INL/MIS-23-75009-Revision-0

PIE Approaches to LOCA Specimens

October 2023

Changing the World's Energy Future

Jason L Schulthess, Colby B Jensen, William C Chuirazzi, Philip G Petersen, Jordan M Argyle, Jerry Anthony Kahn III, Chase Ellsworth Christen, John Allen Stinger, Spencer Hugh Parker, Justin Des Yarrington, Clayton G Turner

Idaho National Laboratory

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INL/MIS-23-75009

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PIE Related Focus Areas

- INL has a broad suite of PIE capabilities that will be utilized to perform pre-LOCA test and post-LOCA test analysis. These include as examples engineering scale profilometry and neutron radiography, and low length scale electron microscopy (SEM, EPMA, TEM, SIMS).
- Intent of this discussion is to discuss approaches/methodology related to the following:
  - Quantifying the strain displacement of the balloon affected region
  - Quantifying the burst opening size
  - Quantifying the dispersed mass
  - Quantifying the relocated mass/packing fraction
  - etc

PIE Related Focus Areas

- Why focus on these areas?
  - Address specific issues identified in the community regarding the NRC Research Information Letter

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

RIL 2021-13

Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal at High Burnup

DRAFT

Date Published: [Month] 2021

Prepared by:
Bales, Michelle
Chung, Alice
Corson, James
Kyriazidis, Lucas

EPRI

Technical Expert Panel Assessment of Existing Fuel Fragmentation, Relocation, and Dispersal Data

Current Understanding and Needs for Future Research

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Axial fuel relocation is the vertical movement of fuel fragments within the cladding. Under normal operation, this process is usually limited by the fuel pellet immediately above or below the pellet in question. For the purpose of this RIL, axial fuel relocation is said to have occurred if postirradiation examination reveals that fuel fragments have moved axially relative to their original location. Evidence that would support this determination includes empty regions of the cladding rod or the observation of additional fuel material in the enlarged volume of the balloon region, or both. In the remaining discussion, "fuel relocation" refers to "axial fuel relocation."

Mobile fuel—Some of the test programs discussed in this RIL aimed to characterize the total amount of fuel that could relocate, even if the relocation did not occur during transient testing. The total amount of fuel that was mobile was often investigated experimentally by minor shaking of the test segment after testing, including inverting the test segment to shake loose fuel fragments from the portion below any ballooned or burst region. Even after shaking, some fuel remained in the test segments, indicating that not all of the fuel fragments were able to move. The fuel that was able to move

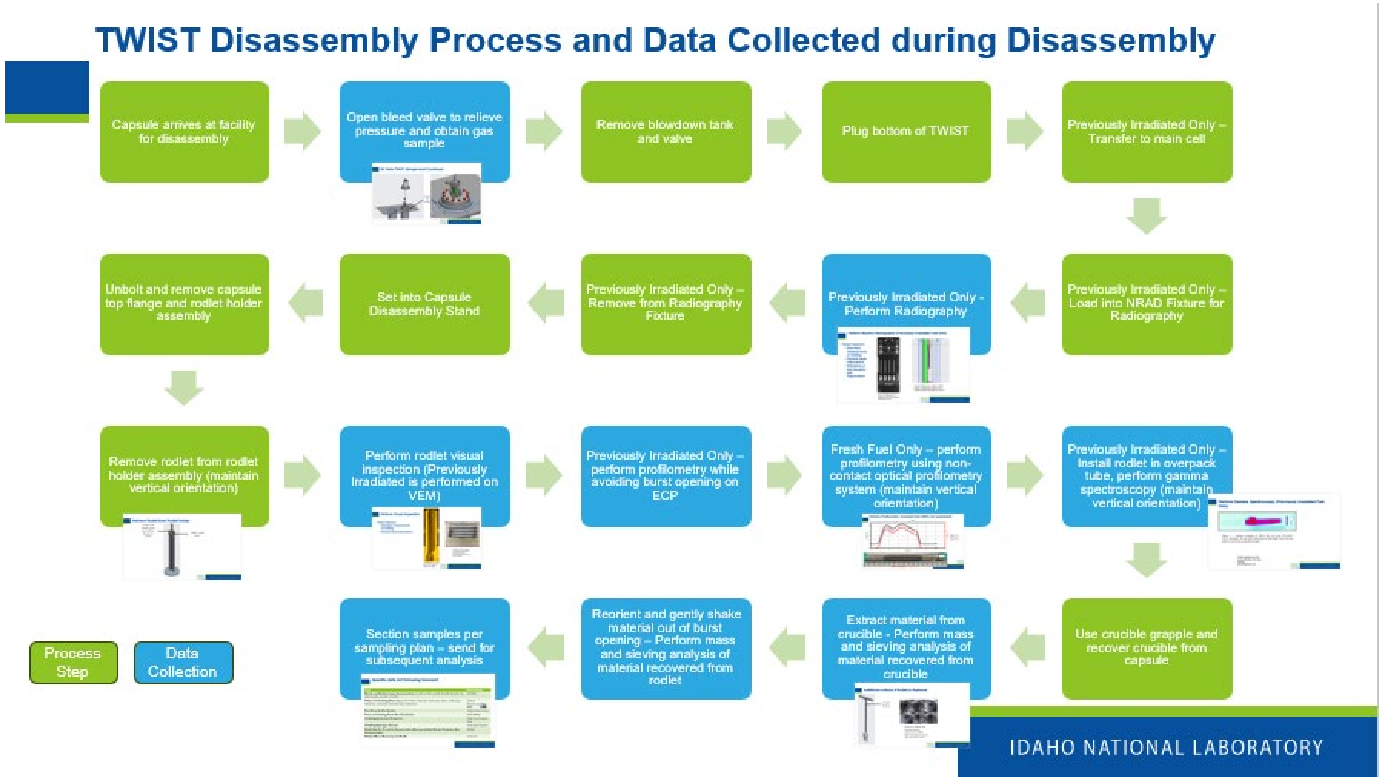
during this shaking procedure was added to any fuel dispersed during transient testing to understand more about the mobility of fuel fragments.

Fuel dispersal—Fuel dispersal is the ejection of fuel fragments or particles through a burst or opening in the cladding into the coolant. As this RIL will discuss, the amount of fuel dispersed during testing varied greatly, and a number of factors influenced dispersal. The RIL will discuss not only fuel that dispersed during the test and was collected from the bottom of the test equipment immediately following transient testing, but also mobile fuel as fuel that could be dispersed under different conditions. It is the position of this RIL that all mobile fuel is susceptible to dispersal and that actual fuel dispersal will depend on several factors.

conditions in an operating reactor. Based on the analysis, the staff recommends a model that will predict the mass of fuel dispersal to be that all fuel will disperse that is above a burnup of 55 GWd/MTU in the length of the rod with greater than 3-percent cladding strain.

