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Advanced Electron Microscopy of TRISO coated Particles: FY2021 Overview

July 2021

Changing the World's Energy Future

Subhashish Meher, Isabella J Van Rooyen, Boopathy Kombaiah, Karen E Wright, Zhenyu Fu, Yong Yang

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ART
Advanced Reactor Technologies

Goals and Objectives

Objectives

- Understanding Effects of Irradiation on TRISO layers
- Fission product chemistry and behavior in UCO kernel
- Identify and Understand Fission Product Transport Mechanisms in TRISO Coated Particles

Outcomes and Impact

- Improve Predictive Behavior Modeling
- Kernel Behavior: Release from kernel
- Kernel chemistry evolution with irradiation and kernel retention of fission product

Work Performed in FY21

- TRISO- Kernel Microscopy Report – INL and UF
- TRISO- SiC Layer Microscopy – INL
- Deliverables/Outcome

AGR-1 and AGR-2 Particle Irradiation History and Characterization

Particle	Ag Retention	Fuel Type	Burnup (% FIMA)	Kernel	SiC layer: FP Distribution and Microstructure				
					EPMA	FIB	STEM	PED	Radiation Damage
AGR1-632-034	0.65	Baseline	11.4						
AGR-523-SP01	0.16	Variant 1	17.4						
AGR1-131-066	0.39	Variant 3 ORNL Lab	15.3						
AGR1-433-001	0.66		18.6 Safety tested*						
AGR1-433-004	0.66		18.6 Safety tested*						
AGR1-433-003 AGR1-433-007	0.66		18.6 Safety tested*						
AGR2-223-R06 (Mount D07)	0.08	BWXT	10.8						
AGR2-223-R034 (Mount D06)	0.84		10.8						
AGR2-222-RS36 (Mount D25)	Not detectable Eu = 0.8		12.55 Safety tested*	FY2020					
AGR2-222-RS19 (Mount D26)	0.20 Eu = 0.54		12.55 Safety tested*	FY2020					
AGR2-222-RS27 (Mount D26)	0.11 Eu = 0.51		12.55 Safety tested*						
AGR2-633-RS28 (Mount D42)	<0.21		7.46	FY2020	FY2020	FY2020	**FY2021****	**FY2021****	**FY2021****
AGR2-633-RS09 (Mount D43)	0.88		7.46		FY2020	FY2020	**FY2021**	**FY2021**	**FY2021**
AGR2-633-RS01 (Mount D43)	0.76		7.46	TBD	TBD	TBD	TBD	TBD	
Unirradiated Baseline As-Fabricated	N/A	AGR1	N/A						
Unirradiated Baseline As Fabricated and Compacted	N/A	AGR2	N/A	**FY2021****		FY2020			

Completed previous years

Planned FY2021

** in progress

* 1600°C, 300h

Report: Irradiated UCO Fuel Kernels of AGR-1 and AGR-2 Particles

Motivation:

- The knowledge of phases and elemental distributions of interested fission products can be used to determine the oxygen partial pressure inside the fuel particles while being in-pile. The work also provides thermodynamic validations for modeling the fission products behavior in UCO fuel kernels.
- The knowledge of irradiated microstructure can provide significant input for future fuel-performance modeling (e.g., BISON model).
- Knowing the spatial distribution and chemical state of Pd and Ag is particularly critical for ensuring the integrity of SiC coating layer and for controlling the release of Ag.

UCO fuel kernel		AGR-1	AGR-2
Diameter (μm)		348.4 ± 8.3	426.7 ± 8.8
Density (g/cm^3)		10.7 ± 0.026	11.0 ± 0.030
^{235}U enrichment (at.%)		19.74	14.03
Chemistry (mole%)	UO_2	67.9	71.4
	$UC_{1.86}$	0.4	12.3
	UC	31.7	16.4

AGR-1 and AGR-2 fuel comparison

Compact	AGR1-632-034	AGR1-433-004	AGR2-223-RS06	AGR2-222-RS36	AGR2-222-RS19	AGR2-633-RS09	AGR2-633-RS28
Burnup (%FIMA)	11.40%	18.60%	10.80%	12.60%	12.55%	7.46%	7.46%
Ag retention (%)	65%	99%	8%	Not detectable	20%	80%	<21%
TAVAT*(°C)	1070	1094	1161	1287	1287	1060	1060
TAPT*(°C)	1144	1179	1335	1354	1354	1134	1134
Safety Test (1600°C,300hrs)	No	Yes	No	Yes	Yes	No	No

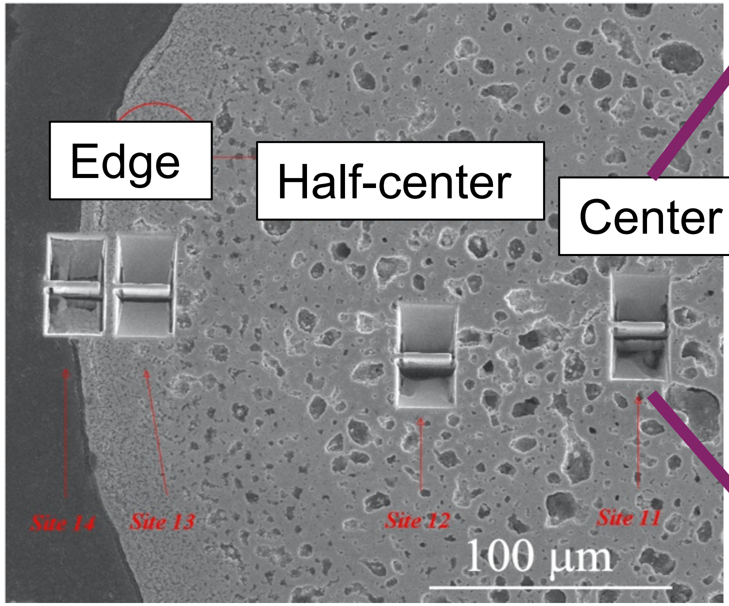
* TAVA = time average volume average, *TAP = time average peak

Results (Fuel Kernel Center)

