INL/MIS-22-70027-Revision-0

Consensus DOE Advanced Fuels Campaign TREAT/SATS Test Plan

November 2022

Changing the World's Energy Future

Robert J Armstrong, Charles P Folsom, Nicolas E Woolstenhulme, David W Kamerman, Fabiola Cappia, Daniel M Wachs, Jason Harp, Nathan Capps, Kory Linton, Colby B Jensen

Idaho National Laboratory

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November 2022

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Consensus DOE Advanced Fuels Campaign TREAT/SATS Test Plan

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Oak Ridge National Laboratory

Advanced Fuels Campaign

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

Outline

- Background & Motivation
- Consensus Test Plan Development
- Test Plan Overview
  - Introduction
  - Prototypical LOCA conditions to experiment
  - Experimental Approach
  - Test Matrix – TREAT TWIST Device Commissioning
  - Test Matrix – LOC/SATS-HBu Experiments
- Summary

Background & Motivation

Background & Motivation

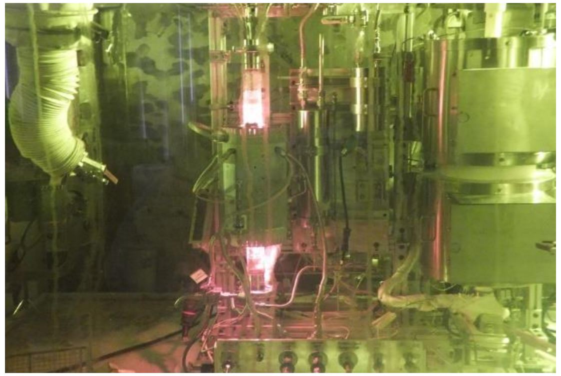
- Nuclear industry is looking to extend light water reactor (LWR) fuel burnup and enrichment limits
  - ~62 GWd/t, 5 wt.% ^{235}U → ~75 GWd/t, ~8 wt.% ^{235}U
  - Requires licensing basis for increased limits
- **Key area:** Behavior of High Burnup (HBu) fuel during a Loss-of-Coolant Accident (LOCA)
  - Phenomena termed Fuel Fragmentation, Relocation, and Dispersal (FFRD) has been observed in HBu LOCA experiments
  - Potential for fuel to finely fragment, relocate axially within the fuel rod, and be expelled from the rod upon cladding rupture
  - Under current burnup limits and fuel management strategies, FFRD is not considered to be an imminent safety concern [1]

[1] SECY-15-0148: EVALUATION OF FUEL FRAGMENTATION, RELOCATION AND DISPERSAL UNDER LOSS-OF-COOLANT ACCIDENT (LOCA) CONDITIONS RELATIVE TO THE DRAFT FINAL RULE ON EMERGENCY CORE COOLING SYSTEM PERFORMANCE DURING A LOCA

Consensus Test Plan Development

Consensus Integral LOCA Test Plan

- Combined integral and semi-integral LOCA test plan developed to address broad stakeholder needs
  - Leverages the best PIE capabilities in the country
- Goal to address cross-cutting stakeholder needs
- Primary emphasis on experimental evaluation of identified R&D gaps in FFRD in a LOCA
  - First of a kind approach using both in-pile and hot cell testing facilities
  - Novel in-situ instrumentation
    - Fuel motion monitoring, tFGR, balloon extent, and improved surface temperature
- Test matrix tailored to LB LOCA conditions



Severe Accident Test Station

2023 | 2024 | 2025 | 2026 | 2027

9 experiments

TREAT LOCA Device Design, Fabrication, and Testing

TREAT-LOC-C Fresh Fuel, In-Pile LOCA Commissioning

3 years, ~9 experiments/each facility

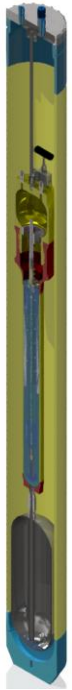
TREAT-LOC-HBu and SATS-HBu

- **Tieback testing to Halden/SCIP**
- **DEH and SEH heating conditions**

- **Burnups from 65-85 GWd/t**
- **Rod length and rod free volume effects**

Phase II

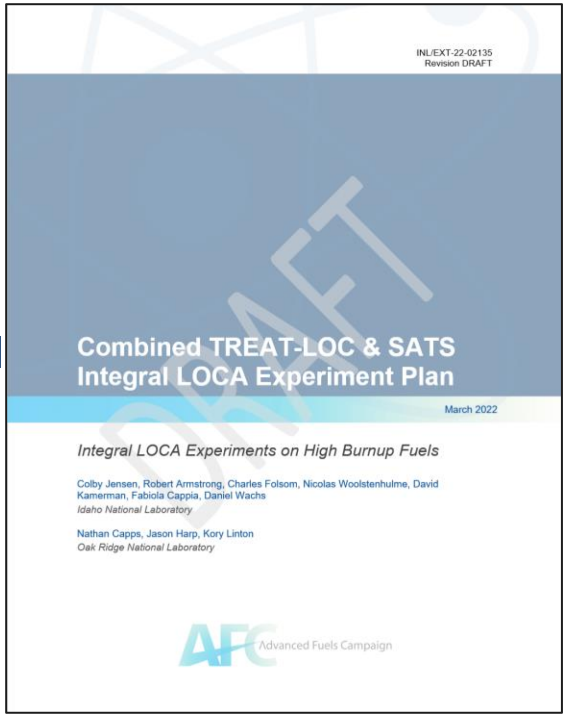
Reirradiation of commercial HBU fuel segments in ATR



TREAT TWIST LOCA Device

Draft test plan was created and distributed to stakeholders for feedback.

- Received 13 full pages of written comments
- Differing interests from reviewers though most interests seem to be captured in the test matrix to some level
  - Contrasting interests in focusing on “traditional LOCA experiment” DEH condition (“slow” ramp rate) vs also evaluating SEH condition, (“fast” initial heat up)
  - Prioritization of tieback testing and in-pile vs out-of-pile evaluations
  - Recommendations for expanded test program for doped fuel
  - Some comments imply IB/SB or BWR LOCA conditions might should be considered
- Concerns about test results from new facilities/experimenters
- Common point on integration with SCIP
- General comments and clarifications regarding QA, process for future plan revisions, and so on.


INL/EXT-22-02135
Revision DRAFT

DRAFT

Combined TREAT-LOC & SATS Integral LOCA Experiment Plan

March 2022

Integral LOCA Experiments on High Burnup Fuels

Colby Jensen, Robert Armstrong, Charles Folsom, Nicolas Woolstenhulme, David Kamerman, Fabiola Cappia, Daniel Wachs
Idaho National Laboratory

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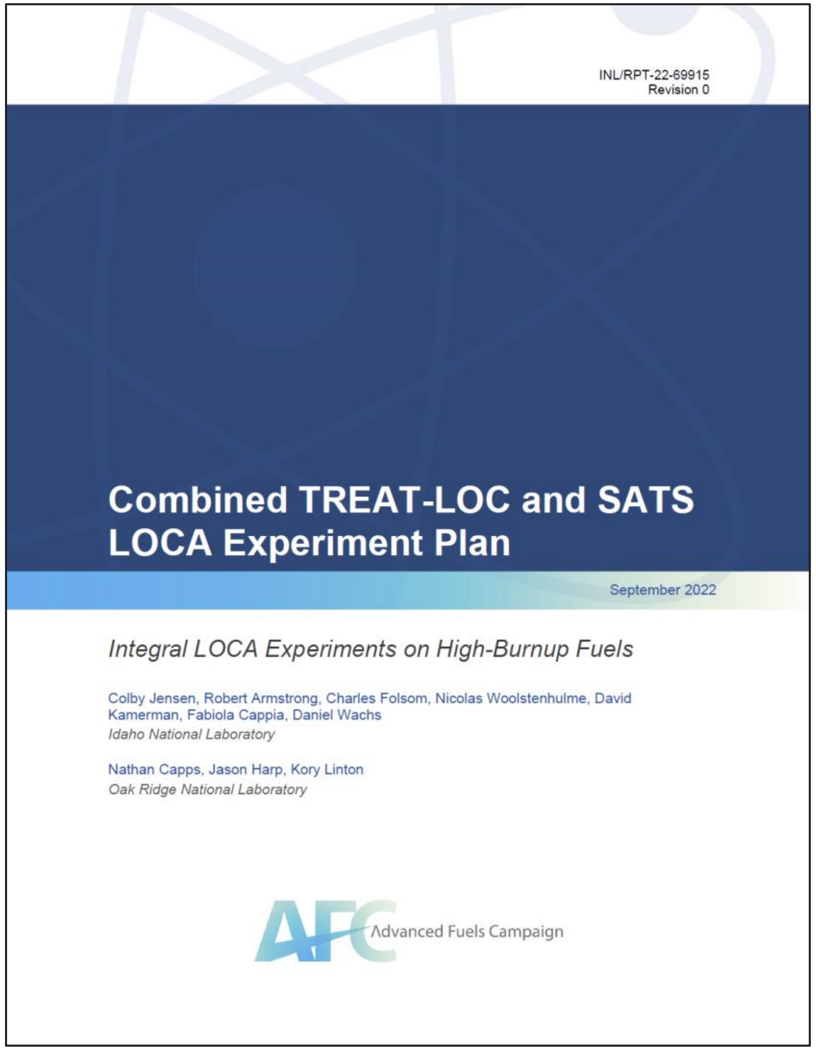
Deliverables



INL/RPT-22-69915
Revision 0

Combined TREAT-LOC and SATS LOCA Experiment Plan

September 2022

Integral LOCA Experiments on High-Burnup Fuels

Colby Jensen, Robert Armstrong, Charles Folsom, Nicolas Woolstenhulme, David Kamerman, Fabiola Cappia, Daniel Wachs
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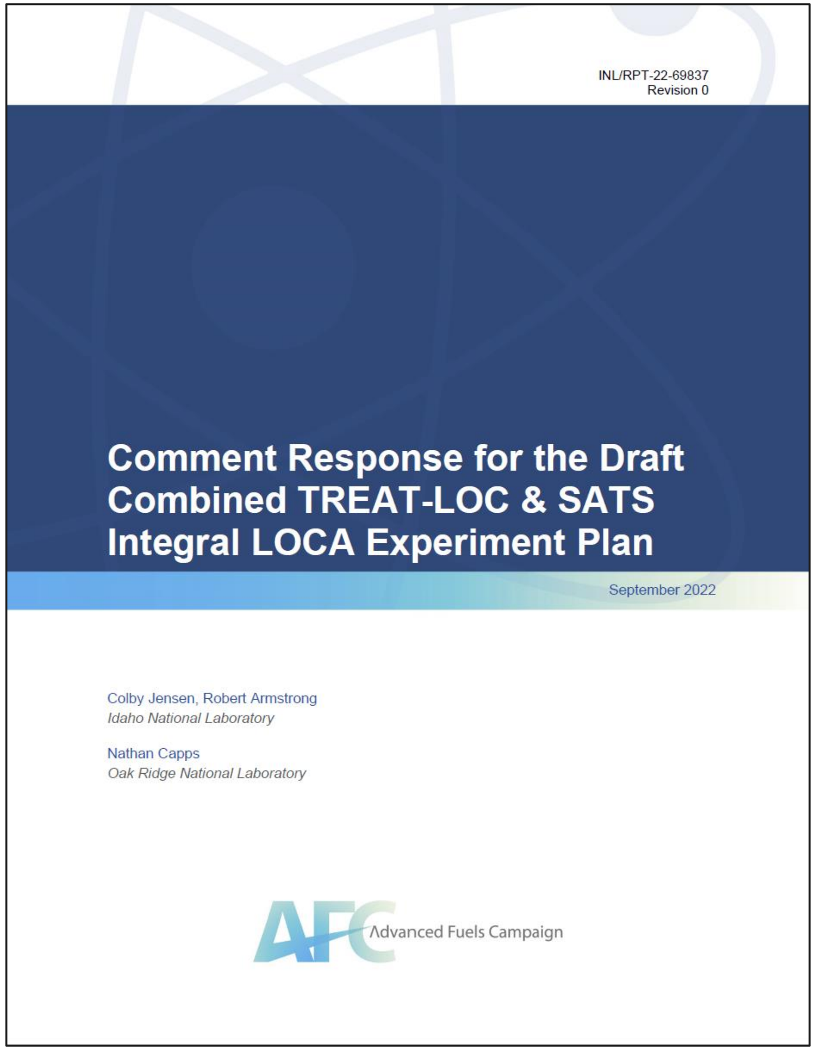

INL/RPT-22-69837
Revision 0

Comment Response for the Draft Combined TREAT-LOC & SATS Integral LOCA Experiment Plan

September 2022

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Test Plan Overview

Introduction

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U.S. LOCA Program Development during last 5 Years