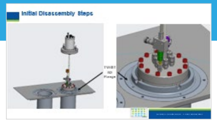
Known Confounding Factors

- Transportation in cask between TREAT and HFEF
- Hot cell handling to disassemble
- These operations may cause additional dispersal of fuel mass out of the burst opening

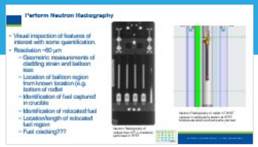


TWIST Disassembly Process and Data Collected during Disassembly

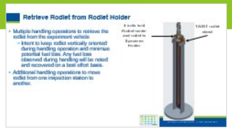
1. Capsule arrives at facility for disassembly
2. Open bleed valve to relieve pressure and obtain gas sample



3. Remove blowdown tank and valve
4. Plug bottom of TWIST
5. Previously Irradiated Only – Transfer to main cell
6. Previously Irradiated Only – Load into NRAD Fixture for Radiography
7. Previously Irradiated Only - Perform Radiography

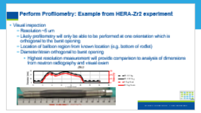


8. Previously Irradiated Only – Remove from Radiography Fixture
9. Set into Capsule Disassembly Stand
10. Unbolt and remove capsule top flange and rodlet holder assembly
11. Remove rodlet from rodlet holder assembly (maintain vertical orientation)

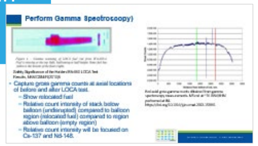


12. Perform rodlet visual inspection (Previously Irradiated is performed on VEM)

13. Previously Irradiated Only – perform profilometry while avoiding burst opening on ECP
14. Fresh Fuel Only – perform profilometry using non-contact optical profilometry system (maintain vertical orientation)

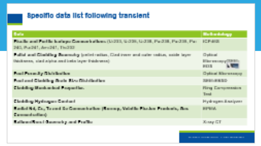


15. Previously Irradiated Only – Install rodlet in overpack tube, perform gamma spectroscopy (maintain vertical orientation)



16. Use crucible grapple and recover crucible from capsule
17. Extract material from crucible - Perform mass and sieving analysis of material recovered from crucible

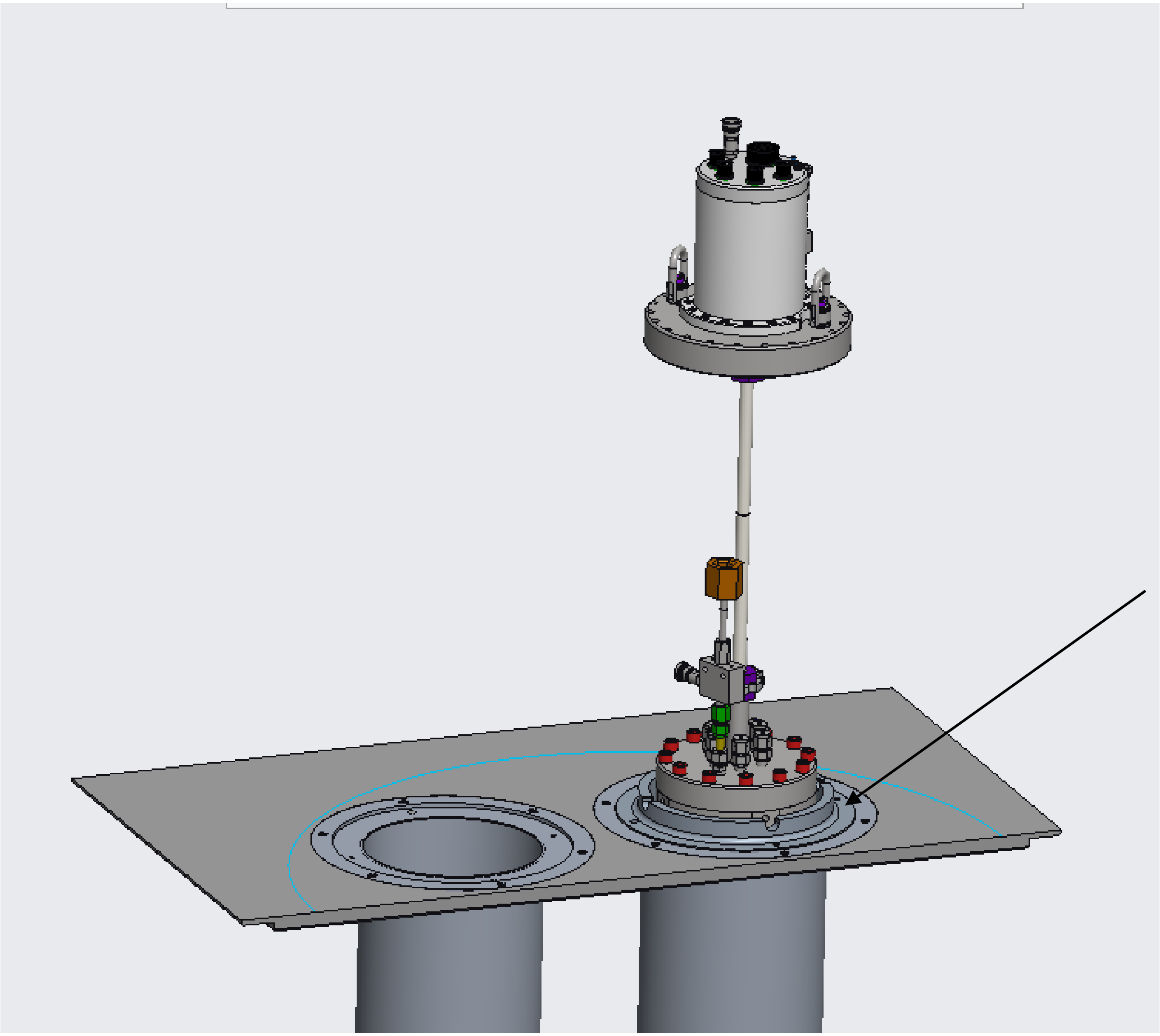
18. Reorient and gently shake material out of burst opening – Perform mass and sieving analysis of material recovered from rodlet
19. Section samples per sampling plan – send for subsequent analysis



