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Nuclear Technology Research and Development

Postirradiation Examination on Innovative Advance Reactor Metallic Fuel Concepts

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Advanced Fuels Campaign

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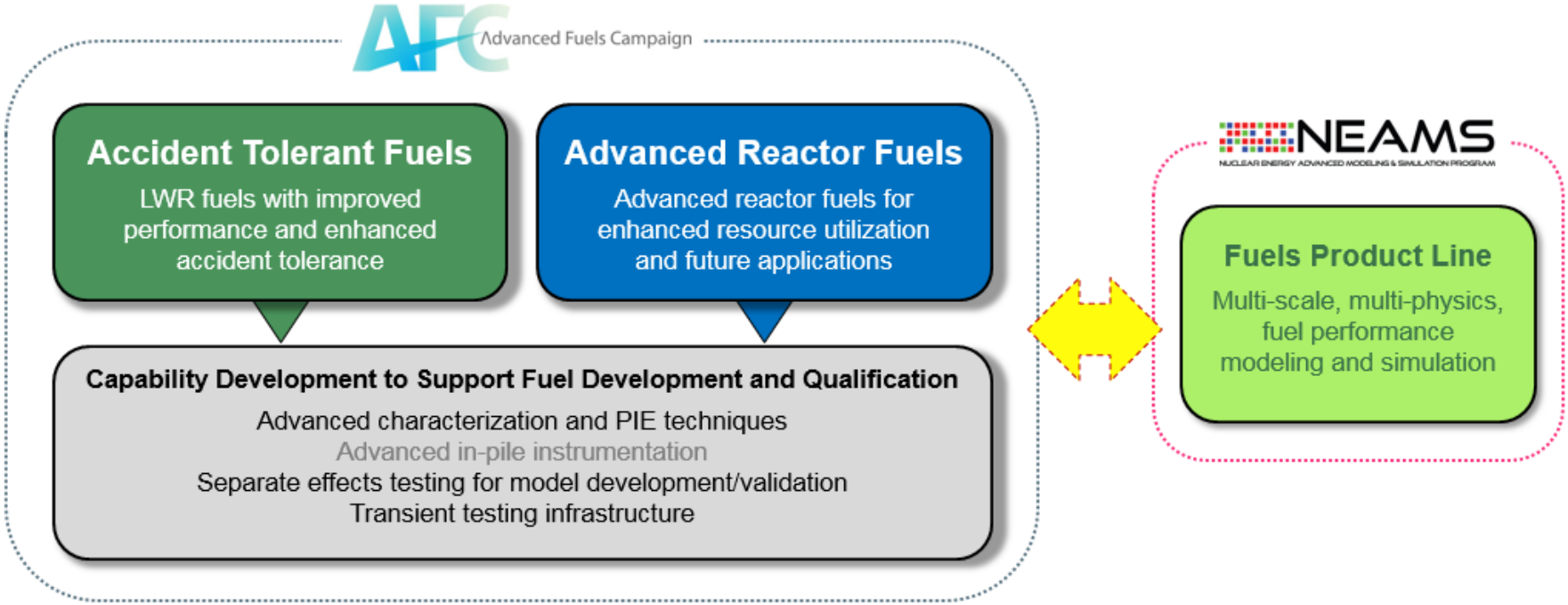
NTRD Advanced Fuels Campaign

- **Enhance the performance and safety of the USA current and future reactors**
- **Enhance proliferation resistance of nuclear fuel**
- **Effectively utilize nuclear energy resources**
- **Address the longer-term waste management challenges**



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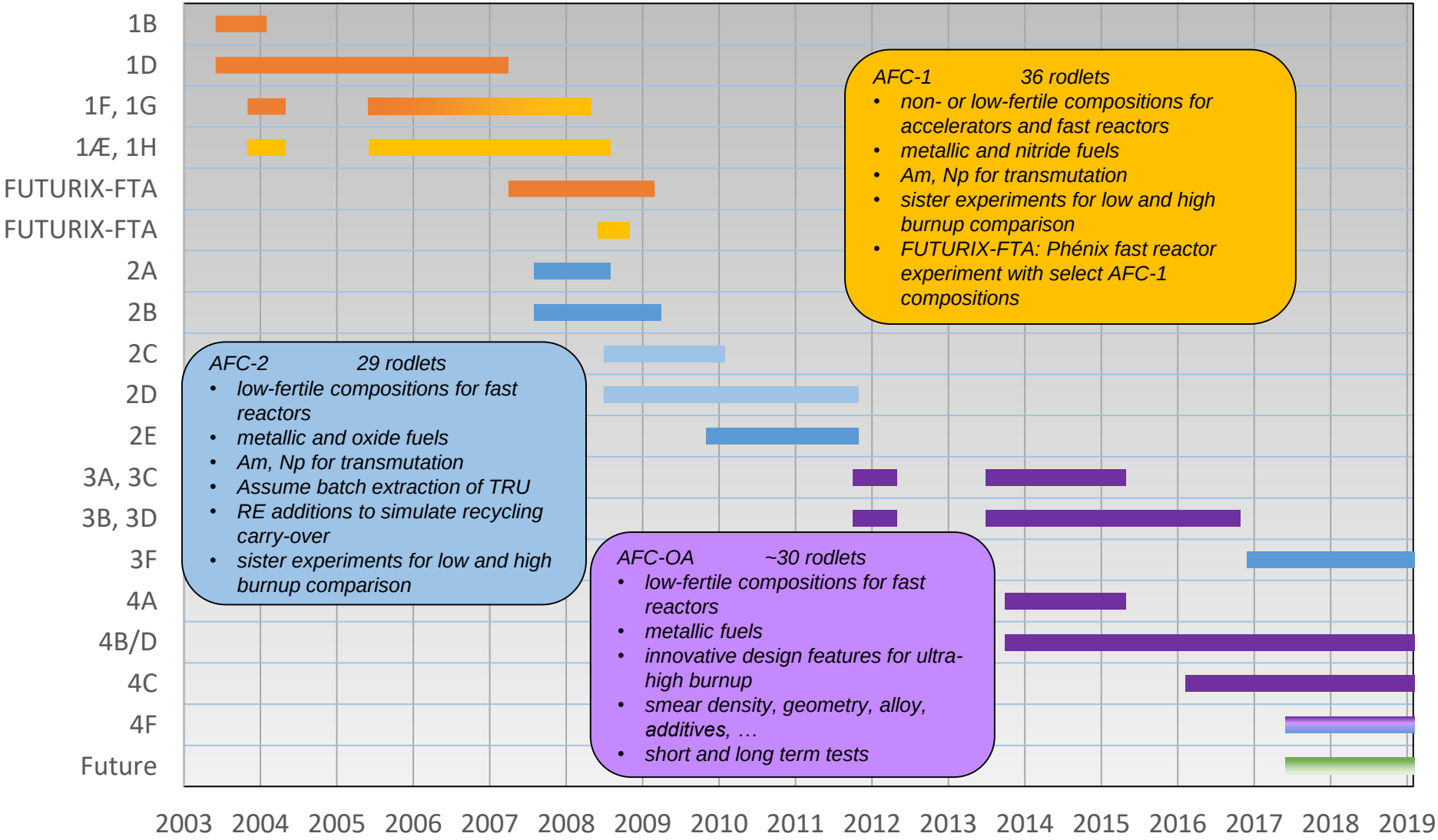
History of the AFC Irradiations



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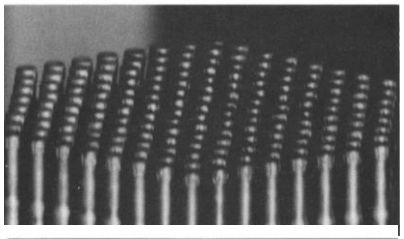
PIE Strategy –
Moving towards a mechanistic understanding of nuclear fuel performance

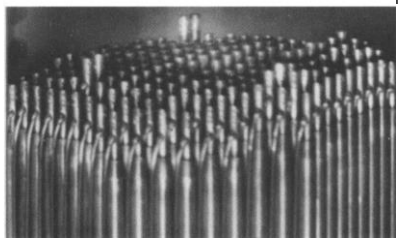
Scale of Exam	Macro			<1 µm
TOOLS	Visual Exams	Neutron Radiography Dimensional Exams	Gamma Spectrometry Fission Gas Release Optical Microscopy Chemistry Analysis	Electron Microscopy SEM, TEM, EPMA Focused Ion Beam Atom Probe
Fuel Performance	Did it Fail Catastrophically	How much did the geometry change	Fission Product Migration Microstructure, Restructuring, FCCI Burnup, Actinide Balance	Elemental distribution 3D microstructure
		Baseline		Beyond Baseline

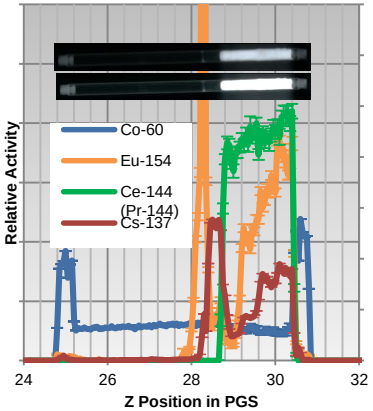
Number of Samples

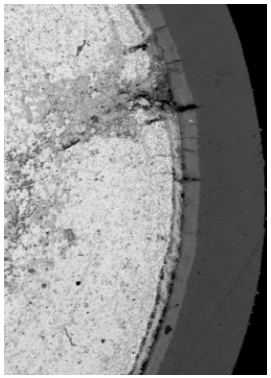
A few pins → Section pins → Select samples to EM → FIB Sample Preparation

