INL/CON-22-69671-Revision-0

Post-Transient Examination Results of RIA Commissioning Teats at the Transient Reactor Test Facility

October 2022

Changing the World's Energy Future

Jason L Schulthess, David W Kamerman, Nicolas E Woolstenhulme, Colby B Jensen, Leigh Ann Emerson Astle, Robert J Armstrong, Daniel M Wachs, Philip G Petersen, Robert Scott Hansen, Charles P Folsom

Idaho National Laboratory

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NuMat 2022 Conference

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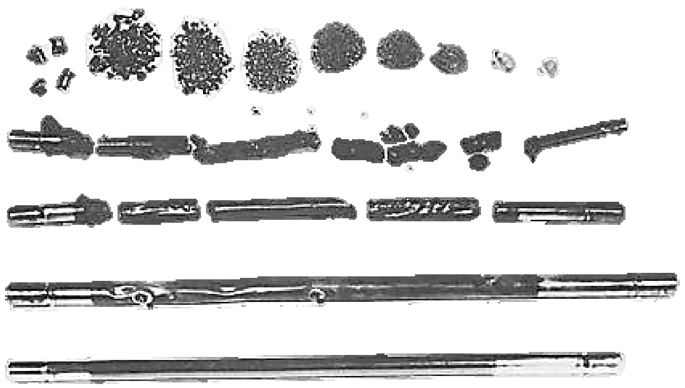
Idaho National Laboratory

Introduction

- This work is focused on developing the capabilities for Reactivity-Initiated Accident testing at TREAT
  - Historically performed in the 1950’s through 1980’s at the
    - Boiling Water Reactor Experiment (BORAX), Special Power Excursion Reactor Test Program (SPERT), Power Burst Facility (PBF) reactors
    - ~100 tests to simulate RIA conditions in the Transient Reactor Test Facility (TREAT) in water filled experiment devices were performed
  - subsequently establish empirical fuel safety criteria for UO2/Zry
- ATF campaign has generated new/changes to fuel and cladding
  - Additionally, burnup extension has renewed interest in transient testing
  - Why re-establishing the capabilities for transient testing is necessary
- Accident Tolerant Fuels program - ***driver for the TREAT restart schedule***

Experiments from the late 1960’s in SPERT CDC in Idaho



Energy deposition ($cal/g\ UO_2$)