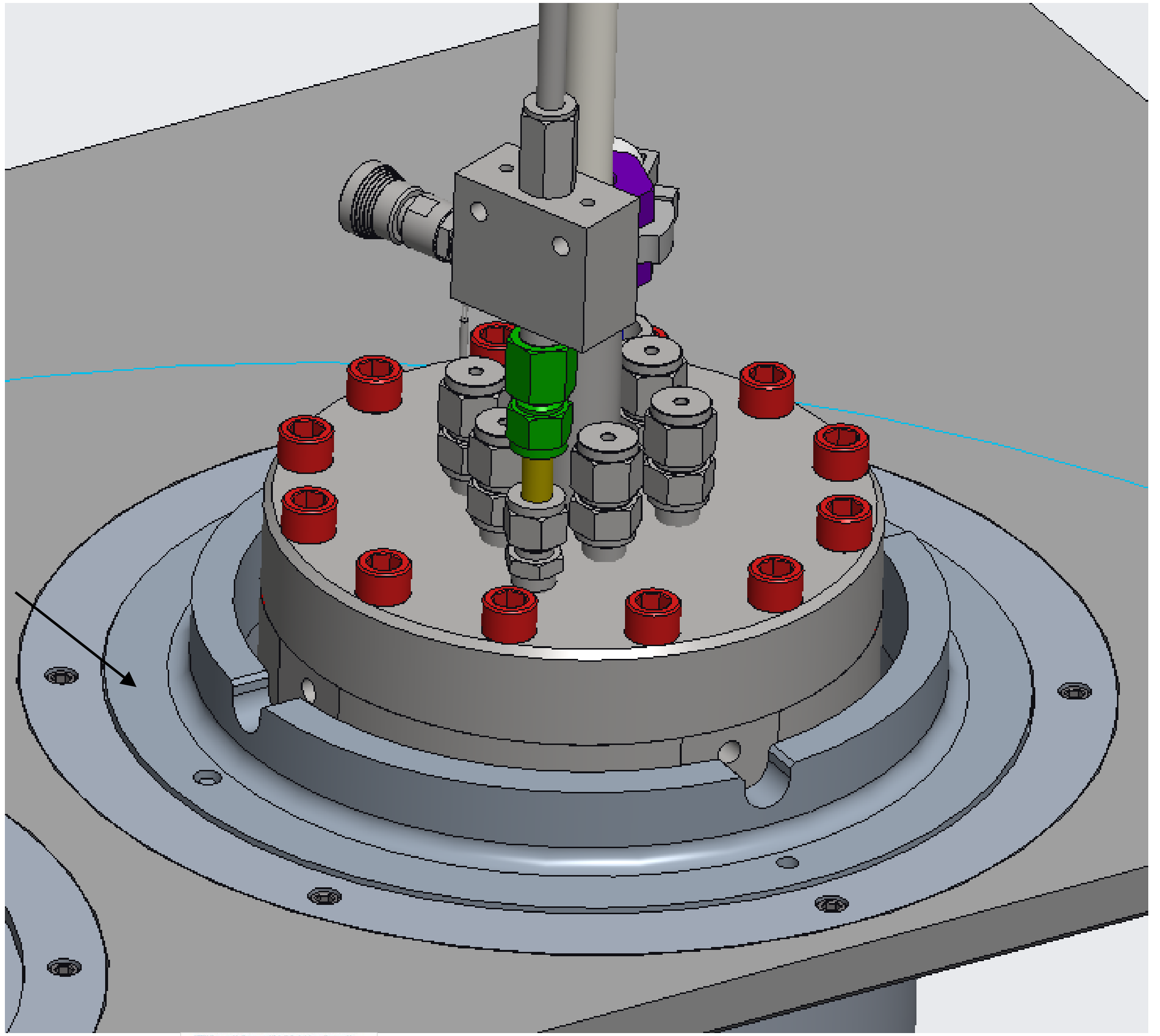
Process Step

Data Collection

Initial Disassembly Steps

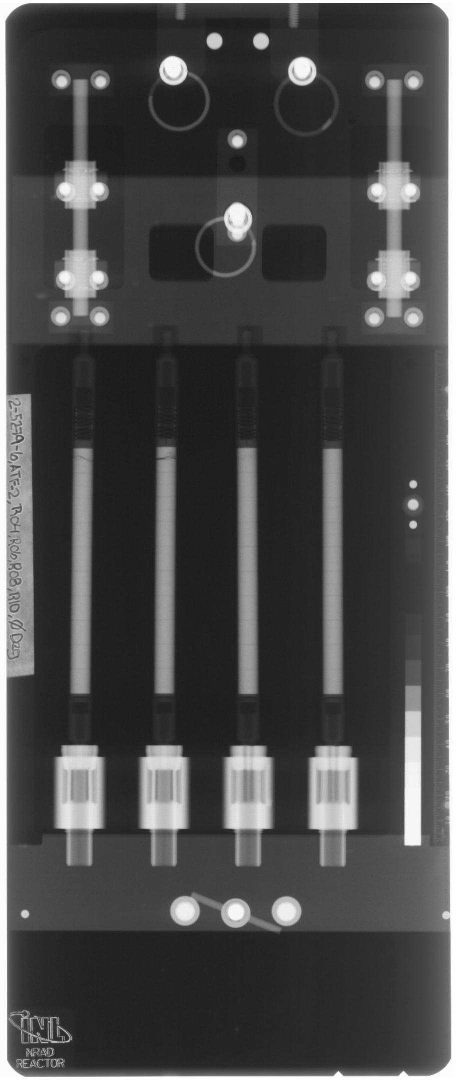


TWIST
5D
Flange

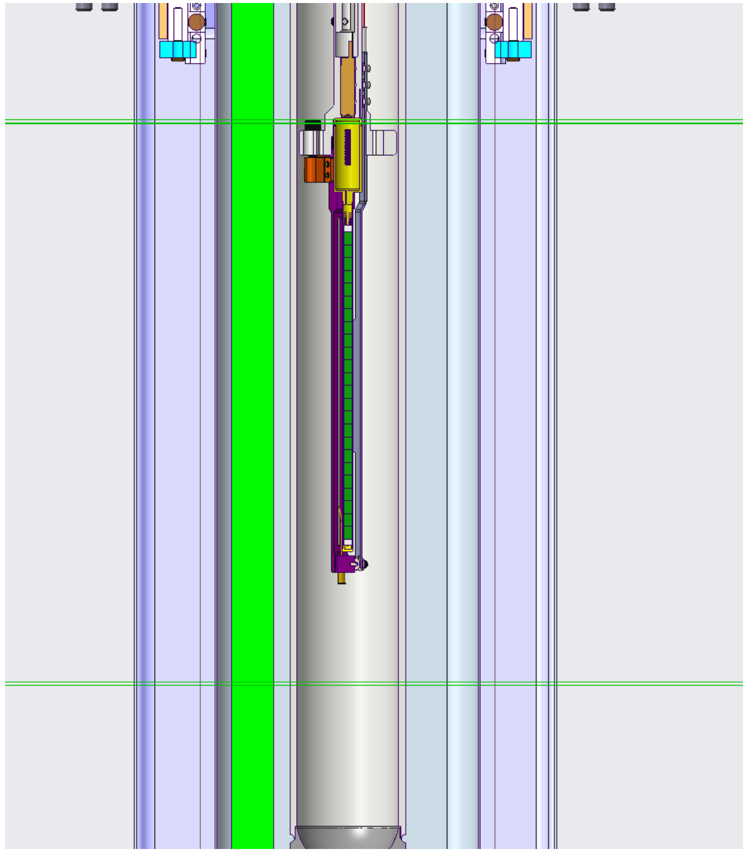


Perform Neutron Radiography

- Visual inspection of features of interest with some quantification.
- Resolution ~60 μm
  - Geometric measurements of cladding strain and balloon size
  - Location of balloon region from known location (e.g. bottom of rodlet
  - Identification of fuel captured in crucible
  - Identification of relocated fuel
  - Location/length of relocated fuel region
  - Fuel cracking???



