3D characterization of nuclear fuels

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ACKNOWLEDGMENTS

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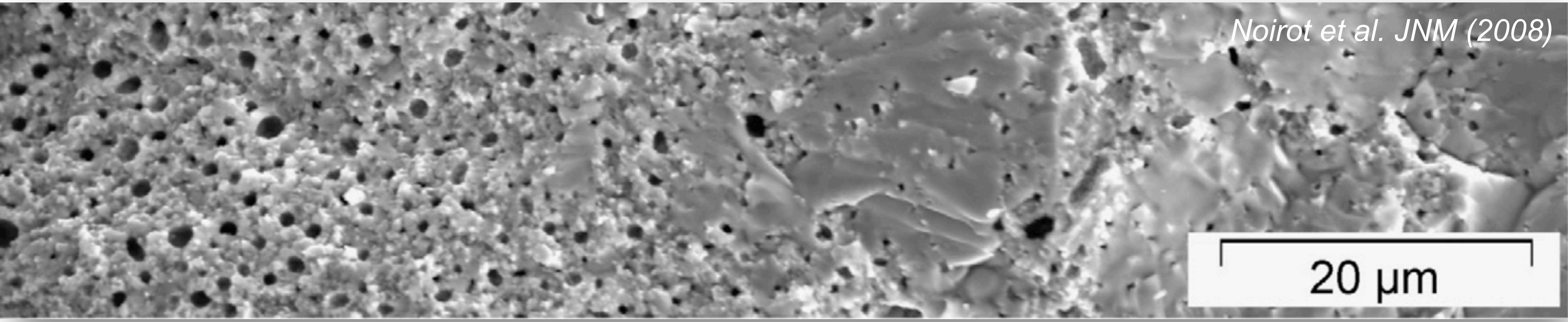
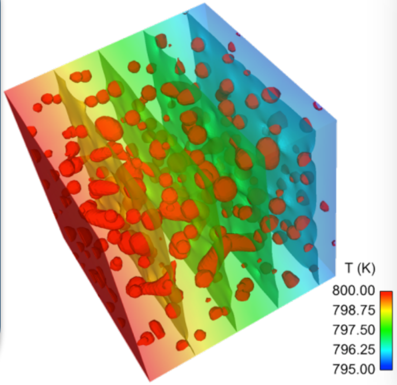
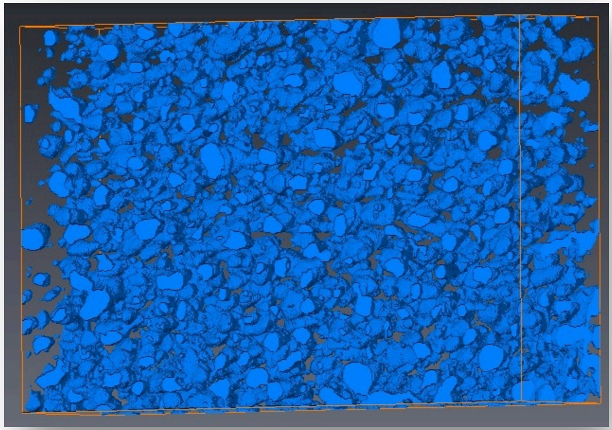
Developing Improved Reactor Materials

- Safety and efficiency issues in current LWR reactor materials are due to problems with the material behavior

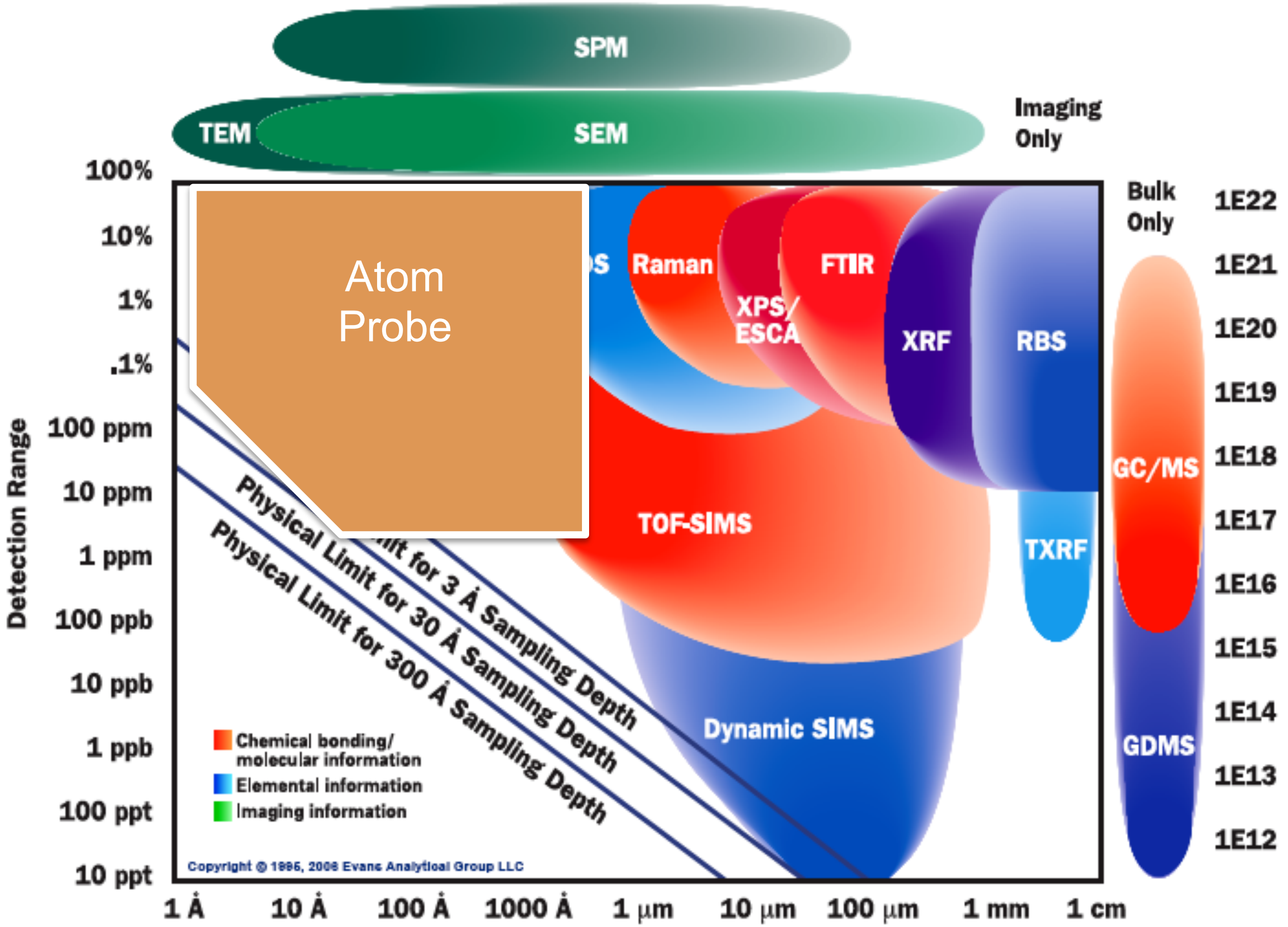


Designing advanced materials for next generation reactors requires a **fundamental understanding** of the **material behavior** of the fuel at the **micron-scale** using **experiments and simulation**.





