INL/CON-21-62748-Revision-1

Overview of the Water-Based RIA Testing in TREAT

October 2021

Changing the World's Energy Future

C.P. Folsom, J.L. Schulthess, D.W. Kamerman, N.E. Woolstenhulme, C.B. Jensen, D.M. Wachs

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Charles Folsom
Jason Schulthess
David Kamerman
Nicolas Woolstenhulme
Colby Jensen
Daniel Wachs

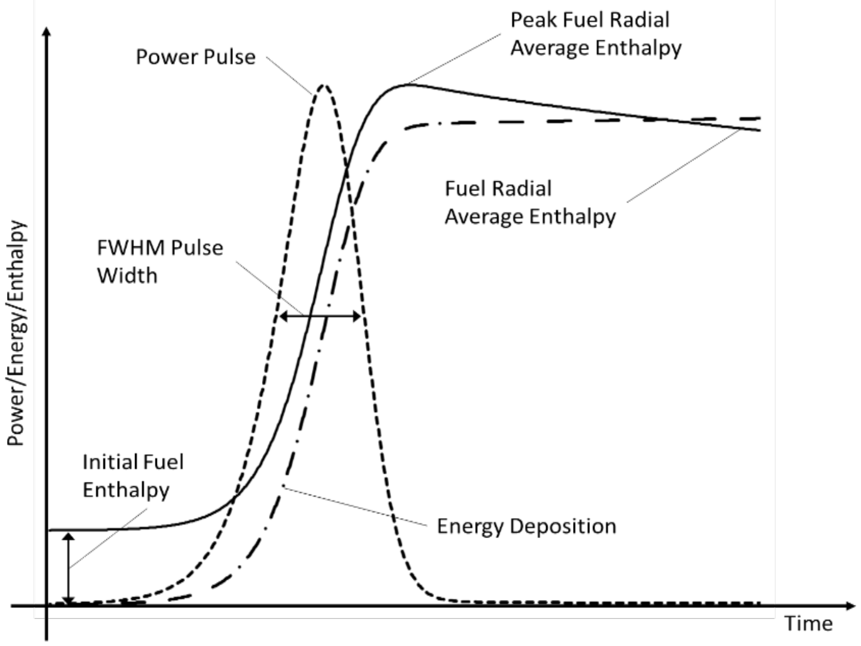
Overview of the Water-based RIA Testing in TREAT

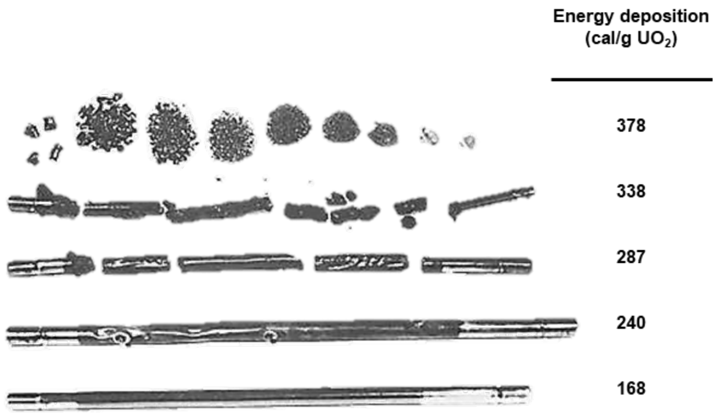
TopFuel 2021, Santander, Spain

Idaho National Laboratory

Introduction

- The mission of the Accident Tolerant Fuel Program is to develop the next generation of LWR fuel that offers better performance during normal operation and exhibits enhanced tolerance to design-basis and beyond design-basis accidents
- Nuclear Industry also has a goal to extend burnup up to 75 GWd/t for current fuels
- Reactivity-Initiated Accident (RIA) is the DBA of interest for this work
  - Nuclear accident involving an unwanted rapid increase in fuel fission rate and thus reactor power
  - ~100 tests to simulate RIA conditions and subsequently establish empirical fuel safety criteria for UO2/Zry.
  - **Still ongoing debate for modern claddings and high burnup fuels**