Neutron Radiography of rodlets from ATF-2 Irradiation performed in HFEF



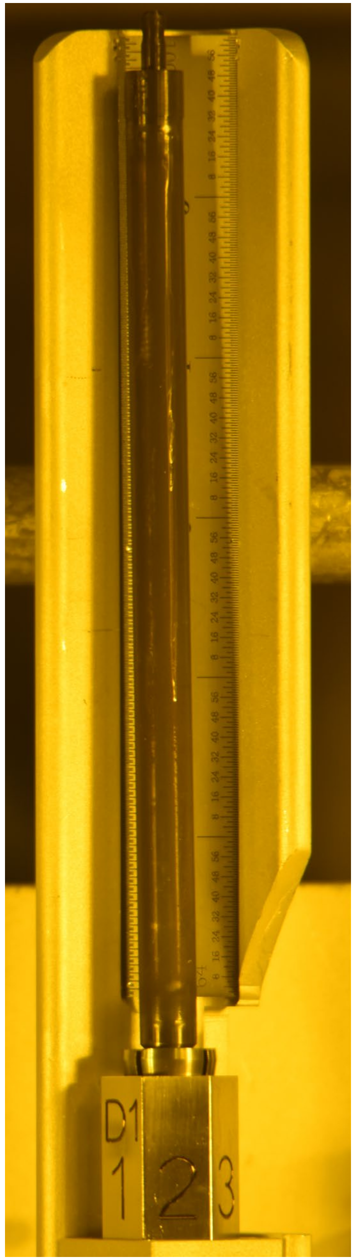
Neutron Radiography of rodlet in TWIST capsule in radiography station at HFEF. Multiple elevations and azimuths planned.

Retrieve Rodlet from Rodlet Holder

- Multiple handling operations to retrieve the rodlet from the experiment vehicle
  - Intent to keep rodlet vertically oriented during handling operation and minimize potential fuel loss. Any fuel loss observed during handling will be noted and recovered on a best effort basis.
- Additional handling operations to move rodlet from one inspection station to another.

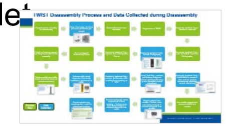
Perform Visual Inspection

- Visual inspection
  - Scale incorporated into image frame at the same plane as the center axis of the rodlet.
  - Multiple azimuthal rotations will be captured.
  - Geometric measurements of cladding strain and balloon size
  - Location of balloon region from known location (e.g. bottom of rodlet
  - Burst opening size
  - ~0.049 mm/px



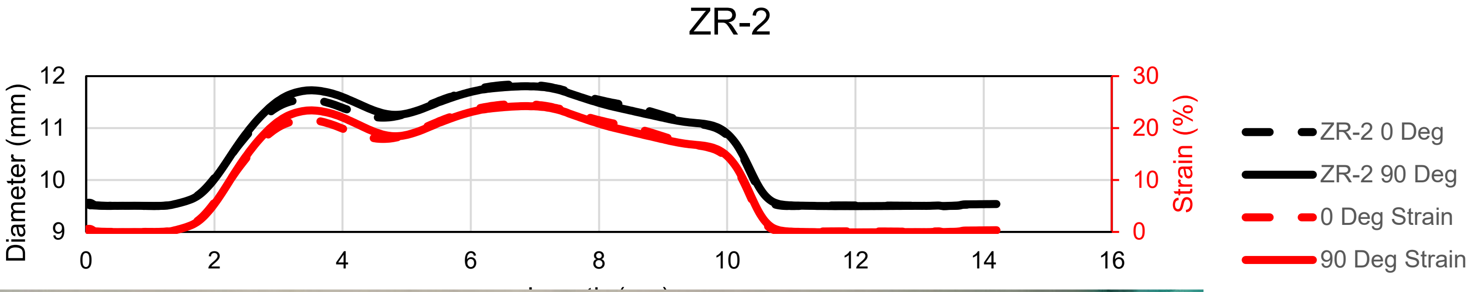
Visual Inspection of rodlet from ATF-2 Irradiation performed in HFEF

Example of Visual Inspection of rodlet after LOCA testing performed by ORNL https://doi.org/10.1016/j.jnucmat.2020.152750



Perform Profilometry: Example from HERA-Zr2 experiment

- Visual inspection
  - Resolution ~5 um
  - Likely profilometry will only be able to be performed at one orientation which is orthogonal to the burst opening
  - Location of balloon region from known location (e.g. bottom of rodlet)
  - Diameter/strain orthogonal to burst opening
    - Highest resolution measurement will provide comparison to analysis of dimensions from neutron radiography and visual exam



Perform Gamma Spectroscopy)

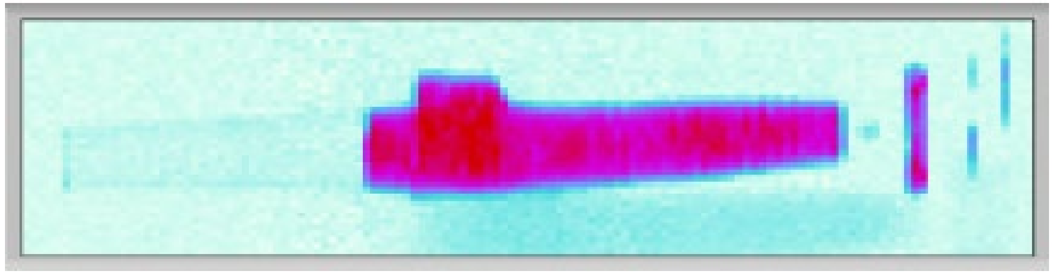
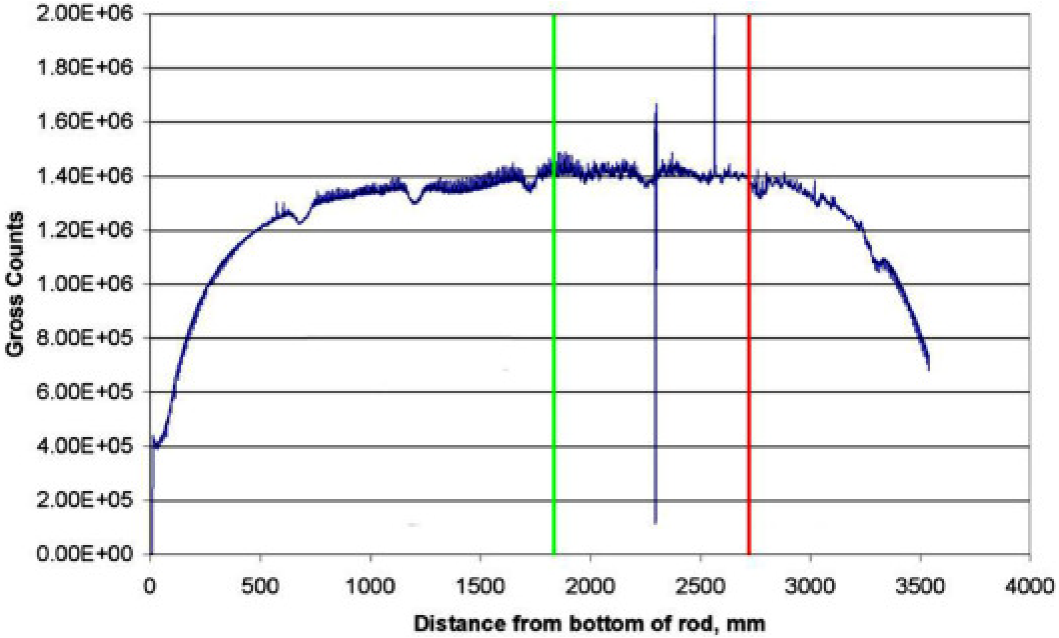


Figure 4 – Gamma scanning of LOCA fuel rod from IFA-650.4. Fuel is missing at the top (left), ballooning at half height. Some fuel has fallen to the bottom of the flask (right).