Characterization techniques



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Challenges of working with radioactive samples

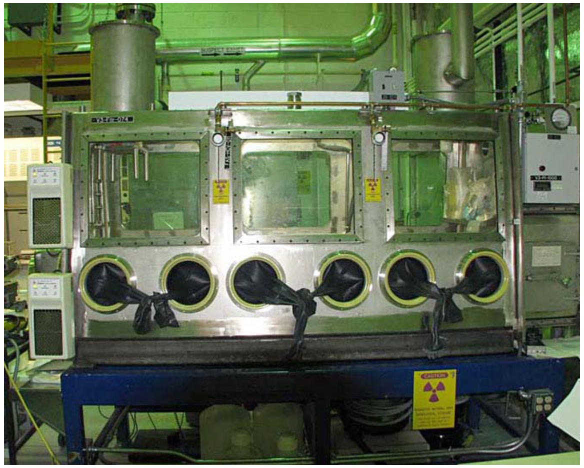
Irradiated fuels

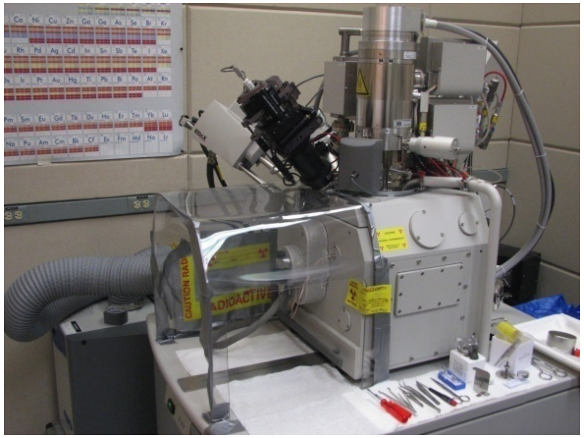
- Highly radioactive. It might take several years of "cooling" before the sample can be analyzed
- A sample volume of 1 mm^3 can have 200R β and several hundred mR γ
- Samples can be brittle
- Rapid oxidation of samples, especially Pu-bearing samples
- Microstructural features may be lost or altered during sample preparation
- Hot cells and glove-boxes are required for sample preparation

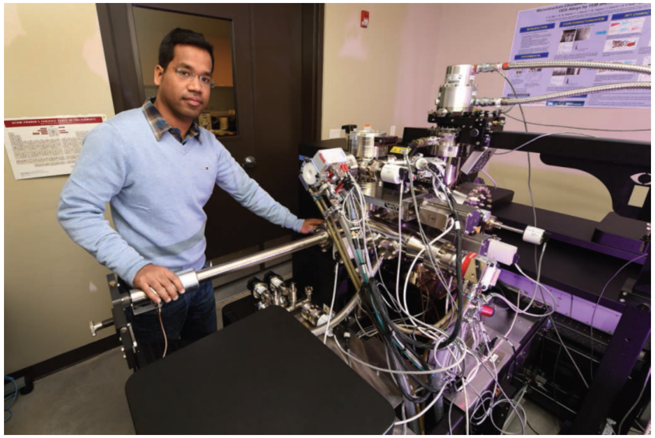
Irradiated materials

- High γ radiation fields (several R)
- Local shielding for sample preparation is required
- Personal radiation exposure control (has to be within ALARA limits)
- Hot cells and glove-boxes are required for sample preparation
- EDS compositional analysis is not feasible as detectors get saturated from high γ background radiation

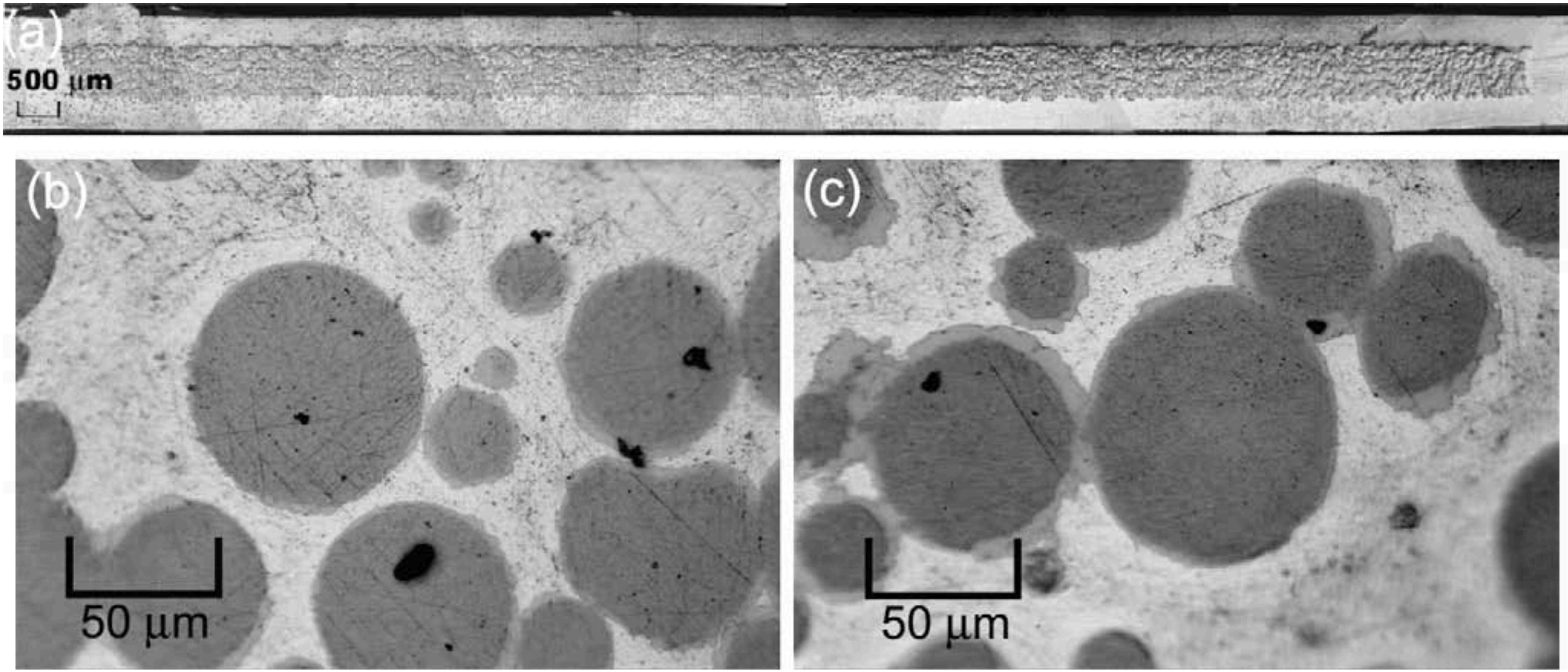
Sample preparation (irradiated fuels)