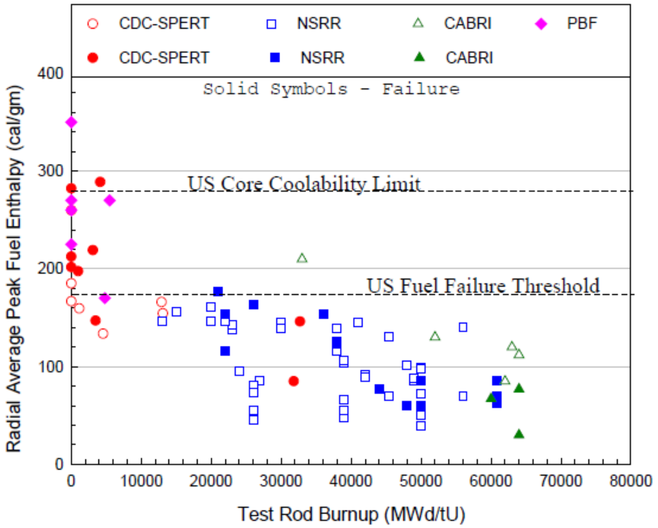
378

338

287

240

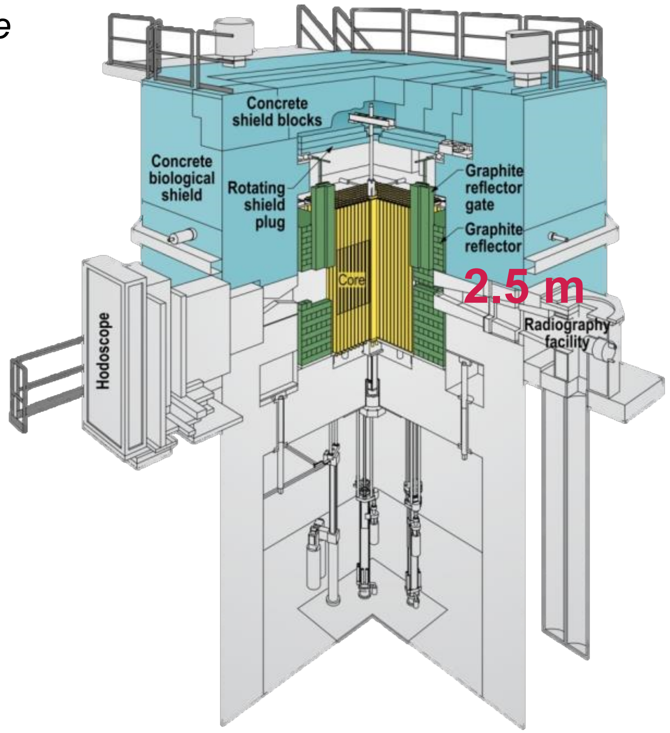
168

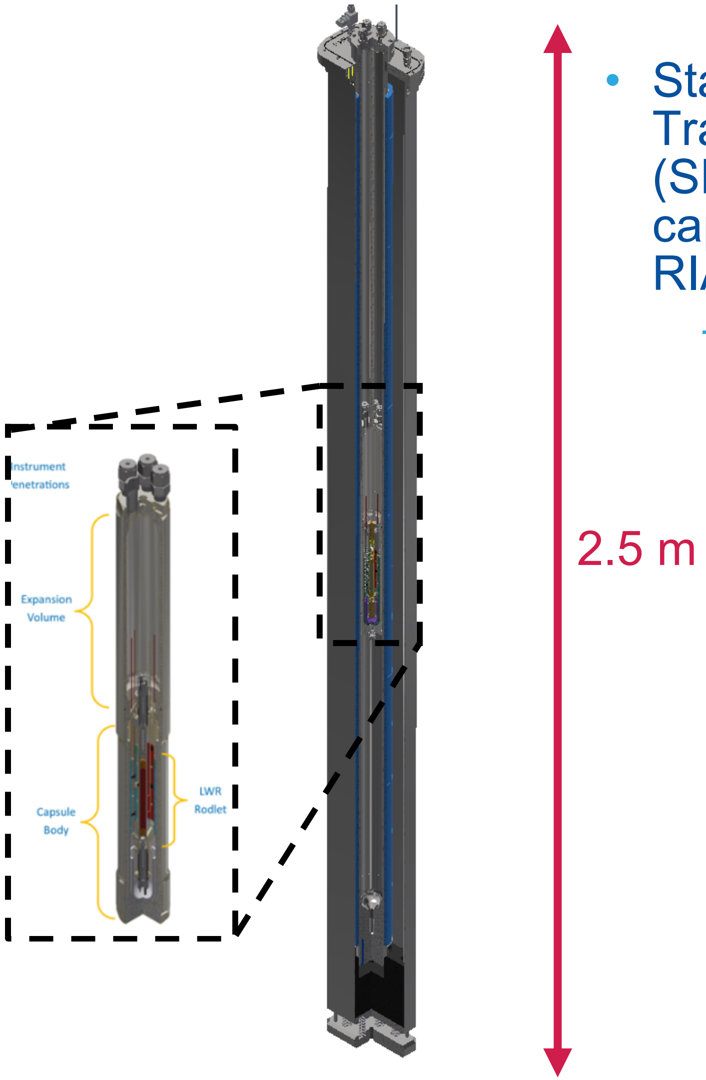


TREAT Experiment Design

- Modular experiment device strategy
  - Contains specimen, instrumentation, thermal hydraulic systems, containment, etc.
  - Allows good flexibility for instrumentation
  - Compatibility with hot cell, fuel rod refabrication

