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Experiment and Modeling Developments to Support RIA Testing at TREAT

September 2024

Changing the World's Energy Future

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Idaho National Laboratory

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Experiment and Modeling Developments to Support RIA Testing at TREAT

Light Water Reactor Fuel Workshop/Collaborative Research for Advanced Fuel Technology (CRAFT) meeting September 2024

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Advanced Fuels Campaign

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

Outline

- Background & Motivation
- Road to RIA
- Beginning of RIA Modeling at INL
- RIA Sensitivity and UQ
- Thermal-Hydraulics Importance
- TREAT Experiments
  - Commissioning
  - HERA
  - CCZ
  - HBu
- BISON Improvements
- Summary & Conclusions

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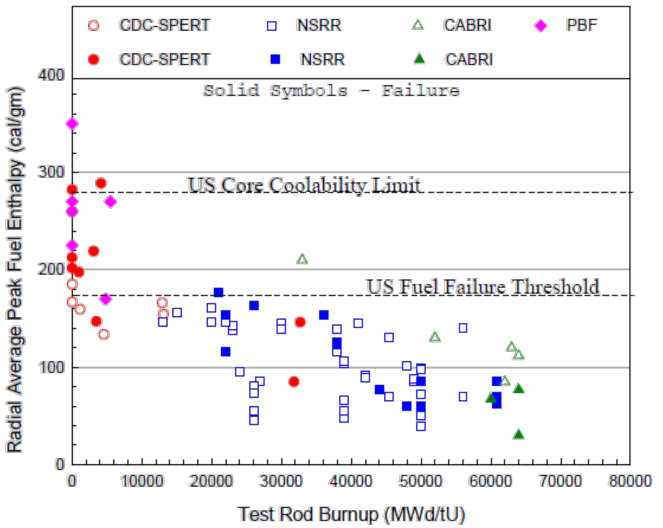
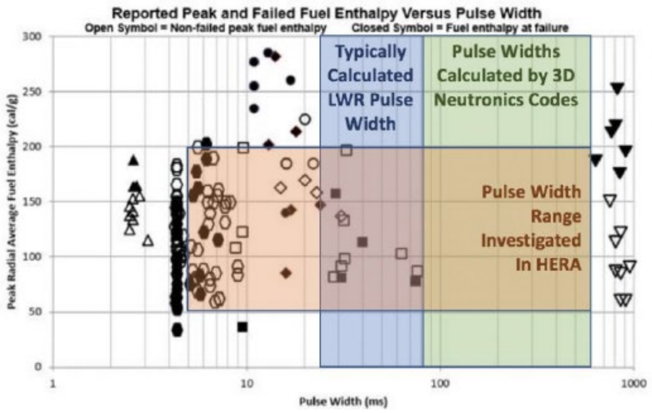
Background & Motivation

- Industry has goals in the near future to:
  - Extend burnup
  - Deploy and continue developing/testing ATF concepts
- For licensing, both paths will require understanding of fuel failure limits
  - Historically, 100s of tests have been performed to define the failure limit
  - Modern experiments are expensive and its not financially possible to extensively test like was done historically
- Advanced modeling and simulation in conjunction with limited, well characterized experiments can help accelerate the qualification for HBu or ATF
  - Some believe everything can be done through modeling efforts, but those who work in both the experimental and modeling worlds knows there is still a lot of work to do
- DOE through AFC and NEAMS has been progressing down parallel paths for M&S and experiments
- This presentation will highlight the work that has been done to support Reactivity-Initiated Accident (RIA) modeling and experiments





Overview of historical tests used to develop current failure threshold

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Road to RIA

2018 | 2019 | 2020 | 2021 | 2022 — 2024

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

ATR Loop 2A Pre-irradiated fuel to TREAT (ATF-R)

Current Programs

FIDES HERA JEEP Simulated HBU fuel and HBU fuel

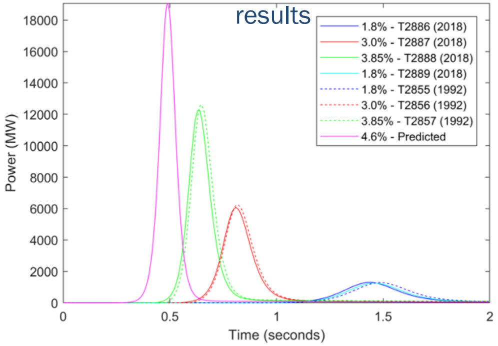
NSUF-RIA-CCZ experiments on fresh coated cladding materials

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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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	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
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

