INL/MIS-23-75187-Revision-0

Transient Overpower Testing in THOR -- Pre-Test PIE of Previously Irradiated Fuel and NDE PIE Results of Commissioning Test

November 2023

Changing the World's Energy Future

Jason L Schulthess, Colby B Jensen, Luca Capriotti, Klint Stephens Anderson, Chase Ellsworth Christen, Jordan M Argyle, Clayton G Turner, Philip G Petersen, Allison Probert, William C Chuirazzi

Idaho National Laboratory

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Advanced Fuels Campaign

Transient Overpower Testing in THOR – Pre-Test PIE of Previously Irradiated Fuel and NDE PIE Results of Commissioning Test

Jason Schulthess, Colby Jensen, Luca Capriotti, Klint Anderson, Chase Christen, Jordan Argyle, Clayton Turner, Phil Petersen, Allison Probert, William Chuirazzi, and many others…

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U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Experiments Objectives Overview and In-Situ Data

- **THOR-C**: commissioning experiments on fresh metallic fuels in BUSTER and Big-BUSTER (6 specimens/capsules)
  - Deploy THOR system across INL facilities
  - Measurement and validation of energy deposition in THOR in TREAT
  - ‘Qualify’ experiment system and in-situ instrumentation
- **THOR-MOXTOP**: experiments on high burnup, advanced design MOX pins (2 specimens/capsules)
  - Fuel Clad Mechanical Interaction (FCMI) impacts for transient overpower (TOP) conditions with 50% areal melt fraction
- **THOR-M**: experiments on high burnup metallic fuel pins (2 specimens/capsules)
  - TOP condition to creep driven failure mode (non-prototypic, phenomena focused)
  - Loss of flow (LOF) condition under Beyond Design Basis Accident (BDBA) condition (no failure)

Data Priorities

1. Time vs. Specimen Power/Temperature
2. Cladding failure
3. Fuel melting (MOX)
4. Cladding deformation
5. Fuel expansion and potential relocation
6. Transient fission gas release
7. Constituent redistribution

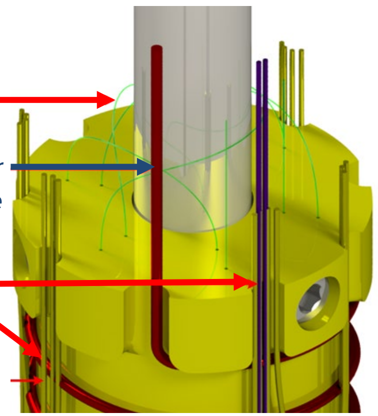
In-Situ Solutions in THOR Capsule

Optical fiber for Distributed Temperature Sensing

Heater Cable

23 thermocouples

IR pyrometer (special case)



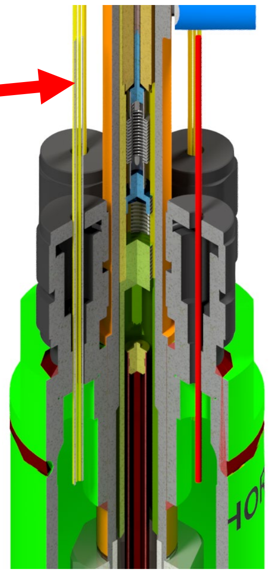
LVDT pressure sensor

Acoustic emissions sensor

LVDT fuel elongation sensor (special case)

TREAT hodoscope

PIE (Pre/Post)



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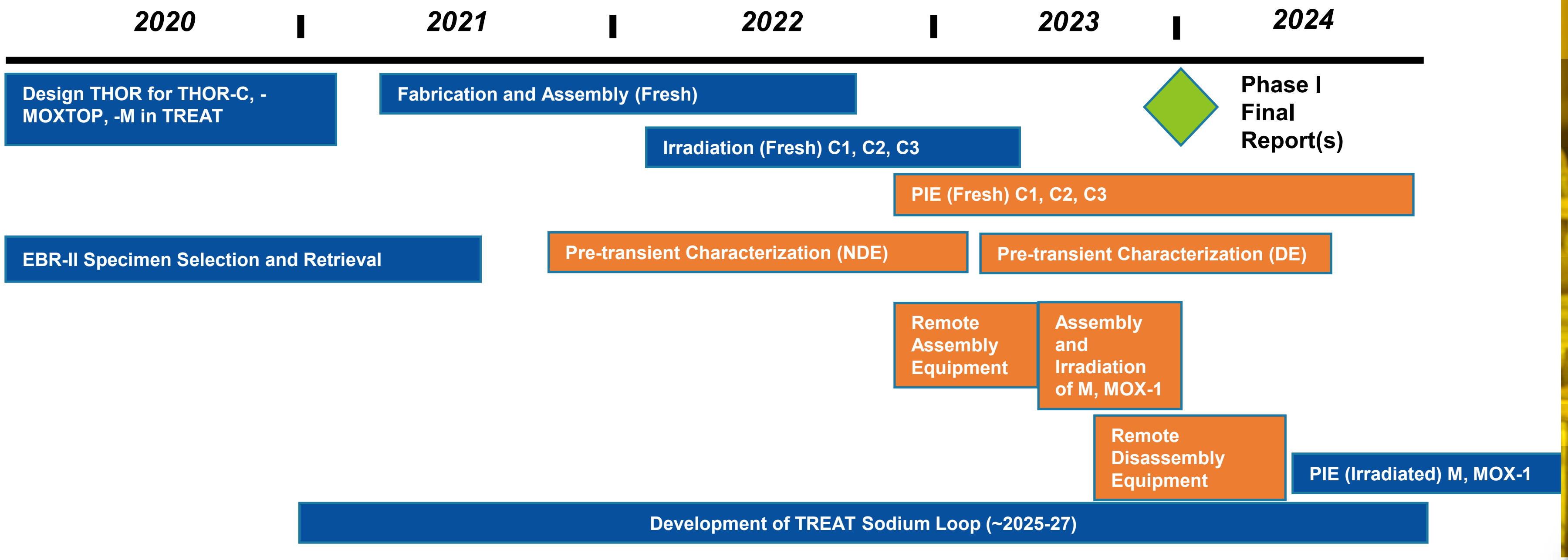
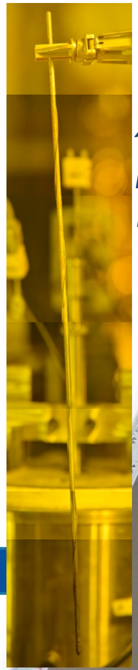
Instrumentation also requires hot cell compatibility

