Fundamentals of Safety Testing

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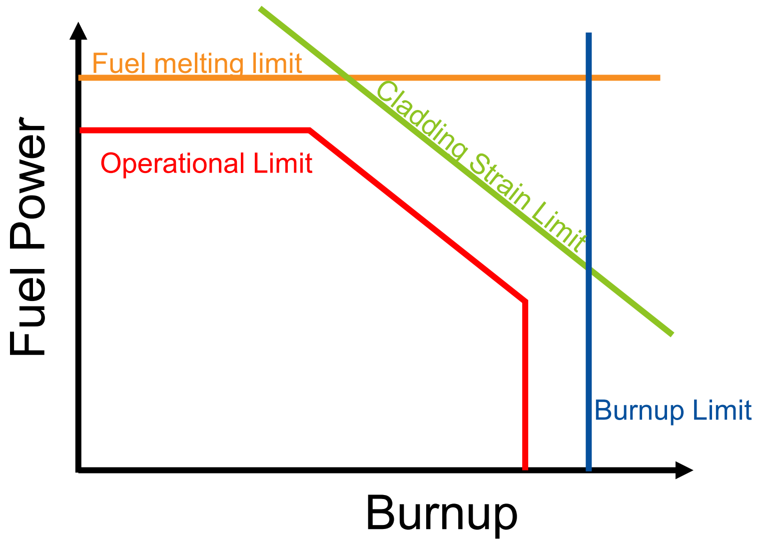
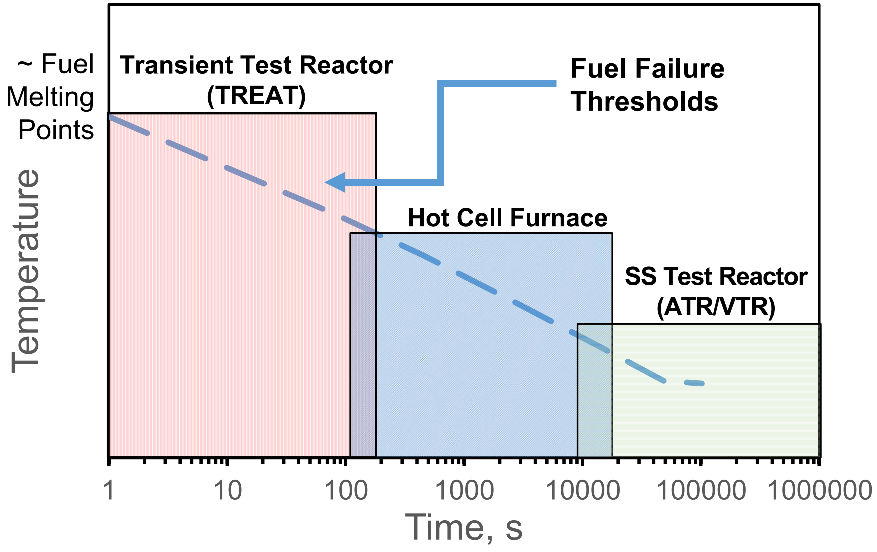
Why Transient Test Nuclear Fuels & Materials?

- **Transient testing is like car crash testing for nuclear fuels**
- Licensing a fuel system *requires* (see NUREG-0800):
  - identification of all **degradation mechanisms and failure modes**
  - definition of **failure thresholds** corresponding to each degradation mechanism
  - applies to **normal operations, anticipated operational occurrences and design basis accidents**
- Many operational limits are dependent on degradation and failure thresholds
- Enables economic reactor operations via improved fuel design and performance understanding



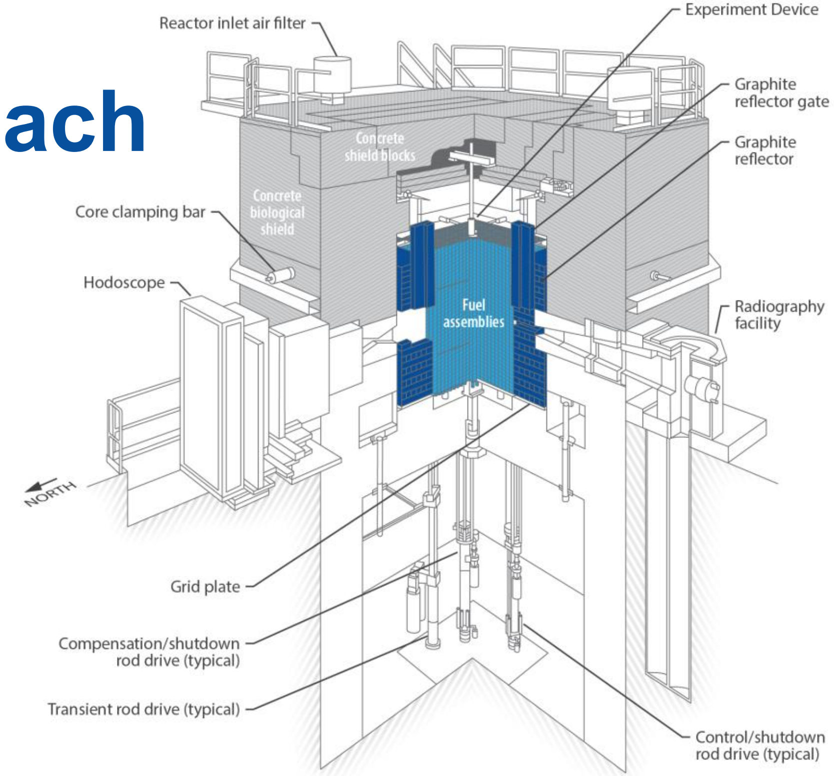
Translating Prototypic Behavior ⇄ Experiments