Insert experiment here



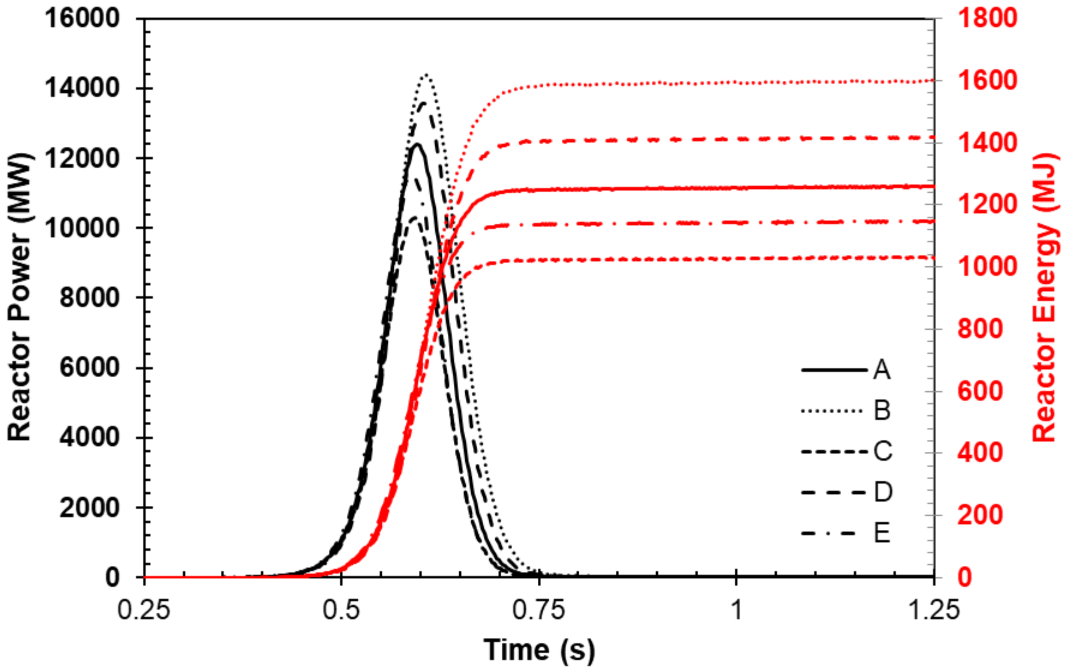


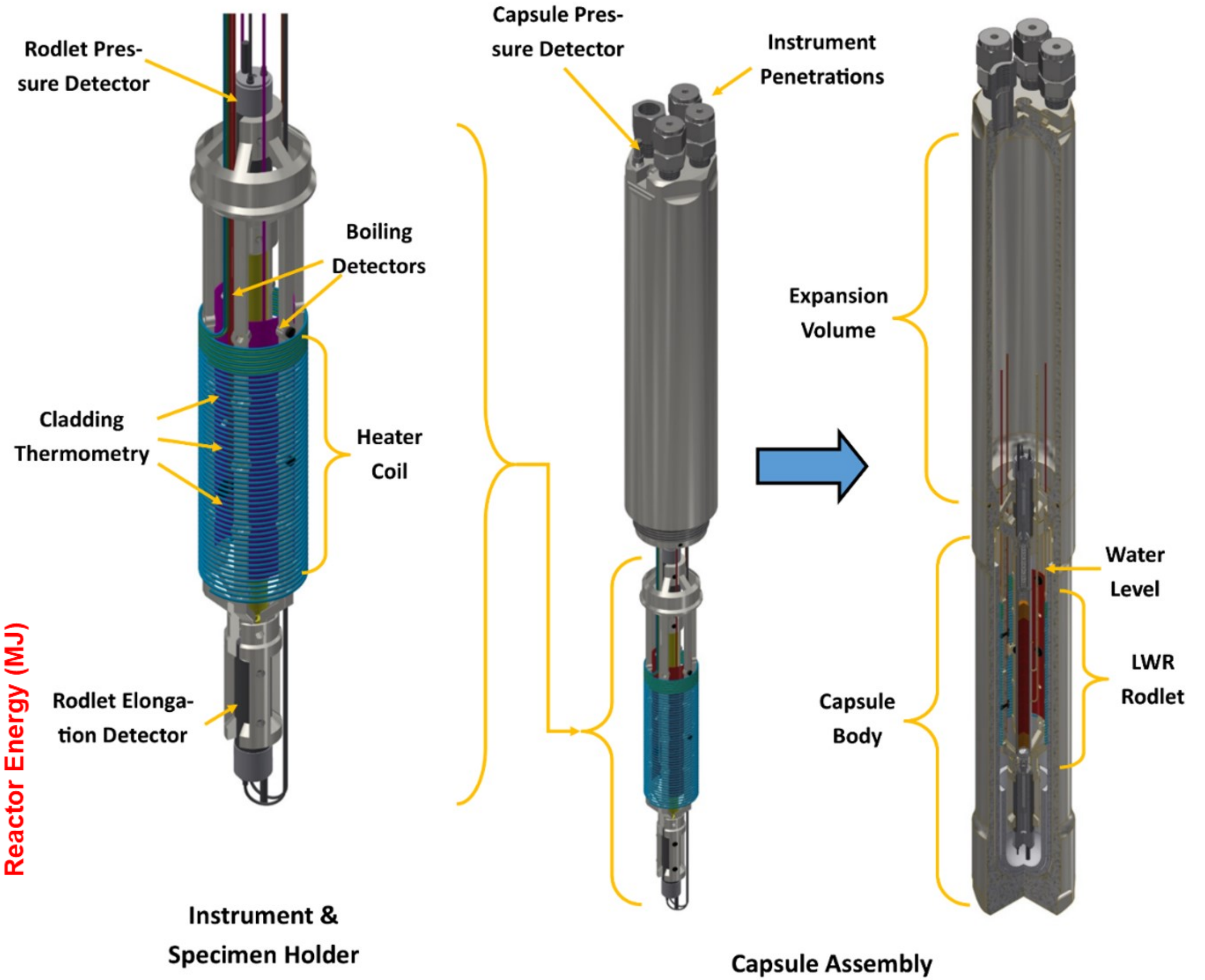
SERTTA
Static pressurized water capsule

- Static Environment Rodlet Transient Test Apparatus (SERTTA) is the parent capsule for water-based RIA tests
  - Variations/modifications are adapted for specific experiment campaigns
    - Commissioning series
    - Pre-irradiated fuel test
    - Separate-effect Critical Heat Flux (CHF) tests
    - High Burnup Experiments in Reactivity Initiated Accidents (HERA) tests

Experiment Capsule and Transient

- SERTTA-RIA-C
  - Commissioning experiments for water-based tests in TREAT using SERTTA capsule
  - RIA Gaussian shaped transient





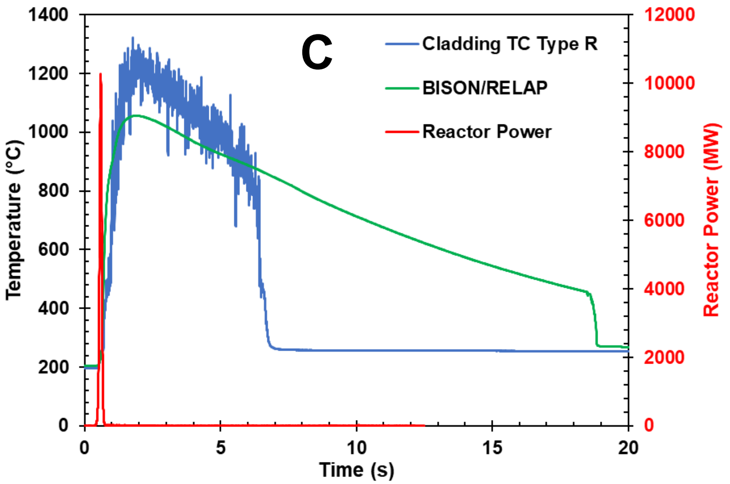
SERTTA-RIA-C Experiments

- Experiment goal was to demonstrate capability to do RIA testing in TREAT
  - First in-pile water-based safety testing in the US in more than a generation
  - Five tests targeting different conditions for specific post-test analysis
    - Initial temperature/pressure, transient/energy deposition, instrumentation demonstration
- Experiments provide valuable data for post-test analysis and validation of fuel performance codes
- Pros/Cons being used to improve future experiments (HERA)

Test ID-	Rodlet Pressure	Capsule Pressure at Temp.	Capsule Temp. (°C)	Step Insertion (%Δk/k)	Specimen Energy Deposition Target (J/g)
SERTTA-RIA-C-A	Atm.	0.1 MPa	22	4.2	870
SERTTA-RIA-C-B	Atm.	0.7 MPa	22	4.2	1110
SERTTA-RIA-C-C	Atm.	2.2 MPa	205	4.2	530
SERTTA-RIA-C-D	2 MPa	2.4 MPa	207	4.2	720
SERTTA-RIA-C-E	2 MPa	2.0 MPa	202	4.2	590

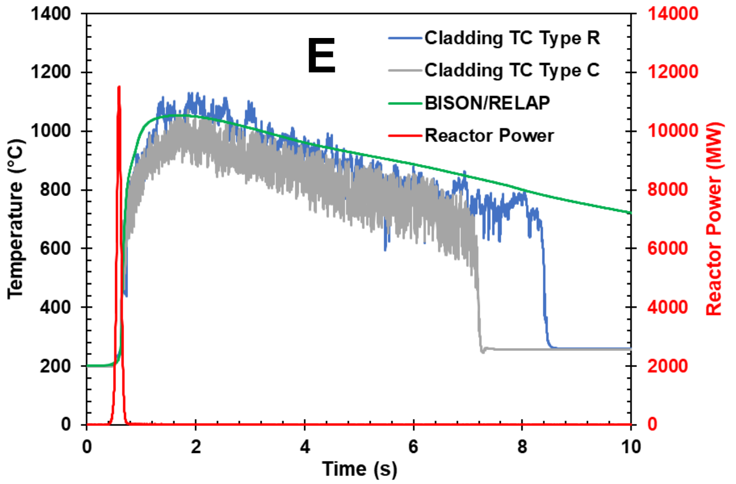
Fuel Performance Modeling (C. Folsom)

- Bison was used to model the fuel rodlet and was coupled to RELAP5-3D for the thermal hydraulic conditions
- Coupling the codes allows for coupling between the thermal-mechanical changes in the fuel rod such as dynamic gap changes due to fuel thermal expansion and cladding inelastic strains (Bison) and the impact those changes have on the heat flux balance between the fuel/clad and cladding/coolant (RELAP5-3D)
- Models also incorporate recent work showing the shift in critical heat flux (CHF) during rapid transients ~3.5x



SERTTA-RIA-C-C experiment cladding thermocouple results along with coupled BISON/RELAP5-3D modeling predictions

530 J/gUO_2 (127 cal/gUO_2) energy deposition



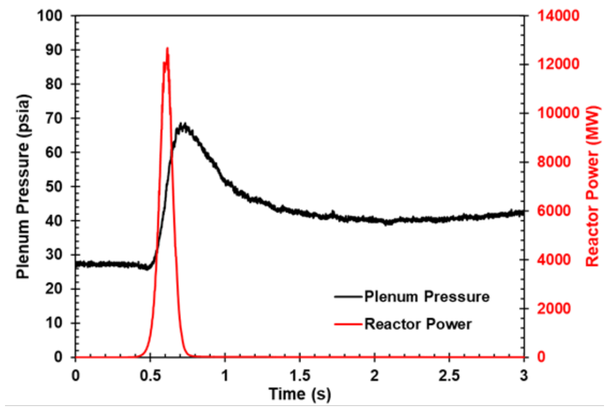
SERTTA-RIA-C-E experiment cladding thermocouple results along with coupled BISON/RELAP5-3D modeling predictions