FY23 Scope

- Supporting the Advanced Reactor Experiments for Sodium Fast Reactor Fuels (ARES) Project
  - Remote assembly/disassembly of experiments using legacy irradiated EBR-II/FFTF fuels
  - Post-irradiation examination
  - Supports safety testing of advanced fuels, and JAEA/AFC joint project



Cask loaded with M-TOP-1



X441A ID#DP40 prior to loading in M-TOP-1

M-Top-1 capsule ready for Na and fuel loading

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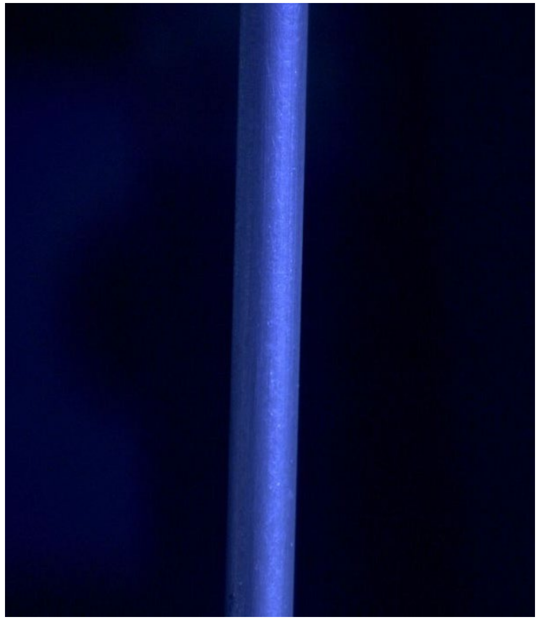
THOR-M-TOP-1 PIE

- THOR-M-TOP-1
  - TOP condition to creep driven failure mode (non-prototypic, phenomena focused)
  - Test & Sibling Pin (DP40 & DP36)
    - X441A High Burnup U-19Pu-10Zr, HT9
      - DP40 11.1 at%
      - DP36 11.2 at%
    - NDE Completed: Visual, Profilometry, Neutron Radiography, Gamma Spectroscopy
    - DE Completed: Gas Puncture/Analysis, Sectioning, Optical Microscopy
      - Sibling Pin Only (DP36)

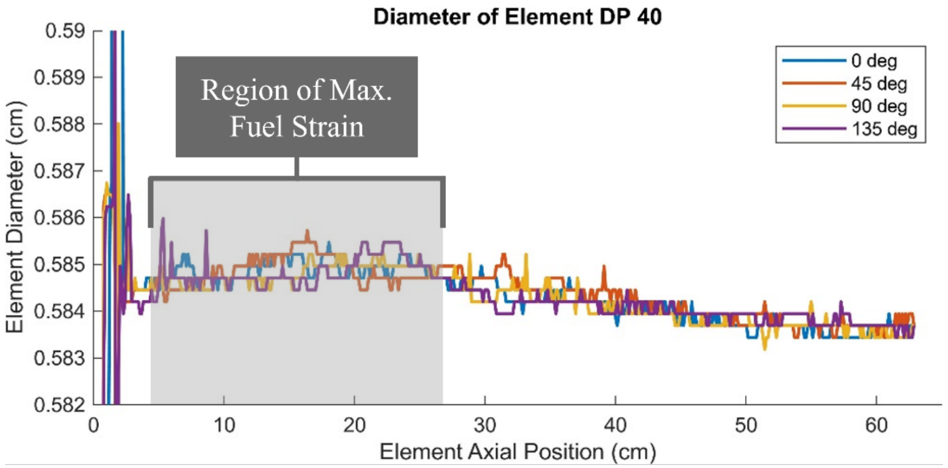
- Pre-transient PIE provides information on fuel state that influences predictions of fuel pin behavior:
  - *Geometry* → Profilometry, neutron radiography
  - *Location of isotopic inventory* → gamma spectroscopy
  - *Plenum pressure* → gas puncture and analysis
  - *Radial and axial fuel restructuring, porosity and cladding wastage* → optical microscopy

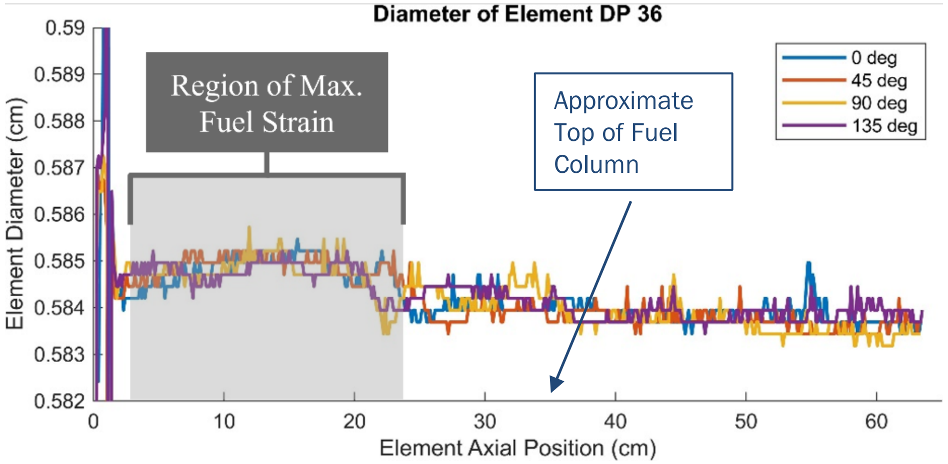
Pre-Transient Visual and Dimensional Analysis for THOR-M-TOP-1 Test Pin and Sibling Pin