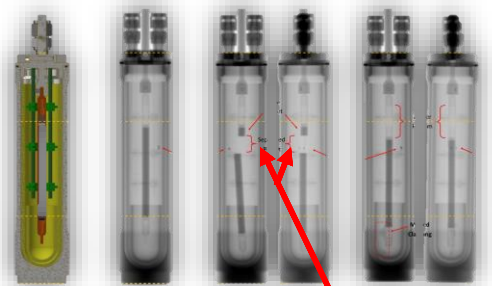
- Boundary conditions are the key to simulating specific behaviors
  - **Nuclear heating** is not easily simulated ex-reactor for certain conditions
  - Variety of **thermal hydraulic** platforms now available and developing (dry, static, flowing)
  - Dominated by **Temperature vs. Time** evaluation of material systems of interest (transient irradiation effects are higher order impacts)
- Key issues of investigation by transient testing
  - Fuel pin **failure** thresholds and mechanisms
  - Core **coolability**
  - Core **reactivity** effects
  - Fission product release and **source term** impacts



TREAT Design & Experimental Approach

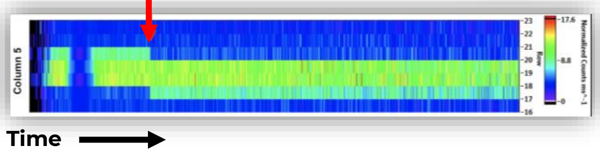
- The Transient Reactor Test Facility (TREAT) operated from 1959-1994 and resumed operations 2017 to support fuel safety testing and other transient science
- Zircaloy-clad graphite/fuel blocks comprise core, cooled by air blowers
  - Virtually any power history possible within 2500 MJ max core transient 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





TREAT neutron radiography shows post-test fuel condition

TREAT fuel motion monitoring system detects fuel motion in-situ



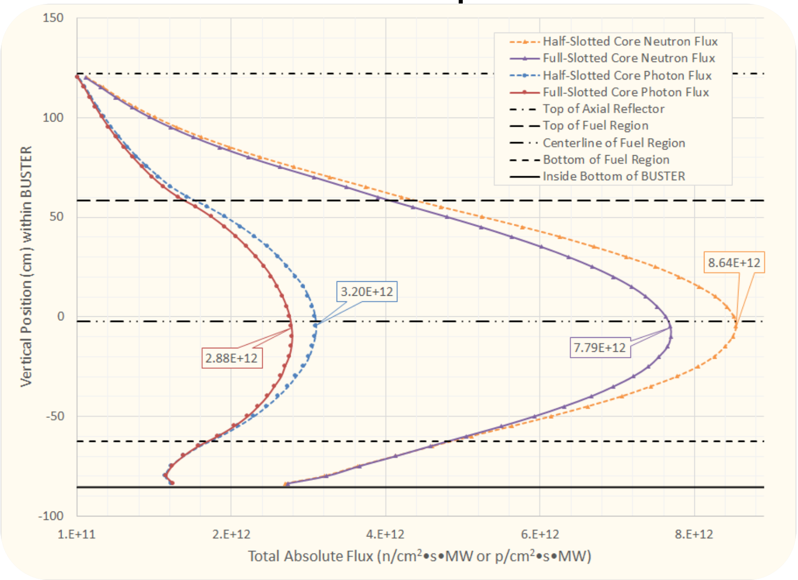
- Reactor provides brief (and typically extreme, up to 10^{17} $n \cdot cm^{-2} \cdot s^{-1}$) shaped neutron flux histories to test specimens
- Experiment vehicle does everything else
  - Safety containment, specimen environment, and instrumentation
- Diversity of TREAT's experiment history and foreseen community science needs and unique capability
  - Emphasized need for modern and multipurpose experimental tools