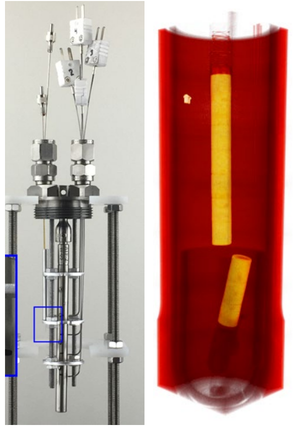
BISON

Detailed uncertainty/ sensitivity studies with international collaboration

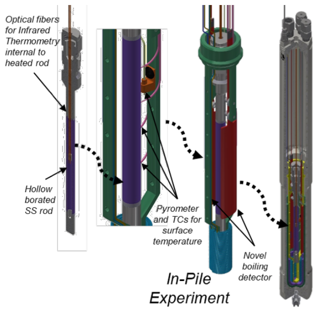
Transient prescription study results

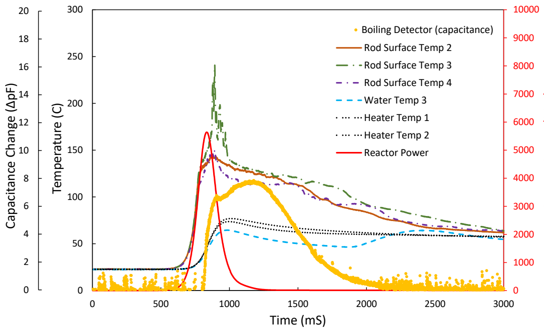


SETH Experiments

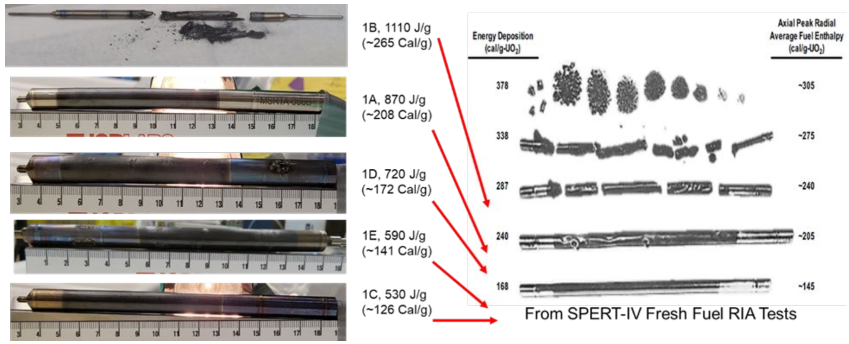


CHF-SERTTA Experiments



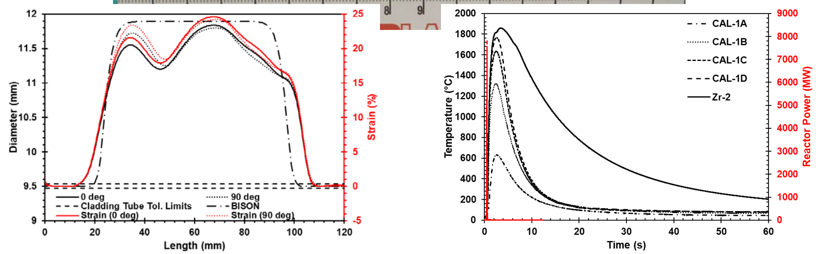


SERTTA-RIA-C (water capsule) Commissioning Experiments



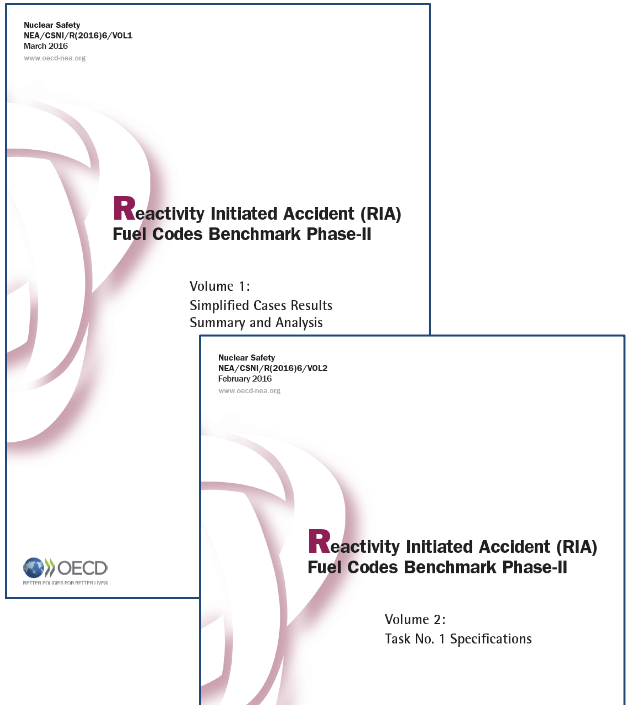
From SPERT-IV Fresh Fuel RIA Tests

HERA Calibration & Baseline Experiments



Beginning of RIA Modeling at INL

- In response to the ATF program, TREAT was restarted
  - One of the main drivers for the TREAT restart was RIA testing of ATF concepts
- In 2015 began modeling RIAs in BISON to help support future tests
  - Participated in Working Group on Fuel Safety RIA Fuel Codes Benchmark
    - Over 15 international organizations participated
    - Provided valuable feedback on BISON capabilities as well as areas of improvements (code and models)