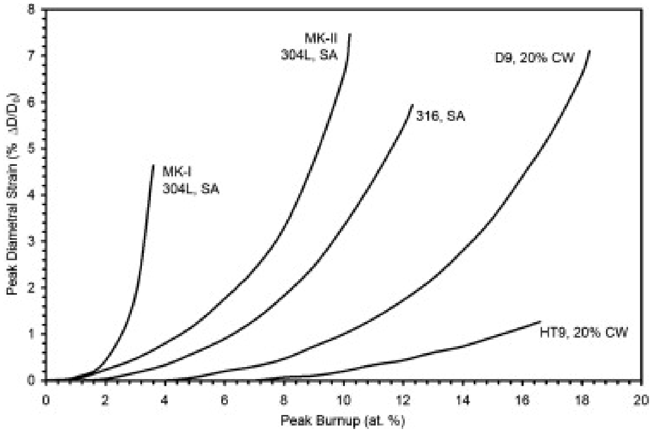
- Visual Inspection
  - No pin breach or corrosion detected
- Profilometry
  - Max Cladding Strain: 0.3% +/-0.14%
  - Modest Fuel Clad Mechanical Interaction



Through window image of X441A-DP40







Profilometer data is consistent with historic data: https://doi.org/10.1016/j.jnucmat.2009.02.035

- Porter and Crawford Proposed a Cladding Strain Limit of 1% (https://doi.org/10.1080/00295639.2021.2009983)
- Cladding failure due to strain is expected at ~6%. (https://doi.org/10.13182/NT92-325)

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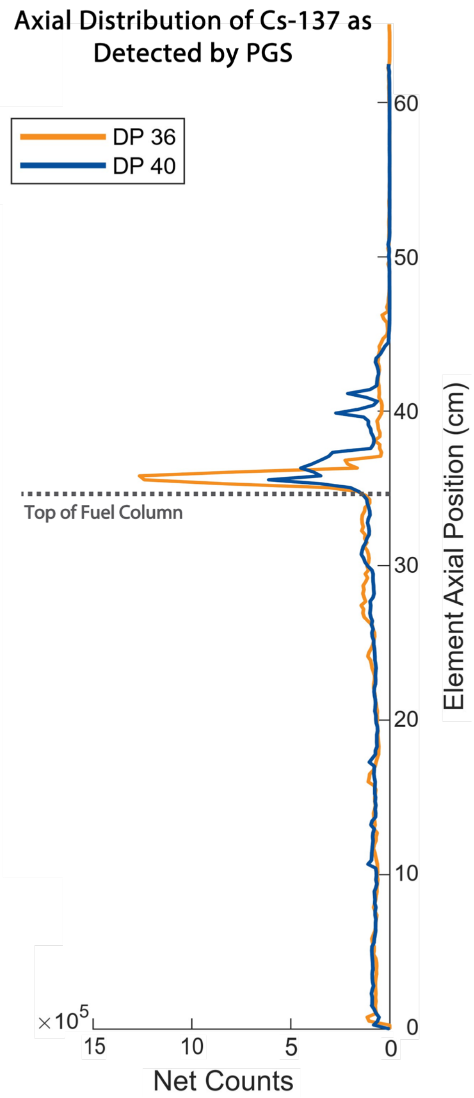
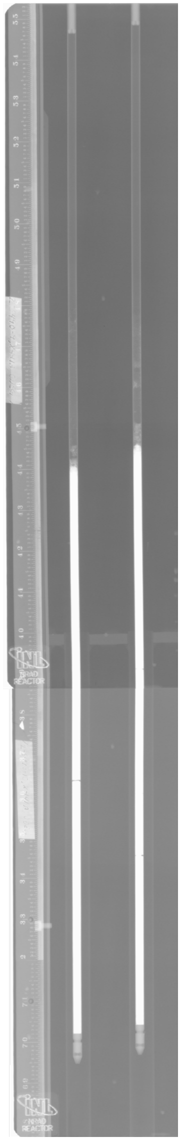
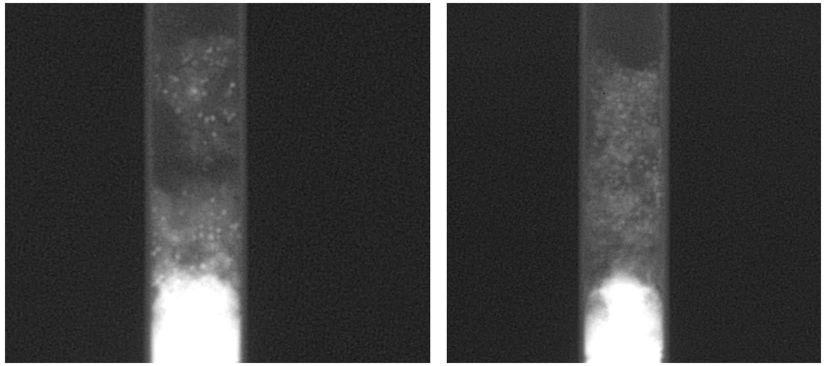
Pre-Transient Neutron Radiography and Gamma Scan Analysis for THOR-M-TOP-1 Test Pin and Sibling Pin





Neutron radiograph of DP-36 (left) and DP-40 (right)

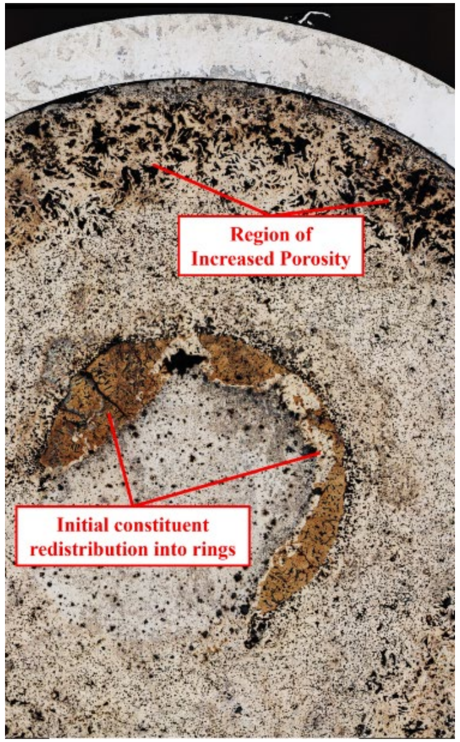
- Neutron Radiography
  - Axial Elongation
    - 3.65% for DP40
    - 2.15% for DP36
  - Low-density fuel-fission product fluff structure at top of fuel column
- Precise Gamma Spectroscopy
  - Cs-137 dissolved in Na bond and mobilized to the top of fuel column