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

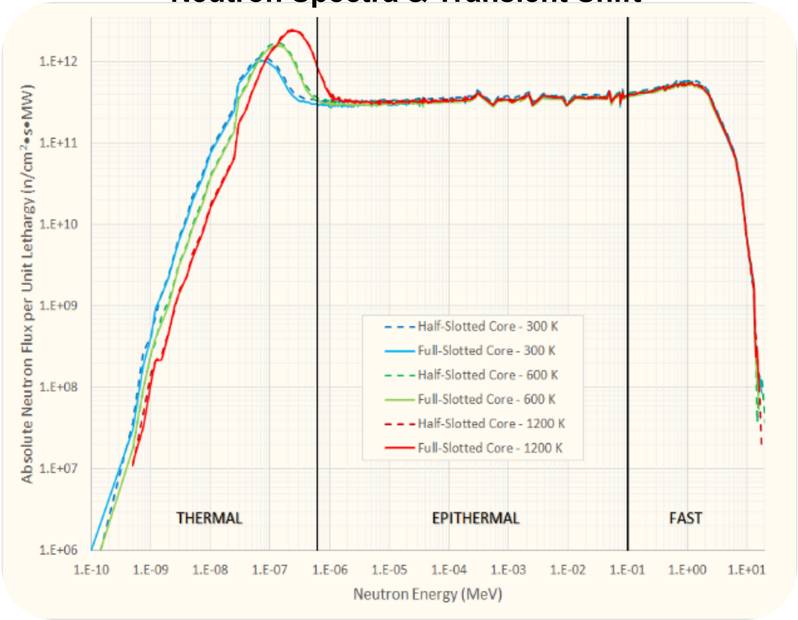
TREAT Experimental Approach

- Typical residence time in the TREAT core for a given experiment is a few days
  - Of which only a few milliseconds to minutes is the transient
  - Even with multiple transients on the same specimen, fluence is extremely low (dpa is effectively zero)
- TREAT is best suited for testing fuels, and materials that could interact with fuels (e.g. cladding, ducts), under extreme conditions for nuclear heated safety research
  - If significant structural burnup or material fluence is needed before transient testing, its better accomplished in another reactor first (e.g. ATR, HFIR)

Axial flux profile



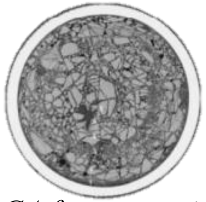
Neutron Spectra & Transient Shift



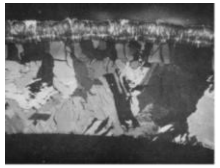
Figures from: Bess et al., Ann. Nucl. Energy 124 (2019) 270

Important Transient Fuel Behavior Examples

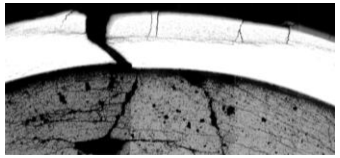
- Pre-failure:
  - Fuel damage mechanisms (initial damage → release of FP)
    - Fuel- (pellet-) cladding mechanical interaction (FCMI/PCMI)
    - Fuel-cladding chemical interaction (FCCI)
    - Cladding pressurization
    - Effect from the state of the fuel rod (preirradiated, etc.)
  - Fuel swelling & relocation
  - In-pin axial fuel motion
  - Fuel melting
  - Fission gas migration & release
  - Solid fission product migration



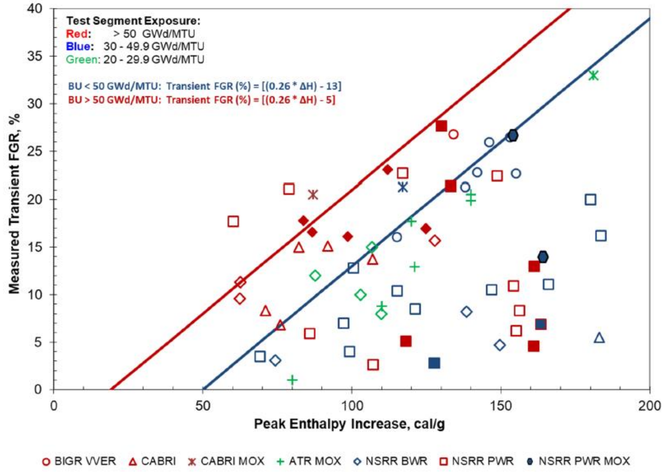
LOCA fragmentation, NEA/CSNI/R(2016)16



Cladding oxidized at LOCA conditions, NEA-6846

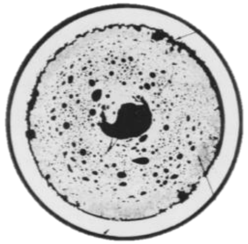


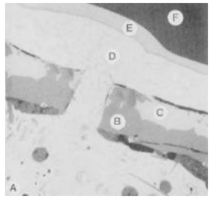
Cladding failure at hydride blister, NEA-6847