Nuclear Safety
NEA/CSNI/R(2016)6/VOL1
March 2016
www.oecd-nea.org

Reactivity Initiated Accident (RIA) Fuel Codes Benchmark Phase-II

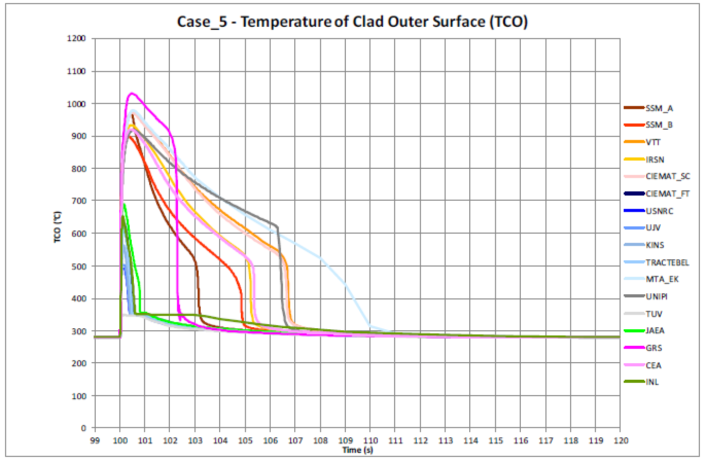
Volume 1:
Simplified Cases Results
Summary and Analysis

OECD

Nuclear Safety
NEA/CSNI/R(2016)6/VOL2
February 2016
www.oecd-nea.org

Reactivity Initiated Accident (RIA) Fuel Codes Benchmark Phase-II

Volume 2:
Task No. 1 Specifications



Cladding temperature predictions amongst codes for a simplified RIA case

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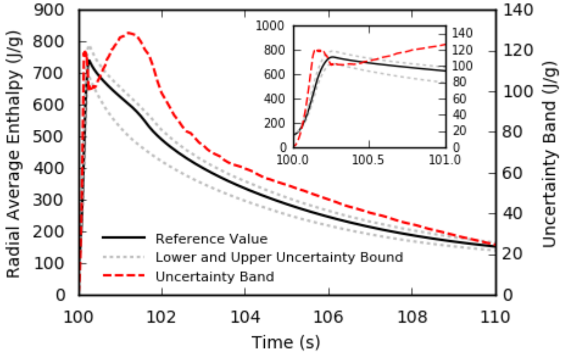
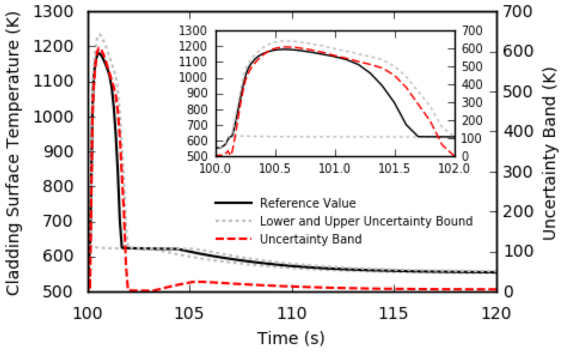
RIA Sensitivity and UQ

- To prioritize needed experimentation and modeling improvements, an RIA modeling sensitivity and uncertainty quantification exercise was performed
  - BISON combined with DAKOTA was used to investigate the effect of over 20 uncertain parameters on phenomena of interest for an expected TREAT experiment
- Thermal-hydraulic parameters such as critical heat flux found to be a very dominating parameter to the uncertainty of many parameters of interest
  - Especially cladding temperature
    - ~70% of uncertainty in cladding temperature from uncertainty in CHF
    - CHF can have significant impact on overall cladding temperature
- Energy deposited in fuel is important to understand
  - Significant efforts in verifying the Power Coupling Factor (PCF) between TREAT and specimen when performing experiments





Uncertainty of fuel radial average enthalpy and cladding temperature

	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
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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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Summation	1.056	1.058	0.982	1.007	1.014	1.027	0.973	1.029	0.944	0.644	0.986

Sobol Indices for each uncertain parameter at the maximum for each parameter of interest

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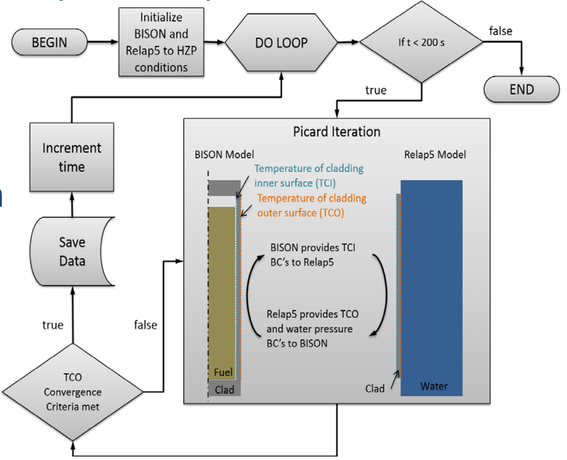
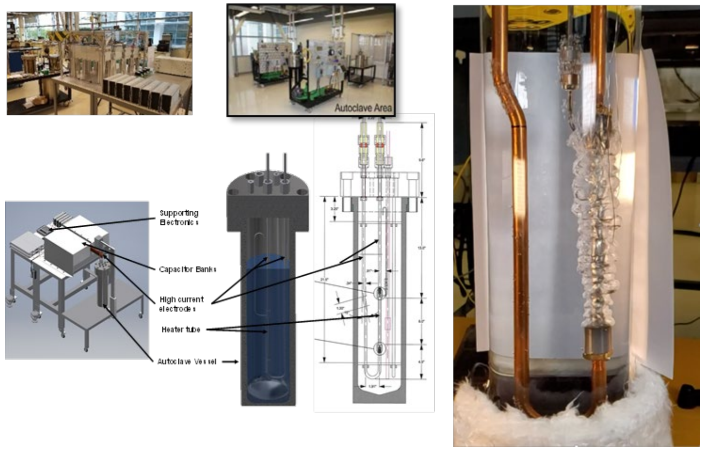
Thermal-Hydraulics Importance