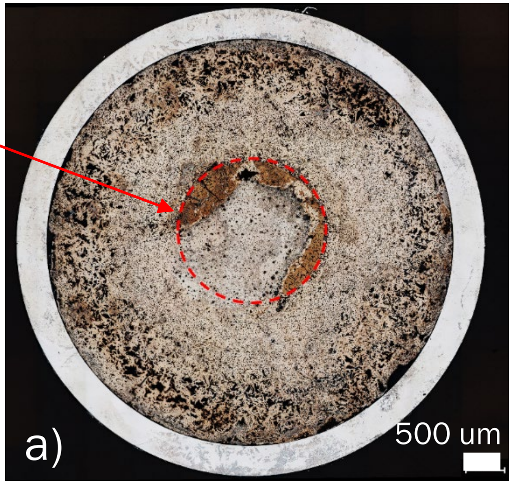


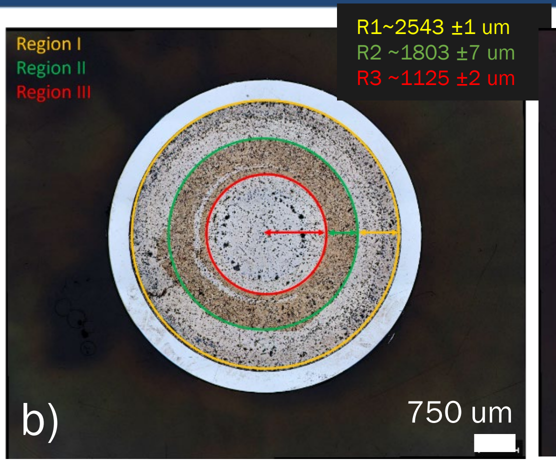
Neutron Radiographs showing fluff structure of DP-36 (left) and DP-40 (right)

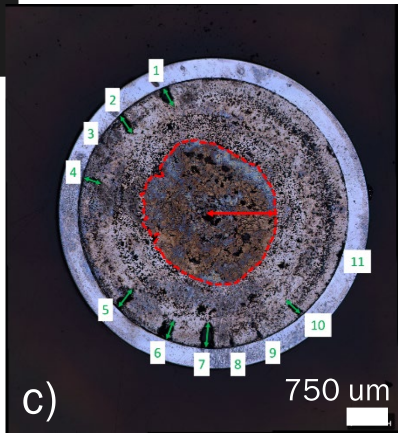
Sectioning and Destructive Testing Plan for THOR-M-TOP-1 Sibling Pin, DP36

R=~911 ±3 um

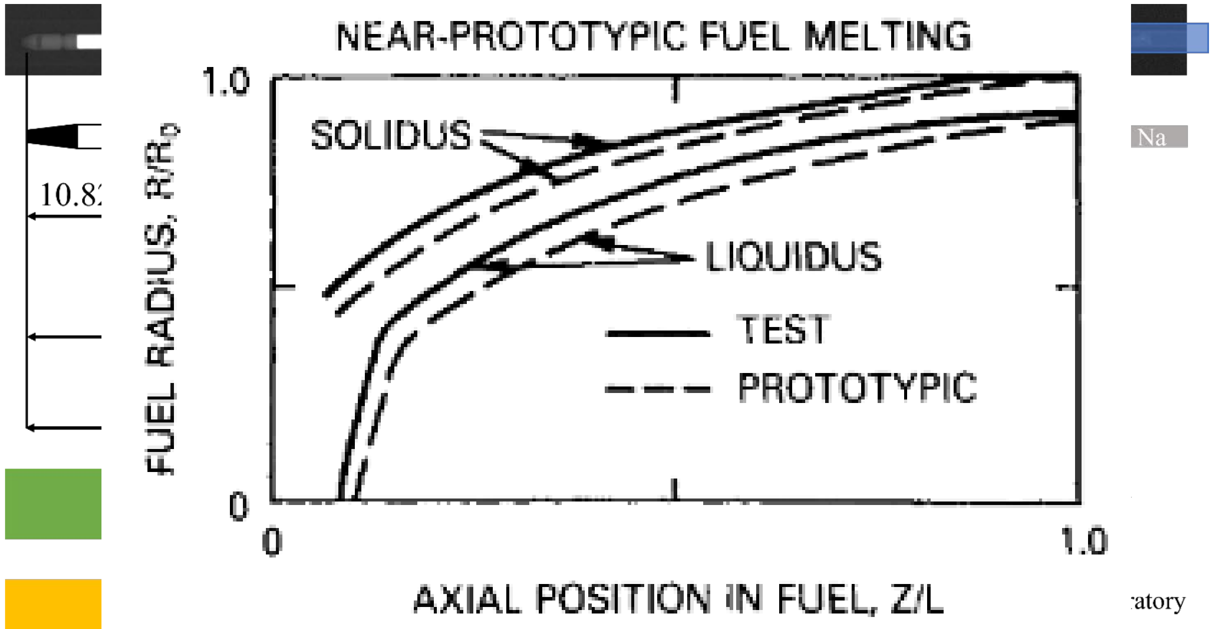


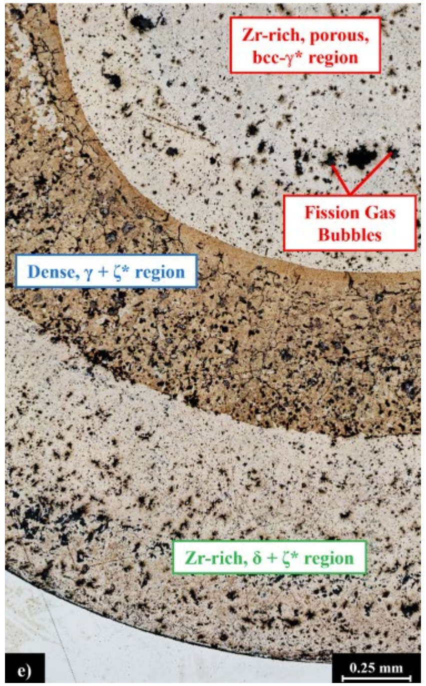






Area of Central Region (mm3)	5.03 ± 0.02
Average Radius of Central Region (um)	1256 ± 13
Length of Crack 1 (um)	403 ± 4
Length of Crack 2 (um)	402 ± 3
Length of Crack 3 (um)	347 ± 6
Length of Crack 4 (um)	440 ± 10
Length of Crack 5 (um)	317 ± 4
Length of Crack 6 (um)	363 ± 4
Length of Crack 7 (um)	478 ± 4
Length of Crack 8 (um)	180 ± 1
Length of Crack 9 (um)	225 ± 2
Length of Crack 10 (um)	404 ± 3
Length of Crack 11 (um)	104 ± 2