2018

Recent Transient Reactor Test (TREAT) Facility restart, and closure of the Halden Boiling Water Reactor raised DOE priority for development of in-pile integral LOCA testing capability

First HBu testing in SATS

2019

Stakeholders (fuel vendors) requested to provide input for to experiment design via input on needs and reference prototypic boundary conditions

2020

DOE Advanced Fuels Campaign (AFC) program led critical review on topic of FFRD in LOCA to highlight main conclusions and identify potential R&D gaps and opportunities

2021

Fuel Performance Testing Technical Expert Group (FPTTEG) performed R&D prioritization survey showing integral LOCA at the top

2022

Test capabilities and plans developed to address needs with flexibility to adapt as required

NRC RIL on FFRD released

Integral LOCA Consensus Plan

Introduction to LOCA Test Plan

- AFC test plan focus on FFRD behavior for PWR LB LOCA on "standard" fuels
- LOCA testing development approach:

Reference Conditions: Define prototypical event of interest (PWR LB LOCA):

fuel boundary conditions and forcing functions

Identify Gaps: Evaluate implications on critical phenomena (FFRD) and define key technical gaps

Experiment Requirements: Establish test design to simulate the necessary boundary conditions and forcing functions

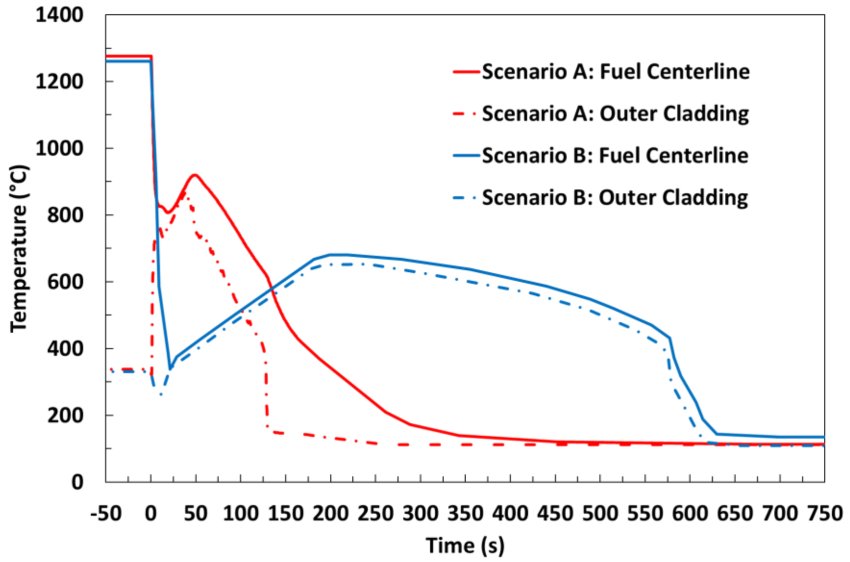
- However, U.S. industry working on Alternative Licensing Strategy (ALS)
  - FFRD in LB LOCA would no longer be main issue shifting to IB/SB conditions, meriting a distinct approach
  - Primary implication is a substantial update to the test matrix specifications
    - Testing capabilities are well suited to address all LOCA conditions
    - Reference conditions for IB/SB conditions are needed!

Test Plan Overview

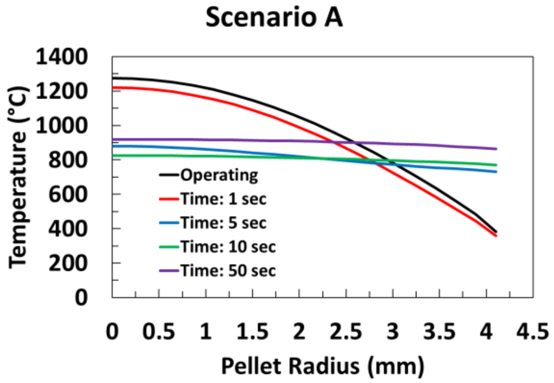
Prototypical Conditions to Experiment

Existing Integral Database Based on Same Boundary Conditions

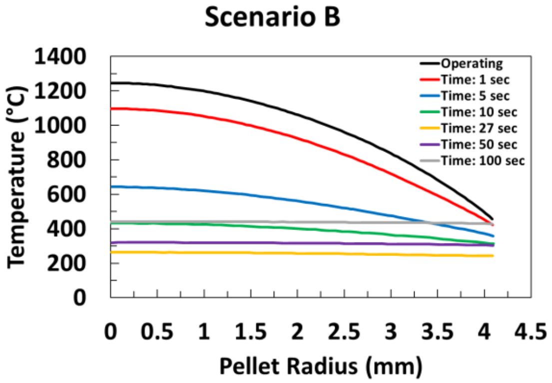
- Singular integral testing approach to date, missing important rate effects.
  - Database based on isothermal heating at ~5 K/s from representative coolant temperature
    - Prototypic of some conditions
    - Seems not to be the most relevant to predicted HBu rod burst conditions
    - Approach derived from long history of LOCA testing focused on cladding criteria - ballooning and embrittlement behaviors
    - Halden tests (and most historical in-pile testing) have very similar transient heating behavior as a furnace
      - Halden tests distinguished by ~24 hr operation (low power) prior to transition to "LOCA mode"
- Evaluation of plant conditions reveals two regimes: "stored energy heat up" (SEH) and "decay energy heat up" (DEH)
  - Primarily distinguished by pretransient operating LHR, break size, PWR vs. BWR, heat transfer coefficients, etc
  - SEH has initial heating rates up to ~100 K/s
  - Peak temperature < 900°C in "bounding scenario"
  - Cladding wall pressure differential vs temperature key relationship



Examples of relevant LOCA heat up conditions; LOCA initiation at time zero.

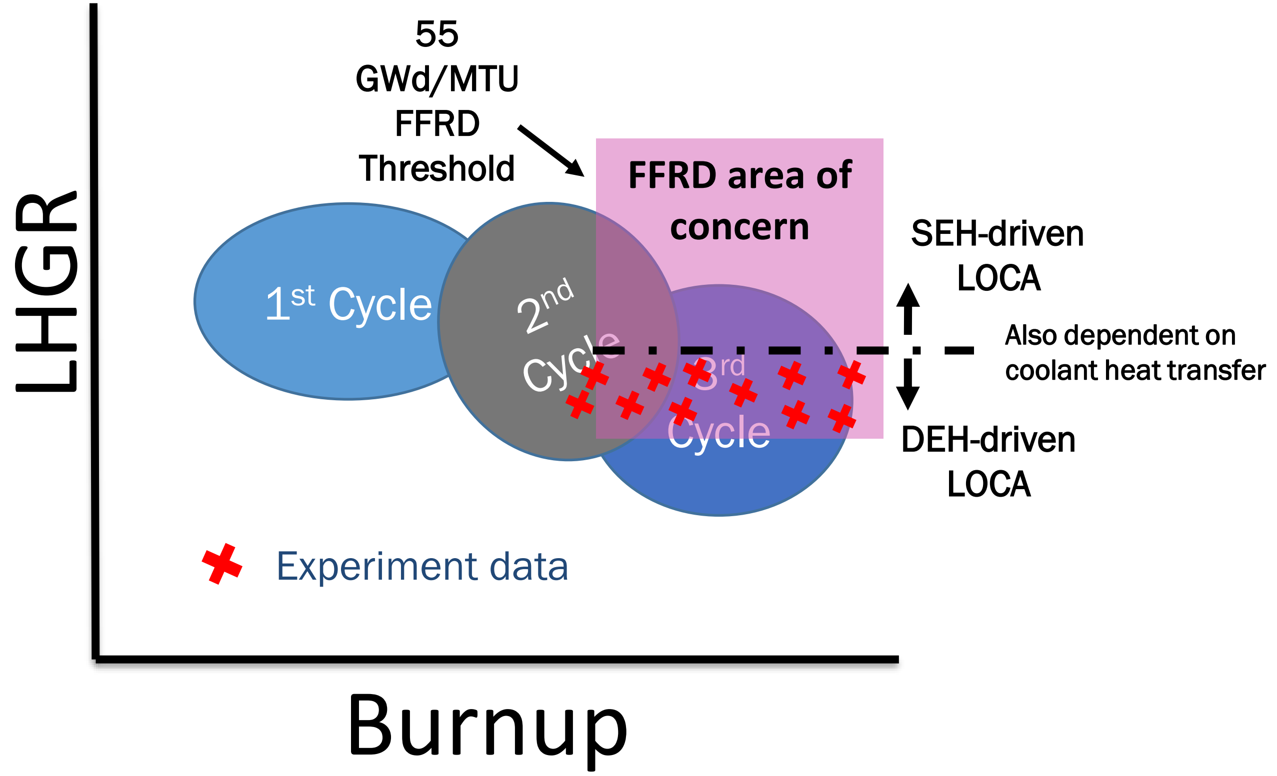


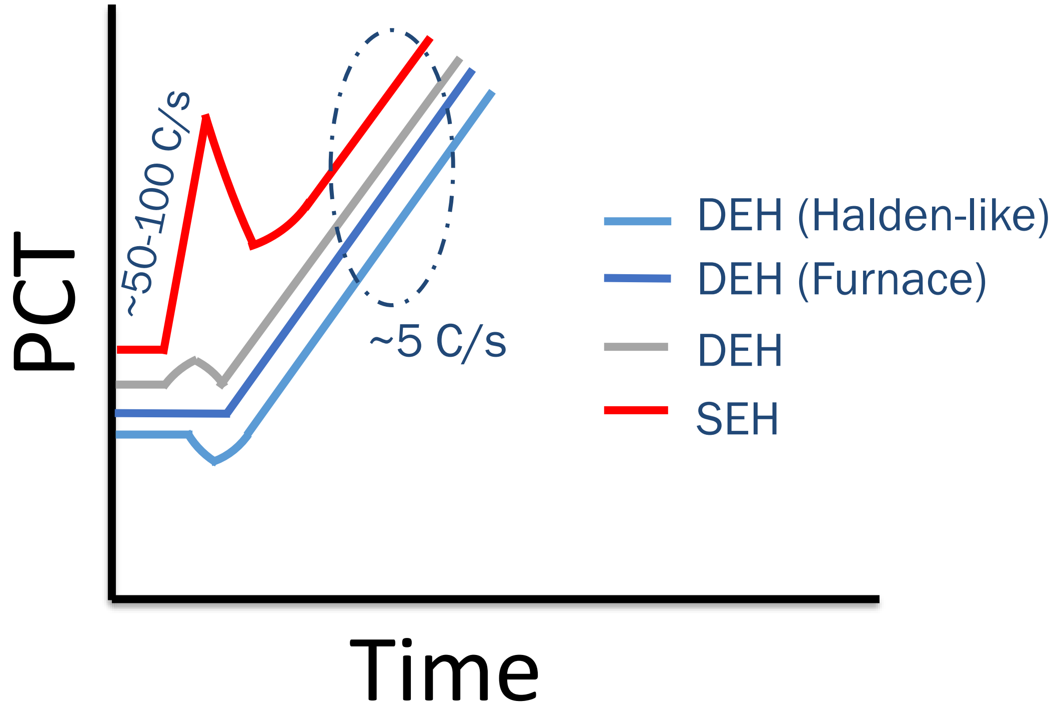
Rapid increase in fuel periphery, rapid decrease in fuel centerline



Fuel temperature decrease followed by slow ~isothermal heat up

Qualitative Representation of Prototypical LOCA Conditions and Experiment Database





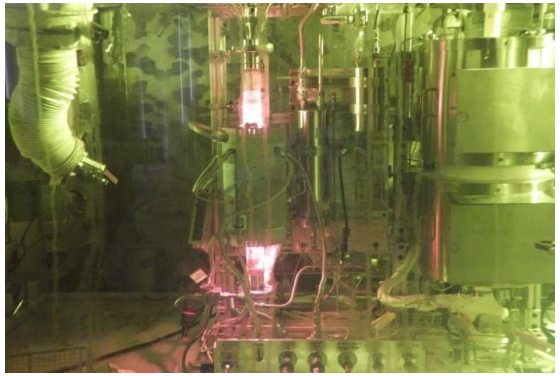
Transition region between DEH and SEH governed by operating LHR and coolant conditions

