INL/CON-24-80028-Revision-1

FUEL PERFORMANCE SIMULATION OF HIGH BURNUP FUELS IN PLANNED INTEGRAL DESIGN BASIS ACCIDENT EXPERIMENTS

September 2024

Changing the World's Energy Future

Charles P Folsom, Robert J Armstrong, David W Kamerman, Colby B Jensen

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Fuel Performance Simulations of High-Burnup Fuels in Planned Integral Design-Basis Accident Experiments

TopFuel 2024
Grenoble, France
October 1, 2024

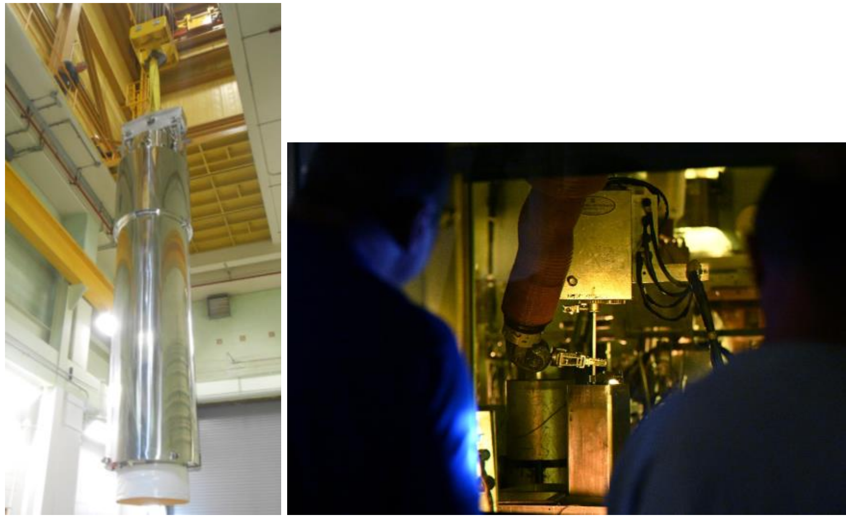
Charles Folsom, Robert Armstrong, David Kamerman, Colby Jensen, Jason Schulthess, Aaron Colldeweih

Idaho National Laboratory

Background & Motivation

- INL recently received a shipment of HBu and ATF fuel rods from the Byron Nuclear Generating Station (BNGS) to support a wide variety of research objectives
  - In-pile Design Basis Accident (DBA) testing at INL in TREAT and out-of-pile furnace experiments at ORNL in the Severe Accident Test Station (SATS)
- DBA testing of HBu and ATF fuels at INL to be performed in the TWIST experiment vehicle
  - High burnup Experiments in RIA (HERA) – NEA Framework for Irradiation Experiments (FIDES)
  - Advanced Fuels Campaign Consensus LOCA test plan (partially included in FIDES)
- This presentation will discuss efforts to model the HBu fuel condition as well as predictions for the DBA experiments

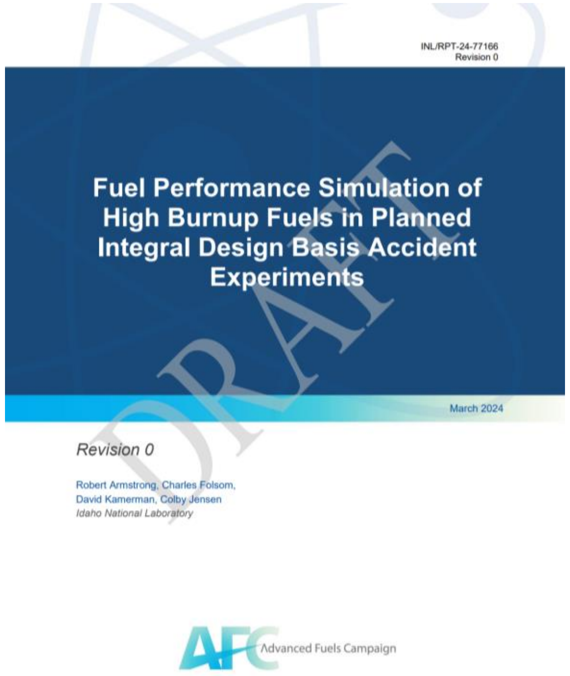
BNGS fuel rods arriving at INL's HFEF



Cask operations and unloading of pins

Modeling Overview

- Detailed BISON fuel performance simulations to support first two HBu LOCA experiments (LOC-HBu-1 & 2) and first HBu RIA experiment (HERA-HBu-1) in TWIST
  - Rod segments all come from same parent rod, termed 9EU
- Commercial Irradiation
  - General operating history data provided by Westinghouse
    - In process of receiving more detailed data
  - Simulation of commercial irradiation on full-length fuel rod
  - Inform PIE of BNGS parent rods and final design of experiments
    - Comparison of modeling predictions to PIE
  - Development of methodology to accurately simulate commercial irradiation on fuel rod segment
- DBA TWIST Experiment Simulations
  - Thermal-hydraulic conditions obtained from RELAP5-3D
  - Simulation results used to drive design decisions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Fuel Performance Simulation of High Burnup Fuels in Planned Integral Design Basis Accident Experiments

March 2024

Revision 0

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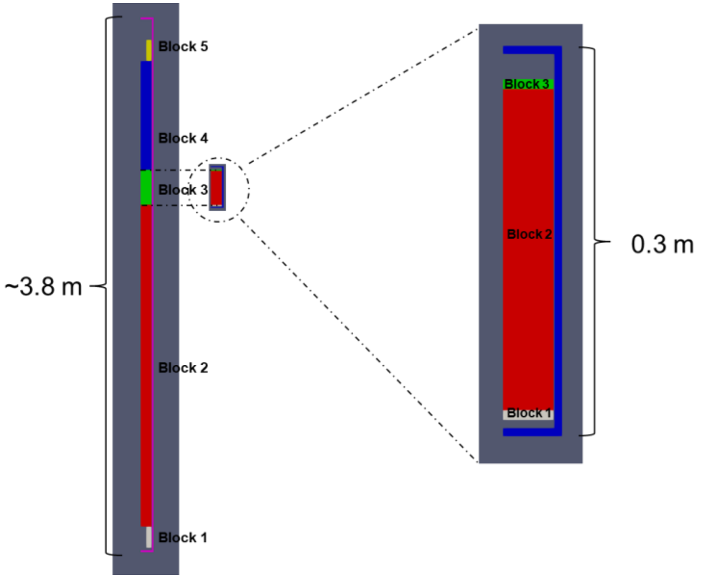
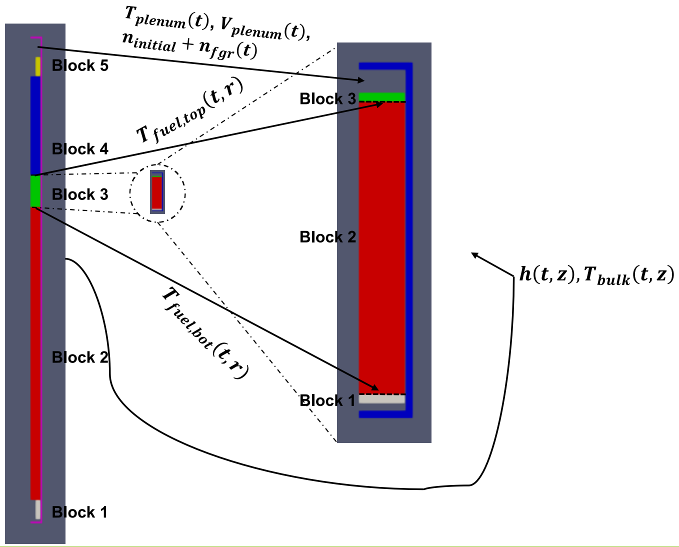
Advanced Fuels Campaign