Bauer et al. https://doi.org/10.13182/NT92-325

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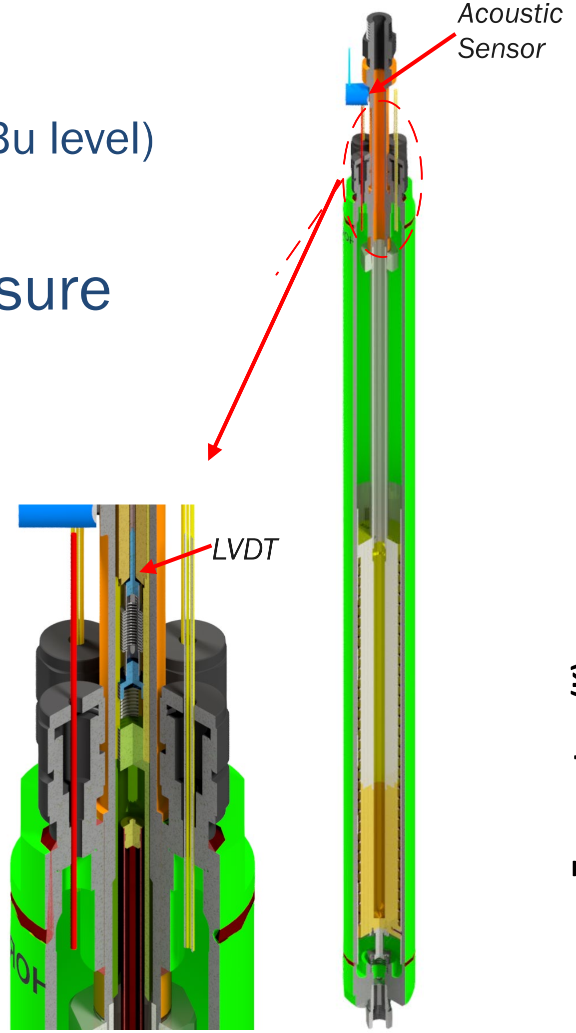
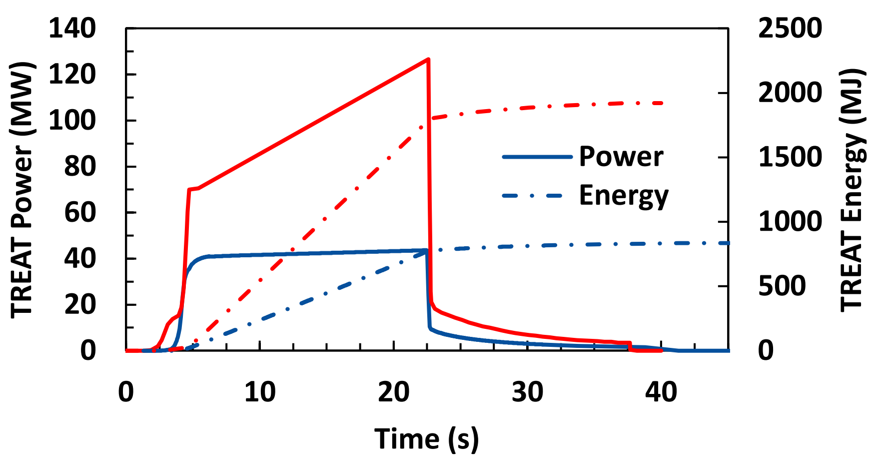
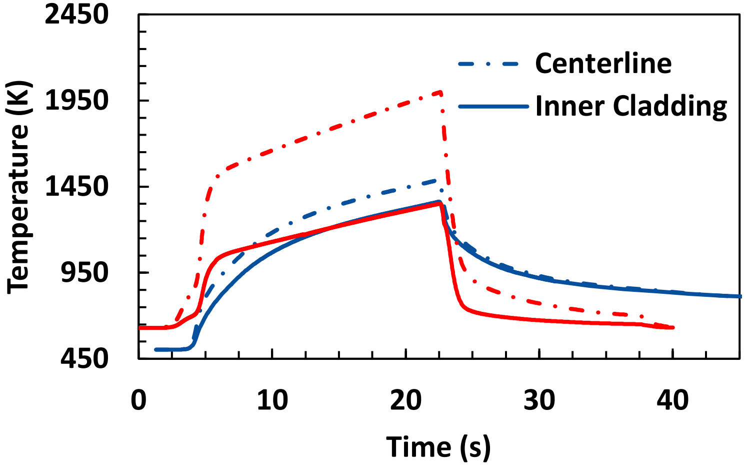
THOR-C-2: Failure diagnostics test

- Simulate fuel conditions designed for test M8 (never performed)
  - Fresh EBR-II Mk-IV metallic driver pin – repressurized to 1.5 MPa cold (near HBu level)
- Assess capsule diagnostics for detecting fuel failure using pressure and acoustic sensors
- Designed to fail due to cladding stress rupture exacerbated by cladding thinning due to eutectic liquefaction.