Test Plan Overview

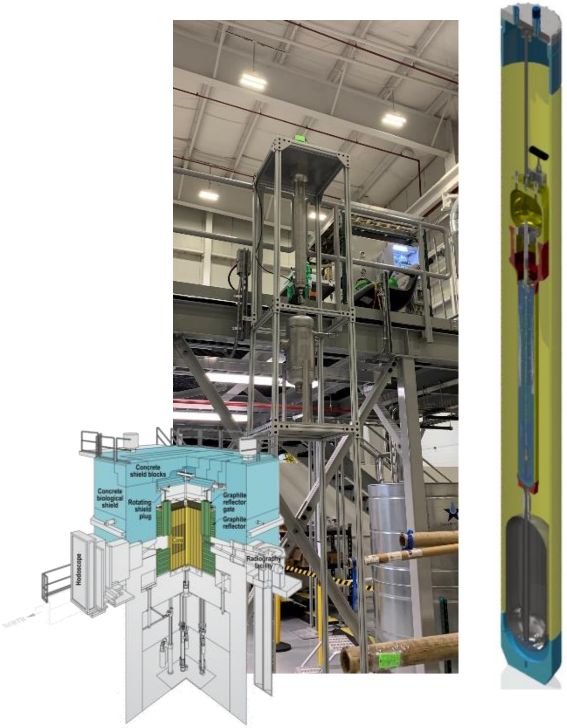
Experimental Approach

Experimental Strategy for TREAT LOC-HBu and SATS-HBu

- Experiment Strategy:
  - Two distinct facilities and methods with some overlap and different relevant boundary conditions (+ potential linkage to Halden and SCIP)
  - Systematically select materials that are identical between certain tests:
    - in the same facility
    - in different facilities
  - Systematically vary limited parameters between tests
  - Separate effects and microstructural characterization must be integrated closely on same materials
- => Utilize capabilities at INL and ORNL (both well positioned!)
  - SATS capability is fully operational and demonstrated - upgrades underway
  - TREAT final design complete for fresh commissioning tests, high burnup tests rapidly maturing with unique SEH blowdown test capabilities
  - Novel in-situ instrumentation
  - Utilize PIE facilities at both labs
- Commercial source materials required and crucial to establish material pedigree with industry's help



Severe Accident Test Station



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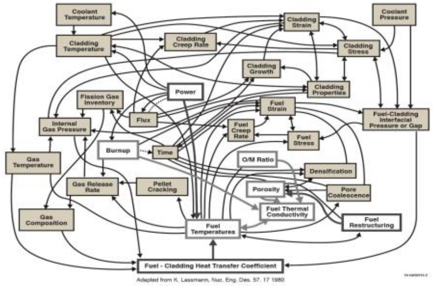
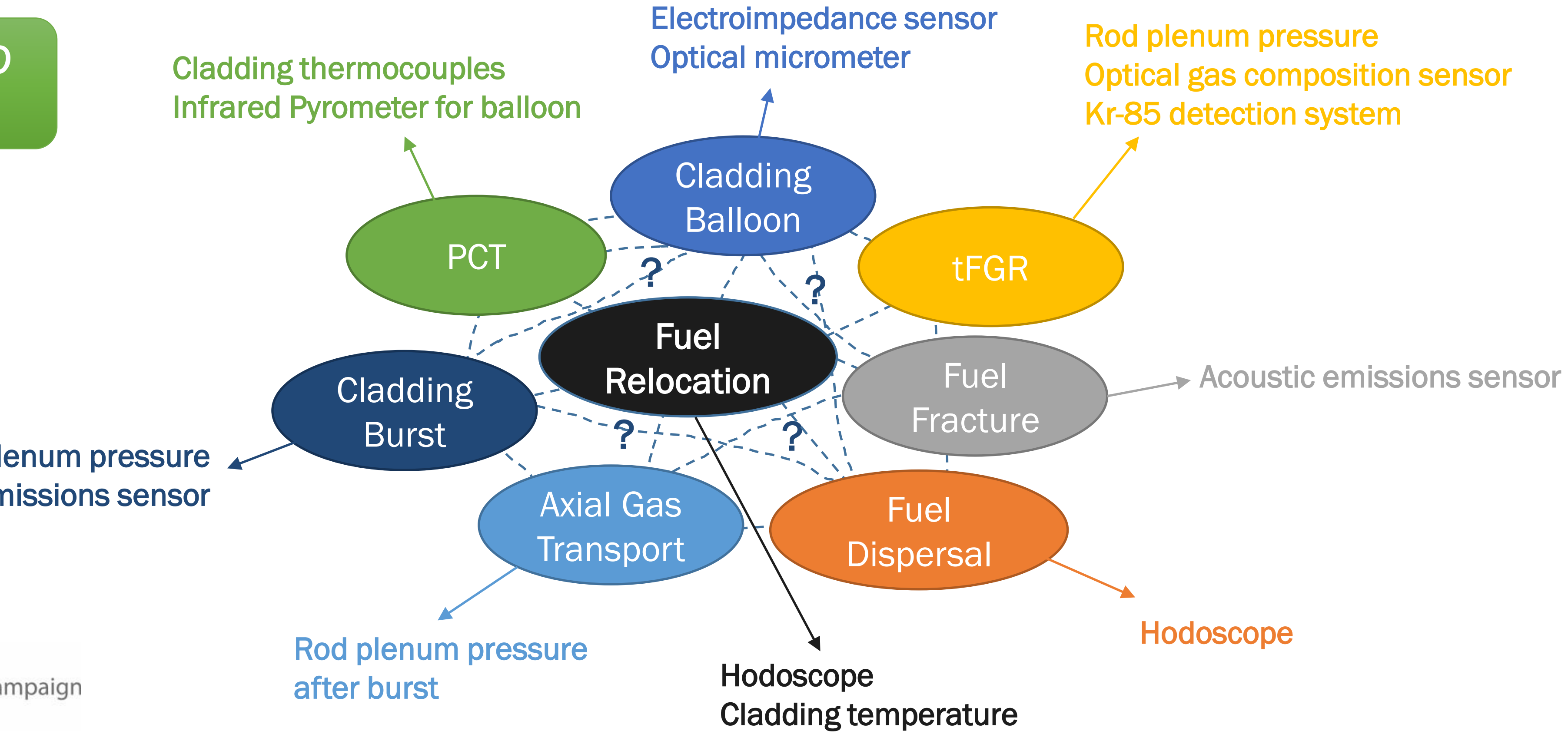
In-Situ Performance Uncertainty

- FFRD phenomena including elements 1-5 and others mentioned in “limitations” section in NRC RIL are highly interrelated
- Improved confidence of event sequencing during LOCA event will reduce important uncertainties (RIL does not consider uncertainties)
- Instrumentation approaches used to date are remarkable but innovative in-situ approaches will improve

How to make the FFRD “spaghetti” chart?





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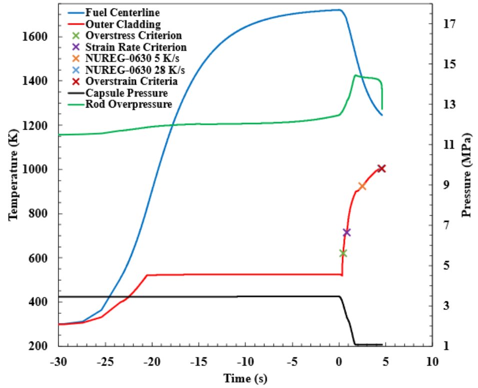
Test Plan Overview

Test Matrix – TREAT TWIST Device Commissioning

TREAT LOC-Commissioning (LOC-C) Test Matrix

- Fresh fuel tests to establish/demonstrate/qualify complete experimental system for LOCA testing in TREAT
- Characterize fuel power, thermal-hydraulic conditions, and instrumentation performance
- Useful for initial modeling "benchmarks"

BlueCRAB simulation of LOC-C-4. Evaluation of failure criteria



Test ID	Fuel Length (cm)	Rod Free Volume (cc)	Rod Internal Pressure (MPa)	Peak Cladding Temp. (K)	Purpose
LOC-C-1	25	15	0.1	Cladding – 520 Fuel - 1600	Fuel power calibration, pre-blowdown, centerline thermocouple
LOC-C-2	25	15	0.1	1173	Fuel power calibration, post-blowdown, centerline thermocouple
LOC-C-3-A thru E	25	15	0.1	multiple transients on same capsule	Detailed thermal hydraulic validation, Instrumentation validation, centerline thermocouple
LOC-C-4	25	15	~12	1173	Balloon/burst Instrumentation validation
LOC-C-5	50	15	~12	1273	Long rod evaluation, balloon/burst, Instrumentation validation

- Measurement of fuel power coupling with reactor
- Thermal-hydraulic characterization
- Full LOCA simulation/ diagnostics for fuel failure
- 'Long' rod evaluation

Test Plan Overview

Test Matrix – LOC/SATS-HBu Experiments

Proposed Test Matrix: Rev0

Based on stakeholder feedback, implemented stronger focus on DEH and comparison with SEH conditions: primary variations include: segment ave. burnup, failure point during SEH condition, rodlet length, plenum size effect

- Each line represents TREAT/SATS companion tests
  - Primary goal of comparing in-pile vs out-of-pile and SEH effects to traditional DEH conditions
  - Each companion tests use materials from same parent rod (to extent possible)
- Detailed material characterization accompanying all pre & post testing

Test ID	Seg. Burnup (GWd/t)	PCT (K)	Max. Temp. Ramp Rate (K/s)	Fuel Length (cm)*	Rod Free Volume (cc)	Purpose
LOC-1 SATS-1	~65	1173	5	25	15	HBWR IFA 650.10/15 and SCIP test 36U-N05 tieback, simulate "classic" Halden/furnace condition
LOC-2 SATS-2	~65	1173	<100 50	25	15	SEH heat-up comparison to test #1
LOC-3 SATS-3	~75	1173	5	25	15	SCIP tieback with higher burnup
LOC-4 SATS-4	~75	1173	<100 50	25	15	SEH vs. DEH heat-up comparison with higher burnup (comparison test #3)
LOC-5 SATS-5	~75	1173	<100 5	25	15	Evaluate different failure condition. Target failure of the rod at a distinct point in the heat up – blow down vs refill phases.
LOC-6 SATS-6	~75	1173	<100 5	25	15	Evaluate non-failure condition. Target similar conditions to #3-5 without rod burst. tFGR data with no burst and no burst effects.
LOC-7 SATS-7	~85	1173	<100 5	25 25	15	Very high burnup
LOC-8 SATS-8	~75	1173	<100 5	50 25	15	Length effects, plenum size, axial gas communication effects, SCIP complements
LOC-9 SATS-9	~75	1173	<100 5	50 25	2.5	Length effects, plenum size, axial gas communication effects, SCIP complements

* Fuel length will be limited to distance between grid spacers or would include a grid spacer if present in the commercial irradiation (likely applicable for 50 cm length specimens in TREAT). Most semi-integral furnace tests have been on segments with a length near 30 cm.

- Halden/Studsvik Tieback Testing
- Store-energy Heating vs Decay Heat Driven
- Higher burnup DEH testing (SCIP tie?)
- Failure fast ramp end vs after alpha-beta transition, pressure effects
- No burst effect – total tFGR in TREAT
- Burnup Threshold (just above)
- Long rod comparison, confirmation of SEH results
- Plenum size effect

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#1: Tieback Testing and First In-Pile HBu Test

- Selected Halden IFA 650.10/15 experiments
  - Similar test conditions and segment burnups
  - Sister segment to 650.15 tested in SCIP-III test 36U-N05
    - Sister materials still exist at Studsvik
  - 650.10 used as IAEA FUMAC benchmark
- Test Conditions
  - PWR, burnup: 61 GWd/t & 65 GWd/t
  - PCT: 1113 K & 1173 K
  - Ramp rate: ~5 K/s

Data and figures from IAEA Report, “Fuel Modelling in Accident Conditions (FUMAC),” IAEA-TECDOC-1889, 2019

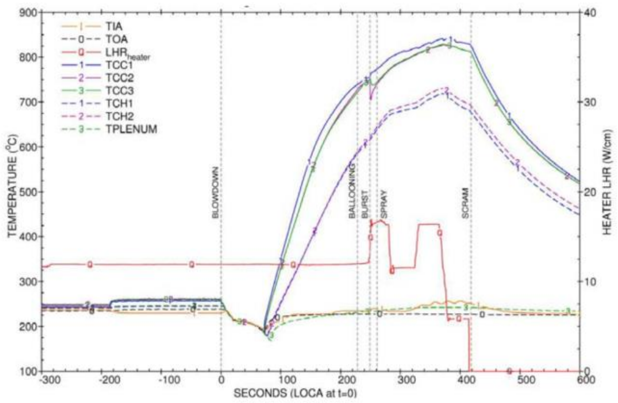


FIG. 20. Cladding and heater temperatures, IFA-650.10.