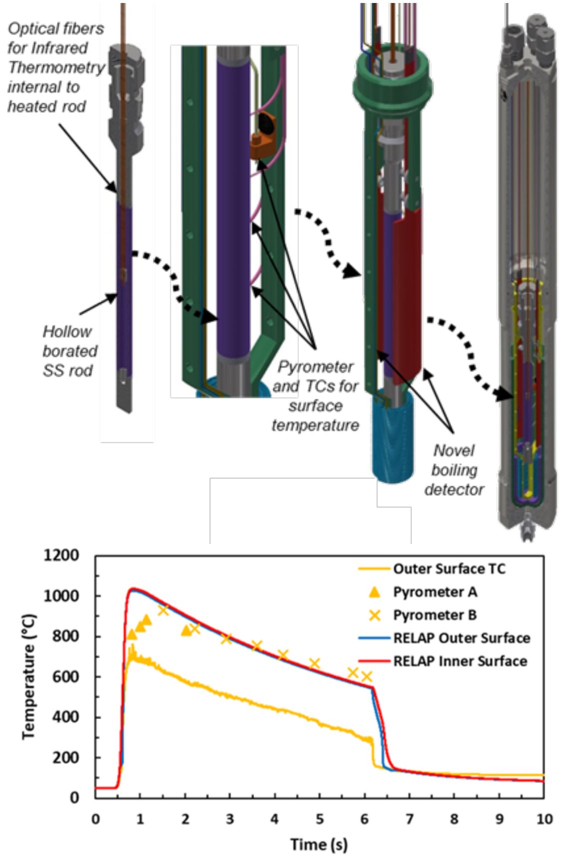
- Uncertainty in thermal-hydraulics and impact on cladding temperature and other important fuel performance parameters spawned multiple research efforts
- Multiple NEUP projects funded since 2018 to study CHF/Heat Transfer for accident conditions or ATF
- CHF-SERTTA and out-of-pile pulsed power system to study CHF under RIA transients
  - 14 transient in three capsules studying the impact of pulse width, energy deposition, and water preheat on critical heat flux
  - Out-of-pile system allowed high-speed video of initiation of CHF, impact of thermocouples attached to cladding surface, conditions from room temperature and pressure to PWR
- In 2016 developed a python-based scheme to tightly-couple BISON and RELAP5-3D to support more prototypic thermal-hydraulic modeling of experiments developed for TREAT
  - Very customized for each specific experiment and was slow
  - Recently capabilities have been added through the MOOSE MultiApp system to allow coupling between BISON and RELAP5-3D



BISON/RELAP5-3D Coupling Scheme



Out-of-Pile Pulsed Power System



In-Pile CHF-SERTTA Experiment

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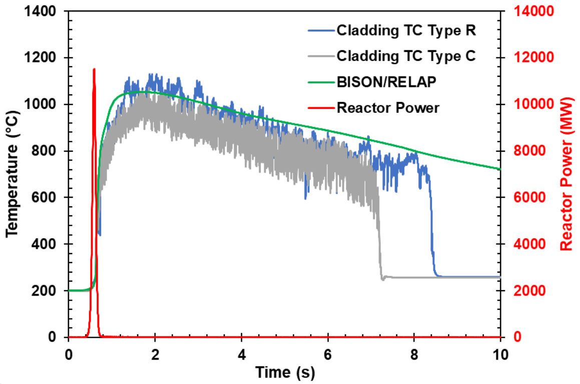
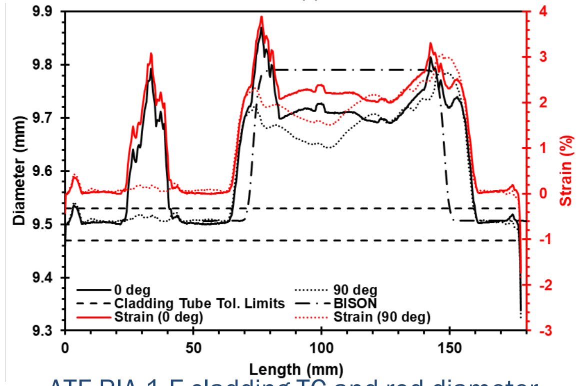
TREAT Experiments – Commissioning

