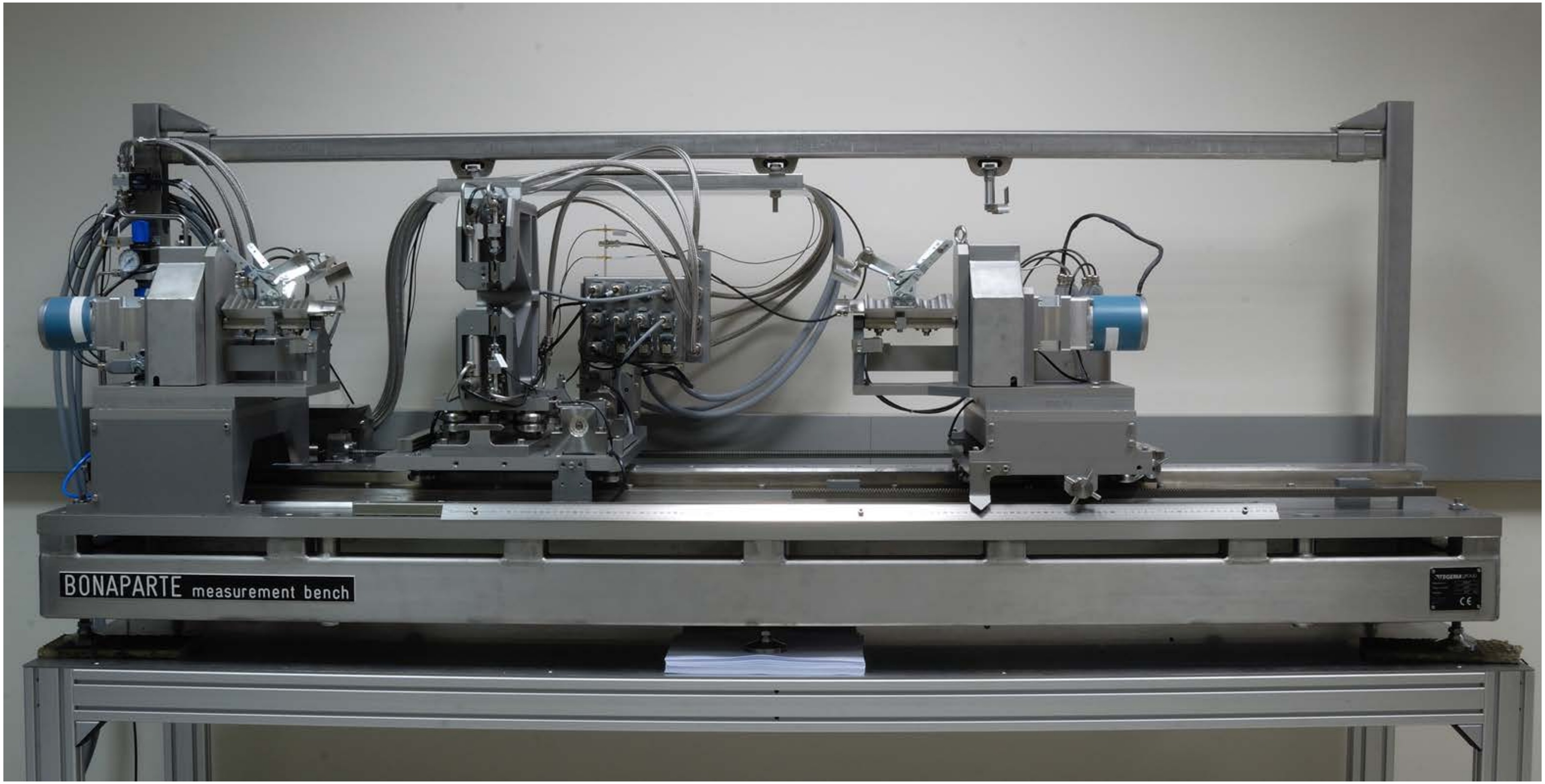

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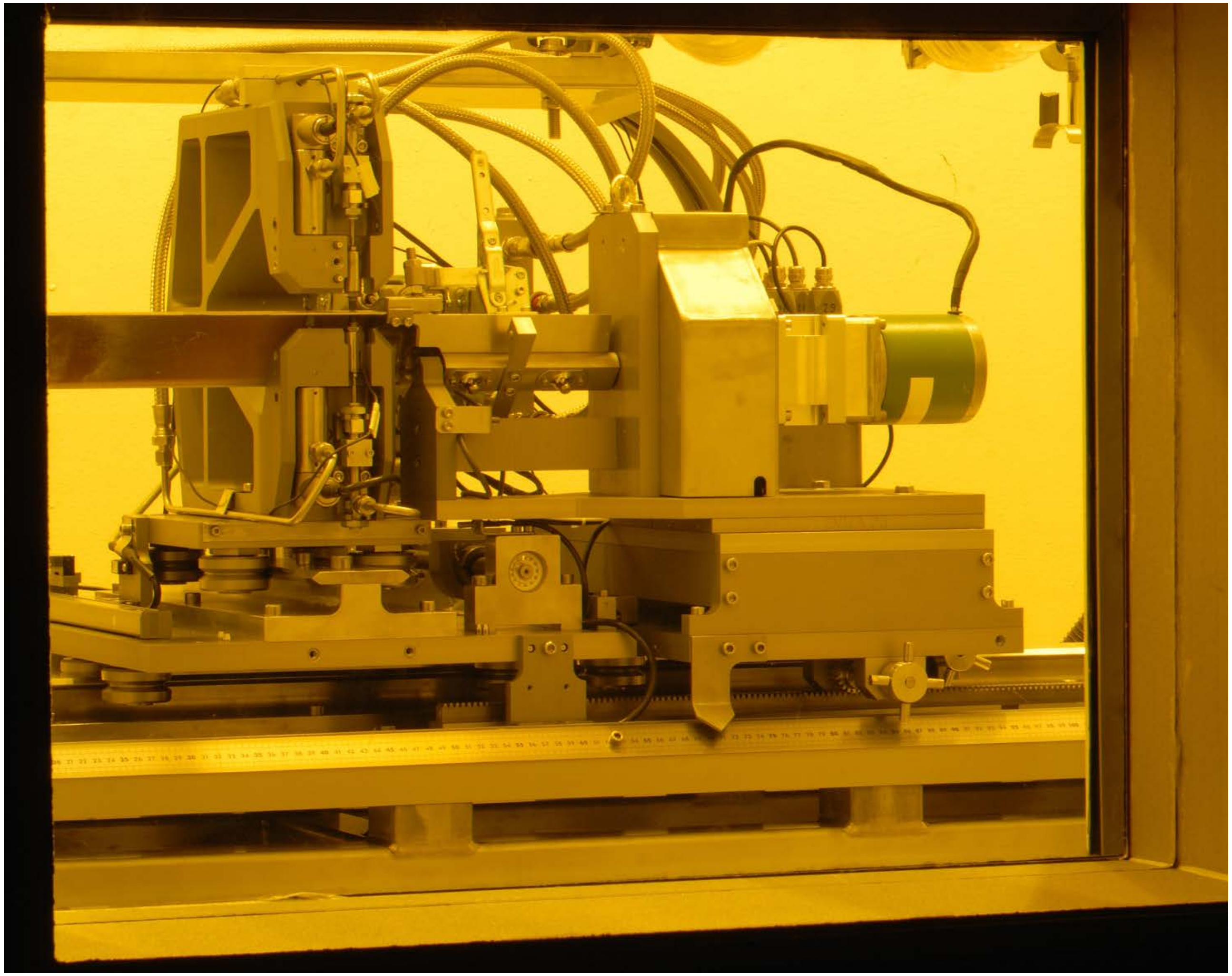
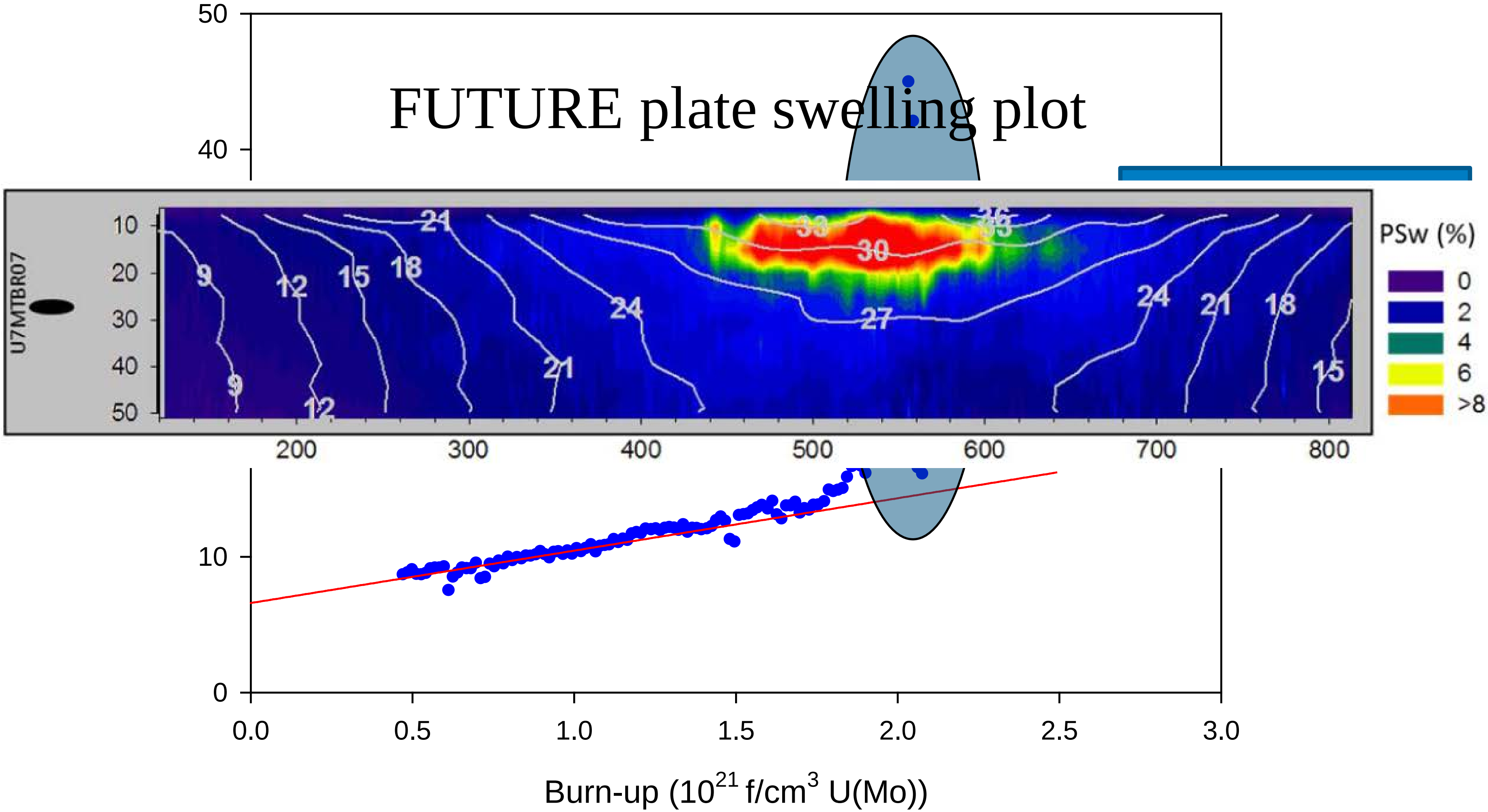