Safety Significance of the Halden IFA-650 LOCA Test Results, NEA/CSNI/R(2010)5

- Capture gross gamma counts at axial locations of before and after LOCA test.
  - Show relocated fuel
  - Relative count intensity of stack below balloon (undisrupted) compared to balloon region (relocated fuel) compared to region above balloon (empty region)
  - Relative count intensity will be focused on Cs-137 and Nd-148.



Rod axial gross gamma counts obtained from gamma spectroscopy measurements. M5 rod at ~76 GWd/tHM performed at INL https://doi.org/10.1016/j.jnucmat.2022.153881

Quantified Data

- Quantifying the strain displacement of the balloon affected region
- Quantifying the burst opening size
- Quantifying the dispersed mass
- Quantifying the relocated mass/packing fraction
  - Proposed that packing fraction be calculated based on the normalized Cs-137 counts from gamma spectroscopy divided by the calculated cross section area from the combination of profilometry, visual exam, and neutron radiography.

- Neutron Radiography of Capsule
- Visual Exam
- Profilometry
- Gamma Spectroscopy
- Mass Balance/Sieving

Decision Point

- At this point, the “dispersed mass” collected is only the mass collected from the crucible. The rodlet has been kept vertically oriented (to the extent possible) and no destructive actions have been performed.
- Others performed “shaking”, bending/breaking, and “wire extraction”
- Both the RIL and the EPRI document mention unquantified “LOCA Forces” but there is no direct connection between these unquantified forces and efforts to further extract the fragmented fuel.
- Options (will be discussed more on following slides):
  - 1) develop “shaking fixture”
  - 2) operator shaking, bending/breaking, “wire extraction”
  - 3) stabilize with epoxy, evaluate multiple cross sections
  - 4) defuel, perform xCT on defueled balloon segment
  - Others???

1) Shaking Fixture

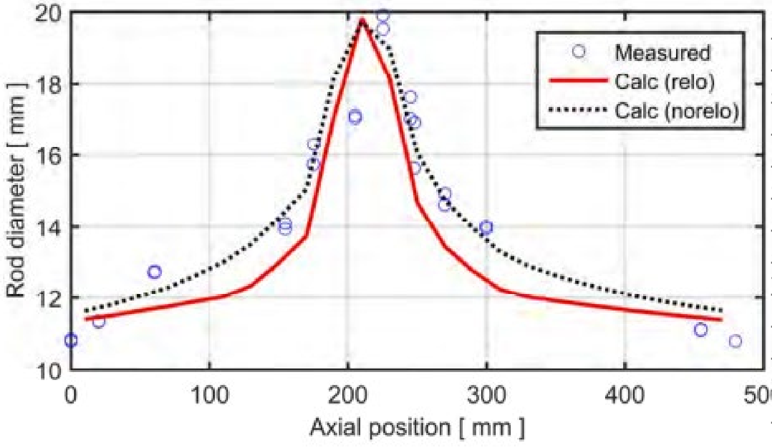
- Develop fixture to hold rodlet in shaking fixture and capture any fuel fragments that are expelled during shaking
- (+)
  - Rodlet maintains vertical orientation
  - Frequency and magnitude of shaking can be controlled
  - Subsequent analysis such as sections for microscopy or xCT can still performed
- (-)
  - No basis for connection to unspecified “LOCA Forces”
  - Not consistent with what others have performed in the open literature

2) Operator shaking, bending/breaking, “wire extraction”

- Operators perform shaking, inversion, bending/breaking on load frame, and wire extraction
- (+)
  - Consistent with others previous efforts
  - xCT could still be performed in the defueled segments and data stitched together
- (-)
  - No basis for connection to unspecified “LOCA Forces”
  - Limits potential microscopy that can be performed on the fuel accumulated in the balloon region

3) Stabilize with epoxy, evaluate multiple cross sections

- Cut rodlet above the balloon region (near the top of the now empty cladding region) stabilize with epoxy and perform analysis on multiple cross sections.
- (+)
  - Consistent with Halden approach on IFA-650.4
  - Microscopy captures details of fuel relocated to the balloon region and below the balloon region and allows high precision measurements of cladding diameter
  - Easiest option to perform, no additional equipment to develop
- (-)
  - Not consistent with approaches of others
  - xCT not possible



https://www.researchgate.net/profile/Lars-Jernkvist/publication/314875563_Computational_assessment_of_LOCA_simulation_tests_on_high_burnup_fuel_rods_in_Halden_and_Studsvik/links/58c6ddecaca272bcc1eccde3/Computational-assessment-of-LOCA-simulation-tests-on-high-burnup-fuel-rods-in-Halden-and-Studsvik.pdftational assessment of LOCA simulation tests on high burnup fuel rods in Halden and Studsvik (researchgate.net)

Fig. 10: Calculated and measured post-test diameter profiles for the IFA-650.4 rodlet [45].

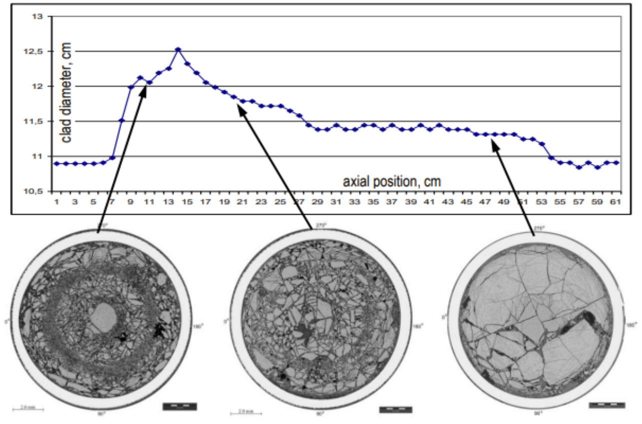


Figure 11 – Different cracking patterns obtained in IFA-650.5 (PCT 1050 °C). The diagram shows the change of cladding diameter along the length of the rod.