- Designed the Static Environment Rodlet Transient Test Apparatus (SERTTA) capsule to perform water-based RIA experiments in TREAT
- Completed a commissioning campaign (completed TREAT experiments and PIE)
  - 5 experiments over a range of energy depositions, test configurations, and instruments





ATF-RIA-1-E cladding TC and rod diameter measurements with BISON predictions

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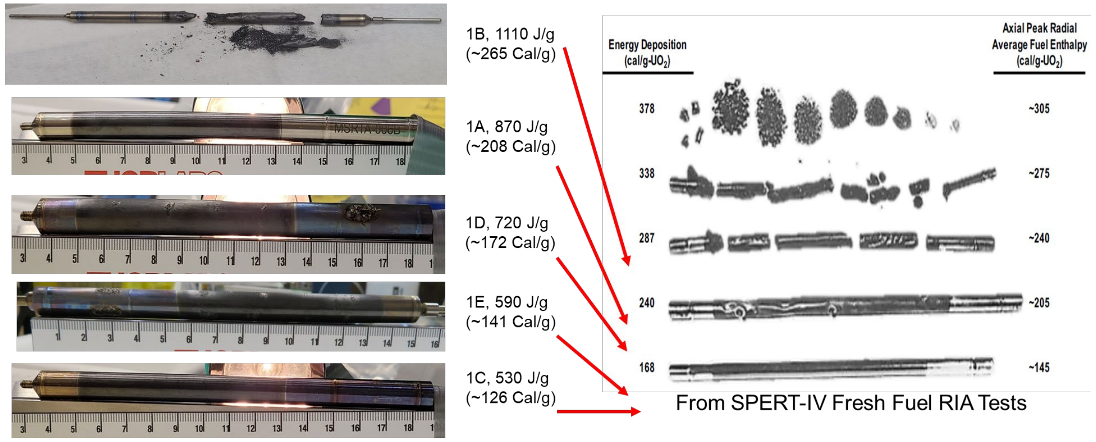
ATF-RIA test campaign test matrix in MARCH-SERTTA capsule.

Test ID	Rodlet Pressure (MPa)	Capsule Pressure (MPa)	Capsule Temperature (°C)	Reactor Energy (MJ)	Specimen Energy Deposition (J/g)	Pulse Width Full-Width-Half-Max (ms)
1-A	0.1	0.1	22	1,272	870	90.5
1-B	0.1	0.7	22	1,617	1,110	99.4
1-C	0.1	2.23	205	1,042	530	89.8
1-D	2.0	2.41	207	1,431	720	93.8
1-E	2.0	1.99	202	1,160	590	89.8

ATF-RIA test matrix



Visual inspections for rodlets A-E compared to historic SPERT-IV tests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Resumption of water capsule reactivity-initiated accident testing at TREAT

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Fuel safety

ABSTRACT

A series of integral reactivity-initiated accident commissioning experiments were completed in a new static water capsule in the Transient Reactor Test Facility (i.e., TREAT), marking the first such tests in the United States in more than 40 years. The test campaign included a verification test followed by five tests in the Static Environment Rodlet Transient Test Apparatus capsule. The capsule's initial conditions varied from room temperature and pressure up to 200 °C and 2.5 MPa, with energy depositions varying between ~ 500–1,100 J/gUO2. The series of tests allowed for a number of instrumentation qualifications and demonstrations, including cladding thermometry, rodlet plenum pressure, cladding elongation, and an electro-impedance boiling detector. Post-transient examinations such as gamma emission spectroscopy, profilometry, and microscopy were performed to document the end state of the fuel rods. The results from the experiments show that the fuel rodlets behaved very similar to historical tests under similar energy depositions. This paper documents the design of the capsule and highlights some results from the commissioning tests and post-transient examination.

1. Introduction

Development and qualification of nuclear fuels requires evaluating their performance over a range of conditions from expected operation to hypothetical accident conditions. These evaluations are required to develop an understanding of fuel failure modes and mechanisms as well as the margins to reach those behaviors. New fuel designs such as Accident Tolerant Fuels (ATFs) have been under development to provide potential performance enhancements that benefit the current light-water reactor (LWR) fleet as well as potential future LWR designs. These fuels should be tested under the range of applicable conditions including primary design basis accident conditions such as reactivity-initiated accidents (RIAs) and loss-of-coolant accidents (LOCAs) (Kamerman et al., 2019). In-reactor RIA and LOCA testing capabilities have been absent in U.S. research and development infrastructure for more than 40 years.