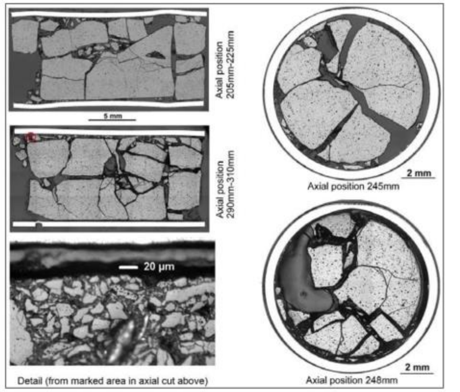
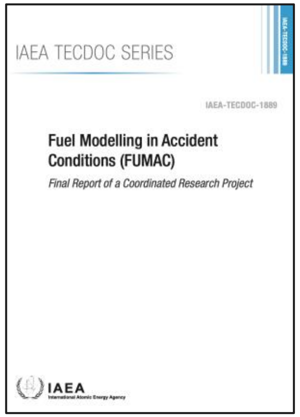


FIG. 26. Ceramography showing fuel fragmentation, IFA-650.10.



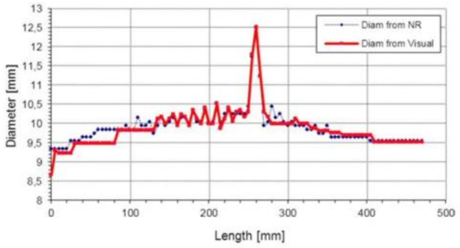


FIG. 24. Diameter profile of IFA-650.10.

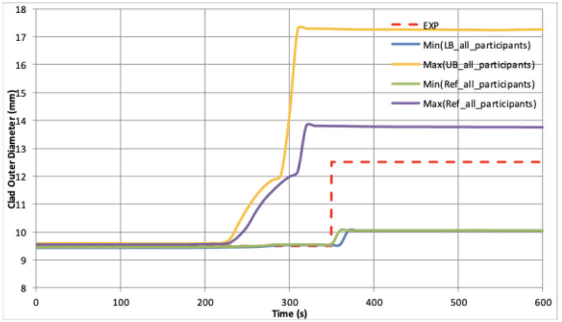


FIG. 169. IFA-650.10: Global reference dispersion and uncertainty width of all participants Clad outside diameter.

Test #	Seg. Burnup (GWd/t)	PCT (K)	Max. Temp. Ramp Rate (K/s)	Fuel Length (cm)	Rod Free Volume (cc)
LOC-1 SATS-1	~65	1173	5	25	15

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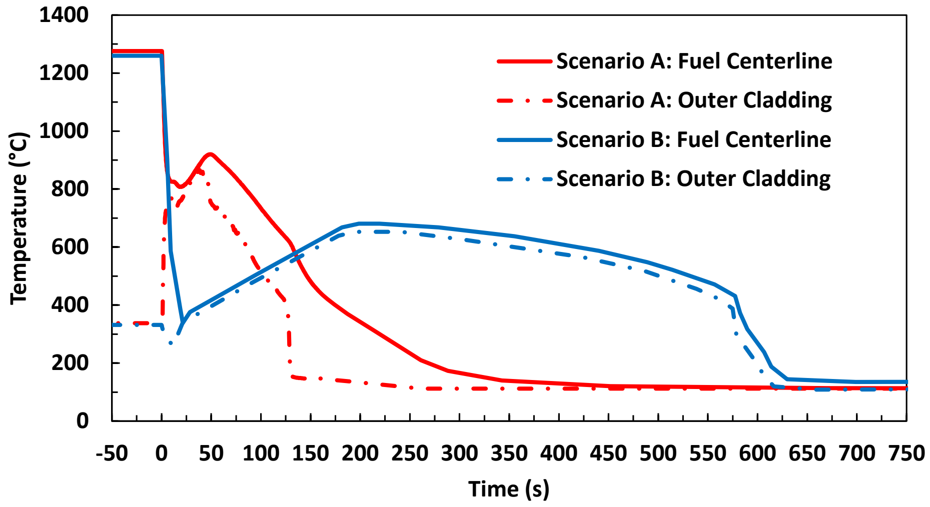
#2: SEH vs DEH Evaluation

- Utilize material sister if possible or similar to #1
- Key identified condition to be evaluated by TREAT in-pile capability
  - Fuel thermal conditioning to simulate EOL operating condition
  - Simulate full blowdown thermal conditions
- Increased ramp rate in SATS test
  - Upgrading to achieve 30-60 K/s
- Target burst condition at peak of first ramp to compare with test #1



Test #	Seg. Burnup (GWd/t)	PCT (K)	Max. Temp. Ramp Rate (K/s)	Fuel Length (cm)	Rod Free Volume (cc)
LOC-2 SATS-2	~65	1173	<100 50	25	15

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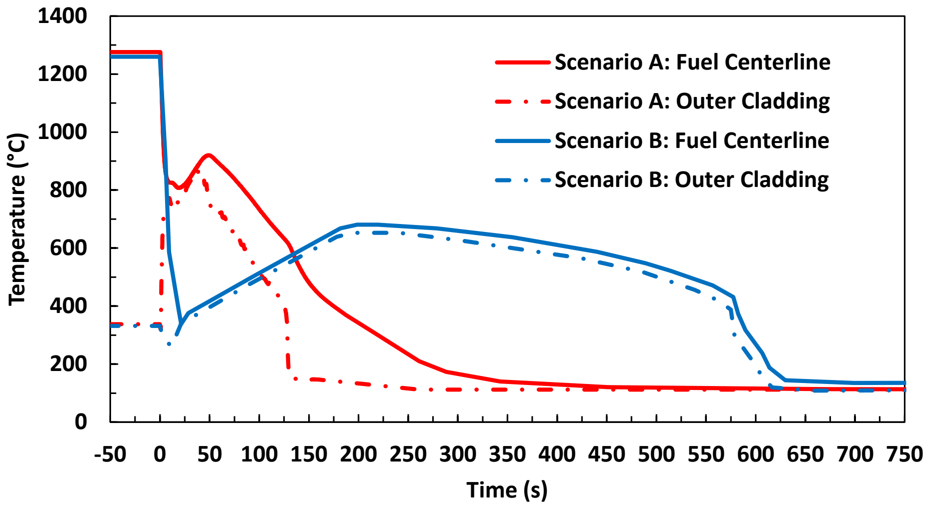
#3-6: Increased Burnup SEH vs DEH

- Target burnup near 75 GWd/t
  - No Halden tests on PWR material in near this burnup
- Similar conditions as Tests #1-2
  - Test #3: DEH heating, SCIP ties?
  - Test #4: SEH comparison to #3
  - Test #5: SEH in TREAT, DEH in SATS; Target early failure (after first ramp) for contrast with late failure expected in test #4
  - Test #6: SEH in TREAT, DEH in SATS; Target non-failure with similar heating as #4/5 but with no burst (similar to IFA 650.14) – tFGR measurement and burst impact on FFRD



Test #	Seg. Burnup (GWd/t)	PCT (K)	Max. Temp. Ramp Rate (K/s)	Fuel Length (cm)	Rod Free Volume (cc)
LOC-3 SATS-3	~75	1173	5	25	15
LOC-4 SATS-4	~75	1173	<100 50	25	15
LOC-5 SATS-5	~75	1173	<100 5	25	15
LOC-6 SATS-6	~75	1173	<100 5	25	15

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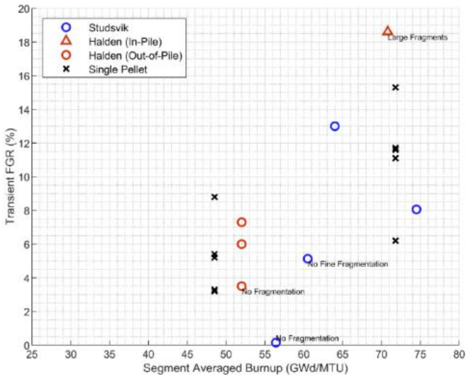
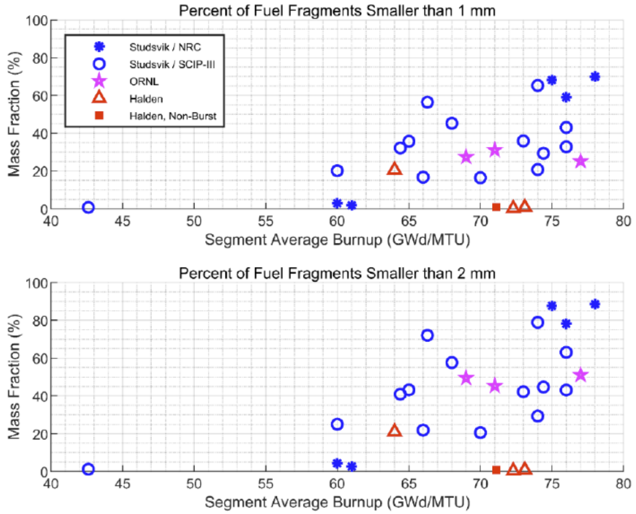
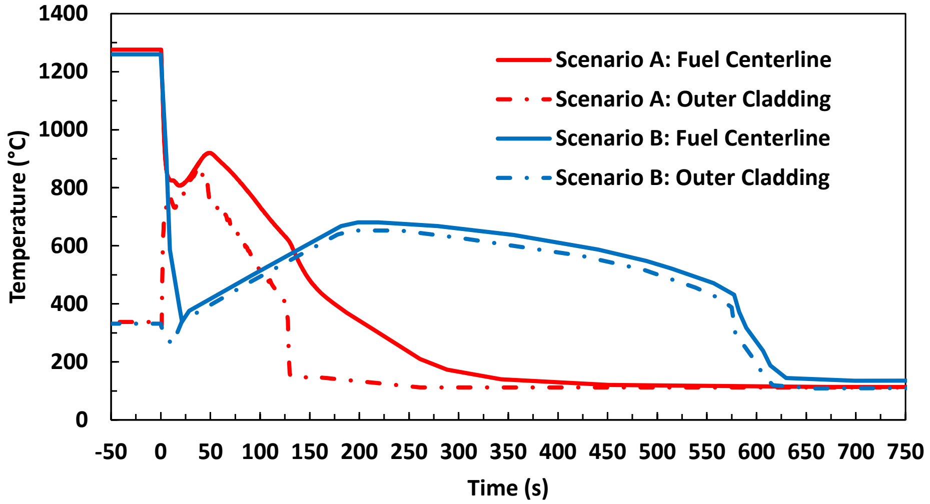
#7: Extended Burnup Comparison

- Target burnup near 85 GWd/t
  - Little data at this burnup, rod peak radial average for 75 GWd/t rod average (or just beyond)
  - Test #7: SEH in TREAT, DEH in SATS



Bales, M., et al., NRC RIL 2021-3

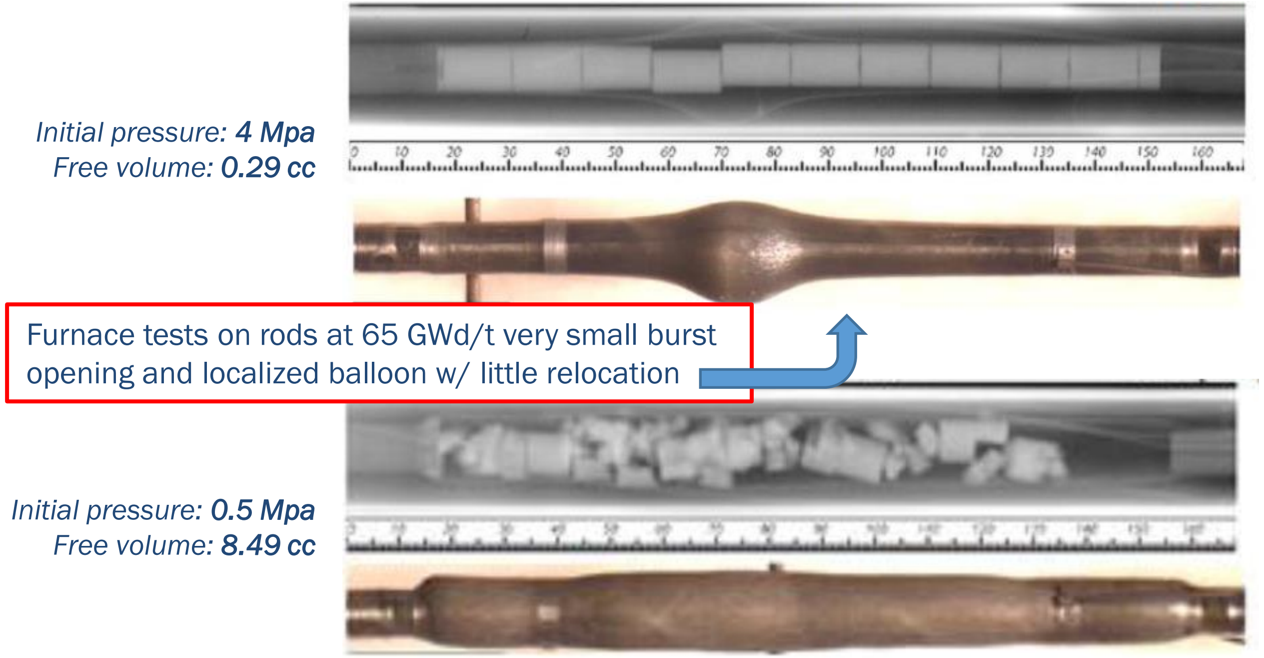




Test #	Seg. Burnup (GWd/t)	PCT (K)	Max. Temp. Ramp Rate (K/s)	Fuel Length (cm)	Rod Free Volume (cc)
LOC-7	~85	1173	<100	25	15
SATS-7			5	25	

#8-9: Rod length and Plenum Size Impacts

- Target burnup near 75 GWd/t
- Test rod design effects
  - Planned to fill gaps from test results from Halden furnace and SCIP tests on plenum size effects
  - Test #8: Confirmatory tests to SATS#3 with DEH and LOC-4 with SEH but with longer rod length in LOC
  - Test #9: Minimized rod internal free volume
  - Long rod config could include grid spacer – unique design



Results from Baurens, B., et al., Proc. Top Fuel 2019, p. 708.