Safety Significance of the Halden IFA-650 LOCA Test Results, NEA/CSNI/R (2010)5

4) defuel, perform xCT on defueled balloon segment

- Cut segments above and below the balloon region, mechanically defuel to the extent possible, chemically defuel remainder, perform xCT
- (+)
  - Very high resolution of balloon geometry with ability to perform 3d reconstruction
  - Very high resolution of balloon volume
- (-)
  - Not consistent with prior approaches
  - What to do with “defueled” fuel mass
  - No microscopy of relocated fuel mass

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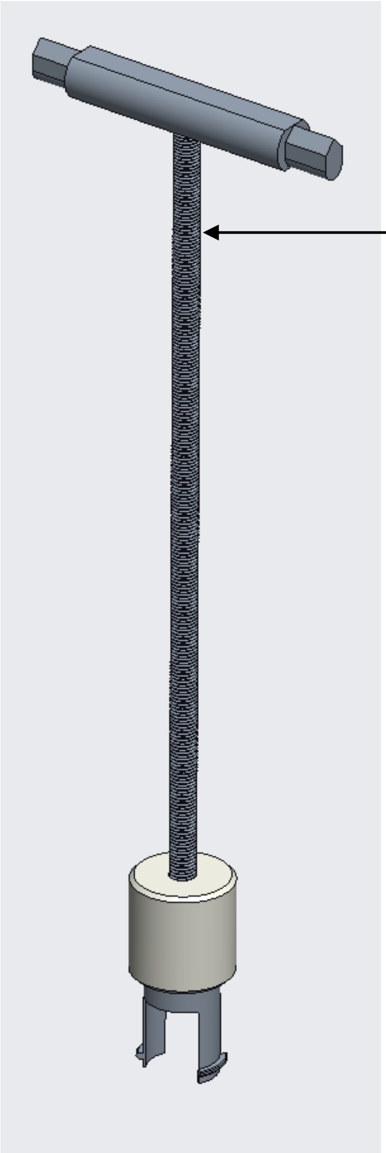
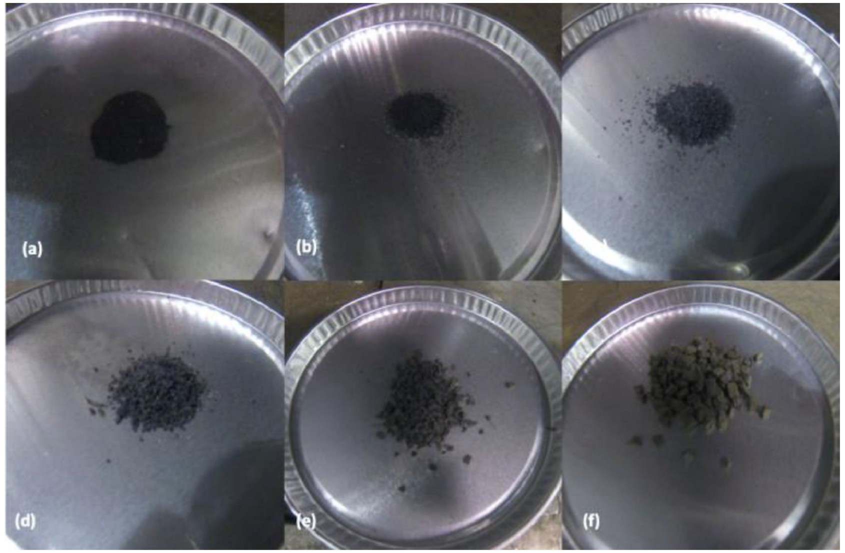
Backup Slides

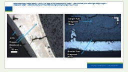
Additional Actions if Rodlet is Ruptured