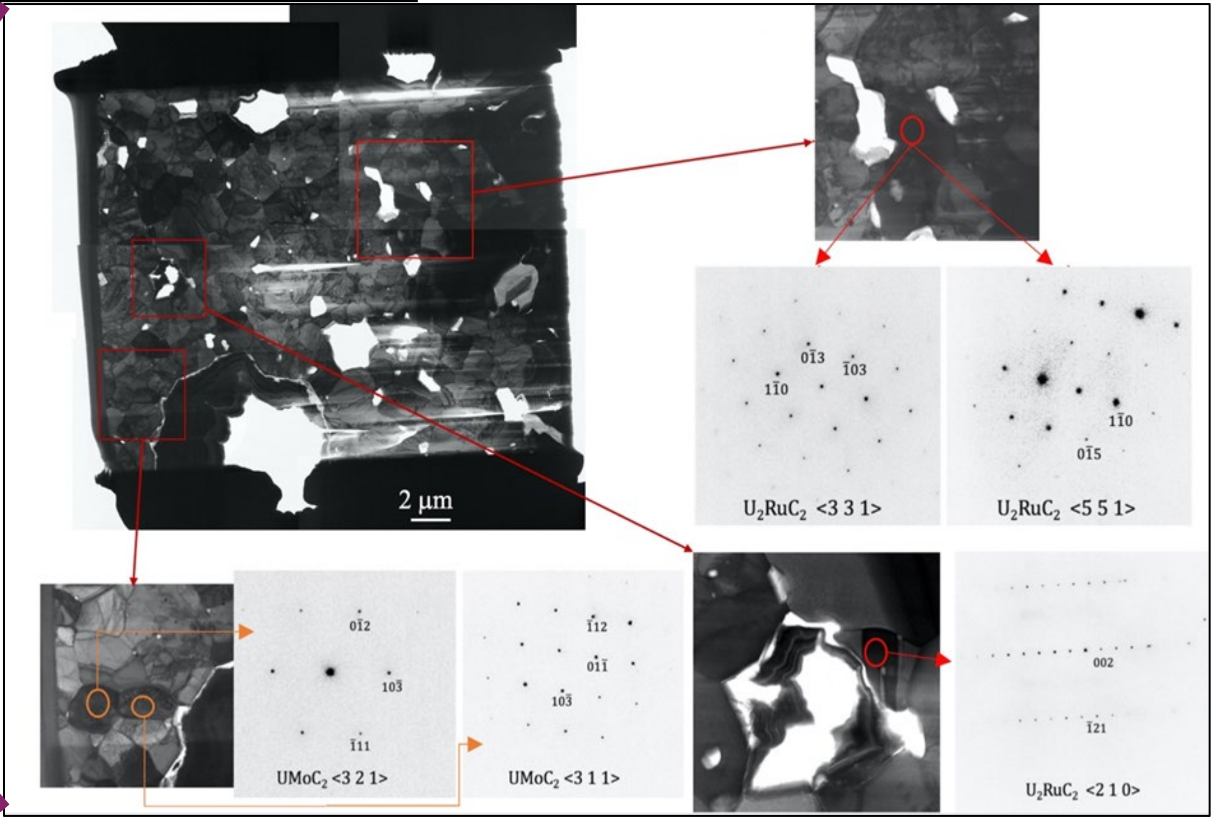
Sample preparation: Focused Ion Beam (FIB) -precise location
Imaging Tool: Transmission Electron Microscopy (TEM) – nanoscale structural and chemical analysis

AGR2-222-RS36 UCO kernel

FIB sample preparation



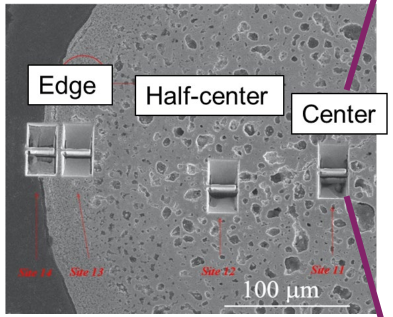
All the particles are analyzed at different kernel areas



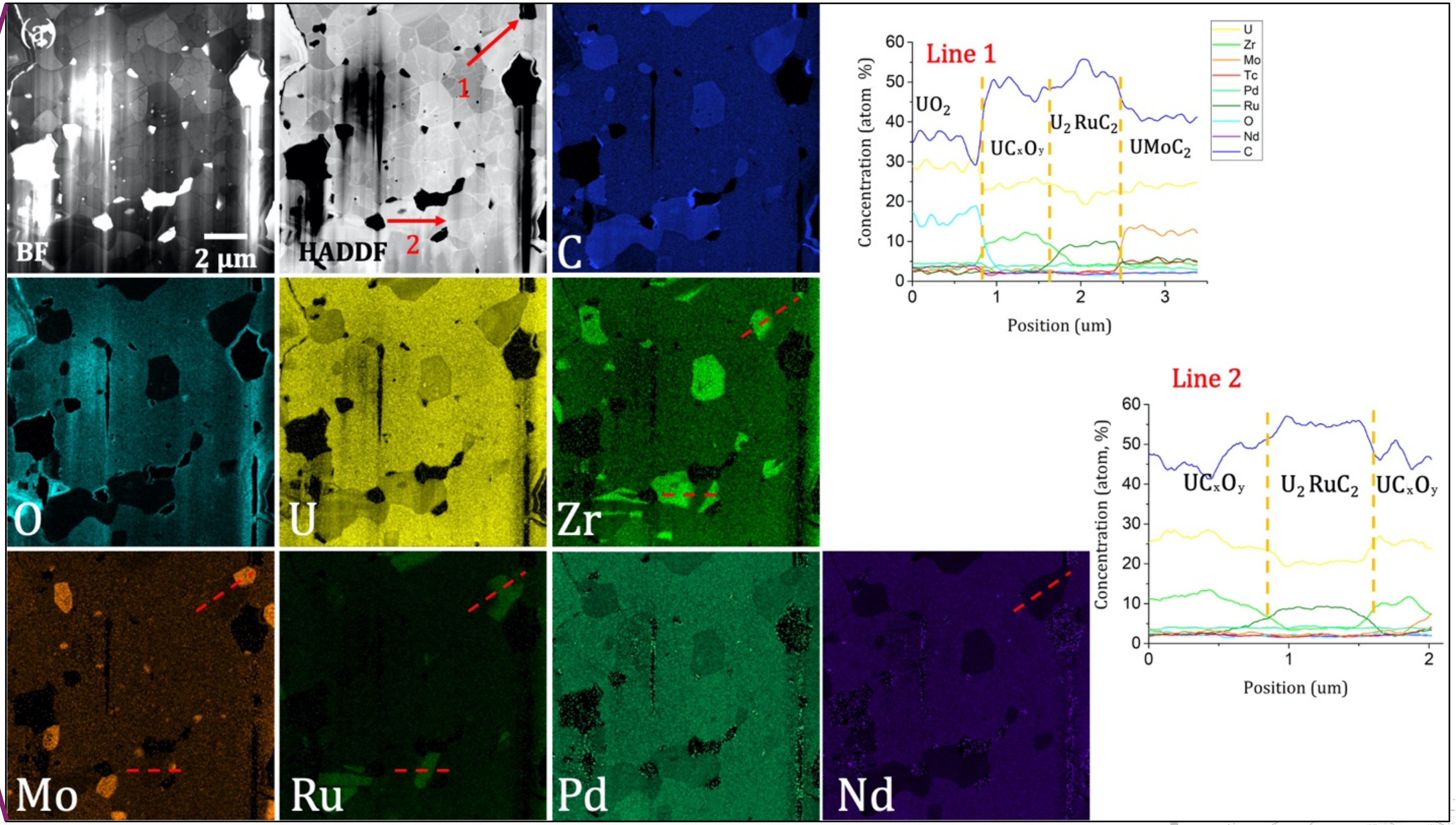
Overview of the fuel center lamellae and the diffraction from the fuel center

