INL/MIS-23-72927-Revision-0

Neutron Imaging of Transient Irradiated Nuclear Fuels

June 2023

Changing the World's Energy Future

Jason L Schulthess

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Neutron Imaging of Transient Irradiated Nuclear Fuels

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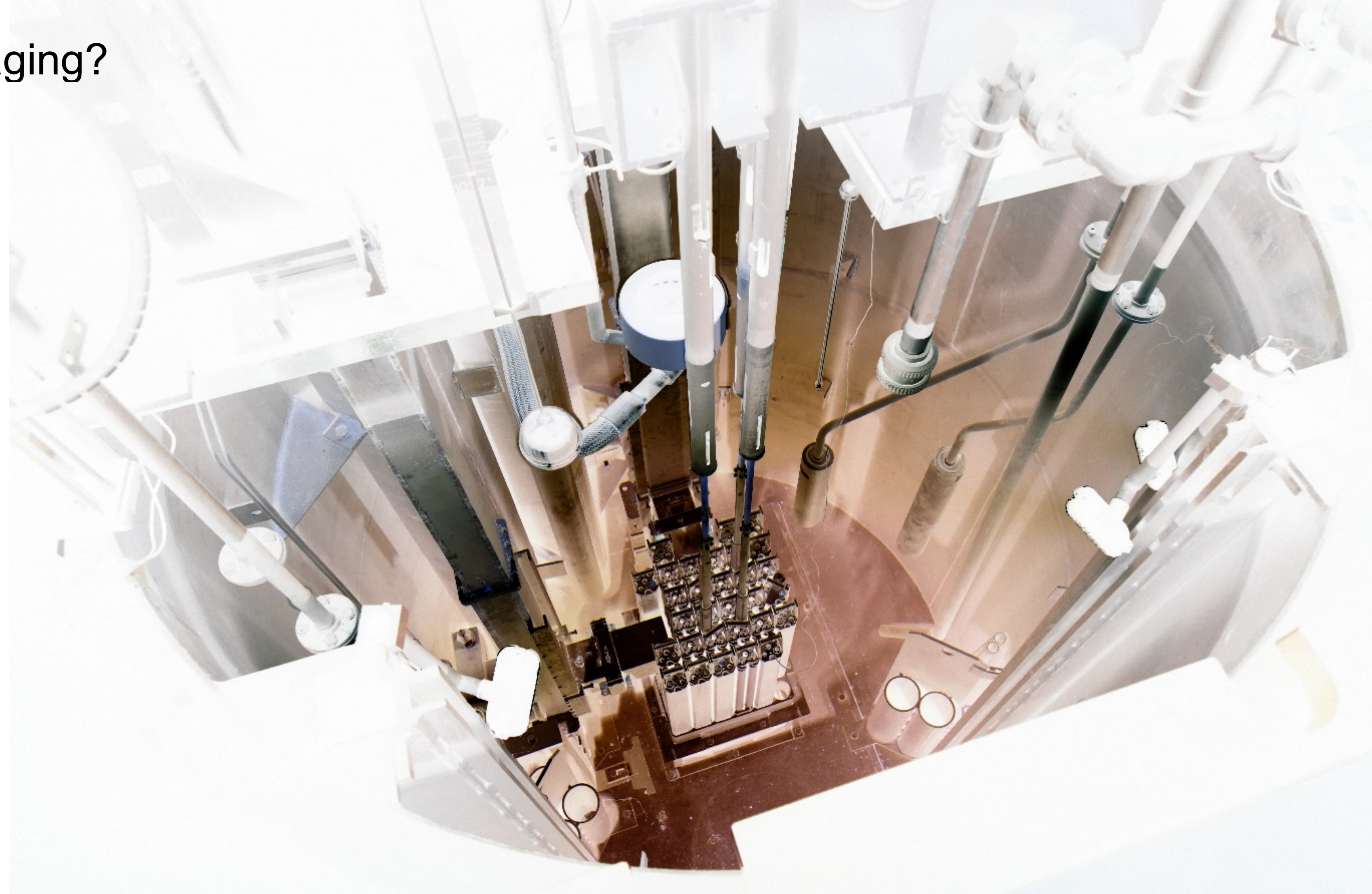
Neutron Imaging of Transient Irradiated Nuclear Fuels

Idaho National Laboratory

Outline

- Transient Testing
- Why do we need neutron imaging?
- Restart of TREAT
- Experimental Outlook
- New examples of digital nCT
  - SETH-D
  - SETH-E
  - Sirius-1
  - THOR-C2



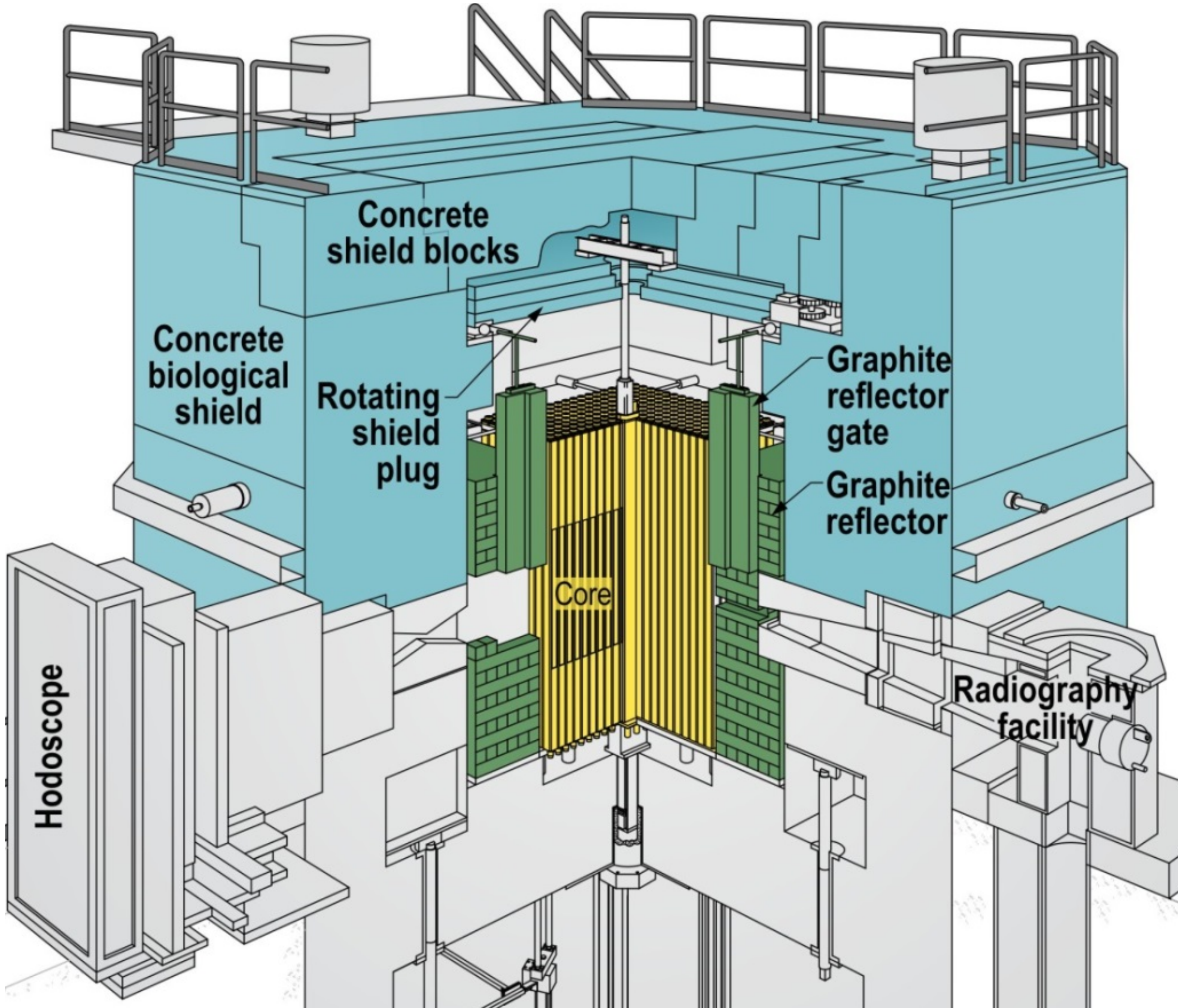
Transient Testing

- Determine safety limits prior to implementation.
- Crash testing a car
- Determine performance in off-normal conditions:
  - Rollover accident, impacts

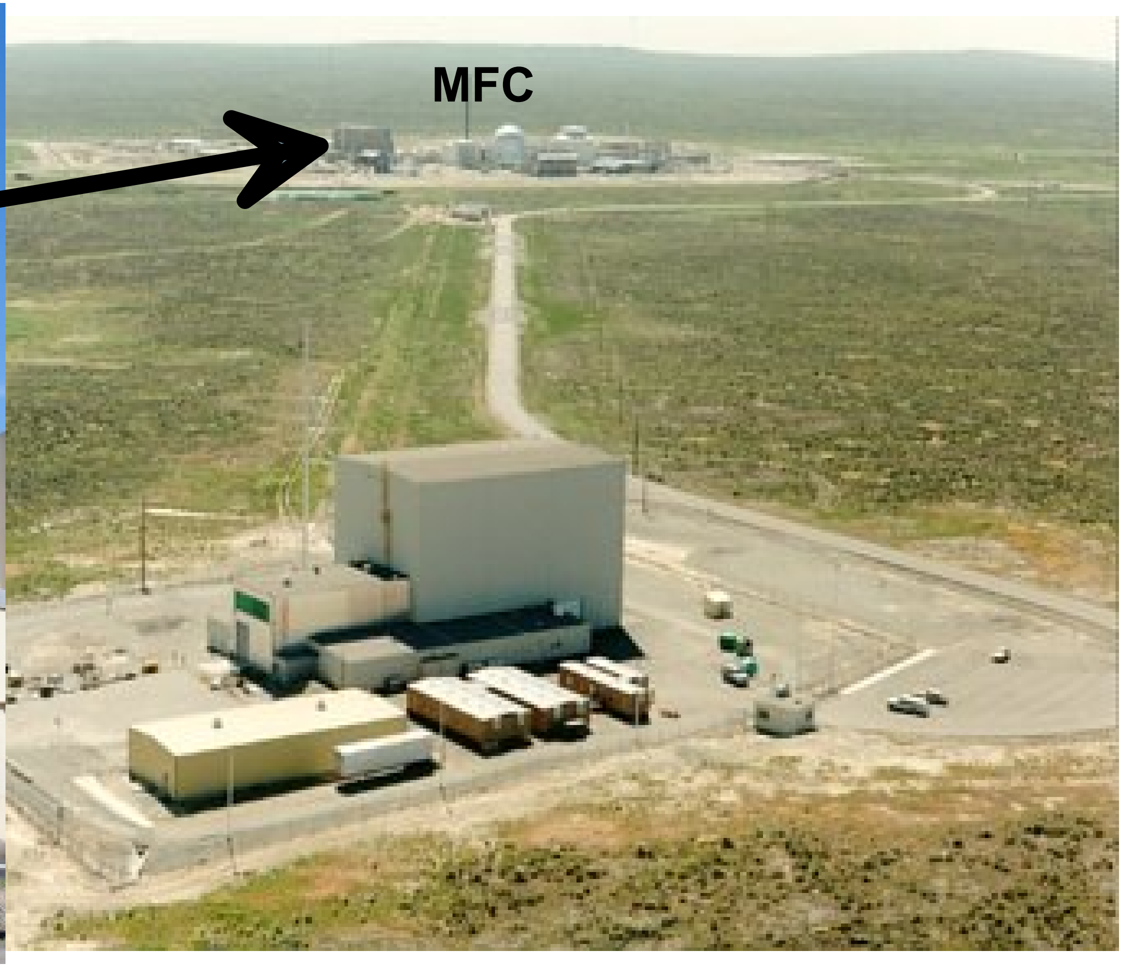
Transient Testing

- Determine safety limits prior to implementation.
- Crash testing **nuclear fuel**
- Determine performance in off-normal conditions:
  - Undercooling and overpower mismatch
  - Reactivity-initiated accidents
  - Loss of cooling accidents
  - Transient over-power
  - Loss of flow

Test at TREAT → Examination at Materials & Fuels Complex (MFC)



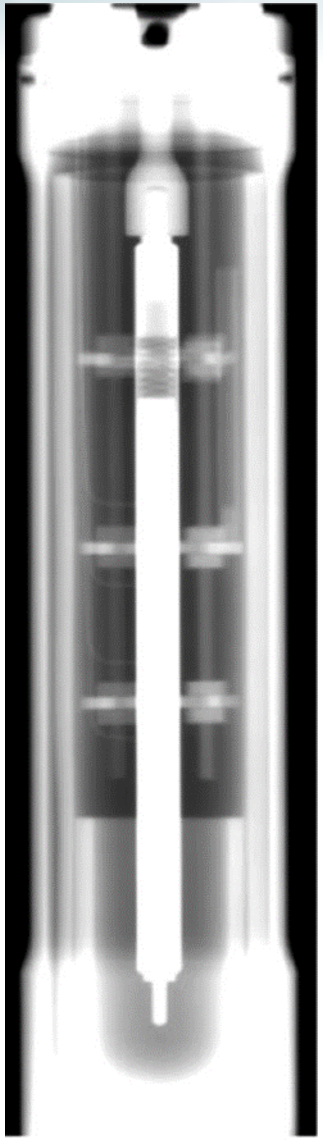
Test at TREAT → Examination at Materials & Fuels Complex (MFC)



Post-Transient Examination

- Your experiment has undergone
  - They look the same, but they may be very different inside.
- Option 1: Open the capsule and look.
  - *Long delay before we know what happened*
  - *Condition may be a surprise*
- Option 2: Use radiography or CT to visualize the internal geometric condition before undisturbed experiment.
  - Visualize the as-tested experiment condition nondestructively
  - Advance notice about experiment condition informs subsequent examinations
  - Increasingly complex experiments have more structural material (e.g. heatsinks) and limits X-Ray utility