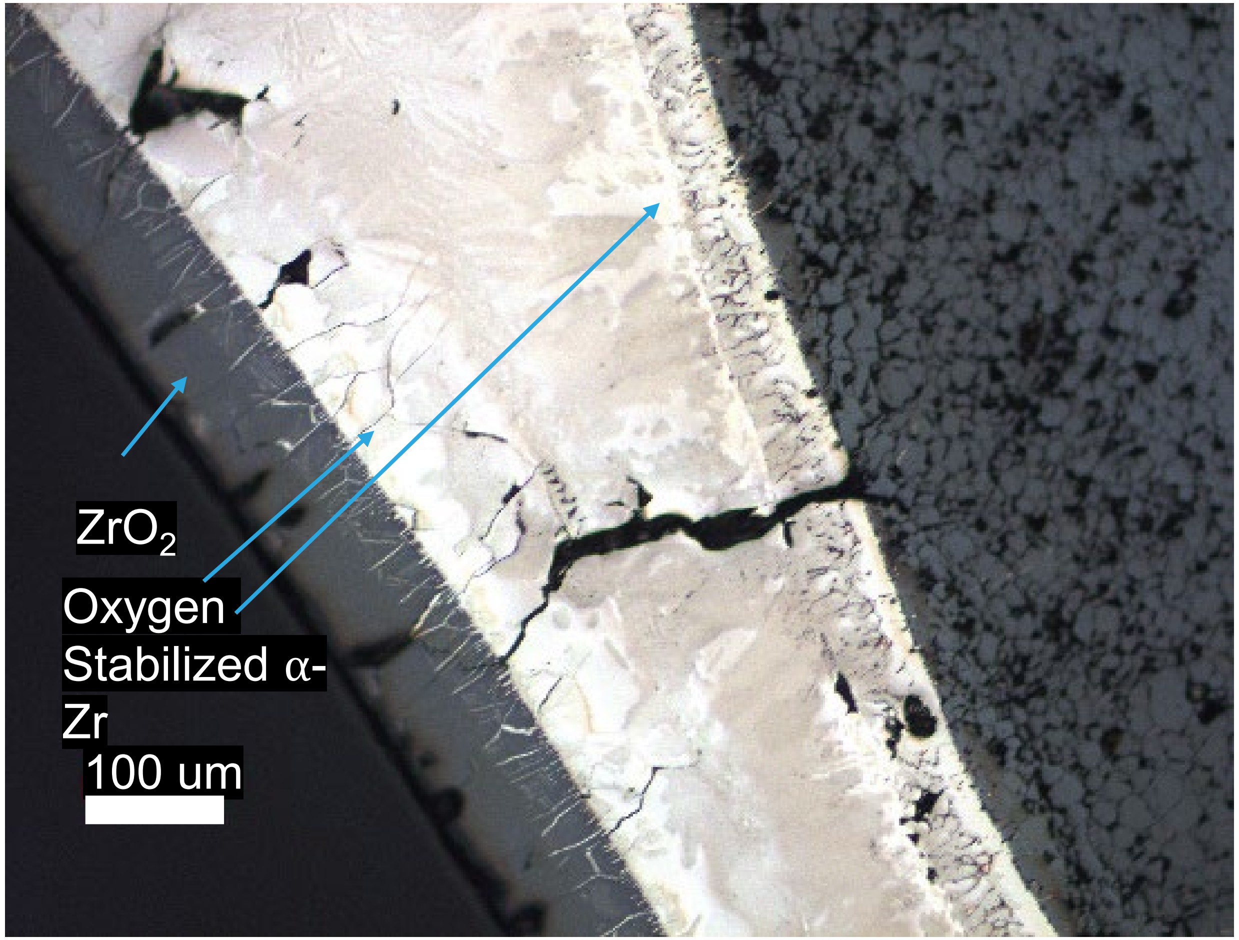


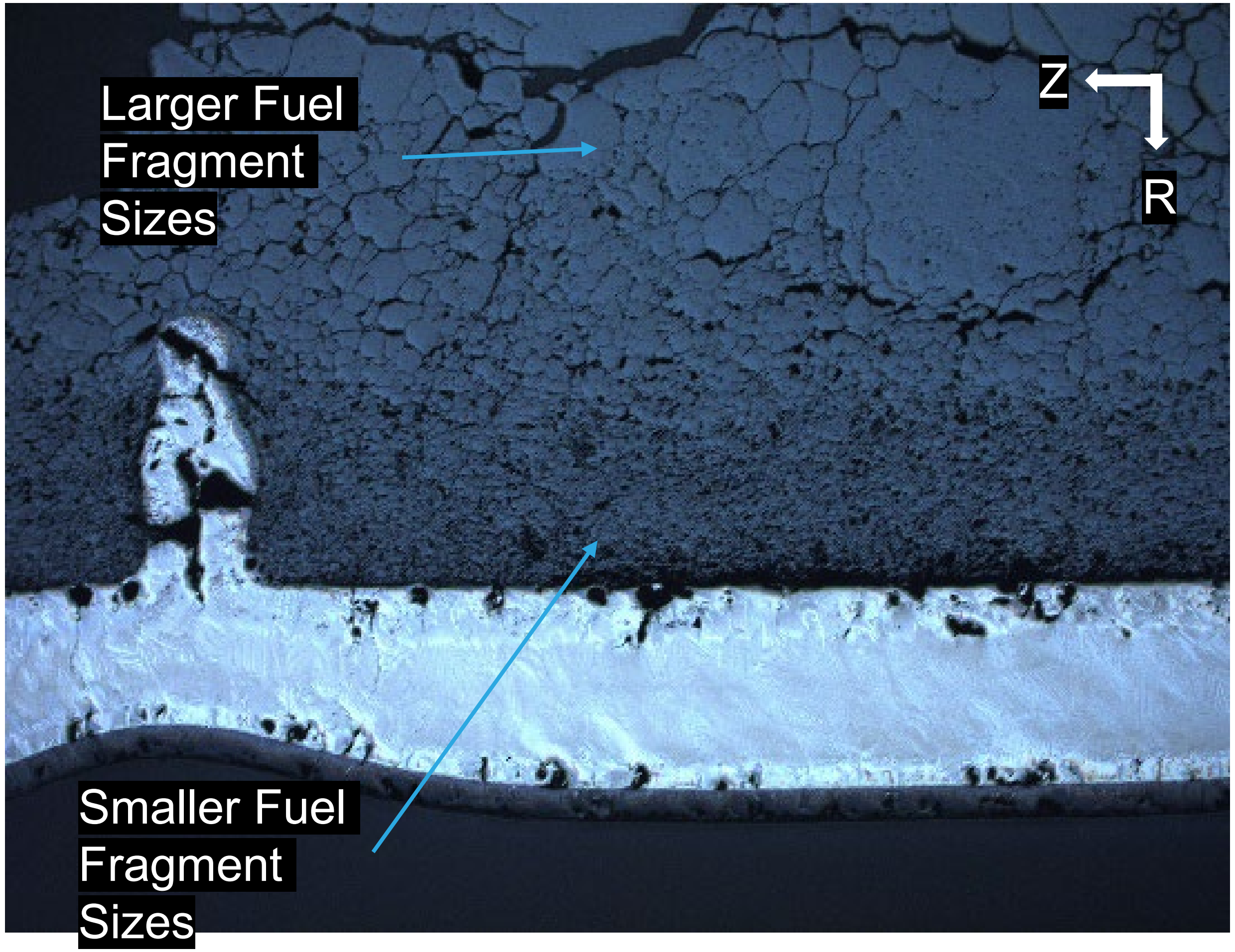
Example of Mass and sieving analysis performed at ORNL. https://doi.org/10.1016/j.jnucmat.2020.152750

Specific data list following transient

Data	Methodology
Fissile and Fertile Isotope Concentrations (U-233, U-235, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Am-241, Th-232	ICP-MS
Pellet and Cladding Geometry (pellet radius, Clad inner and outer radius, oxide layer thickness, clad alpha and beta layer thickness)	Optical Microscopy/SEM-EDS 
Fuel Porosity Distribution	Optical Microscopy
Fuel and Cladding Grain Size Distribution	SEM-EBSD
Cladding Mechanical Properties	Ring Compression Test
Cladding Hydrogen Content	Hydrogen Analyzer
Radial Nd, Cs, Te and Xe Concentration (Burnup, Volatile Fission Products, Gas Concentration)	EPMA
Balloon/Burst Geometry and Profile	X-ray CT

Optical Microscopy Example from ATF RIA 1B Test: Image at left is from transverse sample ~5 mm below mid pellet stack height, Image at right is Longitudinal sample ~20mm from top of pellet stack https://doi.org/10.1016/j.nucengdes.2023.112509





Optical Microscopy Example from IFA-650.5

- Cross sections at multiple elevations
  - Fragmentation size / radius

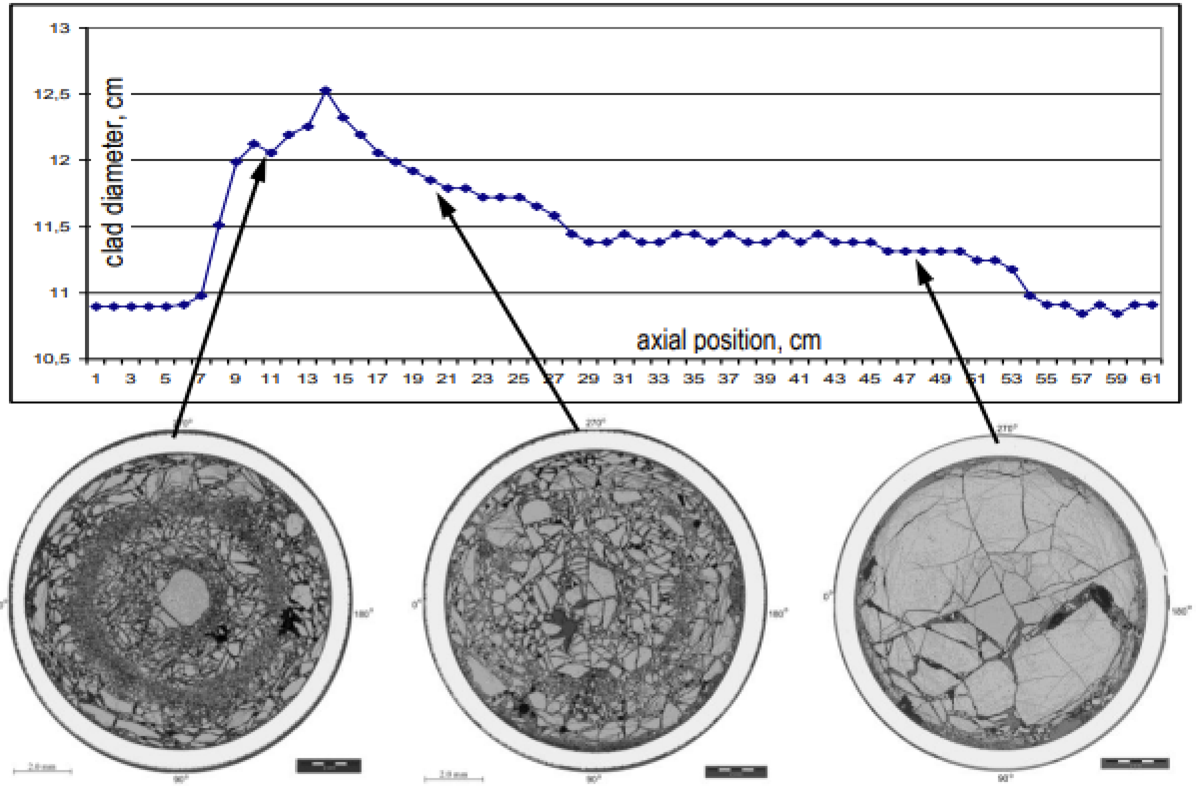
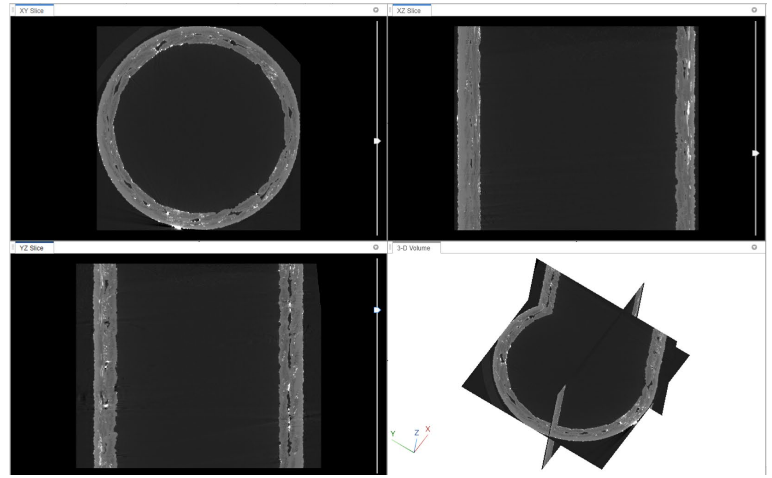