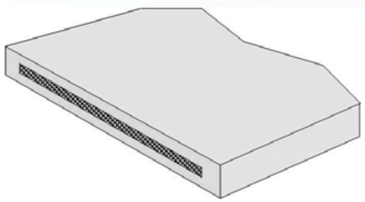


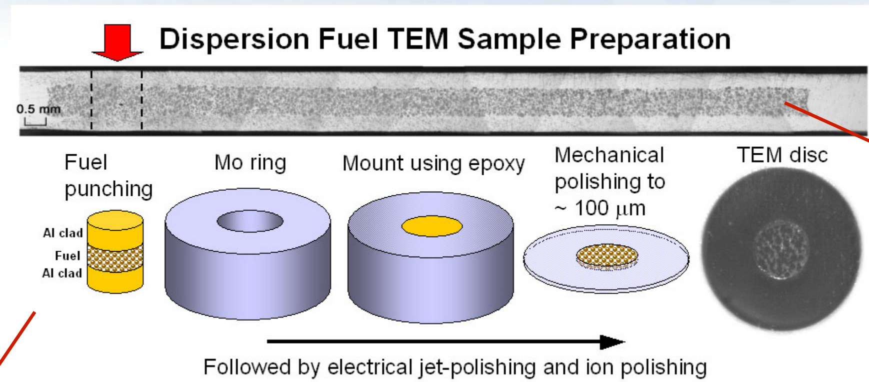


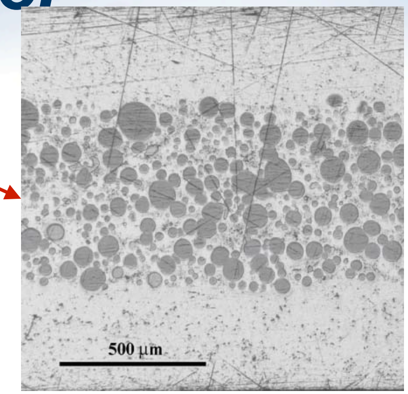
Low-enriched uranium (LEU) U-Mo fuel

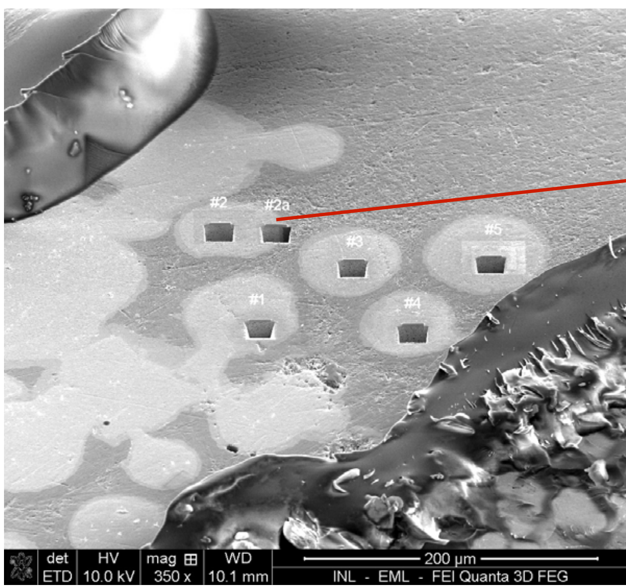


Microstructure of dispersed U-Mo fuel

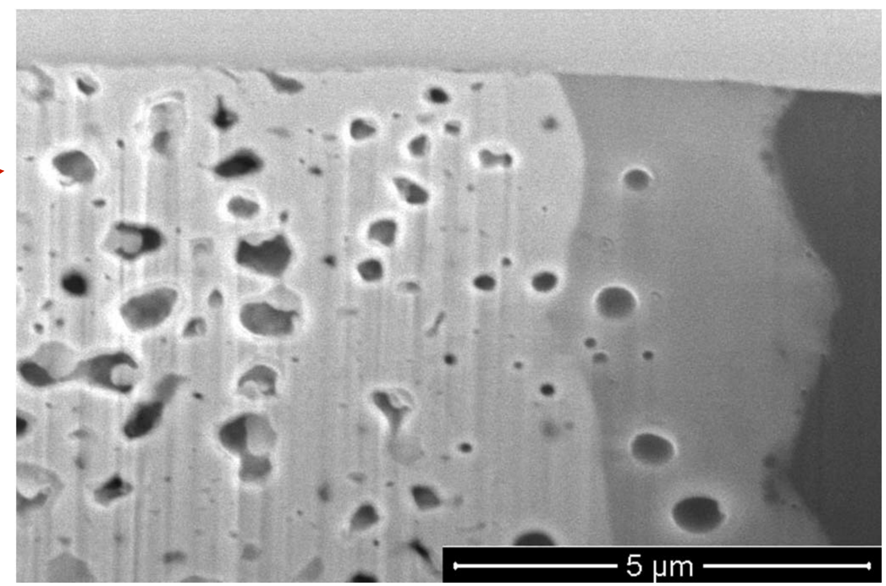








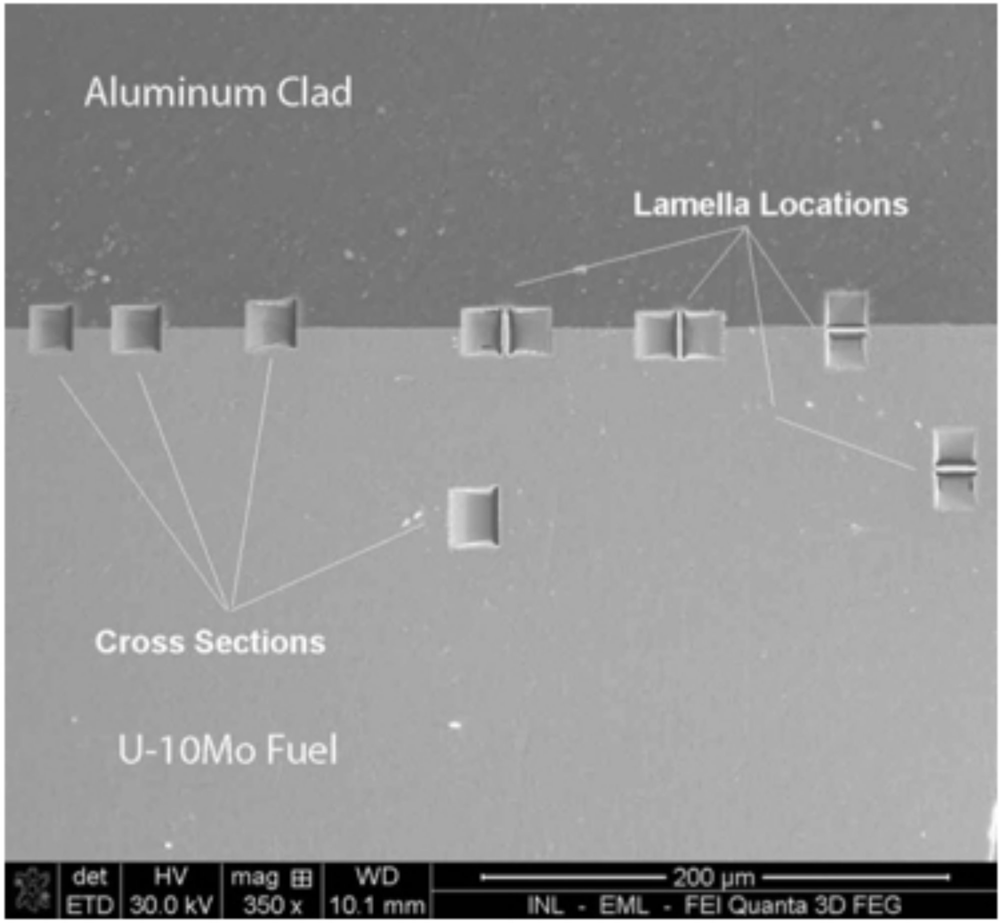
Site-specific lift-out from 1mm punch



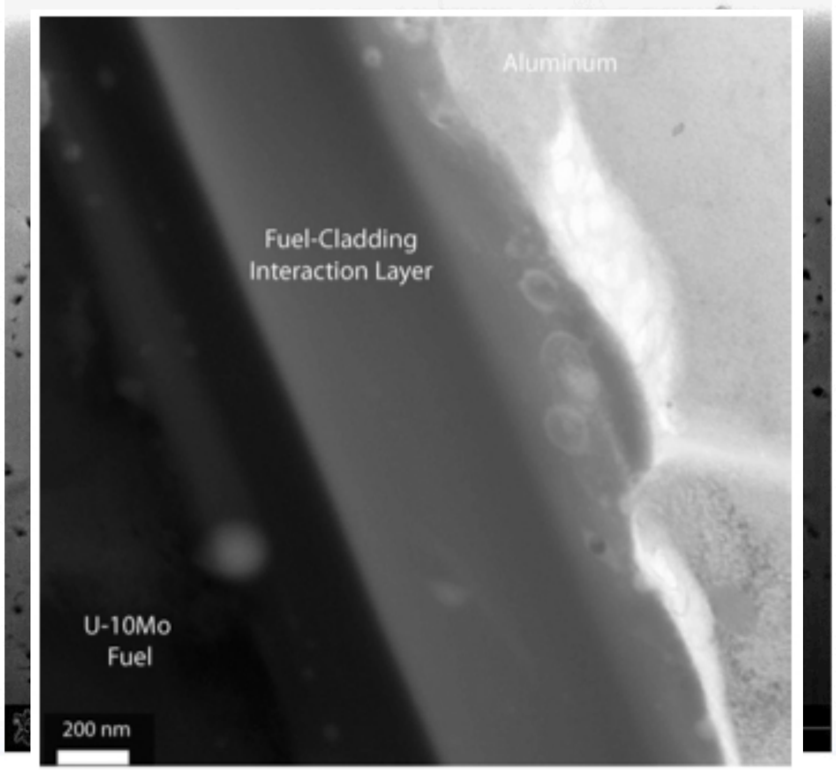