Capsule Photo



X-Ray Radiograph

Projected TREAT Utilization

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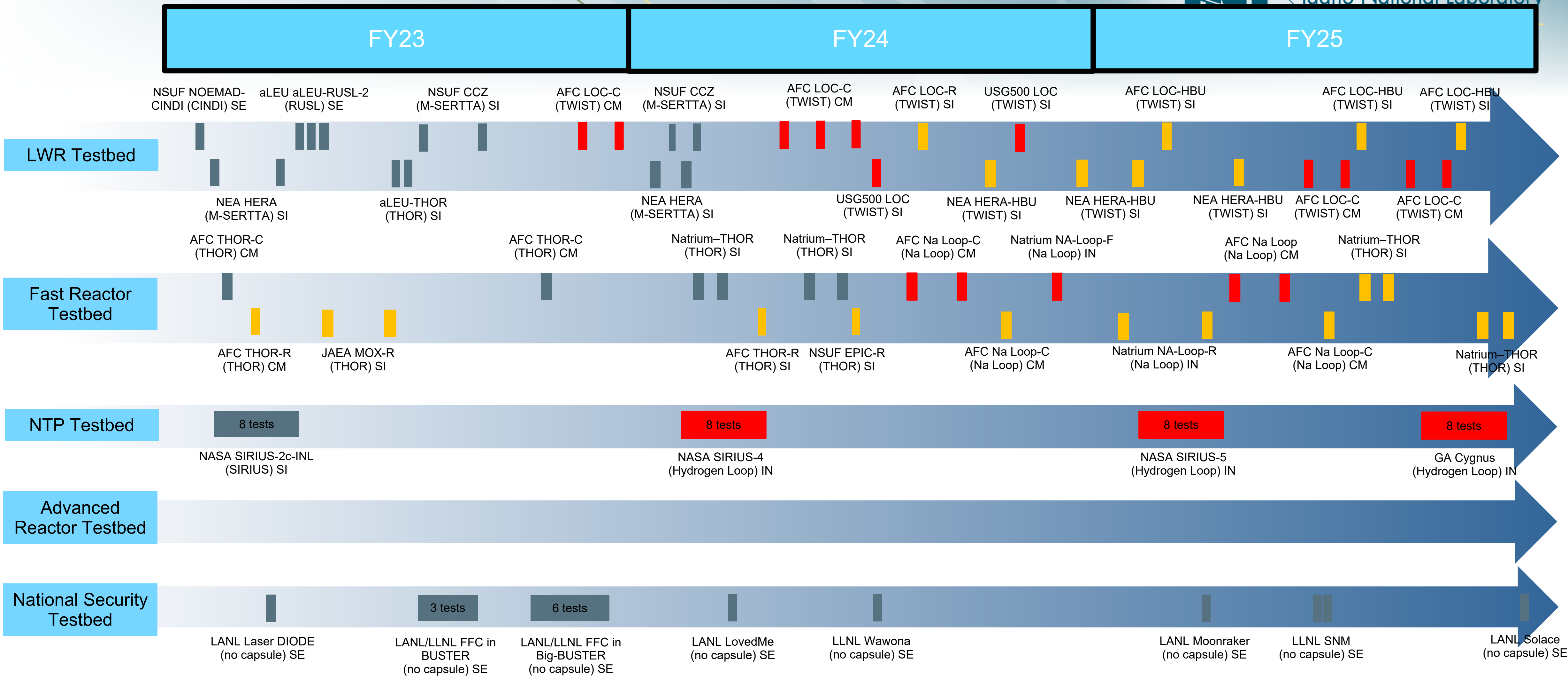


Fresh Fuel Test

Pre-irradiated Test

Labeling:

1. Who the Test is for (AFC, NSUF, aLEU, etc.)
2. Experiment Name (LOC-C, LOC-HBU, THOR-C, etc.)
3. Test Capsule to be used (THOR, TWIST, MARCH-SERTTA, etc.)
4. Type of Experiment (SE, CM, SI, or IN)

Type of Experiment Key:

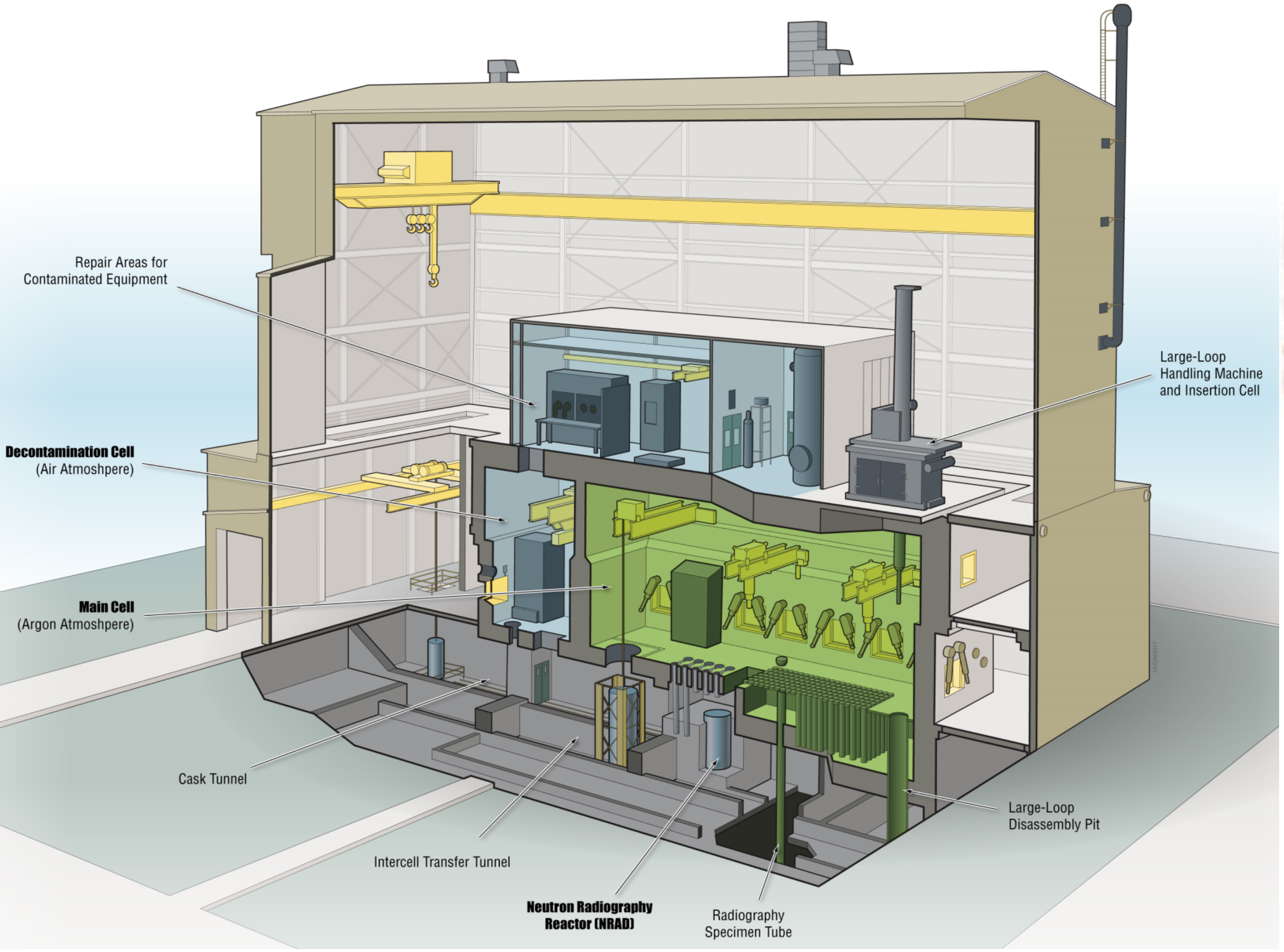
SE	Separate Effects
CM	Commissioning
SI	Semi-Integral Tests
IN	Integral Tests

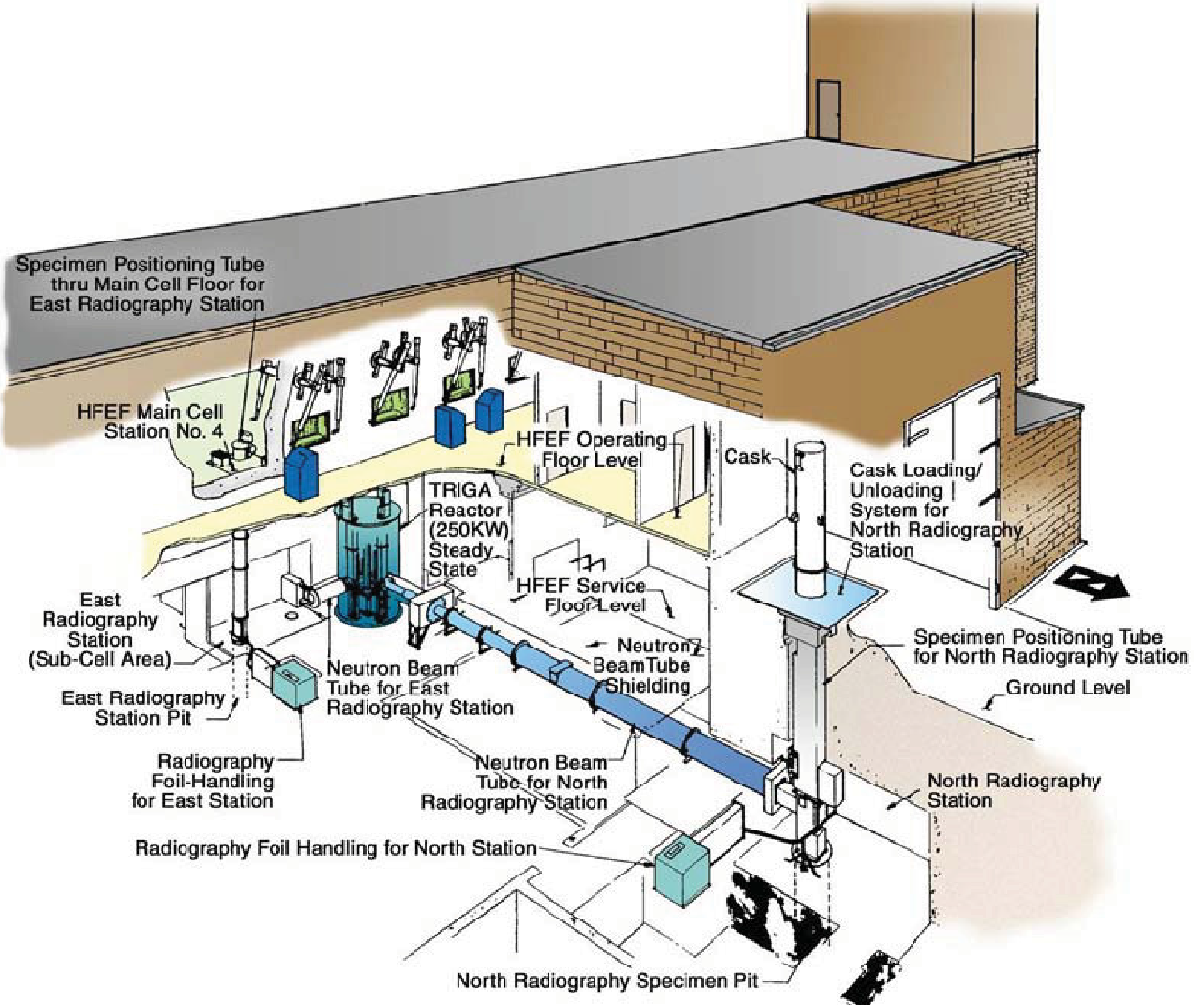
Typical Experiment Lifecycle

Design ~6 months → **Fabricate ~3-12 months** → **Irradiate** → **PIE ~12 months**

Fresh Fuel Test, Experiment disassembled in TREAT or HFEF due to size

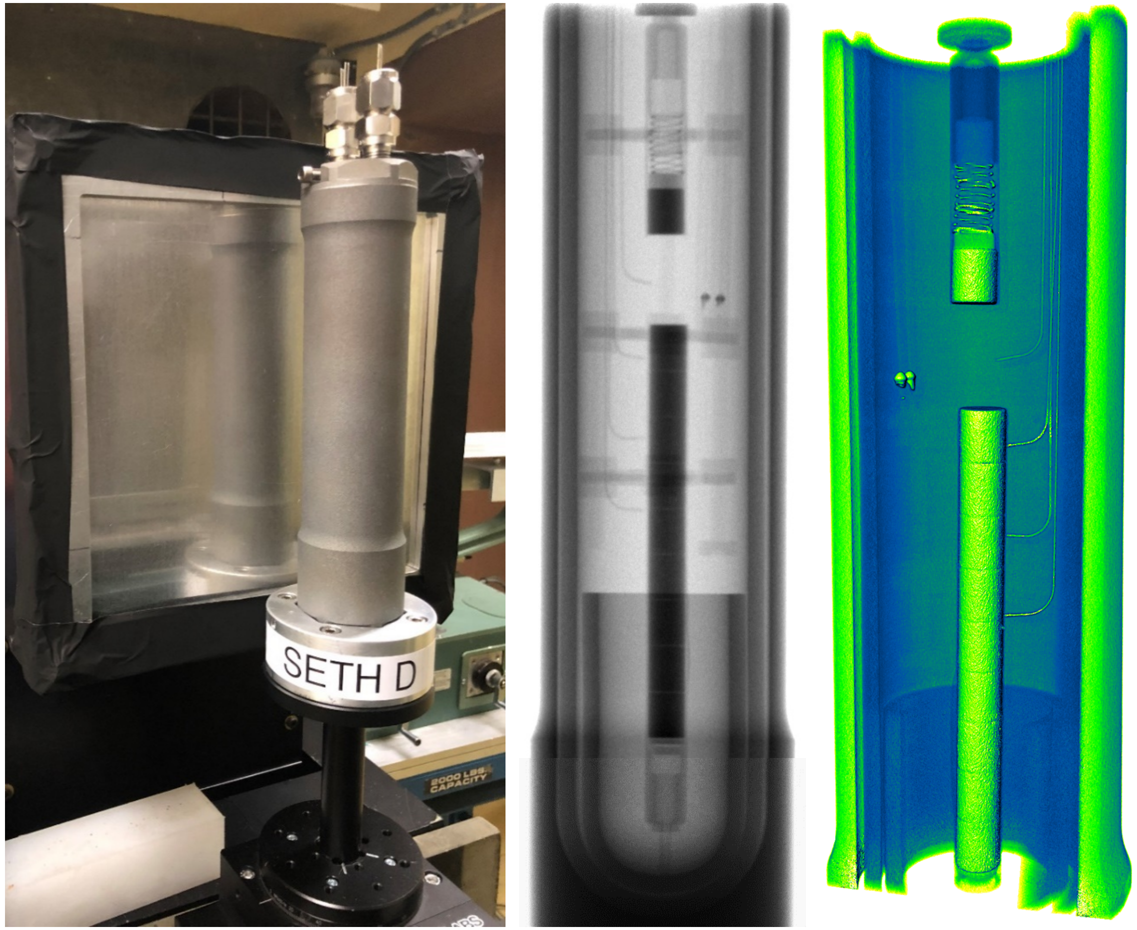
Neutron Radiography & Tomography at NRAD



