INL/MIS-22-66558-Revision-0

RIA Testing Program for ATF

March 2022

Changing the World's Energy Future

Charles P Folsom, Colby B Jensen, Jason L Schulthess, David W Kamerman, Nicolas E Woolstenhulme, Robert J Armstrong, Daniel M Wachs

Idaho National Laboratory

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RIA Testing Program for ATF

11th Annual EPRI/DOE/INL Joint Workshop on Accident Tolerant Fuel

March 29, 2022

Idaho National Laboratory

Outline

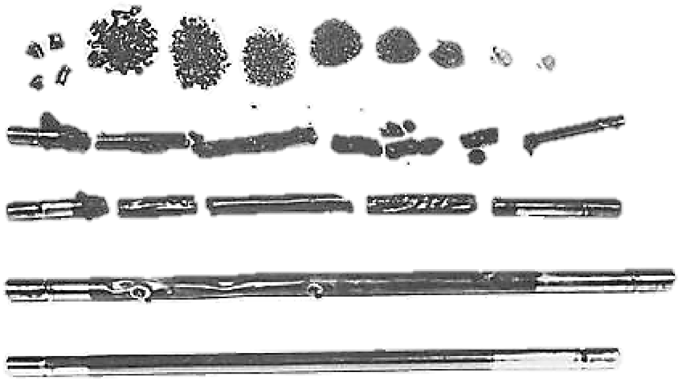
- Introduction
- Overview of RIA Testing at TREAT
- TREAT Experiment Design
  - SERTTA-RIA-C
  - SERTTA-CHF
- SERTTA Commissioning Tests
- SERTTA-CHF
- Conclusions
- Future Work

Introduction

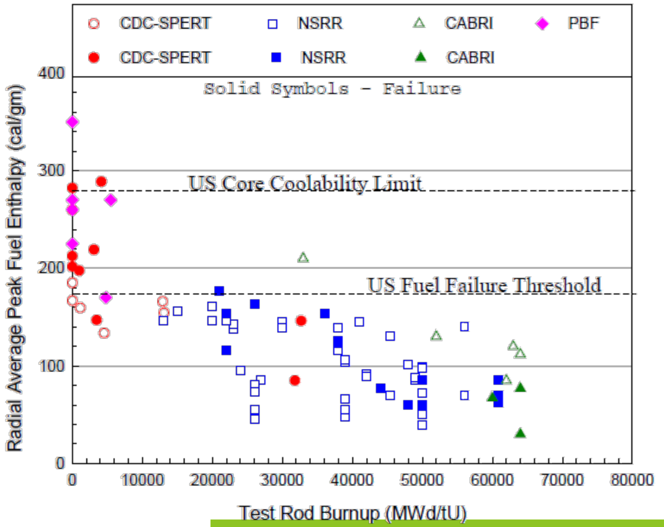
- The work is focused on developing the capabilities for Reactivity-Initiated Accident testing at TREAT
  - Historically relied on ~100 tests to simulate RIA conditions and subsequently establish empirical fuel safety criteria for UO2/Zry
- ATF campaign has generated new/changes to fuel and cladding
  - 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's Road to RIA

2018	2019	2020	2021	2022	2023

Initial

- TREAT Power Prescription for LWR transients
- SETH-C energy deposition studies and dry capsule commissioning
- SETH-ATF Dry capsule testing of ATF materials
- SERTTA-RIA-C water capsule commission/ first irradiated fuel test
- SERTTA-CHF In-pile boiling experiments
- IRP Fuel Fracture Validation Experiment
- ATR Loop 2A Pre-irradiated fuel to TREAT (ATF-R)

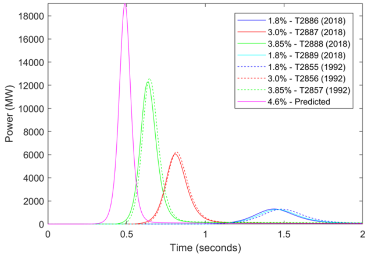
Current Programs

- FIDES HERA JEEP
  Simulated HBU fuel and HBU fuel
- NSUF-RIA-CCZ experiments on fresh coated cladding materials

Sobol Indices											
INPUT paramater	RAE	TFC	TFO	TCI	TCO	CTHS	CHS	FOR	PHS	GAP	HFC
Cladding outside diameter	0.009	0.010	0.003	0.003	0.003	0.007	0.004	0.005	0.005	0.003	0.003
Cladding inside diameter	0.004	0.003	0.010	0.003	0.003	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fuel outer diameter	0.008	0.007	0.007	0.002	0.002	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fuel porosity	0.014	0.015	0.004	0.004	0.003	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cladding roughness	0.009	0.007	0.076	0.014	0.010	0.007	0.017	0.007	0.011	0.005	0.421
Fuel roughness	0.005	0.004	0.063	0.016	0.011	0.000	0.021	0.001	0.005	0.000	0.431
Filling gas pressure	0.001	0.001	0.001	0.002	0.001	0.002	0.002	0.002	0.001	0.001	0.001
Coolant pressure	0.004	0.004	0.005	0.007	0.006	0.005	0.005	0.001	0.004	0.003	0.003
Coolant inlet temperature	0.006	0.006	0.008	0.011	0.011	0.004	0.008	0.005	0.005	0.001	0.003
Coolant velocity	0.005	0.005	0.001	0.001	0.001	0.009	0.003	0.010	0.005	0.004	0.006
Injected energy in the rod	0.863	0.868	0.228	0.096	0.060	0.185	0.012	0.273	0.176	0.156	0.008
FWHM pulse width	0.009	0.004	0.015	0.005	0.003	0.004	0.001	0.003	0.004	0.003	0.005
Fuel thermal conductivity model	0.005	0.005	0.036	0.015	0.010	0.003	0.013	0.004	0.004	0.001	0.003
Clad thermal conductivity model	0.006	0.006	0.008	0.007	0.005	0.006	0.002	0.005	0.007	0.004	0.006
Fuel thermal expansion model	0.002	0.002	0.006	0.004	0.004	0.327	0.160	0.507	0.123	0.208	0.002
Clad thermal expansion model	0.003	0.003	0.002	0.002	0.002	0.002	0.003	0.002	0.005	0.008	0.002
Clad Yield stress	0.003	0.003	0.001	0.002	0.002	0.001	0.008	0.002	0.005	0.003	0.001
Fuel enthalpy	0.079	0.091	0.010	0.006	0.005	0.019	0.010	0.031	0.012	0.034	0.003
Clad to coolant heat transfer	0.004	0.003	0.111	0.162	0.169	0.008	0.110	0.003	0.083	0.005	0.009
Coolant CHF factor	0.012	0.009	0.370	0.643	0.702	0.013	0.350	0.013	0.312	0.056	0.007
Gas conductivity factor	0.004	0.003	0.016	0.003	0.003	0.011	0.003	0.008	0.010	0.002	0.060
Summation	1.056	1.058	0.982	1.007	1.014	1.027	0.973	1.029	0.944	0.644	0.986