- FIB cut across the FCI showing circular bubbles in amorphous FCI
- Solid fission products precipitate at gas bubbles
- More bubbles in the fuel than FCI
- Evidence of bubble intern-linkage

Courtesy of J. Gan

Microstructure of monolithic U-Mo fuel

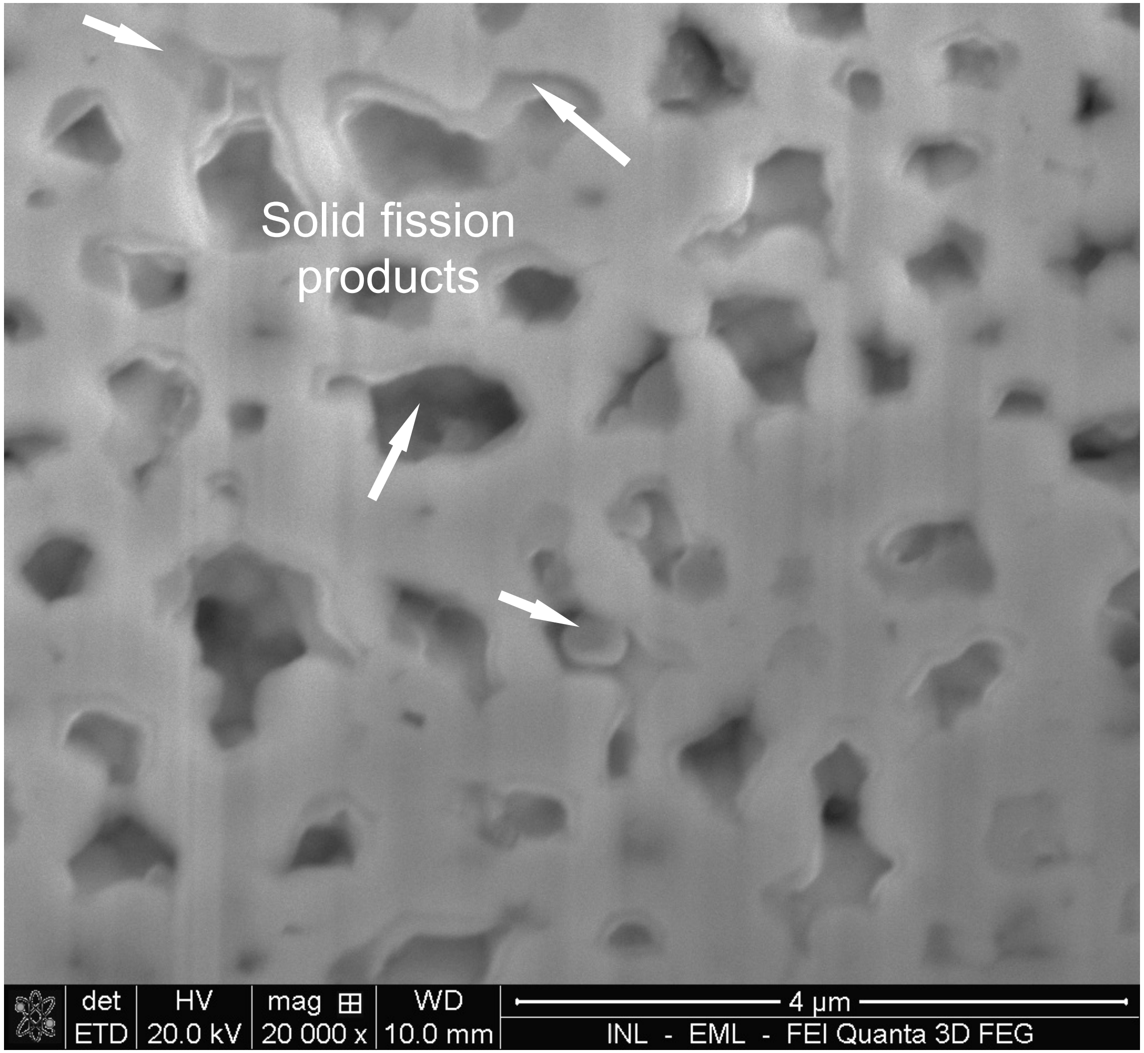


Monolithic U-10wt%Mo foil sandwiched between Al-6061 cladding and irradiated in ATR.