The historic approach









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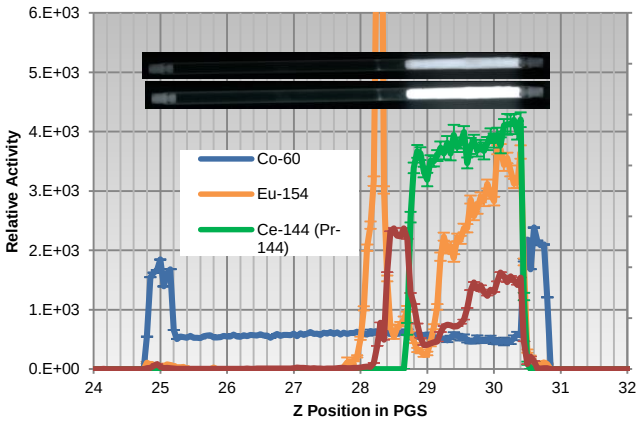
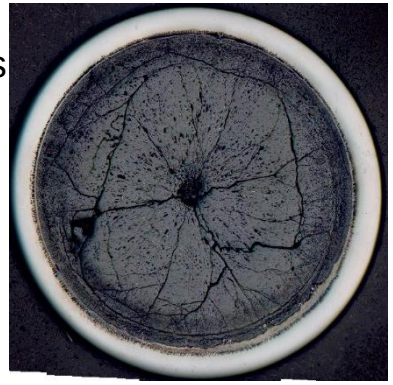
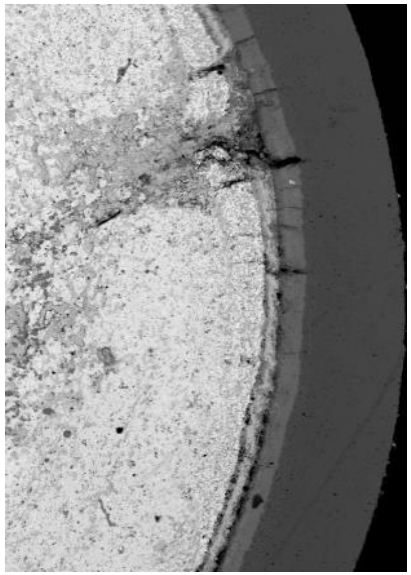
Available PIE

- **Baseline Nondestructive PIE**
  - visual
  - neutron radiography (thermal, epi-thermal)
  - gamma scan (axial isotopic data)
  - metrology (radial swelling)
- **Baseline Destructive PIE**
  - fission gas analysis
  - optical microscopy / metallography
  - microhardness
  - analytical chemistry / burnup analys
  - mechanical properties
- **Advanced PIE**
  - Microstructural analysis (SEM)
  - Microchemical analysis (EPMA, SEM)
  - Phase analysis (pending deployment)
  - Thermal properties (laser flash, TCM)
  - XRD, Micro XT
  - 3D Microstructure (FIB, PFIB)
  - Lower scales (TEM, APT)

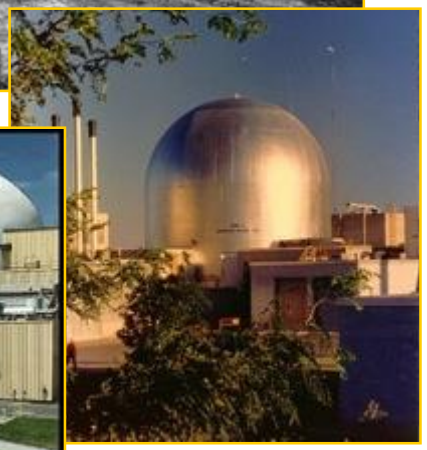


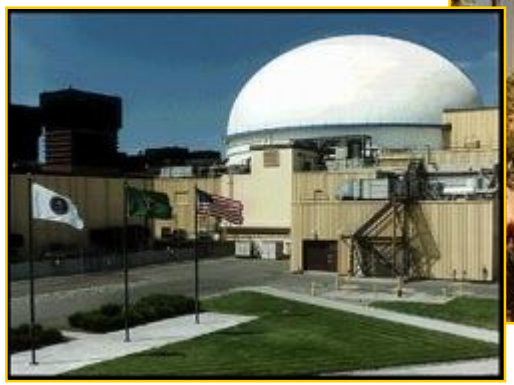




History of Metallic Fuels in Fast Reactors

- **EBR-I** (1951)
  - Unalloyed U
  - U-2Zr
  - Pu-1.25Al
- **UK Dounreay Fast Reactor** (1963)
  - U-0.1Cr
  - U-7Mo
  - U-9Mo
- **Enrico Fermi FBR** (1963)
  - U-10Mo
- **EBR-II** (1964)
  - U-5Fs
  - U-10Zr
  - U-20Pu-10Zr
- **FFTF** (1982)
  - Qualification of U-10Zr
  - Assembly testing of U-20Pu-10Zr





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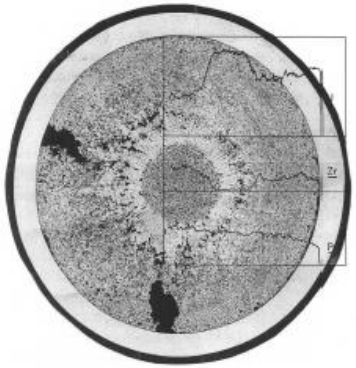
Key Features & benefits of Metallic Fuels

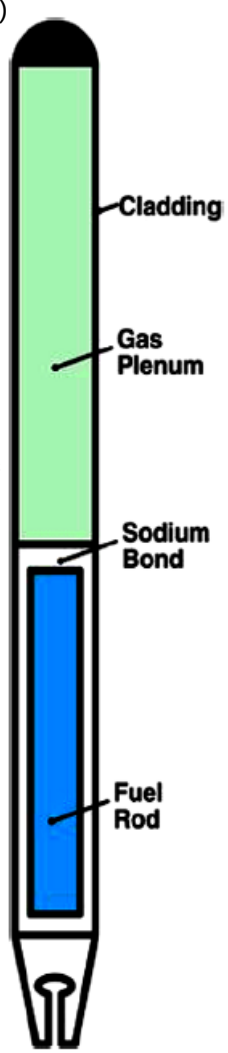
- **Historic benefits**
  - Higher breeding ratio (fissile and fertile)
  - Benign response to accident condition
  - Hard neutronic spectrum
  - Outstanding fuel reliability to high burnup (~20 at.%)
  - Compatibility with proliferation-resistant electrochemical recycle
  - Simple, compact (demonstrated remote) fabrication processes
  - Synergistic with passive approach to reactor safety

- **Metal fuel characteristics**
  - U-Pu-Zr alloy base (good irradiation stability)
  - 75% smeared density (accommodate fuel swelling, mitigate FCMI)
  - Large fission gas plenum (accommodate high gas release)
  - Na bond in fuel-cladding gap (keep fuel temperatures low)
  - Low-swelling FMS cladding (minimize cladding/duct dimensional changes)

Schematic of a metallic, Na bonded, fast reactor element
Carmack et al., J. Nucl. Mater. 392 (2009)



G.L Hofman and L. C. Walters, "Metallic Fast Reactor Fuels," Materials Science and Technology Vol. 10A, 1994.



Fast Reactor Fuel Performance Challenges & New Concepts

New concepts

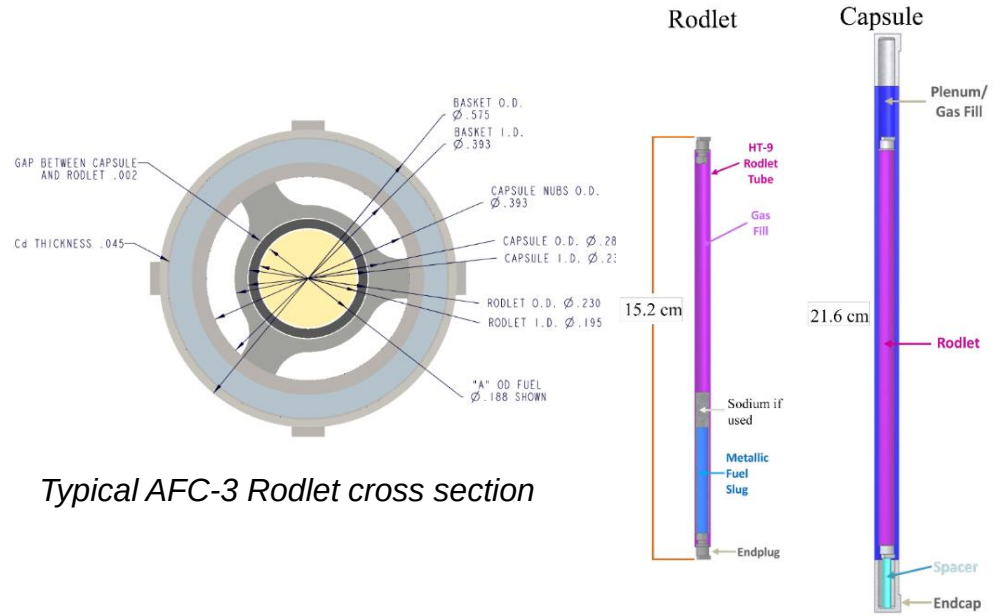
Historical Fuel Performance Issues

- Swelling - limited burnup to 3 at. %, Solved early in EBR-II testing with lowering Smeared Density to 75% to allow for interconnected porosity releasing fission gas, solid fission product build-up limits fuel to 15-20 at.% burnup → **Annular / low smear density**
- Alloying elements to raise the fuel melting temperature and tailor the phase of U or U+Pu in the fuel (Zr, Fs, Mo, Ti) → **New alloys**
- Fuel Cladding Chemical Interaction (FCCI) → **Additives**
  - *FCCI occurs at nominal operating conditions in U and U-Mo fuels and limits burnup to 10at. % (U-Fe, U-Ni interaction typically)*
  - *FCCI occurs at nominal operation conditions in U-Zr and U-Pu-Zr fuels beyond 10at.% burnup (Lanthanide – Fe interaction typically)*
- Fuel Constituent Redistribution – an effect of phase transitions → **New alloys**
  - *U, U-5Fs, and U-10Mo do not redistribute*
  - *U-10Zr does redistributes where Zr migrates to the center of the fuel*
  - *U-Pu-10Zr redistributes with Zr migrating to the central region and the periphery*