590 J/gUO_2 (141 cal/gUO_2) energy deposition

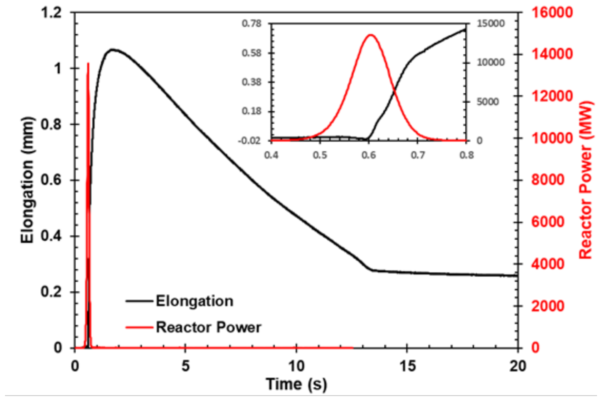
Armstrong, R., et al., *Calculation of Critical Heat Flux Using an Inverse Heat Transfer Method to Support TREAT Experiment Analysis*, in *28th Conference on Nuclear Engineering* 2020: Anaheim, California.
Folsom, C.P., et al., *Design of separate-effects In-Pile transient boiling experiments at the TREAT Facility.* Nuclear Engineering and Design, 2022. **397**: p. 111919.
Hernandez, R., et al., *Sensitivity analysis of in-pile CHF experiments in the TREAT facility: Characterization of impacts of fuel system thermal properties.* Annals of Nuclear Energy, 2022. **165**: p. 108645
Armstrong, R.J., et al., *Results of the CHF-SERTTA In-Pile Transient Boiling Experiments at TREAT*, in *Top Fuel 2021*. 2021: Santander, Spain.

In-Pile Elongation and Rodlet Pressure

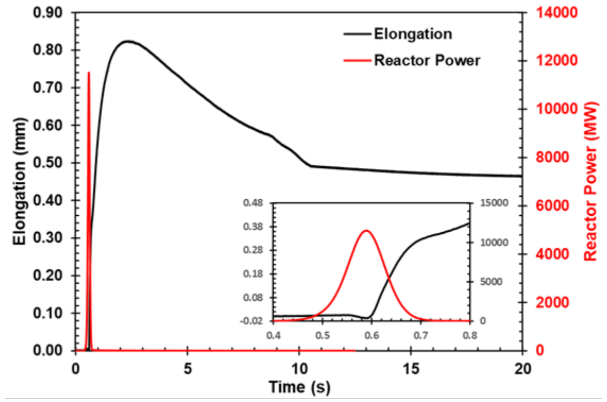
- Capsules B, D, and E utilized the plenum pressure bellows with LVDT
- Capable over a large range of pressures
- Capsules D and E utilized a lower LVDT to measure cladding elongation
- Trends are similar as those seen in fuel performance modeling benchmarks for RIAs



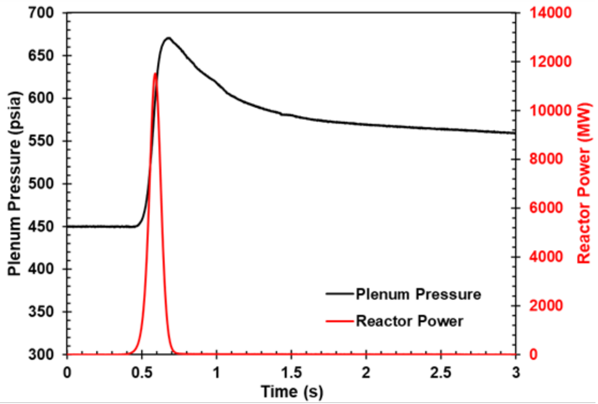
SERTTA-RIA-C-B
1110 J/gUO$_2$ (265 cal/gUO$_2$) energy deposition



SERTTA-RIA-C-D
720 J/gUO$_2$ (172 cal/gUO$_2$) energy deposition



SERTTA-RIA-C-E
590 J/gUO$_2$ (141 cal/gUO$_2$) energy deposition



SERTTA-RIA-C-E
590 J/gUO$_2$ (141 cal/gUO$_2$) energy deposition

Visual Examinations

- PTE of experiments show the fuel rodlet condition is similar to historical SPERT-IV tests
- Some rodlet bowing observed in “A”, “D”, and “C” tests. Evidence of non-uniform circumferential temperature distribution and deformation taking place in the anisotropic hexagonal alpha zirconium phase

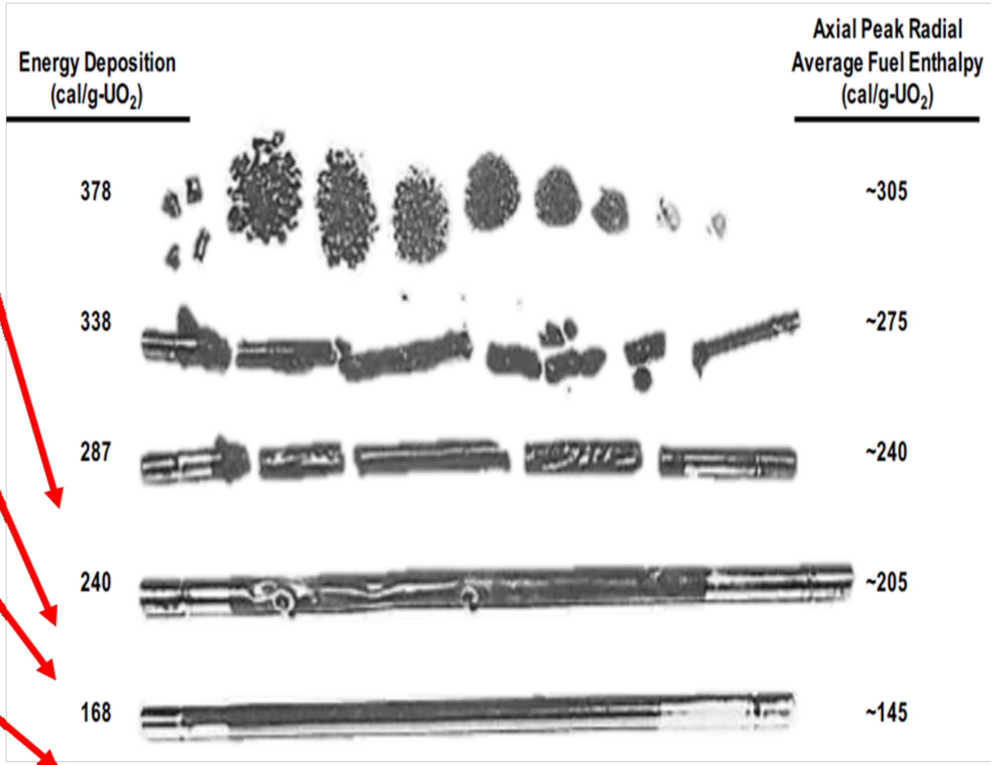
B, 1110 J/g (~265 Cal/g)