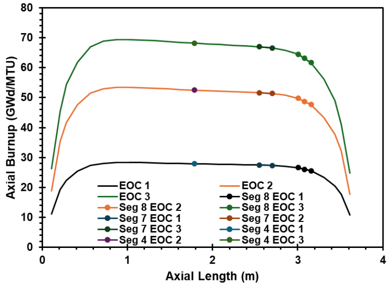
DRAFT

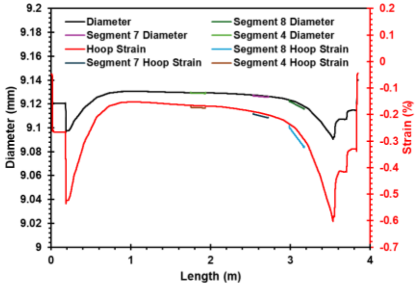
Full-length to Rod Segment Simulations

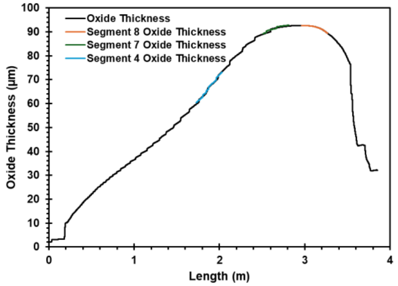
- BISON does not offer a straight-forward way to translate commercial irradiation simulation on a full-length rod to a rod segment
- Typically, the method is to simulate commercial irradiation on only rod segment geometry
  - Does not capture all important fuel behaviors
    - Fuel temperature at top 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











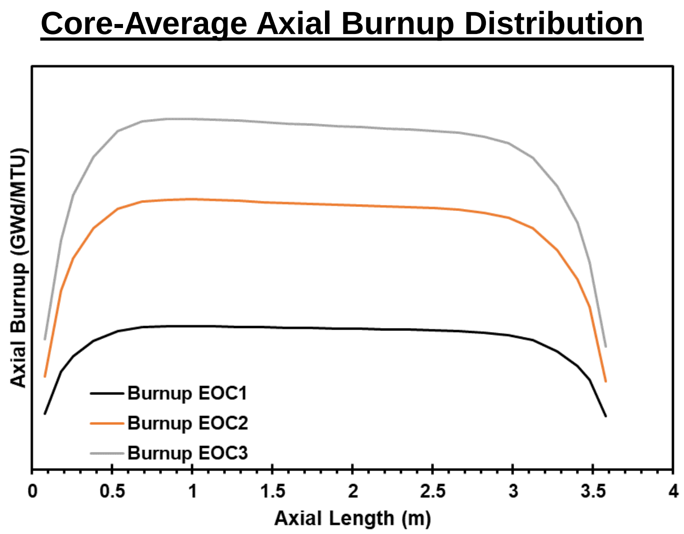
Commercial Irradiation Data and Model Inputs

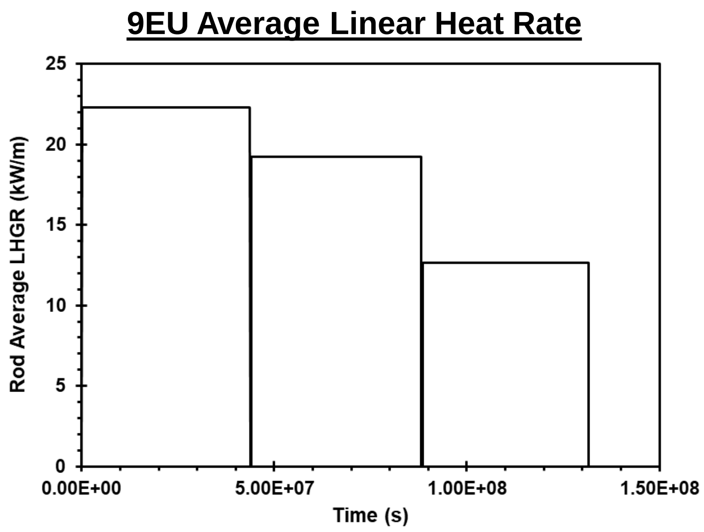
Operational Data

- 9EU consists of UO_2 fuel clad in ZIRLO® cladding
- Fuel rod was irradiated for 3 cycles to an estimated average burnup of 62.7 GWd/MTU
- General operating history
  - Core-average axial burnup distribution at beginning of cycle (BOC) and end of cycle (EOC)
  - Average rod burnup at BOC & EOC

9EU BISON Model Assumptions

- Axial power profile follows core-wide burnup profile
- Constant linear heat rate over cycle to achieve reported average rod burnup