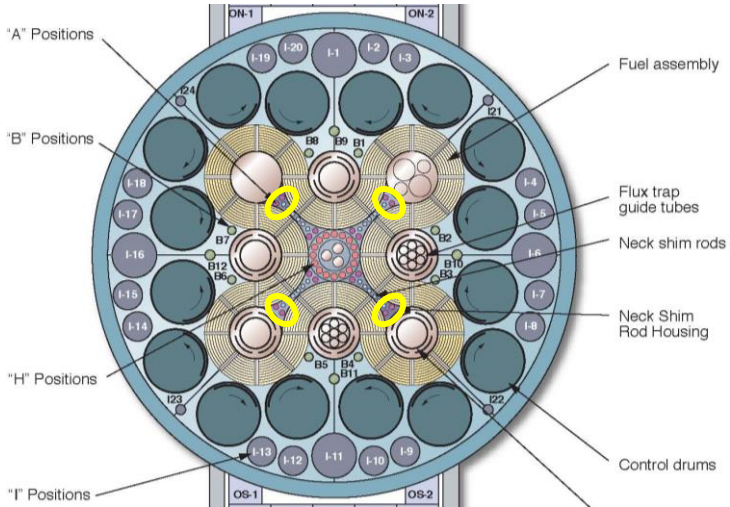
Fs – 49.8Mo-38Ru-6Rh-4Pd-2Zr-0.2Nb

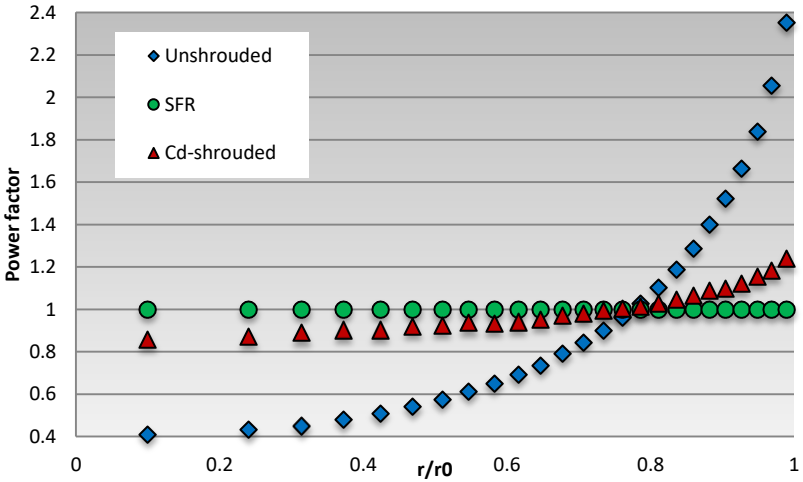
Fast Reactor Testing in ATR – Recent AFC tests

- **Testing Fast Reactor Fuels in a thermal reactor**
  - Rodlet – capsule – Cd basket system
  - Comparison between true fast spectrum vs ATR irradiations: proper temperature profile is created in ATR irradiations
  - This allows for the study of fuel performance phenomena that are primarily dependent upon temp. / temp. gradient



Typical AFC-3 Rodlet cross section





AFC-3 A/B/C/D and AFC-4A series

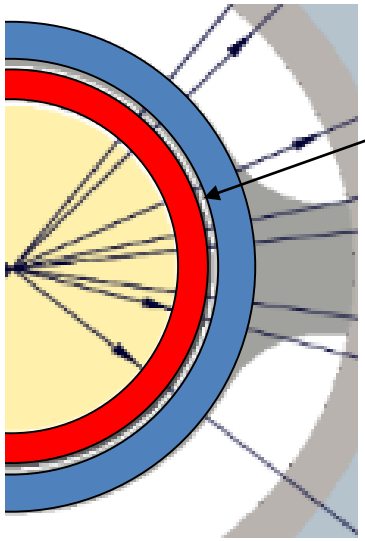
- **AFC-3A/B/C/D and AFC-4A is an alloy exploration test**
  - Alternate alloys and forms to U-10Zr, Sodium Bonded, 75% SD
  - Pd additive to mitigate FCCI
  - Annular Forms to eliminate Na treatment issues
- **Meant to test early alloy performance against the historical experience**
- **Irradiation Issues**
  - Capsule Fabrication 3A/B
  - Reactor Uncertainty

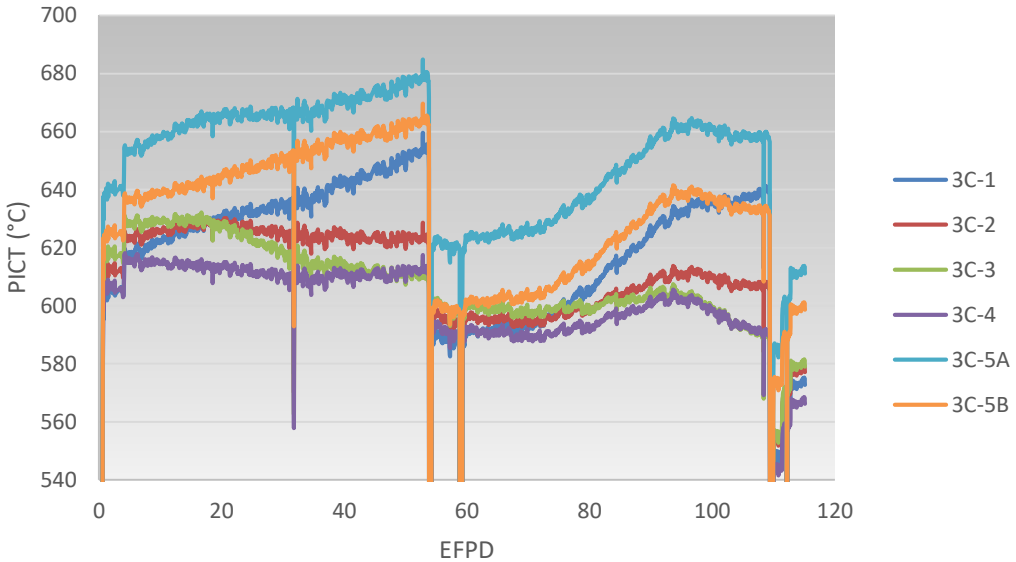
Rodlet ID	Alloy	Fuel Form	Bond Material	Nominal Smear Density
3A-R1	U-10Mo	Solid	Sodium	75%
3A-R2	U-10Mo	Annular	Helium	55%
3A-R4	U-10Zr	Annular	Helium	55%
3A-R5A	U-1Pd-10Zr	Solid	Sodium	75%
3A-R5B	U-2Pd-10Zr	Solid	Sodium	75%
3B-R1	U-4Pd-10Zr	Solid	Sodium	55%
3B-R2	U-4Pd-10Zr	Annular	Helium	55%
3B-R4	U-10Mo	Solid	Sodium	55%
3B-R5	U-10Mo	Solid	Sodium	55%

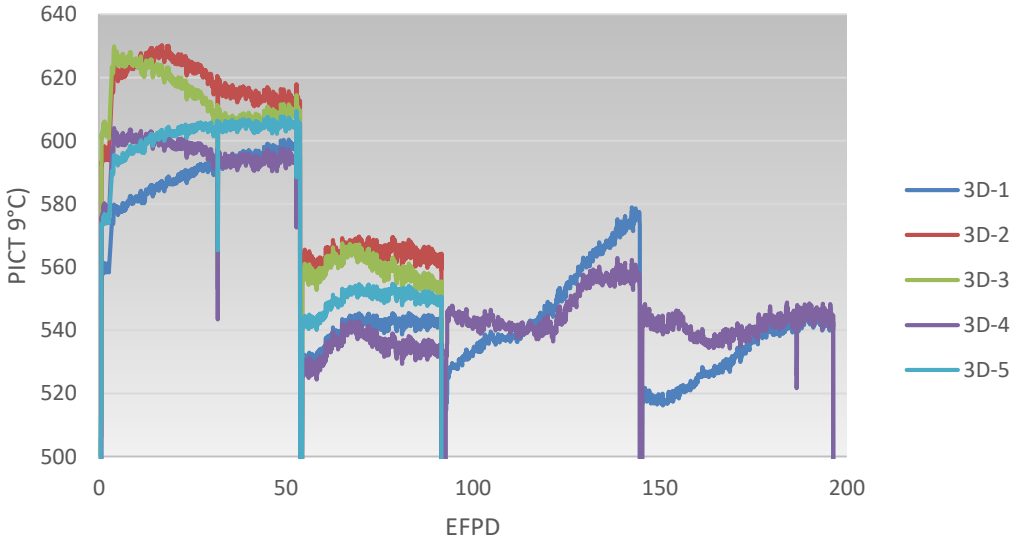
Rodlet ID	Alloy	Fuel Form	Bond Material	Nominal Smear Density
3C-R1	U-10Mo	Solid	Sodium	75%
3C-R2	U-10Mo	Annular	Helium	55%
3C-R3	U-10Zr	Sodium	Solid	65%
3C-R4	U-10Zr	Annular	Helium	55%
3C-R5A	U-1Pd-13Zr	Solid	Sodium	75%
3C-R5B	U-2Pd-13Zr	Solid	Sodium	75%
3D-R1	U-10Zr	Annular	Helium	55%
3D-R2	U-4Pd-13Zr	Solid	Sodium	55%
3D-R3	U-10Mo	Solid	Sodium	55%
3D-R4	U-10Mo	Annular	Helium	55%
3D-R5	U-4Pd-13Zr	Annular	Helium	55%
4A-R1	U-10Mo	Annular	Helium	65%
4A-R3	U-5Mo-4.3Ti-0.7Zr	Solid	Sodium	75%
4A-R4	U-5Mo-4.3Ti-0.7Zr-2Pd	Solid	Sodium	75%
4A-R5	U-10Zr	Solid	Sodium	75%

AFC-3C/3D –Irradiation History

- **AFC-3C had irradiation temperature**
  - Peak Inner Cladding Temperature (PICT) exceeded 600°C for 3 or 4 rodlets
  - PICT in R1 and R5 likely exceeded 650°C
  - Experiment removed from ATR early after 3 cycles
- **AFC-3D had reasonable PICT temperatures and appears to have better performance**