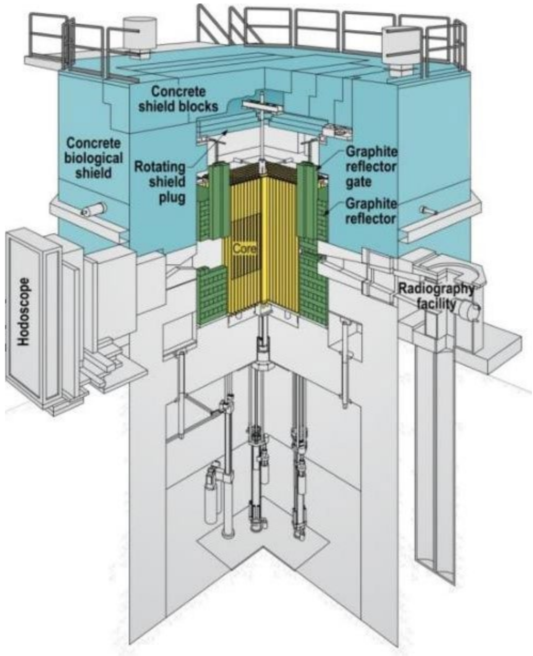


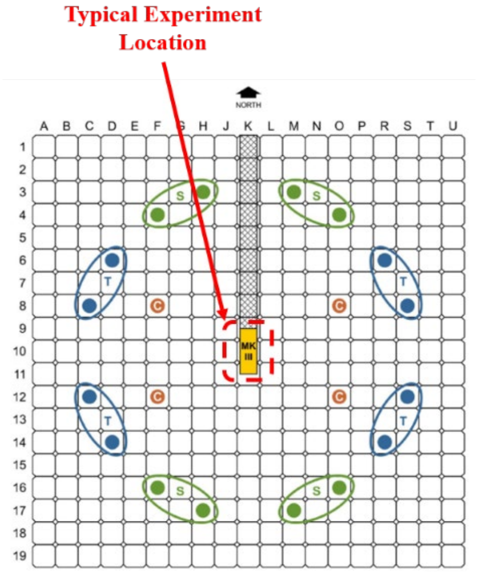


Experiments from the late 1960's in SPERT CDC in Idaho

Transient Reactor Test Facility

- Transient Reactor Test Facility (TREAT) resumed operations in order to support fuel safety testing and other transient science
  - ATF was the main driver for the TREAT restart schedule
  - 19x19 grid of Zircaloy-clad graphite/fuel blocks comprise core, cooled by air blowers
  - Virtually any power history possible within 2500 MJ max core transient energy
  - Graphite-pile – currently capable of 89 ms FWHM pulse width, ^{3}He clipping system being developed to shorten ~45 ms
  - No reactor pressure vessel/containment, facilitates access for in-core instrumentation
  - Reactor provides neutrons, experiment vehicle does the rest
- Objective of this work was to commission the experiment vehicle for water-based RIA testing in TREAT
  - Incremental improvements/advancements from dry RIA experiments on ATF concepts to separate-effects water-based tests