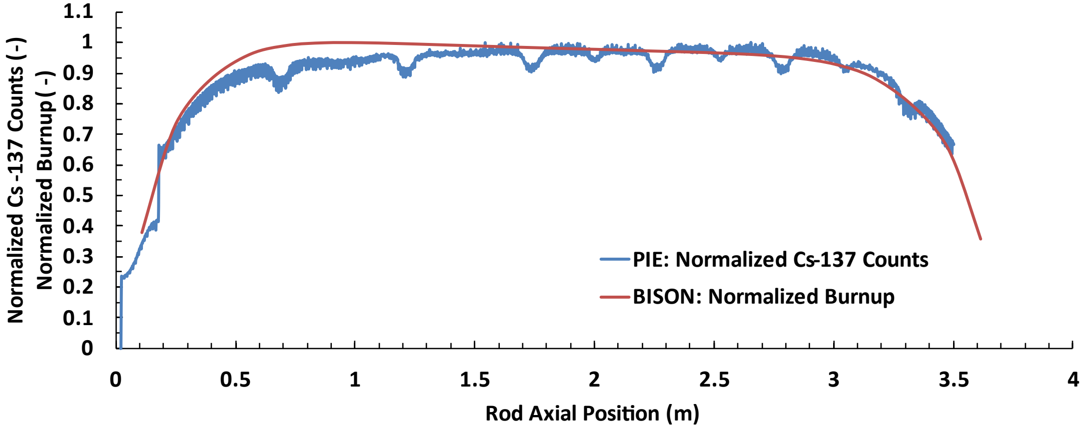




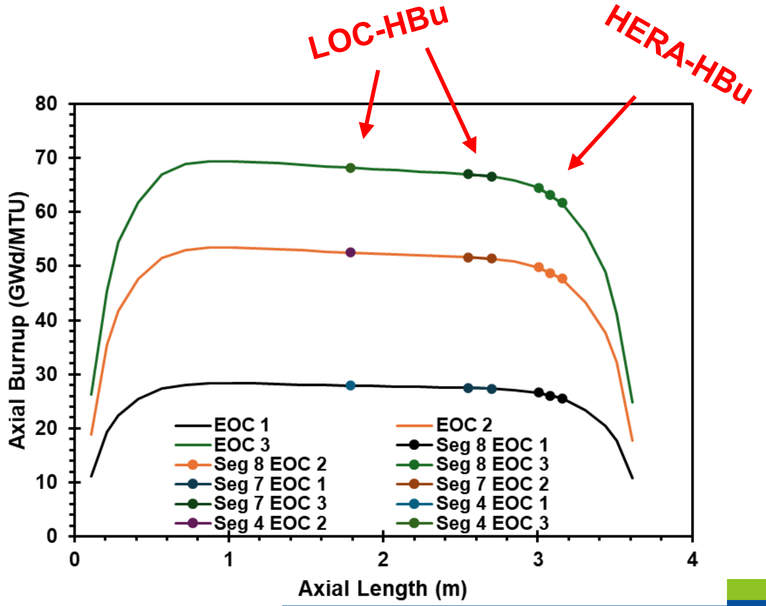
PIE and Modeling Comparison: Burnup Profile

- Gamma spectroscopy performed on 9EU rod
  - Normalized Cs-137 counts provides relative burnup profile
    - Chemical analysis of burnup at various locations is underway
  - Normalized BISON burnup prediction at end of commercial irradiation
- Gamma spectroscopy indicates peak burnup towards top of fuel rod
- BISON predicts highest burnup toward bottom portion of rod
    - Due to core-wide axial burnup distribution assumption for rod axial peaking
- Working on getting more detailed rod-level power distributions

Normalized Gamma Scan and BISON Burnup Predictions

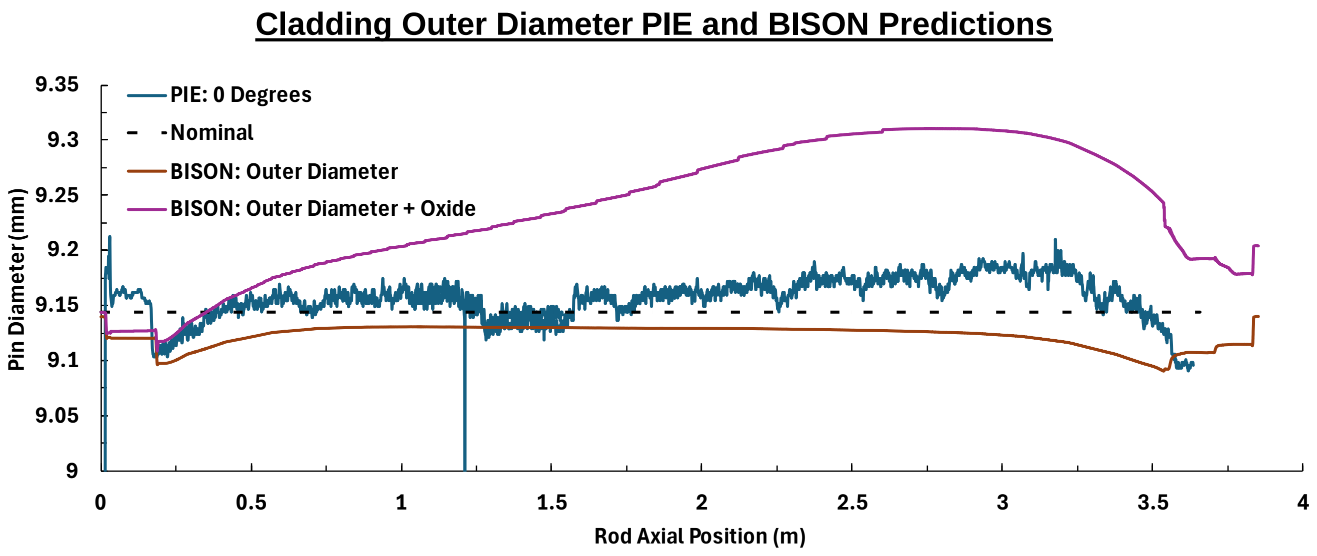


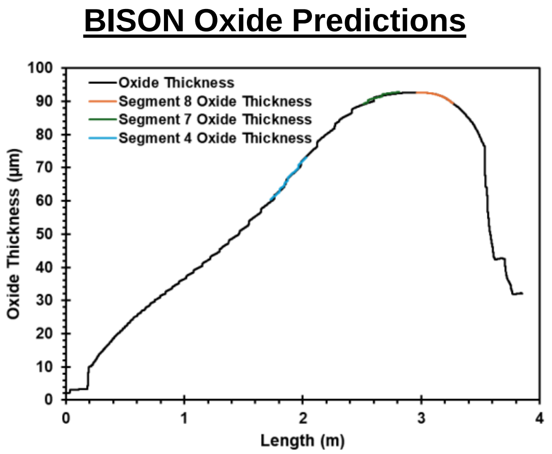
BISON EOC Axial Burnup Predictions



PIE and Modeling Comparison: Outer Cladding Dimensions

- Profilometry measurements along rod
- Oxide thickness impacts profilometry measurements as well as impacting thermal and mechanical properties of cladding
- BISON does not have an oxidation model for ZIRLO
  - Overpredicting oxide thickness
  - Estimated coolant inlet temperatures
- BISON predicts creep down of cladding
- Need more detailed rod-level power distributions and coolant conditions
  - Inlet temperature
  - Flow rates
  - Chemistry