Test #	Seg. Burnup (GWd/t)	PCT (K)	Max. Temp. Ramp Rate (K/s)	Fuel Length (cm)	Rod Free Volume (cc)
LOC-8 SATS-8	~75	1173	<100 5	50 25	15
LOC-9 SATS-9	~75	1173	<100 5	50 25	5

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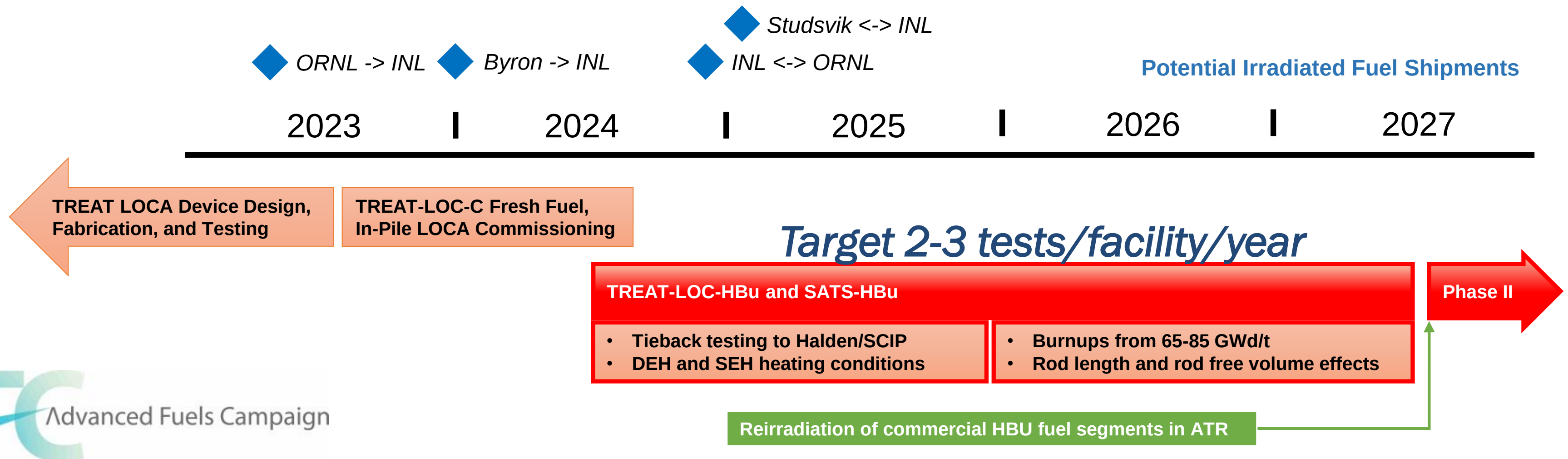
Summary

- Consensus integral LOCA test plan incorporating input from stakeholders
- Systematic integration of in- and out-of-pile integral LOCA testing
  - And characterization and separate effects testing
  - Built on existing knowledgebase
- Application of innovative/new instrumentation
- Test Matrix has LB LOCA focus: Decay Energy Heating vs Stored Energy Heating
- Plan to be updated as needed (~annually) under consultation with FPT TEG
  - ALS success would likely have significant impacts to test matrix objectives



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Thanks for your attention

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Clean. Reliable. Nuclear.

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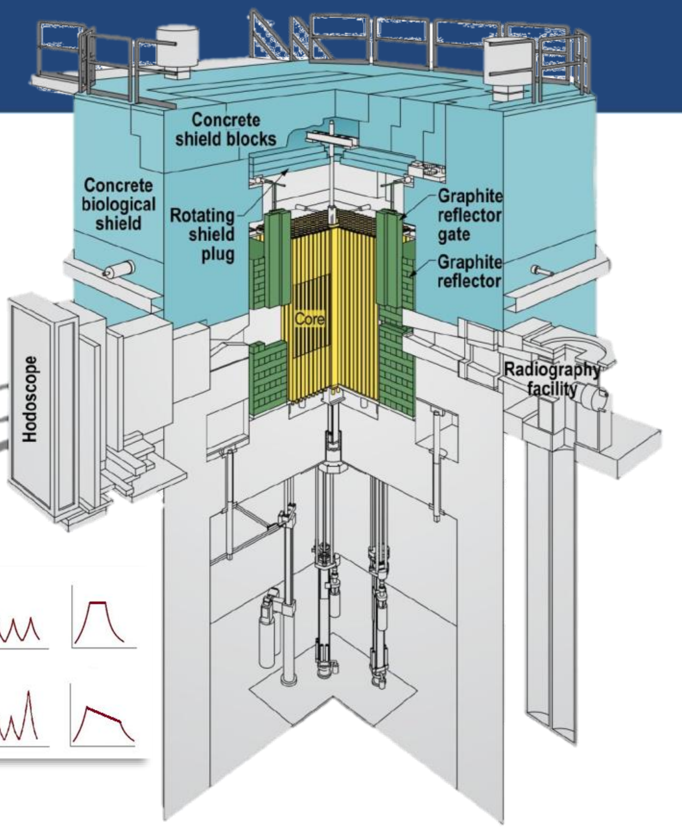
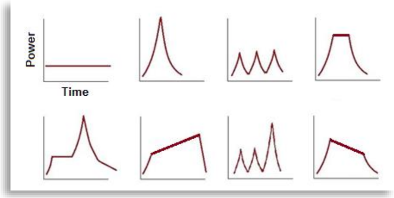
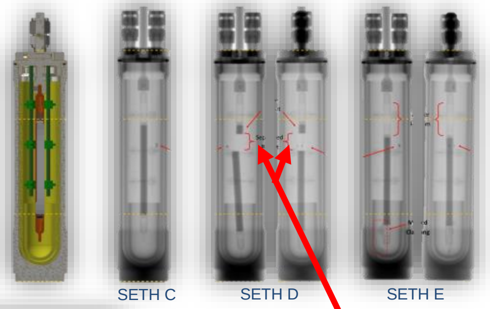
Backup Slides

TREAT Design & Experimental Approach



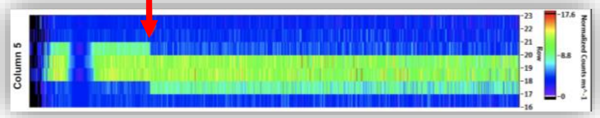
- The Transient Reactor Test Facility (TREAT) at Idaho National Laboratory operated from 1959-1994 and resumed operations 2017 to support fuel safety testing and other transient science
- Zircaloy-clad graphite/fuel blocks comprise core, cooled by air blowers
  - Virtually any power history possible within 2500 MJ max core transient energy
  - No reactor pressure vessel/containment, facilitates access for in-core instrumentation
  - 4 slots view core center, 2 in use for fuel motion monitoring system & neutron radiography
- Reactor provides relatively short (and potentially extreme, up to 10^{17} $n \cdot cm^{-2} \cdot s^{-1}$) shaped neutron flux histories to test specimens





TREAT neutron radiography shows post-test fuel condition

TREAT fuel motion monitoring system detects fuel motion in-situ



Time →

- Experiment vehicle does everything else
  - Safety containment, specimen environment, and instrumentation
- TREAT restart project only addressed facility refurbishment
  - Historic assembly and support infrastructure had largely dissolved
- Diversity of TREAT's experiment history and foreseen community science needs and unique capability
  - Emphasized need for modern and multipurpose experimental tools

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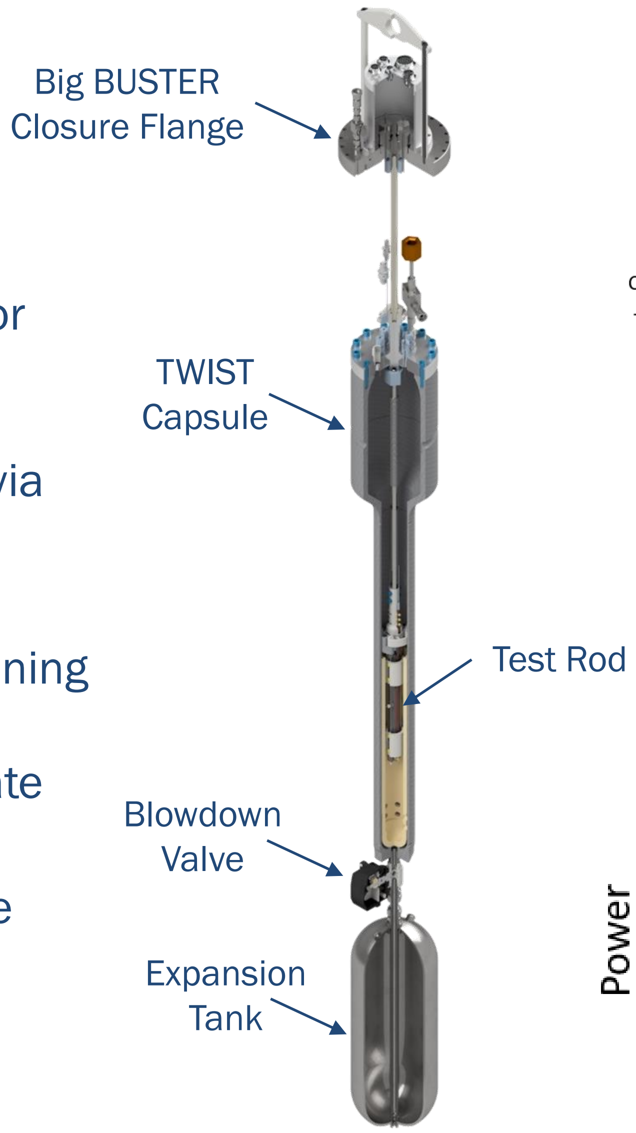
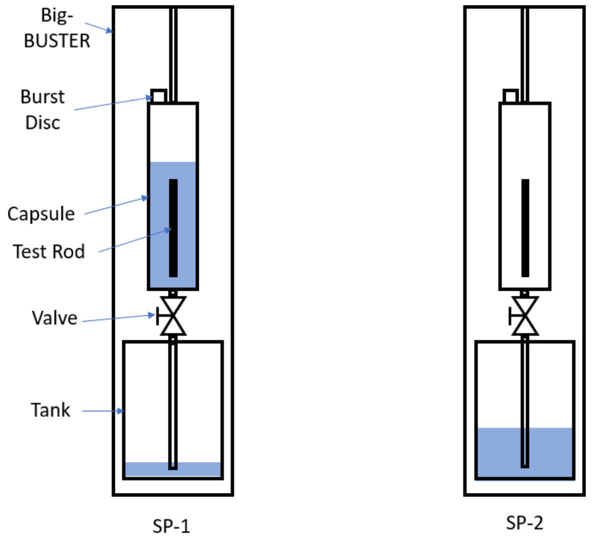
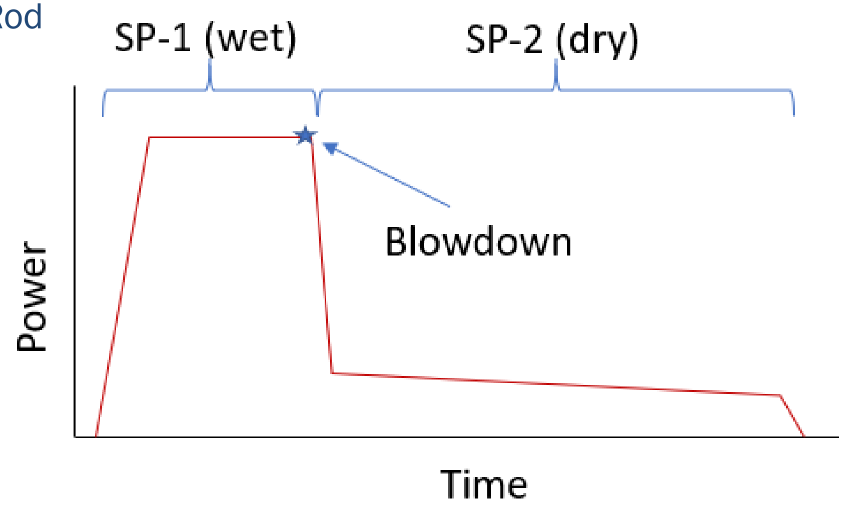
Virtual facility tour: https://inlgov360.b-cdn.net/TREAT/tour.html