The LWR RIA is postulated due to the rapid ejection of the control rods/blades from the nuclear reactor's core, which causes a prompt increase of the fission rate density until the negative temperature feed-back reduces p… time, causes a …

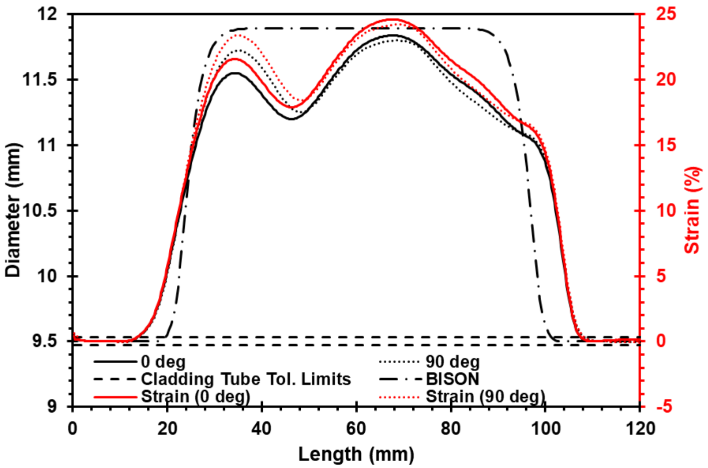
expansion of the fuel pellet closes the gap between fuel pellet and cladding (if not already in contact due to fission product swelling) and imposes a complex mechanical strain to the cladding. This pellet-cladding mechanical interaction (PCMI) can cause a failure of the cladding early in the transient, but if sufficient heat is transported from the fuel to the cladding prior to failure, then cladding temperature and ductility increase and its deformation path changes from strain driven by pellets to pressure loading driven by internal gas pressure which can cause ballooning and rupture. During normal operation, cladding is degraded by corrosion and irradiation damage while the fuel undergoes significant restructuring and generation of fission products, thus fuel design limits can depend strongly on burnup and reactor residence time.

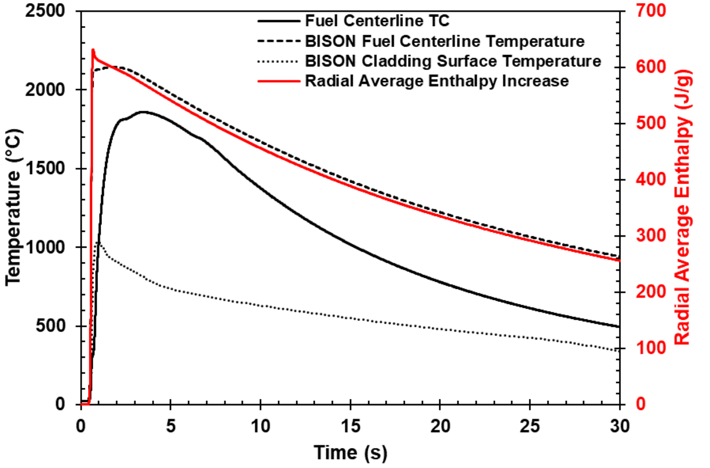
The phenomenological processes occurring in the fuel during RIAs are driven by complex multiphysics, typically under relatively extreme temperatures and timescales which can only be fully represented using in-reactor integral test capabilities. The Transient Reactor Test Facility (TREAT) at the Idaho National Laboratory (INL) offers unique capabilities in conducting transient irradiation experiments on nuclear fuels supporting broad nuclear technology needs including ATF and LWR fuel systems in general. A new water capsule, termed the Static Environment Rodlet Transient Test Apparatus (SERTTA), was designed for RIA testing …

https://www.sciencedirect.com/science/article/pii/S0029549323003588

TREAT Experiments – HERA

- High-Burnup Experiments in Reactivity-Initiated Accidents (HERA) program being executed under the NEA FIDES program
  - Six RIA tests with pre-hydrided cladding and oversized UO2 pellets at different pulse widths
    - Study effects of pulse width on simulated high-burnup rodlets
  - Four RIA tests with actual high burnup material
  - Modelling and Simulation Exercise
- To-date 4 experiments have been performed
  - 2 at NSRR and 2 at TREAT
  - Last 2 experiments in TREAT planned by the end of 2024
- Prior to pre-hydrided, tests completed four tests to verify the fuel coupling factor for specimens
- HERA-Zr-1 experiment ran to confirm transient will target 650 J/gUO_2 peak radial average enthalpy rise prior to pre-hydrided tests
- Modelling and Simulation Exercise was organized and ran under the FIDES program
  - 20 participants from 12 countries using 14 different fuel performance codes
  - Synthesis paper under review in Nuclear Engineering and Design https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4883226