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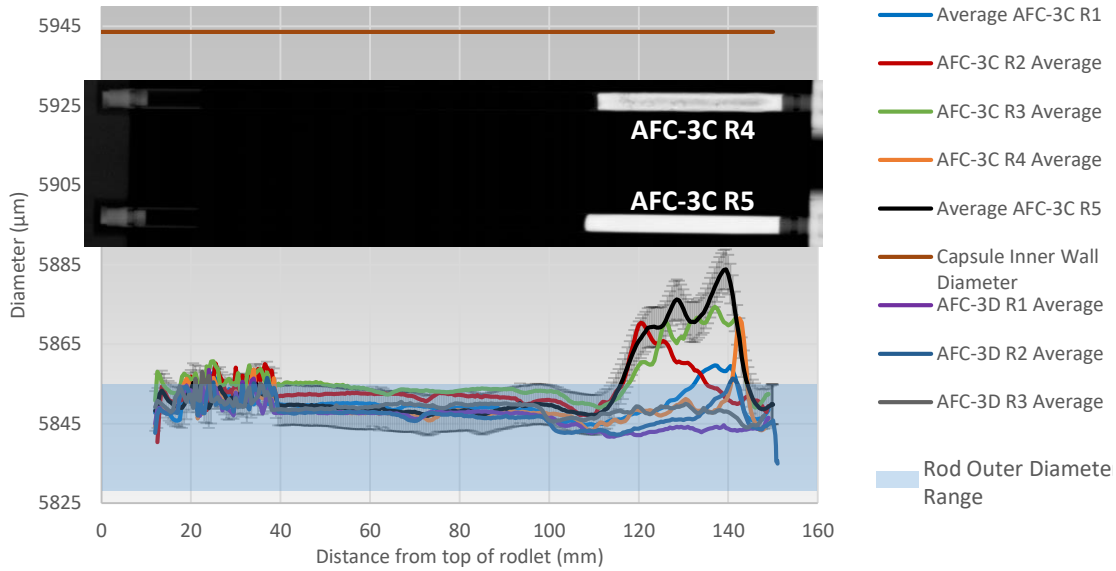
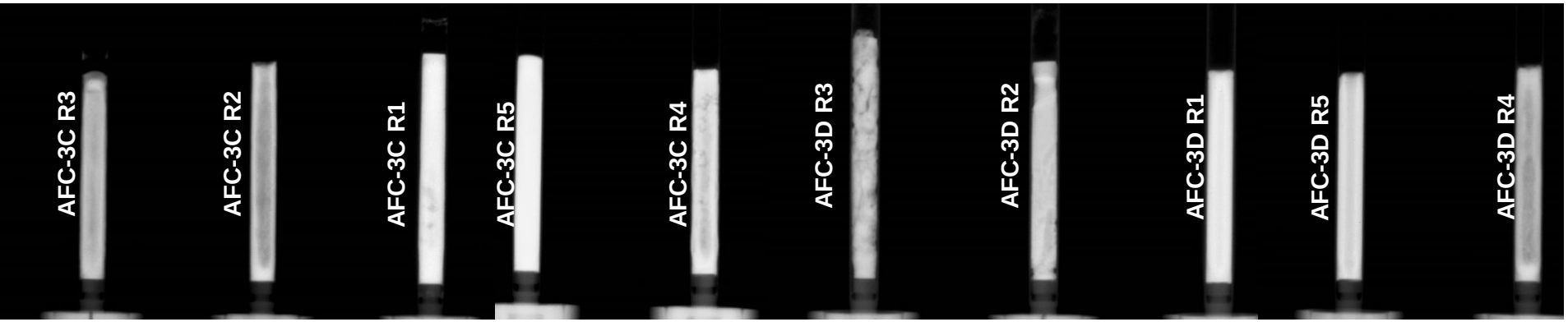
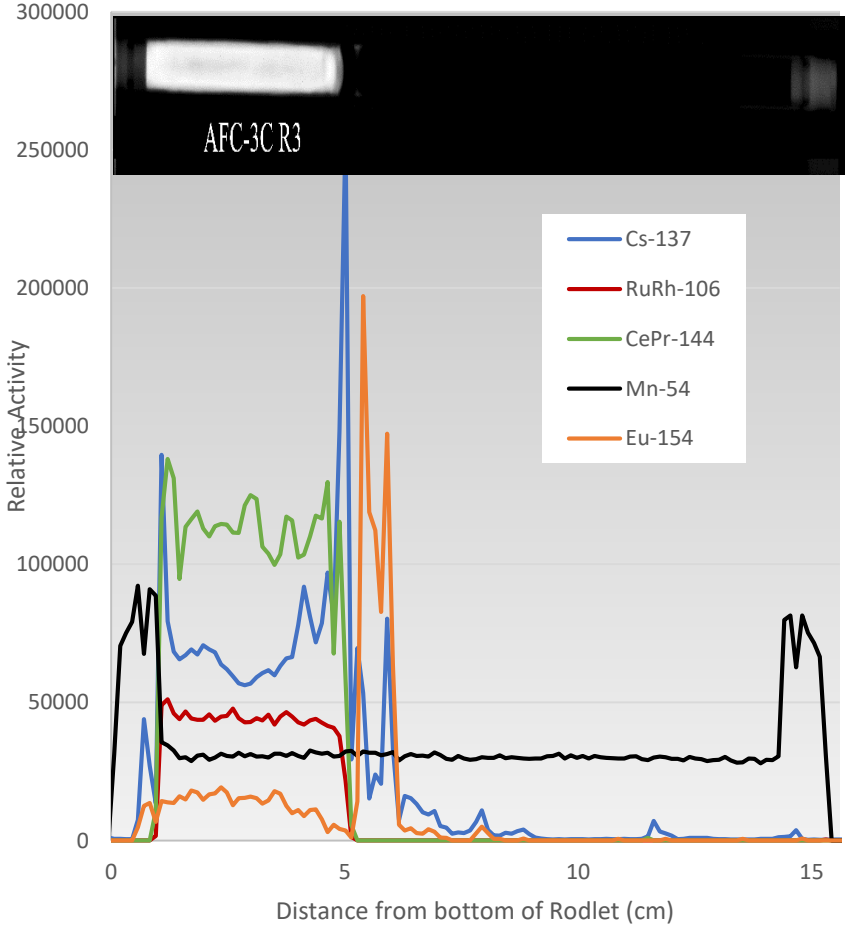
AFC-3C/3D – NDE highlights

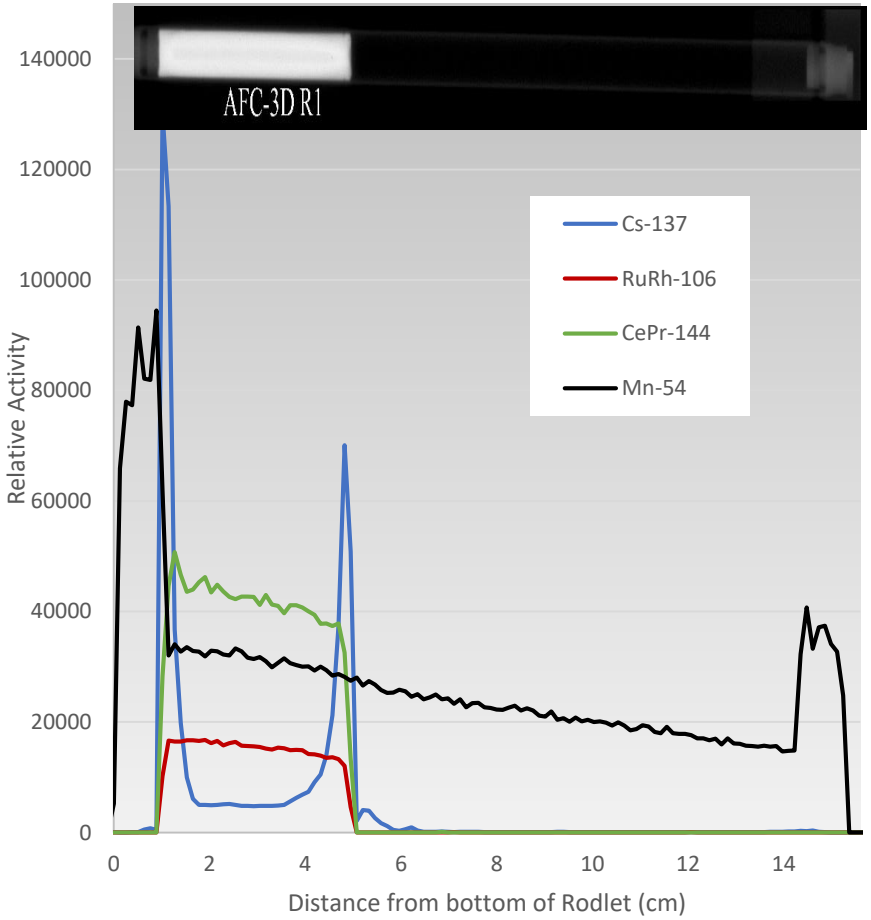
- **Profilometry**
  - AFC-3C presents some degree of diametrical strain (max 0.7% strain)
  - AFC-3D no measurable change in diameter
- **Thermal neutron radiography**
  - Annular fuel pins (e.g. 3C-R4) maintained their annuli
  - Visible change in grey scales shows variation in density