Transient Water Irradiation System for TREAT (TWIST)

- **State Point 1 (SP-1)**
  - Water in capsule at 20 °C and ~3.5 MPa
  - TREAT power ramped up and held constant for ~20-30 seconds
  - Achieve radial temperature profile in test rod consistent with LWR at operating conditions via nucleate boiling
- **State Point 2 (SP-2)**
  - Valve opens, depressurizing capsule and draining water into expansion tank
  - Simultaneously, TREAT power drops to simulate decay heat in test rod
- Transients consisting of only SP-1 or SP-2 may be performed depending on experiment objectives







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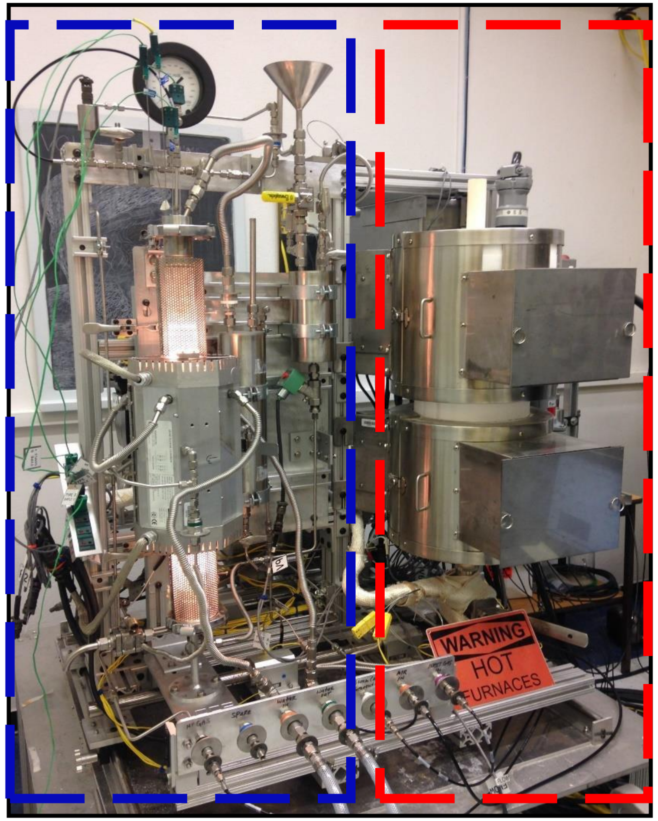
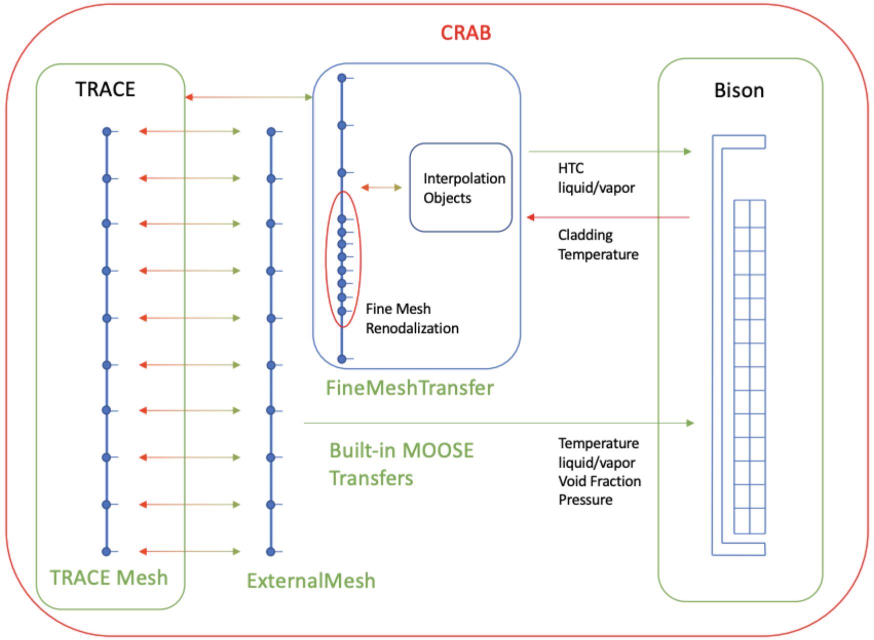
Severe Accident Test Station (SATS) at Oak Ridge National Laboratory



Parameter	Design Basis Accident Module: LOCA Integral Test	Design Basis Accident Module: Oxidation-Quench Test	Beyond Design Basis Accident Module High-Temperature Test Station
Sample specification	Fueled rod	Defueled rod	Defueled rod or coupon with 3 mm hole
Sample segment (mm)	~200–300	~25–50	~25–50
Maximum pressure at 300 °C (MPa)	~ 20	0.1	0.1
Maximum temperature (°C)	1,200	1,200	1,700
Heating rate, 4-lamp furnace (°C/s)	5, range 1–17	5; maximum 17	.25; maximum 0.33
Heating rate, 12-lamp furnace (°C/s)	30–60	30–60	N/A
Steam flow rate (mg/cm^2-s)	~5.7	~5.7	3.0–7.0
Gas environment	Steam or argon	Steam or argon	Steam or argon
Quench (°C)	@ 20–800	@ 20–800	None
Quench condition	Rising water around sample	Rising water around sample	None
Reflood elevation change rate (mm/s)	≥15	≥15	None
Test time (minutes)	≥30	≥30	Multiple days

TREAT TWIST LOCA Design

BlueCRAB = Coupled BISON+TRACE

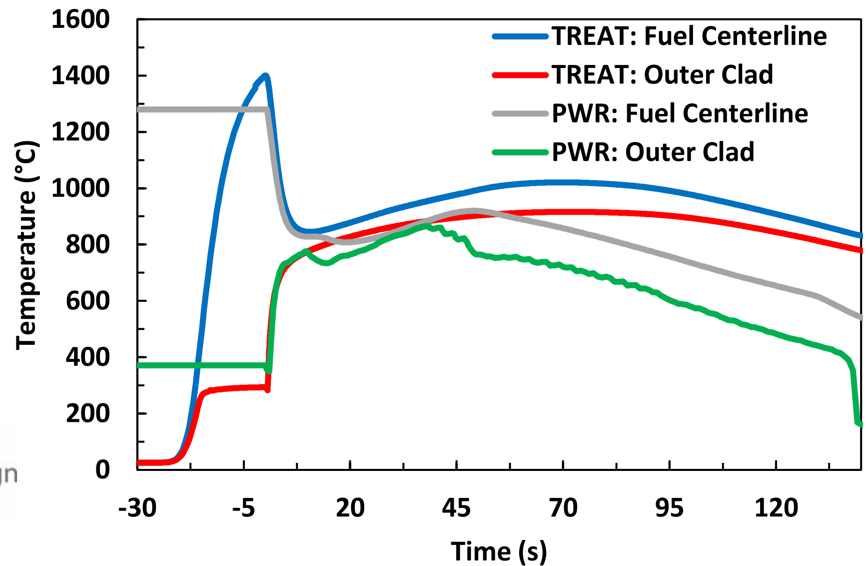


Capsule

Full-size TWIST non-nuclear out-of-pile prototype constructed

Blowdown Tank

Comparison of TREAT LOCA thermal histories with 4-loop HBu core during a LB LOCA scenario



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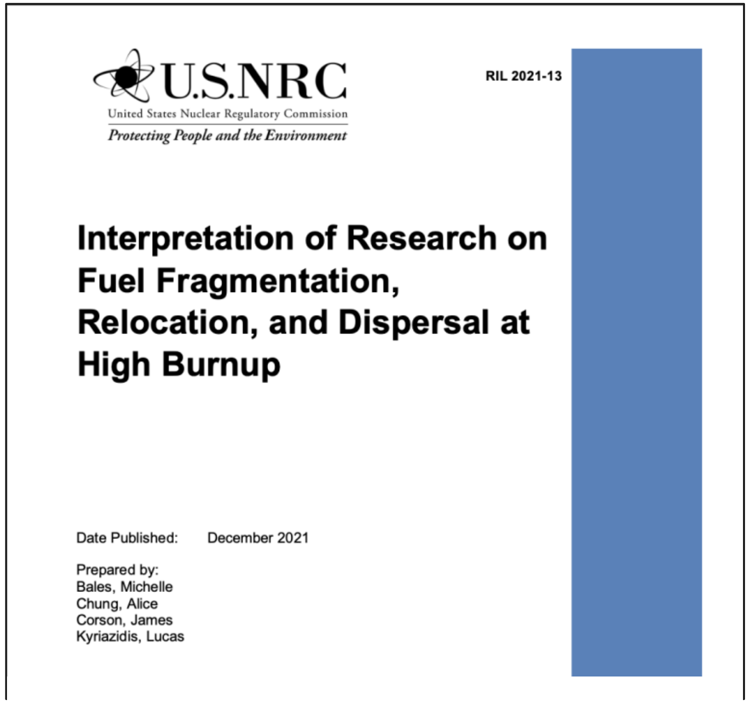
LOCA Conditions of Interest

Highlighted Final Thoughts from ACRS Letter Report on RIL 2021-13 for FFRD

- The **conditions of the experiments often differed significantly from conditions that would exist at PWR operating conditions.** Depending on the specific test, key variables that were not always prototypic include: **linear heat generation rate (low)**, terminal temperature (high) and **heatup rate (low).**
- It is one thing to determine an observed burnup at which fuel fragmentation begins to occur. In this case, it is essential to **determine the difference between conditions of a test/examination and the conditions that would exist under actual operating conditions.** A careful evaluation of uncertainty will be key. It is quite another thing to determine the point at which FFRD actually influences LOCA performance. The RIL made no claims in this area, one that is critical to determination of practical consequences. **There are a number of experimental programs that will produce data that more closely approach PWR conditions including the TREAT tests. These results will likely provide more prototypic data and hence reduce uncertainty.**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RIL 2021-13

Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal at High Burnup

Date Published: December 2021

Prepared by:
Bales, Michelle
Chung, Alice
Corson, James
Kyriazidis, Lucas

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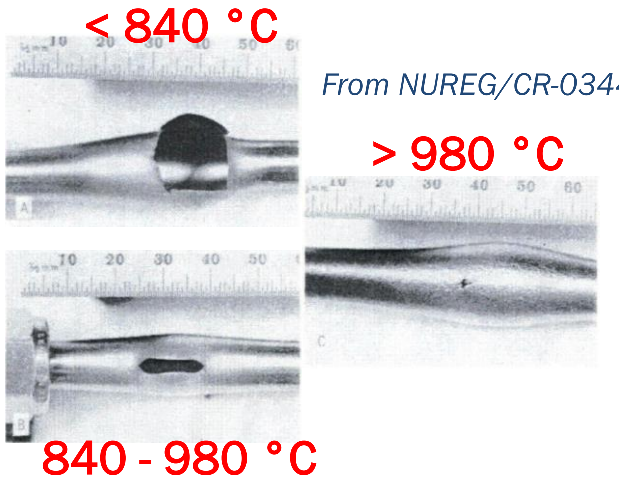
Important Observations on Rate Effects (SEH vs DEH)

Cladding Balloon/Burst

- Heat up rate ↑
  - Clad balloon size ↓
  - Burst temperature ↑
  - Rupture size ↓
- Fragmentation/relocation limited by cladding restraint (delayed deformation)

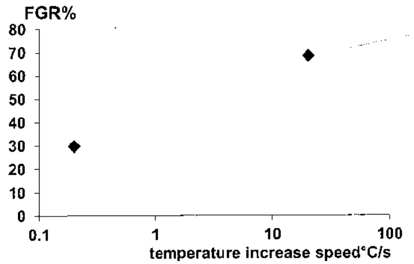


From NUREG/CR-0344

Transient Fission Gas Release (tFGR)

- tFGR correlated with fragmentation behavior
- Positive correlation between heating rate and tFGR
- Observed change in tFGR mechanism > 50 – 200 °C/s from time-dependent bubble growth and interlinkage to prompt grain boundary rupture

Competing effects of cladding restraint and tFGR increases complexity when describing FFRD behavior



Plot from NFIR program, Noirot, et al., Fuel Safety Research Meeting, Japan, 2019

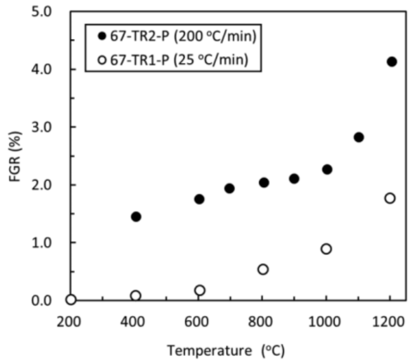


Figure 15. Evolution of the FGR of samples 67-TR1-P and 67-TR2-P vs. temperature. The two samples were obtained from the periphery of ST53 (segment burnup: 66.7 GWd/tU).