Metallic U-Mo fuel is being developed to replace throughout the world

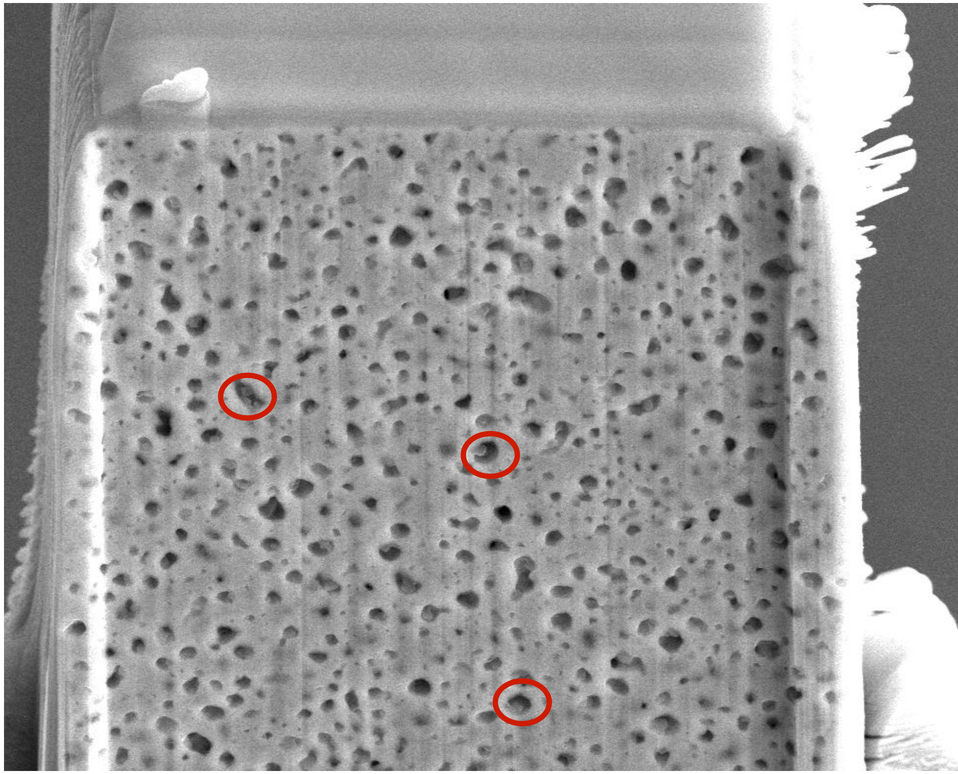
Irradiated monolithic U-10wt%Mo fuel



Fission gas bubbles can contain: Zr, Sr, Y, Ce, Ba, Nd, Pd, and Te (in the solid fission products)

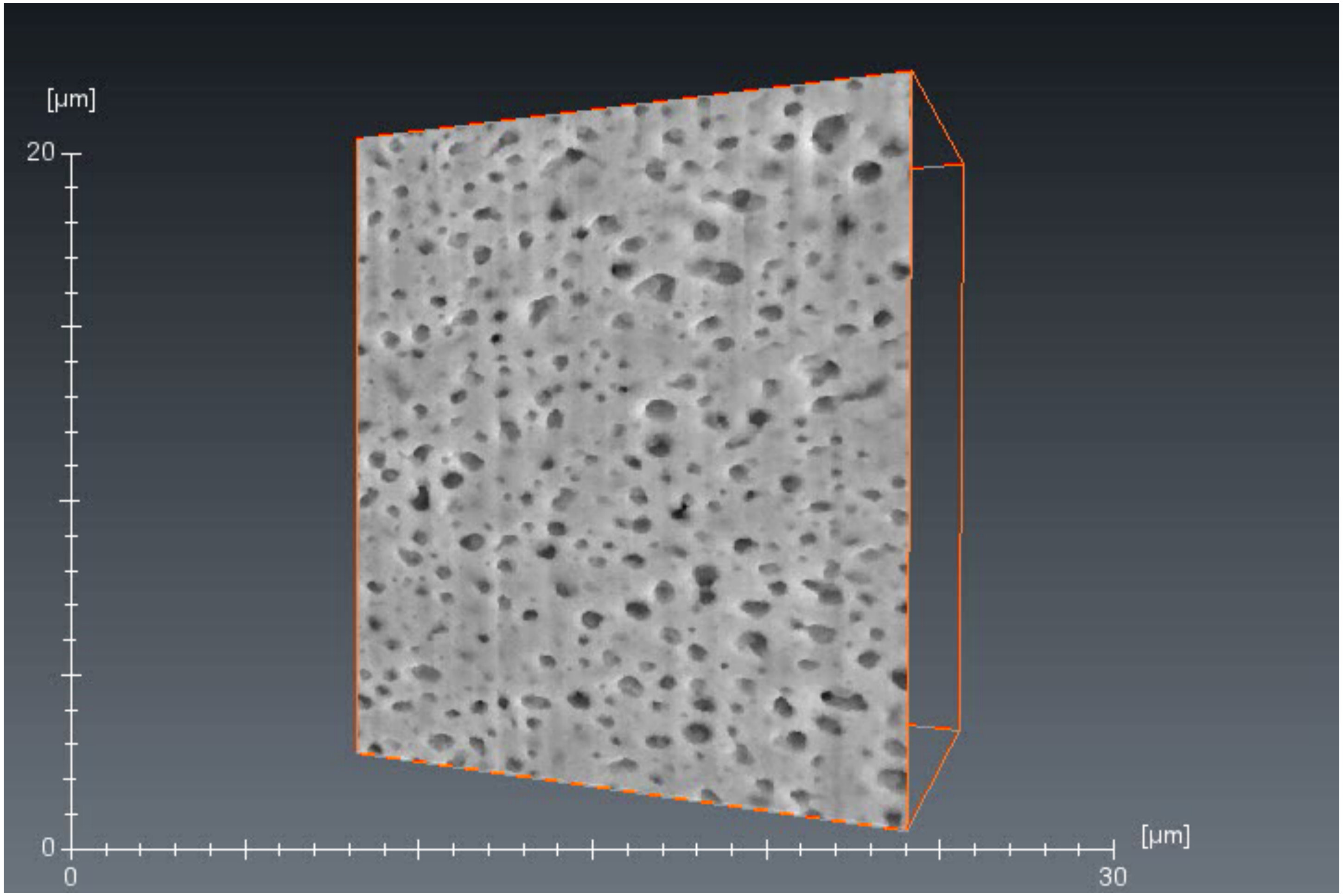
What can be learned from 3D Data sets?

- From just images
  - Look of distributions of pore sizes, no need for 2D to 3D pore conversions
  - Total porosity fraction
  - Interconnection of porosity
  - Pore shapes
- From combined EDS/EBSD
  - 3D distribution of fission products
  - Impact of grain orientations and composition on restructuring