AFC 3C/D - Fission Product Distribution





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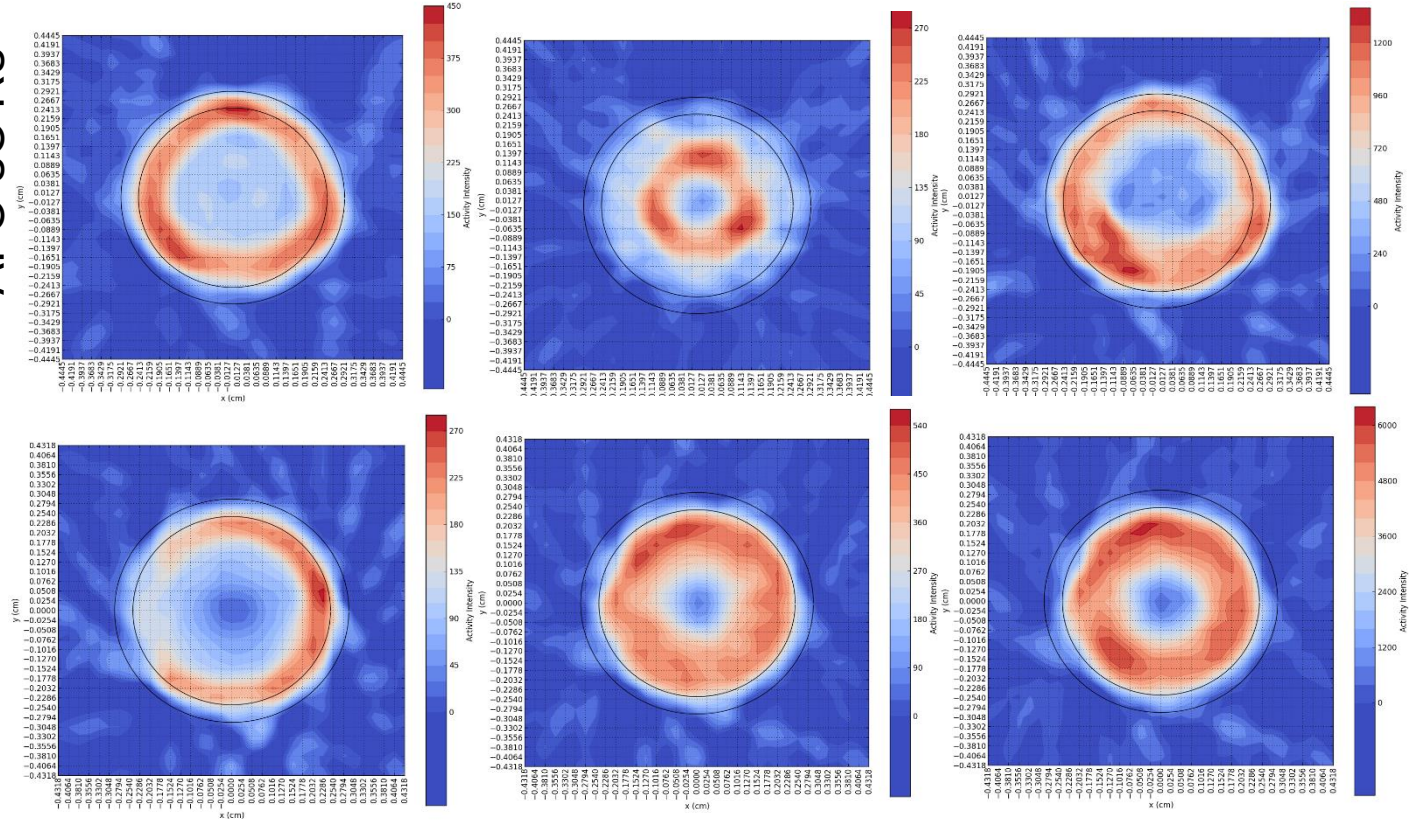
AFC 3C/D - Fission Product Distribution

- **Gamma Emission Tomography reveals the transverse distribution of fission products**
- **Signals exist for most major types of fission products**

Cs-137 | Ru-106 | CePr-144

AFC-3C R3

AFC-D R1



U-10Zr 65% SD, solid

U-10Zr 55% SD, annular

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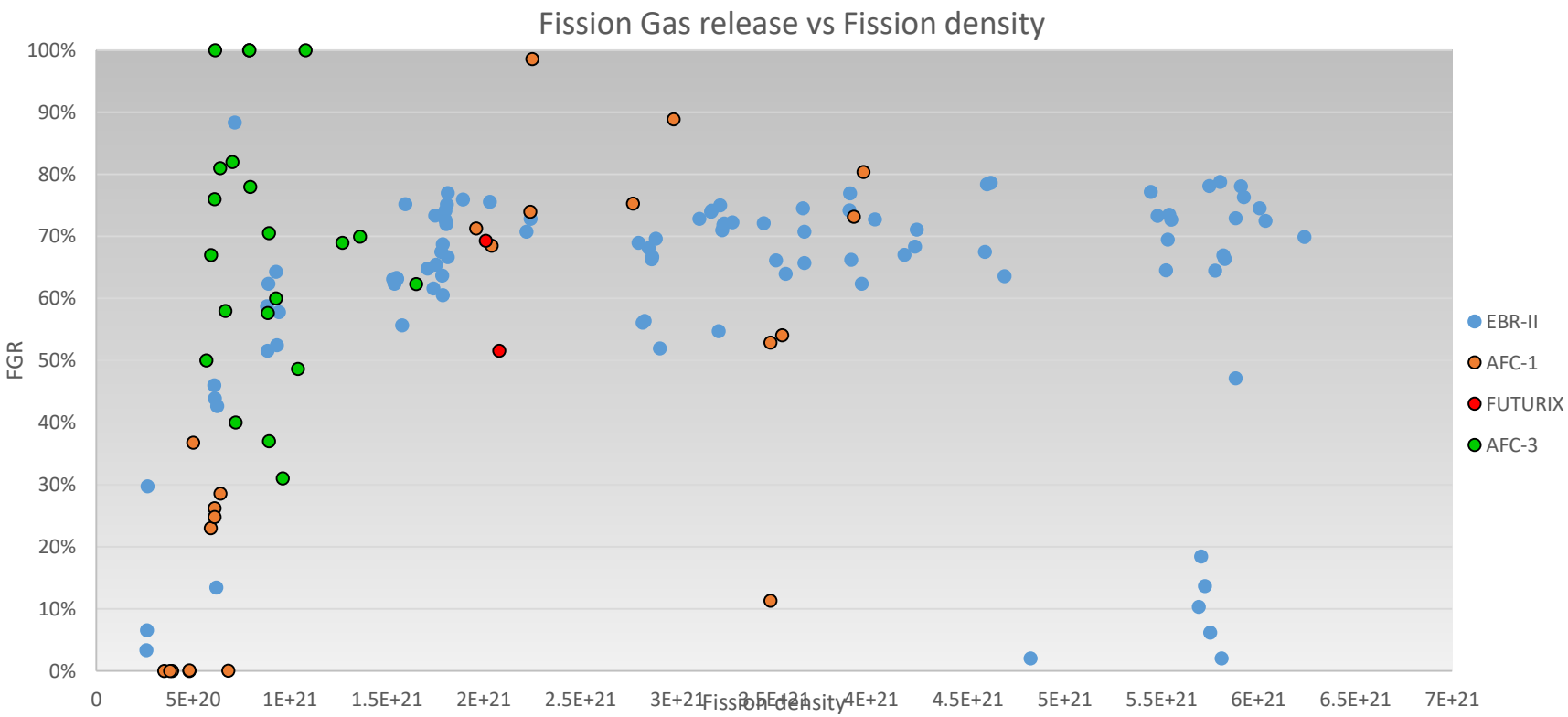
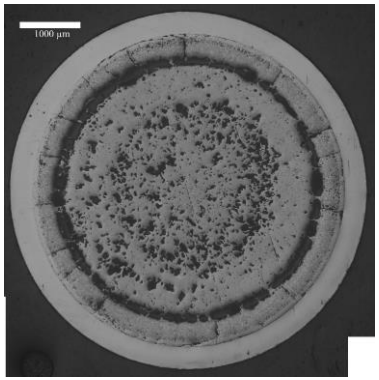
Fission Gas Release



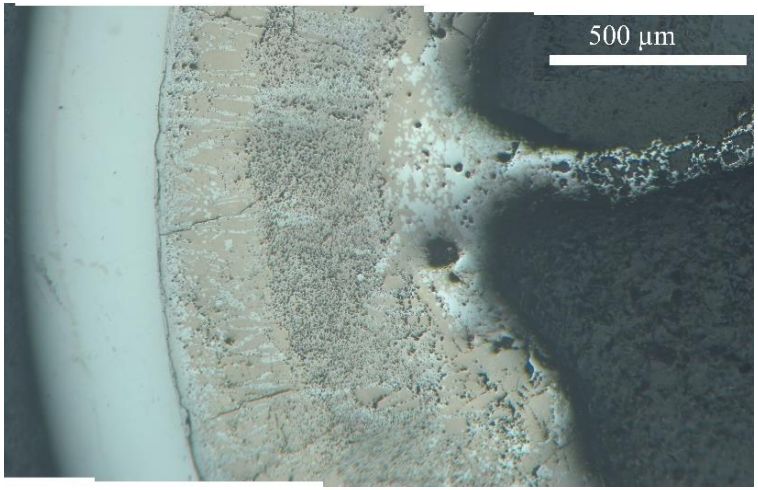
- **The EBR-II data suggests that FGR is 70±10% after 1.5x10^{21} fiss/cc (~4 at.%)**
- **Other AFC tests and transmutation fuel (FUTURIX) tests also follow this general trend**
- **The AFC-3 tests often also follow this trend**
  - There is some evidence that low smear density, annular fuel, and U-Mo fuel release fission gas earlier

AFC 3C / 3D U-Mo Metallography



AFC-3C R1 (U-10Mo, 75% SD, solid, Na, 2.3%FIMA, 650° C)

AFC-3C R2 (U-10Mo, 55% SD, annular, He, 3.3%FIMA, 625° C)



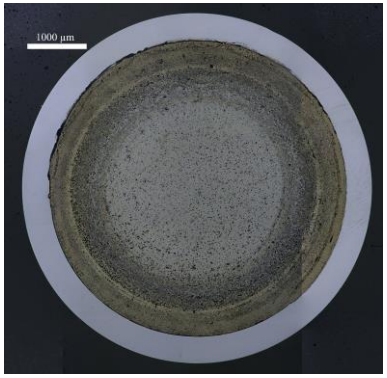
AFC-3D R3 (U-10Mo, 55% SD, solid, Na, 2.1%FIMA , 625° C)

AFC-3D R4 (U-10Mo, 55% SD, annular, He, **4.5%**FIMA, 600° C)

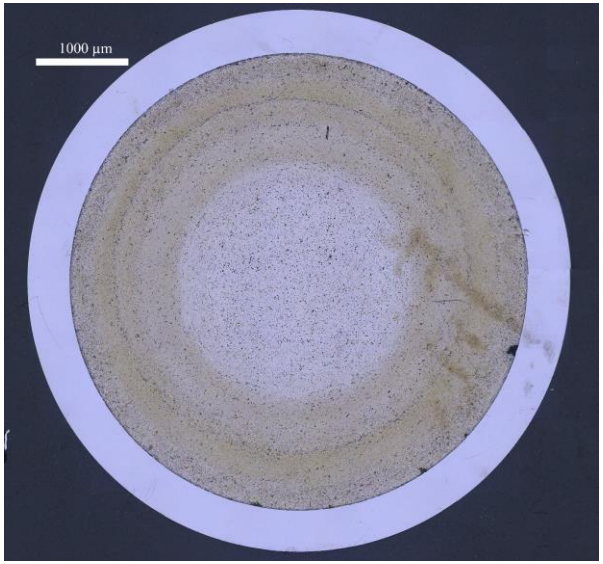
AFC 3C / 3D U-Zr solid Metallography

AFC-3C R3 (U-10Zr, **65% SD**, solid, Na, 2.9%FIMA, 630° C)