tFGR during RIA, NRC Reg Guide 1.236

Result for TREAT test M7 (metal-SFR), ANL-IFR-124



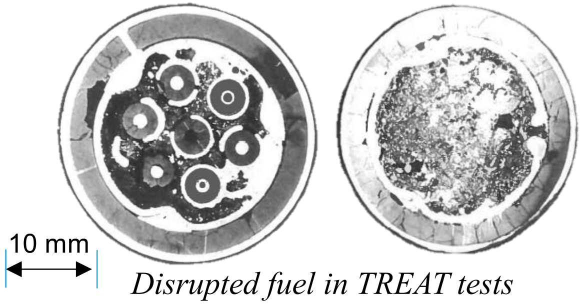


FCCI in TREAT test M5 (metal-SFR), ANL-IFR-124

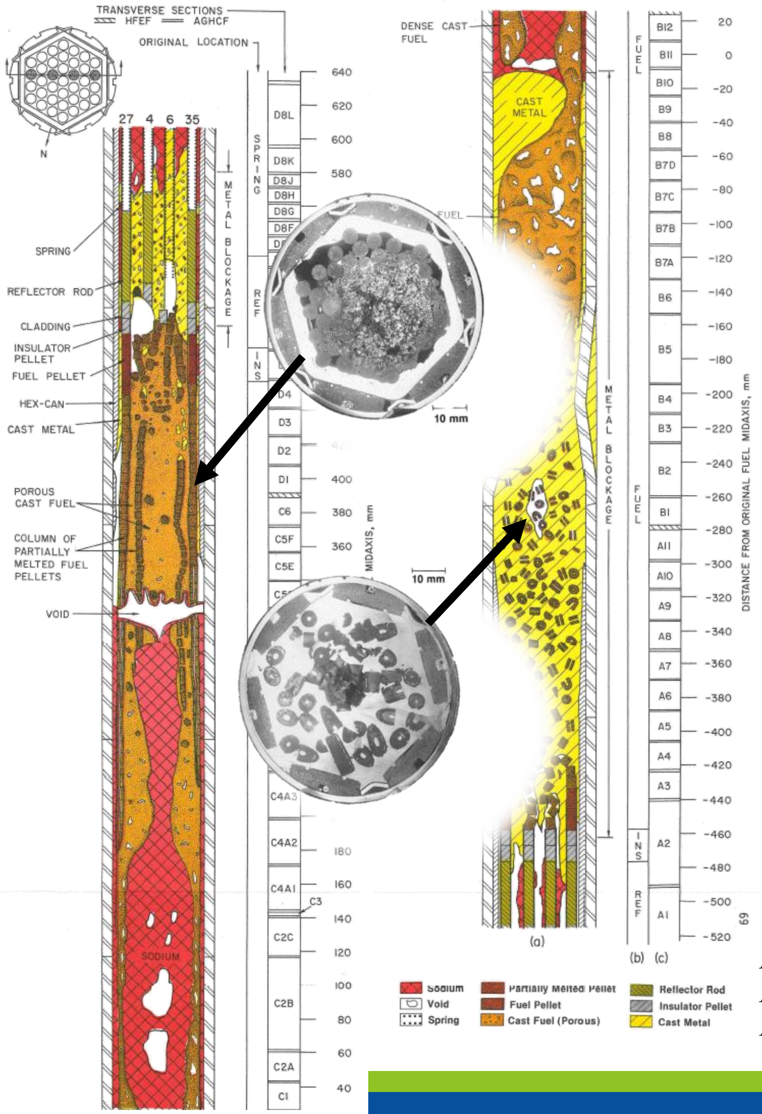
Important Transient Fuel Behavior Examples

- Post-failure:
  - Cladding failure mode and location
  - In-pin fuel motion
  - Fuel dispersal/ejection
  - Fuel-coolant interaction
  - Mixing and motion of disrupted fuel, cladding, and coolant

Cladding failure and dispersed fuel inventory for high burnup fuel, NEA-6847



Disrupted fuel in TREAT tests (oxide-SFR), AEA-RS-5411



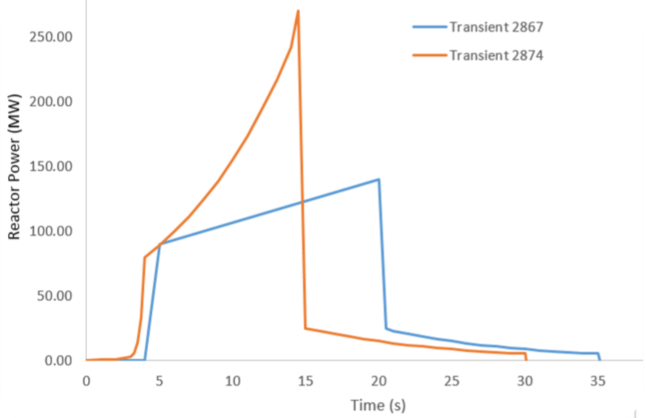
Results from SLSF experiment P3, ULOF (oxide-SFR), ANL-RAS-84-30

Reactor Power Control

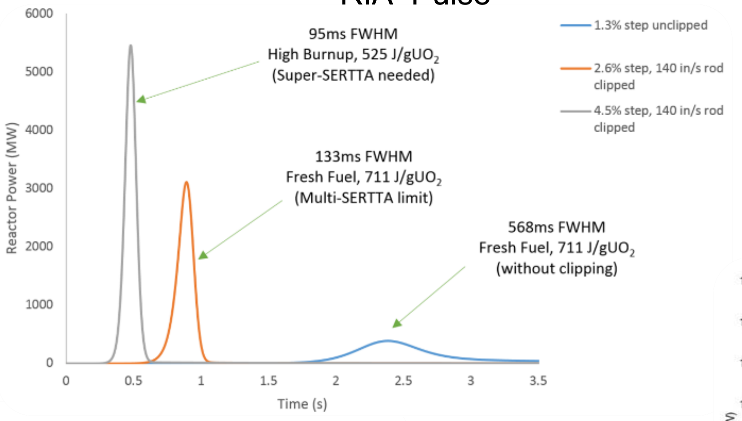
- TREAT is a transient reactor, not only a pulse reactor – “windowed” power histories
- Graphite heat sink, nimble control rod system → flexible power maneuvers
- Rod control system can accept feedback from experiment instrumentation