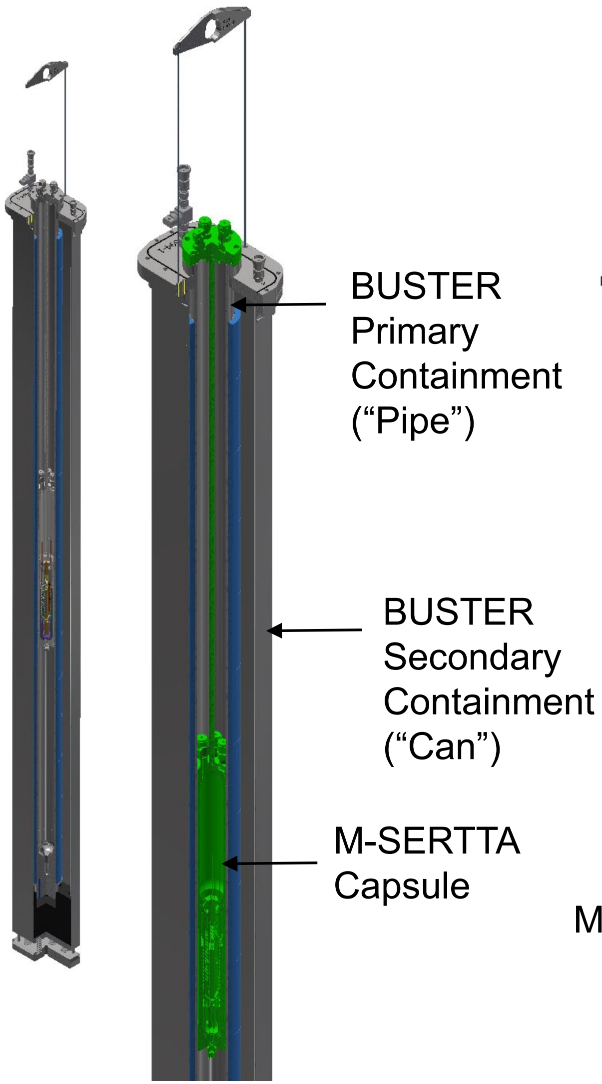


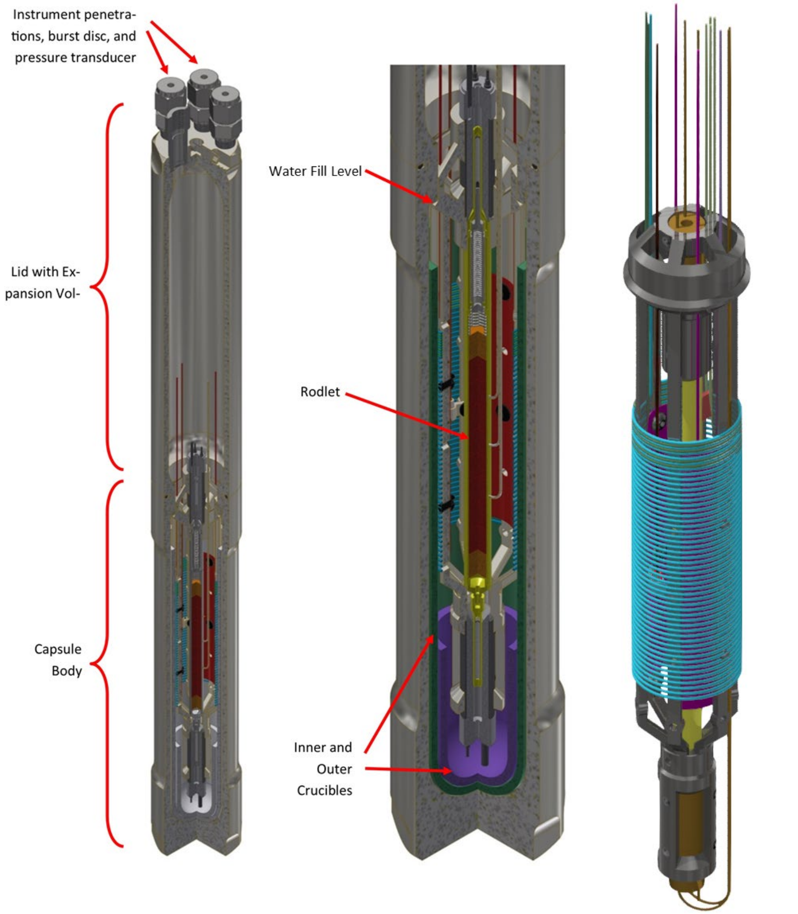


MARCH-SERTTA Experiment Vehicle

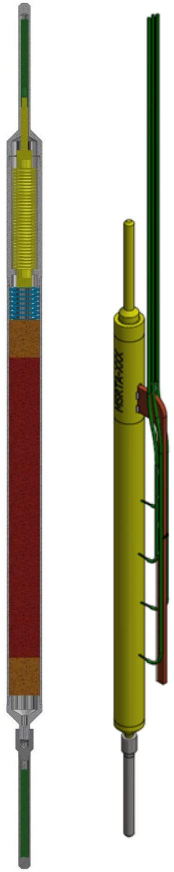
- Minimal Activation Retrievable Capsule Holder–Static Environment Rodlet Transient Test Apparatus (MARCH-SERTTA)
  - Capsule designed to fit within the BUSTER primary containment assembly
  - M-SERTTA Capsule allows for fuel tests in static water with a wide variety of instrumentation
  - Rodlet design
    - 8 “enriched” with 2 Zirconia end pellets
    - LVDT end cap adaptations on top and bottom

MARCH System



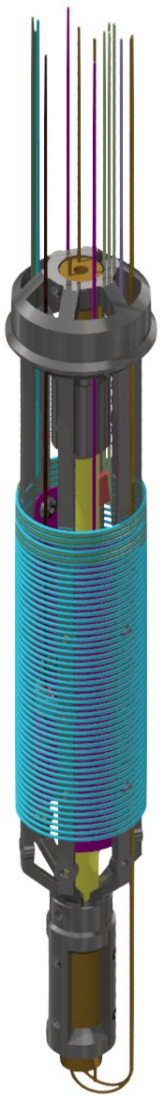


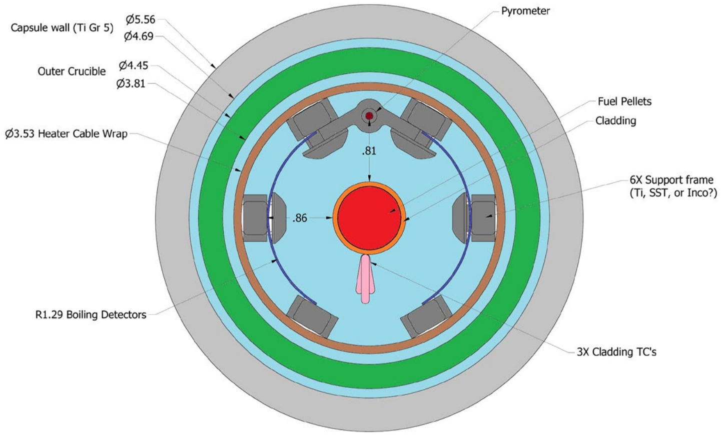
M-SERTTA Capsule (Left, Center), Rodlet Holder (Right)



M-SERTTA rodlet

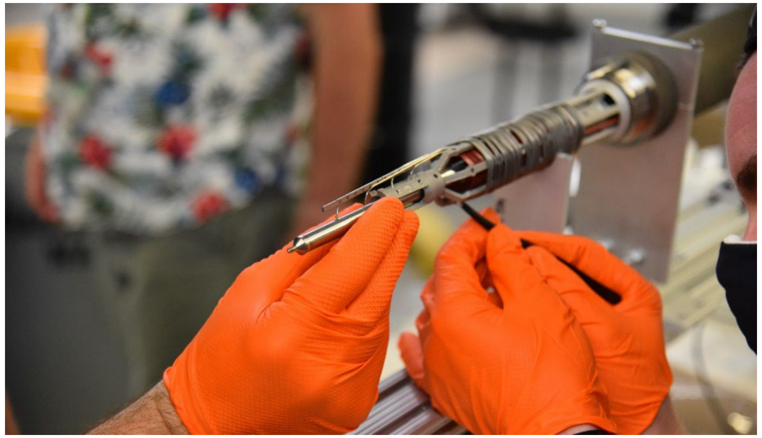
MARCH-SERTTA Instrumentation



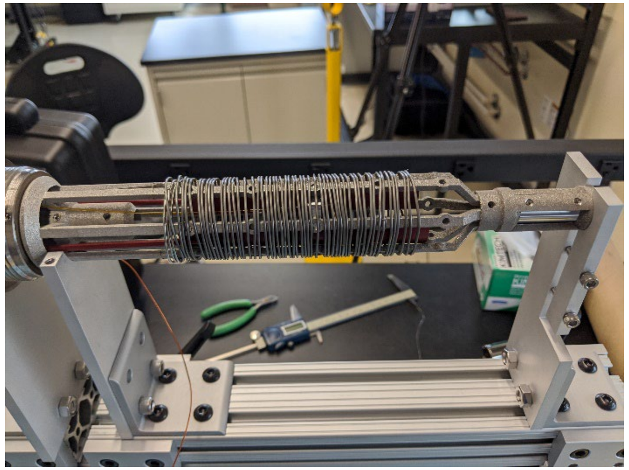


Instrument	Lead	QTY	Notes
Top LVDT	1 mm MIMS, 3 wires	1	Measures rodlet plenum pressure via bellows
	1 mm MIMS, 2 wires	1	
Bot LVDT	1 mm MIMS, 3 wires	1	Measures cladding axial expansion
	1 mm MIMS, 2 wires	1	
Heater and control TCs	1+ mm MIMS, 2 wires, NiCr heater wire	1	Enables elevated temperature starting conditions, 2 TCs PLC redundancy
	1 mm MIMS, 2 wires, type K	2	
Boiling Detector	1 mm MIMS, 1 wire	1	Measures boiling via capacitance, leads need to be coaxial
Rodlet TC	1 mm MIMS, 2 wires, Type R exposed junction	4	Cladding temperature, type R exposed junction welded to cladding
Pyrometer	1 mm, single fiber, in capillary tube at conax	1	Cladding temperature, unproven in water environment, including one
Water temp TC	1 mm MIMS, 2 wires, type K	1	1 type K sheathed near rodlet in water
Capsule Pressure	3 conducter 26 AWG Shielded, Kulite ETL-76A-190 (M)	1	Will be placed on top of capsule so leads won't go through capsule conaxes, but will go through flange conax