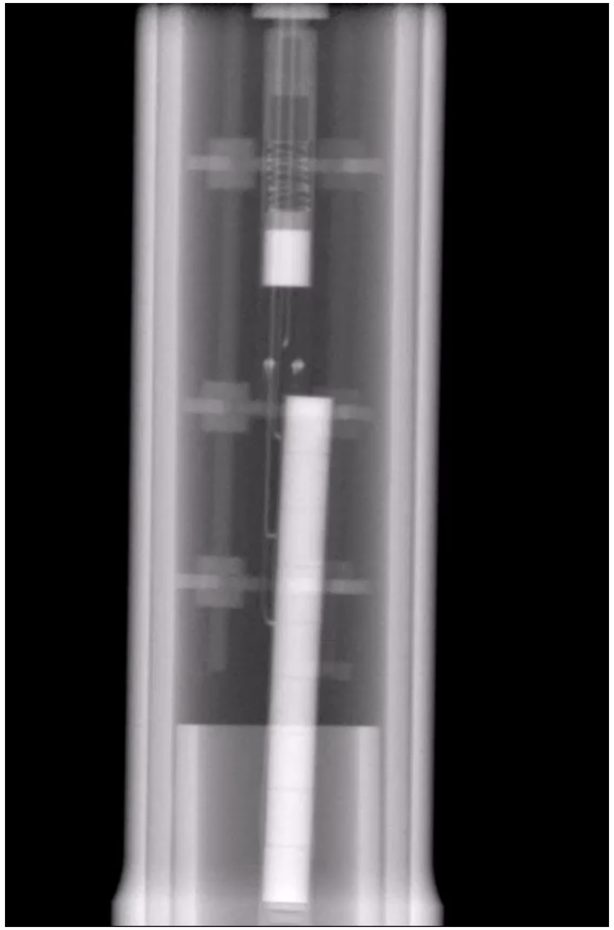


SETH-D – Neutron Imaging

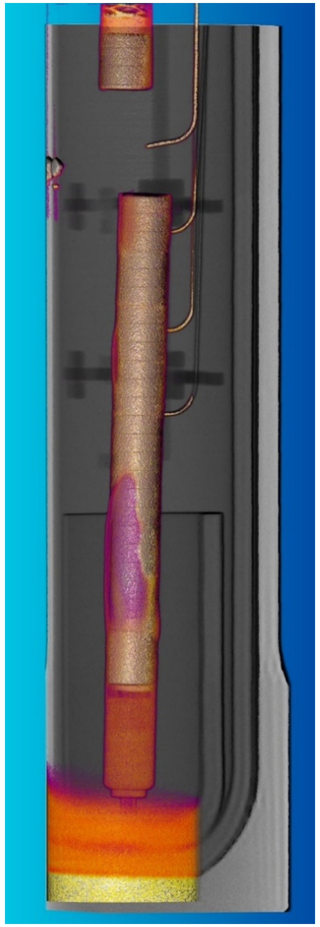
BEFORE: SETH-D neutron radiograph before transient testing



AFTER: (left) Picture of SETH-D experiment mounted in front of the nCT system, (center) example neutron radiograph, and (right) tomographic reconstruction of the SETH-D experiment capsule.

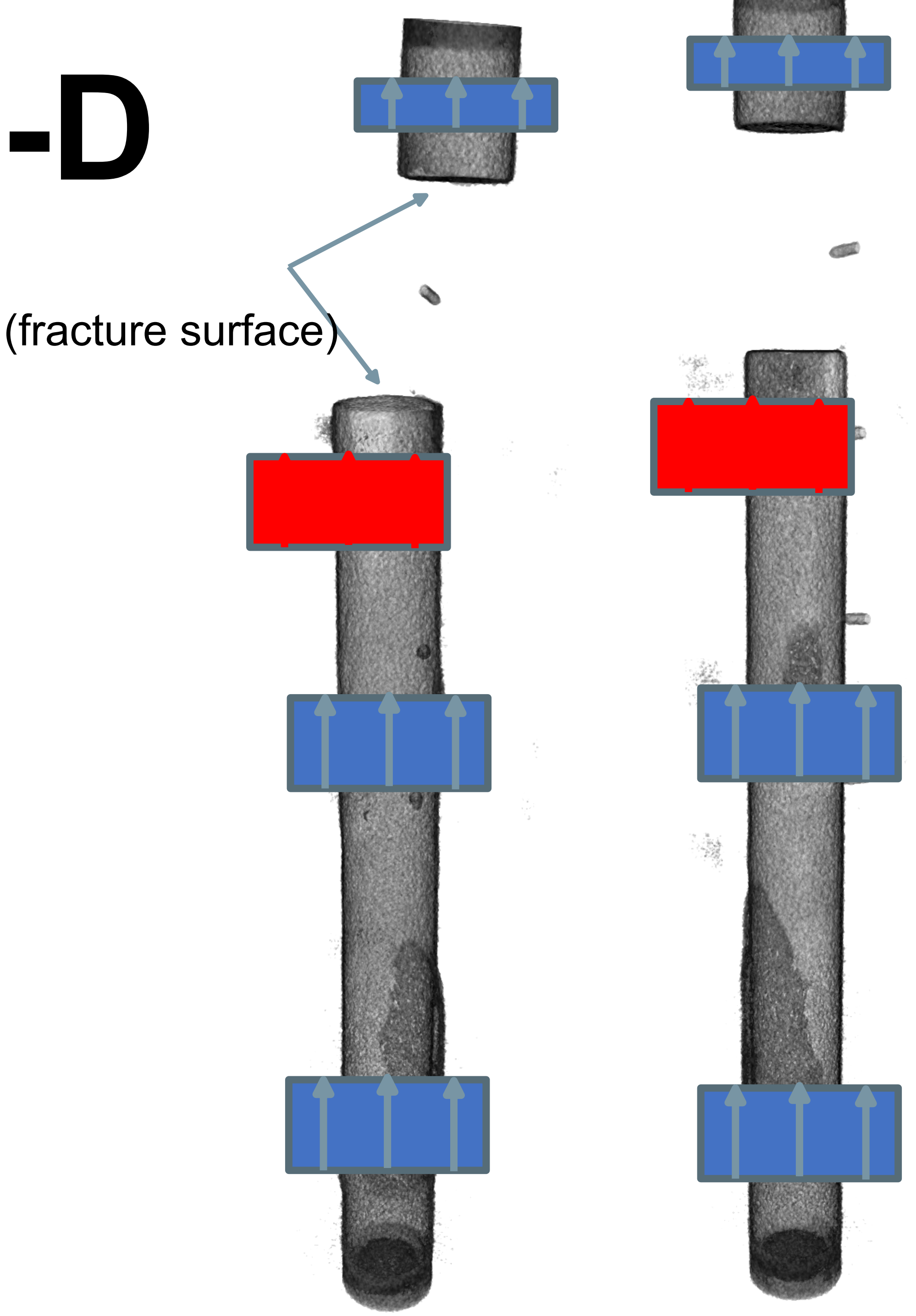


Video of the digital neutron radiographs of SETH-D over the full 360° rotation.



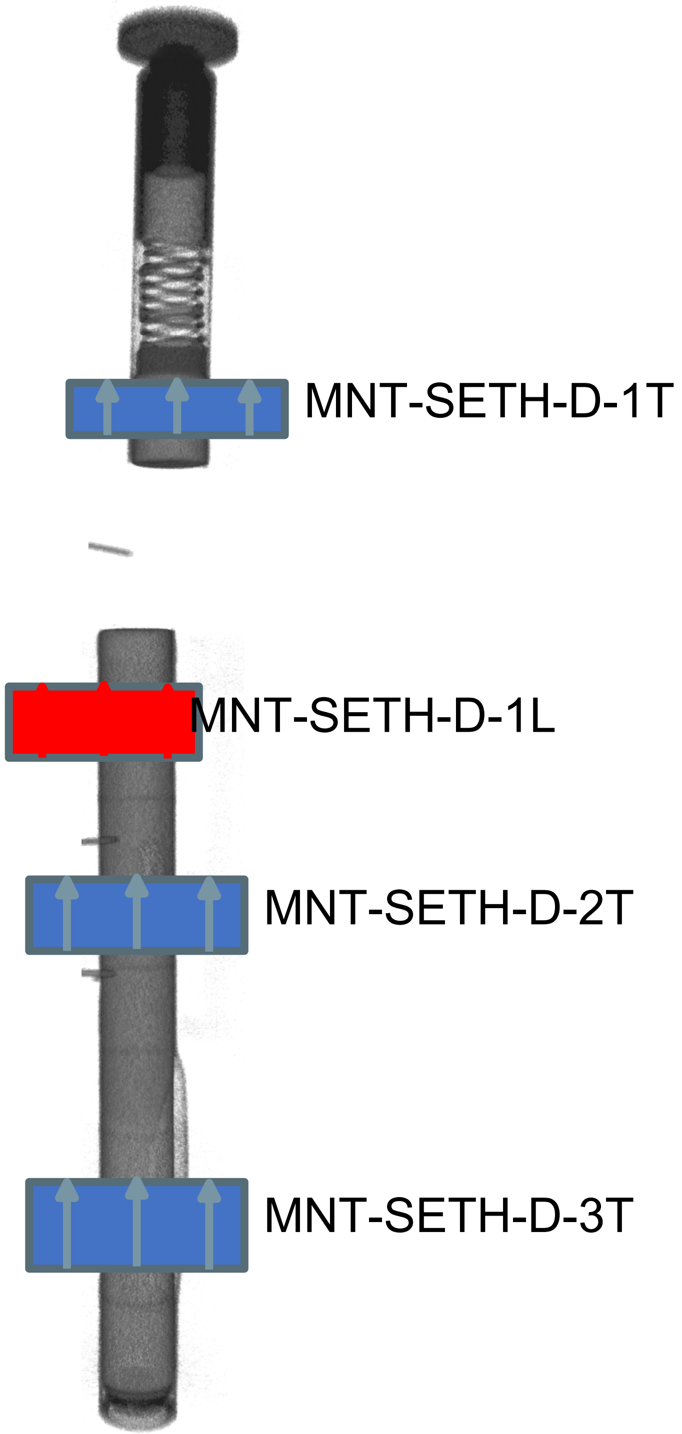
Blisters in the cladding along the length of the pin.

-D



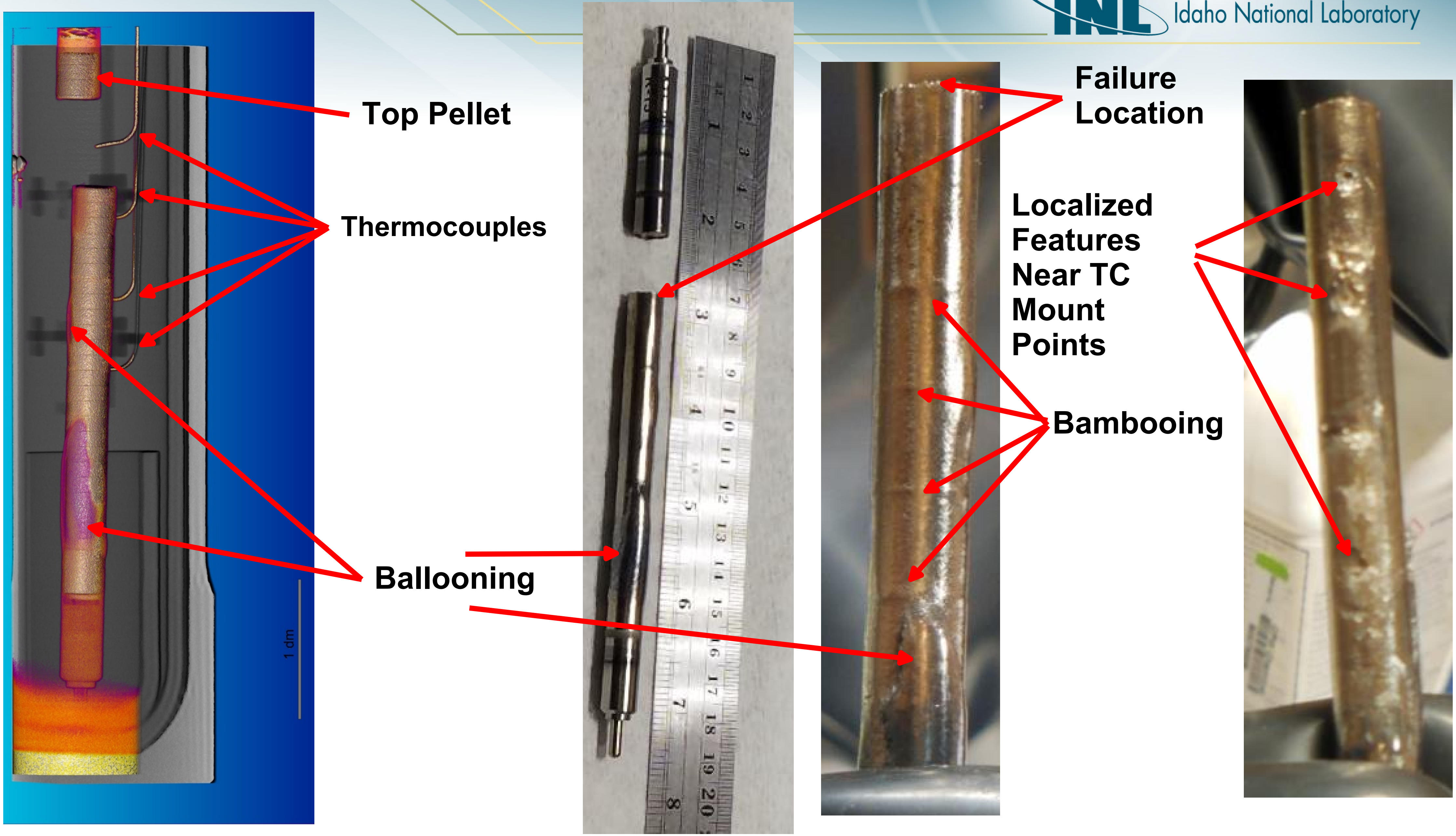
Blue box and arrows indicate approximate location of cross section mount. Arrows point to polishing surface