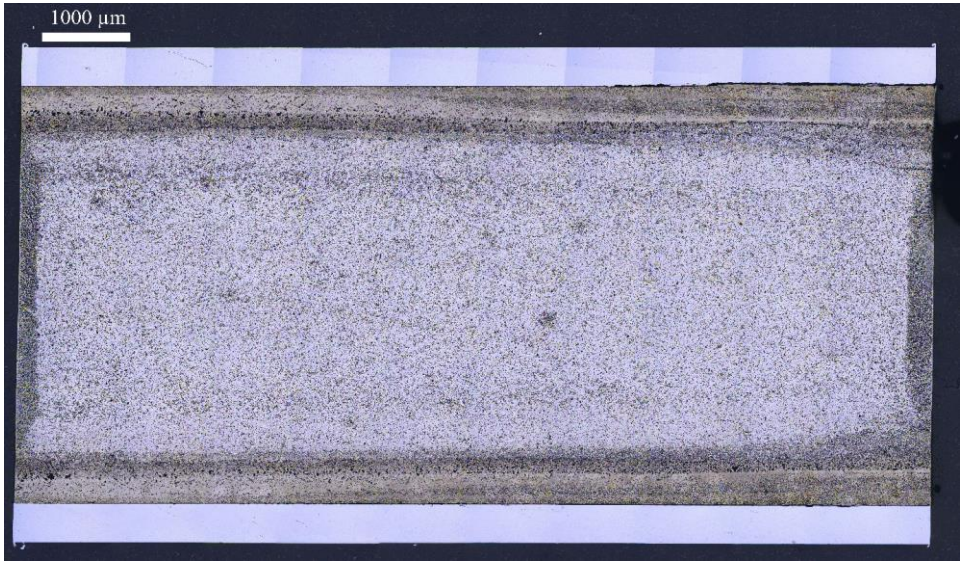
AFC-3D R2 (U-4Pd-13Zr, 55% SD, solid, Na, 2.8%FIMA, 630° C)



AFC-3C R5A (U-1Pd-13Zr, 75% SD, solid, Na, 2.6%FIMA, 680° C)



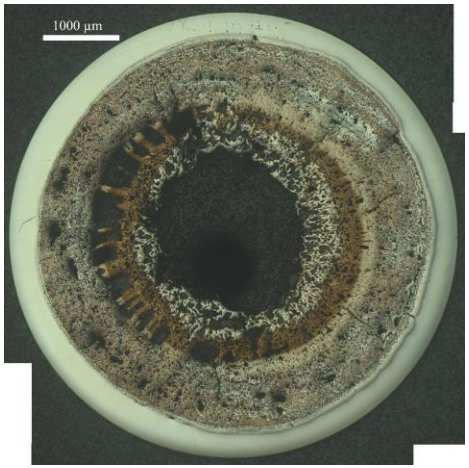
AFC-3C R5B (U-2Pd-13Zr, 75% SD, solid, Na, 2.6%FIMA, 660° C)



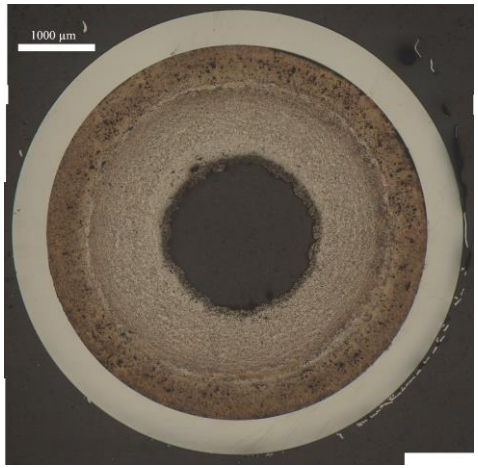
Fuel Mid-plane

Fuel Top

AFC 3C / 3D U-Zr annular Metallography

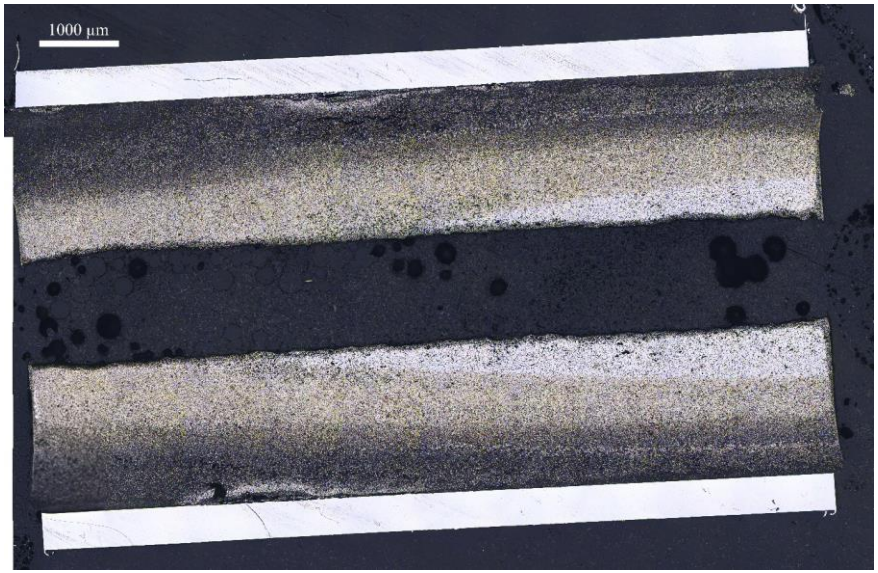


AFC-3C R4 (U-10Zr, 55% SD, annular, He, 3.0%FIMA, 620° C)



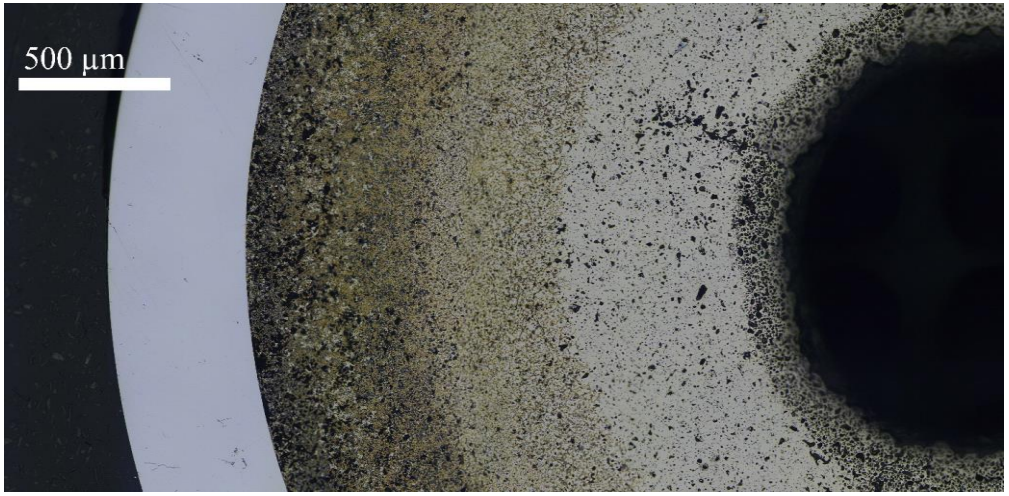
AFC-3D R5 (U-4Pd-13Zr, 55% SD, annular, He, 2.9%FIMA, 610° C)

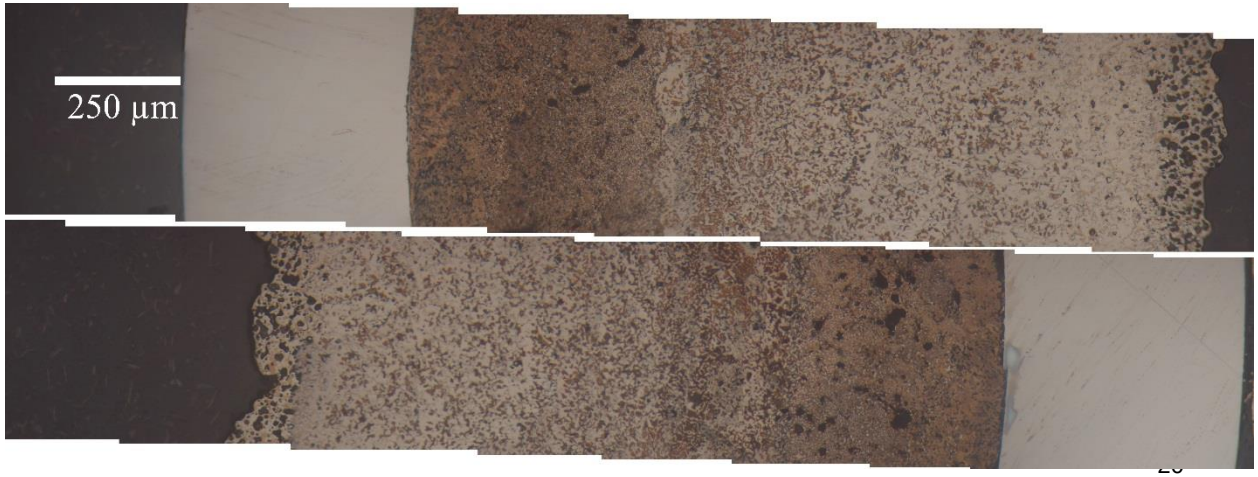
AFC-3D R1 (U-10Zr, 55% SD, annular, He, **4.3**%FIMA, 600° C)



AFC 3C / 3D U-Zr annular Metallography

- **Two of the Annular U-Zr variants performed exceptionally well**
- **Two contributing factors**
  - Appropriate PICT at all times during irradiation
  - Well machined fuel slugs

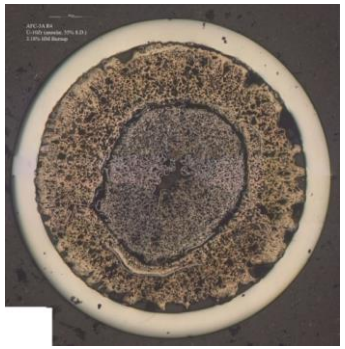




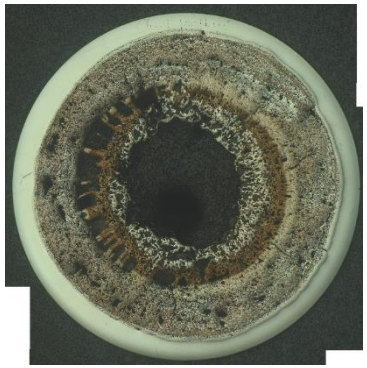
U-10Zr prelim. comparison between AFC-series