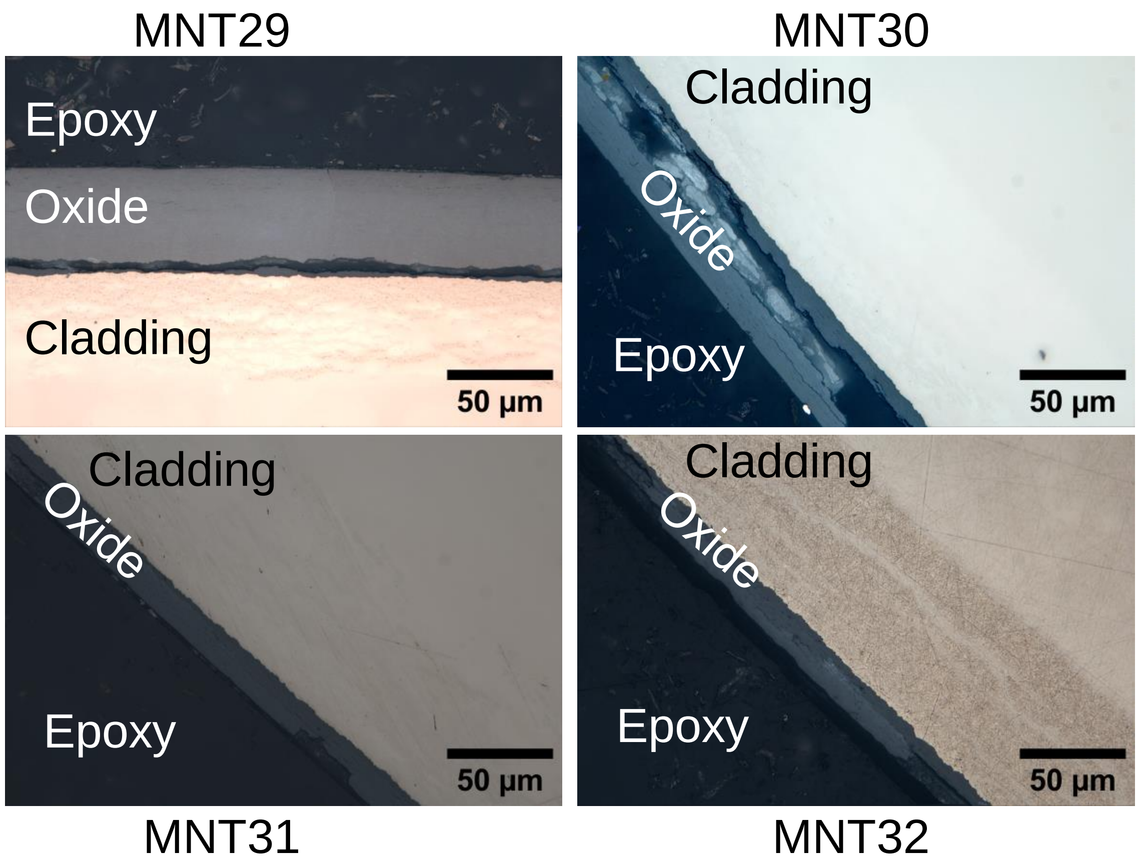


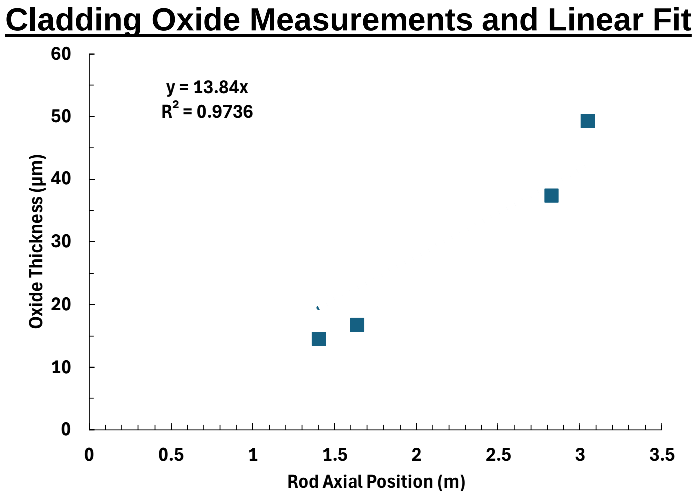


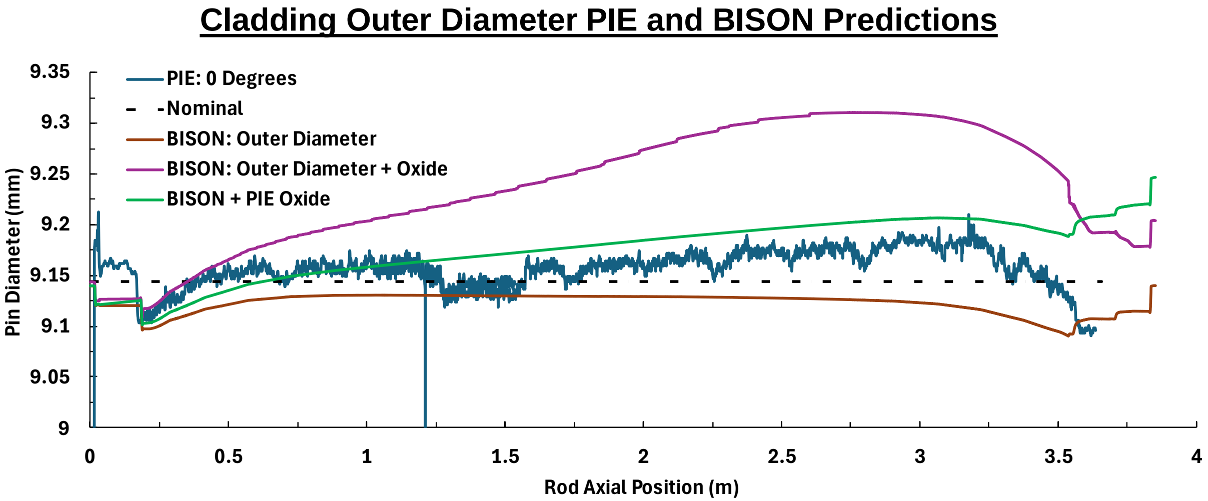
PIE and Modeling Comparison: Oxide Thickness

- PIE Oxide Thickness Measurements

Mount # (elevation)	29 (3.05 m)	30 (2.83 m)	31 (1.64 m)	32 (1.40 m)
Ave oxide thickness (µm)	49.32	37.42	16.7	14.47



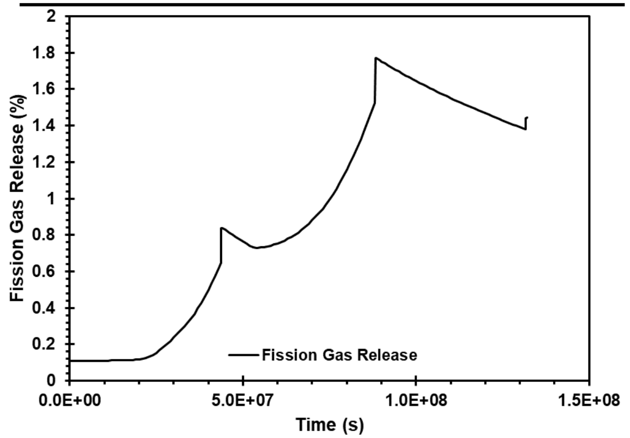




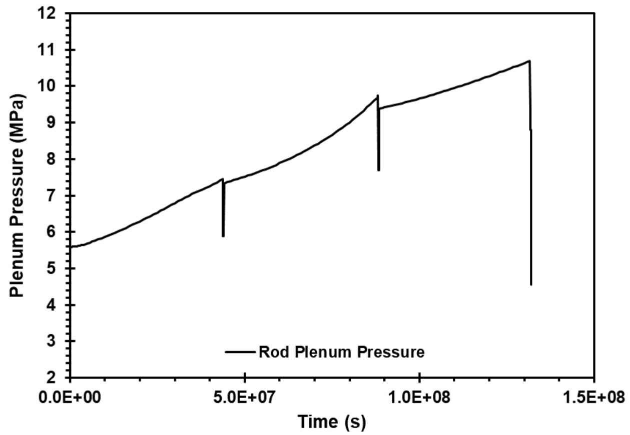
PIE and Modeling Comparison: Fission Gas & Rod Pressure