Fuel Kernel Center

EDS maps and line scans over selected phases

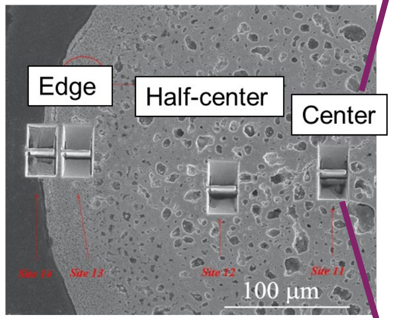


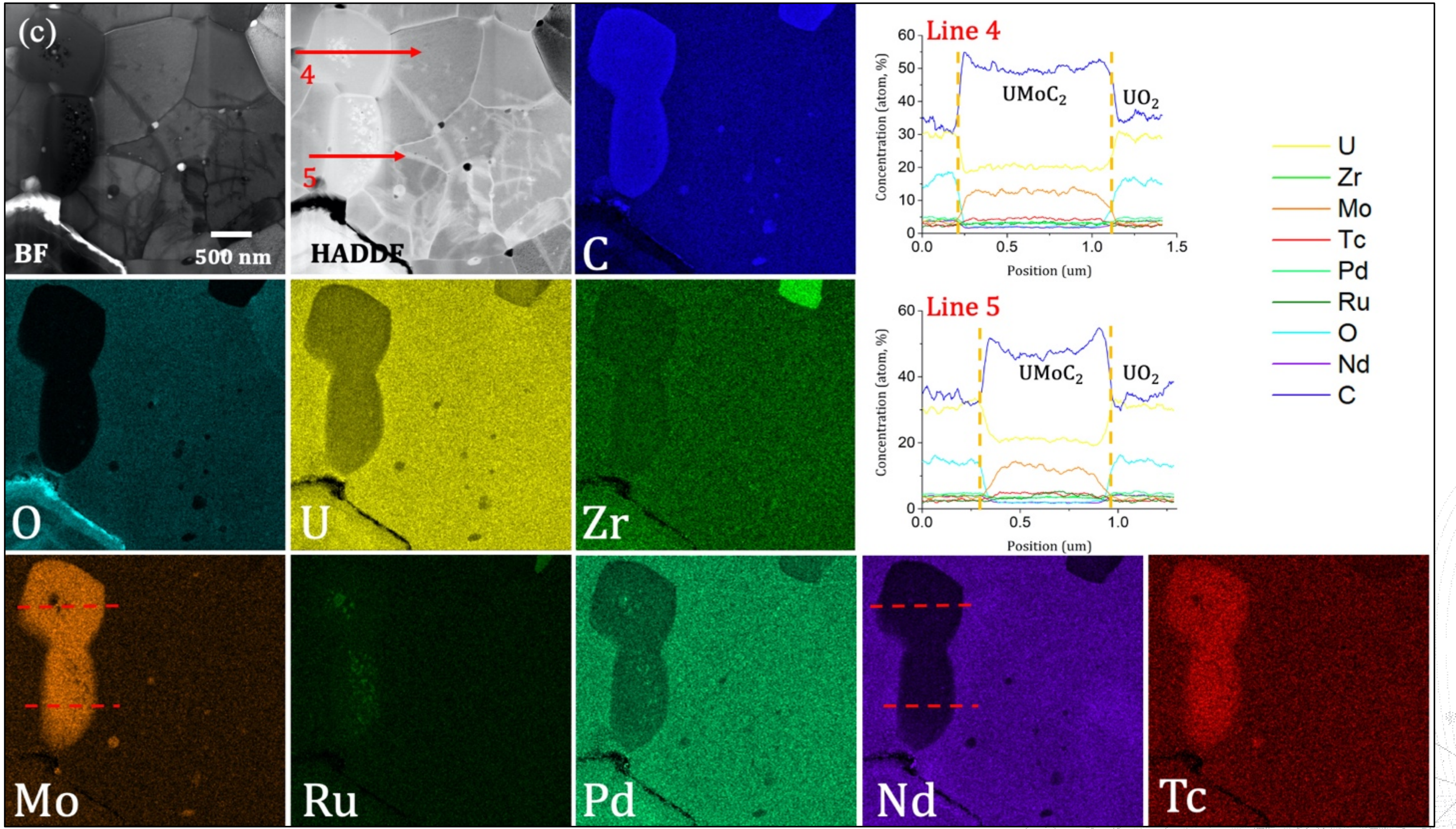
AGR2-222-RS36 UCO kernel



Fuel Kernel Center

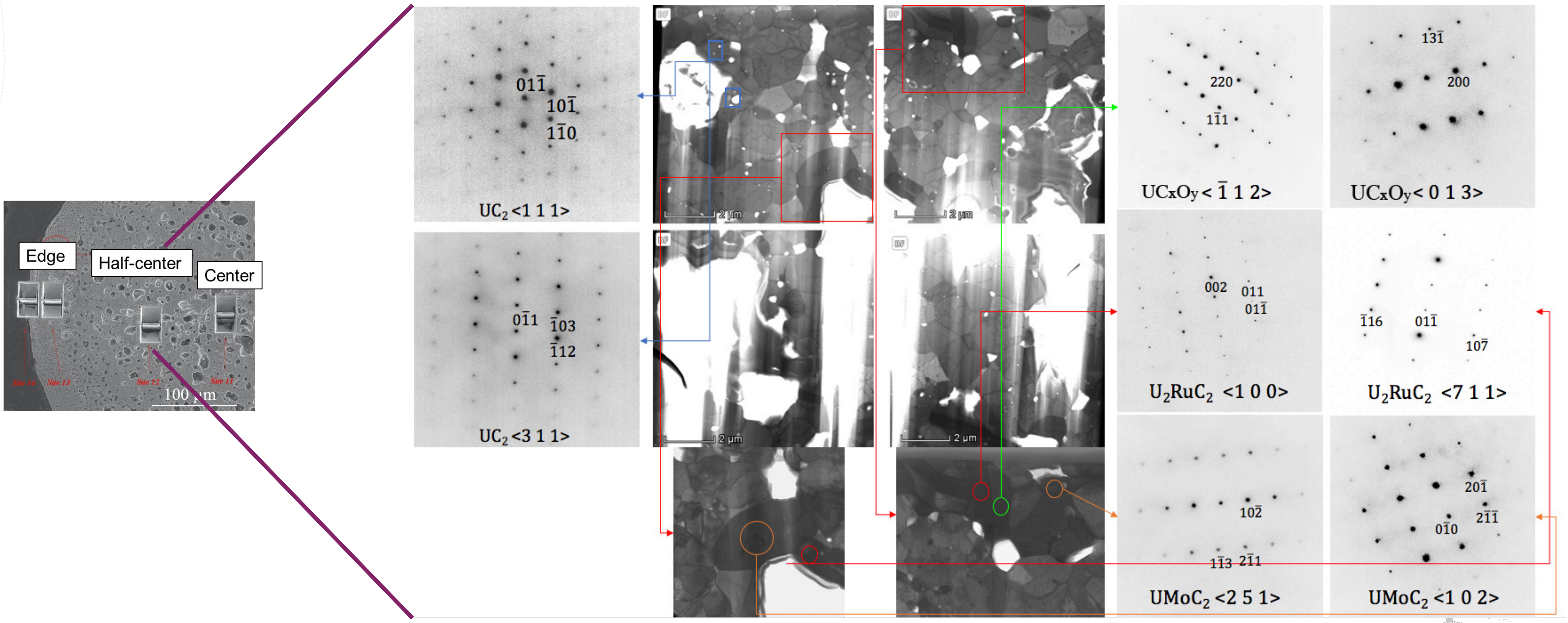
EDS maps and line scans over selected phases