BONAPARTE measures fuel swelling

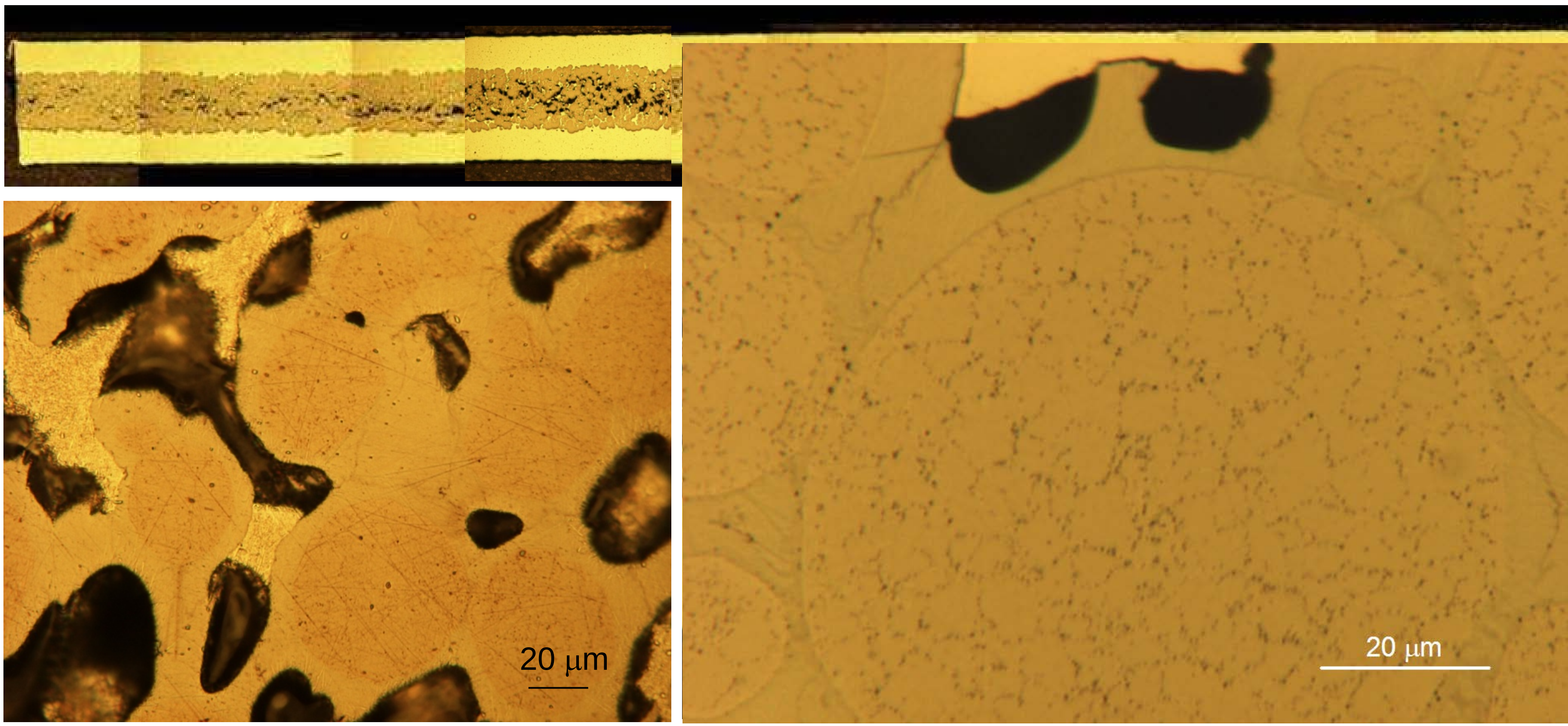
- BONAPARTE provides
  - Matrix (1x5mm) of plate thickness measurements over full plate
  - Matrix (1x5mm) of oxide thickness measurements over full plate
- Neutronics provides
  - Matrix of calculated burnup values over full plate (gamma spectro)
- Interpolation/repositioning of all matrices to a single metric
- Correction of plate thickness matrix for oxide formation
- Calculation of plate swelling matrix using initial thickness
- Conversion of plate swelling to fuel swelling through loading and meat thickness → Fuel swelling matrix
- Averaging fuel swelling values at corresponding burnups
- **Fuel swelling versus burnup plot**

BONAPARTE measures fuel swelling



The “FUTURE” Irradiation Test

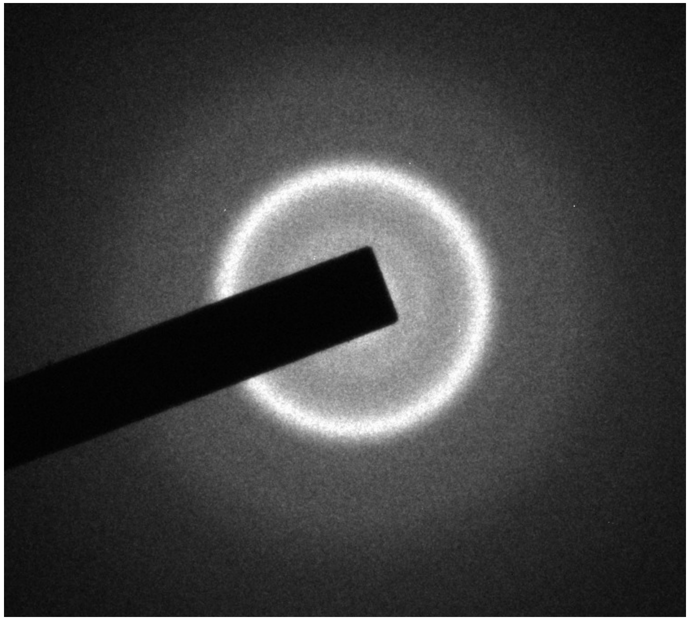
- Interaction between fuel and matrix leads to formation of crescent shaped “porosity” causing blistering*



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

Observations and conclusions

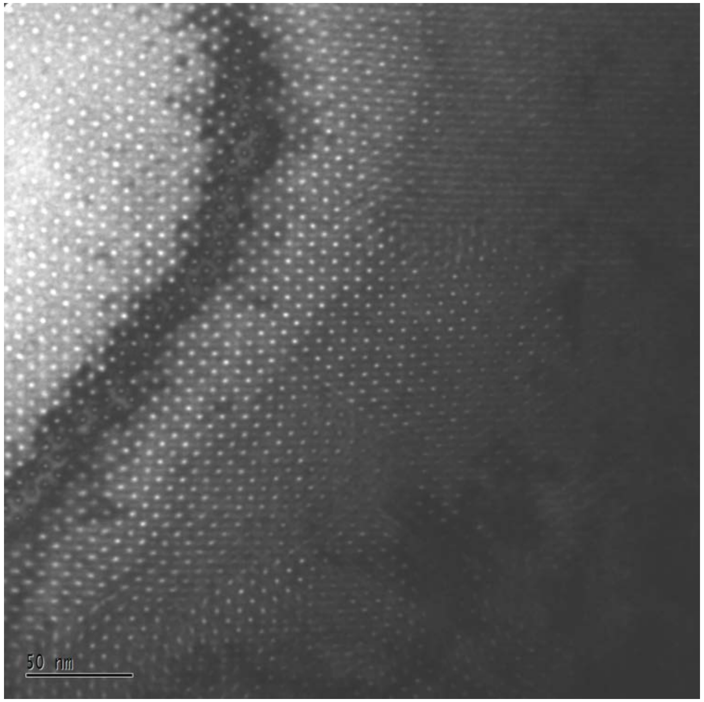
- Formation of large “pores” related to interaction layer (IL) between U(Mo) and Al matrix
  - IL formation ‘sweeps up’ fission products, creating weak interface
  - IL is amorphous* (metallic glass), providing poor host for fission gas



* S. Van den Berghe et al., JNM 375 (2008), pp. 340-346

The fission gas nanobubble lattice

- Fission gas (Xe-Kr) is homogeneously implanted in UMo kernels by fission.
- Low solubility of noble gases in UMo → precipitation
- Self-organising nanobubbles form superlattice with UMo crystal structure as host
- Similar to He ion implantation in metals (P.B. Johnson)



Observations and conclusions

- 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
- Mitigation strategies
  - Reduce/avoid interaction layer (IL) formation
  - Improve IL properties with respect to fission gas retention
- “Old” solution : silicon
  - Used to prevent U-Al interaction in BR1 fuel° (>60y old)
  - High affinity for U, insoluble in Al, free volume reduction of metallic glass (influences viscosity, diffusivity,…)
  - Addition of Si to Al matrix shows positive effect on IL formation

* S. Van den Berghe et al., JNM 375 (2008), pp. 340-346

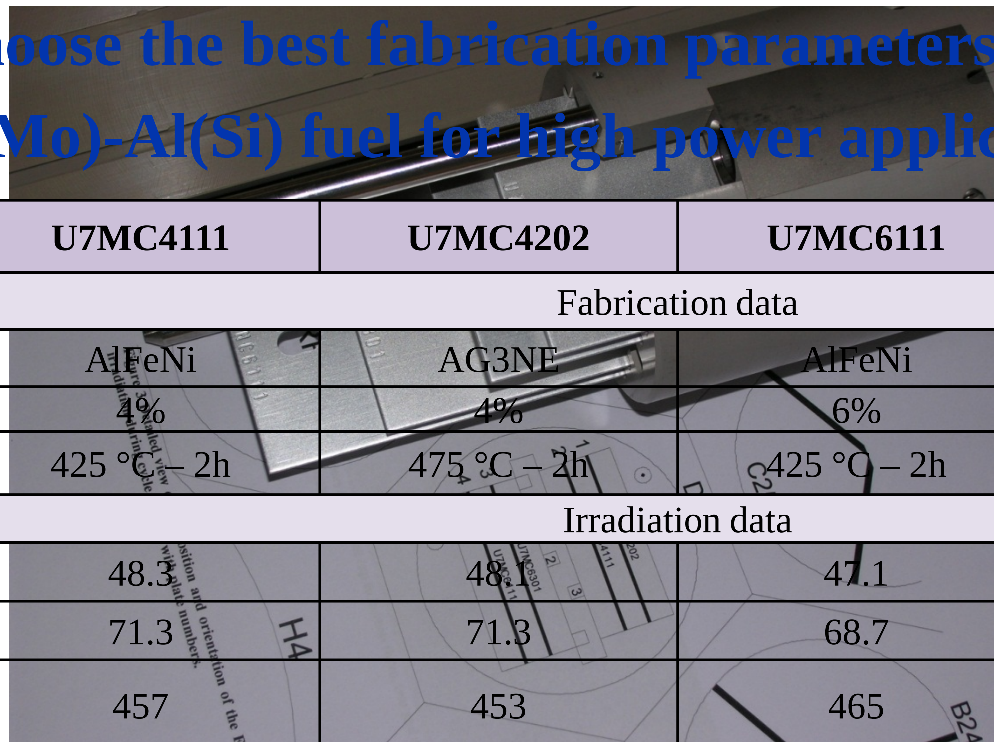
° A. Leenaers et al., JNM 381 (2008) pp. 242-248

Si addition → restart qualification

- Same approach: evolution medium to high power
  - CEA irradiation IRIS-3 : medium power (OSIRIS)
    - Plates with Si behaved markedly better than plates without !
  - Confirmation of Si benefit by international community
  - Quantity of Si to be added ?
    - Stabilisation of IL believed to require >5at% Si in IL, based on metallurgical and thermodynamic contemplations
- High power irradiation → E-FUTURE in BR2
  - 470 W/cm² at BOL for 3 cycles up to 70% ^{235}U depletion
  - 4 flat fuel plates in new FUTURE-type device
  - 4 and 6 w% Si added to matrix, thermal treatments to force diffusion of Si to UMo kernel surfaces

The "E-FUTURE" Irradiation Test

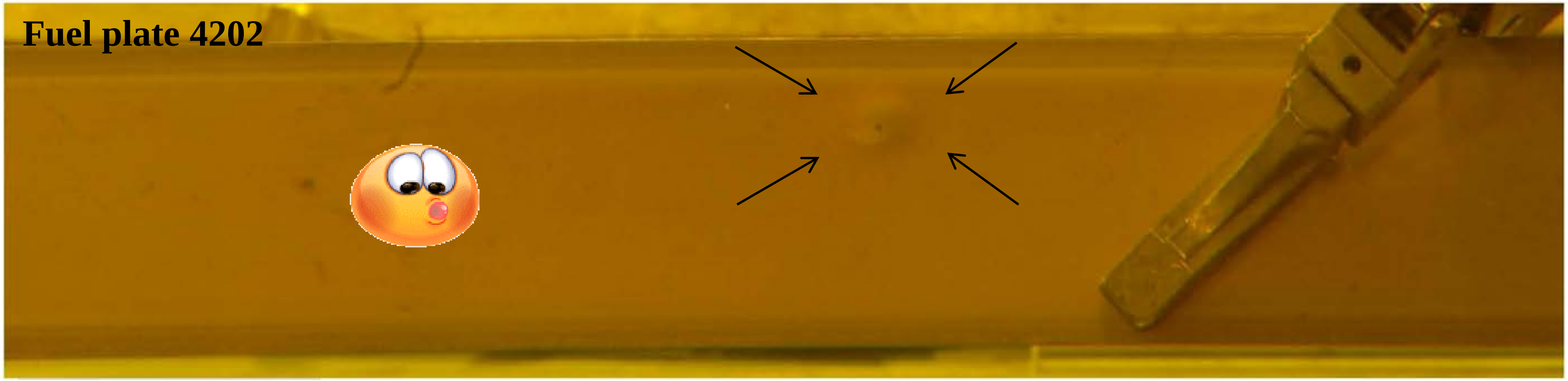
- 2010 : first irradiation of the **LEONIDAS** fuel qualification program
- Irradiation of four flat fuel plates in BR2 (E-FUTURE device)
- U7Mo atomised powder (KAERI) dispersion in Al(Si) matrix
- Density: 8 g/cm^3 , Enrichment: 19.7 % ^{235}U



Choose the best fabrication parameters of the U(Mo)-Al(Si) fuel for high power applications

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

First visual inspection → pillowing



All 4 plates show important swelling in the highest burn-up region

Plate number	Maximum plate thickness (µm)	Reported as-built plate thickness (mm)	Maximum swelling (%)
U7MC4111	3045	1.29	138
U7MC4202	3390	1.29	165
U7MC6111	2345	1.28	84
U7MC6301	1842	1.29	44