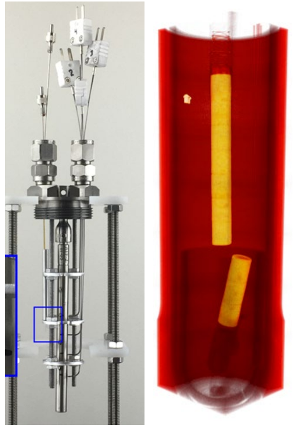
BISON

Detailed uncertainty/ sensitivity studies with international collaboration

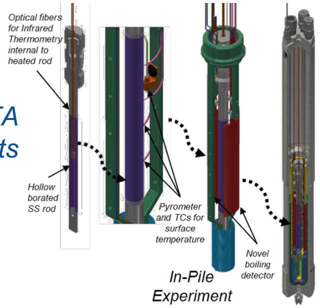


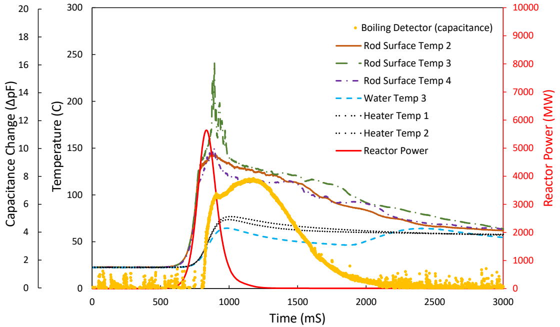
Transient prescription study results

SETH Experiments

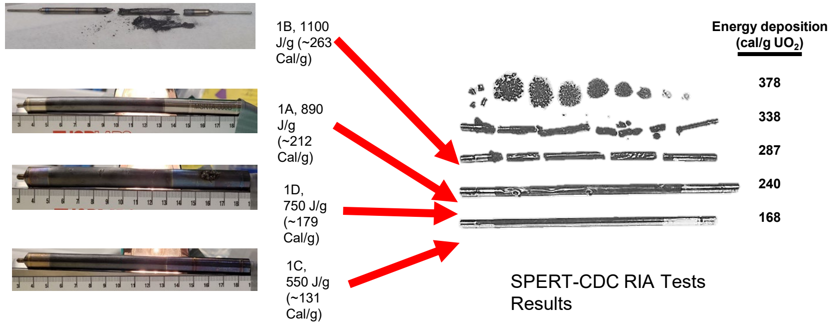


CHF-SERTTA Experiments





SERTTA-RIA-C (water capsule) Commissioning Experiments

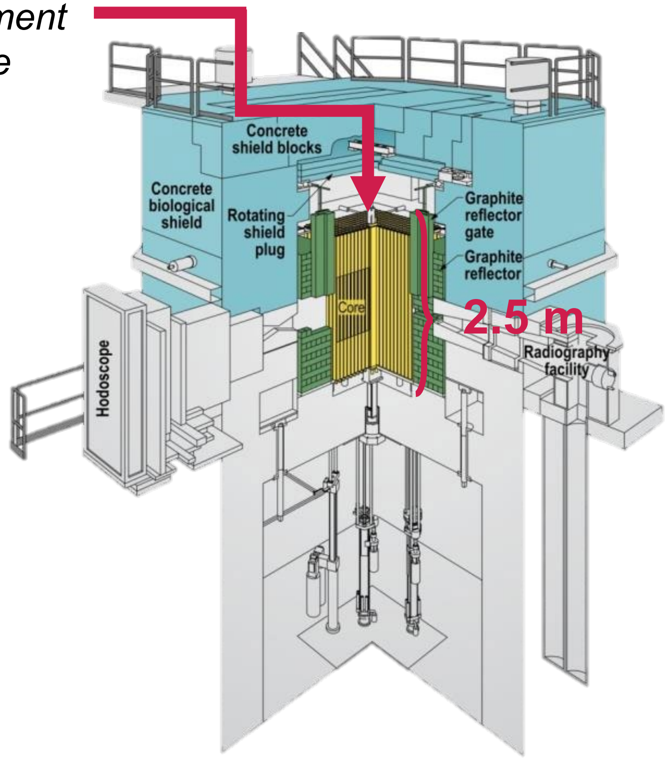


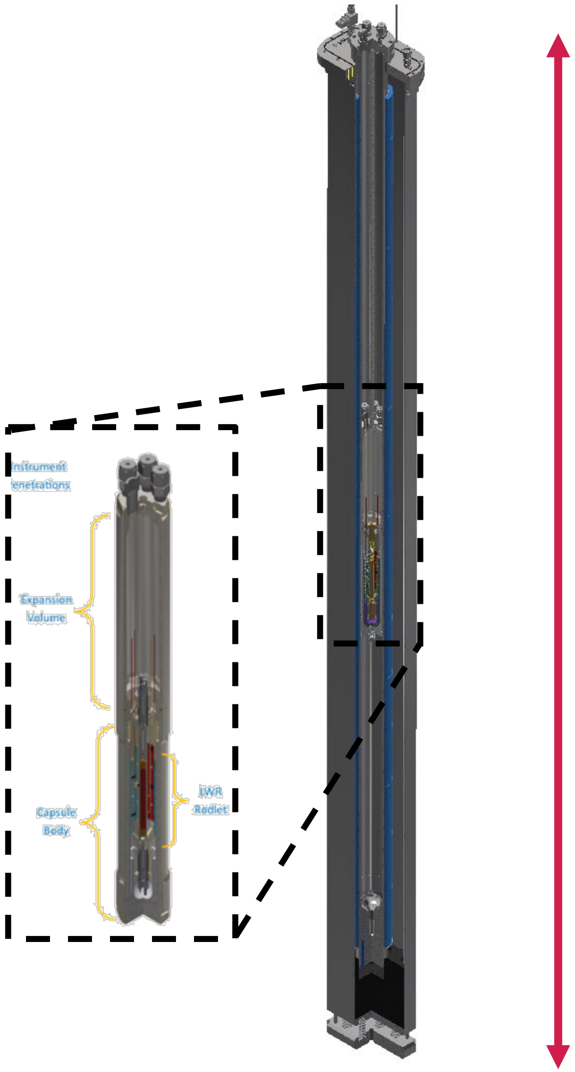
SPERT-CDC RIA Tests Results

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





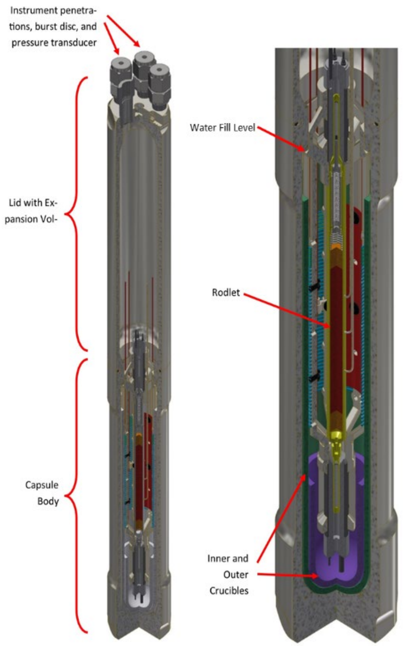
SERTTA
Static pressurized water capsule

2.5 m