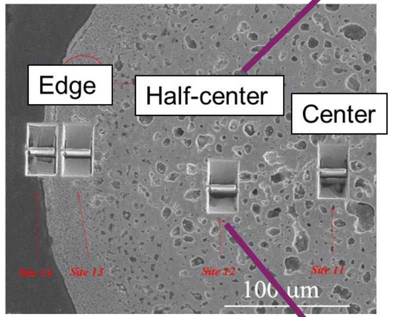
Fuel Kernel Half Center

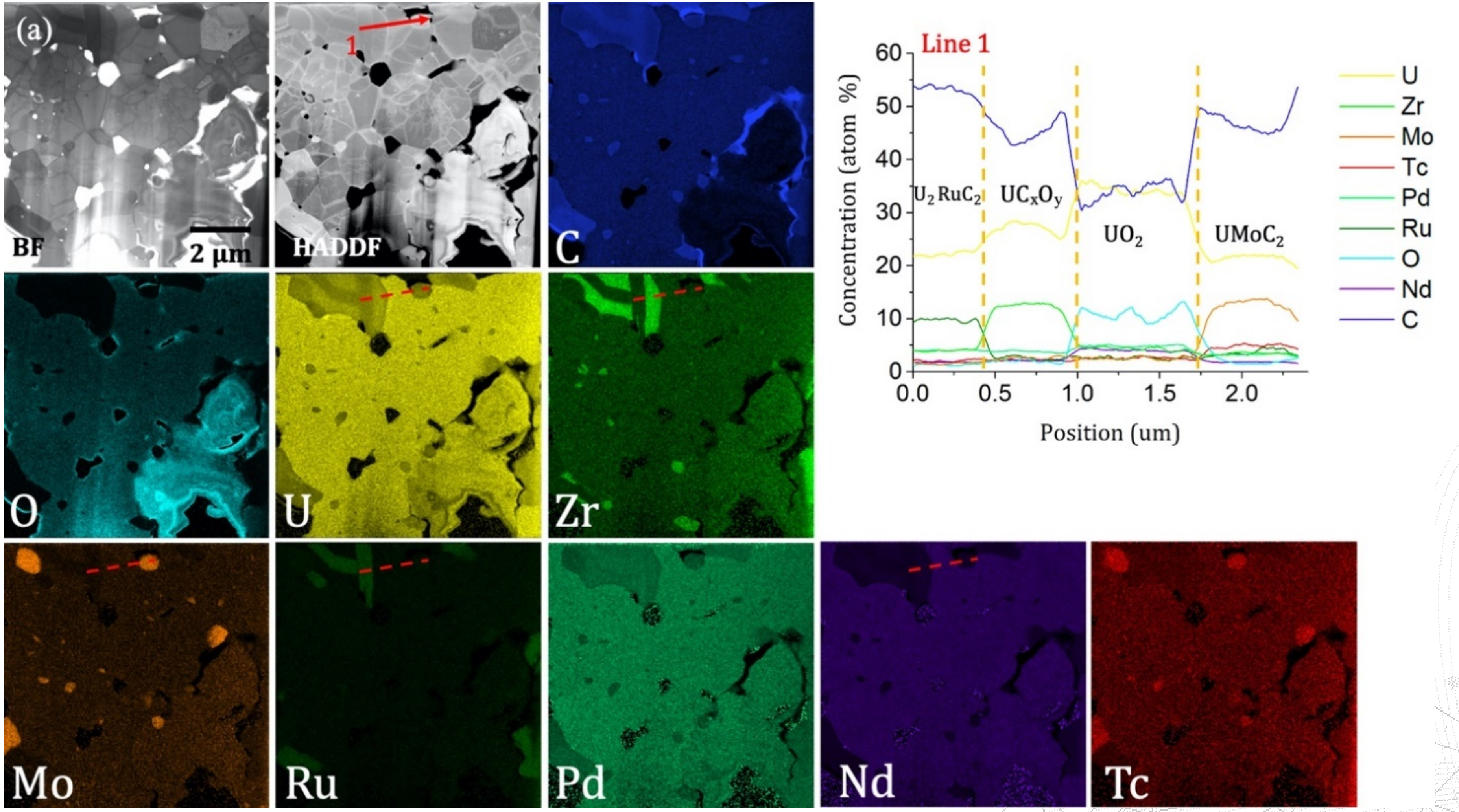
Overview TEM images of fuel half-center lamellae and diffraction patterns from selected areas



Fuel Kernel Half Center

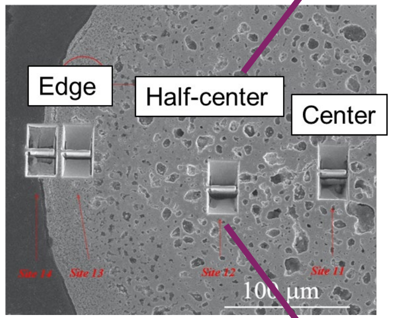
EDS maps and line scans over selected phases