	Pin Pressure (MPa)	Rod Free Volume (cc)	Fission Gas Release (%)
PIE	5.58	11.28	3.7
BISON	4.55	9.59	1.4

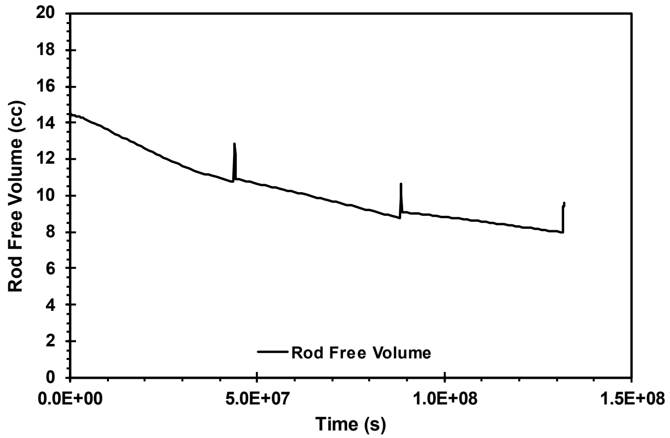
BISON Fission Gas Release Predictions



BISON Plenum Pressure Predictions



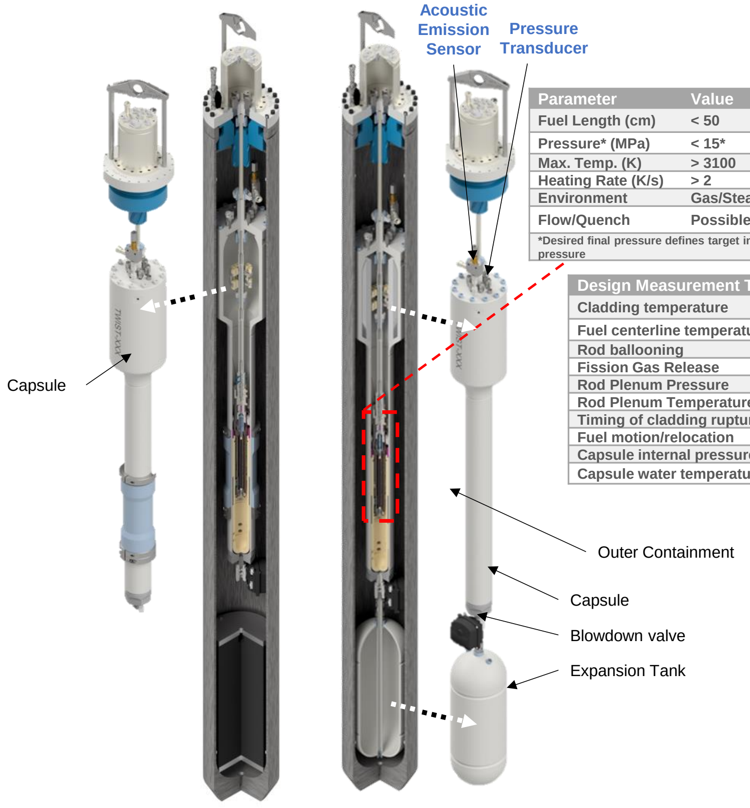
BISON Rod Free Volume Predictions



- Pin puncture and gas analysis indicate ~3.7% fission gas release
- BISON predicted 1.5%
  - BISON slightly under predicts fission gas release and thus final rod pressure
    - Constant linear heat rate assumption
  - BISON slightly under predicts rod free volume
    - Overprediction of fuel swelling due to fission gas retention?
    - Help final rod diameter predictions move in right direction
- Need more detail on as-built rod description

TWIST DBA Experiments

- Transient Water Irradiation System for TREAT (TWIST)
  - Capsule-type irradiation vehicle for LWR fuel safety testing in the Transient Reactor Test (TREAT) facility
- LOCA configuration contains blowdown capabilities
- Thermal-hydraulics simulated with RELAP5-3D

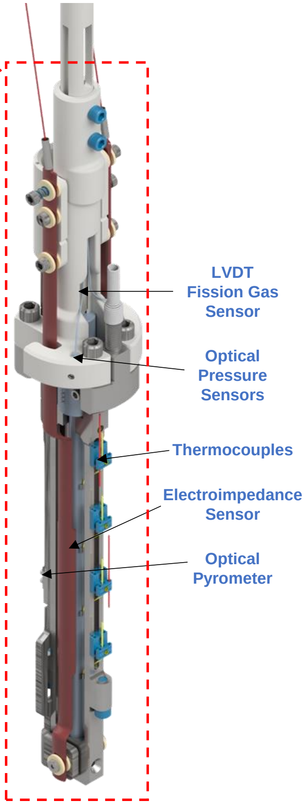


Parameter	Value
Fuel Length (cm)	< 50
Pressure* (MPa)	< 15*
Max. Temp. (K)	> 3100
Heating Rate (K/s)	> 2
Environment	Gas/Steam/Water
Flow/Quench	Possible

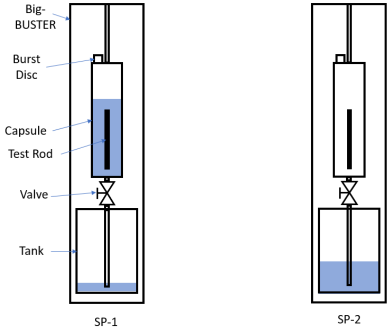
*Desired final pressure defines target initial pressure

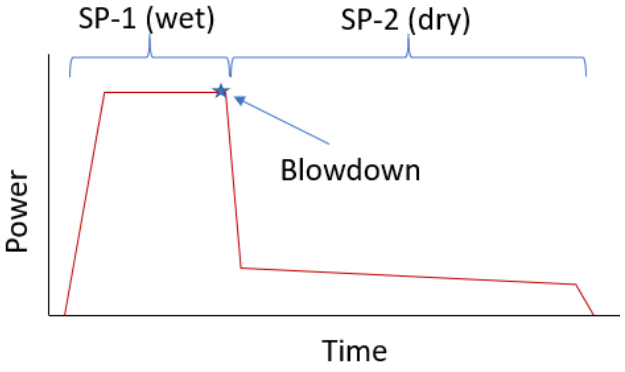
Design Measurement Targets
Cladding temperature
Fuel centerline temperature
Rod ballooning
Fission Gas Release
Rod Plenum Pressure
Rod Plenum Temperature
Timing of cladding rupture
Fuel motion/relocation
Capsule internal pressure
Capsule water temperature