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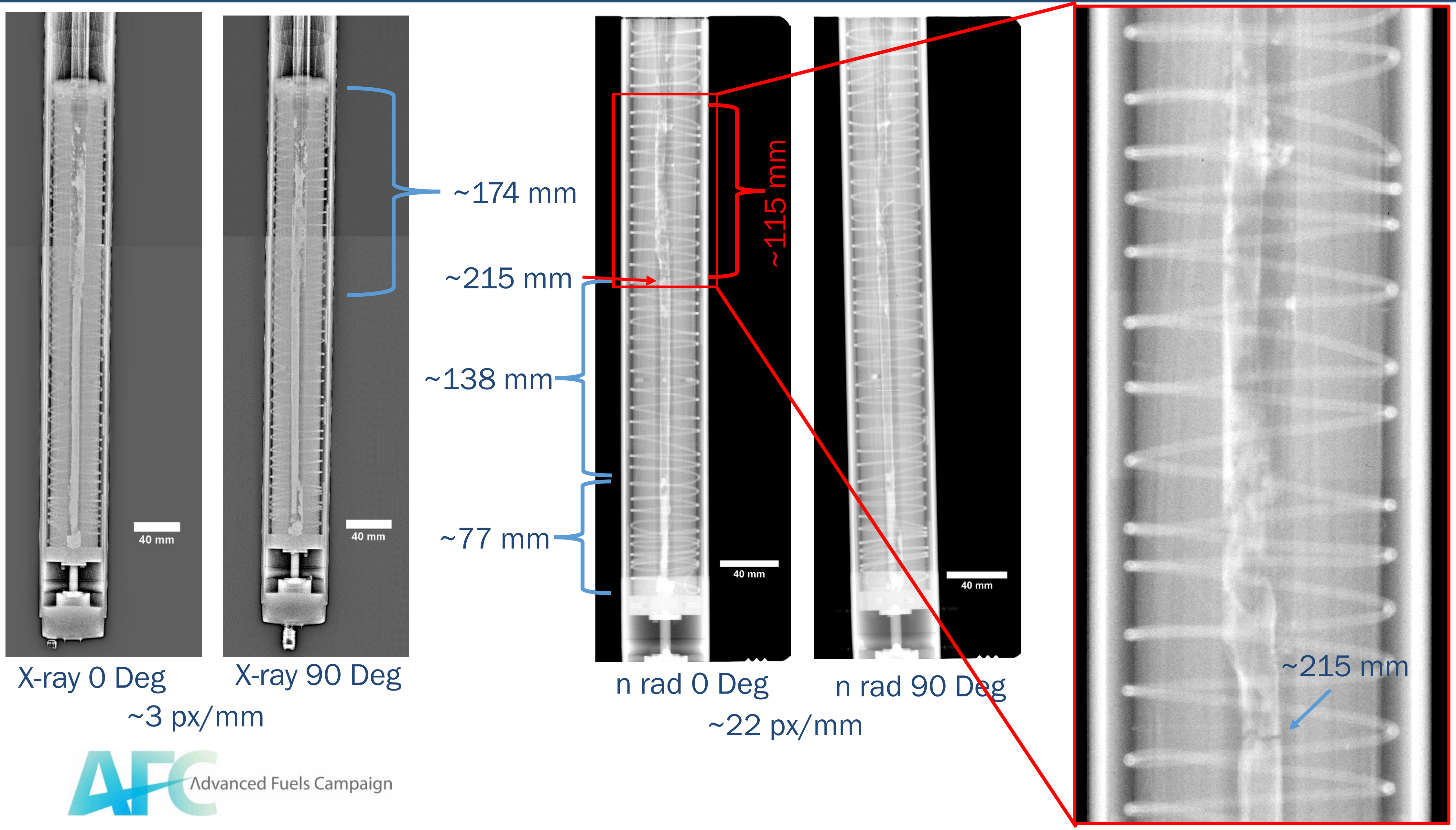
THOR-C2 Radiography



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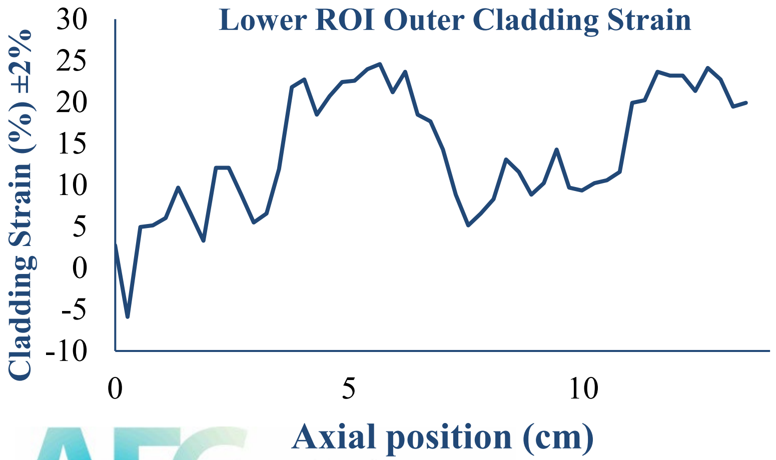
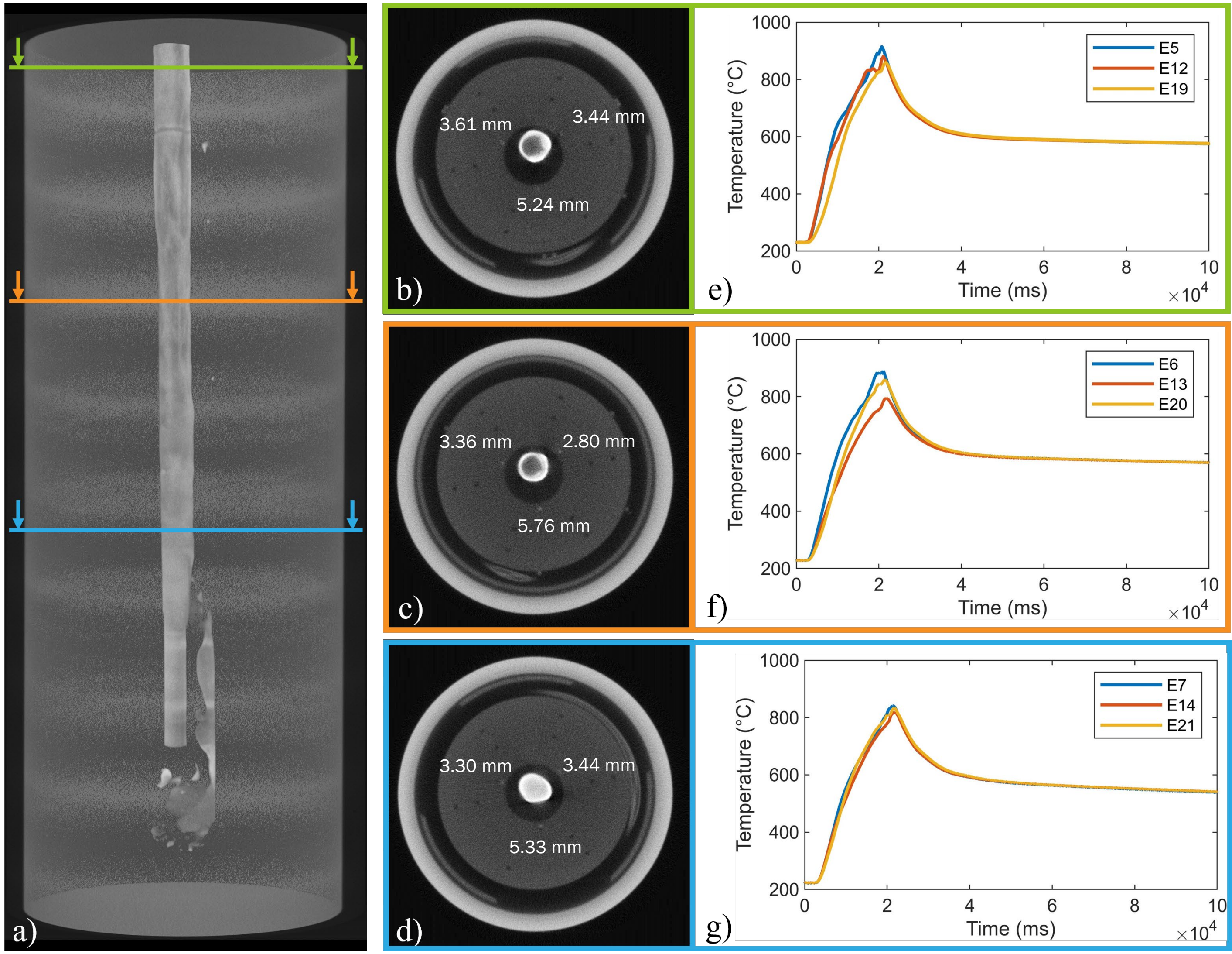
Thermal Pin Behavior during THOR-C-2 Transient Irradiation