TREAT subpile room

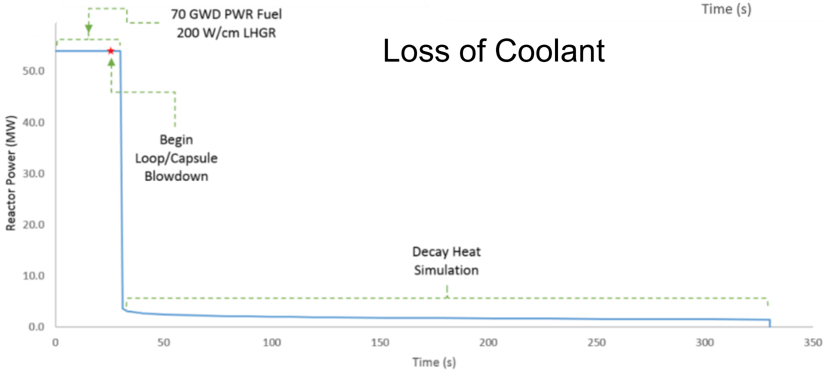
Power Ramps



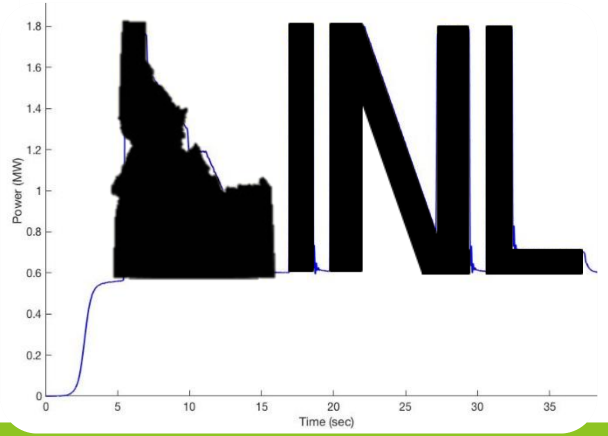
RIA “Pulse”



Loss of Coolant



Complex Shaped Transient
and so on...



Transient Testing Testbeds and Infrastructure

- TREAT programs fall within 5 product lines, each of which is supported by its own test bed infrastructure

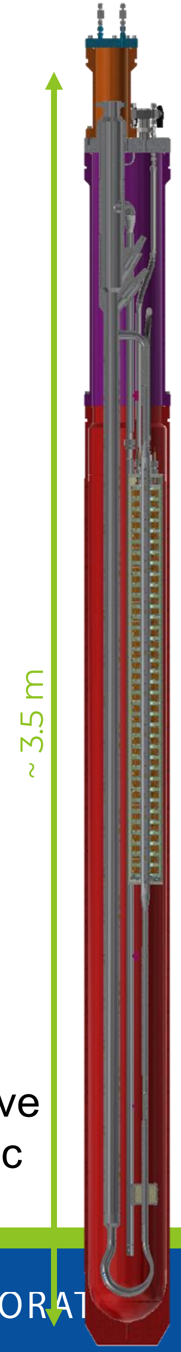
- Light Water Reactor
- Sodium Fast Reactor
- Advanced Gas Reactor
- Space Nuclear Propulsion
- National Security
- *Instrumentation and Modeling Platform*

- Each testbed naturally divides in two size scales also distinguished by passive and active cooling
- Most R&D plans include tests from both size scales

"Capsule-scale"
More affordable static environment devices

Cartridge-in-console architecture used whenever possible for general infrastructure