RIA Config ← TWIST Capsule → LOCA Config

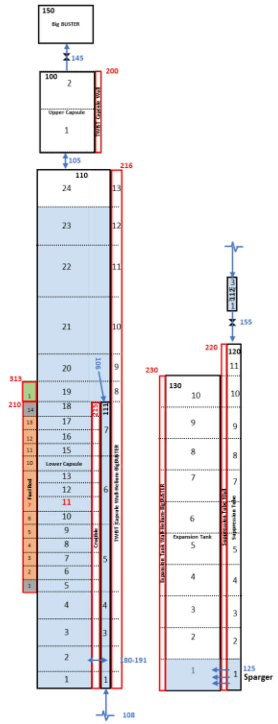


Instrumented Specimen Holder





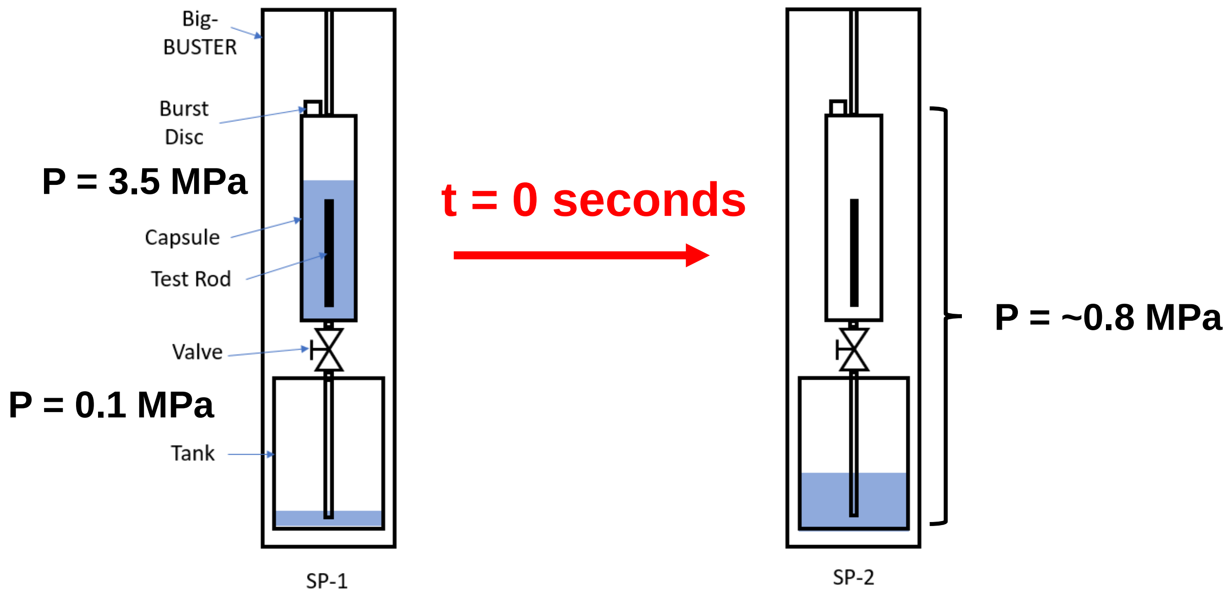
TWIST LOCA configuration showing blowdown and TREAT reactor power

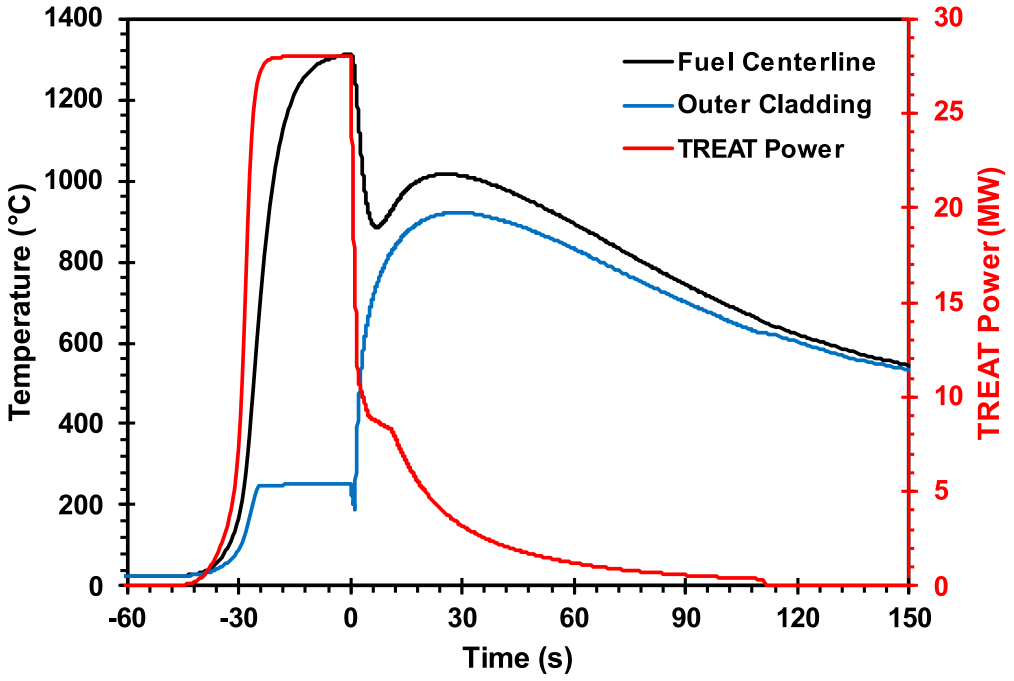


TWIST RELAP5-3D nodalization

LOC-HBu-2 Experiment

- Designed to simulate pre- to post-blowdown thermal conditions consistent with that of an LWR fuel rod at operating conditions transitioning to a LBLOCA
  - Main objective of this test will be evaluating the impact of stored-energy heatup (SEH) conditions on HBu LOCA behavior.
  - Targeting 900 °C cladding temperature