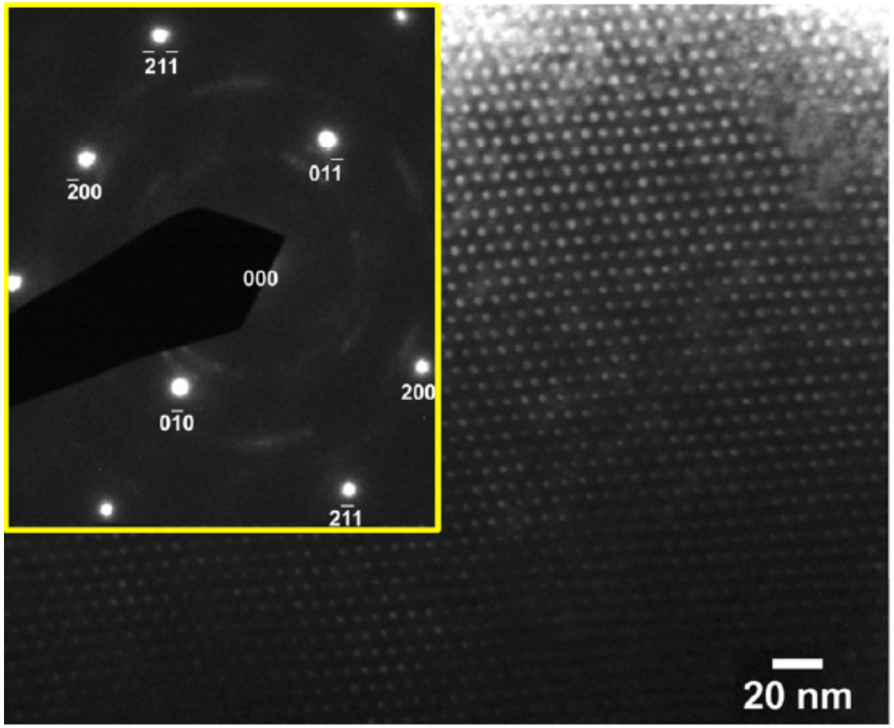


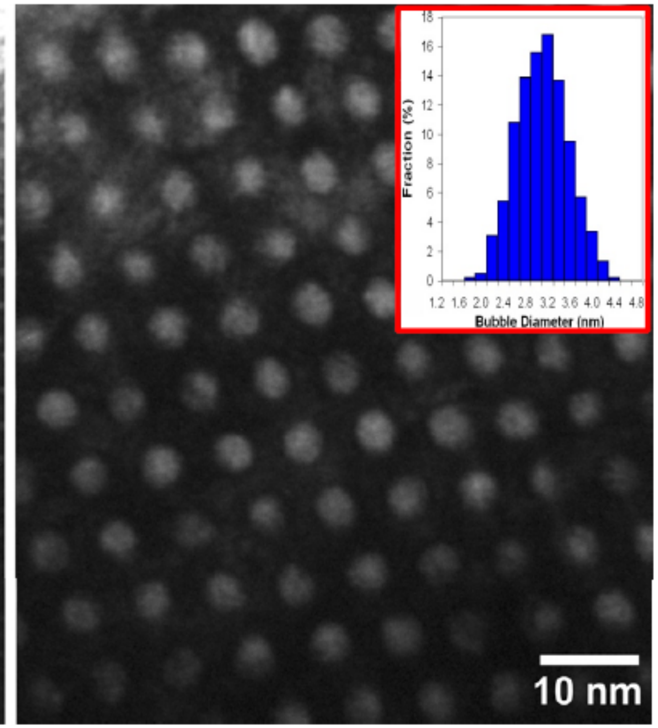
Suspected fission products in pores

FIB tomography (6.3x10^{21} fissions/cm^3)



Fission gas bubble supperlattice

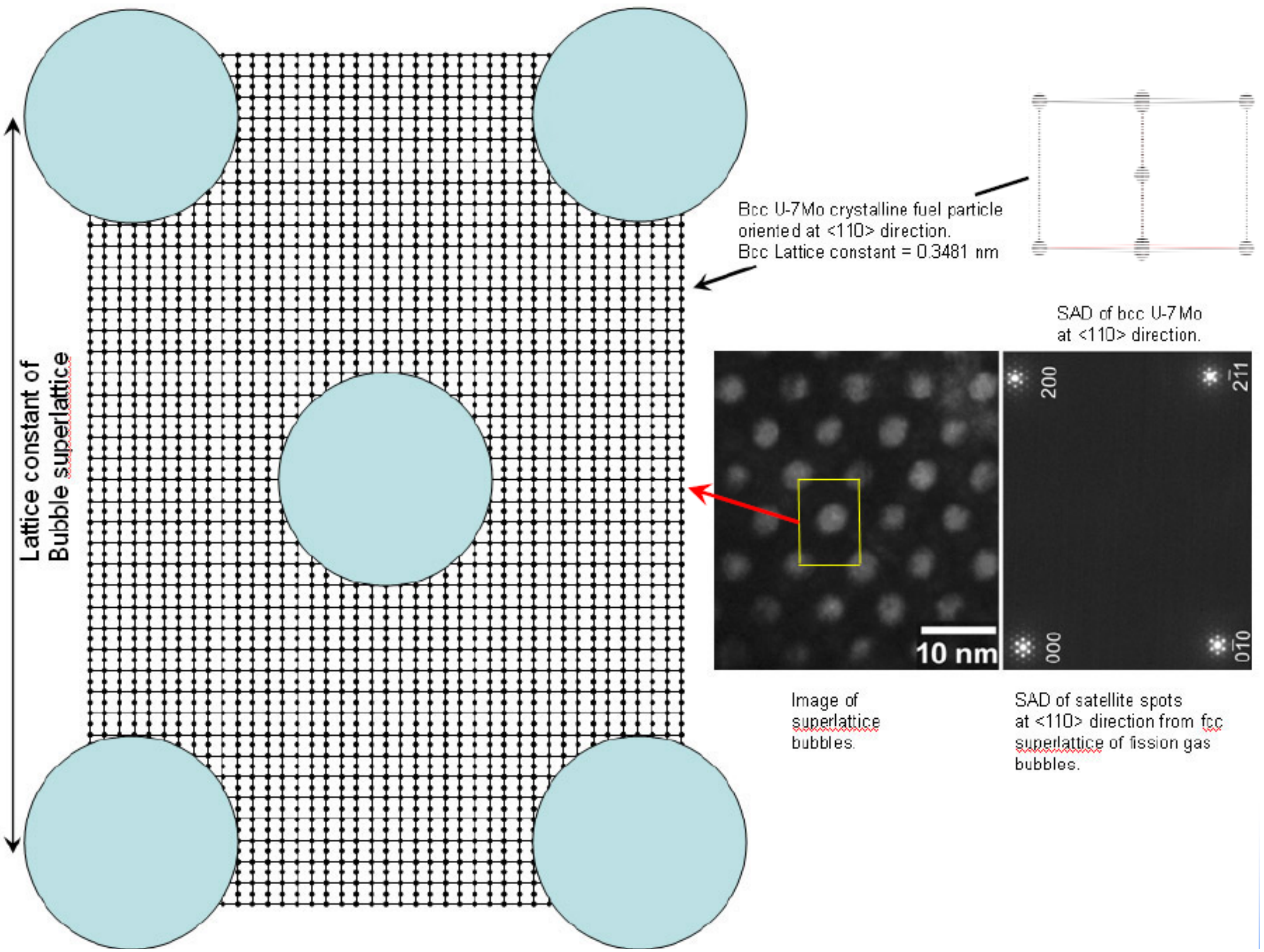




- Ordered bubbles in fuel (bcc) imaged at zone [011] at low and high magnifications
- Coherent orientation between U-7Mo fuel (bcc) and bubble supperlattice (fcc)
- Measured average bubble size is 3.1±0.4 nm
- Measured fcc superlattice constant 12.07±0.06 nm