Red box and arrows indicate approximate location of longitudinal mount. Arrows point to polishing surface

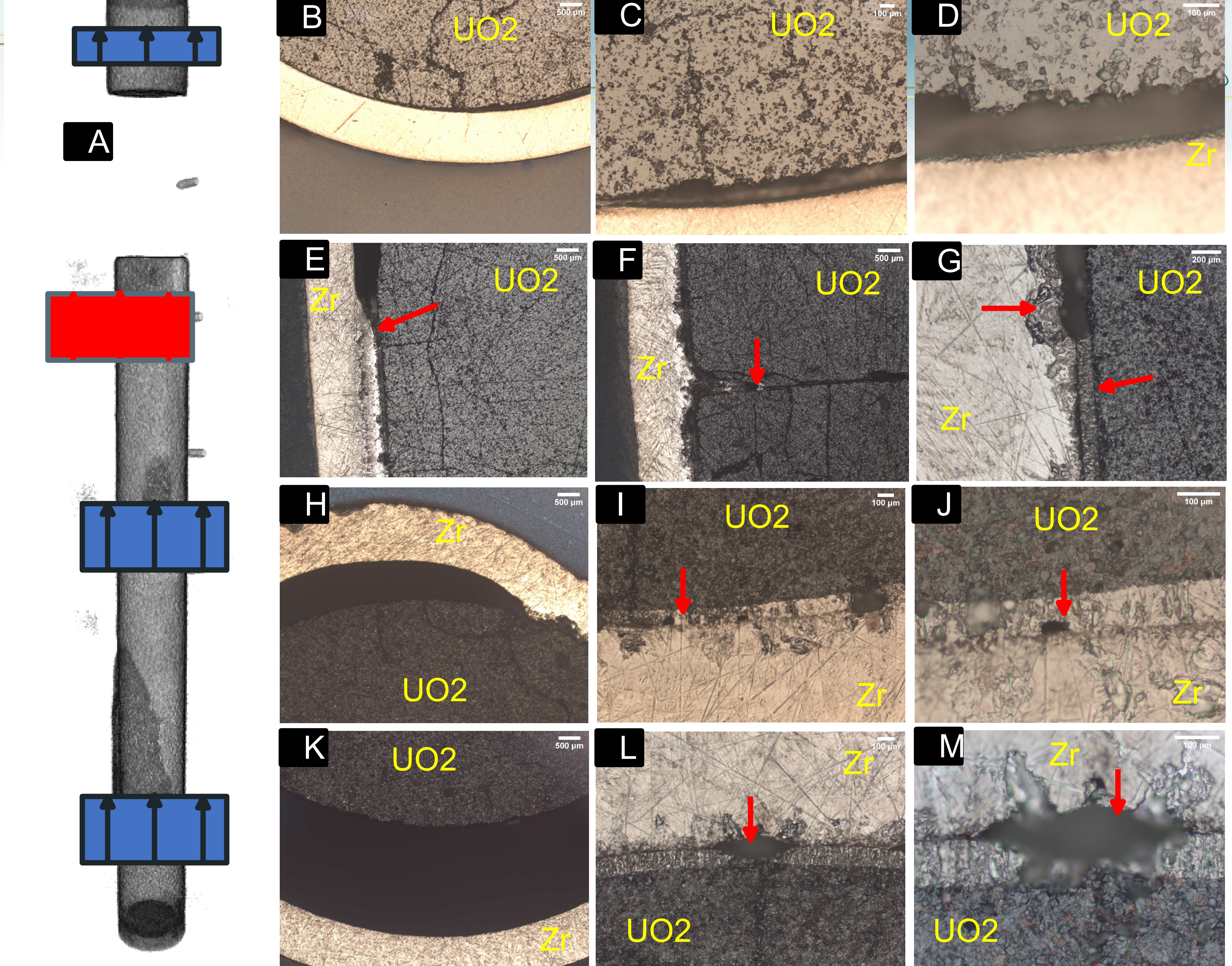


SETH-D – Opening SETH-D

SETH-D


Top Pellet
Thermocouples
Ballooning
1 dm
Failure Location
Localized Features Near TC Mount Points
Bambooing

-D

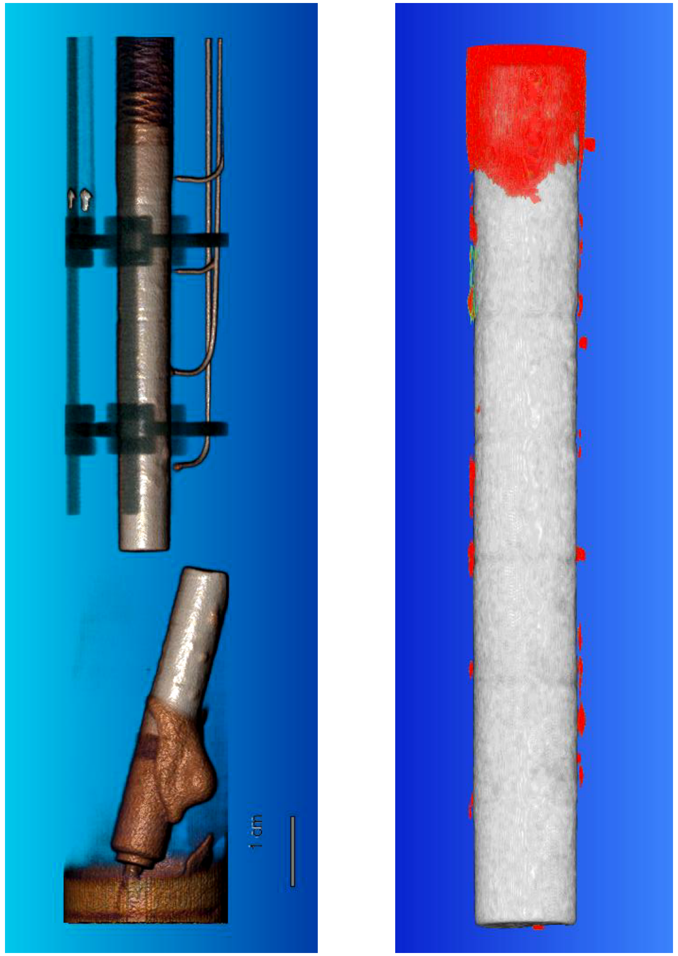


Key observations:

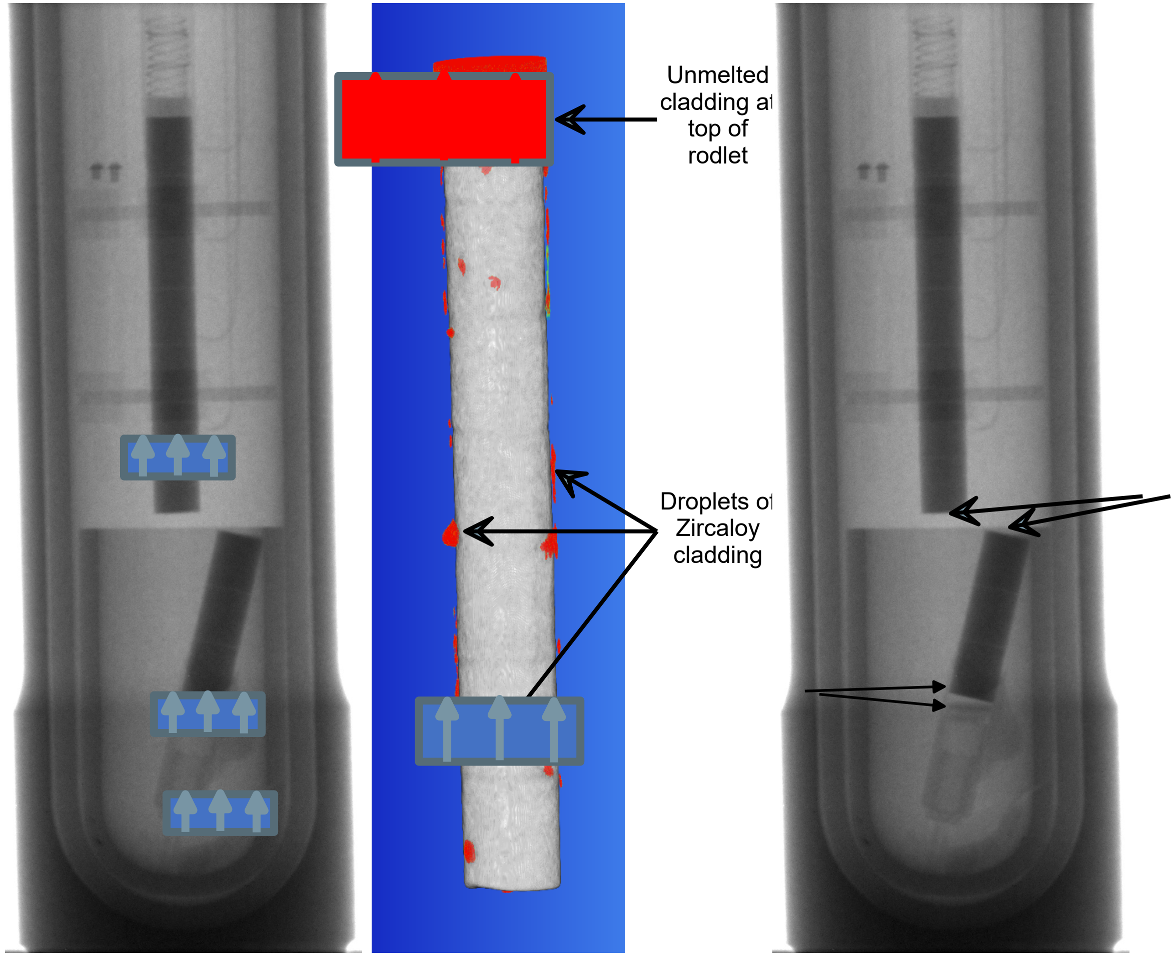
- Axial Temp profile
- No cracks in balloon regions
- Large amount of strain in balloon regions
- Previously molten cladding region
- U-Zr duplex region ~90-100 um thick (G, I, J, L, M)
- Voiding (I, J, L, M)
- Smaller voids in I and J
  - 69 um X 51 um, 60 um X 30 um,
- Medium void in I
  - 214 um X 140 um
- Large void in L and M
  - 466 um X 134 um
- Zr wicking or capillary action
- No gross clad relocation, likely not long enough above melt temp for viscous flow

SETH-E – Neutron Imaging & Plans for PIE

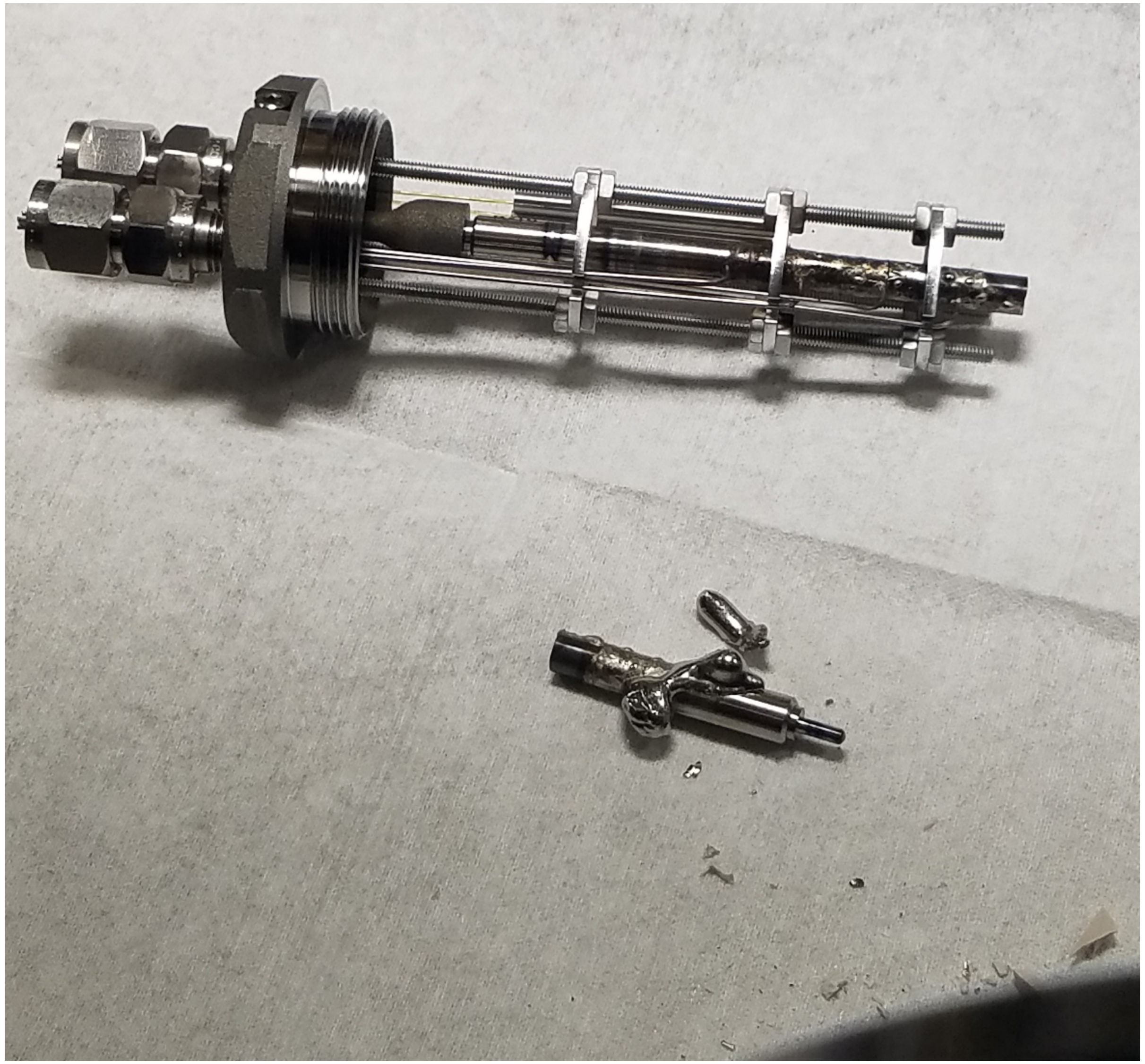
Neutron radiographs of the transient irradiated ATF SETH-E experiment.