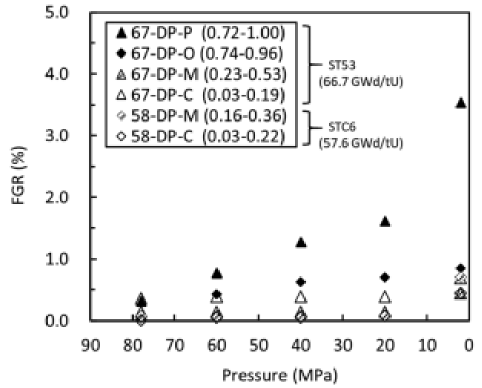


Figure 16. Evolution of FGR under depressurization. The numbers in the legend indicate the relative radius for each sample.

Plots from A. Yamauchi, Journal of Nuclear Science and Technology, 2021

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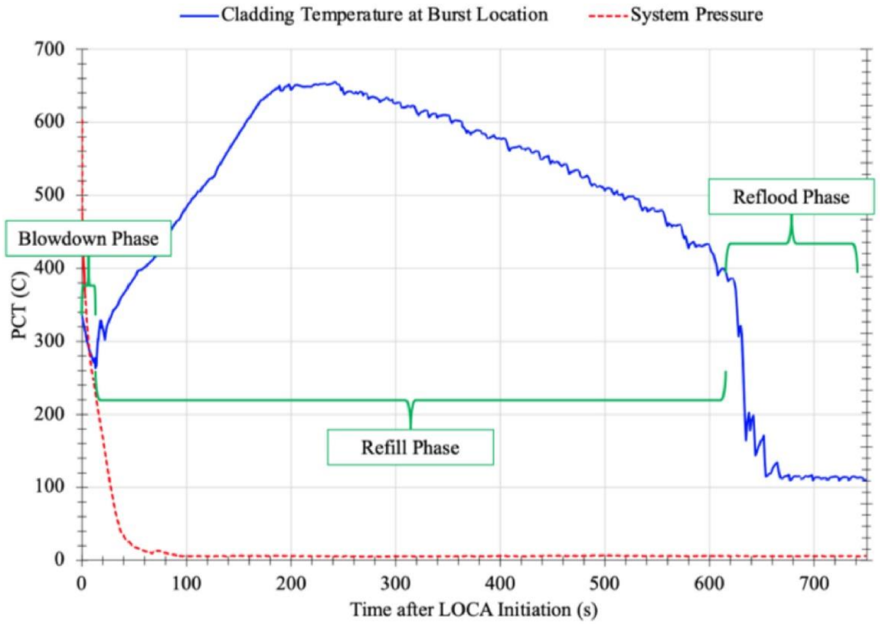
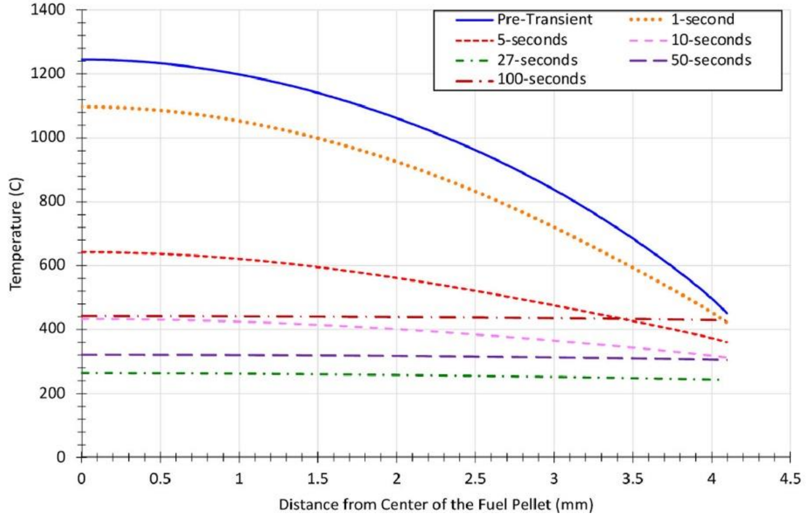
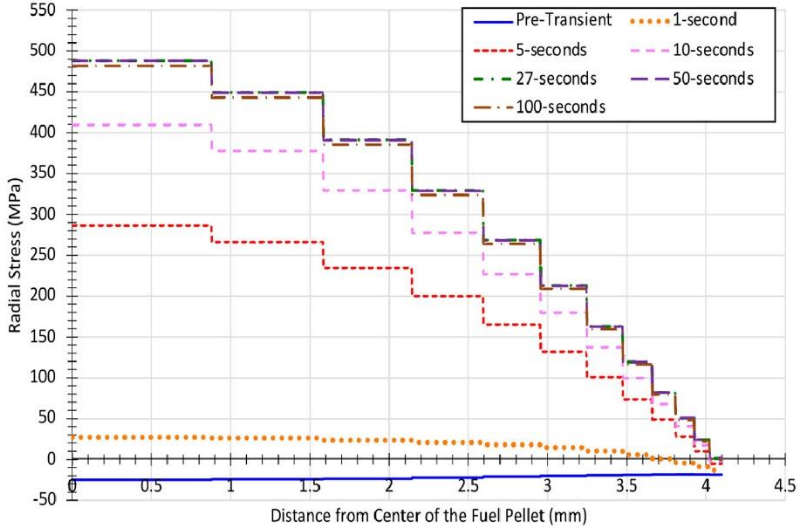
Boundary Condition Development

Heat up rates in current FFRD database are representative of DEH-driven LOCA conditions

- Database consists of isothermal heating at 2-9 °C/s starting from coolant temperature
  - Analysis comparing a DEH-driven LOCA to out-of-pile furnace-heated experiments, found the radial temperature profile in the fuel and thermally induced pellet stresses resulting from both methods should be similar (Capps, N. et al., 2021)







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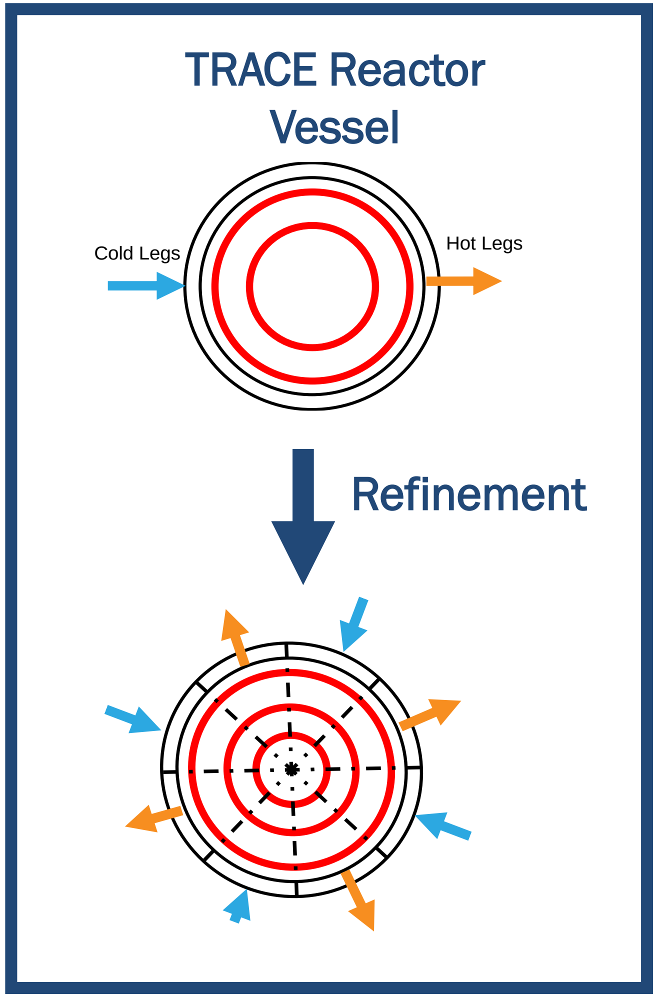
Figures from High-burnup fuel stress analysis prior to and during a LOCA transient, Capps, N. et al., 2021

Full core PWR LOCA modeling using BlueCRAB

- Comprehensive Reactor Analysis Bundle (CRAB)
  - Coupled BISON/TRACE
- A generic 4-loop PWR TRACE model was refined to better capture radial and azimuthal variations in thermal-hydraulic conditions
- 24-month cycle core-wide power and burnup distribution at end-of-cycle used as input parameters to BlueCRAB (Stewart, R. et al., 2021)



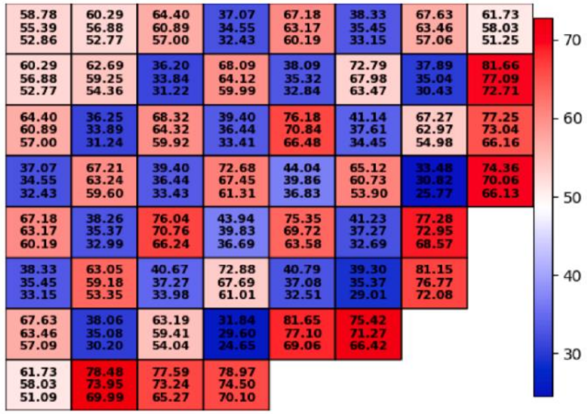
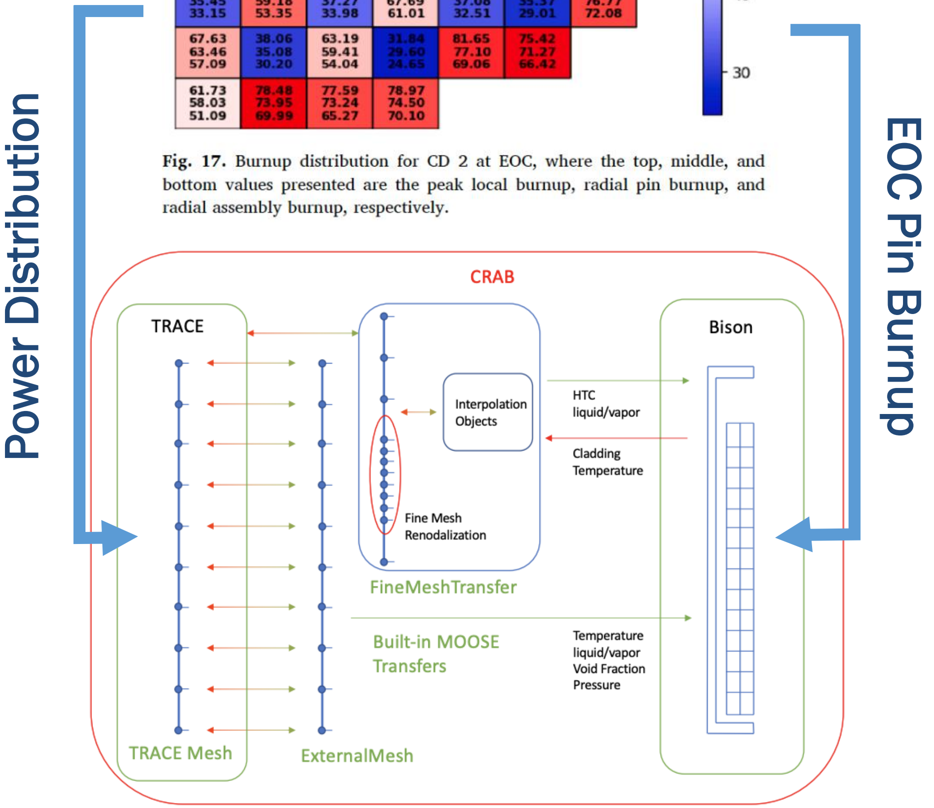


Fig. 17. Burnup distribution for CD 2 at EOC, where the top, middle, and bottom values presented are the peak local burnup, radial pin burnup, and radial assembly burnup, respectively.