- 3D nCT projected image of the lower region of interest (a)
  - Breached pin, expelled fuel
- Individual nCT slice showing thermocouple (TC) locations above the bottom of the fuel column at:
  - ~12.5 cm (b),
  - ~8.3 cm (c), and
  - ~4.1 cm (d) above the bottom of the fuel stack
- Corresponding TC temperature readings to axial positions (e,f,g)





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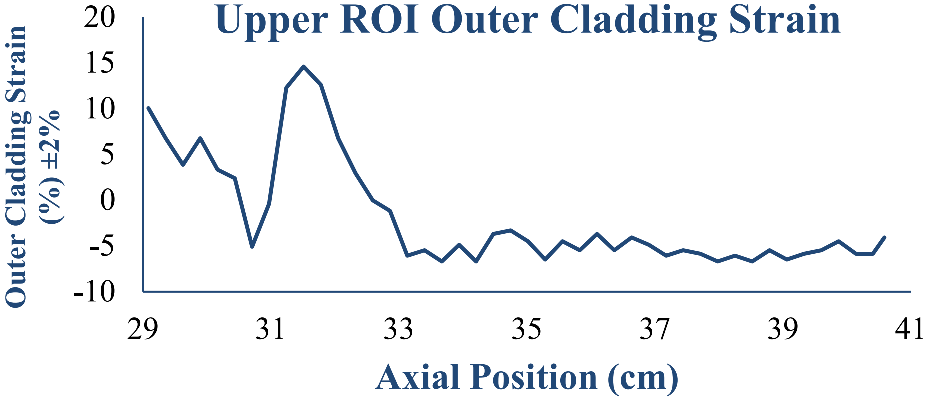
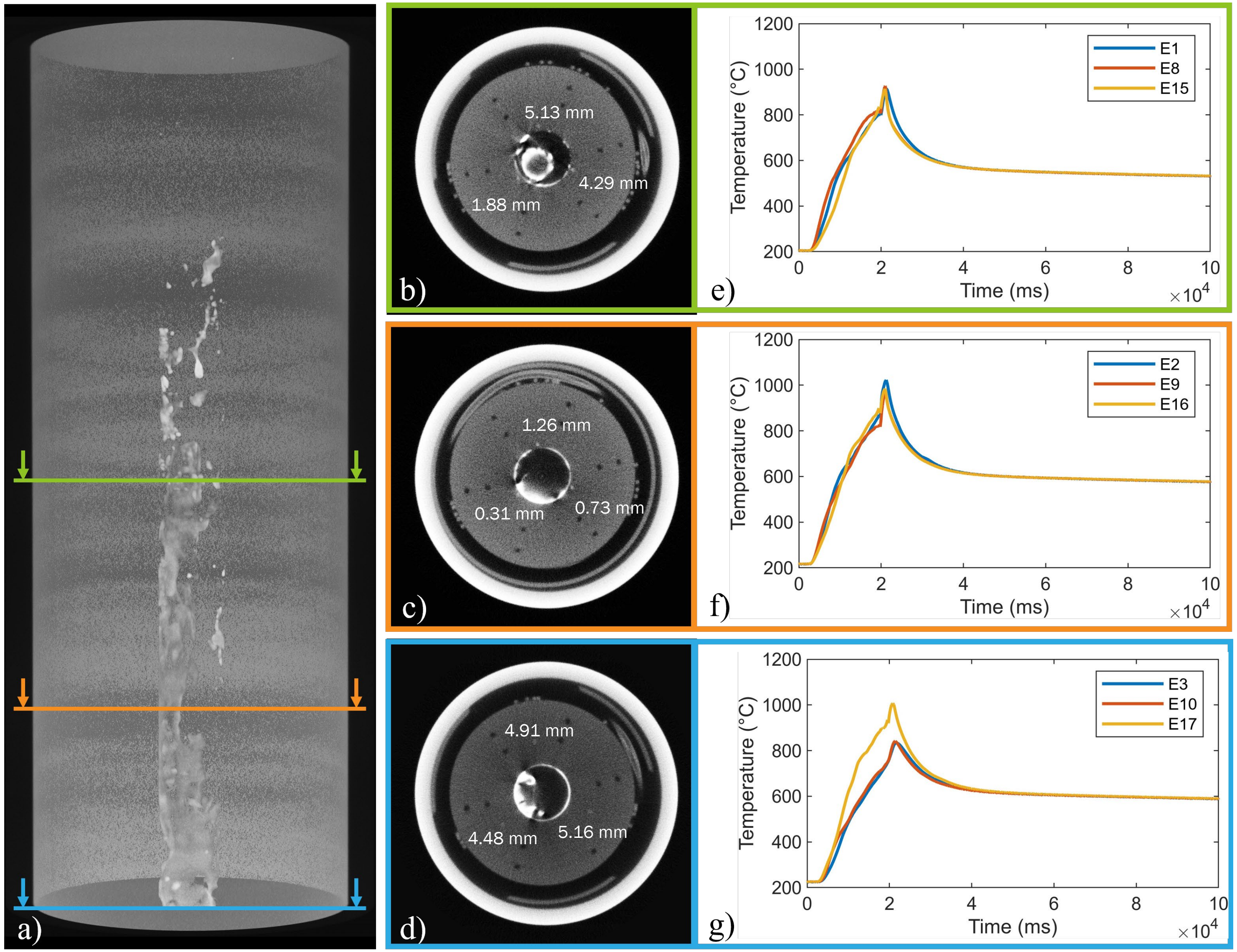
Thermal Pin Behavior during THOR-C-2 Transient Irradiation