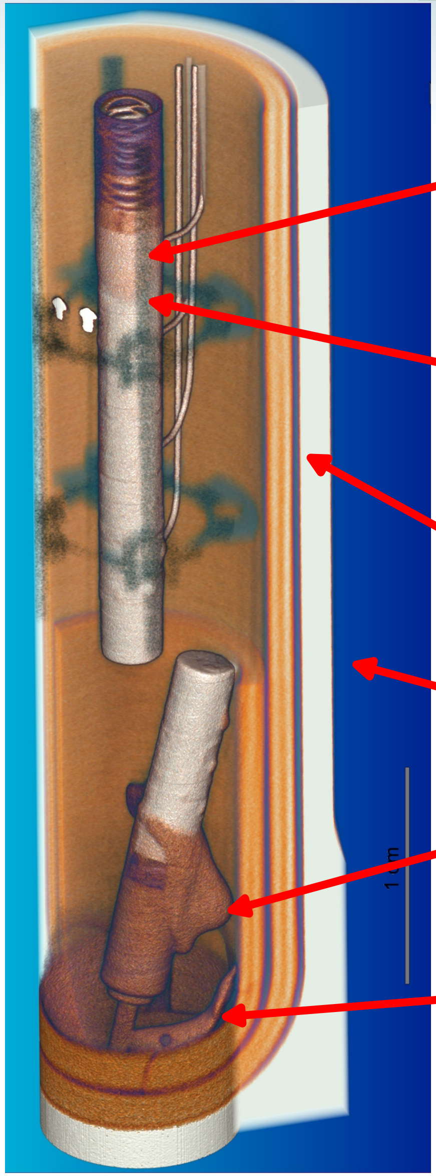
Segmented tomographic reconstruction highlighting the (left) whole fuel pin and (right) solidified Zircaloy droplets.



SETH-E – Opening SETH-E



SETH-E



Intact un-melted cladding

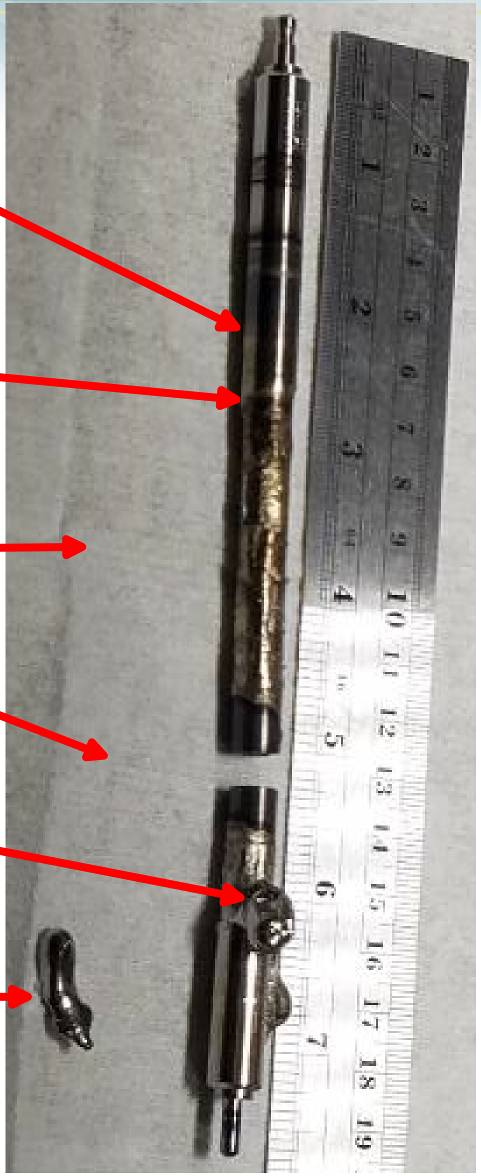
Melt transition location

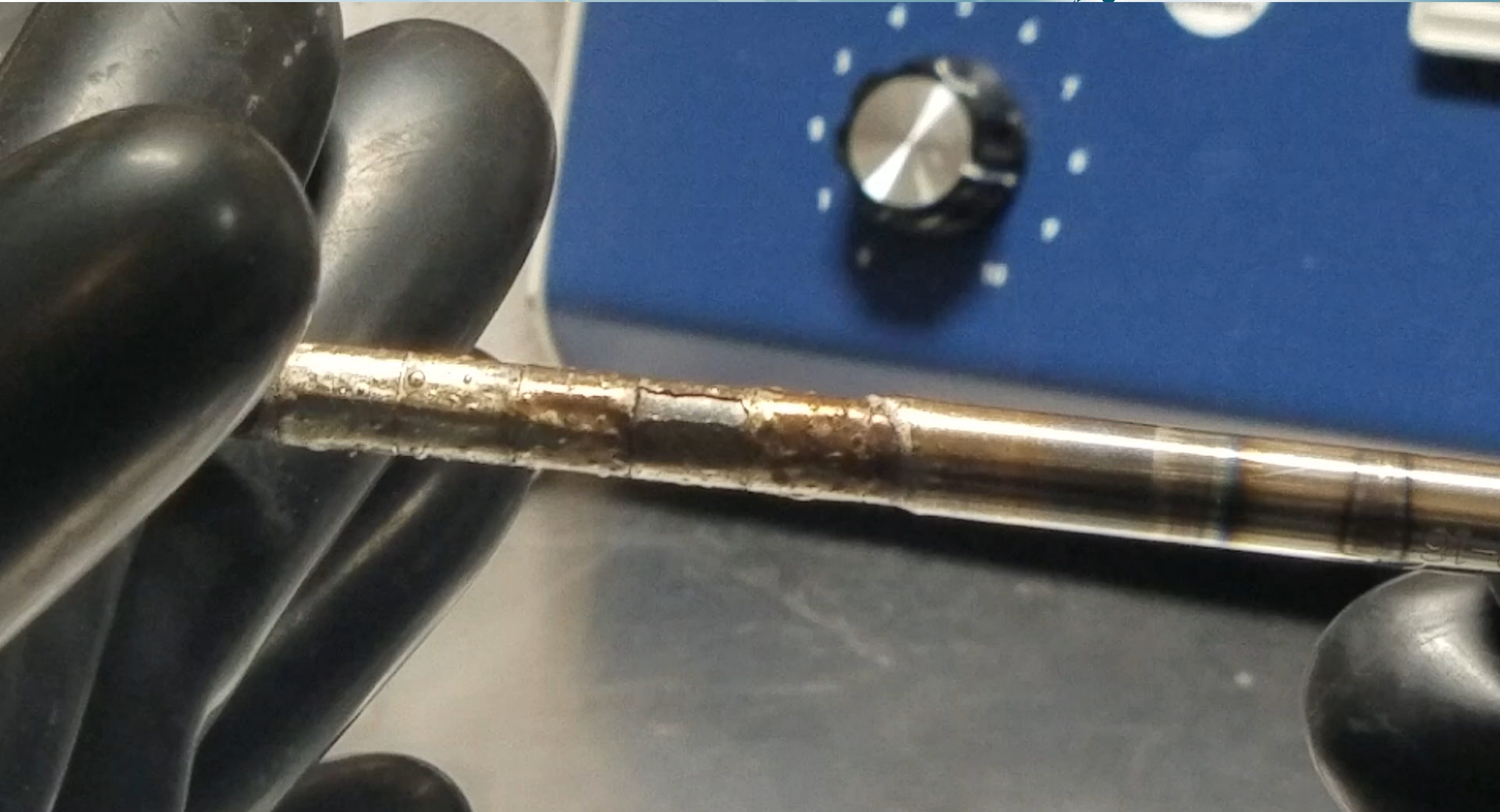
Very thin layer of re-solidified cladding

Bare fuel pellets

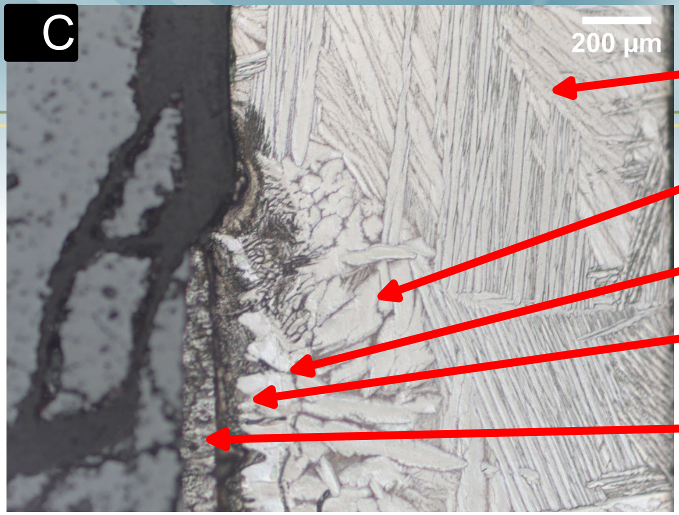
Relocated cladding “Candling”

Relocated cladding “Debris”





-E



Prior β-Zircaloy (~426-522 um)

Oxygen stabilized **α**-Zircaloy (~280-350 um)

Melt/freeze front

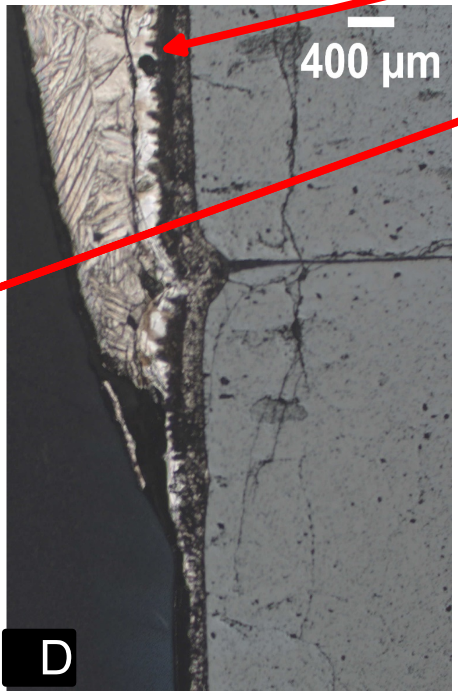
Zr-rich (U, Zr) duplex reaction layer (~200-270 um)

U-rich (U, Zr) duplex reaction layer (~100-170 um)

Cladding thickness increase (~300 um)

Void formation in (U, Zr) duplex reaction layer (~148 X 155 um)

Remnant (U, Zr) duplex reaction layer on to pellet surface (~134 um)



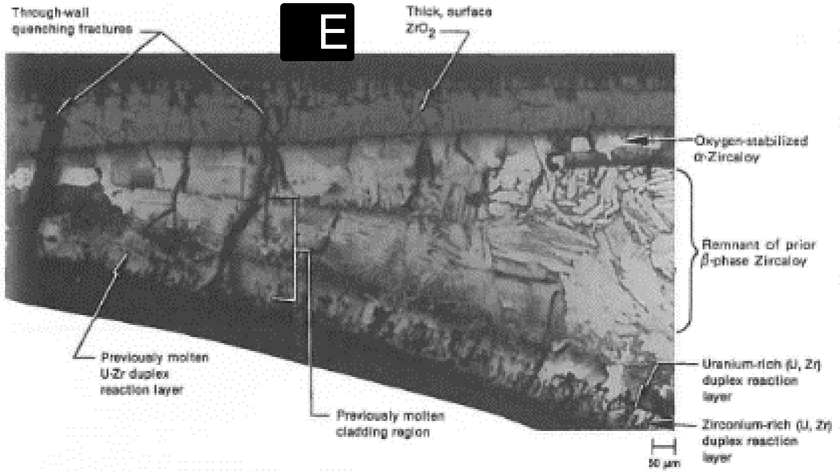


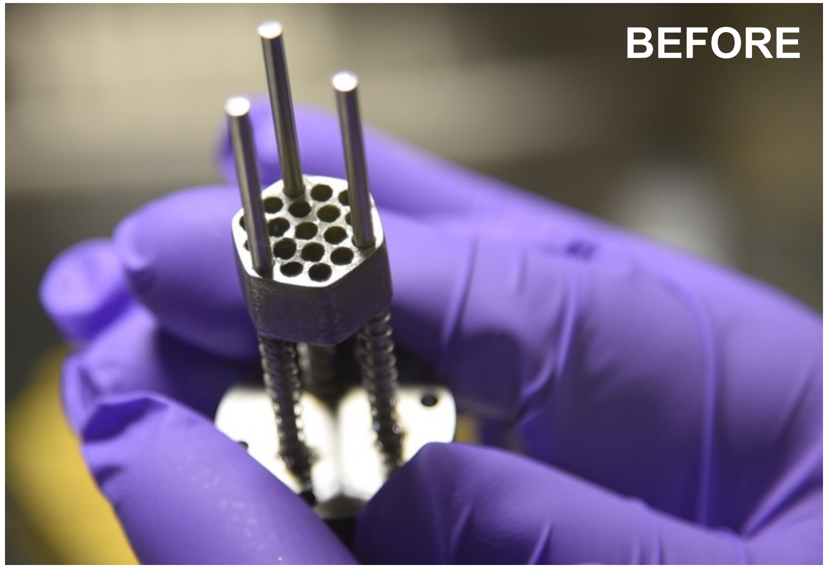
Fig. 12 Cladding cross section at the 0.354-m elevation showing partial wall melting during test RIA-ST-1 (peak enthalpy deposition of 250 cal/g UO_2).