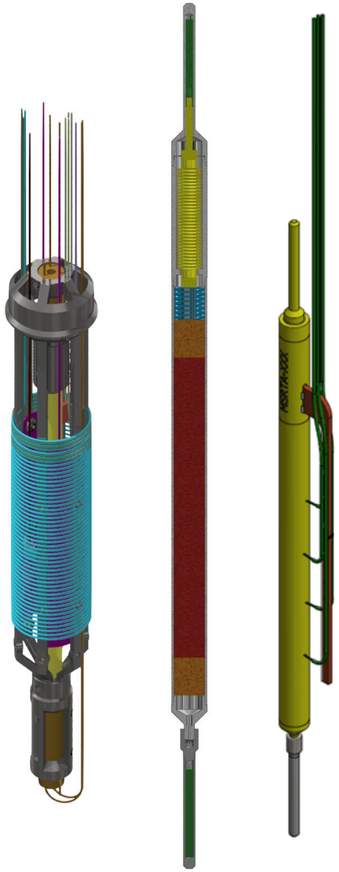
- Static Environment Rodlet Transient Test Apparatus (SERTTA) is the parent capsule for water-based RIA tests
  - Variations/modifications are adapted for specific experiment campaigns
    - Commissioning series
    - Pre-irradiated fuel test
    - Separate-effect CHF tests
    - HERA tests

Significance of Experiments to Date

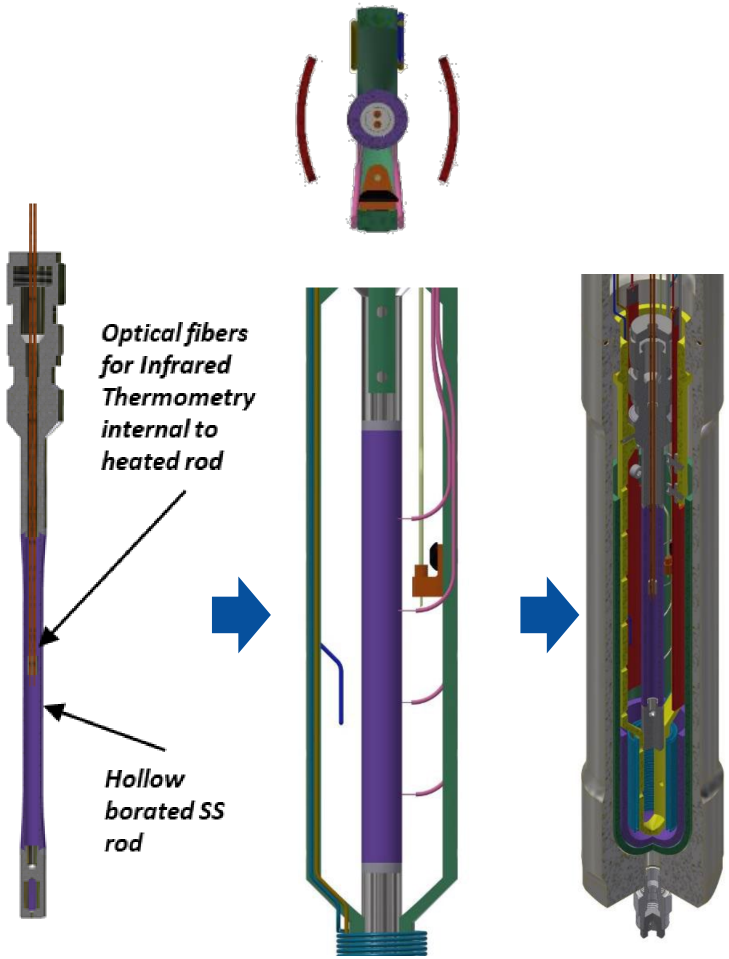
- SERTTA-RIA-C
  - Commissioning experiments for water-based tests in TREAT using MARCH-SERTTA capsule
- SERTTA-CHF
  - Separate-effect test to study thermal-hydraulic phenomena under rapid heating experiments
    - Sophisticated first-of-its-kind experiment