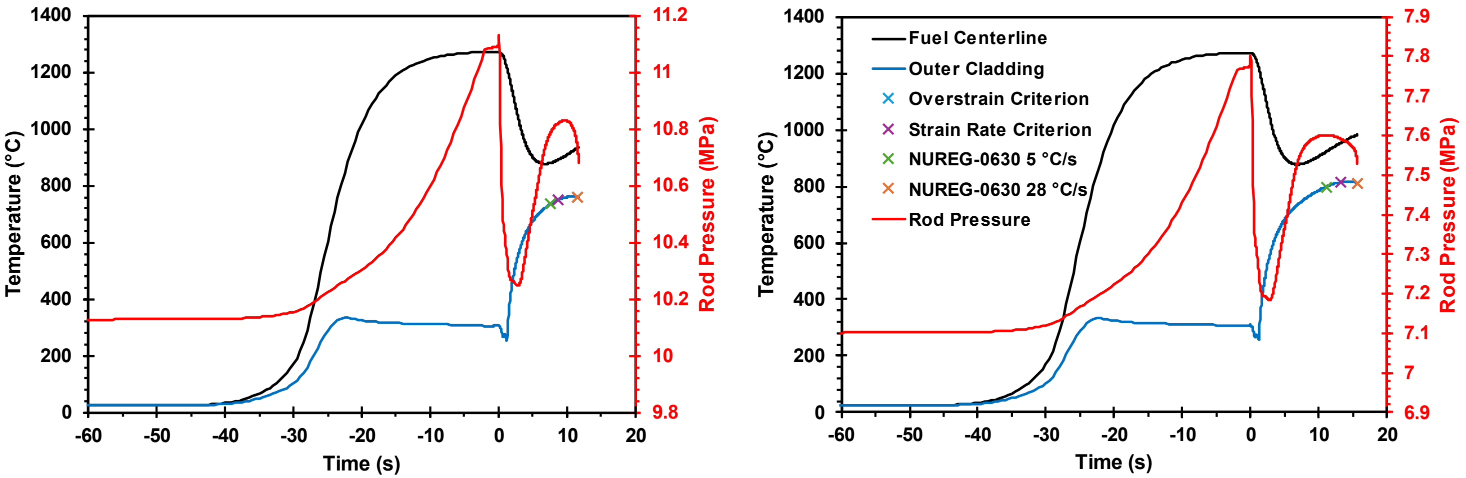




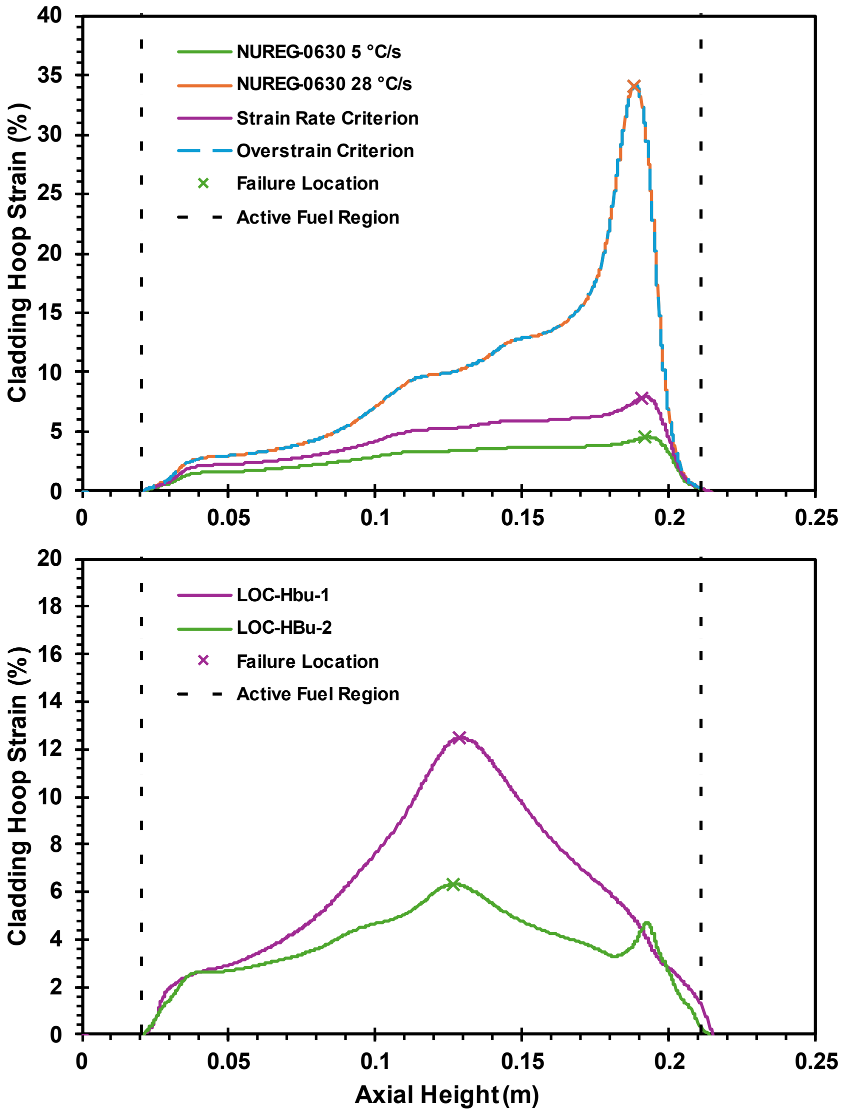
LOC-HBu-2 TREAT power history and RELAP5-3D fuel centerline and outer cladding temperature history

LOC-HBu-2 Experiment

- Study the effect of plenum pressure on predicted failure
  - 7 MPa plenum pressure predicts failure between 800-814°C
  - 10 MPa predicted failure ~720°C
  - 15 MPa predicted failure ~610°C
- Original TWIST design resulted in axial power profile with peaking towards top of rod resulting in balloon and burst occurring closer to top
- This work resulted in flux shaping modifications to TWIST design to reduce end peaking



BISON fuel and cladding temperature predictions and failure time for 10 MPa plenum pressure (left) and 7 MPa plenum pressure (right)



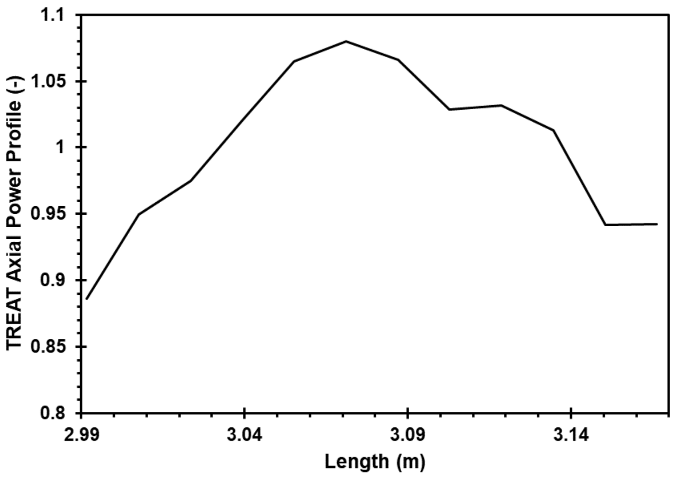
BISON hoop strain predictions for the 7 MPa plenum pressure case with original axial power profile (top) and modified profile (bottom)

TWIST RIA HERA-HBu-1 Experiment

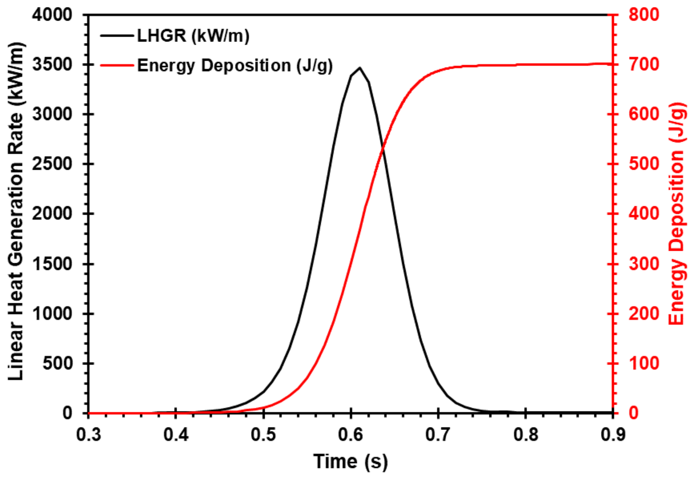
- HERA experiments have the goal to investigate fuel failure thresholds for very HBu fuels with several cladding types ranging from moderate to low hydrogen pickup claddings as well as two UO2 fuel compositions
- Rod is pressurized to 1 atm (0.1 MPa)
- Capsule pressurized to 0.68 MPa
- Transient targets 700 J/g energy deposition (~650 J/g radial average enthalpy)