MARCH-SERTTA Capsule Assembly

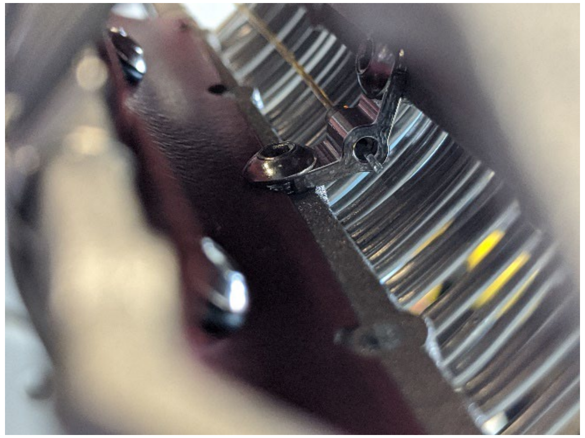


Insertion of rodlet/TC assembly into holder

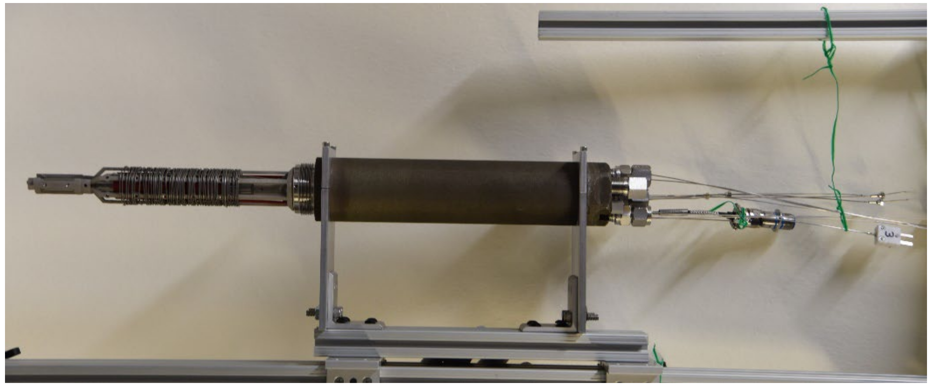


Rodlet holder with heater wire wrap

Lower capsule installation



Close-up of optical pyrometer and inside electro-impedance boiling detectors



Upper capsule with rodlet holder assembly

MARCH-SERTTA Test Matrix

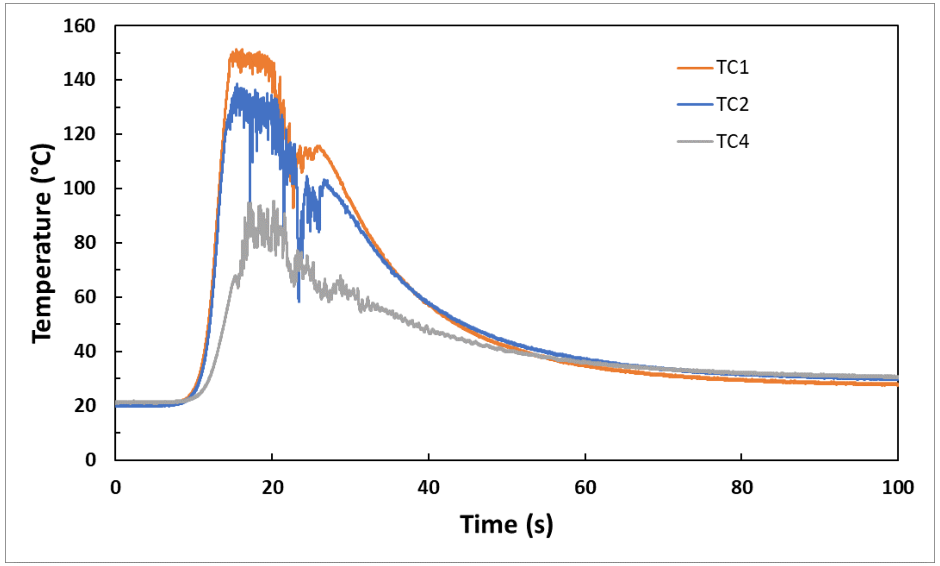
- Gamma test to calibrate the fuel-to-core power coupling factor
- Series of five tests
  - Successfully completed the final test on 4/28/2021
- Each test to target different conditions for specific post test analysis or instrumentation demonstration
  - LVDT demo
  - B, D, and E capsules tested the plenum pressure bellows
  - D and E capsules tested cladding elongation
- Capsule E tested thermocouple types and sizes
- Planned post-test analysis
  - cladding ring compression, ring tensile, bending, and compression testing