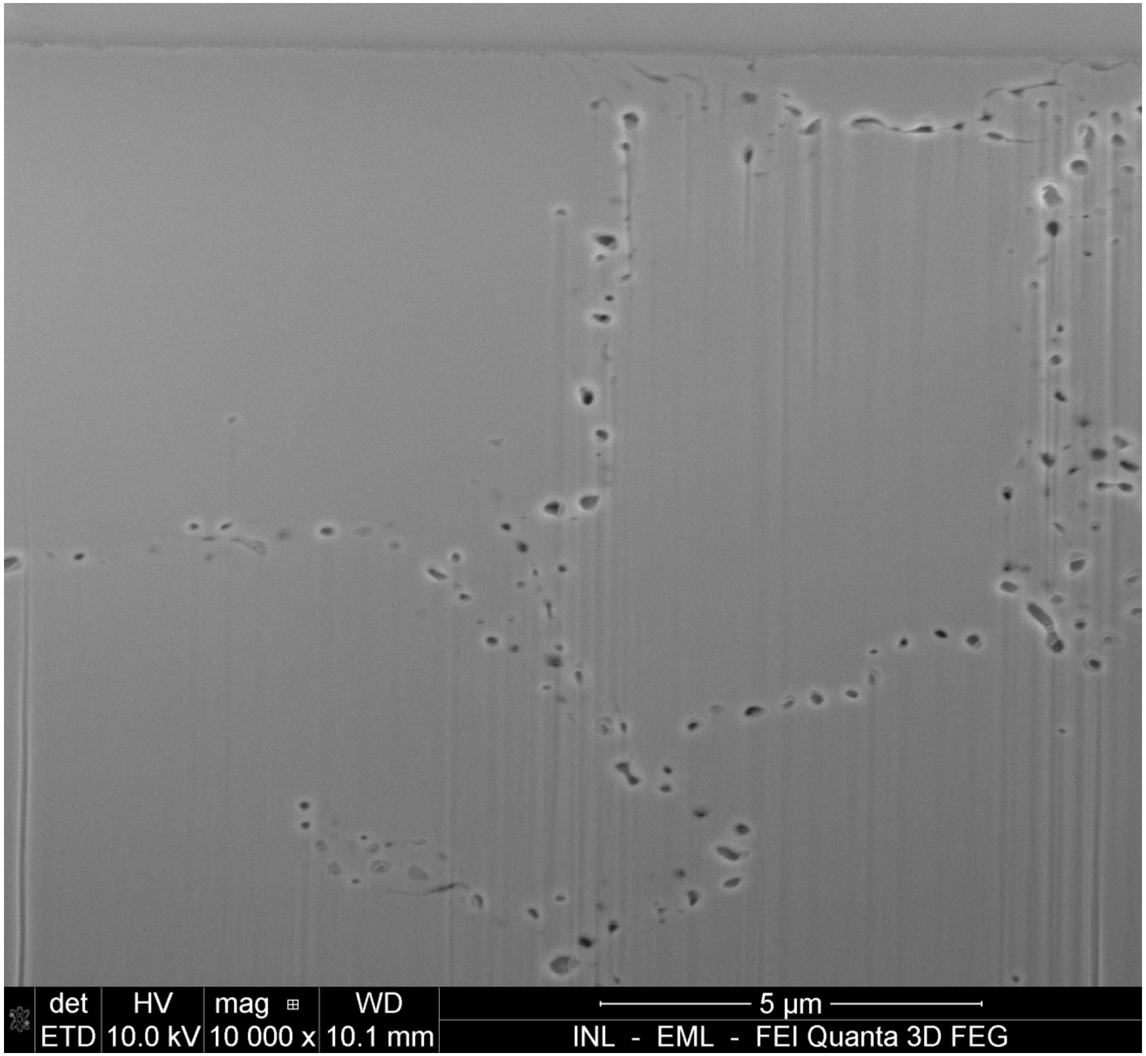
Courtesy of J. Gan

Orientation of bubble superlattice vs. U-Mo lattice



Courtesy of J. Gan

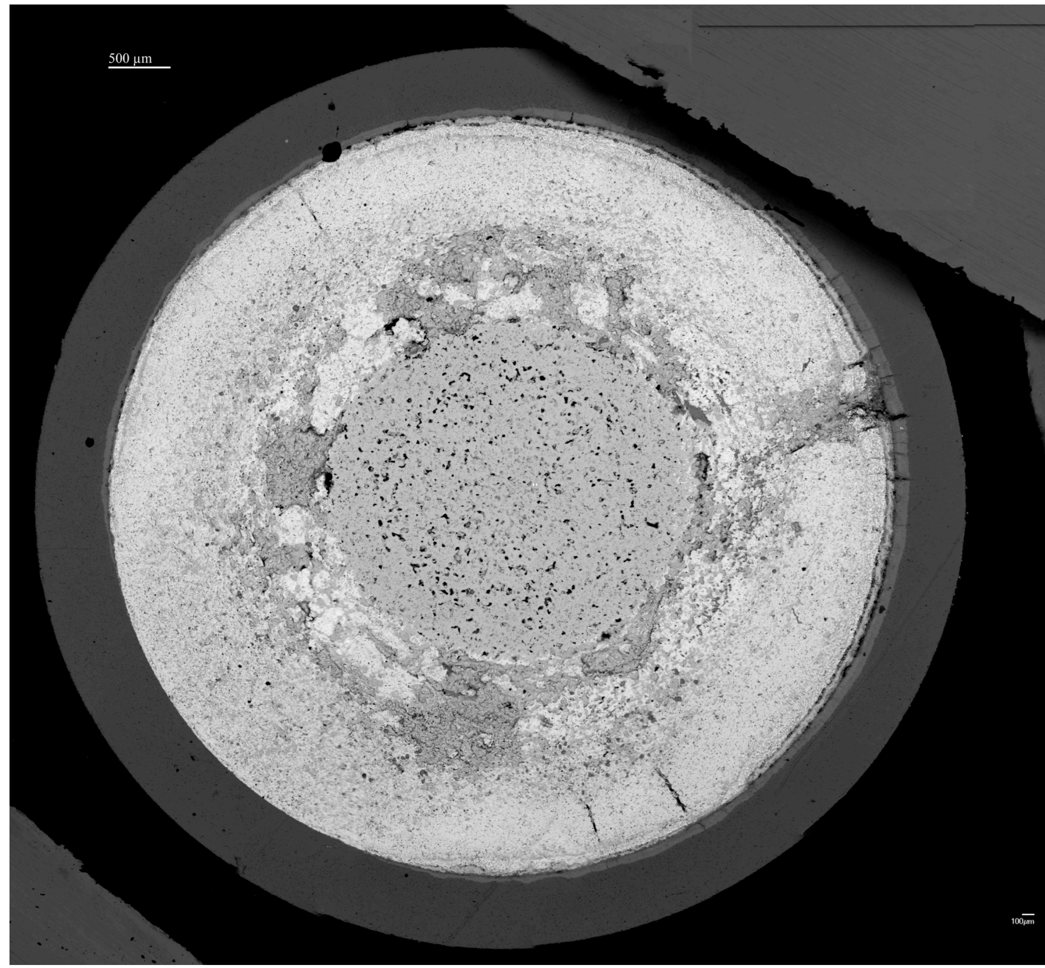
Sample preparation



Fast spectrum reactor metal fuel

U-Pu-X (Zr/Mo) metal fuels:

- Simple fabrication
- High burn-up
- Good thermal response
- Relatively simple recycling using melt refining or electro-refining processes



Fast spectrum reactor metal fuel (cont.)