A, 870 J/g (~208 Cal/g)

D, 720 J/g (~172 Cal/g)

E, 590 J/g (~141 Cal/g)

C, 530 J/g (~126 Cal/g)



From SPERT-IV Fresh Fuel RIA Tests

Profilometry

- High resolution optical micrometer with ±2 μm diameter and ±2.5 μm axial location
- Some of the rods experienced permanent cladding deformation
- Bambooing from individual pellets seen in some cases
- Final cladding strain expected based on plenum/capsule pressure differentials
    - E showed > 2.5% strain
    - D ~ 1.0% strain
    - A ~ -0.75% strain

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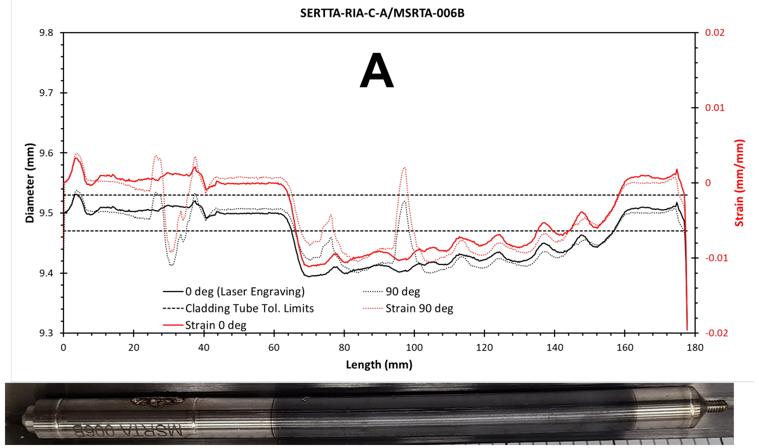
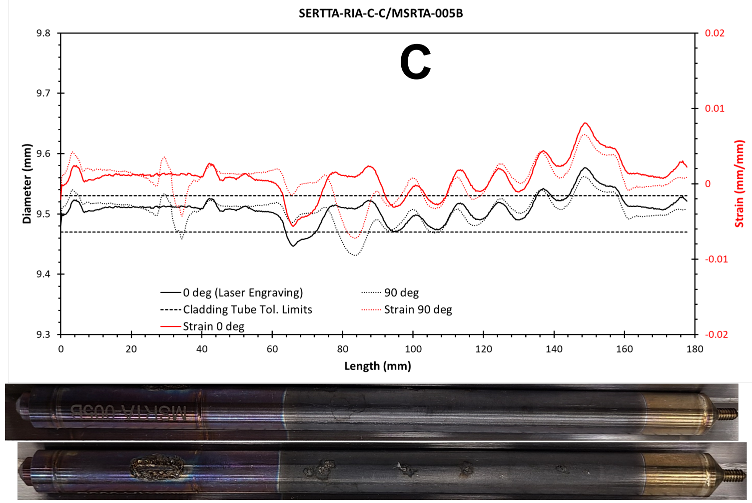
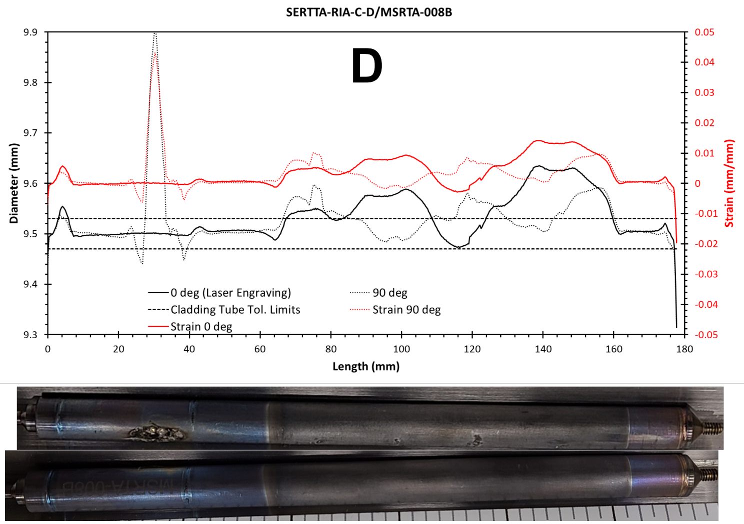
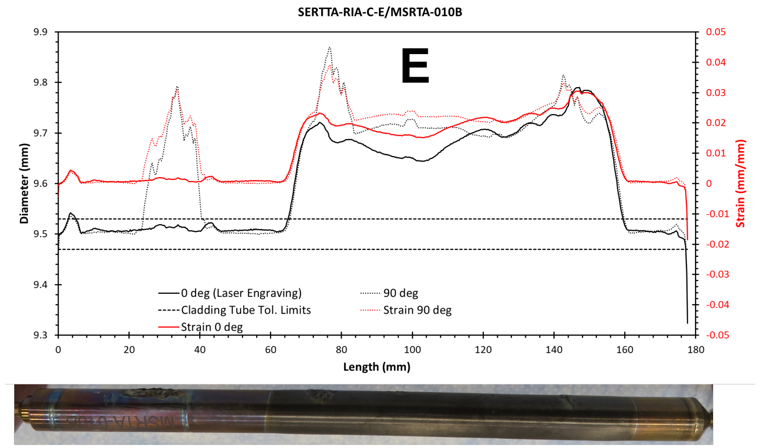