MARCH-SERTTA Capsule



SERTTA-RIA-C Rodlet holder and rodlet

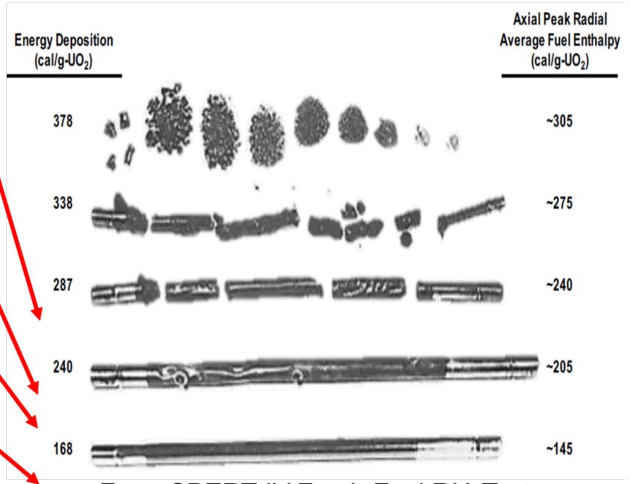


SERTTA-CHF heater rod in MARCH-SERTTA capsule

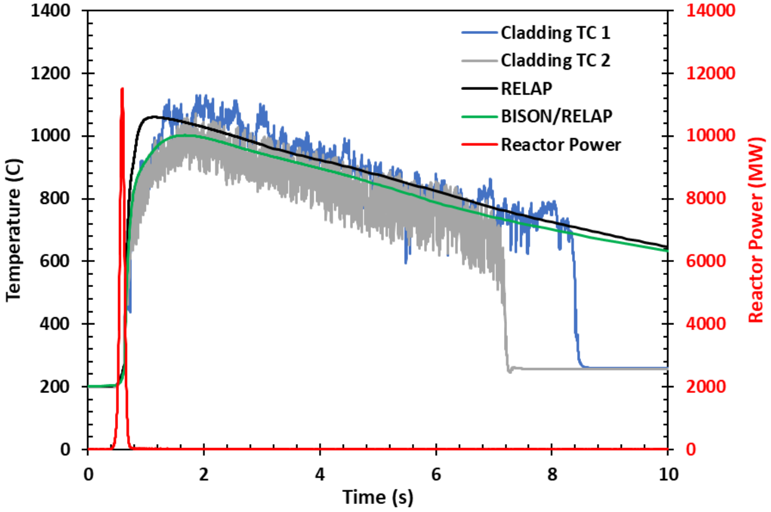
SERTTA-RIA-C Experiments

- 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
- PIE of experiments show the fuel rodlet condition is similar to historical SPERT-IV tests
- Experiments provide valuable data for post-test analysis and validation of fuel performance codes
- Pros/Cons being used to improve future experiments (HERA)

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

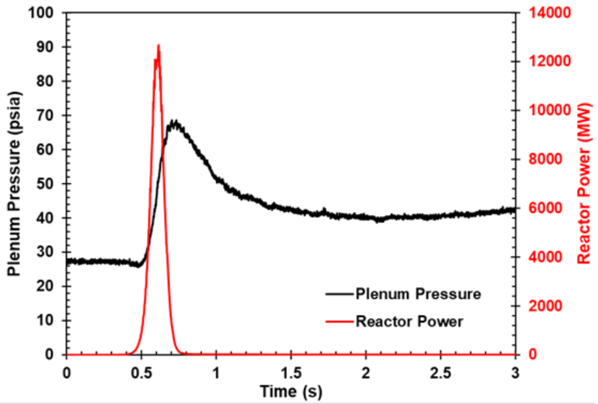


SERTTA-RIA-C-E experiment cladding thermocouple results along with RELAP5-3D modeling predictions and coupled BISON/RELAP5-3D modeling predictions

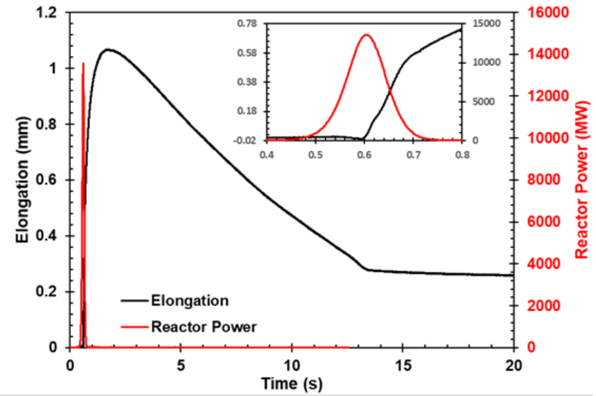
590 J/gUO_2 (141 cal/gUO_2) energy deposition