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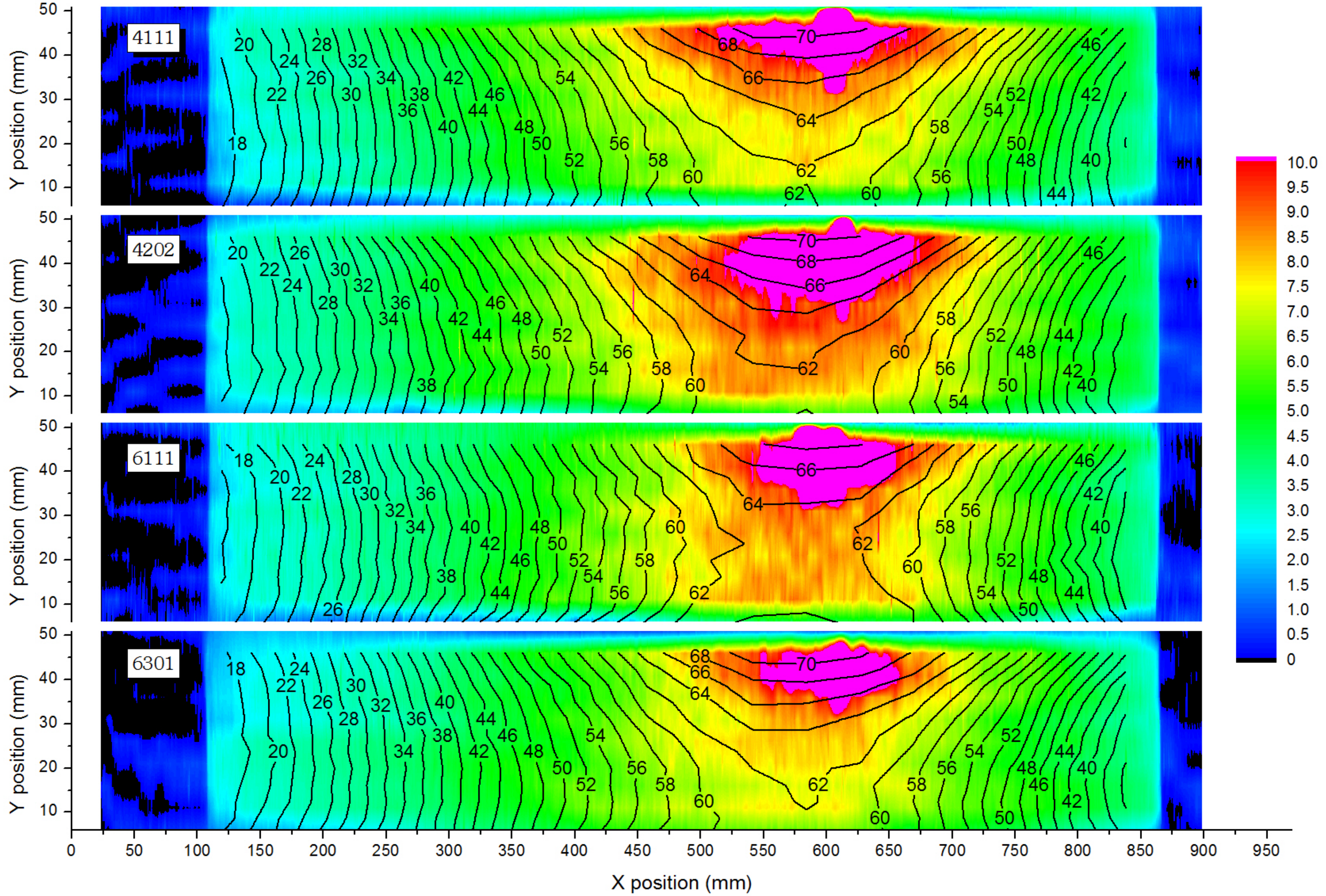

BONAPARTE measures fuel swelling

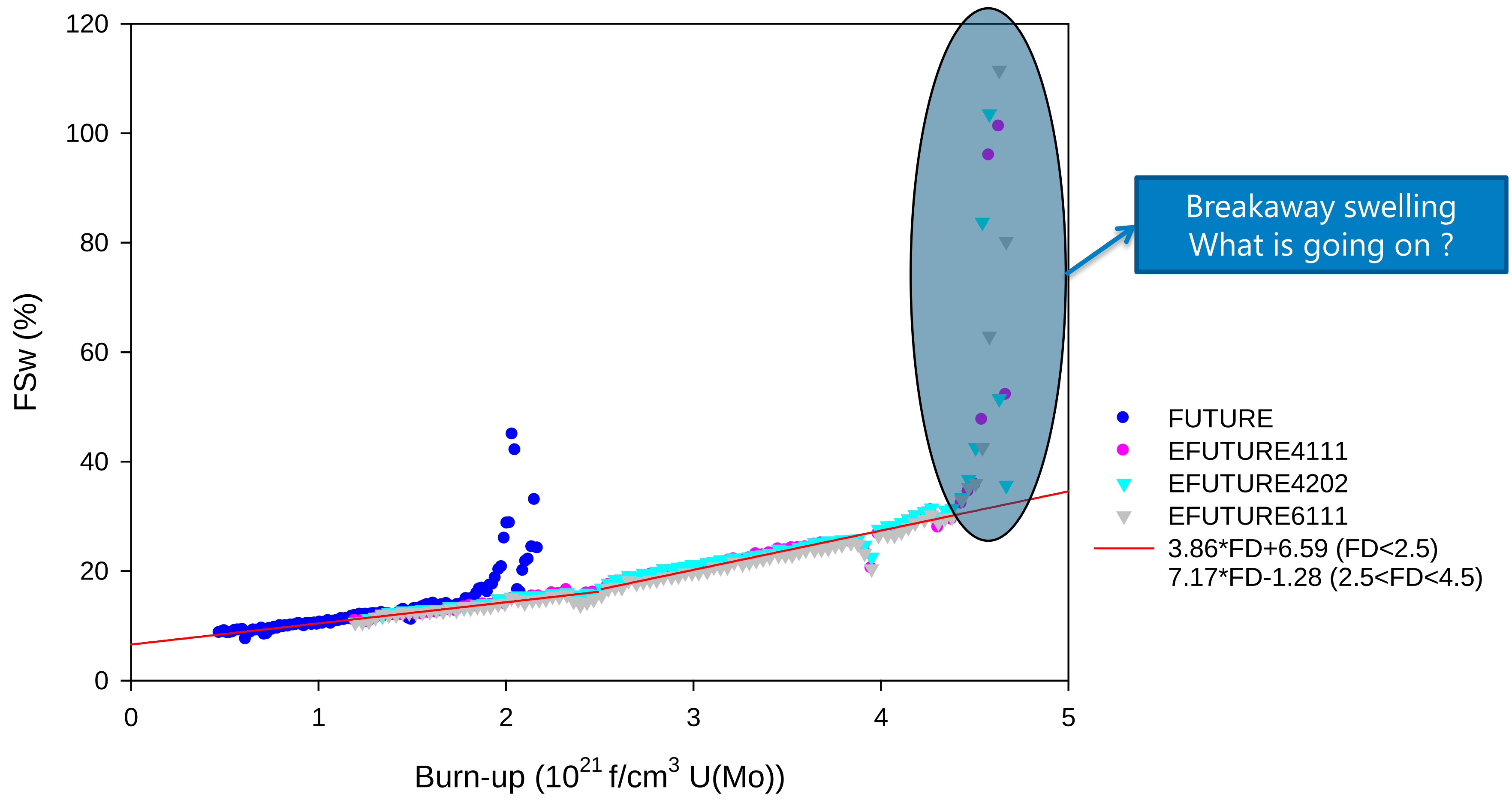

Plate 6111 : 6w%Si, 425 °C – 2h

*Sample M3 : average burn-up ~**64** %^{235}U*

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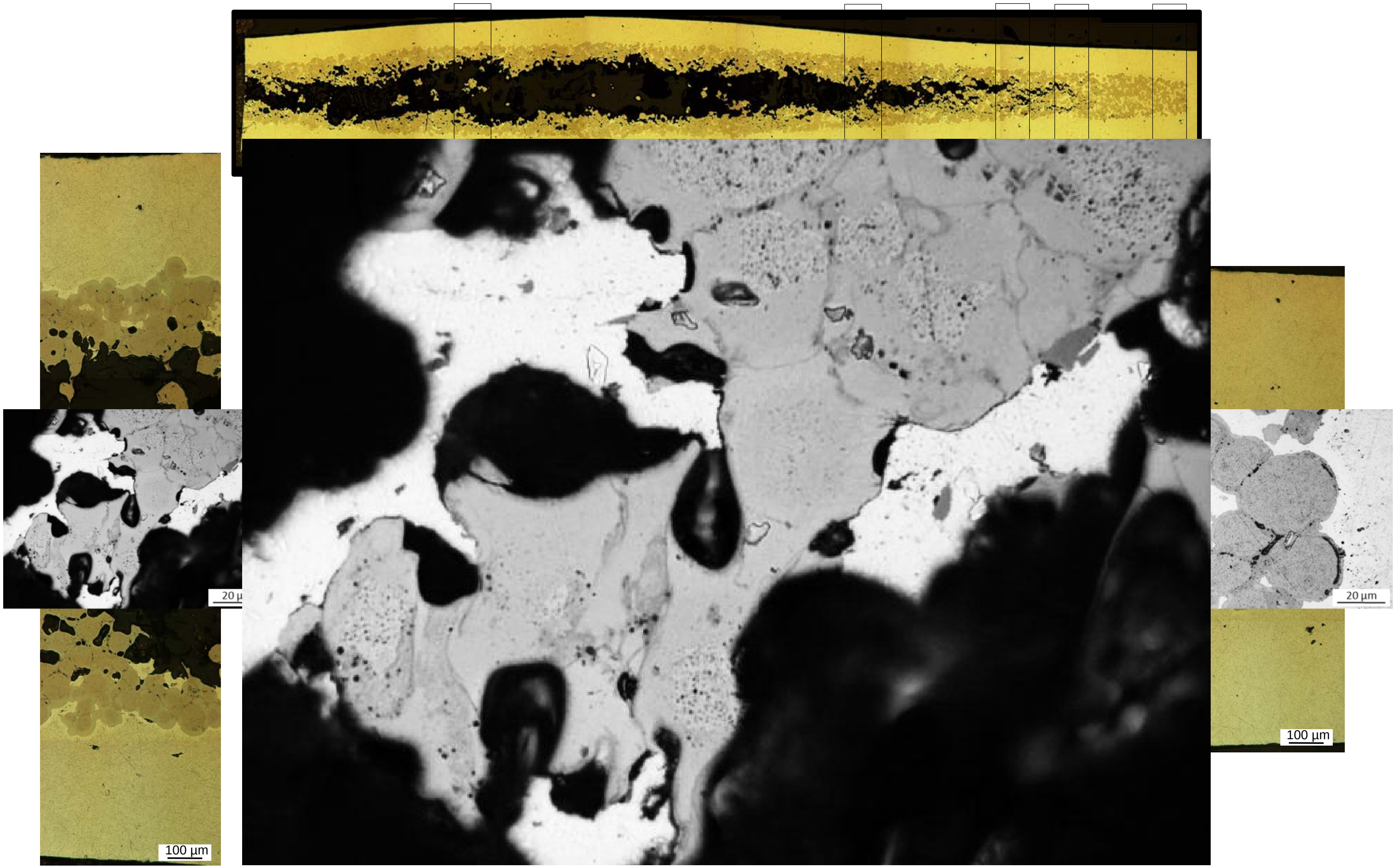
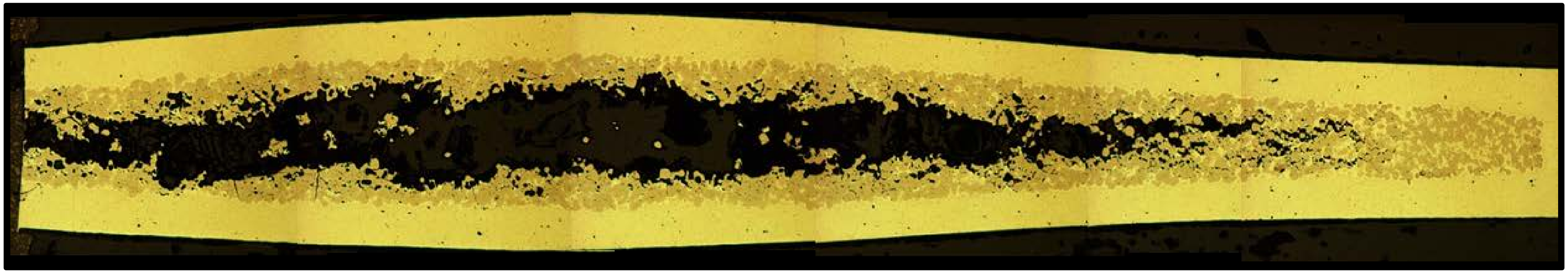


Observations and conclusions

- In the deformed area (blister) :
  - Stable fuel behavior, no excessive growth of the formed interaction layer, still matrix left.
  - Weakening of the matrix interaction layer interface (decohesion) due to fission product accumulation (snowplowing effect)
  - Under the internal force of fission gases and thermal stresses, plastic deformation of the meat causes the plates to show a local mechanical instability → pillowing.