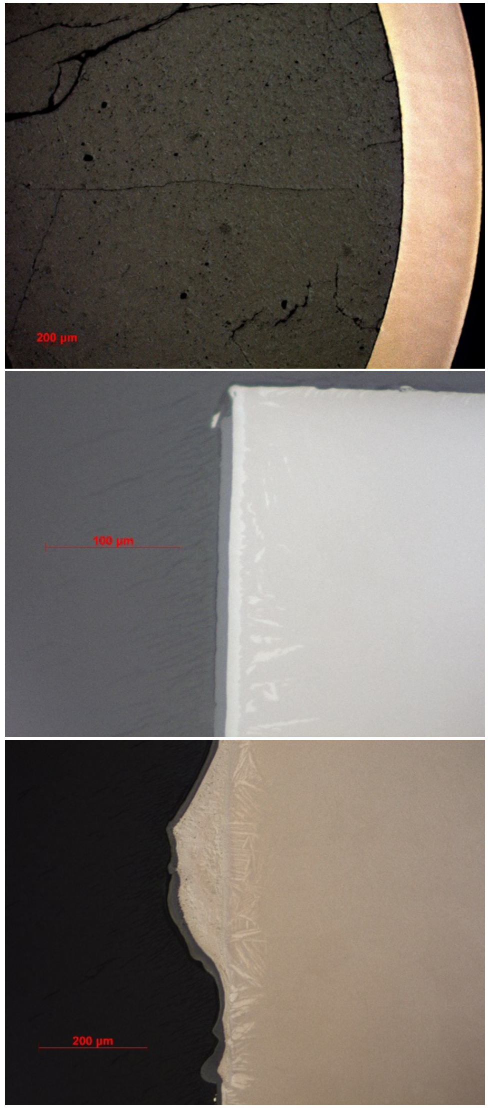




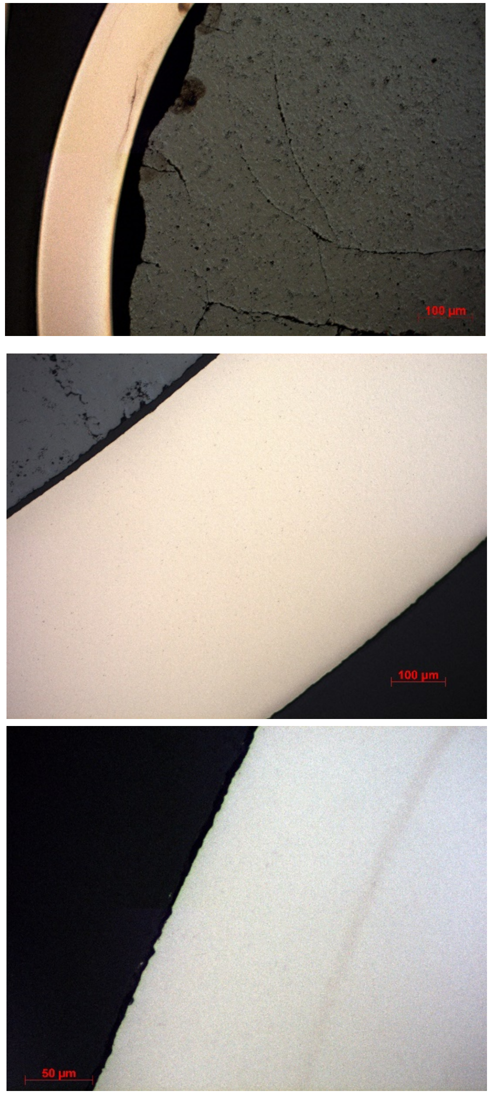


Optical Microscopy

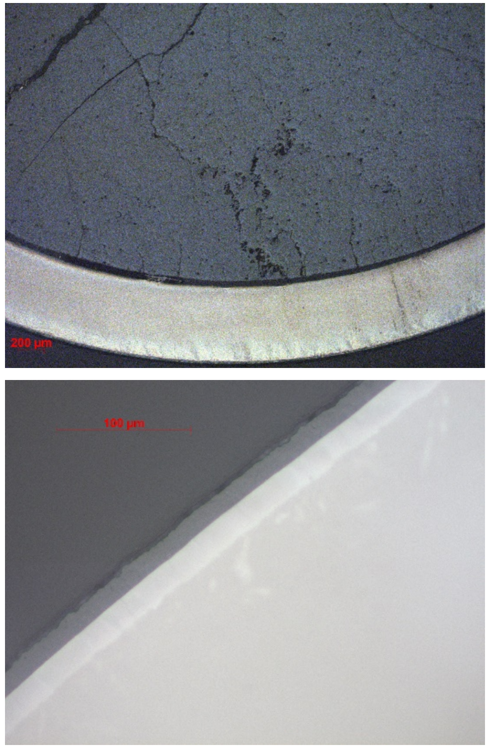
“C” 530 J/gUO2



“E” 590 J/gUO2

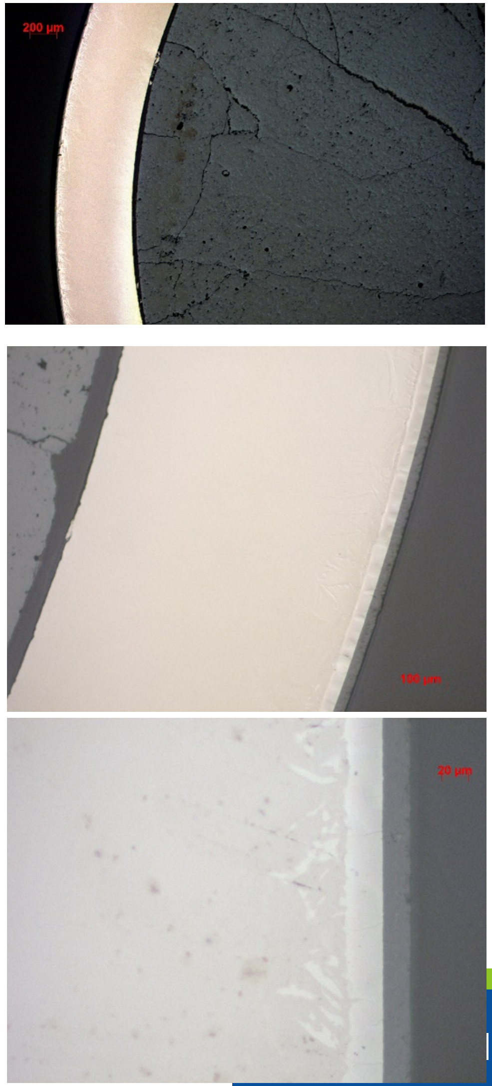


“D” 720 J/gUO2

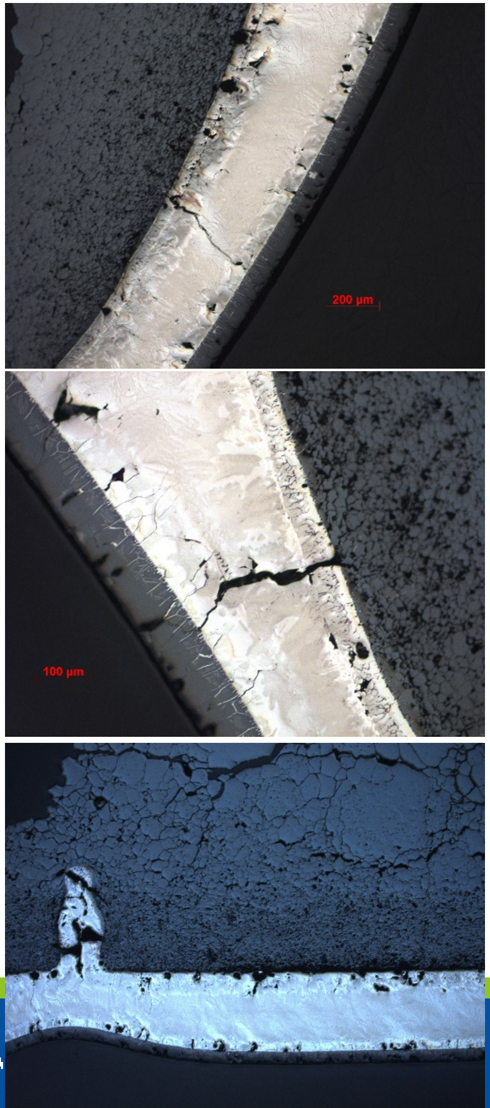


E – No oxide layer!
C – Extra oxide thickness on TC
B – Particle size gradient with radius

“A” 870 J/gUO2

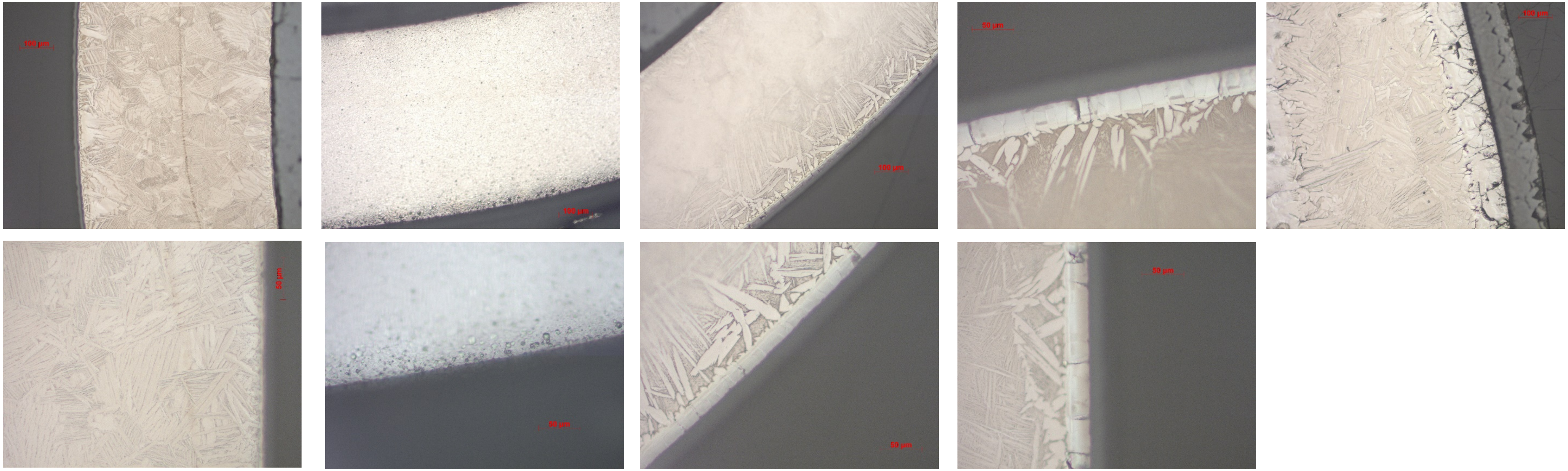


“B” 1110 J/gUO2



Optical Microscopy after Etching Cladding with HNO3