U-10Zr, annular, 55% sd

AFC-3A R4*



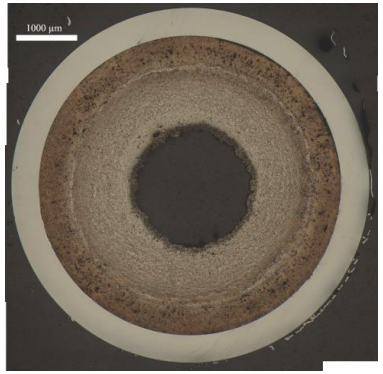
AFC-3C



AFC-3D

U-4Pd-10/13Zr, annular, 55% sd

AFC-3B R2*



- **U-10Zr annular: AFC-3D behaves better compare to -3A-3C**
  - Machining, gap ~50µm AFC-3A R4 vs 17µm AFC-3C R4 → 177ºC vs 60ºC
  - Periphery temperature maintained below the critical temperature for Zr migration (Beta phase)

*AFC-3A: U-10Zr, bu 3.2 at.%, PICT 530°C / U-1/2Pd-10Zr, bu 2.5 at.%, PICT 585°C

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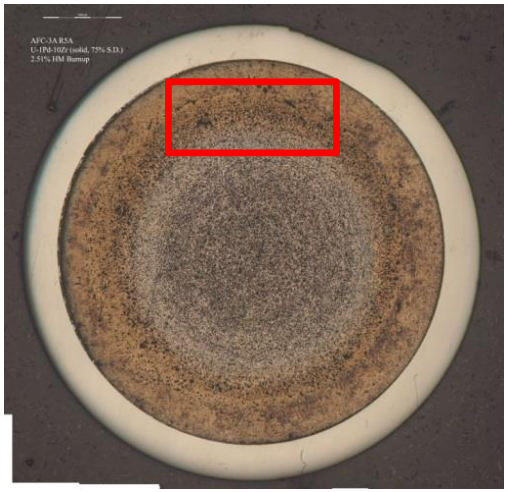
SEM preliminary results

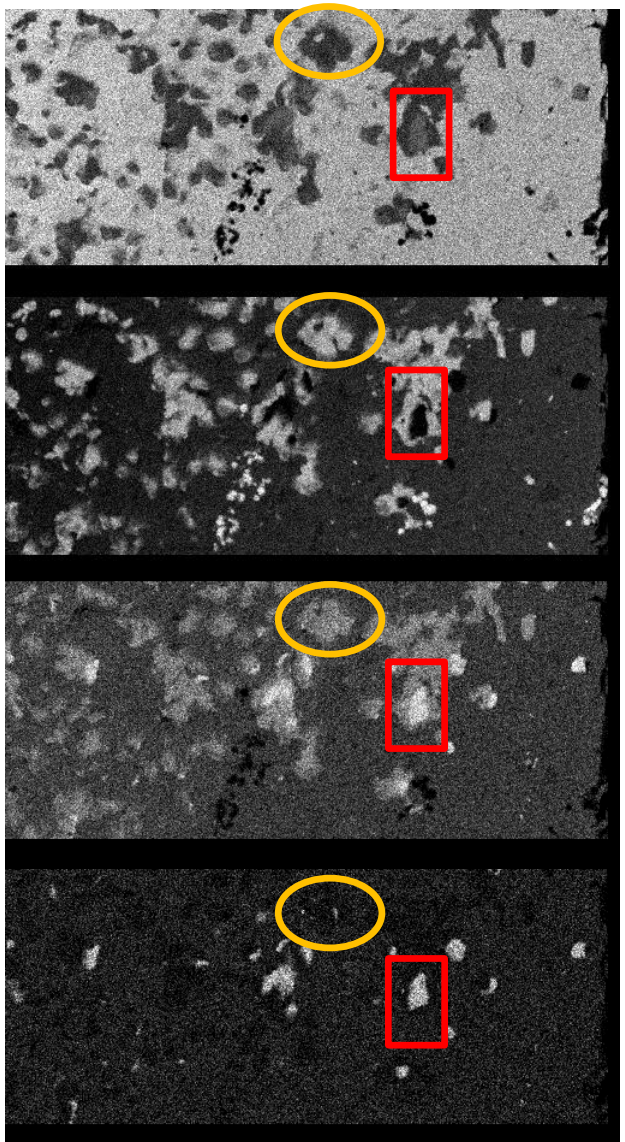
- **AFC-3A/B/C/D electron microscopy examination**
  - Challenges to prepare samples (high dose)
  - A more quantitative understanding of the different phases and feature is required
    - *New additives work?*
    - *FCCI*
    - *Temp / gap effect*

Rodlet ID	Alloy	Fuel Form	Bond Material	Nominal Smear Density
3A-R1	U-10Mo	Solid	Sodium	75%
3A-R2	U-10Mo	Annular	Helium	55%
3A-R4	U-10Zr	Annular	Helium	55%
3A-R5A	U-1Pd-10Zr	Solid	Sodium	75%
3A-R5B	U-2Pd-10Zr	Solid	Sodium	75%
3B-R1	U-4Pd-10Zr	Solid	Sodium	55%
3B-R2	U-4Pd-10Zr	Annular	Helium	55%
3B-R4	U-10Mo	Solid	Sodium	55%
3B-R5	U-10Mo	Solid	Sodium	55%

Rodlet ID	Alloy	Fuel Form	Bond Material	Nominal Smear Density
3C-R1	U-10Mo	Solid	Sodium	75%
3C-R2	U-10Mo	Annular	Helium	55%
3C-R3	U-10Zr	Sodium	Solid	65%
3C-R4	U-10Zr	Annular	Helium	55%
3C-R5A	U-1Pd-13Zr	Solid	Sodium	75%
3C-R5B	U-2Pd-13Zr	Solid	Sodium	75%
3D-R1	U-10Zr	Annular	Helium	55%
3D-R2	U-4Pd-13Zr	Solid	Sodium	55%
3D-R3	U-10Mo	Solid	Sodium	55%
3D-R4	U-10Mo	Annular	Helium	55%
3D-R5	U-4Pd-13Zr	Annular	Helium	55%

AFC-3A R5 SEM (U-2Pd-10Zr) – Alloying Element Behavior





- **The behavior of Zr and Pd are important for this fuel to well perform**
  - Zr needs to stayed alloyed with U for fuel performance
  - Zr and Pd intermetallics need to be avoided
  - Pd needs to form intermetallics with Lanthanides (LnPd and Ln_7Pd_3)
  - Alloy addition steps are important

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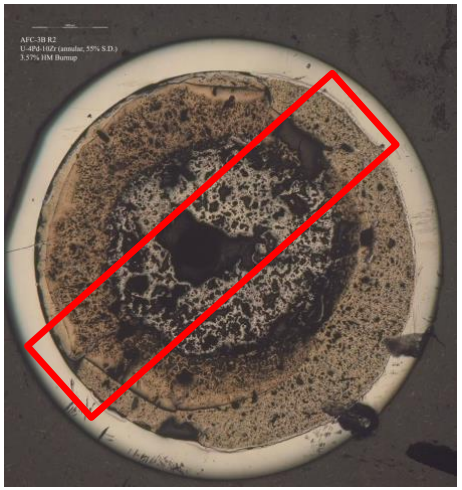
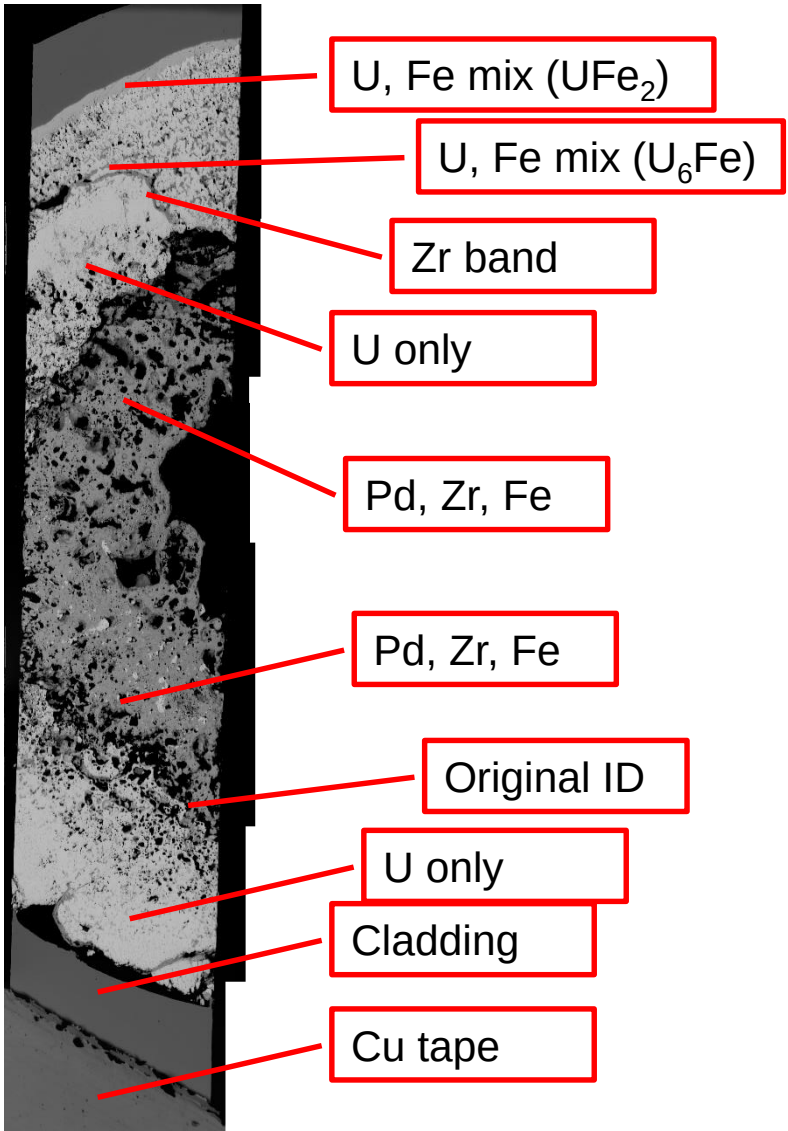
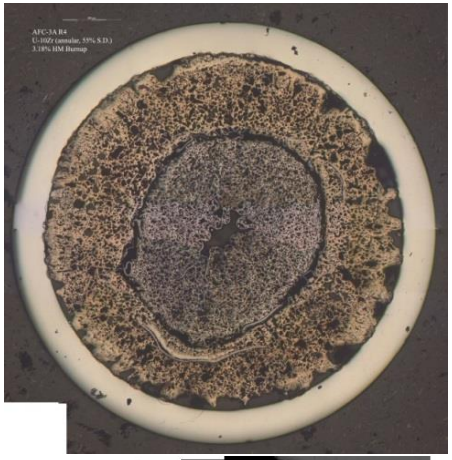
AFC-3B R2 SEM (U-4Pd-10Zr) – FCCI – Alloying behavior