"Loop-scale"
Devices with active thermal-hydraulic manipulation



TREAT Experimental Testbeds

- Reactor *and* hot cell facility integration

General purpose

0.3 m

SETH
Separate effects static capsule

Water testbed

0.6 m

SERTTA
Static pressurized water capsule

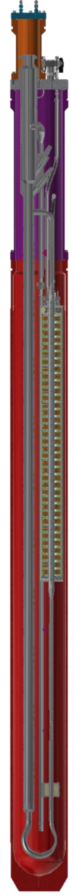
2 m

TWIST
Pressurized water blowdown capsule

Sodium testbed

1 m

THOR
Liquid-metal-bonded heat-sink capsule



3.5 m

Mark-IIIR
Flowing Na Loop

Advanced Gas Reactor & Space nuclear testbed

1 m

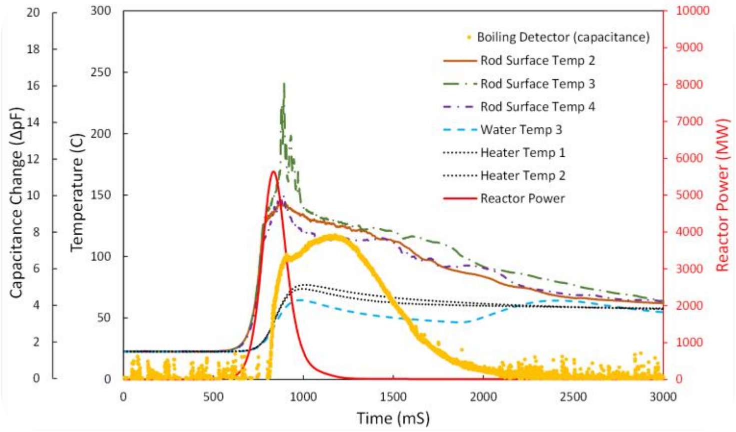
SIRIUS
Static Gas Capsule

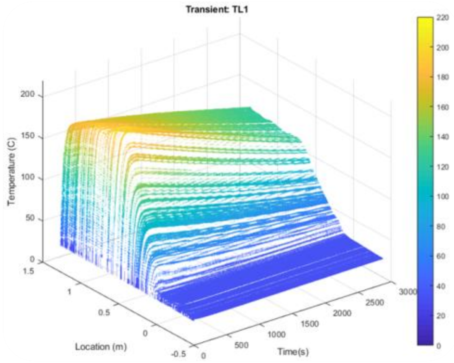
2.5 m

Flowing Hydrogen/Helium Loop

In-Situ Instrumentation

- Extensive in-situ measurements are routine in TREAT
  - Unparalleled core access
- Desired data should be important initial consideration
  - Wide array of options available today
  - Development of custom approaches is expected and welcome
- Laboratories have dedicated facilities and expertise for designing, fabricating, qualifying, and interpreting advanced instrumentation





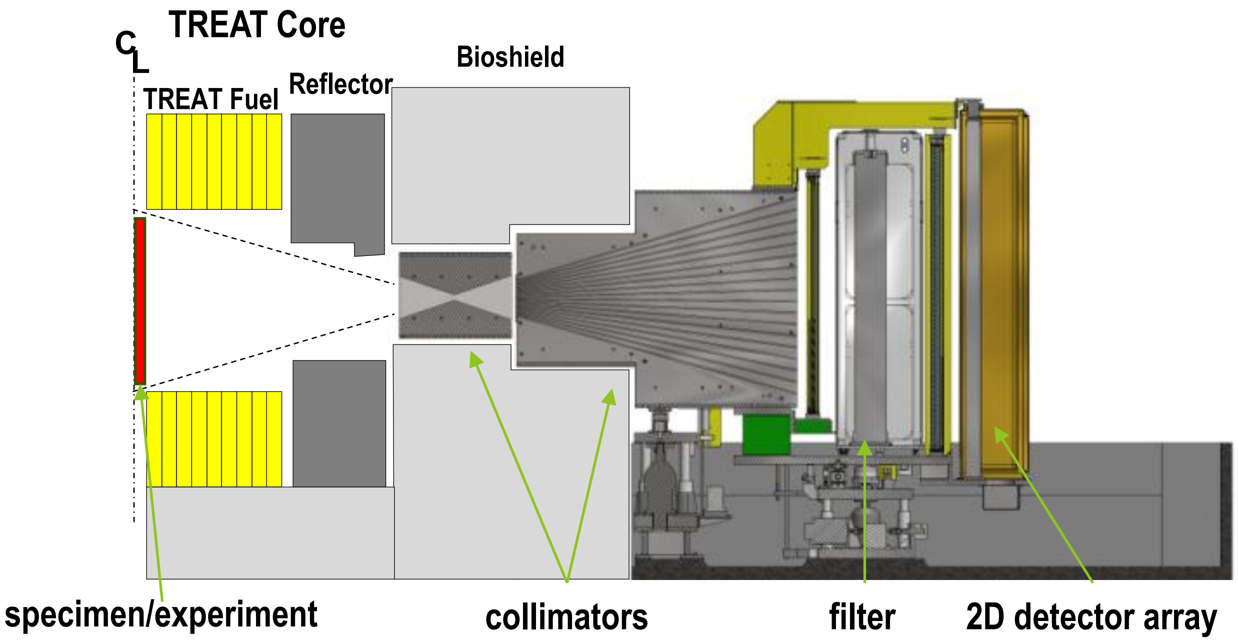
In-situ data using advanced instrumentation