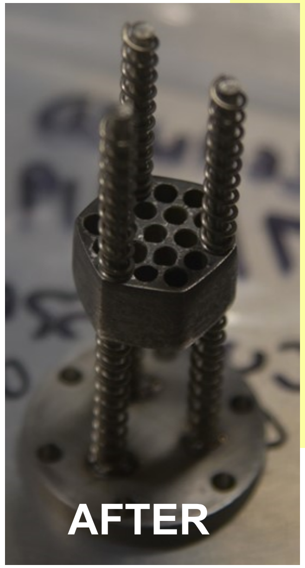
NUCLEAR SAFETY, Vol. 21, No. 5, September–October 1980

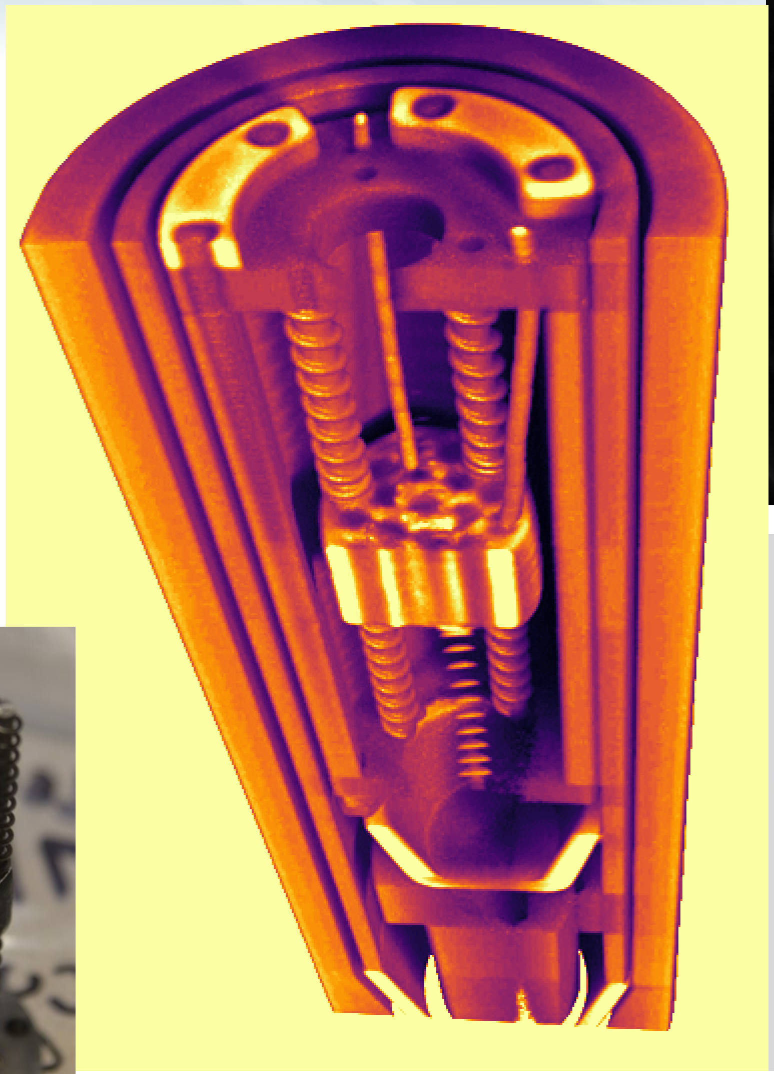
MacDonald et al., Nuc. Safe, 1980

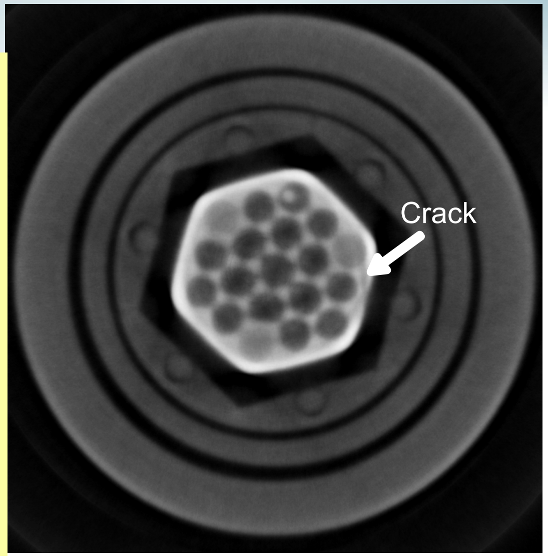
Sirius-1 – Neutron Imaging

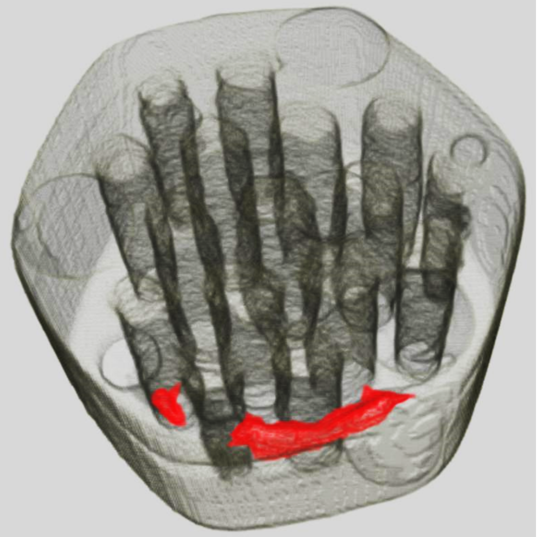
- SIRIUS-1 capsule irradiated at TREAT and nCT performed at the NRAD Reactor.
- Reconstruction revealed a crack in the fuel and distortion of the fuel's surface.
- Detection of a crack months before the capsule was opened allows M&S time to evaluate failure mechanisms.