"C" 530 J/gUO2 | "E" 590 J/gUO2 | "D" 720 J/gUO2 | "A" 870 J/gUO2 | "B" 1110 J/gUO2

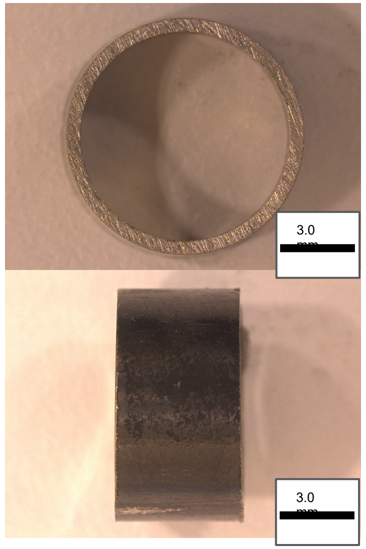


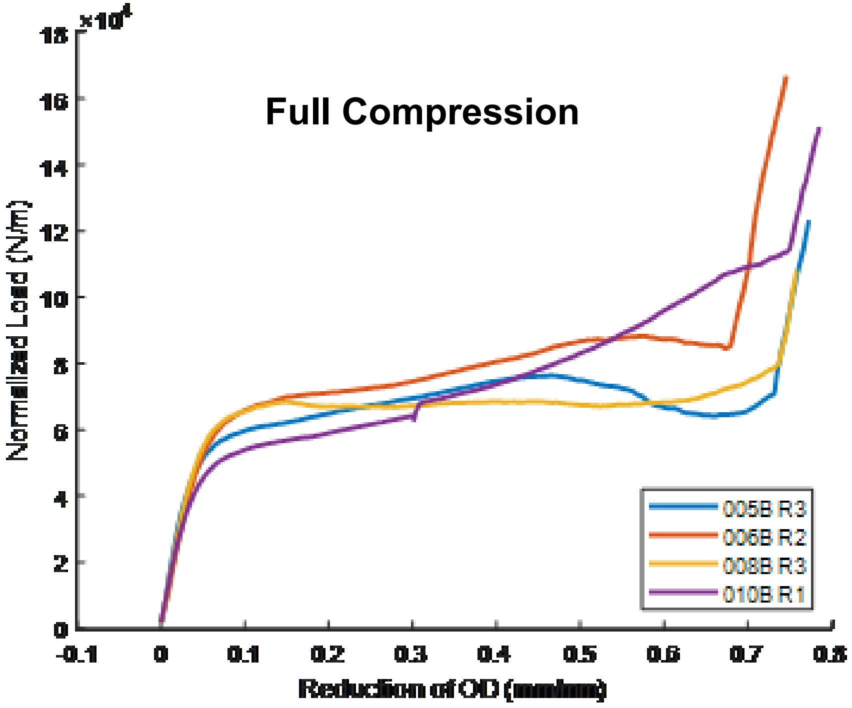
Test ID	Energy Deposited (J/gUO2)	Nominal wall thickness (um)	ZrO2 Thickness (um)	Alpha Thickness (um)	Alpha + Beta Thickness (um)
SERTTA-RIA-C	530	1143	11	NA	NA
SERTTA-RIA-E	590	1143	NA	NA	NA
SERTTA-RIA-D	720	1143	16	25	62
SERTTA-RIA-A	870	1143	20	29	76
SERTTA-RIA-B	1110	1143	87	76	140