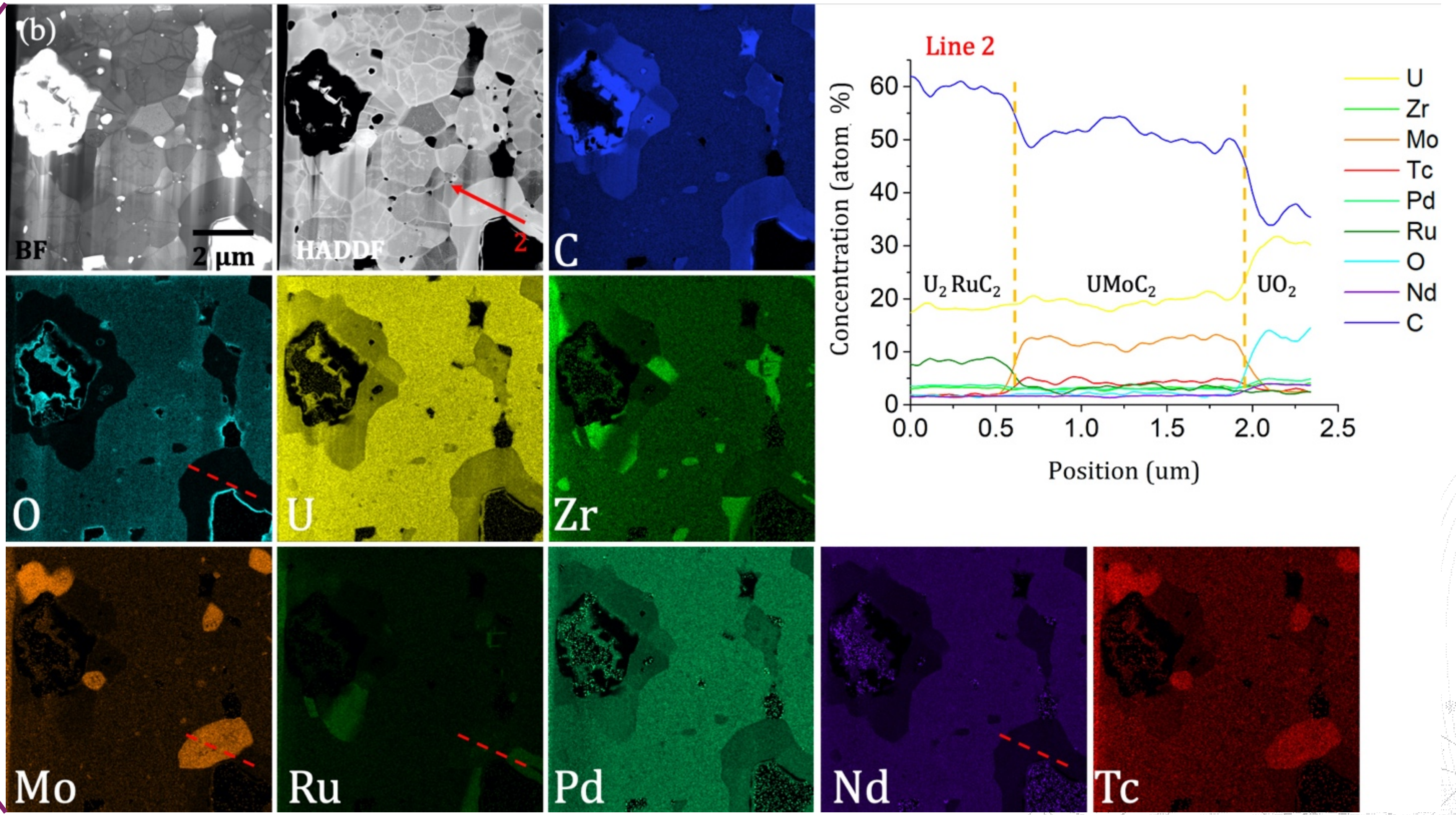




Fuel Kernel Half Center

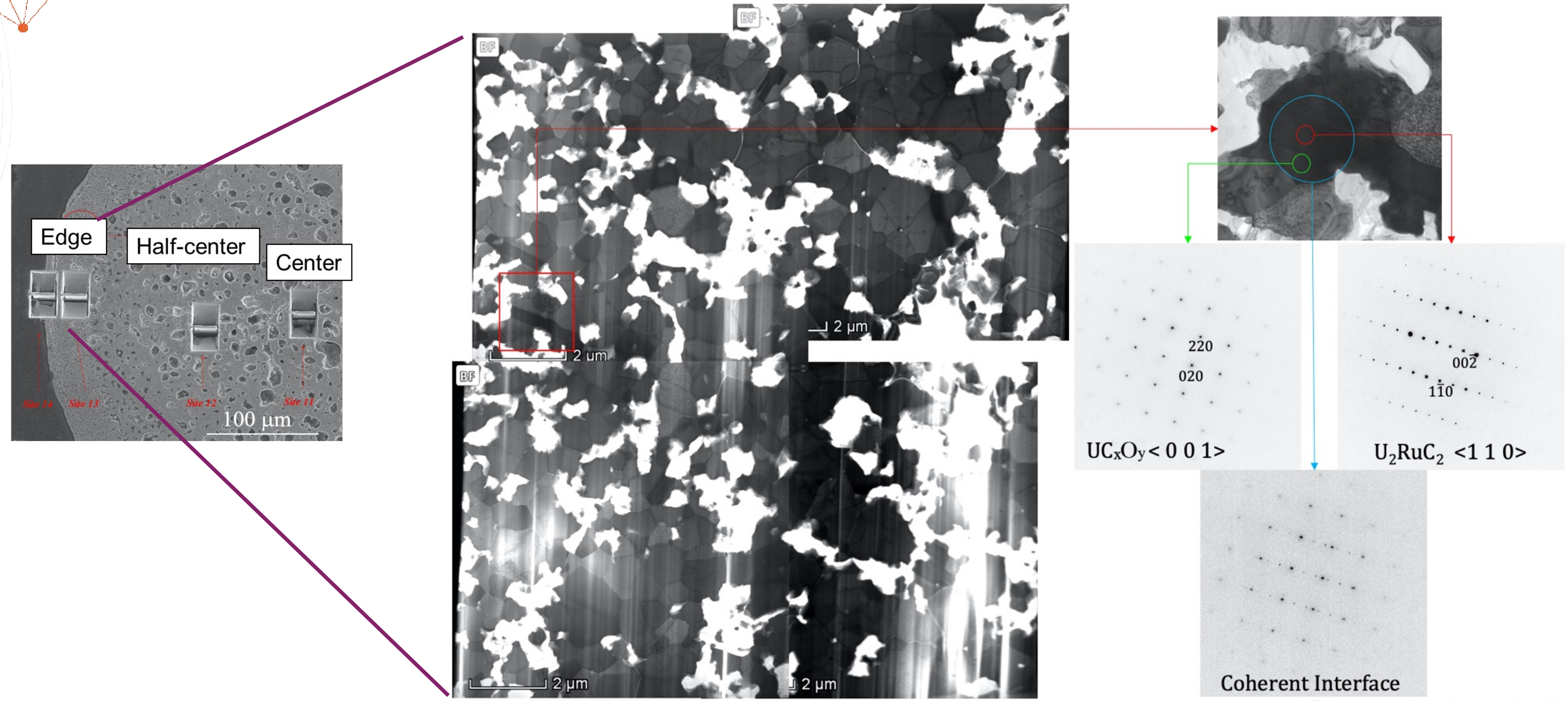
EDS maps and line scans over selected phases



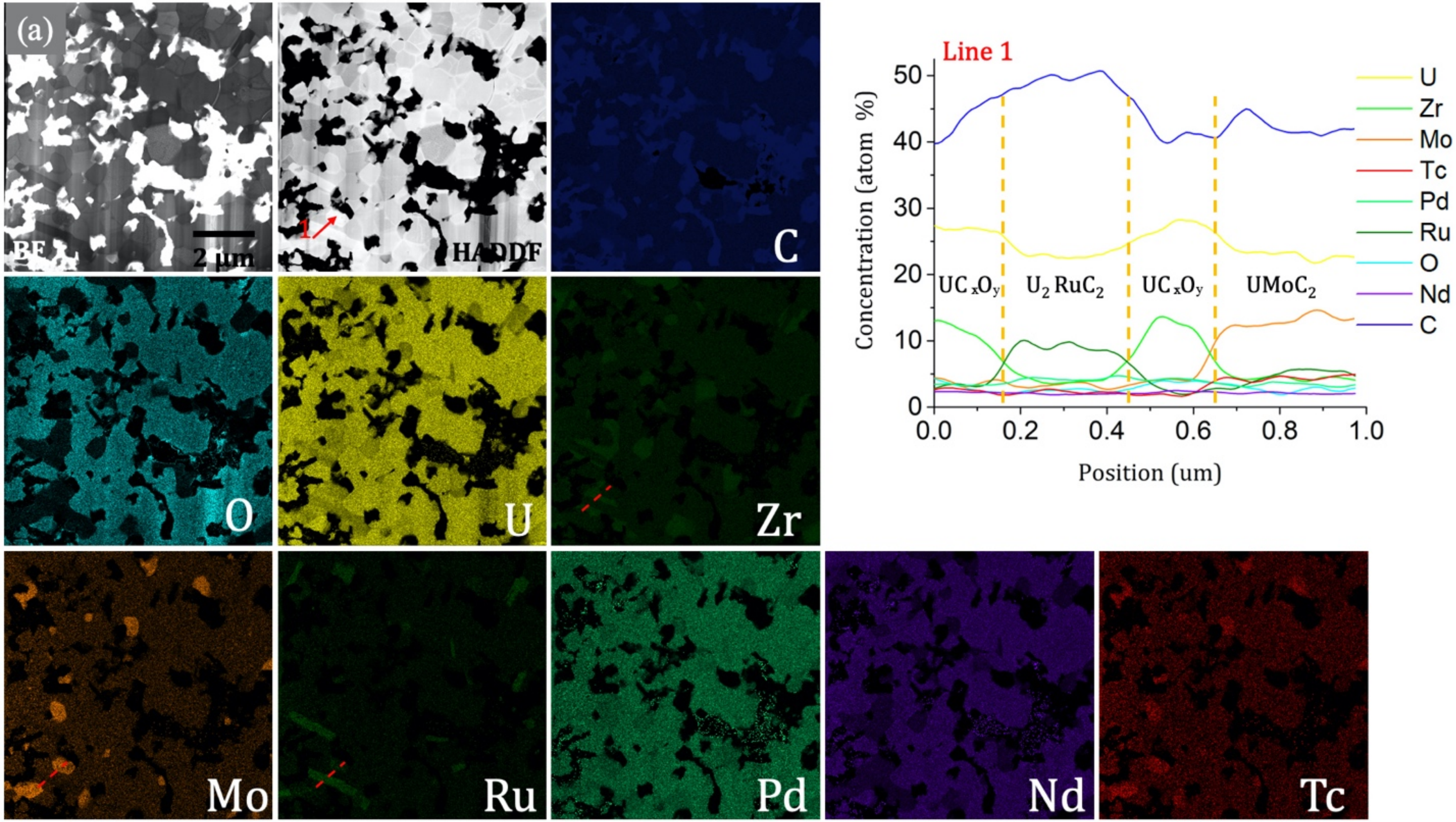


Fuel Kernel Edge

Overview of the fuel kernel edge zone lamellae: TEM images and diffraction patterns from selected areas