Test ID	Rodlet Pressure	Capsule Pressure at Temp.	Capsule Temp. (°C)	Step Insertion (%Δk/k)	Specimen Energy Deposition Target (J/g)	Reactor Energy (MJ)	FWHM (ms)	Cladding Temp. Targets (°C)	Anticipated Failure Mechanism	Test Purpose
ATF-RIA-1-A	Atm.	0.1 MPa	22	4.2	870	1272	90.5	≤ 1200	None	Achieve Film Boiling from RTP Initial Conditions
ATF-RIA-1-B	Atm.	0.7 MPa	22	4.2	1110	1617	99.4	> 1200	High Temp Embrittlement	Observe Cladding Embrittlement without Burst
ATF-RIA-1-C	Atm.	2.23 MPa	205	4.2	530	1042	89.8	~850	None	Achieve Film Boiling with slightly subcooled initial conditions
ATF-RIA-1-D	2 MPa	2.41 MPa	207	4.2	720	1431	93.8	≤ 1200	Ballooning and Burst	Demonstrate Ballooning and Bursting during Film Boiling
ATF-RIA-1-E	2 MPa	1.985 MPa	202	4.2	590	1160	89	< 1200	None	Thermocouple test

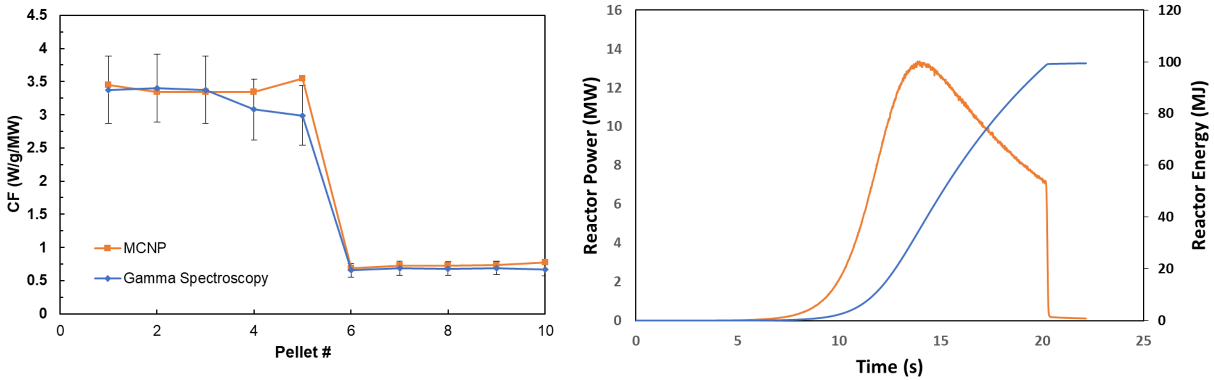
Results: Calibration test

- ATF-RIA-1-Gamma
  - Irradiated first week in January 2020
  - Gamma test utilized 5 4.95% U^{235} pellets and 5 0.74% U^{235} pellets
    - Provide upper and lower Power Coupling Factor (PCF) bounds for all UO_2 tests
  - Irradiated using a 0.6%Δk/k transient clipped to 100 MJ
  - MCNP predictions on PCF show good agreement with gamma spectroscopy results
    - Average deviation was less than 6%

ATF-RIA-1-Gamma capsule disassembly



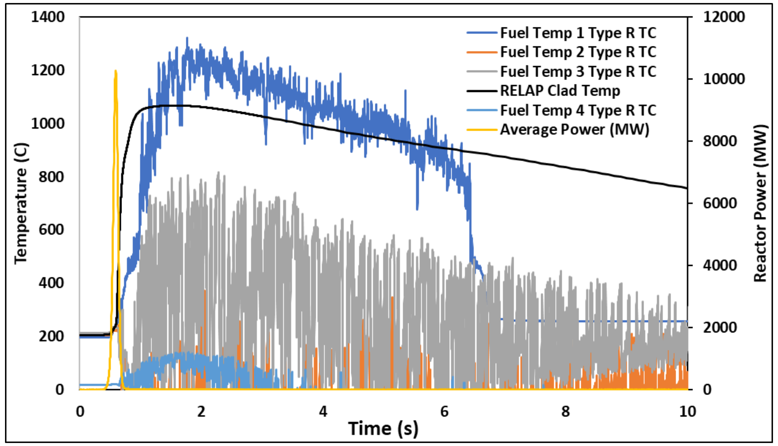
Cladding thermocouple measurements



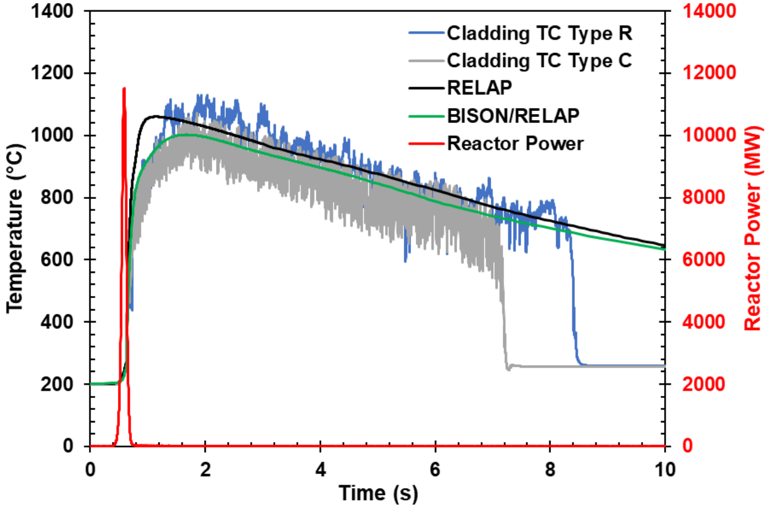
Pellet by pellet PCF and ATF-RIA-1-Gamma reactor power and energy

Temperature Results

- Reliable thermocouple results was a challenge throughout the experiment campaign
  - Integral junction TCs were used (better response time)
  - Difficulties in attaching resulted in some failed TCs during the experiments
  - By the final experiment (ATF-RIA-1-E) the performance improved significantly
- These are preliminary results, more detailed analysis to come
- Both RELAP5-3D and BISON/RELAP5-3D coupled predictions were used for post-test analysis
  - Thermal-hydraulic parameters in the RELAP5-3D model taken from results of the CHF-SERTTA experiments
    - Track 5 presentation given by Robert Armstrong “Results of the CHF-SERTTA In-Pile Transient Boiling Experiments at TREAT”