SERTTA-RIA-C Experiments

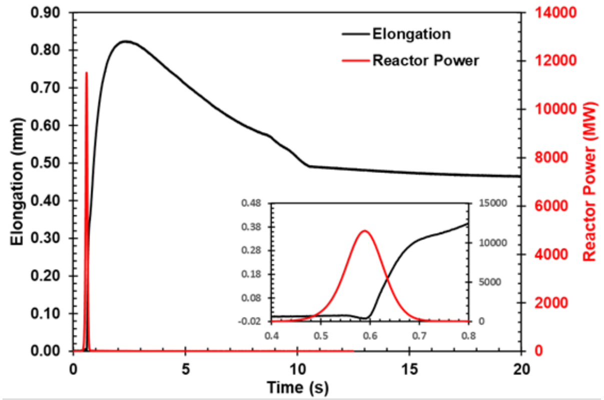
- Capsules B, D, and E utilized the plenum pressure bellows with LVDT
- Capable over a large range of pressures
- Capsules D and E utilized a lower LVDT to measure cladding elongation
- Trends are similar as those seen in fuel performance modeling benchmarks for RIAs



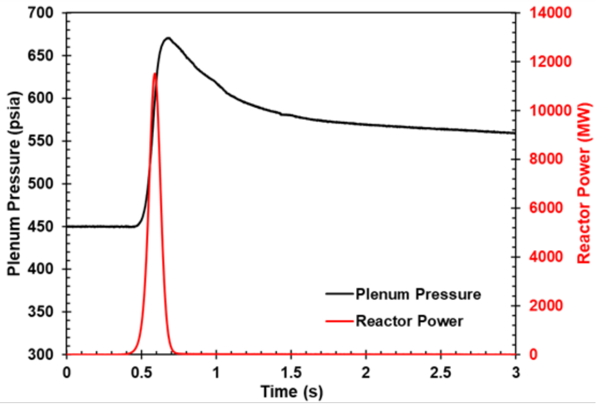
SERTTA-RIA-C-B
1110 J/gUO$_2$ (265 cal/gUO$_2$) energy deposition



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

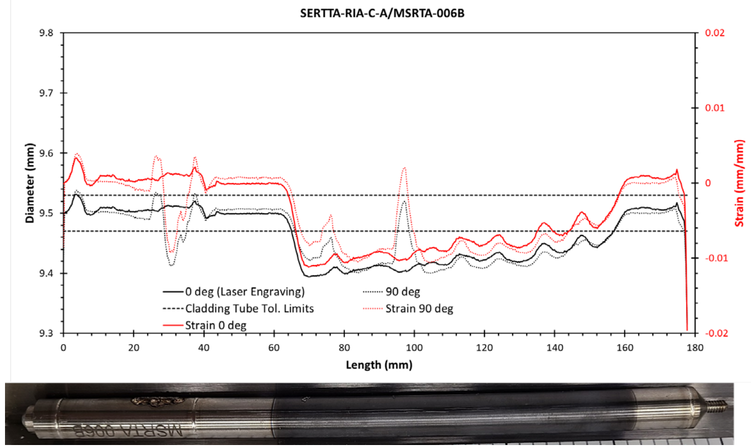


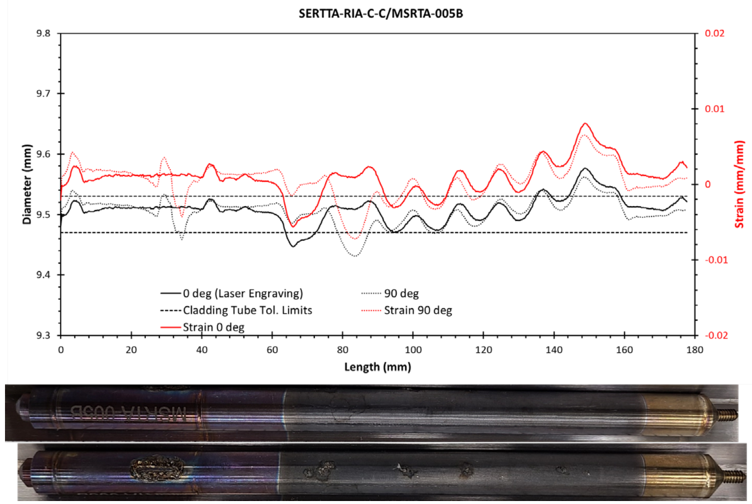
SERTTA-RIA-C-E
590 J/gUO$_2$ (141 cal/gUO$_2$) energy deposition

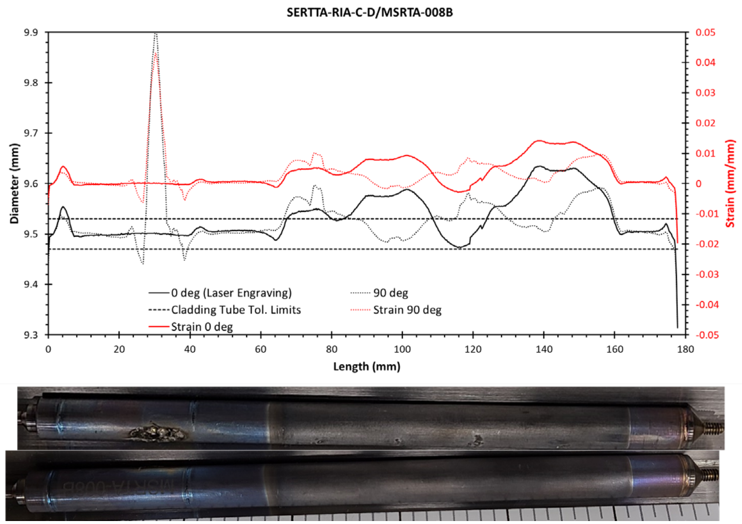
SERTTA-RIA-C Post Transient Examinations