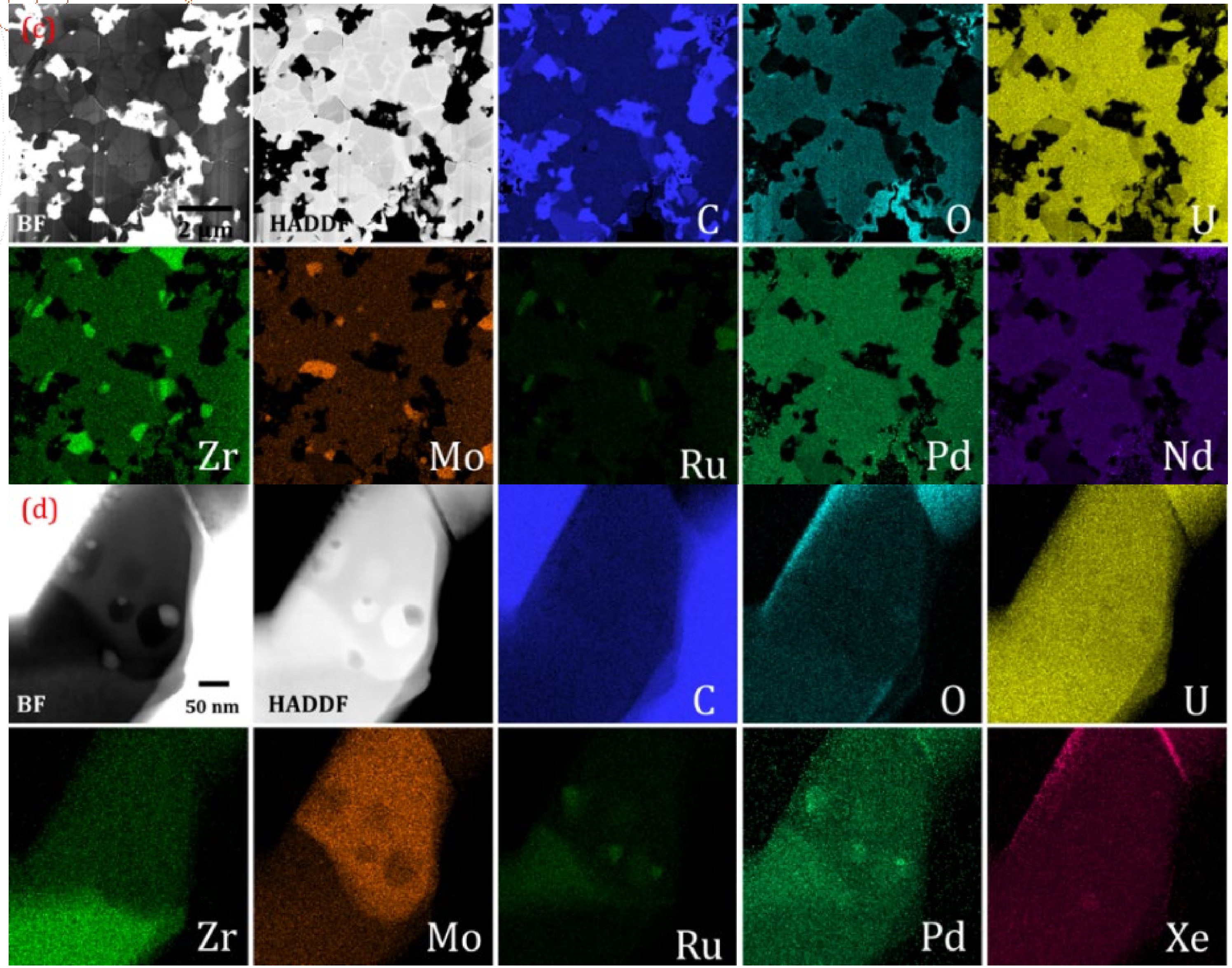


Fuel Kernel Edge



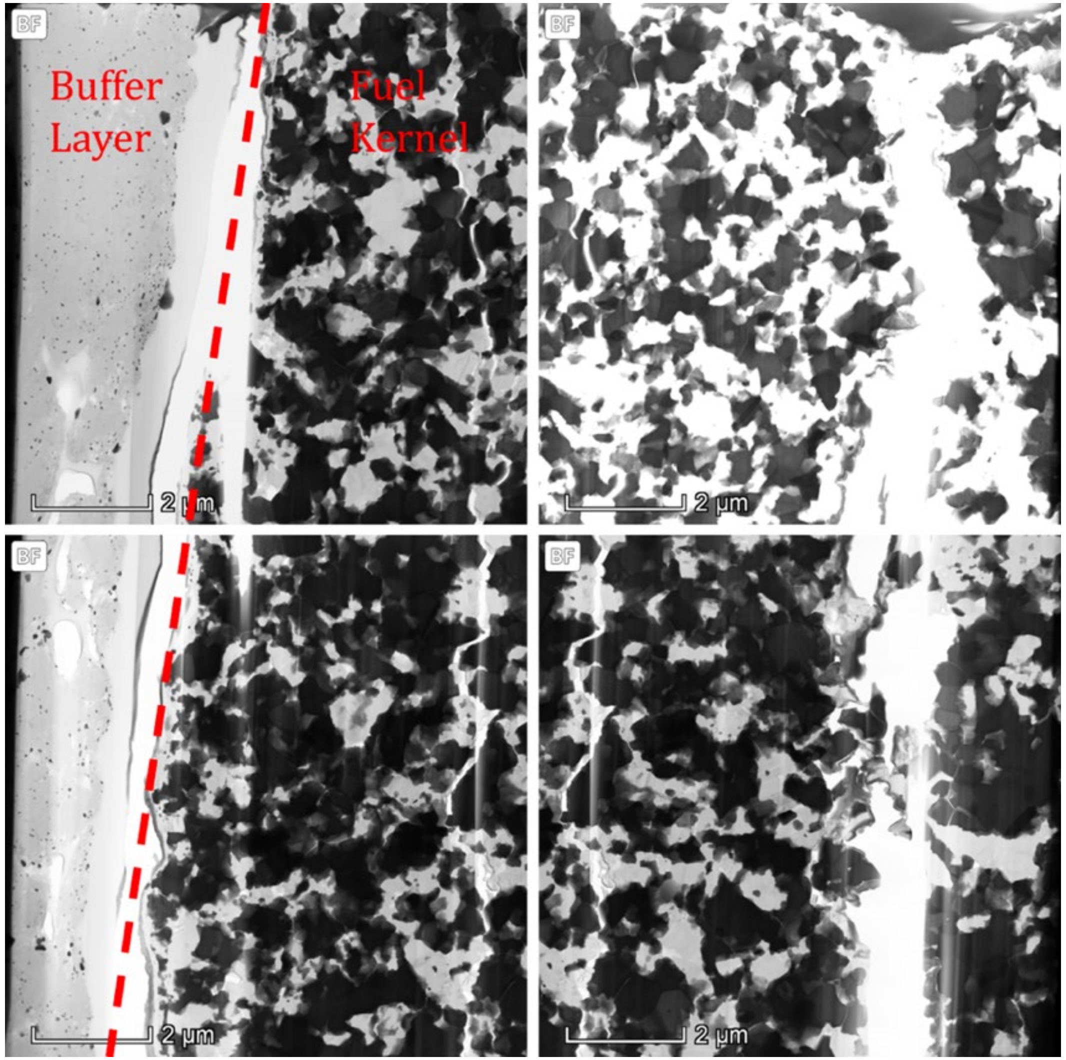
EDS maps and line scans over selected phases