Still too much interaction layer formation ?

Alternative : include a diffusion barrier

Reducing interaction layer growth
Chemical and/or Physical ?

Stabilisation of IL properties

Interdiffusion barrier

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Surface Engineering of Low ENrIched Uranium Molybdenum fuel

Applying coatings on U(Mo) kernels using PVD

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SCK•CEN setup : STEPS & DRUMS

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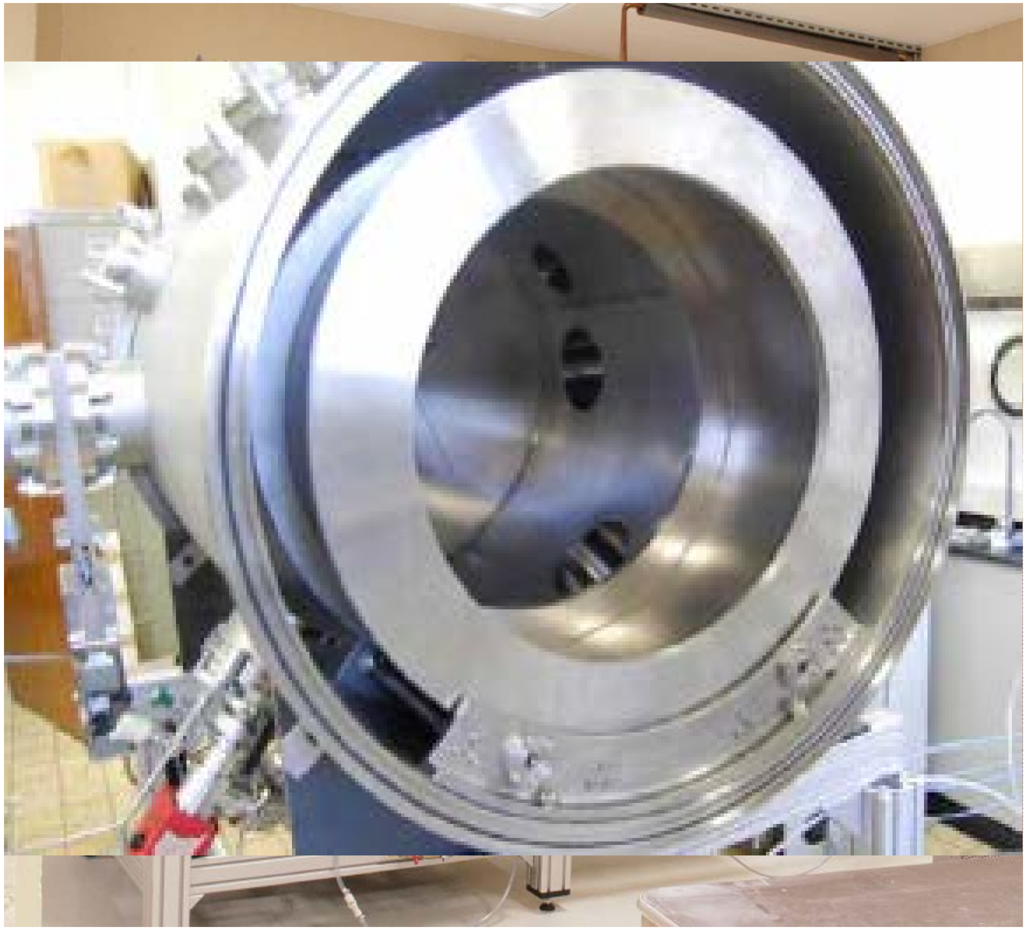
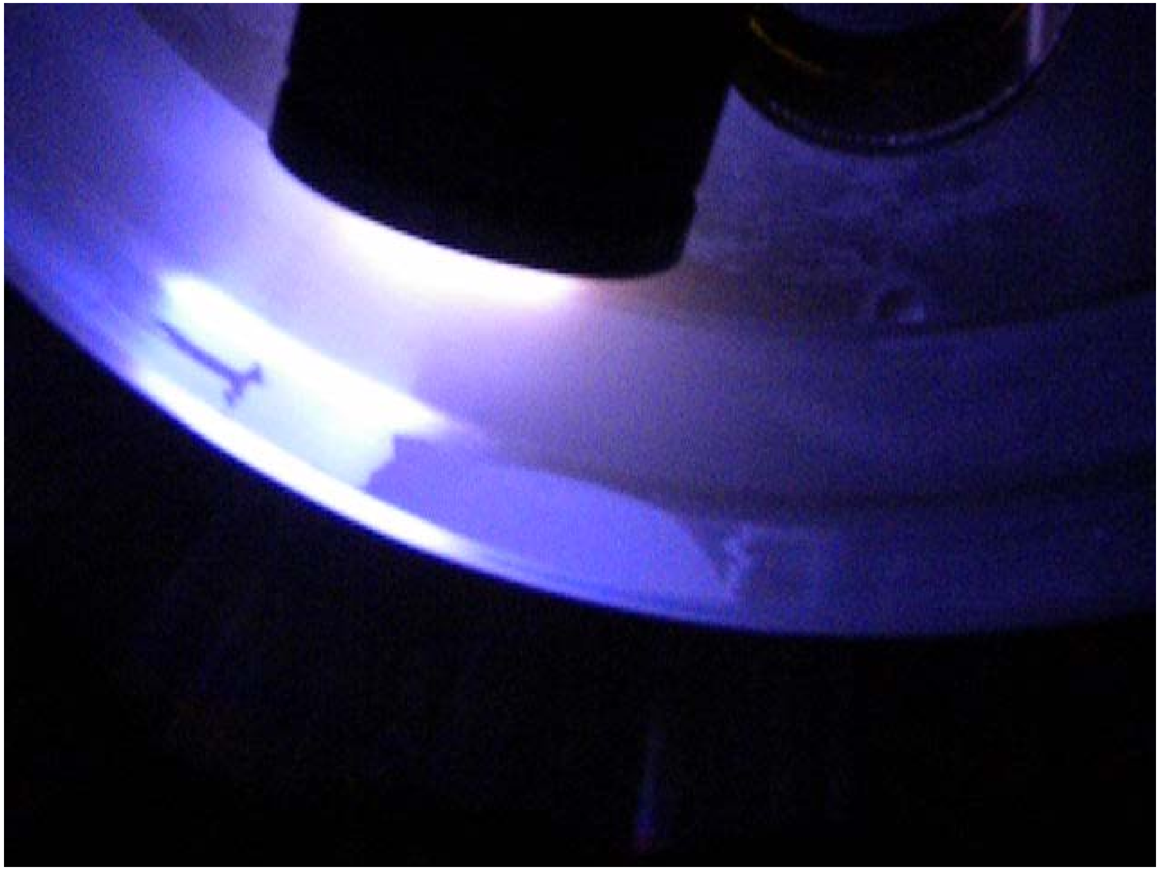


Coated kernel production



The "SELENIUM" Irradiation Test

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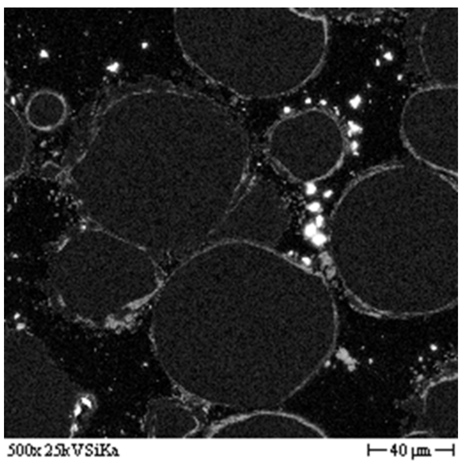
- 2012 : first-of-a-kind irradiation of coated **U(Mo)** fuel
- Irradiation of two flat fuel plates in BR2 (E-FUTURE device)
- U7Mo[Si] and U7Mo[ZrN] dispersion in Al matrix
- Density: 8 g/cm^3 , Enrichment: 19.7 % ^{235}U



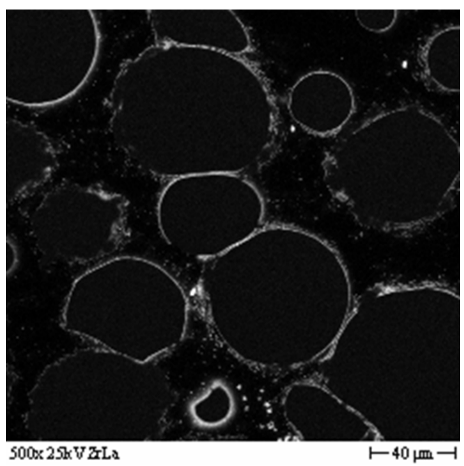
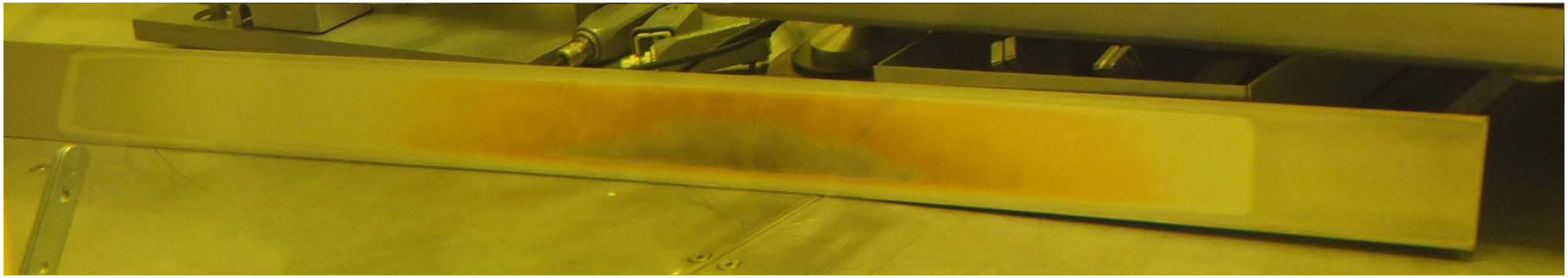
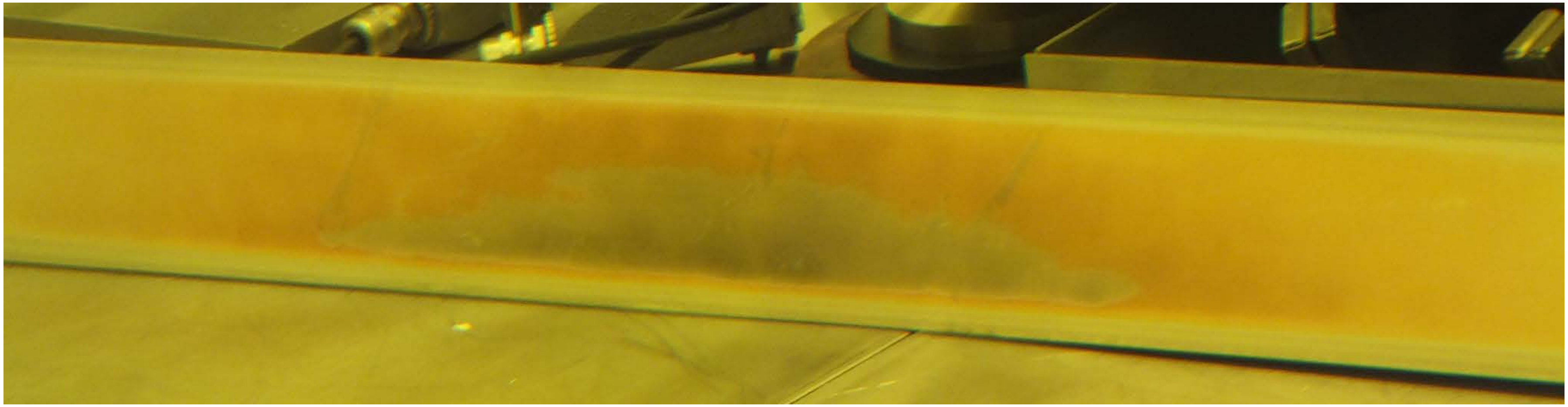


Plate Id.	**U7MD1231**	**U7MD1231**
	Fabrication data	
Cladding	AG3-NE	AG3-NE
Matrix	Al	Al
Coating	~600 nm Si	~1000 nm ZrN
	Irradiation data	
Max BU (%^{235}U)	70	70
Peak Heat Flux (W.cm^{-2})	470	470