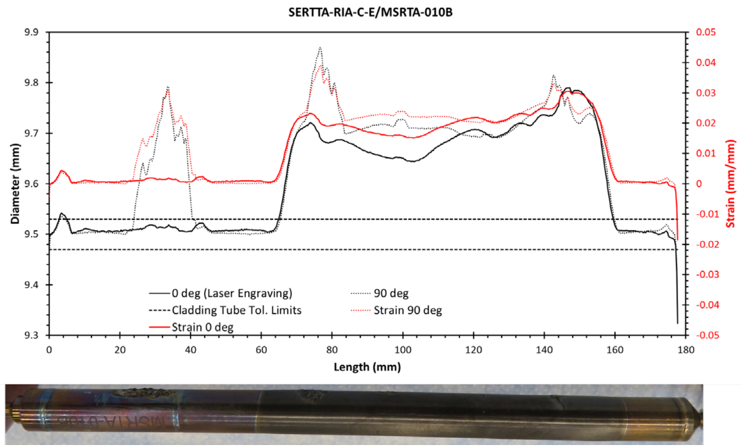
- Some of the rods experienced permanent bowing deformation
- Measurements made with a high resolution profilometer
  - Bambooing from individual pellets seen in some cases
  - Final cladding strain expected based on plenum/capsule pressure differentials
    - E showed > 2.5% strain
    - D ~ 1.0% strain
    - A ~ -0.75% strain

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



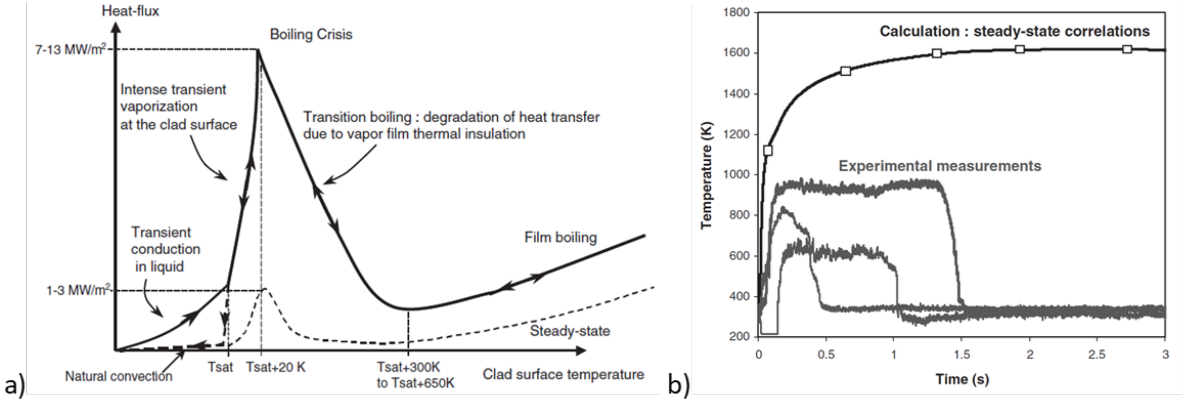






SERTTA-CHF Experiments

- One of the key uncertainties related to RIA failure threshold applicable to current UO_2/Zr fuel rods and ATF fuel rods is the critical heat flux under transients
- It is well-known that critical heat flux (CHF) during rapid transient boiling conditions is significantly higher than under steady-state conditions (NEA/CSNI/R(2016)6/VOL1)
  - This impacts the fuel performance predictive capability for cladding-to-coolant heat transfer during transient irradiation conditions
  - Key safety limit for LWRs is intended to avoid CHF
  - Fuel performance predictions for RIA events conservatively predict behaviors but with significant margin in many cases due to inadequate CHF correlations
- Improved modeling and predictive capability is a crucial need for LWR fuel technology
  - Need data and experiments such as SERTTA-CHF especially for ATF concepts and high-burnup fuel rods



a) Schematic view of the experimental boiling curve in the NSRR Tests compared to steady-state predictions [Bessiron, 2007]. b) Clad temperature evolution from NSRR test TK-6 (38 GWd/t burnup rod, maximum fuel enthalpy of 494 J/g) showing a comparison to steady-state correlation prediction [Bessiron, 2007].

	Sobol Indices										
INPUT paramater	RAE	TFC	TFO	TCI	TCO	CTHS	CHS	FOR	PHS	GAP	HFC
Cladding outside diameter	0.009	0.010	0.003	0.003	0.003	0.007	0.004	0.005	0.005	0.003	0.003
Cladding inside diameter	0.004	0.003	0.010	0.003	0.003	0.329	0.198	0.009	0.132	0.110	0.002
Fuel outer diameter	0.008	0.007	0.007	0.002	0.002	0.080	0.042	0.135	0.030	0.034	0.007
Fuel porosity	0.014	0.015	0.004	0.004	0.003	0.003	0.003	0.005	0.004	0.003	0.004
Cladding roughness	0.009	0.007	0.076	0.014	0.010	0.007	0.017	0.007	0.011	0.005	0.421
Fuel roughness	0.005	0.004	0.063	0.016	0.011	0.000	0.021	0.001	0.005	0.000	0.431
Filling gas pressure	0.001	0.001	0.001	0.002	0.001	0.002	0.002	0.002	0.001	0.001	0.001
Coolant pressure	0.004	0.004	0.005	0.007	0.006	0.005	0.005	0.001	0.004	0.003	0.003
Coolant inlet temperature	0.006	0.006	0.008	0.011	0.011	0.004	0.008	0.005	0.005	0.001	0.003
Coolant velocity	0.005	0.005	0.001	0.001	0.001	0.009	0.003	0.010	0.005	0.004	0.006
Injected energy in the rod	0.863	0.868	0.228	0.096	0.060	0.185	0.012	0.273	0.176	0.156	0.008
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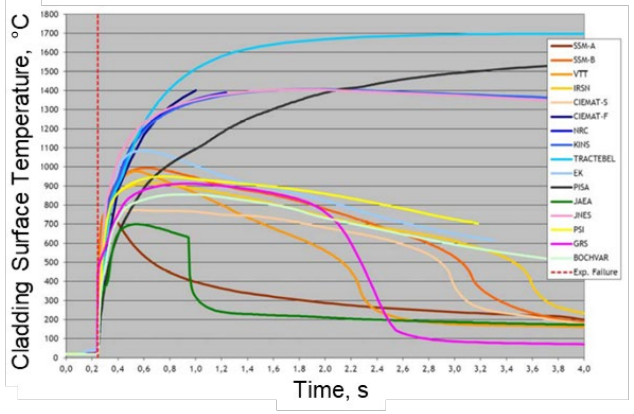
Fuel thermal expansion model	0.002	0.002	0.006	0.004	0.004	0.327	0.160	0.507	0.123	0.208	0.002
Clad thermal expansion model	0.003	0.003	0.002	0.002	0.002	0.002	0.003	0.002	0.005	0.008	0.002
Clad Yield stress	0.003	0.003	0.001	0.002	0.002	0.001	0.008	0.002	0.005	0.003	0.001
Fuel enthalpy	0.079	0.091	0.010	0.006	0.005	0.019	0.010	0.031	0.012	0.034	0.003
Clad to coolant heat transfer	0.004	0.003	0.111	0.162	0.169	0.008	0.110	0.003	0.083	0.005	0.009
Coolant CHF factor	0.012	0.009	0.370	0.643	0.702	0.013	0.350	0.013	0.312	0.056	0.007
Gas conductivity factor	0.004	0.003	0.016	0.003	0.003	0.011	0.003	0.008	0.010	0.002	0.060
Summation	1.056	1.058	0.982	1.007	1.014	1.027	0.973	1.029	0.944	0.644	0.986