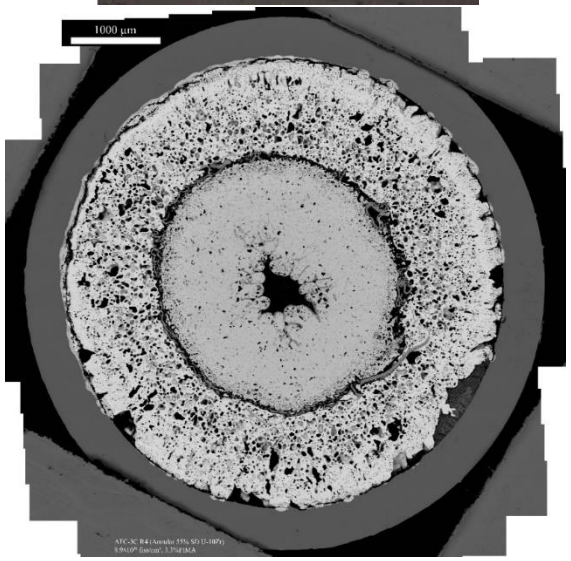


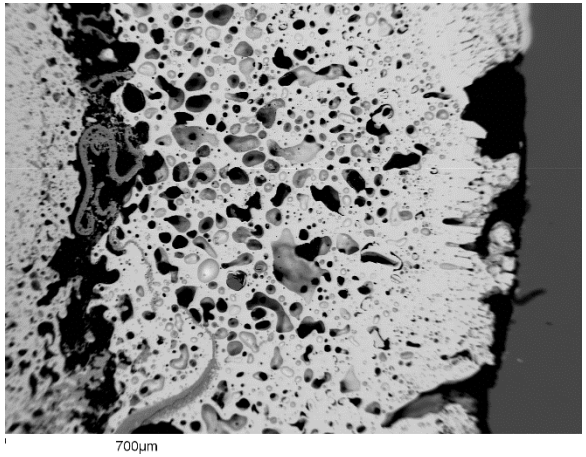
- **FCCI occurred in this sample similar to the same levels observed in U-Mo**
- **Too much Pd can be detrimental to fuel performance**
  - Pd and Zr will form high temperature intermetallics leaving U unalloyed ($PdZr_2$)
  - Pd alloying addition order can significantly change as-cast intermetallic behavior (understood after this irradiation was fabricated)
- **Cast annular fuel without a Na bond is susceptible to local overheating**



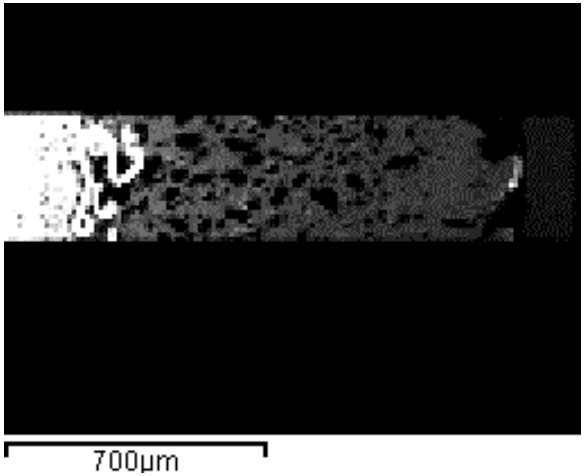
AFC-3A R4 SEM (U-10Zr annular) – FCCI - Helium gap effect



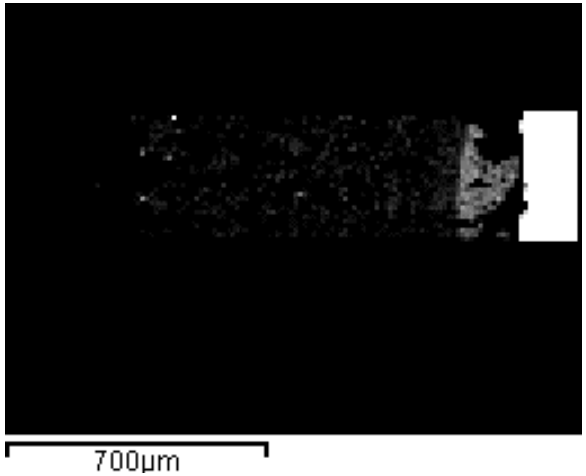




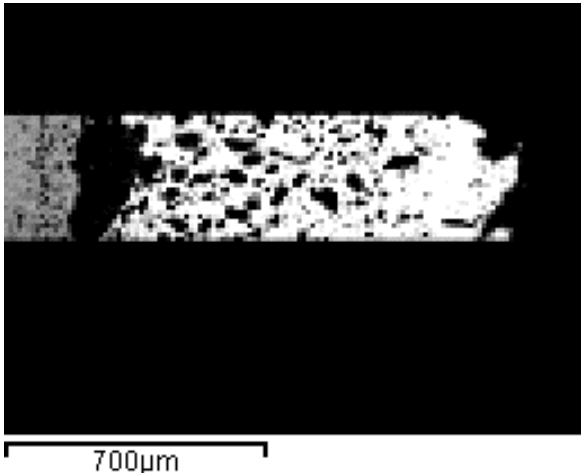
BSE



Zr



Fe



U

AFC-3A R4 (U-10Zr, 55% SD, annular, He, 3.3%FIMA, 540-600+° C)

Summary & Prospective

- **Advanced metallic fuel form**
  - Raise from the needs to elevate utilization and reach higher burnup
  - Improve historical issue of metallic fuel
- **AFC-3 and -4 experiments**
  - Alloys exploration test (annular, alternative alloys, additives)
  - Some promising design and value data are examined for the first time
  - U-Mo performance are quite below U-Zr
  - Annual fuel (well machined) and Pd additives fuel form are somehow promosing
- **Future and Prospective**
  - Extended examination are needed (also supported by modelling and simulation)
  - Extended burnup / experiment on some promising fuel form are needed
  - Safety / transient test on promising fuel from are the natural next step

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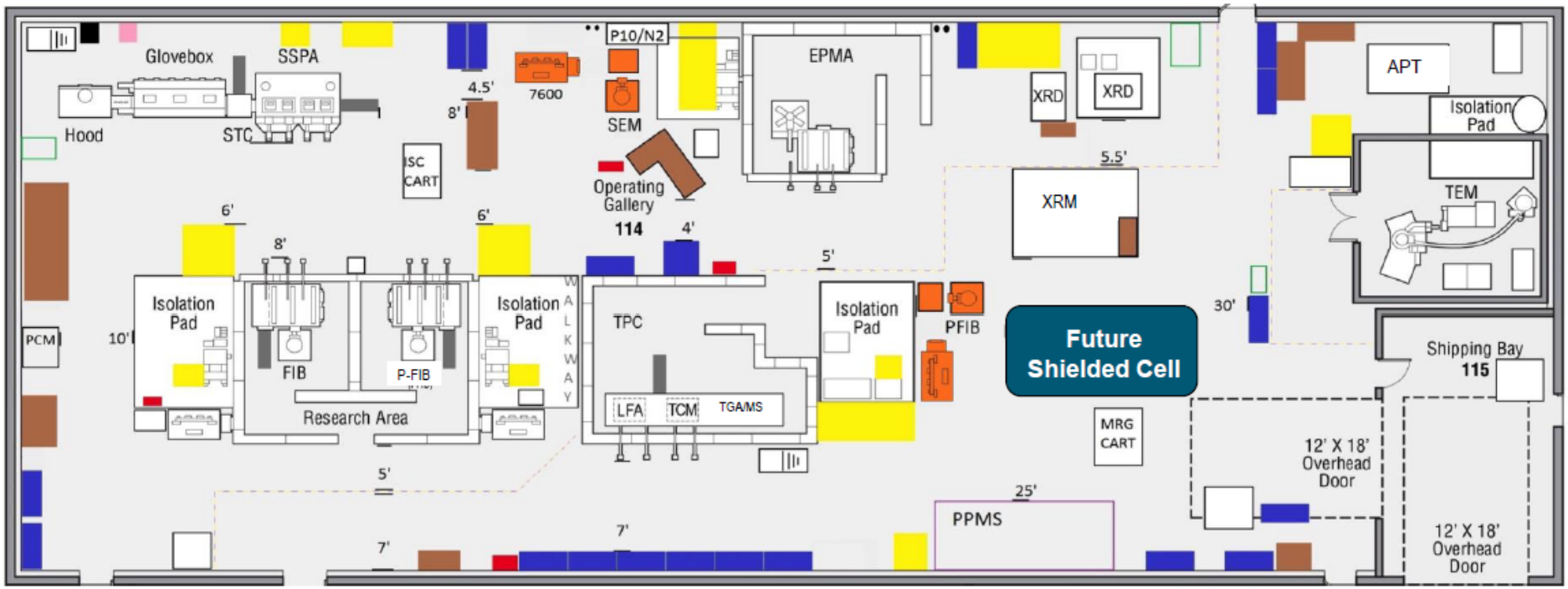
Irradiated Material Characterization Laboratory (2019-2020)



SSPA – Shielded Sample Preparation Area
SEM – Scanning Electron Microscope
TCM – Thermal Conductivity Microscope
EPMA – Electron Probe MicroAnalyzer
XRD – X-Ray Diffraction

TGA/MS – Thermogravimetric Analyzer/ Mass-Spectrometer
APT – Atom Probe Tomography
FIB – Focused Ion Beam
XRM – X-Ray Microscope

P-FIB – Plasma Focused Ion Beam
TEM – Transmission Electron Microscope
PPMS – Physical Property Measurement System
LFA – Laser Flash Analyzer

Come work with us!

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