SELENIUM – Hot cell observations





ZrN coated

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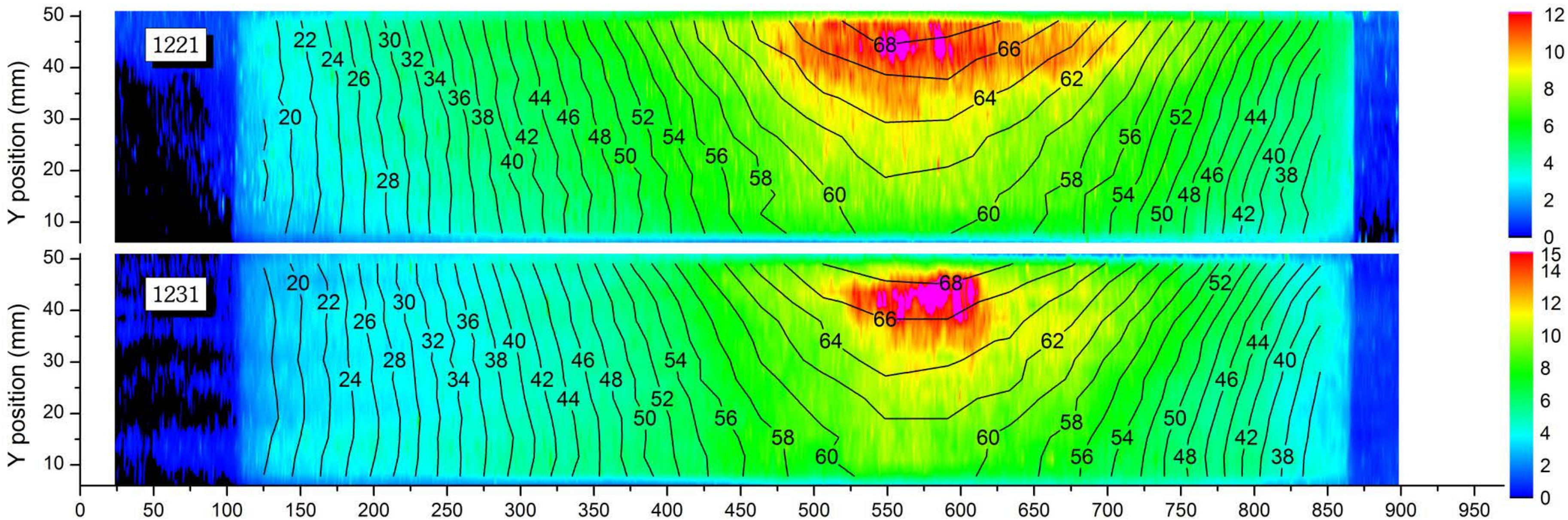
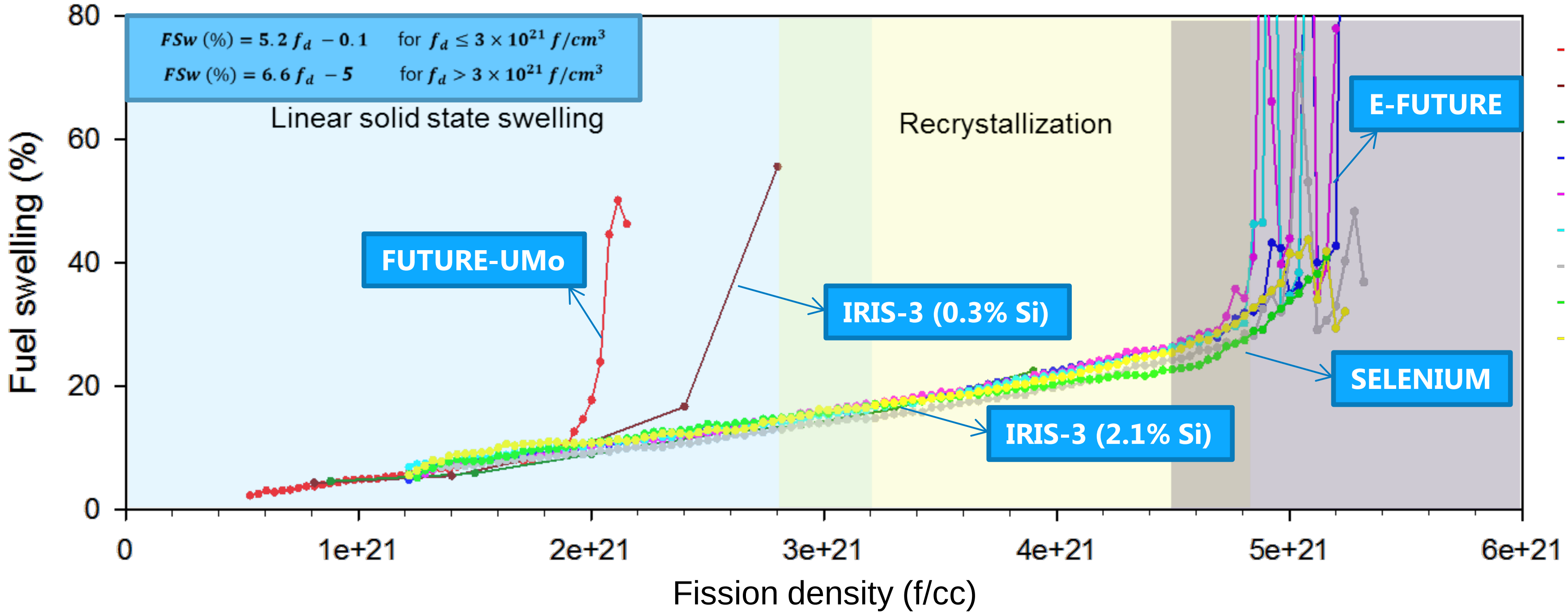


- Maximum swelling measured (before oxide correction) :
  - Si coated plate (1221) : ~13%
  - ZrN coated plate (1231) : ~18%
- Expected swelling (based on E-FUTURE) : ~10%

BONAPARTE measures fuel swelling

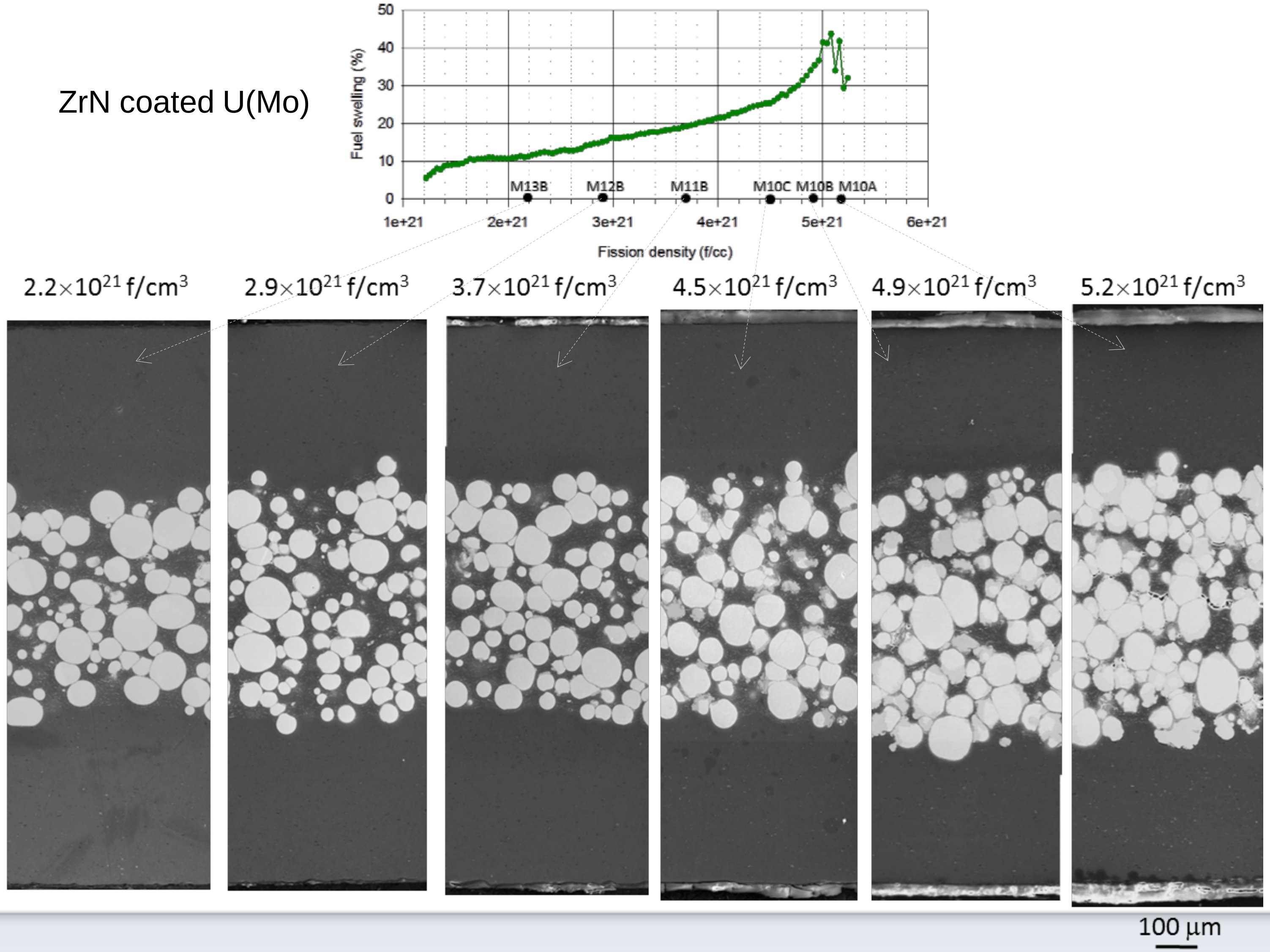


- SELENIUM & E-FUTURE have similar swelling evolution
  - No pillowing for SELENIUM, but acceleration visible, independent of Si addition, Si or ZrN coating !

→ The high BU swelling is intrinsic to UMo !

Destructive analysis of swelling

ZrN coated U(Mo)



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Comparison IL formation

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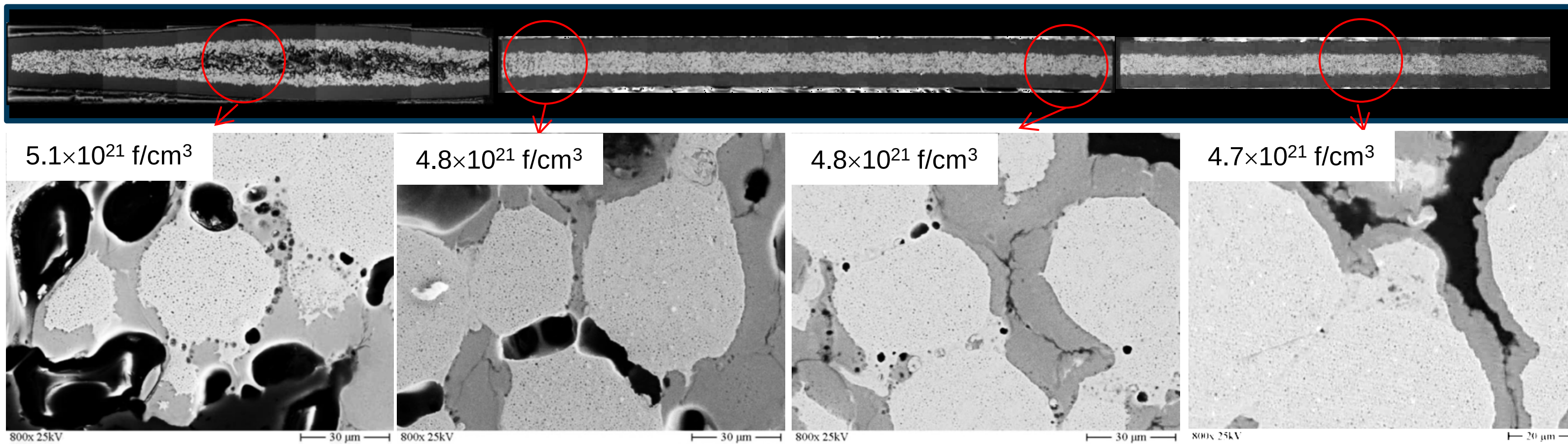
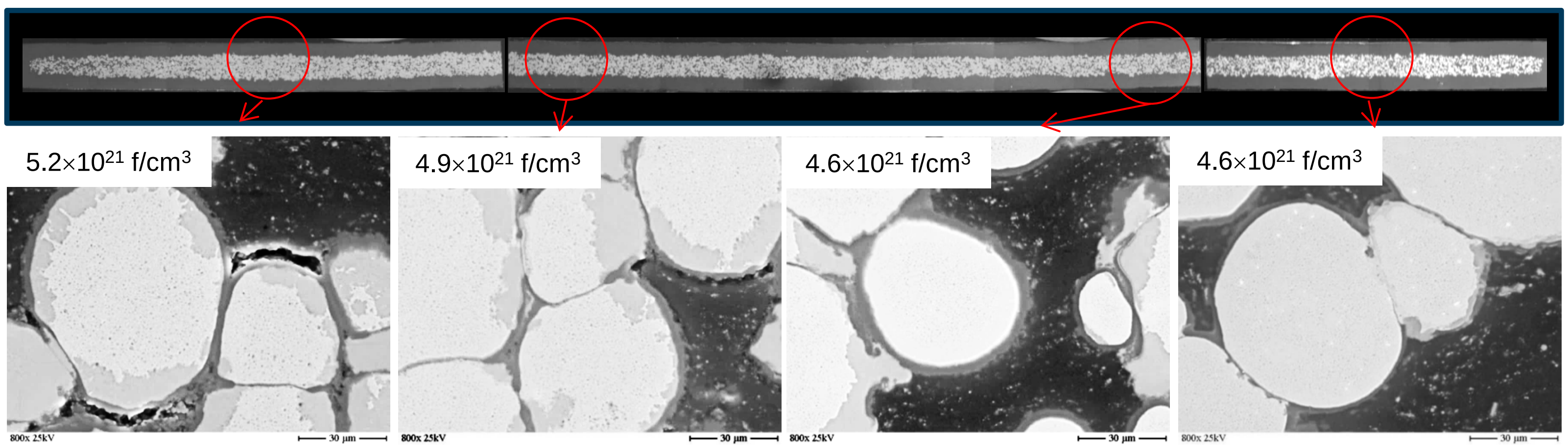
EFUTURE
U7MC6111
(Al-6%Si)



SELENIUM
U7MD1231
(ZrN coated)



IL formation is low → not the problem here !
The swelling is intrinsic to U(Mo) with the as-atomised microstructure
What causes the accelerated swelling at high burnup (fission density) ?