E – No oxide layer, also could not get grains to show
C – Minimal to no alpha layer
B – Pits in oxide layer
All – No hydrides observed

Post-Transient mechanical testing

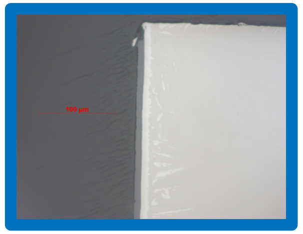
Test Samples



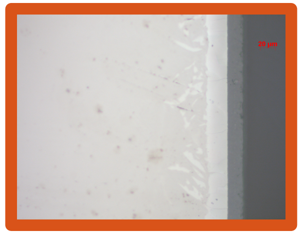


- 5mm wide ring samples were cut from four intact cladding rodlets after transient testing in TREAT
- Tested in HFEF on remote load frame using ring compression method; both to estimated 2% reduction in diameter (2 per rod), and to full compression of ring (1 per rod).
- 2% reduction experiments confirmed no drastic loss of ductility, similar strengths for each rod
- Full compression showed some degradation of load bearing capacity for each rod except for the single rod which did not develop an oxide layer (010B).

Oxide images

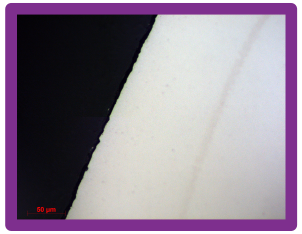


005B
530 J/gUO2
11um oxide
C



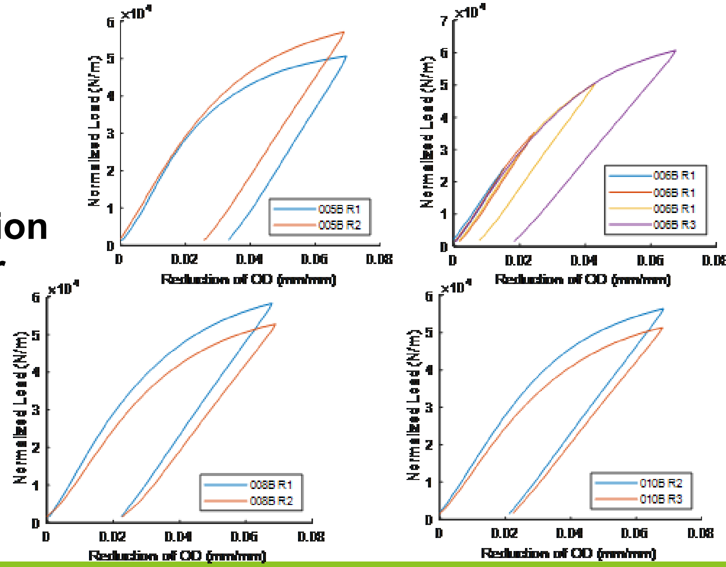
006B
870 J/gUO2
20um oxide
A

008B
720 J/gUO2
16um oxide
D



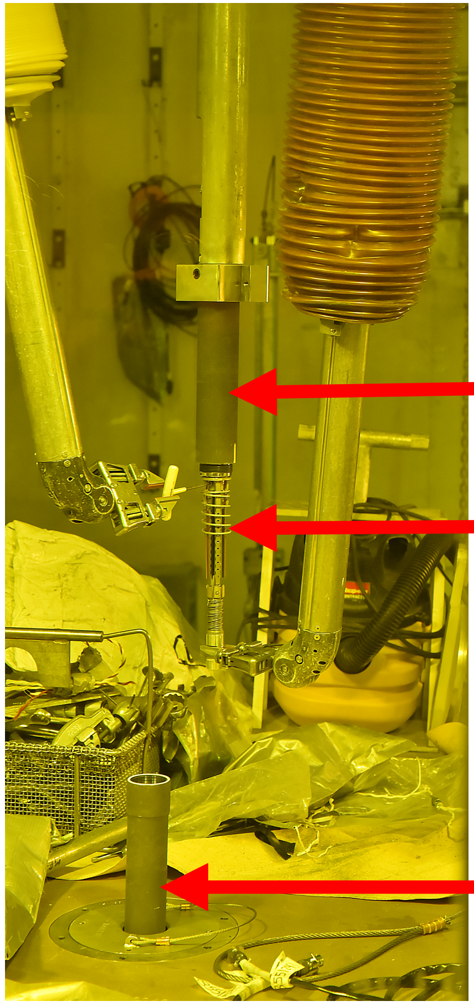
010B
590 J/gUO2
No oxide
E

2% Reduction In Diameter



ATF-R (First Commissioning Test Using Previously Irradiated Fuel)

- Fuel from the ATF-2 experiment irradiated in the Advanced Test Reactor (ATR) at INL. UO2/Zr-4 ~9 GWd/MTU
- SERTTA experiment capsule at 22 C and 1.65 MPa
- Demonstrate tools and procedures to assemble experiment remotely and perform irradiation test.
- Target Energy Deposition 630 J/gUO2



Loading fuel rodlet into the SERTTA Capsule

Conclusions

- Successfully completed the SERTTA-RIA-C series of tests
  - Significant step in demonstrating our capabilities for water-based accident testing
  - PTE completed and results are consistent with models and historic experiments
  - Improved design and implementation for future experiments such as HERA
- Learned a lot regarding design, operation, and instrumentation performance
  - Demonstrated the LVDT plenum pressure and cladding elongation measurement capabilities
    - Performed very well under high flux transient conditions
- Completed the ATF-R test which was the first experiment using previously irradiated fuel in the modern TREAT era
  - Required restoration of a number of capabilities (HFEF-15 cask, fixturing, instrumentation, and processes for hot cell assembly)

Future Work

- Multiple tests in the future as part of the international NEA FIDES HERA project
- NSUF-CCZ-RIA tests to study cladding coatings
- Performing scoping studies of RIA experiments in a Pumped TWIST capsule design
  - Modifications to the larger LOCA capsule can allow for a flow channel and forced circulation of coolant around the fuel rodlet

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