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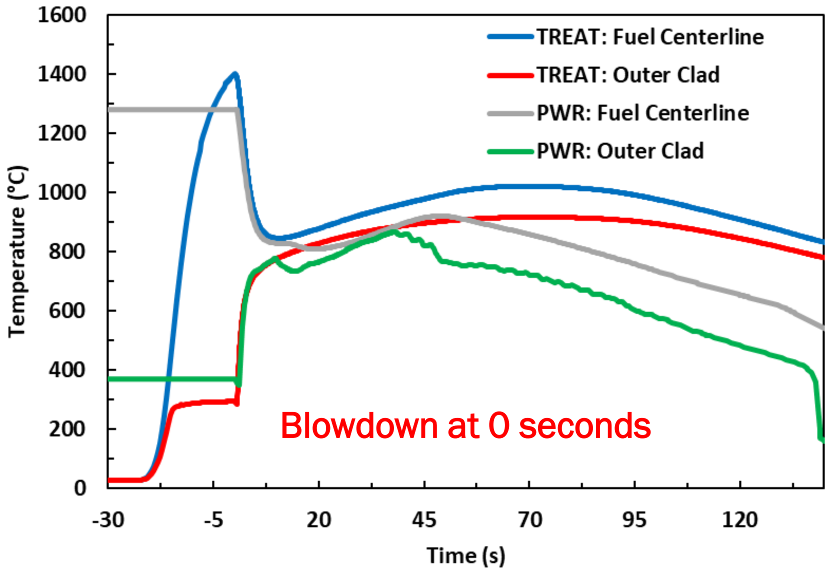
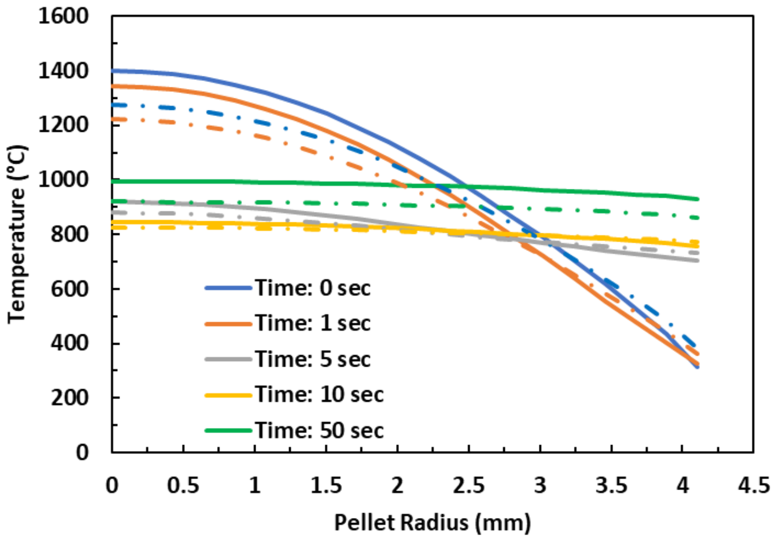
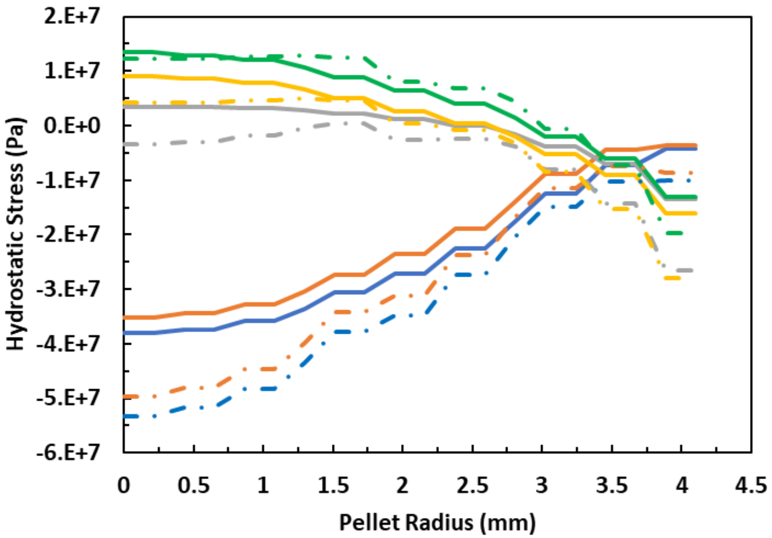
Simulation of a SEH-driven LOCA in TREAT

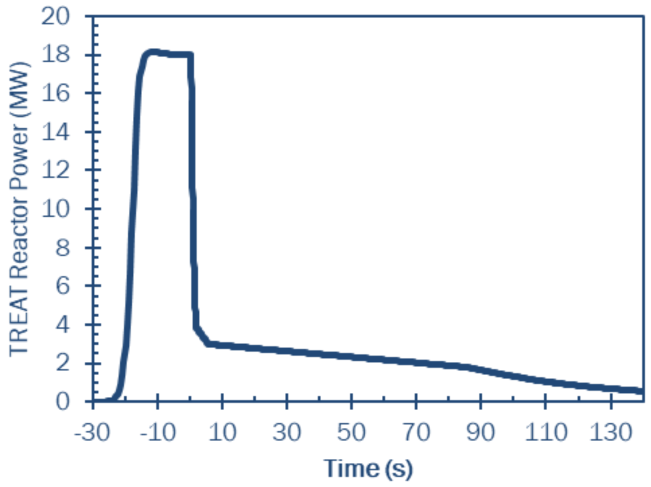
- Excellent agreement with PWR LOCA simulation
  - Ramp rate
  - Energy redistribution
  - Stress transition
- TREAT power transient shaping to achieve desired temperature history







*TREAT also has capability to simulate DEH-driven LOCA



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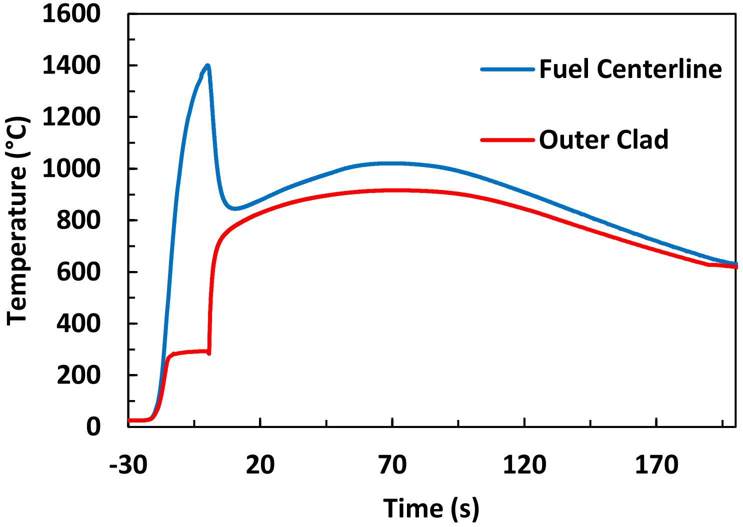
Solid Lines: TREAT

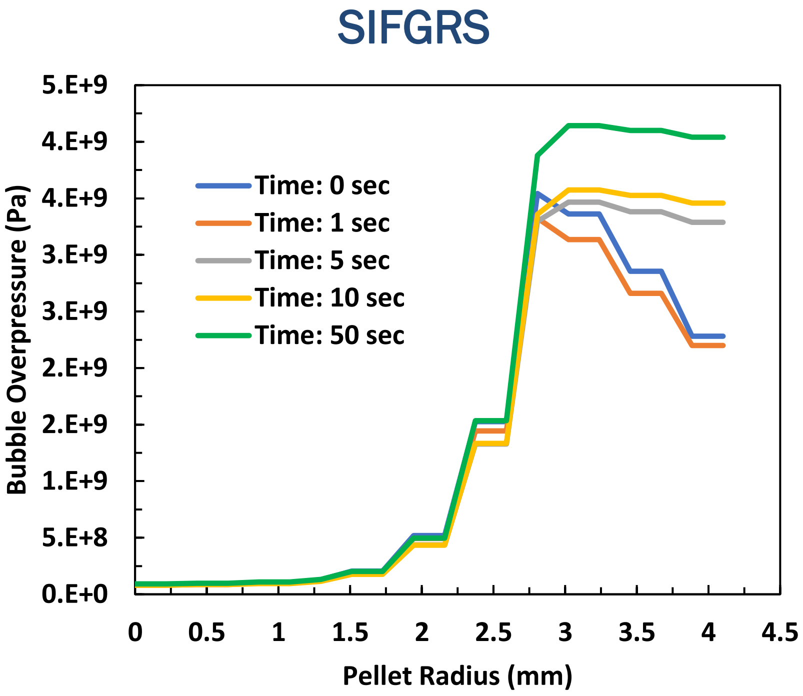
Dashed Lines: PWR

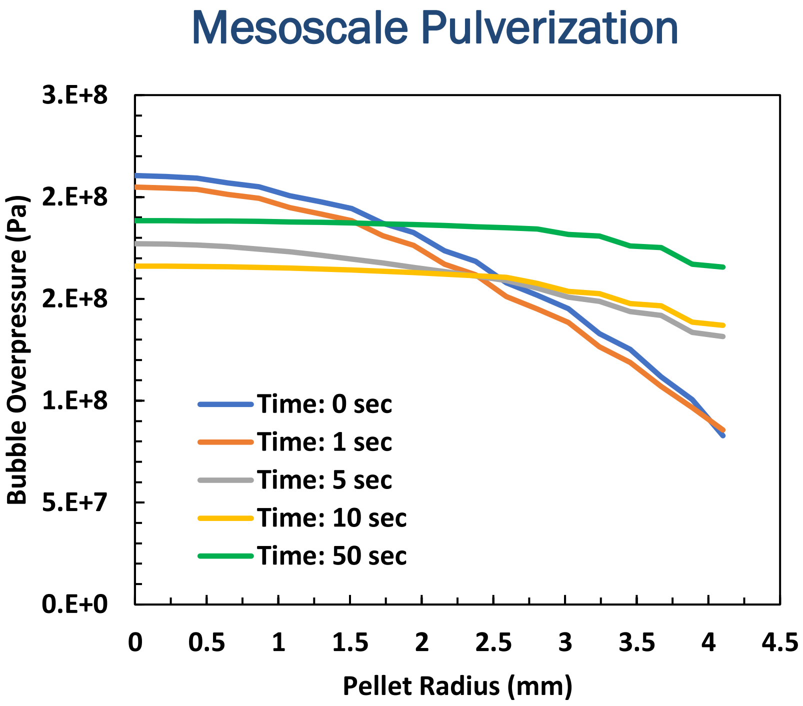
Related LOCA Separate Effects Testing

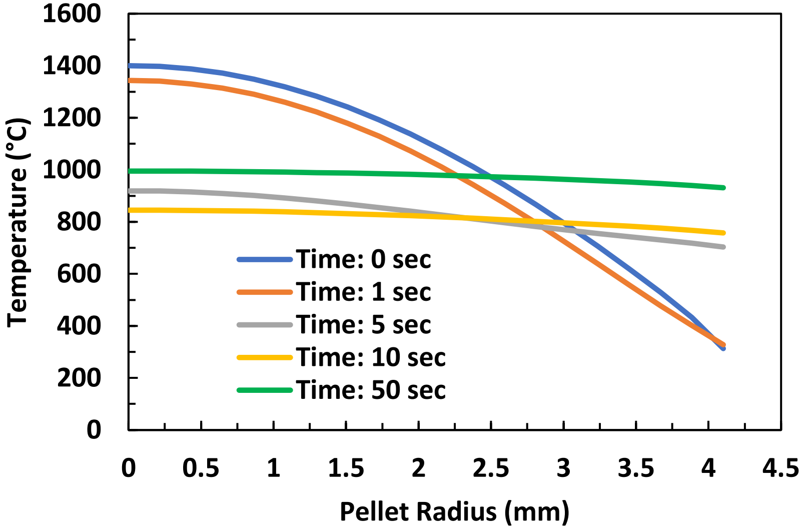
- Transient fission gas release
  - ORNL SATS facility added online measurement capability
  - TREAT tests use plenum pressure sensor
    - Considering separate effects design for small segments under wide range of transient conditions
  - Developing transient heating capability at INL
    - New design for transient furnace for segments (likely IR heating approach)
    - TGA+MS system undergoing testing/development for micro-/meso-scale samples
    - Hot Isostatic Press Furnace system for pressure transients (developed by different program may be available in a few years)
- High burnup fuel microstructure characterization and properties measurement
  - INL & ORNL
- Several university projects (NEUP) underway – mostly in modeling

Illustration of current fission gas bubble pressure models applied to TREAT LOCA simulation









Identify model applicability over range of LOCA conditions and data needs

- Microstructure characterization on HBu samples
- Rate effects on material properties (fracture strength)?