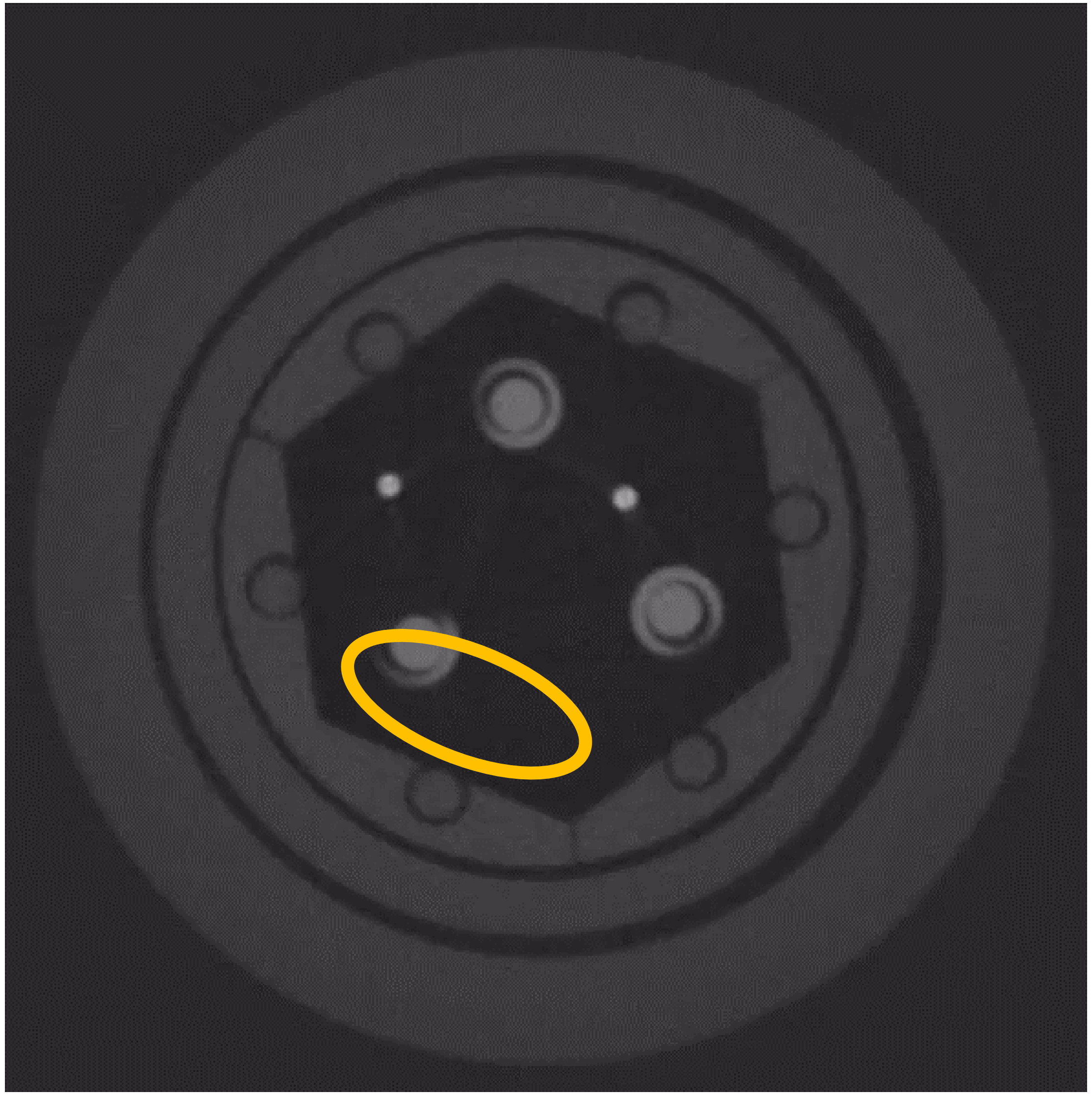


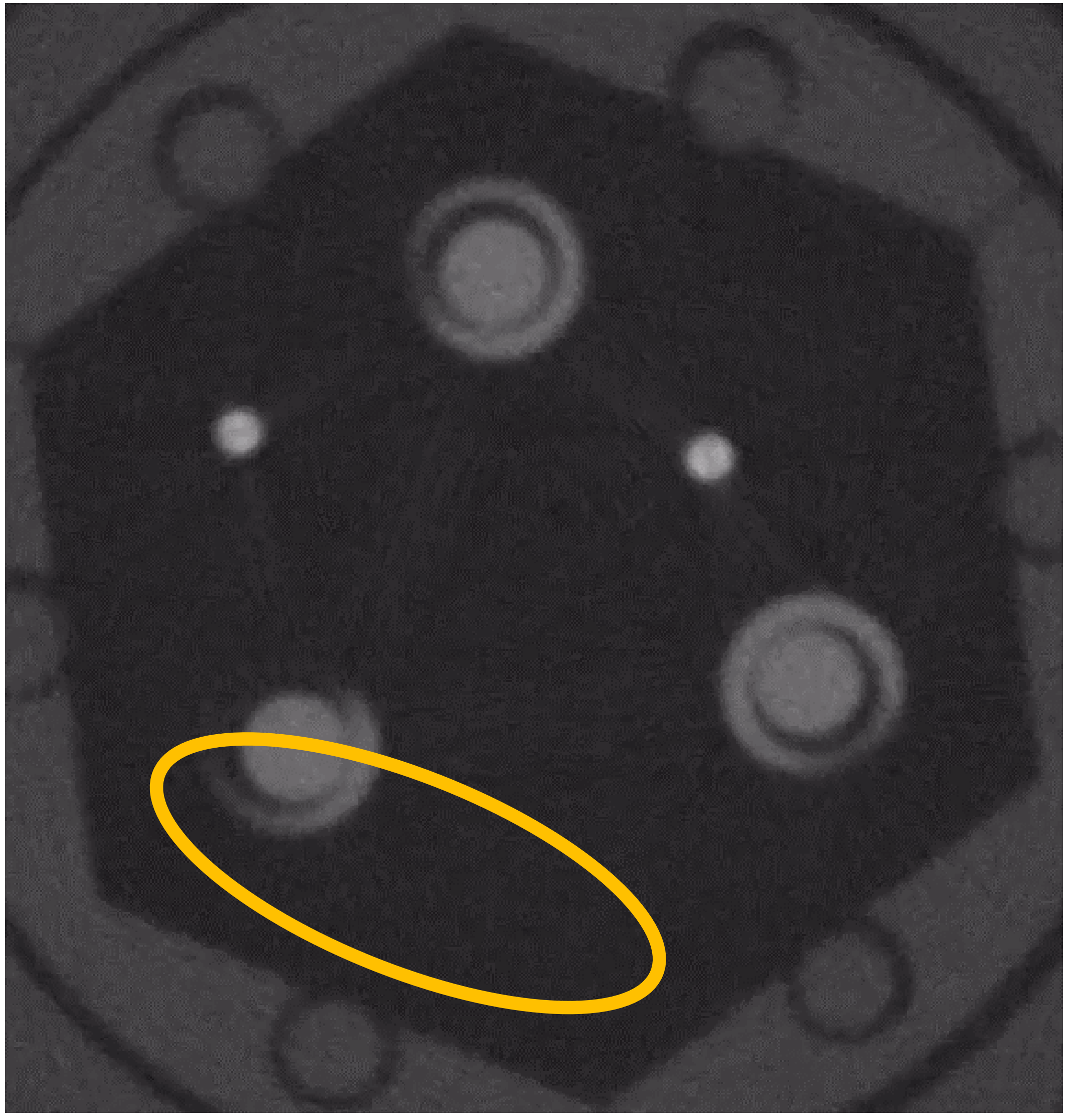




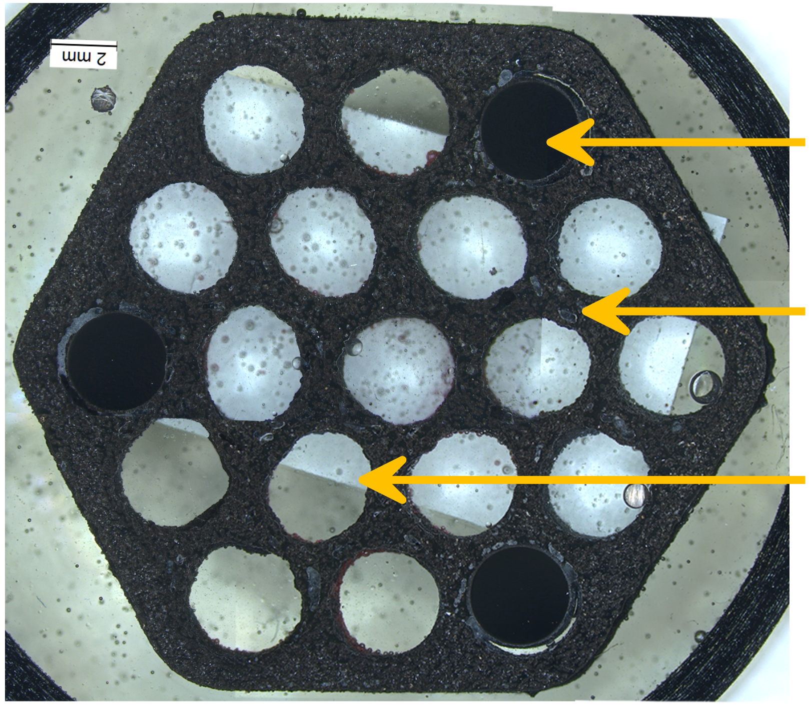
(Left) A 3D rendering of the SIRIUS-1 capsule. (Top Right) A reconstructed slice of the SIRIUS-1 capsule showing cracking in the fuel. (Bottom Right) A 3D rendering of the fuel region with the crack emphasized in red.

nCT of SIRIUS-1 Capsule, cont.





Sirius-1 – Destructive Examination

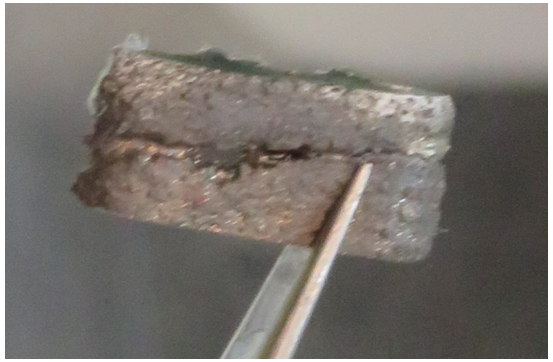


Tungsten rod

from holder.

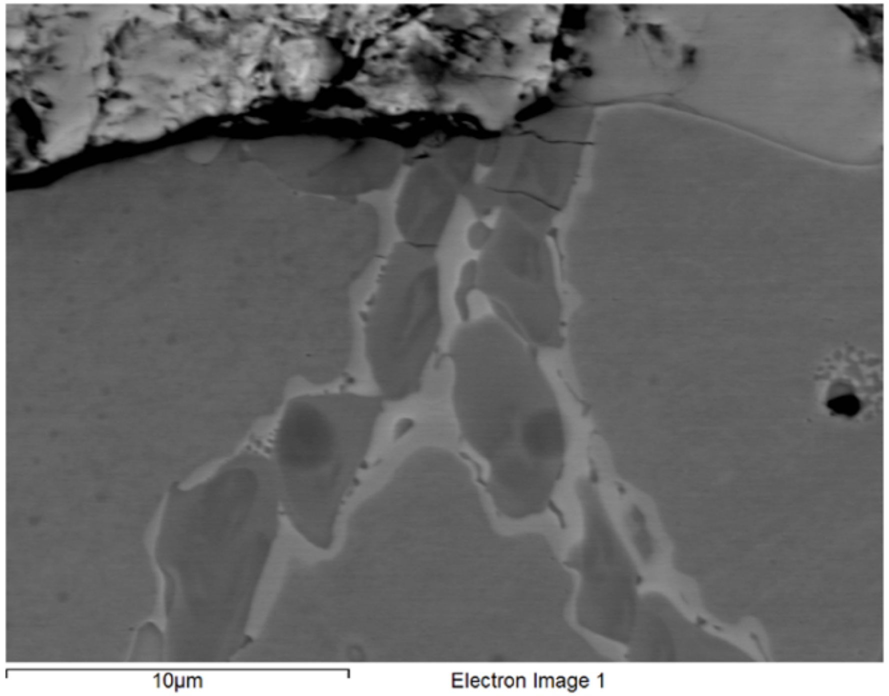
Porosity

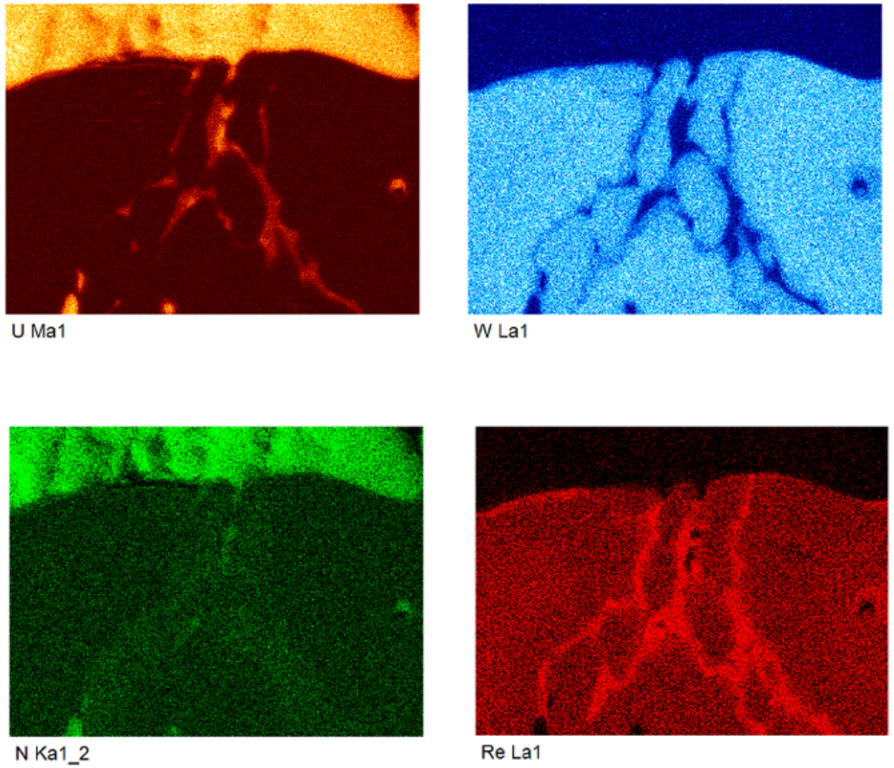
Coolant channel
distortion.



Sirius-1 SEM/EDS

- Diffusion zones identified near interfaces between fuel particles and matrix
- Microcracking observed in the matrix, very near the fuel particle

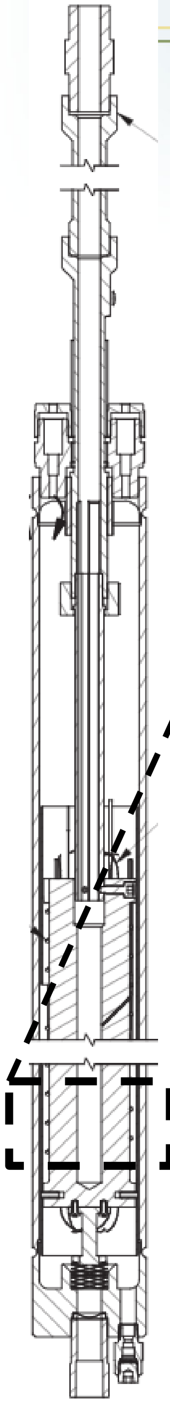


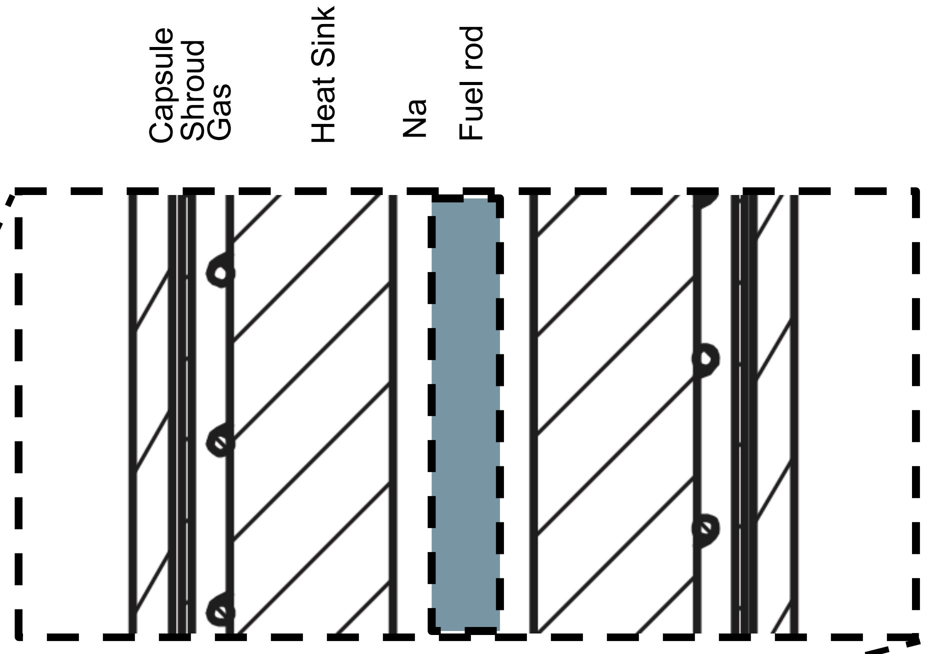


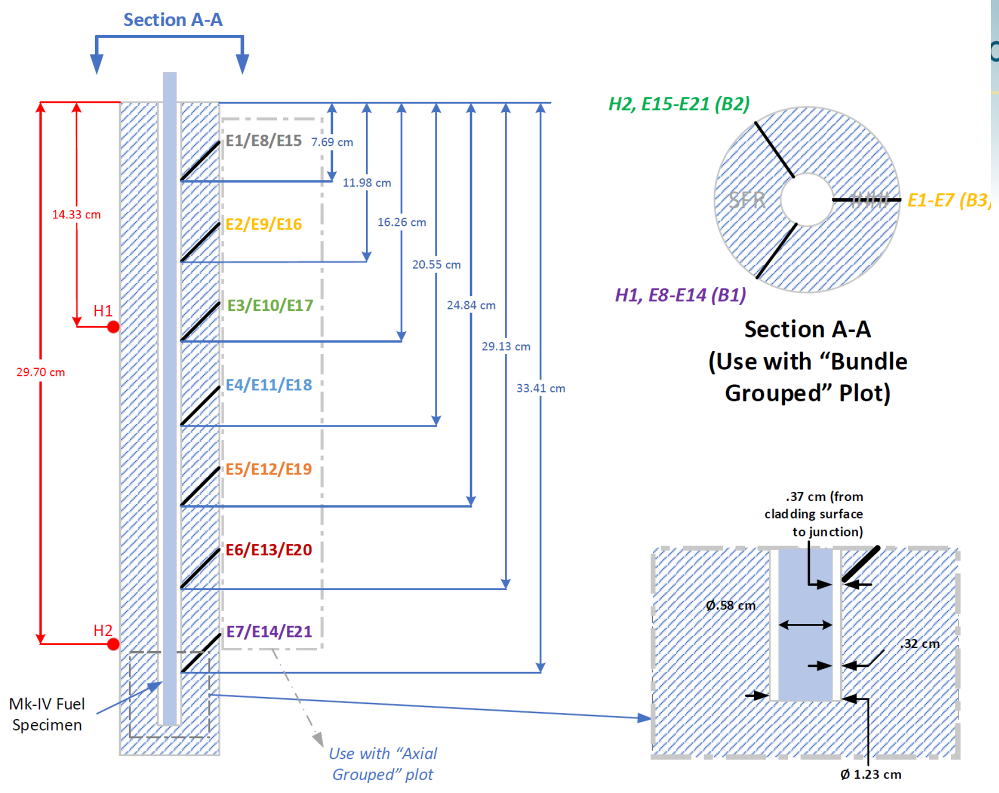
THOR-C2

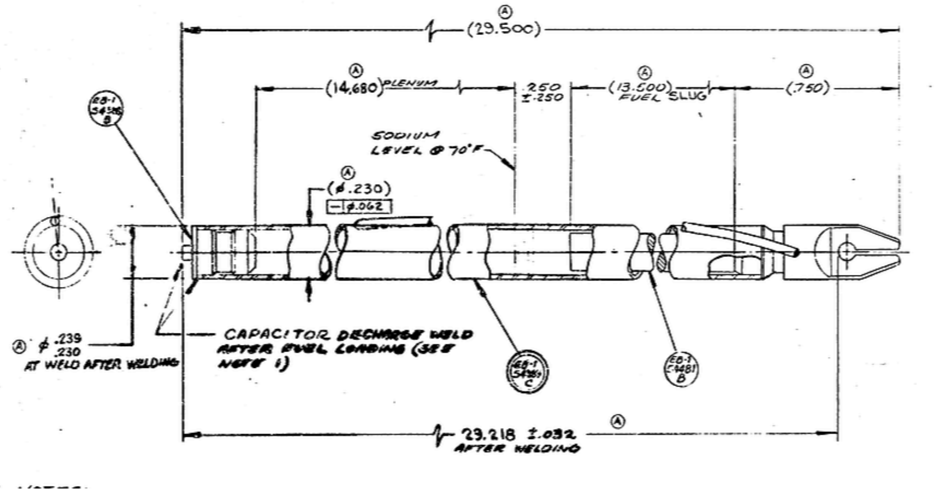
- U-10Zr in HT9 cladding
- Commissioning test intended to test in-situ instrumentation and fail fuel pin by high temperature creep rupture.