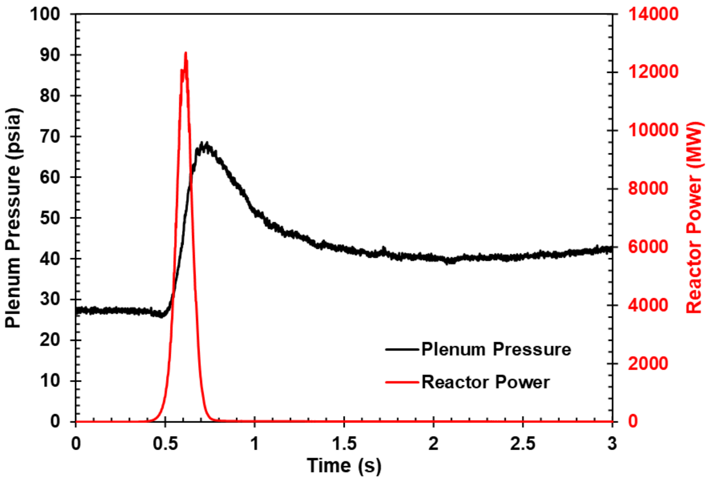
ATF-RIA-1-C
530 J/gUO_2 (127 cal/gUO_2) energy deposition



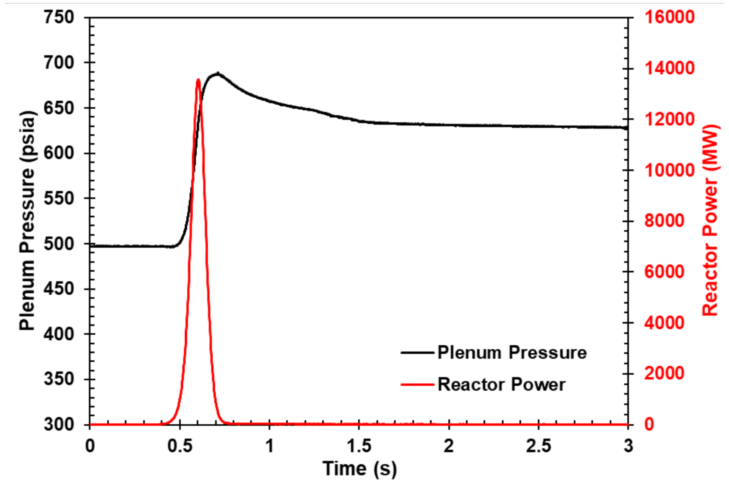
ATF-RIA-1-E
590 J/gUO_2 (141 cal/gUO_2) energy deposition

Plenum Pressure

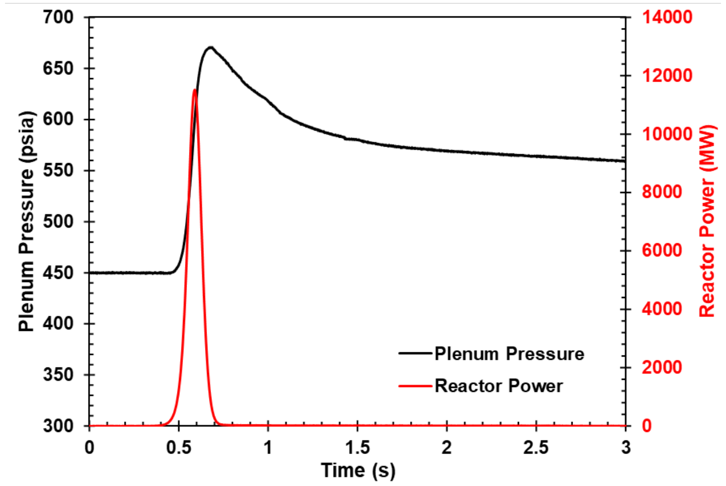
- Capsules B, D, and E utilized the plenum pressure bellows with LVDT
- Capable over a large range of pressures
- Still working on BISON modeling to compare to the measured results
  - Details to figure out
    - How gamma heating of bellows impacts results
    - Proper plenum gas temperature implementation in fuel performance modeling
- Trends are similar as those seen in fuel performance modeling benchmarks for RIAs



ATF-RIA-1-B
1110 J/gUO$_2$ (265 cal/gUO$_2$) energy deposition



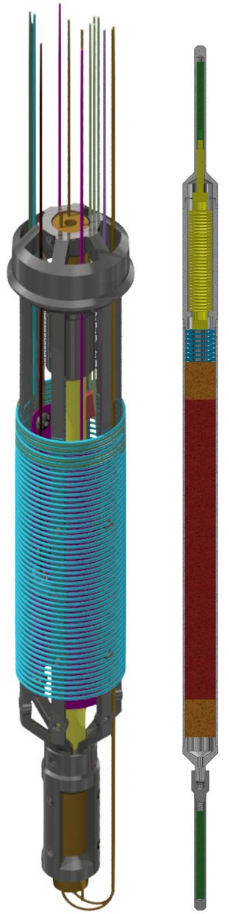
ATF-RIA-1-D
720 J/gUO$_2$ (172 cal/gUO$_2$) energy deposition