Figure 11 – Different cracking patterns obtained in IFA-650.5 (PCT 1050 °C). The diagram shows the change of cladding diameter along the length of the rod.

Safety Significance of the Halden IFA-650 LOCA Test Results, NEA/CSNI/R(2010)5

X-ray Computed Tomography of Defueled Segment

- High Resolution 3-dimensional view, with ability to highly quantify features of interest
  - Burst opening,
  - Ballooning/strain profile



Example of xCT following transient irradiation of fueled SiC test rodlet. Rodlet was defueled prior to performing xCT.

PIE Approach Architecture

Objectives:

- Provide data that is useful for model development and validation
- Provide data that is useful for fuel licensing activities
- Provide data that is useful for fuel development and optimization

State Points:

- As-received conditions
- Re-fabricated conditions
- Post-transient conditions

Phenomenological Focus:

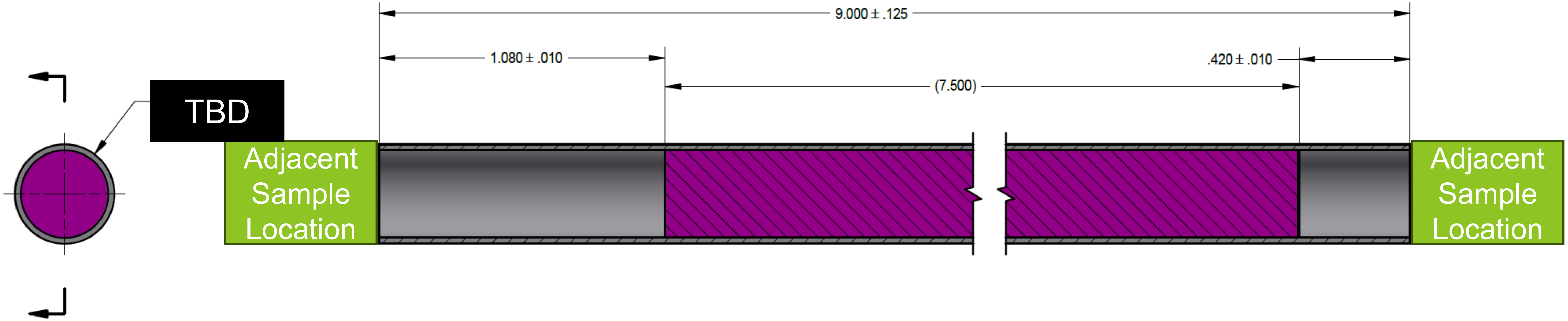
- e.g. Transient Fission Gas Release
- e.g. cladding oxidation and oxygen diffusion
- e.g. cladding mechanical properties

Techniques and Methods:

- e.g. Pre and Post Transient Gas Puncture and Analysis
- e.g. Optical Microscopy and Scanning Electron Microscopy with Energy Dispersive x-ray Spectroscopy for Elemental Analysis/Electron Probe Micro Analysis (EPMA)
- e.g. cladding mechanical testing/hardness testing
- Measurement and Test Equipment Calibrations
- etc

Nominal Re-fabricated Segment (units are inches)

- NDE prior to segment cutting
  - **Cladding diameter**/profilometry
  - **State of fuel and cladding**/Neutron radiography/Visual Inspection
  - **Raw Isotopic Content (Cs-137 distribution)**/axial gamma spectroscopy
- DE prior to segment refabrication
  - **Rod internal Pressure, Plenum Volume, Gas Content/Rod puncture, gas analysis**
- Adjacent samples taken near re-fabrication segment where possible provides microscopy data, chemistry data, material properties data, etc.
  - Data may be limited by quantity of material available and representativeness of sample location



Specific data list for adjacent samples (State of as-received material and start of transient irradiation)

Data	Methodology
Fissile and Fertile Isotope Concentrations (U-233, U-235, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Am-241, Th-232	ICP-MS
Pellet and Cladding Geometry (pellet radius, Clad inner and outer radius, oxide layer thickness, clad alpha and beta layer thickness)	Optical Microscopy/SEM-EDS
Fuel Porosity Distribution	Optical Microscopy
Fuel and Cladding Grain Size Distribution	SEM-EBSD
Cladding Mechanical Properties	Ring Compression Test
Cladding Hydrogen Content	Hydrogen Analyzer
Radial Nd, Cs, Te and Xe Concentration (Burnup, Volatile Fission Products, Gas Concentration)	EPMA

Specific Data List For Refabrication

Data	Methodology
Overall As-fabricated Rod Length	Calculated based on segment length + added structure (end caps)
Fuel Stack Height	Calculated based on segment length – measured defueled length
Free Volume of Upper and Lower Plenum	Calculated based on measured defueled length and cladding ID – measured volume of spacers, springs, endcaps, etc.
Dimensions of Plenum Spacers, Springs, etc	Measured from fabrication
Fill Gas Composition	Documented from gas supplier
Fill Gas Pressure at ~40 °C	Documented during seal welding