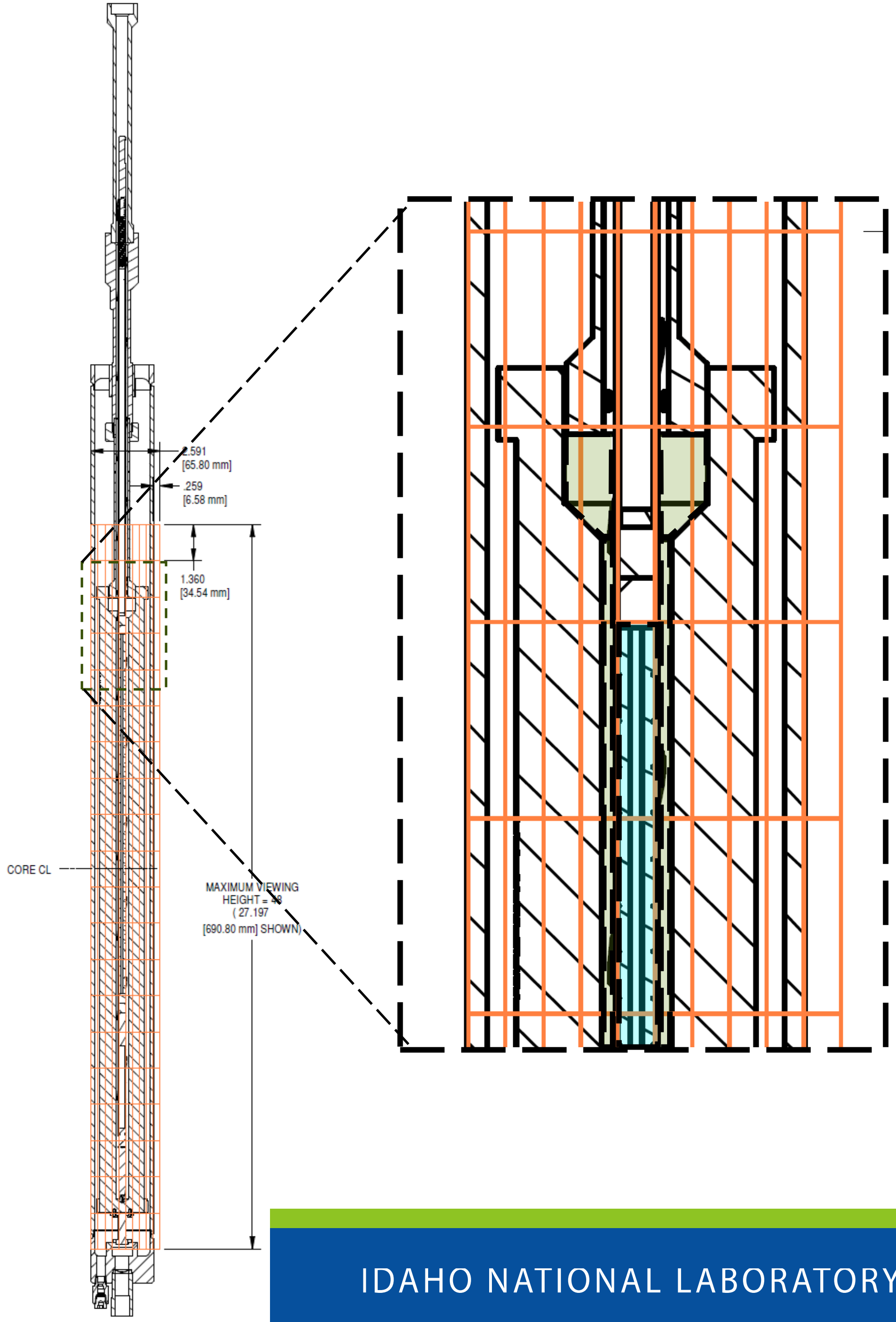
Out-of-Pile Characterization

In-Pile Characterization

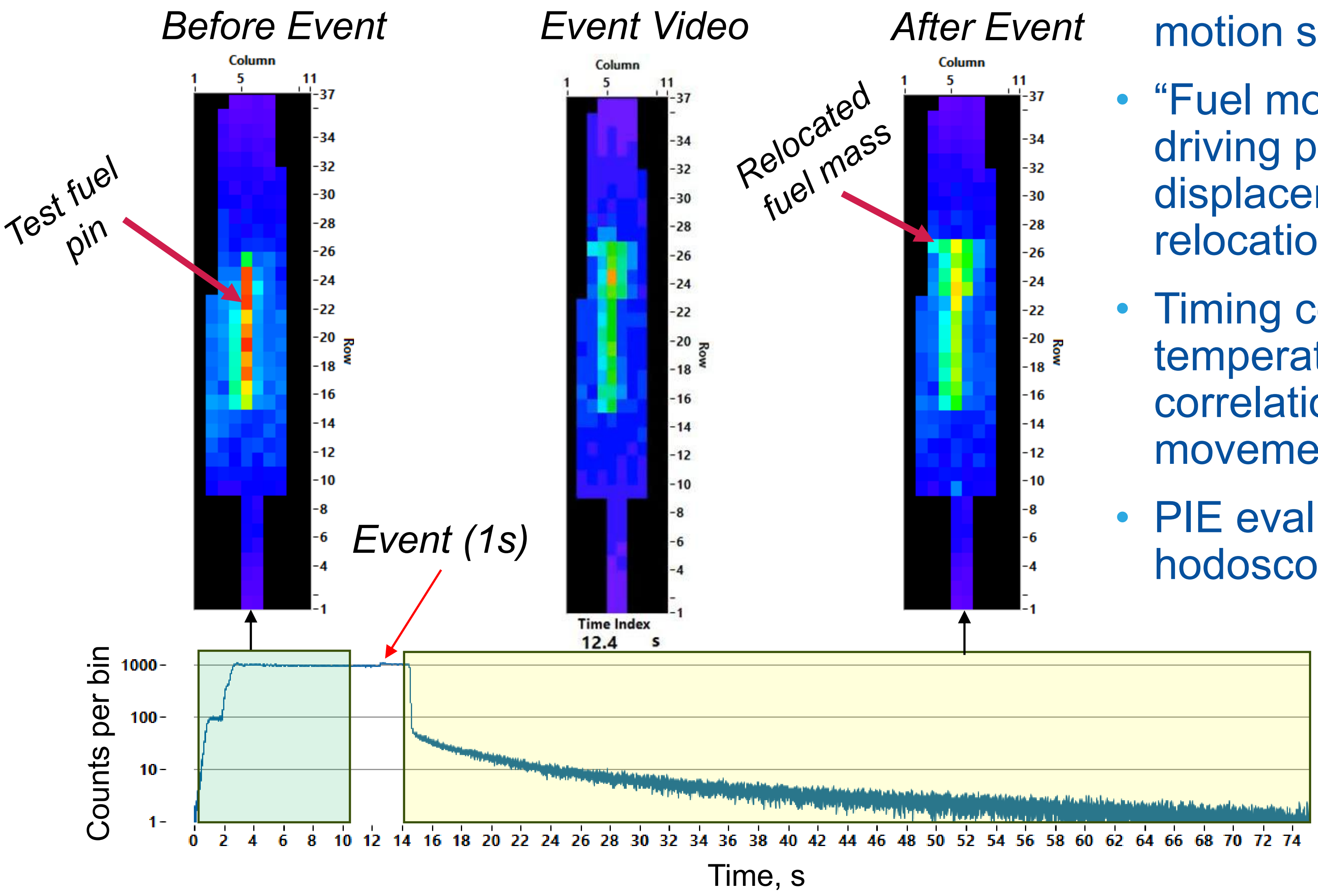
TREAT Hodoscope

- TREAT Fuel Motion Monitoring System “hodoscope”
  - Fission-born fast neutrons (primarily emitted by test specimen) detected to create 2-dimensional time-resolved experiment “image”
    - Detectors are proton scintillators (ZnS)
  - Recent upgrades include expansion from 96 to 192 detectors (360 slots available) via NSUF support
    - Each pixel is approx. 9.35 mm x 33.05 mm





TREAT Hodoscope Results Example



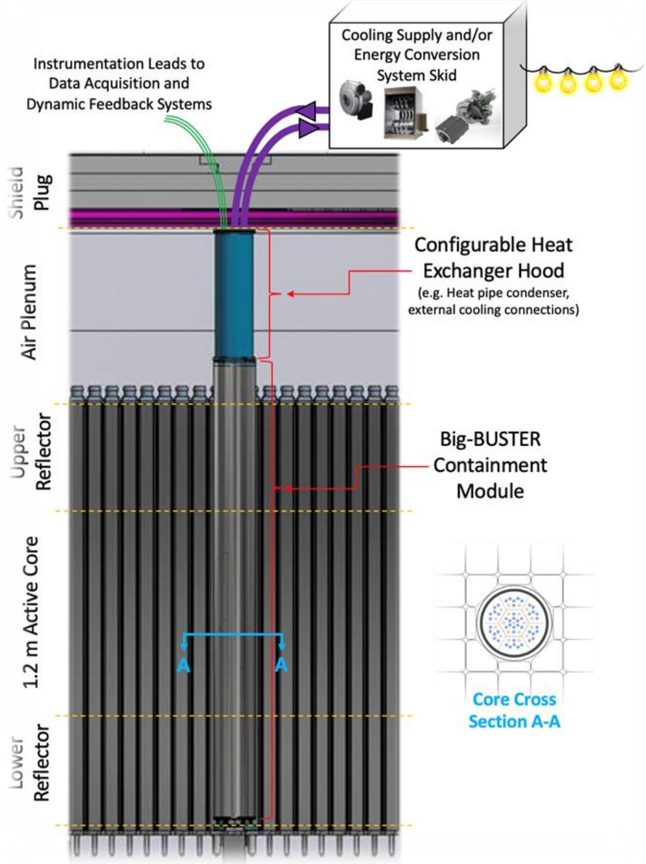
Total Detector Counts over time

- Hodoscope results indicate significant fuel motion started near 12.4 s
- “Fuel motion” could be caused by several driving phenomena (bowing, gas driven displacement, molten/fragmented fuel relocation, sodium vapor driven effects, etc)
- Timing correlates with changes seen in the temperature response, no observed correlation of acoustic event to fuel movement, temperature responses
- PIE evaluations are key to unraveling hodoscope puzzle

Non-Traditional Applications of the TREAT Facility

(Beyond Transient Testing Nuclear Fuels)

- Fission effects on material properties
- Nuclear materials under extreme conditions (very high temperature properties and behaviors)
- Dynamic multiphysics instrumentation testing and model benchmarking
- System-scale core component testbed with nuclear heating
  - Non-safety category automatic reactor control system



NIMBLE Concept

Reactor Core Component System Testbed

TREAT User's Guide

- Published reference including facility overview, experimental capabilities
- Experiment information contact:
  colby.jensen@inl.gov, Program Technical Lead
  nicolas.woolstenhulme@inl.gov Experiment capability lead
  todd.pavey@inl.gov, Program Manager
- Acknowledge support from DOE Office of Nuclear Energy NE-3, NE-4 (Advanced Fuels Campaign Program), and NE-7 (Advanced Sensors and Instrumentation and Nuclear Science User Facilities Programs) for TREAT operations and experimental capabilities development