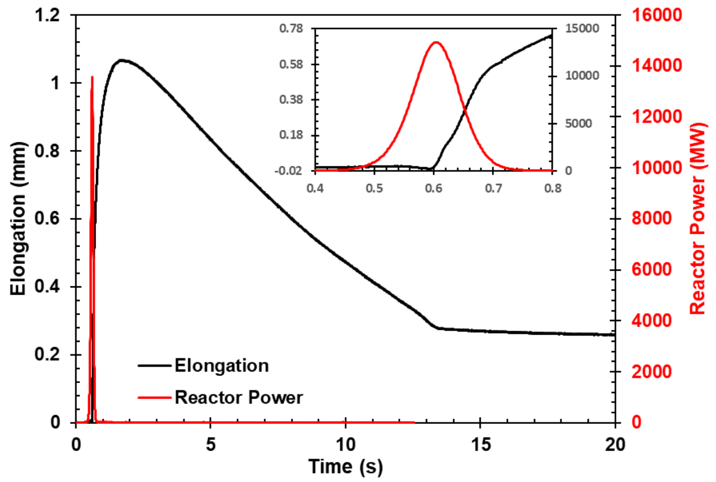


ATF-RIA-1-E
590 J/gUO$_2$ (141 cal/gUO$_2$) energy deposition

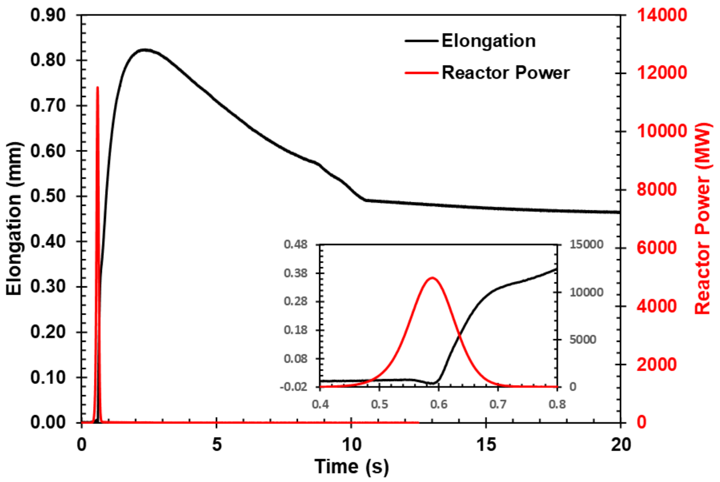
Rodlet Elongation

- Capsules D and E utilized a lower LVDT to measure cladding elongation
- Still working on BISON modeling to compare to the measured results
  - Details to figure out
    - How gamma heating of the rodlet holder affects LVDT measurements
- Trends are similar as those seen in fuel performance modeling benchmarks for RIAs





ATF-RIA-1-D
720 J/gUO_2 (172 cal/gUO_2) energy deposition



ATF-RIA-1-E
590 J/gUO_2 (141 cal/gUO_2) energy deposition

Post Irradiation Examination

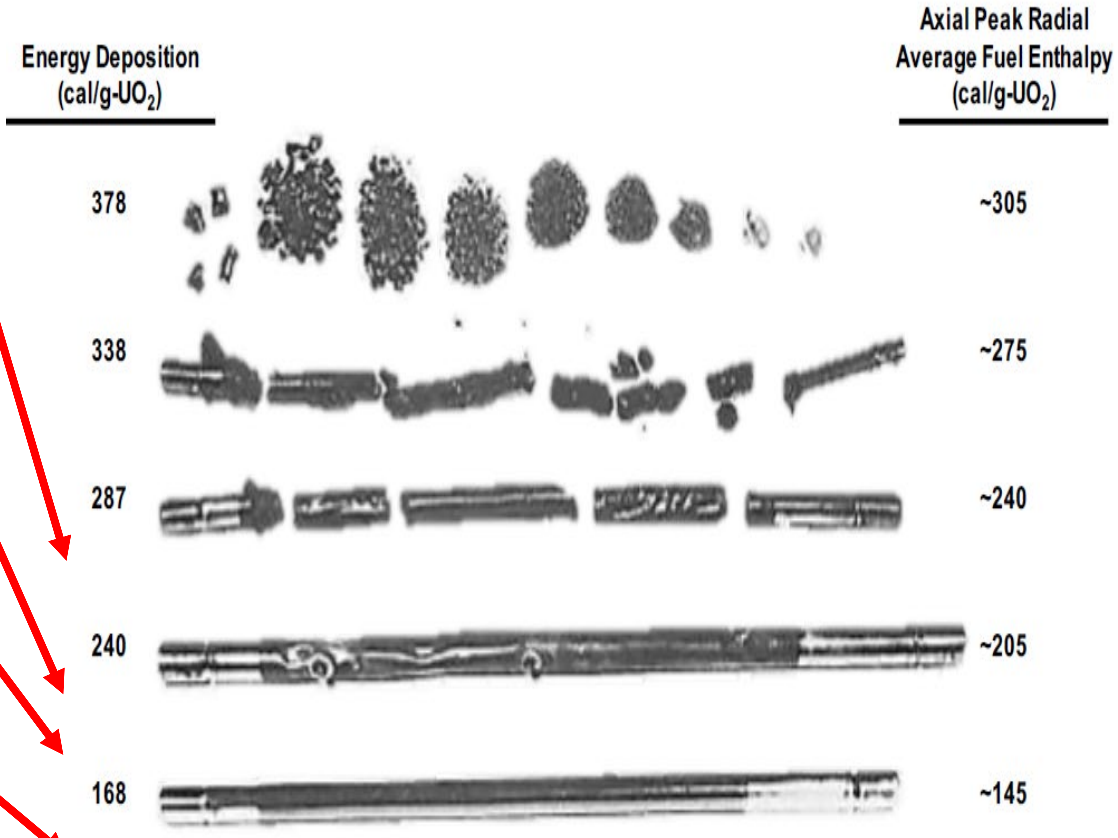
1B, 1110 J/g (~265 Cal/g)