BISON fuel performance sensitivity study shows over 70% of the cladding temperature uncertainty comes from CHF uncertainty and CHF uncertainty is one of the dominant factors in almost all fuel performance metrics

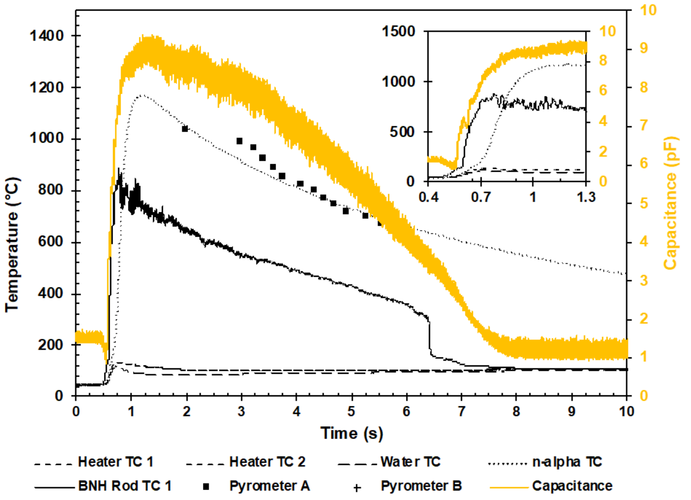


Fuel performance predictions for cladding surface temperature during RIA (NEA/CSNI/R(2013)7)

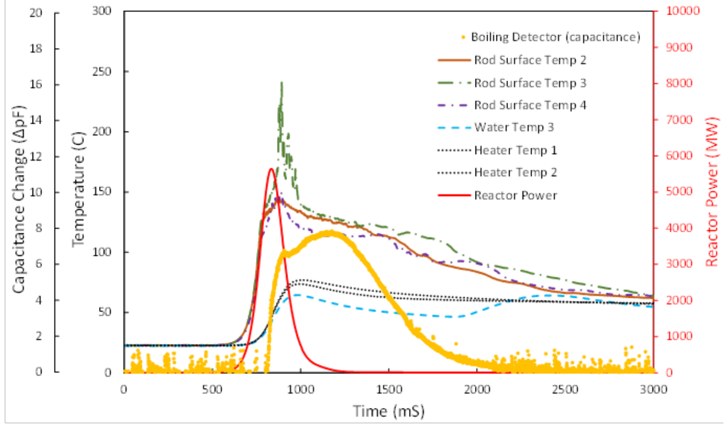
SERTTA-CHF Experiments

- Three capsules each with 4-5 transients tested various energy depositions and heating rate effects
- Experiments showed great demonstration of new instrument technology
  - Electro-impedance boiling detector
  - n-alpha thermometer
- Data is being analyzed through an inverse heat transfer method with RELAP5-3D and DAKOTA to determine what CHF will provide the best fit between model and experiment results
  - Seeing between 200-400% increase in CHF depending on the rate of heating
  - Supported by a recent MIT publication*
  - Still need more data and analysis to understand post-CHF thermal-hydraulics
- Data being used to provide better modeling capabilities for SERTTA-RIA-C experiments and HERA experiments

Trans.	SERTTA-CHF-A Step Insertion (dk/k) Total Target Energy	SERTTA-CHF-B Step Insertion (dk/k) Total Target Energy	SERTTA-CHF-C Step Insertion (dk/k) Total Target Energy
1	3.0% 1000 MJ	4.2% 1800 MJ Initial Temp: 45°C	3.4% 1400 MJ Initial Temp: 45°C
2	3.0% 1000 MJ	4.2% 1800 MJ Initial Temp: 45°C	3.4% 1400 MJ Initial Temp: 45°C
3	3.0% 1000 MJ	4.2% 1800 MJ Initial Temp: 45°C	3.4% 1400 MJ Initial Temp: 45°C
4	3.0% 1000MJ	4.2% 1800 MJ Initial Temp: 45°C	3.8% 1400 MJ Initial Temp: 45°C
5	N/A	4.2% 1800 MJ Initial Temp: 20°C	4.2% 1400 MJ Initial Temp: 45°C