Fuel Kernel Edge



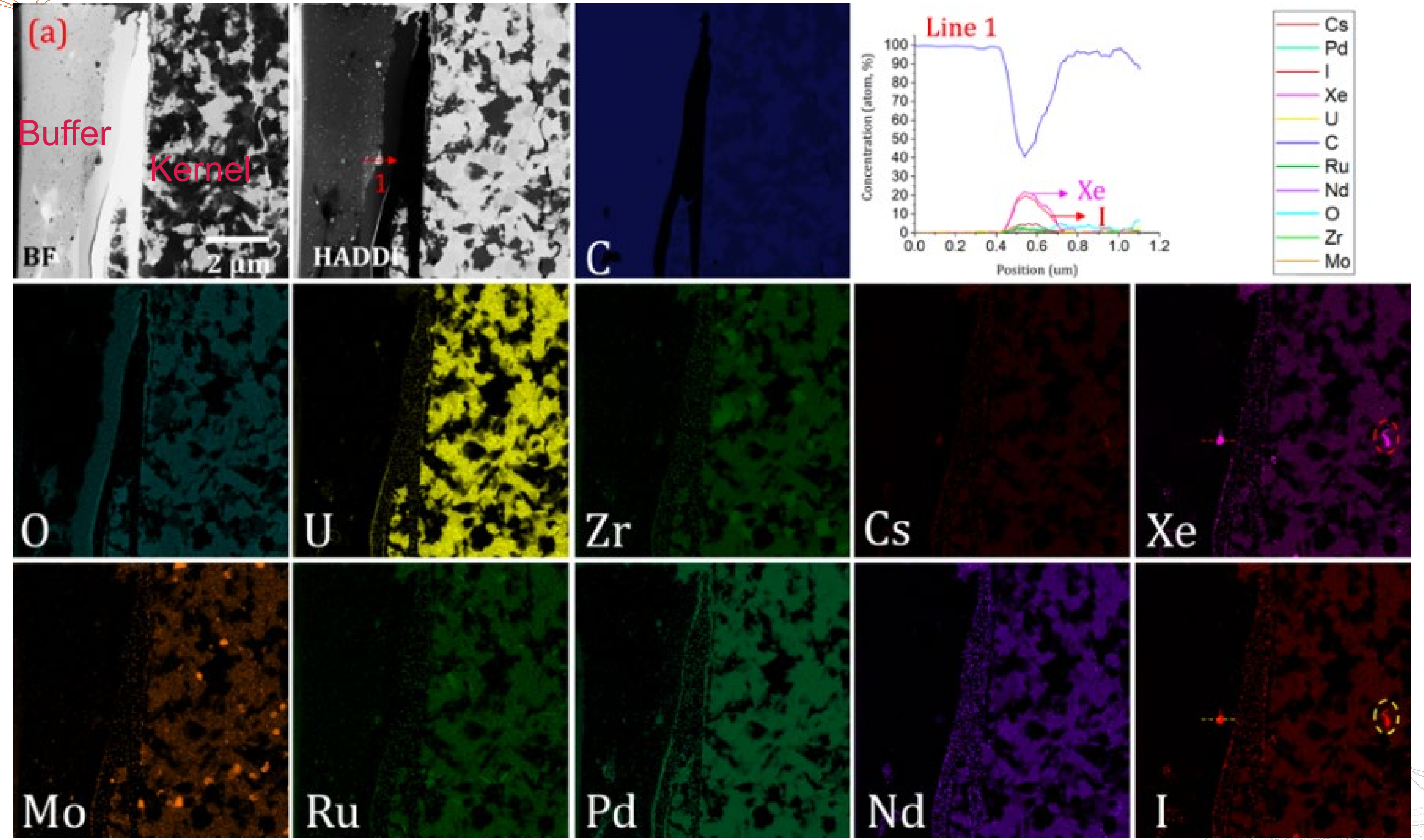
TEM images and EDS maps

Fuel Kernel-Buffer Interface



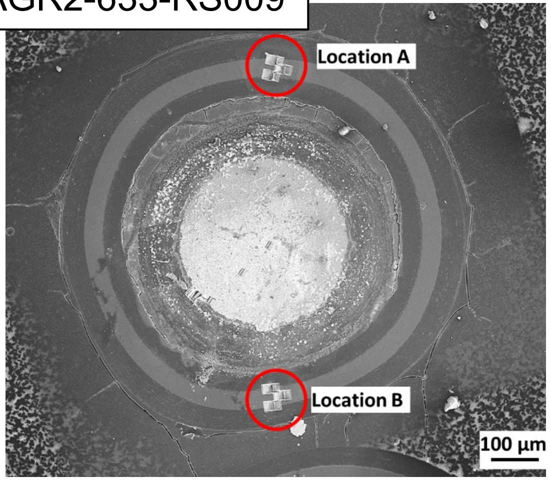
Fuel Kernel-Buffer Interface

EDS maps and line scans over selected phases

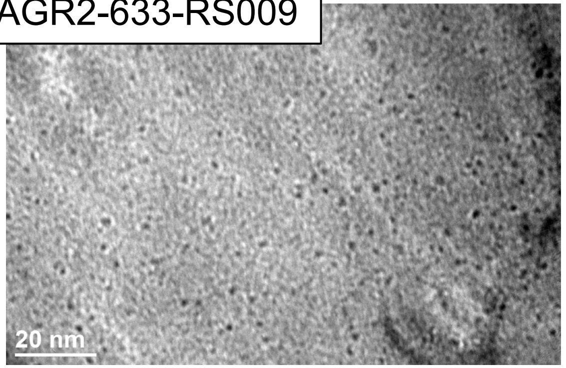


Silicon Carbide layer – FY21 AGR2-633-RS009

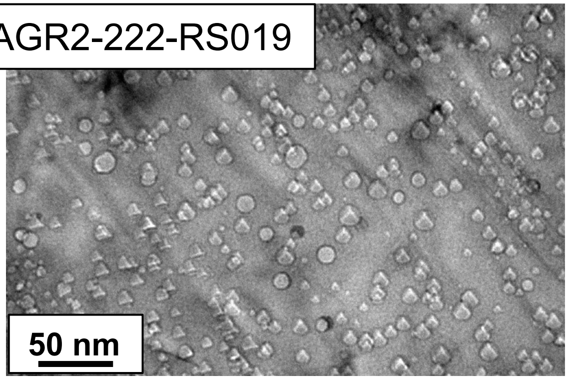
AGR2-633-RS009

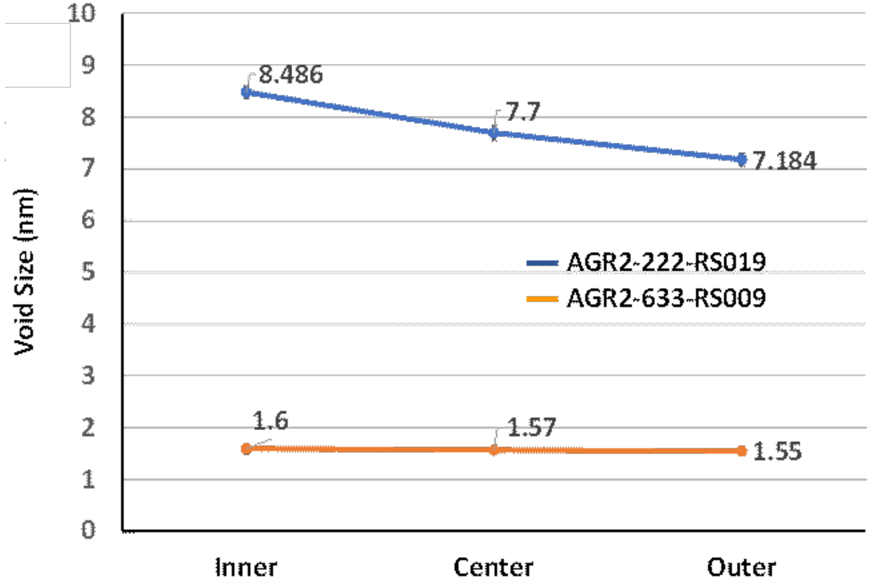


AGR2-633-RS009



AGR2-222-RS019





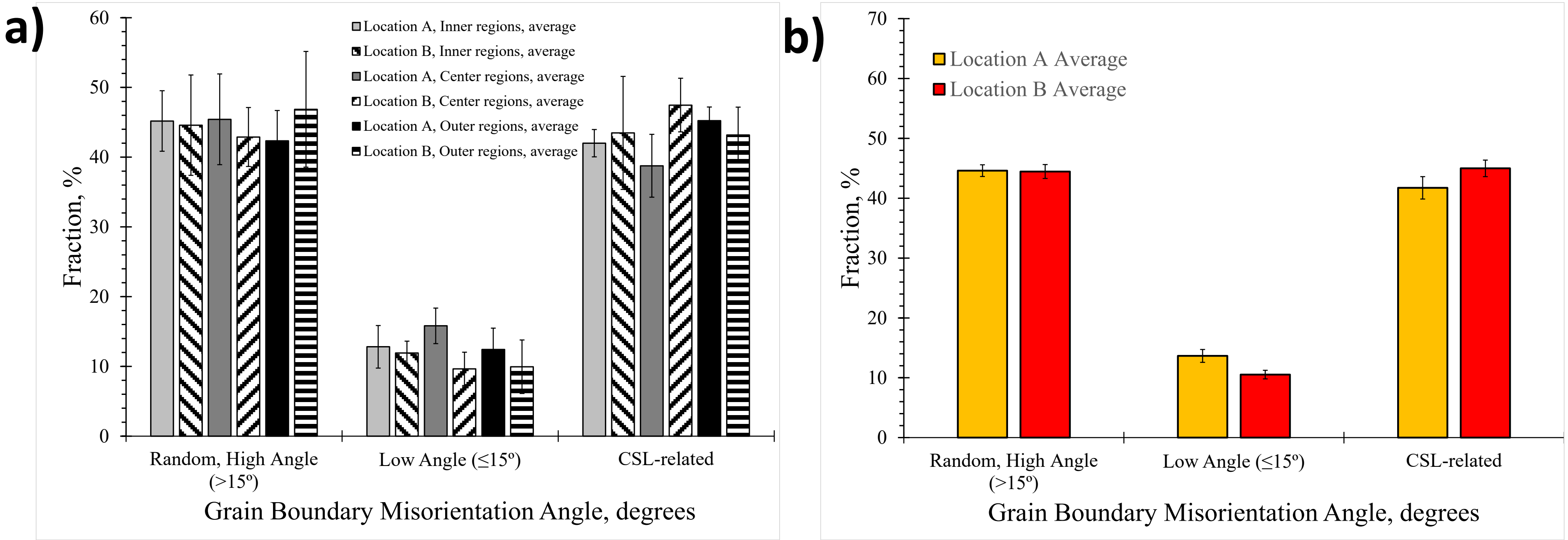
The irradiation damage size directly corresponds to the irradiation temperature

Effect of Neutron Irradiation Damage on Fission Product Transport in the SiC Layer of TRISO Fuel Particles (HTR2018) – described the relation of damage sizes and irradiation parameters

Particle	Particle Ag Retention (%)	Irradiation Properties Averaged Over the Entire Compact. Actual particle properties will vary.			
		Burnup (%FIMA)	Fast Neutron Fluence, × 10^{25} n/m^2	TAVA Temp (°C)	Time-Ave Peak Temp (°C)
AGR2-222-RS019 (Safety Tested)	20	12.55	3.39	1287	1354
AGR2-633-RS009	88	7.46	2.14	970	1134

Characteristics and average compact irradiation conditions for TRISO particles

AGR2-633-RS009 – SiC Grain boundaries



Plots showing the distribution of low angle, high angle and CSL grain boundaries for (a) each lamella and (b) average of Location A and B of particle AGR2-633-RS009.

- Like previously analyzed particle, most of the grain boundaries are high angle and CSL (coincidence site lattice) grain boundaries where most of the fission transport occur.

Summary

Key points from UCO kernel study:

- Unirradiated as-compacted fuel kernels contain three phases with different area fractions: ~70% UO_2, 20% UC_2, and 5% UC. Remainder is porosity.
- After irradiation, kernels are comprised of UO_2 and UC_xO_y.
- Safety testing causes enhanced migration of fission products to the kernel periphery (KP).