THOR-C2 Geometry

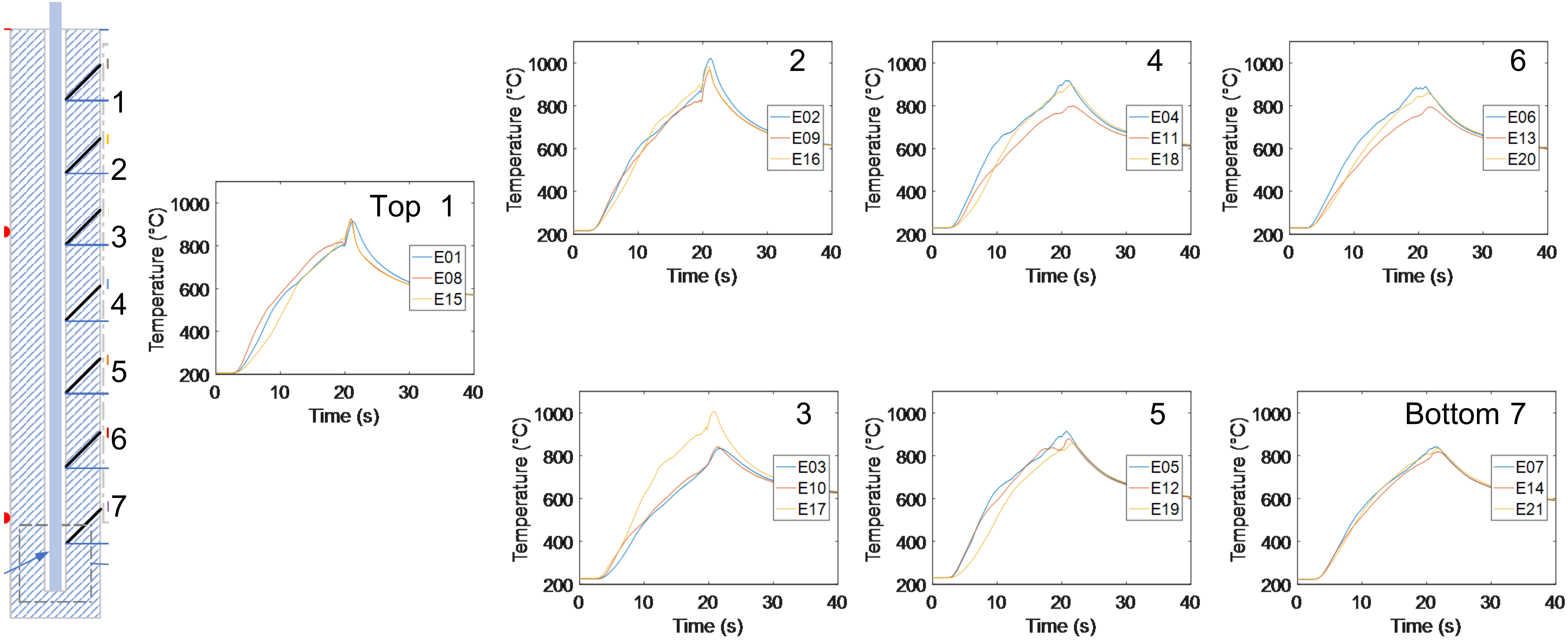




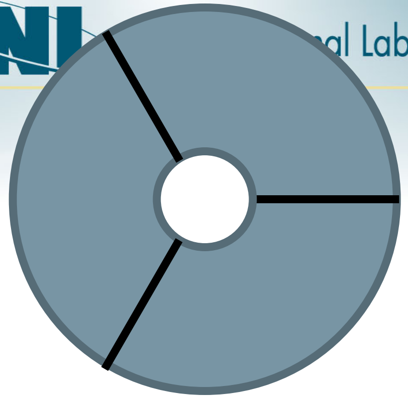


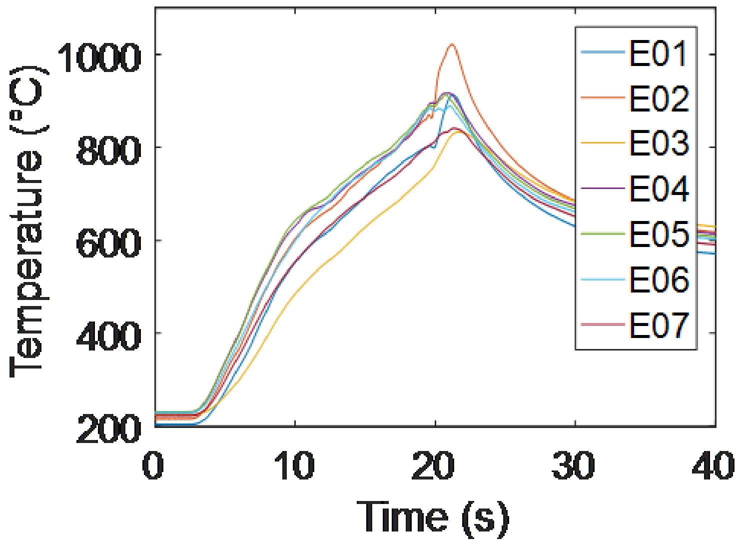


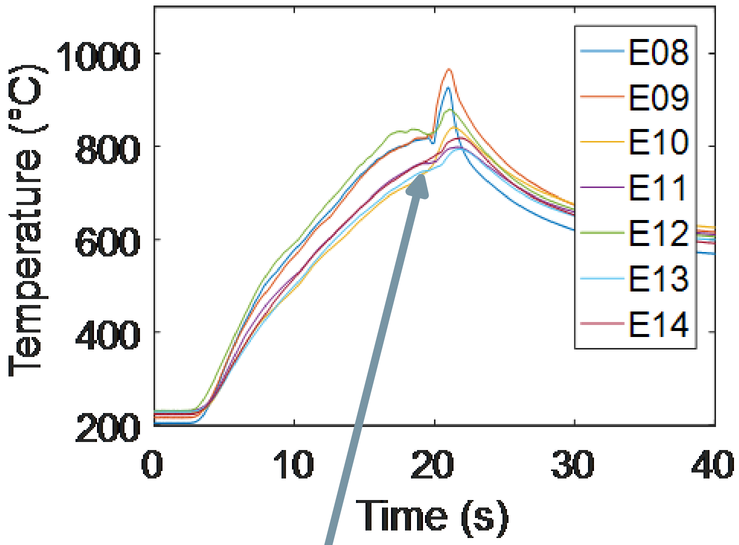
THOR-C2 Temperatures by Axial Plane

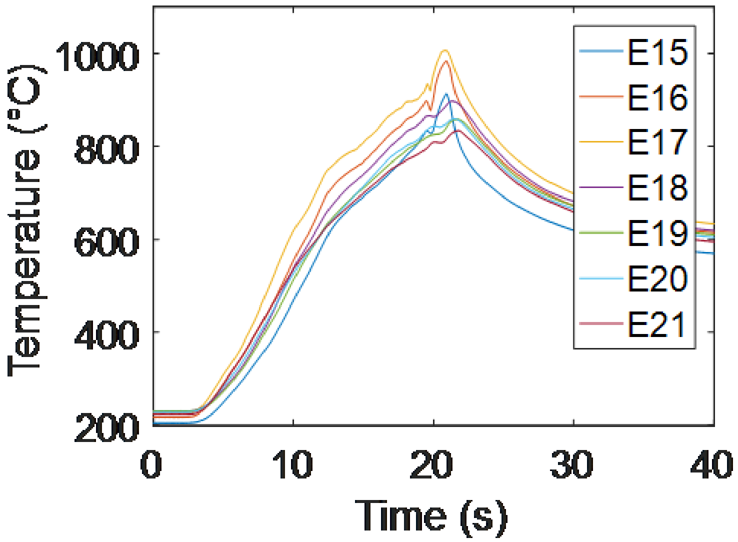


THOR-C2 Temperatures by Azimuth





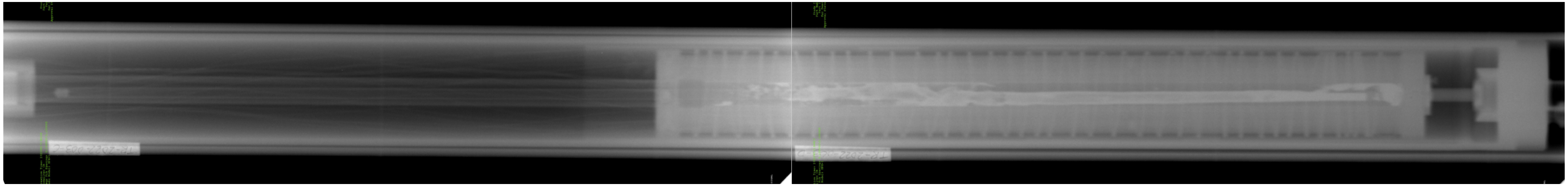




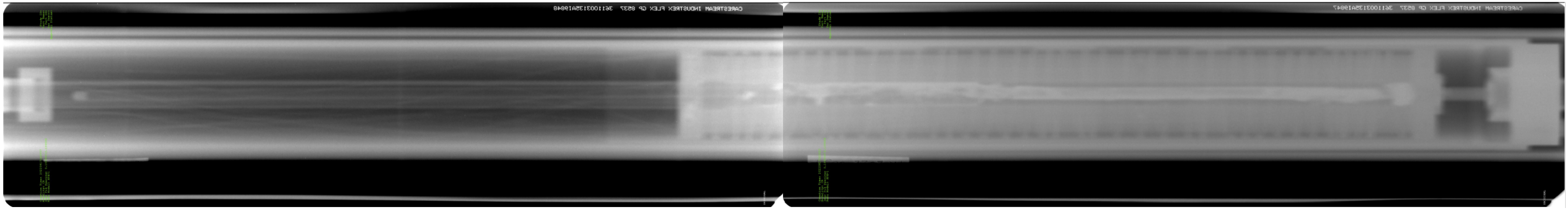
Indicates significant disruption to heat flow – potential rupture and fuel dispersal…

THOR-C2 TREAT Neutron Radiography

0°

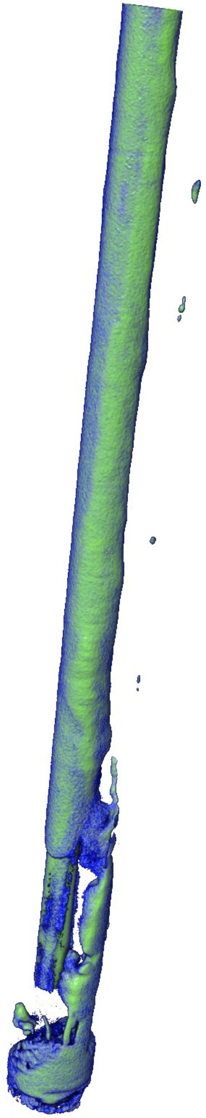


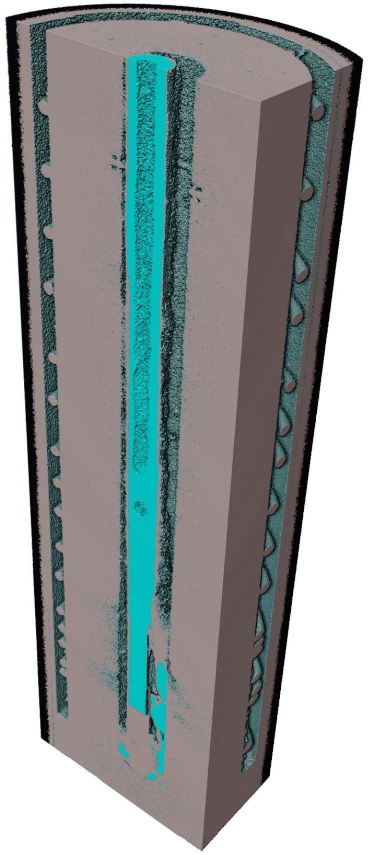
90°



THOR-C2 nCT

Upcoming
- Radiography slices at TC locations
- Plan disassembly





Summary & Future Needs

- Neutron CT provides valuable information that is unavailable otherwise.
  - Visualize internal condition of the <u>undisturbed</u> experiment.
  - Identify potential hazards prior to opening the sample.
    - Powdered material, particulates
  - Inform researchers about the fuel's performance long before the experiment is opened.
- Calibration standards used for dimensional inspection quality control.
- Future Needs:
  - Developing nCT capabilities for *highly* radioactive samples.
  - Future needs include:
    - High-resolution: FOV = 30 mm, effective spatial resolution ~20 μm.
    - Multi-FOV Neutron Imaging System with FOV's of 10, 20 and 60 cm.
  - Develop X-ray CT for water-filled experiments.
  - Element identification and segmentation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