SERTTA-CHF-B-1

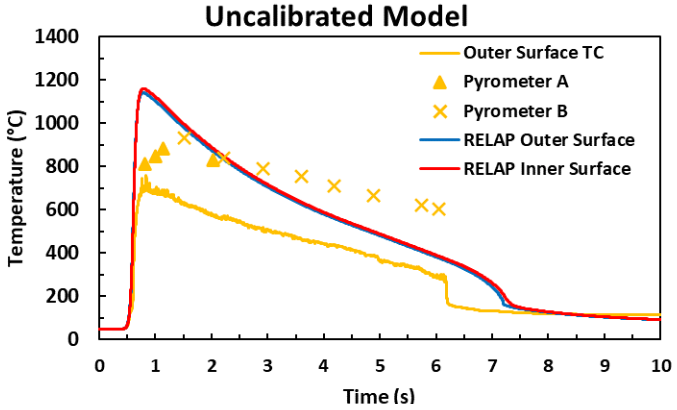


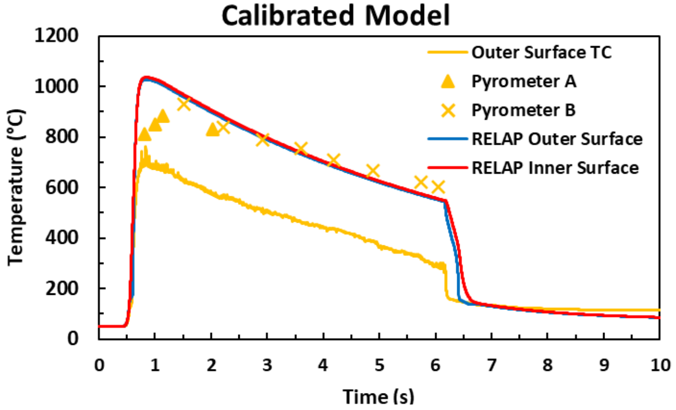
SERTTA-CHF-A-1

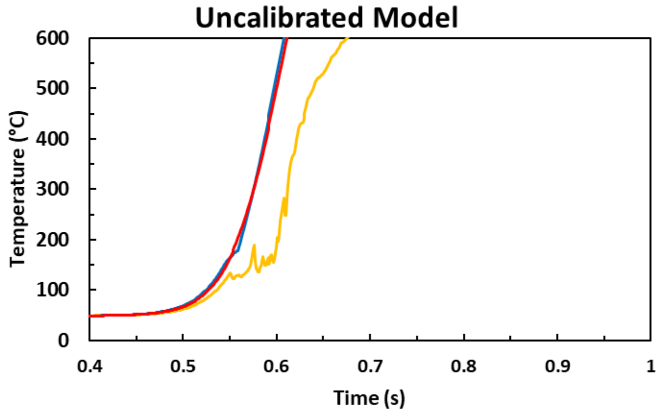
*Chavagnat, F., Nop, R., Dorville, N., Phillips, B., & Bucci, M. (2021). Single-phase heat transfer regimes in forced flow conditions under exponential heat inputs. International Journal of Heat and Mass Transfer, 174, 121294.

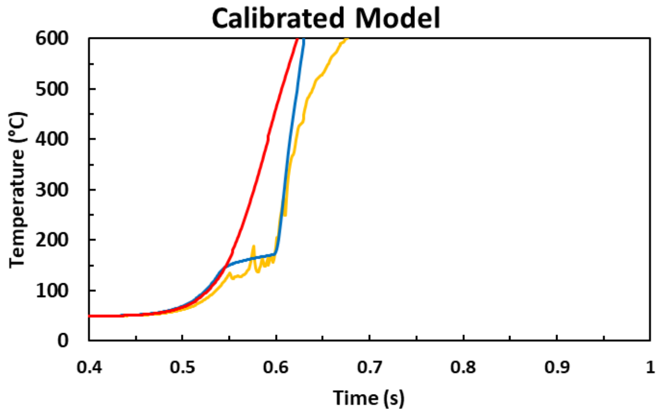
Analysis of SERTTA-CHF-B-2

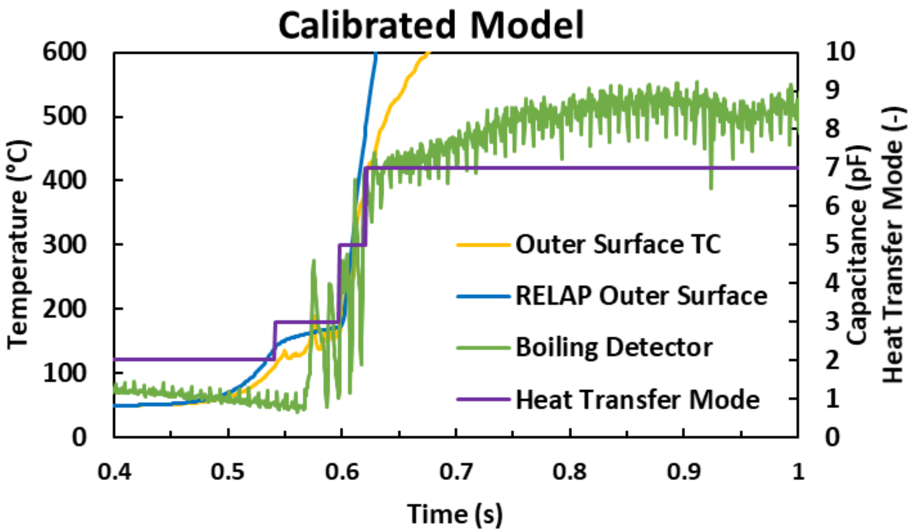
- Calibrated model predicts CHF ~16 MW/m²; 4 times greater than steady-state correlation
- Increased nucleate boiling and transition boiling heat transfer coefficients
- Decreased film boiling heat transfer coefficient
- TCs measuring ~200 °C low











Conclusions

- Successfully completed the SERTTA-RIA-C series of tests
  - Significant step in demonstrating our capabilities for water-based accident testing
  - Non-destructive PIE completed and destructive PIE is in process
  - 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
  - Impedance-based boiling detector provided valuable timing of boiling and CHF event in SERTTA-CHF experiments
- 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

Idaho National Laboratory

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