Recrystallisation accelerates swelling

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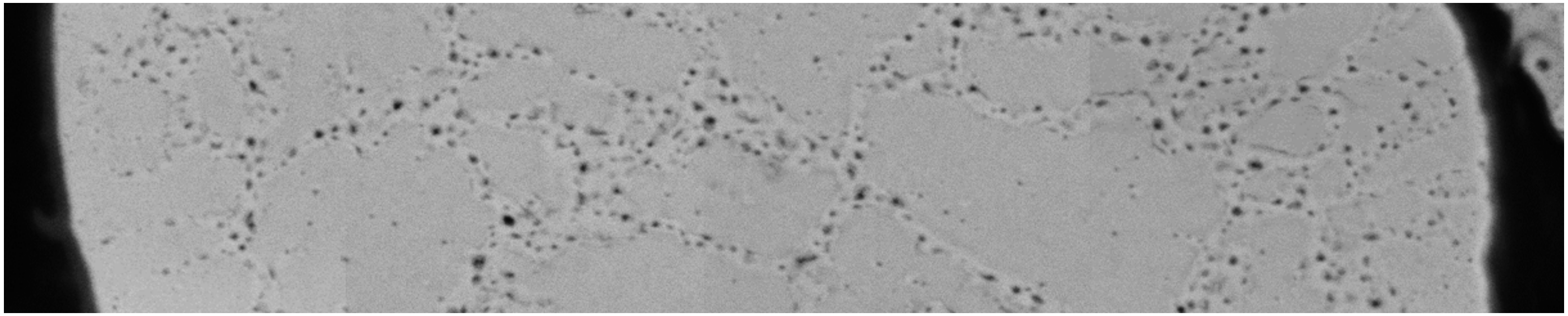
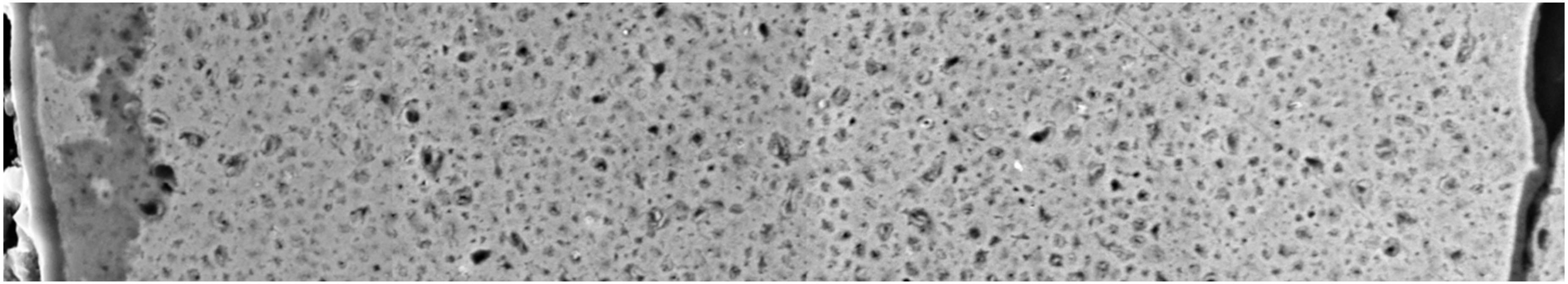
Starts at the cell boundaries (low in Mo content) ~FD 3×10^{21} f/cc

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

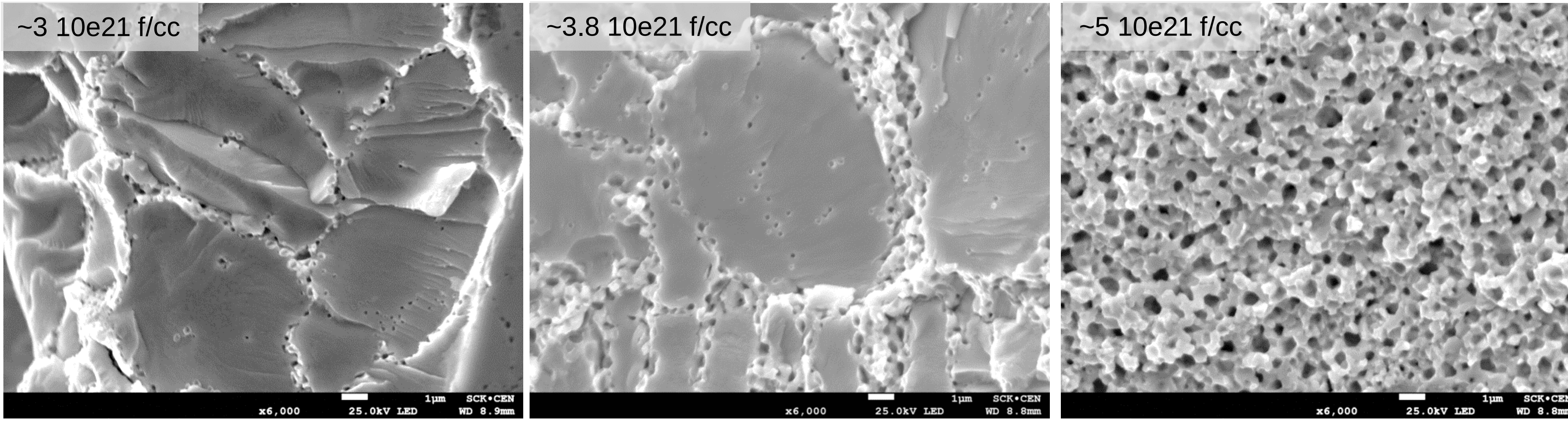


Consequence of recrystallization is the ‘release’ of the overpressurized fission gas (nano)bubbles