- 3D nCT projected image of the upper region of interest (a)
- Individual nCT slice showing TC locations above the bottom of the fuel column at:
  - ~29.7 cm (b),
  - ~25.4 cm (c), and
  - ~23.9 cm (d) above the bottom of the fuel stack
- Corresponding TC temperature readings to axial positions (e,f,g)
  - Higher temp. of E17 indicates TC closest to relocated fuel (g)
  - Axial position for TCs in (g) is ~21.1 cm





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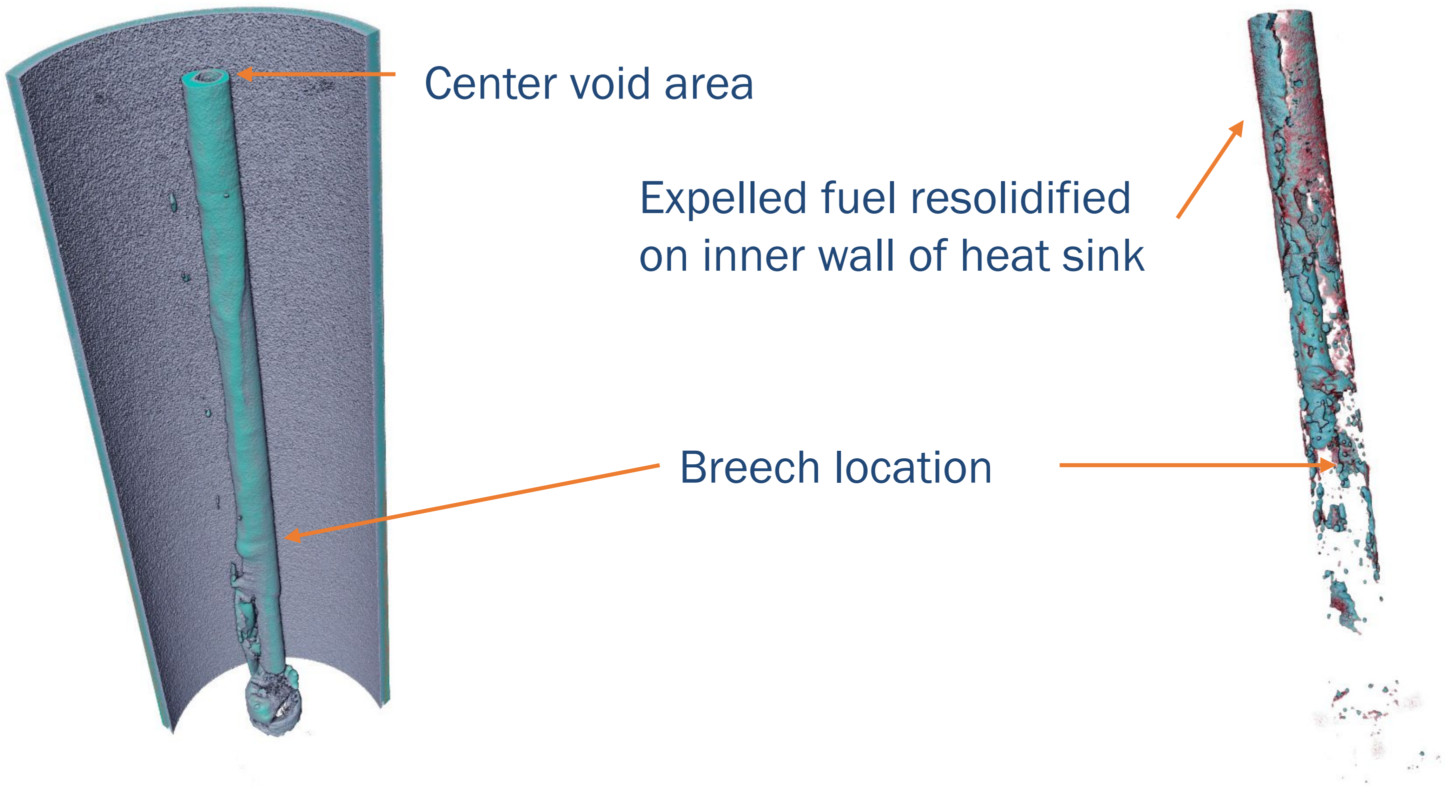
THOR-C2 Radiography Renderings

- Lower Region
- Upper Region



Next steps

- Complete install and demonstration of THOR Capsule Disassembly Equipment
- Disassemble THOR-M-TOP, THOR-C2, THOR-MOXTOP-1
- PIE
- Assemble THOR-MLOF, THOR-MOXTOP-2

Questions?

Clean. Reliable. Nuclear.

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