BISON predictions of the HERA-Zr-1 as-run transient compared to PIE profilometry

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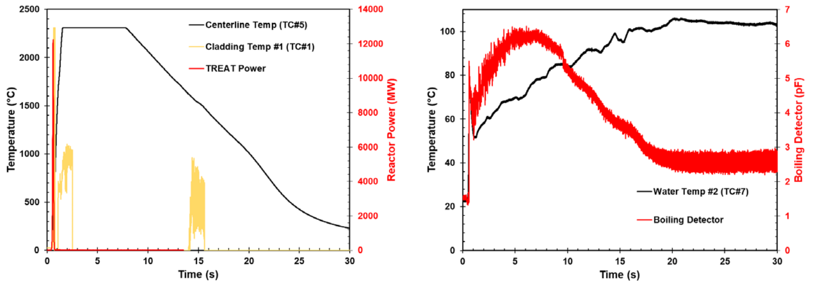
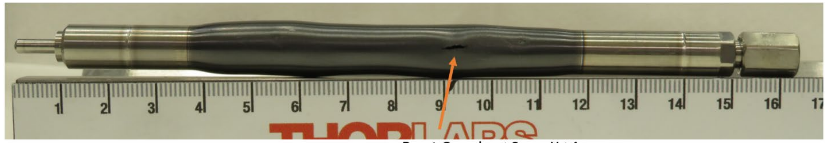
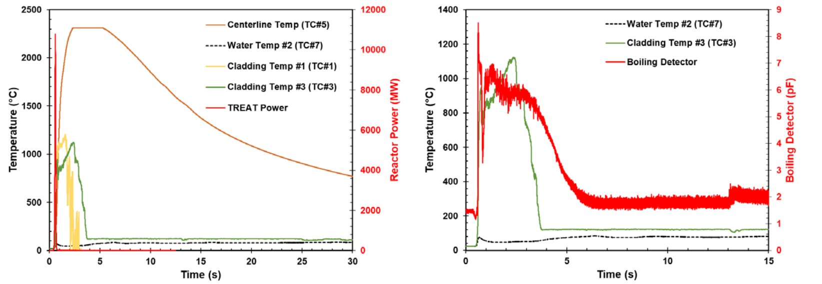
TREAT Experiments – CCZ

- The NSUF-Chromium Coated Zr (CCZ-RIA) experiment
  - Will investigate thermal, mechanical and irradiation response of Cr-coated zirconium alloy (Zr-alloy) claddings under RIA conditions in comparison with uncoated Zr-alloy cladding
  - Cr coatings deposited by cold spray
- Performed two experiments on uncoated cladding to date
  - CCZ-Zr-2 deposited ~1006 J/gUO_2
  - CCZ-Zr-3 deposited ~1153 J/gUO_2
- Exceeded temperature limit of Type C thermocouple >2310°C (fuel centerline)
- Cladding TC and boiling detector indicate DNB occurred
- Cladding failed in both tests
- Have 3 experiments planned on cold spray chrome coated cladding specimens under similar test conditions as CCZ-Zr-2 and 3 experiments
  - Tests planned to be completed before end of 2024



CCZ-Zr-2 thermocouple and boiling detector results





CCZ-Zr-3 thermocouple and boiling detector results

Transient Test ID	Experiment ID	Cladding	Fuel Diameter (mm)	Rodlet Fill Gas	Rodlet Plenum Pressure (MPa)	Capsule Fill Gas	Capsule Pressure (MPa)	Test Objectives: Specimen energy deposition target (J/g)	Step Insertion[1] (dk/k)	Test Purpose
NSUF-CCZ-3	CCZ-CS-1	Cold Spray Chrome Coated Zr-4	UO2-8.2	Helium	2	Helium	0.1	1150	4.2% Clipped	High Enthalpy Burst
NSUF-CCZ-4	CCZ-CS-2	Cold Spray Chrome Coated Zr-4	UO2-8.2	Helium	2	Helium	0.1	1000	4.2% Clipped	Moderate Enthalpy Burst
NSUF-CCZ-5	CCZ-CS-3	Cold Spray Chrome Coated Zr-4	UO2-8.2	Helium	0.1	Helium	0.1	1150	4.2% Clipped	High Enthalpy Oxidation

Future CCZ-RIA planned experiments

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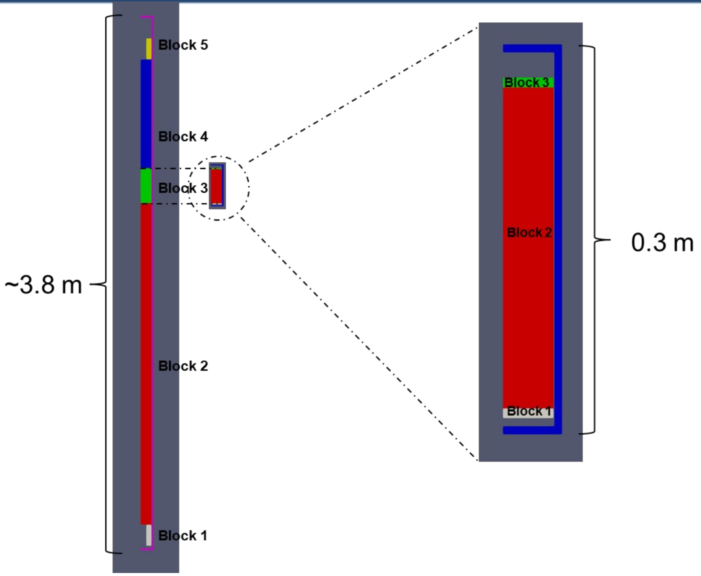
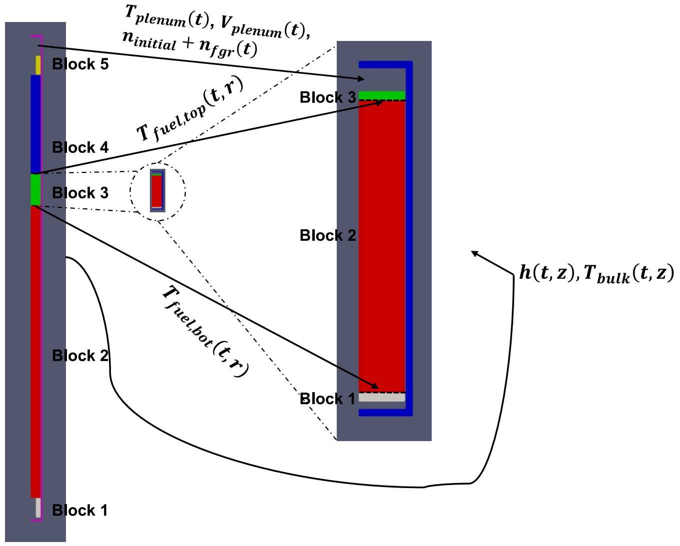
TREAT Experiments - HBu Modeling and Developments to Enable It