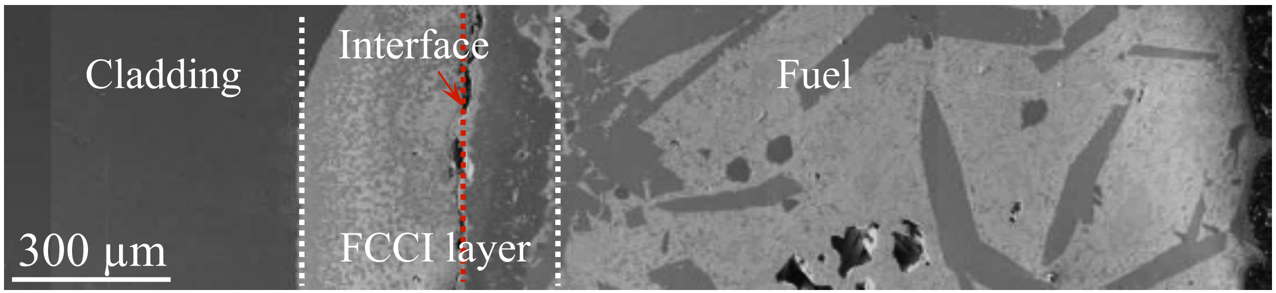
Metallic fuel performance phenomena:

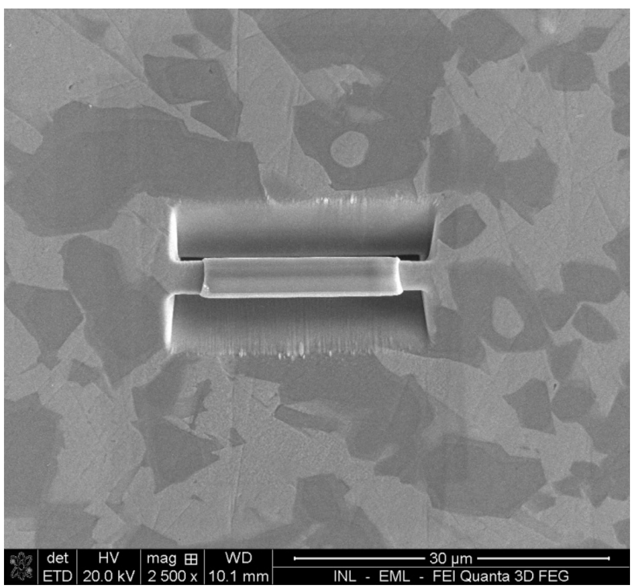
- Irradiation growth
- Fuel swelling
- Fuel-cladding mechanical interaction (FCMI)
- Gas release
- Fuel constituent redistribution
- Fuel-cladding chemical interaction (FCCI)

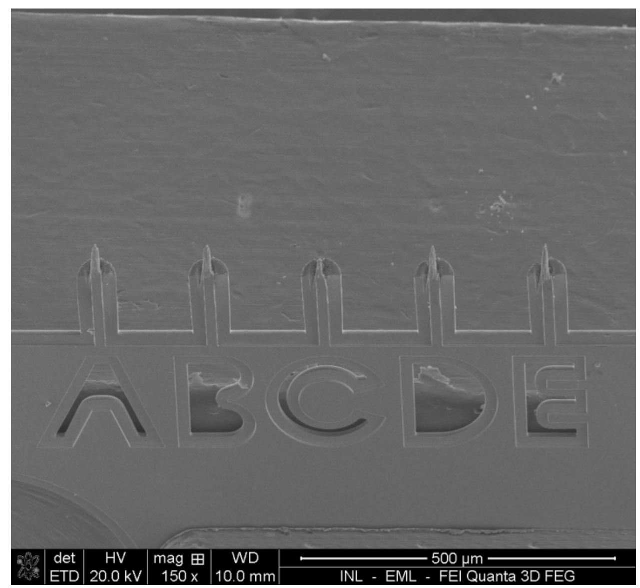
FCCI: RE fission products (La, Ce, Pr, Nd) and Pu react with cladding, produces brittle interaction product, which is considered to be cladding wastage.

Fast spectrum reactor metal fuel

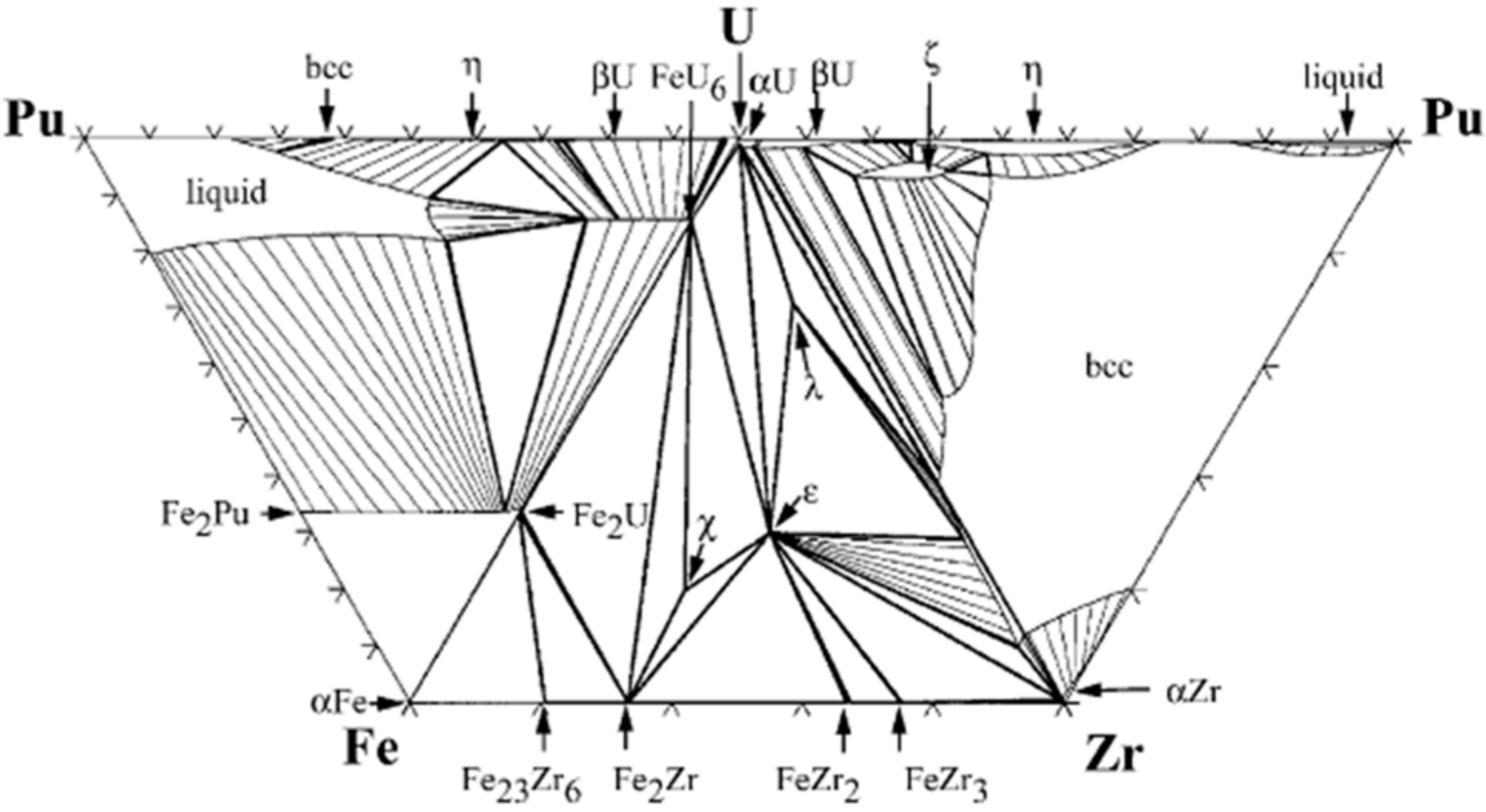
U-25Pu-14Zr vs. Fe cladding







Phase diagram for U-Pu-Zr-Fe system



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