- Volatile elements such as Xe, Cs, and I are symmetrically distributed across the particle.
- Eu, Sr, Ba, and Te tend to behave similarly. At low burnup they are retained by the kernel and are symmetrically distributed across the kernel. At higher burnup they concentrate in the KP and do so asymmetrically.
- Pd concentrates in the U_2RuC_2 phase or precipitates together with Xe bubbles. Ag was mainly identified at the interface between the fuel kernel and buffer layer, and the Ag at the interface is often associated with Zr, U, and Pd.

Key point from recent SiC study:

- Void sizes in SiC from irradiation damage increase with irradiation temperature.

Publications and Presentations: FY2021

Reports:

- Advanced Microscopy Report on UCO Fuel Kernels from Selected AGR-1 and AGR-2 Experiments, IJ Van Rooyen, Y Yang, Z Fu, B Kombaiah, KE Wright, Idaho National Lab.(INL) INL/EXT-21-62124
- Electron Microscopic Examination of an Irradiated TRISO Coated Particle of AGR-2 Experiment: AGR2-222-RS019, S Meher, IJ Van Rooyen Idaho National Lab.(INL) INL/EXT-20-60569

High Temperature Reactor Conference papers (not online yet):

- Microstructural and Micro-Chemical Evolutions in Irradiated UCO Fuel Kernels of AGR-1 and AGR-2 TRISO Fuel Particles, Zhenyu Fu, Yong Yang, Isabella J. van Rooyen, Subhashish Meher, Boopathy Kombaiah, Proceedings of HTR 2020, INL/CON-20-58859.
- Micro- and Nano-techniques for the Study of Fission Product Precipitation in SiC Layer, Isabella J. van Rooyen, S. Meher, Karen Wright, Thomas Lillo, Proceedings of HTR 2020, INL/CON-20-58872.

Conferences:

- Microstructure and chemical states of fission products in irradiated AGR-1 and AGR-2 TRISO particle UCO fuel kernels, TMS conference- 2021, VIRTUAL
- On the Role of Neutron Irradiation Damages on Fission Products Transport in the SiC Layer of TRISO Fuel Particles, TMS conference- 2021, VIRTUAL

Acknowledgements

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