- Recent work has been performed to support High-burnup modeling of experiments in TREAT (support LOC-HBu and HERA-HBu experiments)
- **Problem:** BISON does not offer a straight-forward way to translate commercial irradiation simulation on a full-length rod to a rod segment
- Typically, the method is to simulate commercial irradiation on only rod segment geometry
  - Does not capture all important fuel behaviors
    - Fuel temperature at top and bottom of rod segment stack
    - Rod internal pressure evolution which influences fission gas release
    - Cladding surface oxidation
- Developed a method to initialize rod segment with commercial irradiation
  1. Simulate commercial irradiation on full-length fuel rod to capture all life history boundary conditions for the test segment of interest
     - Fuel temperature at top and bottom of segment
     - Plenum temperature, volume, and fission gas released
     - Coolant heat transfer coefficient and bulk temperature
  2. Simulate commercial irradiation on the test segment using the boundary conditions from step 1
  - Examples of this will be shown in a later presentation
- Have had some discussion with BISON developers on ways to improve this





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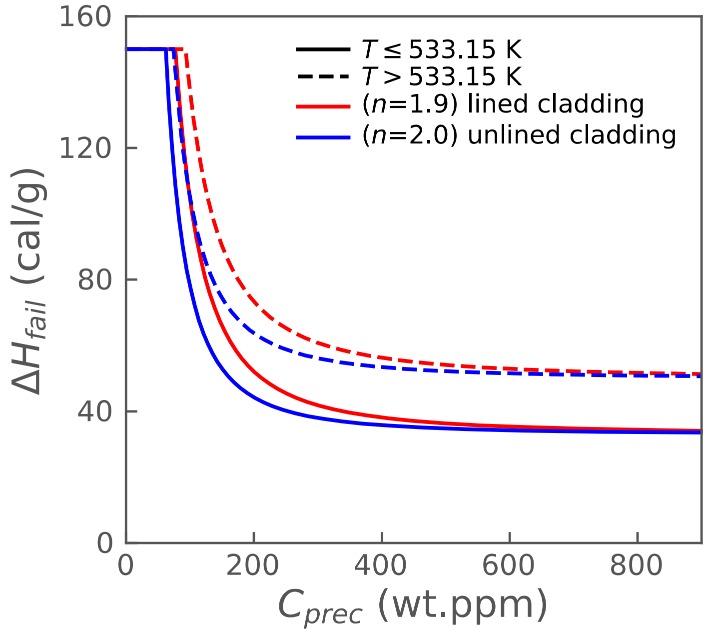
BISON Improvements for RIA Analysis

- Over the last several years new or improved capabilities have been added to BISON for RIA analyses.
  - Improved radial average enthalpy calculation that does not rely on the user selecting an axial location where the peak value is expected.
  - Addition of an RIA-based failure model based upon NRC RG 1.236.
  - Inclusion of hydrogen and hydride behavior models in RIA analysis and coupling to failure model.
  - Leveraging MOOSE mortar-based contact for improved convergence when modeling frictional contact.
  - Improved plenum pressure calculation for Layered1D simulations of RIA events to account for relative motion between fuel and cladding.



Failure model based on NRC RG 1.236

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BISON Improvements for ATF and HBu

- Through a variety of funding sources, additions and modifications have been made to BISON in support of ATF and HBu applications.
  - Internal mesh generation capabilities to support coatings and liners on cladding.
  - Updated material and behavioral models for SiC-SiC composite claddings
  - Mechanistically developed creep model for doped UO_2
  - Migration of models for several ATF concepts to use automatic differentiation to improve robustness
  - Refactoring of the UO_2 fission gas behavior model to account for high-burnup structures.
  - Implementation of transient fission gas release models.
  - Mechanistically informed fine fragmentation (pulverization) models.

Summary & Conclusions

- Goal of TREAT experiments and BISON developments is to support burnup extension and accident tolerant fuels qualification and deployment
- AFC has been supporting RIA experiments and modeling since 2015
- BISON fuel performance code has been instrumental in designing and evaluating TREAT experiments through pre-test prediction, as-run simulations, and UQ/SA
  - Many improvements have been made to BISON supporting reactivity-initiated accidents, HBu, and ATF
- TREAT has performed many RIA experiments developing capabilities to support burnup extension and ATF
  - CHF-SERTTA
  - SERTTA Commissioning
  - HERA
  - CCZ

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