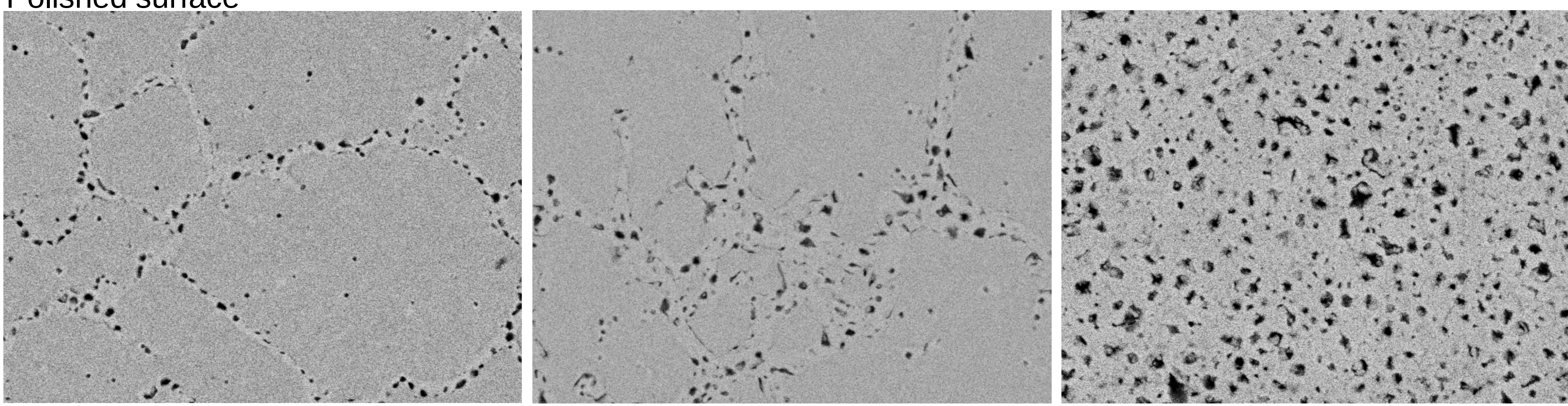
→ Increased swelling rate

Recrystallisation

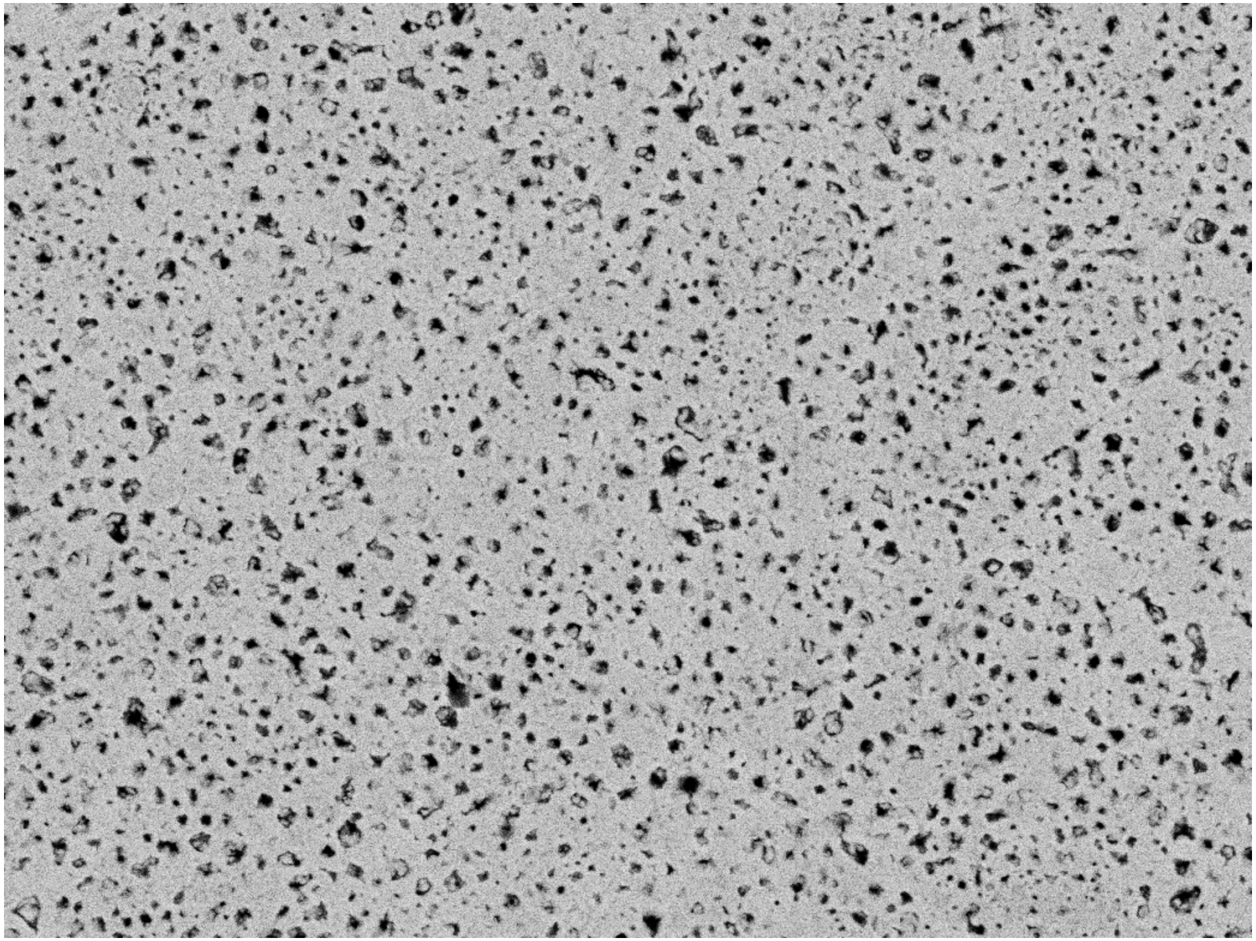
Fracture surface

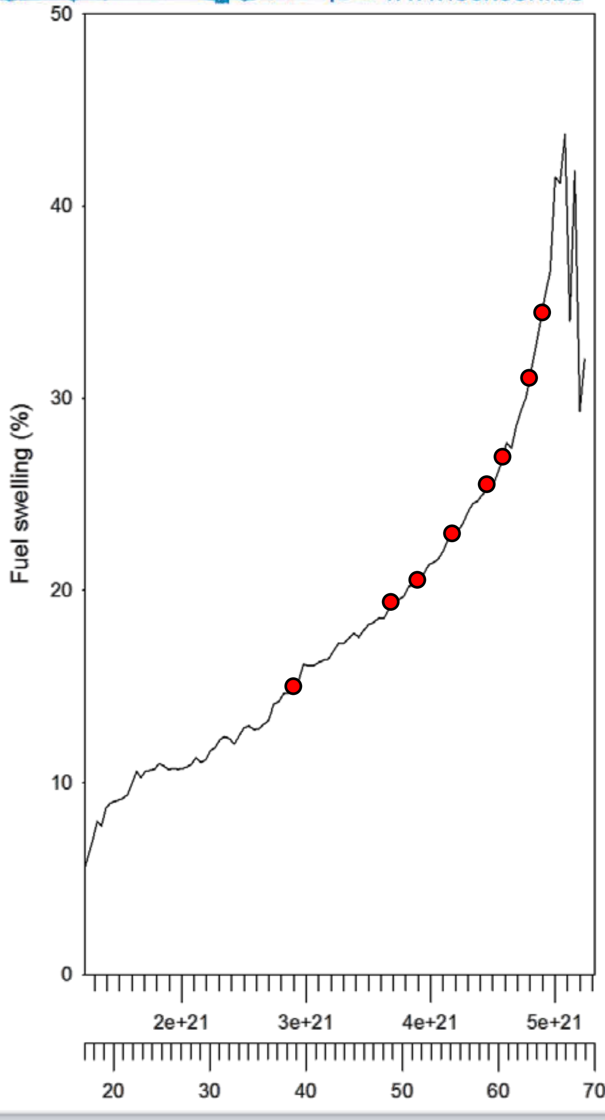


Polished surface



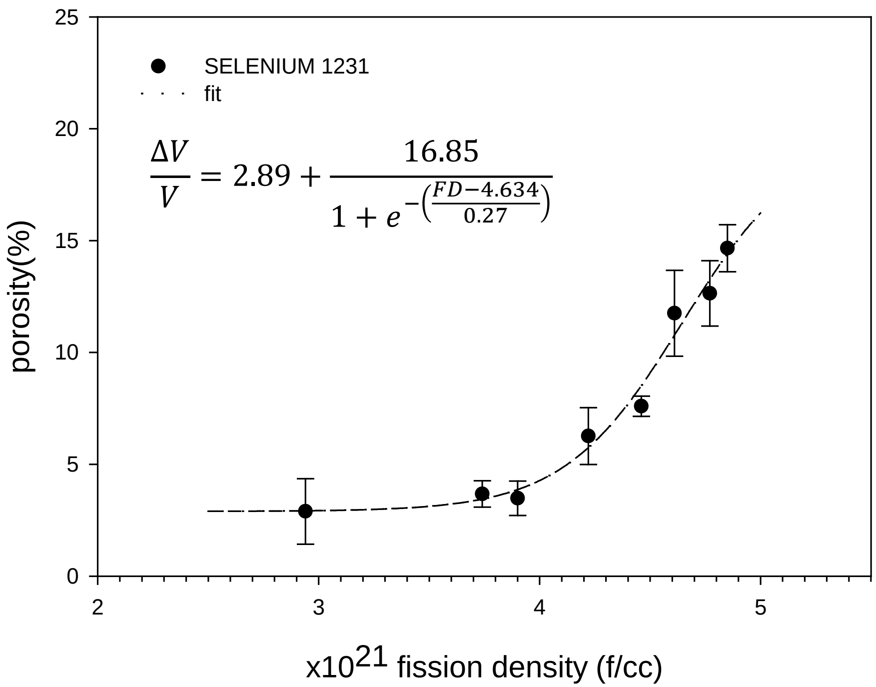
Recrystallization

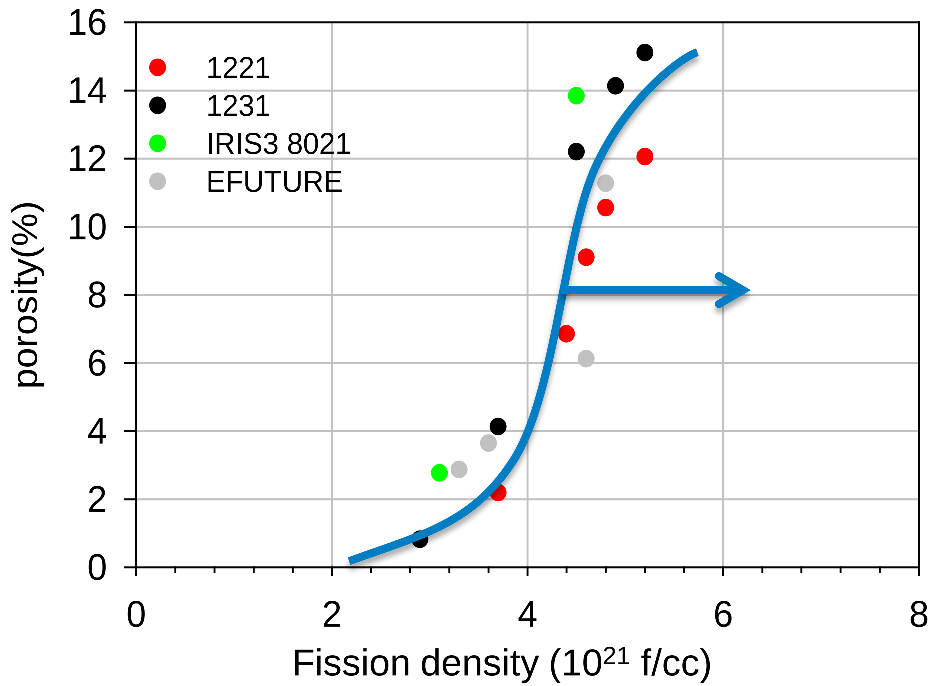




The initiation of restructuring occurs predominately along the preexisting grain boundaries and Mo depleted zones around them. Subsequently, the restructuring front moves toward the grain center eventually consuming the entire grain.

Recrystallisation accelerates swelling





- Evolution of bubbles in the fuel due to recrystallisation between 2.5 and 5×10^{21} f/cc
- Delay in recrystallisation also delays bubble formation and thus reduces swelling rate

BONAPARTE measures fuel swelling

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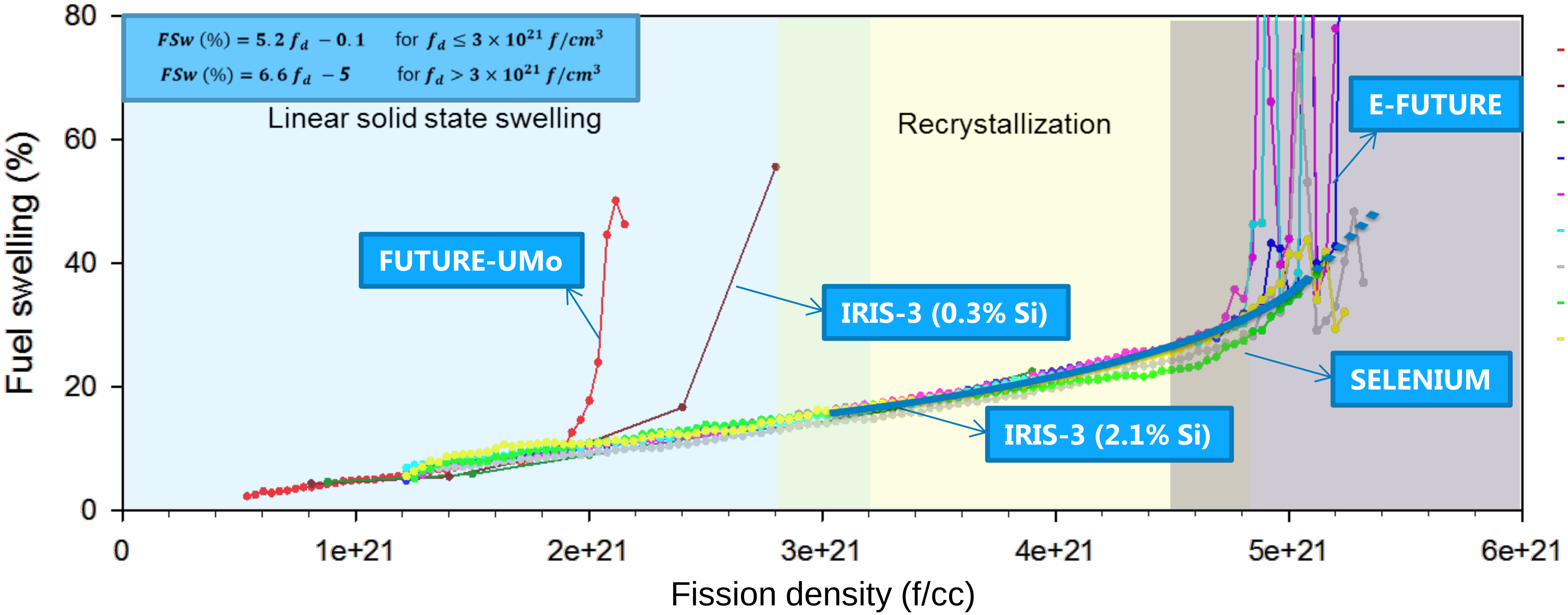

- During recrystallisation gradual increase in swelling rate
- Swelling rate becomes faster than matrix can creep → tearing
- Tears accumulate fission gas and cause pillowing

→ Need to engineer fuel system for recrystallisation

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Conclusions

- The UMo-Al system generates too much IL in early life
  - Need for engineering to reduce IL formation
  - → Si addition to matrix or ZrN coating
- At higher burnup, the intrinsic swelling behaviour of the as-atomised UMo causes more swelling
  - Recrystallisation progresses and increases swelling rate
  - Need for engineering to delay recrystallisation
  - → Heat treatment for homogenisation and grain growth
- Combination of engineering for IL formation and recrystallisation has a genuine basis of confidence, based on the results of E-FUTURE and SELENIUM, combined with comprehension phase advanced PIE, the KOMO-5 results and literature.

Engineering of the UMo dispersion fuel

UMo-Al

FUTURE	Breakaway swelling

LOGIC ↓ **PHENOMENA**

UMo-Al(Si) – add Si to matrix

E-FUTURE	Breakaway swelling

LOGIC ↓ **PHENOMENA**

UMo[ZrN]-Al – use barrier coating

SELENIUM	Swelling acceleration

LOGIC ↓ **PHENOMENA**

UMo HT[ZrN]-Al or UMo HT-Al(Si) – Use heat treatment

SEMPER FI & EMPIRE	Recrystallisation delay

SCK•CEN in the UMo development

- SCK•CEN has made crucial contributions to and investments in the UMo dispersion fuel development
  - The **TEM** analyses demonstrating the amorphous nature of the IL and fission gas bubble lattice in FUTURE material
  - The engineering and use of **BONAPARTE** to arrive at a comprehensive overview of fuel plate swelling evolution, rather than scattered individual measurements
  - The ZrN (and Si) coating used in the **SELENIUM** irradiation to suppress the IL formation, allowing separate views on the intrinsic UMo swelling and recrystallisation phenomenon by comparison with the E-FUTURE results
- We are continuing our unilateral contributions, while also participating in the multilateral efforts !