Test Number	Cladding	Segment Burnup (GWd/MTU)	Target Pulse Width (ms)	Target Peak Radial Average Enthalpy (J/g)
HERA-HBU-1	Modern Zirconium Alloy	~70	100	~650 J/g*
HERA-HBU-2	Advanced Zirconium Alloy	~80	100	~650 J/g*
HERA-HBU-3	Cr coated Optimized ZIRLO	~33	100	~650 J/g *
HERA-HBU-4	Cr coated Optimized ZIRLO	~33	100	~650 J/g *

*Determined based on cladding excess hydrogen

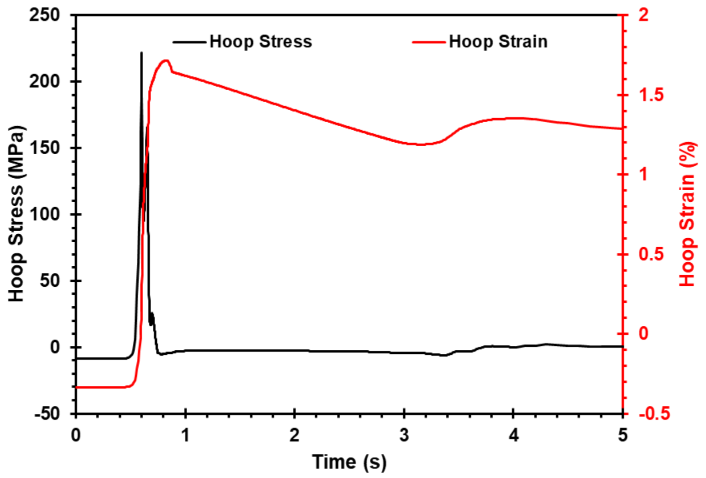


TREAT axial power profile for HERA-HBu-1 test

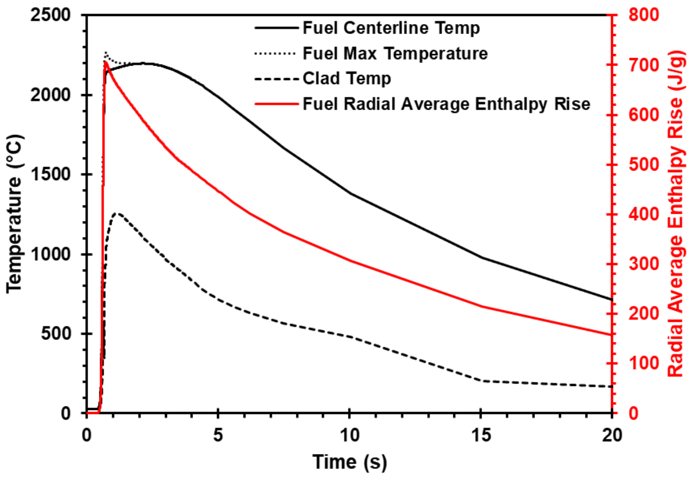


TREAT RIA transient for HERA-HBu-1

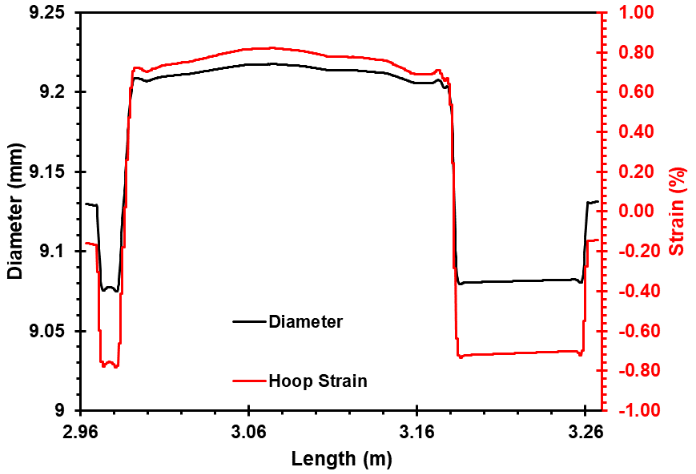
TWIST RIA HERA-HBu-1 Experiment



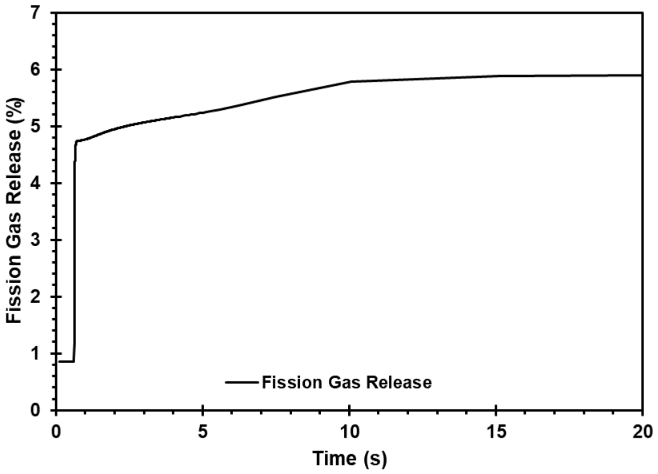
Cladding hoop stress and strain evolution



HERA-HBu-1 temperature histories with predicted fuel radial average enthalpy rise



Final HERA-HBu-1 rodlet diameter and hoop strain along the length of the rod following the TREAT transient



Transient fission gas release predictions for the HERA-HBu-1 experiment

- Peak fuel temperature occurs at pellet periphery (2265 °C)
- Peak radial average enthalpy rise 706 J/g
  - Higher than target because of axial peaking
- Transient fission gas release 5.5%
- Post-transient final clad hoop strain 0.8%
- Peak cladding hoop stresses of 220 MPa
- Peak hoop strain 1.7%

Conclusions & Future Work

- Fuel performance simulations supporting the first two HBu TWIST LOCA experiments (LOC-HBu-1 & 2) and the first HBu RIA experiment (HERA-HBu-1) were performed
- **Highlights**
  - A new methodology was developed for accurate simulation of commercial irradiations on fuel segments, so all depletion conditions are represented in DBA experiment simulations
  - Axial power profile was found to induce ballooning at top of rod, design modifications were made to reduce peaking and shift balloon to center
  - Modeling capability developments will enable more informed experiment conditions to target desired outcomes
- **Future Work**
  - Additional data is still under development to support refined inputs to the BISON model including details related to the irradiation histories
  - Implementation of new models as they become available
  - Development of a capability to tightly couple BISON and RELAP5-3D is underway which should significantly improve the multiphysics modeling of the thermal-hydraulics and fuel performance

Acknowledgments

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