1A, 870 J/g (~208 Cal/g)

1D, 720 J/g (~172 Cal/g)

1E, 590 J/g (~141 Cal/g)

1C, 530 J/g (~126 Cal/g)



From SPERT-IV Fresh Fuel RIA Tests

- Appearance of rods show good agreement with historical tests

PIE: Diameter and Strain Measurements

- Some of the rods experienced permanent bowing deformation
- Final cladding strain expected based on plenum/capsule pressure differentials
  - 1E showed > 2.5% strain
  - 1D ~ 1.25% strain
  - 1C ~ -0.75% strain

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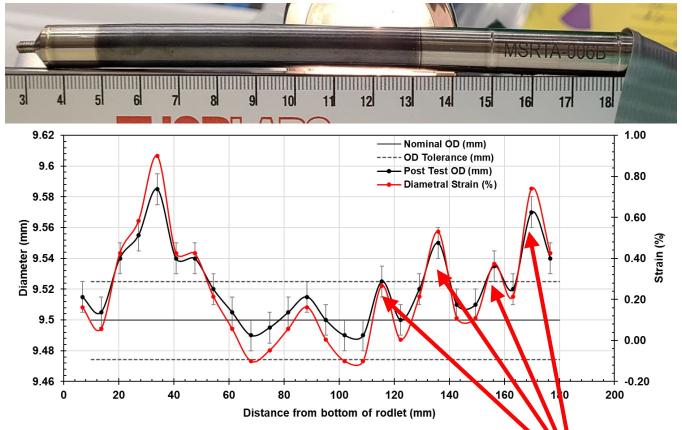
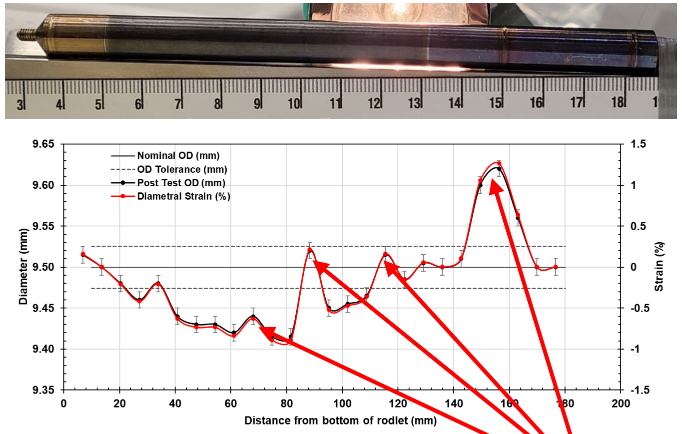
ATF-RIA-1-E	2 MPa	1.985 MPa	202	4.2	590



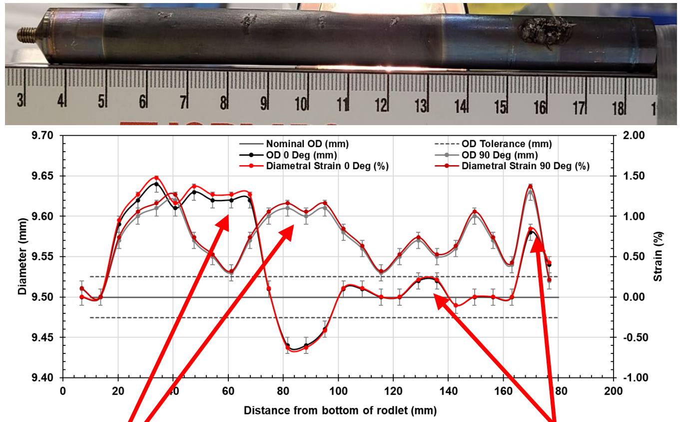
ATF-RIA-1-A

Weld Locations



ATF-RIA-1-C

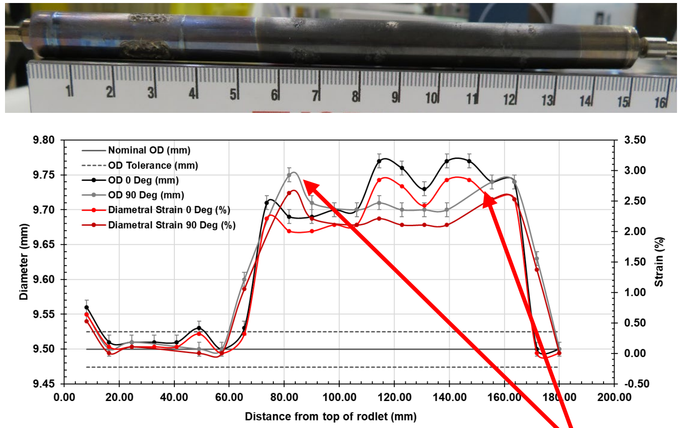
Weld Locations



ATF-RIA-1-D

Weld Locations

Eccentric diametral strain and cross over



ATF-RIA-1-E

Weld Locations

Conclusions

- Successfully completed the ATF-RIA-1 series of tests
  - Significant step in demonstrating our capabilities for water-based accident testing
- Learned a lot regarding design, operation, and instrumentation performance
- Reliable thermocouple performance is much more difficult than previously anticipated
  - Improved design and implementation for future experiments such as HERA
- Demonstrated the LVDT plenum pressure and cladding elongation measurement capabilities
  - Still modeling and analysis required to fully understand the results
- Boiling detector did not perform as expected
  - Modification made to future experiments which showed excellent results in the CHF-SERTTA experiments
- Non-destructive PIE has been performed on all the rodlets
  - 1B rod failure, bowing observed in other rods. High pressure rods (1D & 1E) cladding expansion
- Destructive PIE will begin in FY2022

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