HERACLES

- HERACLES = EU collaboration framework between CEA (RJH & Orphée), CERCA, ILL (RHF), SCK•CEN (BR2) and TUM (FRM-2)
  - Evolved out of LEONIDAS (E-FUTURE irradiations)
  - Addition of TUM → also monolithic UMo development
- HERACLES roadmap
  - Primary objective : qualify UMo (dispersion) fuel for HPRR
  - Production R&D in roadmap (CERCA), costly but necessary
  - First goals :
    - Understand the UMo behaviour and test the knowledge → definition of fuel system engineering options
    - Based on comprehension, select the appropriate method to engineer the in-pile behaviour and restart the qualification process
  - Main comprehension phase deliverable: SEMPER FI irradiation

HERACLES and the EU

- EU funding for financing first phase of the HERACLES roadmap :
  - EURATOM project for 6.3M€ granted
  - Main objectives : SEMPER FI and atomisation
  - Funding available from september 2015
  - Future funding second call HORIZON-2020 ?
- HERACLES roadmap relies on EU funding for 2014-2018 funding period
  - Consensus reached on funding by HERACLES partners, contractual agreement pending

HERACLES and USA

- Priorities defined by FDEG/FMEG (joint technical efforts)
  - Fuel Development/Manufacturing Expert Group = US+EU
  - Recognised technical advisory board for TechCom.
  - Very positive collaboration, generates technical progress and political basis for decisions
- Irradiation testing: SEMPER FI (BR2) and EMPIRE (ATR)
  - Aimed at identifying and understanding phenomena, mechanisms and mitigation strategies
  - The fuel system needs to be robust, so small differences cannot have large impact on basic in-pile behaviour !
- Funding of EU activities by US is under scrutiny (high income)
  - Conversion is US demand, supported by EU non-proliferation concerns
  - High income countries have become high cost - low budget countries
  - Domestic investments of US-DOE funding in EUFD need to be aligned with priorities defined in consensus (FDEG-FMEG)

HERACLES and SCK•CEN

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- SCK•CEN has a duty to keep BR2 operational
  - Medical radioisotope production is important for society
- SCK•CEN remains committed to conversion of BR2
  - Contributes to the qualification of a suitable LEU fuel
- SCK•CEN is ready to continue the EU effort on an equitable basis with reasonable funding
  - SCK•CEN takes much of the risk (irradiation/waste)
- Successful completion of roadmap allows qualification of fuel suitable for BR2 conversion by 2026
  - Technical approach based on logic and phenomenological understanding has support of FDEG (US and EU)
  - Option to operate BR2 after 2026 remains open

Current technical situation

- The FDEG 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 homogenisation + grain growth (limiting GB)
  - IL formation : Si addition, ZrN coating
- Next step : SEMPER FI and EMPIRE irradiations

Fuel swelling

- Models provide acceptable prediction of total swelling
  - Swelling is fission density related and has only minor influence from fission rate, IL formation, …
  - Further benchmarking required for qualification
    - SELENIUM-1A (SCK•CEN unilateral initiative) will provide a test case !
- Modelling of underlying phenomena less accurate
  - Distribution of overall swelling over gas bubbles, solid precipitates, fission products in solid solution and in nanobubbles, …
    - Modelling efforts ongoing at ANL
  - Parameterization of UMo recrystallization required
    - Advanced PIE of SELENIUM samples performed

IL formation

- Existing correlations for interaction layer formation and fission rate, temperature and time (fission density)
  - Basis : UMo-Al(Si) irradiations performed in the past.
  - Continuous evaluation, but FDEG considers no immediate actions required to improve the modelling.
  - Coating expected to eliminate IL formation
- IL formation is mainly fission rate dependent
  - SELENIUM-1A will provide data on low fission rate – high fission density conditions.
- Systematic FR-FD conditions in EMPIRE and SEMPER FI

Heat treatment

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- KOMO-5 and RERTR-3 data provide support to HT as mitigation for recrystallisation
  - Effect on recrystallisation can only be studied by high burnup irradiation, no alternatives
- HT parameters set (FDEG consensus)
  - 1000±25°C; 2h±15 minutes; Ar/vacuum; oxygen getter
  - Process yields appropriate microstructure; further characterisation will be performed (grain size variation, Mo homogeneity, …)
  - KAERI parameters similar (1h instead of 2h)
- ANL, SCK•CEN have capability, CERCA/TUM developing
  - Processing of larger batches for production in EMPIRE and SF
- Assess influence of powder production process (expected to be minor)

Coating

- Limited irradiation results available
  - Advanced PIE on SELENIUM samples done
  - PIE on coating evolution → FIB/TEM-SEM of SELENIUM
- Only ZrN considered at this moment
  - Optimisation studies by ion irradiation (TUM)
  - ZrN is well known from IMF and has baseline in RR fuel
- Deposition techniques : PVD and ALD
  - Compare fuel/coating µstructures after rolling
  - Evaluate relative response under ion irradiation
  - In case no difference under irradiation → FMEG decides
- Influence of HT on coating ?
  - Surface modification of kernels

What we need from the irradiations…

- Engineering
  - Effect of the heat treatment ?
    - HT delays recrystallisation sufficiently to reduce swelling at high BU ?
  - 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.
  - Deposition method for coating ?
    - Differences between ALD and PVD ? Effect of AlN interlayer ?
  - CERCA powder
- Qualification and modelling
  - Fission rate versus fission density dependences
  - Parameterization of recrystallisation (with/without HT)
  - Benchmark effect of variables (kernel size distribution, Mo content, loading, …)

SEMPER FI and EMPIRE

- EMPIRE evaluates coating methods
  - Is there a significant influence of the way the coating was applied or its microstructure on the in-pile fuel performance ?
- SF evaluates need for coating
  - With reduced swelling rates thanks to annealing, is the IL formation in Al-Si matrix still a problem ?
- EMPIRE evaluates kernel size distribution variation
- SF evaluates CERCA powder productions
- EMPIRE evaluates Mo content variation (needs >20% ^{235}U)
- Both: separation of fission rate and fission density related effects
  - High FR (=power), short irradiation time and low FR, long irradiation time lead to same FD (=BU)
  - Comparison of high and low FD (=BU) acquired at similar FR (=power)
- Both: suitability of heat treatment to delay onset and slow down progress of recrystallisation to limit swelling rate at high burnup.
- Both: plate size and reactor effects + complementary PIE

EMPIRE matrix

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Left Test Train

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

Right Test Train

Cycle 1

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

- MOD vs. STD : size distribution
- PVD vs. ALD : coating method
- U10Mo vs. U7Mo : Mo content
- ZrN vs. ZrN-AlN : AlN interlayer
- CERCA vs. KAERI powder : powder production method (link SF)
- Heat vs. no Heat : HT effect
- 1 cycle vs. 2 cycles : FD effect
- A/D vs. B/C : FR effect

Cycle 2

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

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SEMPER FI matrix

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- Full size plates !
  - More representative
  - Better defined irradiation conditions
  - Different FR conditions : top/bottom/center
  - Different FD conditions :
    1 cycle, 3 cycle and 4 cycle
- Al-Si vs. coating
- HT vs. non HT
- All CERCA powder

Row	Cycle	1	2	3	4
Top	1	ZrN PVD Mod PSD HT	ZrN PVD Mod PSD	Al-6 Si Std PSD HT	Al-6 Si Std PSD HT
	2	ZrN PVD Mod PSD HT			ZrN PVD Mod PSD
	3				
	4				
Center		ZrN PVD Mod PSD HT	ZrN PVD Mod PSD HT	Al-6 Si Std PSD HT	Al-6 Si Std PSD HT
	2	ZrN PVD Mod PSD HT			ZrN PVD Mod PSD
	3				
	4				
Bottom	1	ZrN Mod PSD HT	ZrN PVD Mod PSD HT	Al-6 Si Std PSD HT	Al-6 Si Std PSD HT
	2	ZrN PVD Mod PSD HT			ZrN PVD Mod PSD
	3				
	4				

FR-FD separation

HT effect

Coating vs. Al-Si

EMPIRE and SEMPER FI

- Engineering
  - Effect of the heat treatment ?
    - HT delays recrystallisation sufficiently to reduce swelling at high BU ?
  - 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.
  - Deposition method for coating ?
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  - CERCA powder
- Qualification and modelling
  - Fission rate versus fission density dependences
  - Parameterization of recrystallisation (with/without HT)
  - Benchmark effect of variables (kernel size distribution, Mo content, loading, …)

General conclusions

- The irradiations performed have allowed the UMo dispersion fuel developers to identify 2 distinct engineering challenges for the fuel system : IL formation at high fission rate (power) and recrystallisation (elevated swelling rate) at high fission density (burnup)
- Each challenge was studied in detail, resulting in the currently established comprehension, the identified mitigation strategies and in the definition of 2 new irradiation tests (SEMPER FI and EMPIRE)
- The HERACLES consortium has laid out a realistic timeline for UMo dispersion (and monolithic) fuel qualification, but still has a lot of challenges ahead.

Acknowledgements

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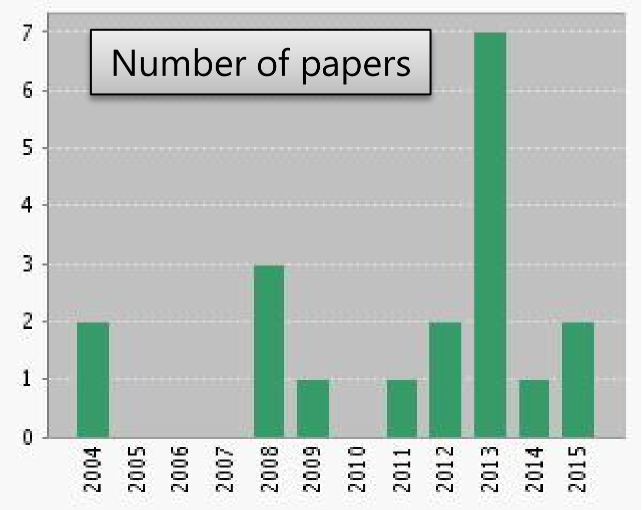
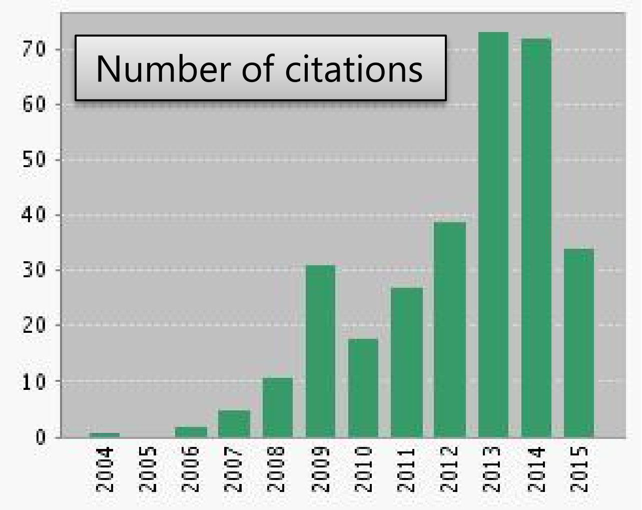
- Reactor support : S. Van Dyck, V. Kuzminov, H. Ooms and W. Claes + full neutronics, BR2 operations and BR2 hotcell teams
- Rig design and construction : P. Jacquet + full design and engineering teams
- PIE : Y.Parthoens, W.Van Renterghem and L. Adriaensen + full MNA and RCA teams
- Financial support from the SCK•CEN management

Publication overview

www.sckcen.be

- 20 publications in 16 years
- Average 16 citations per paper
  - Top paper (2004) ~100 citations
  - h-index = 10
- RRFM and RERTR conferences
  - Papers/references not indexed !

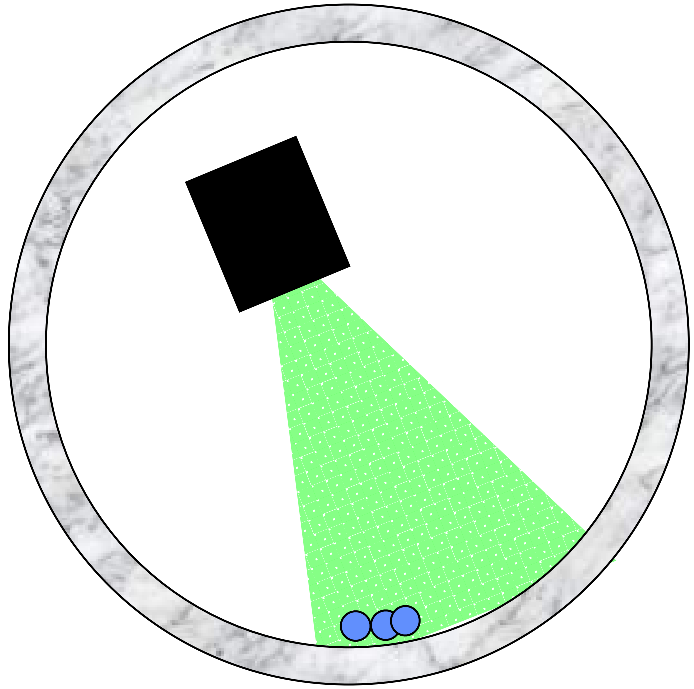




Post-irradiation examination of uranium-7 wt% molybdenum atomized dispersion fuel
By: Leenaers, A; Van den Berghe, S; Koonen, E; et al.
JOURNAL OF NUCLEAR MATERIALS Volume: 335 Issue: 1 Pages: 39-47 Published: OCT 1 2004

Transmission electron microscopy investigation of irradiated U-7 wt%Mo dispersion fuel
By: Van den Berghe, S.; Van Renterghem, W.; Leenaers, A.
JOURNAL OF NUCLEAR MATERIALS Volume: 375 Issue: 3 Pages: 340-346 Published: APR 30 2008

Irradiation behavior of ground U(Mo) fuel with and without Si added to the matrix
By: Leenaers, A.; Van den Berghe, S.; Van Renterghem, W.; et al.
JOURNAL OF NUCLEAR MATERIALS Volume: 412 Issue: 1 Pages: 41-52 Published: MAY 1 2011



Thank you for your attention

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