Transient Testing Instrumentation Needs

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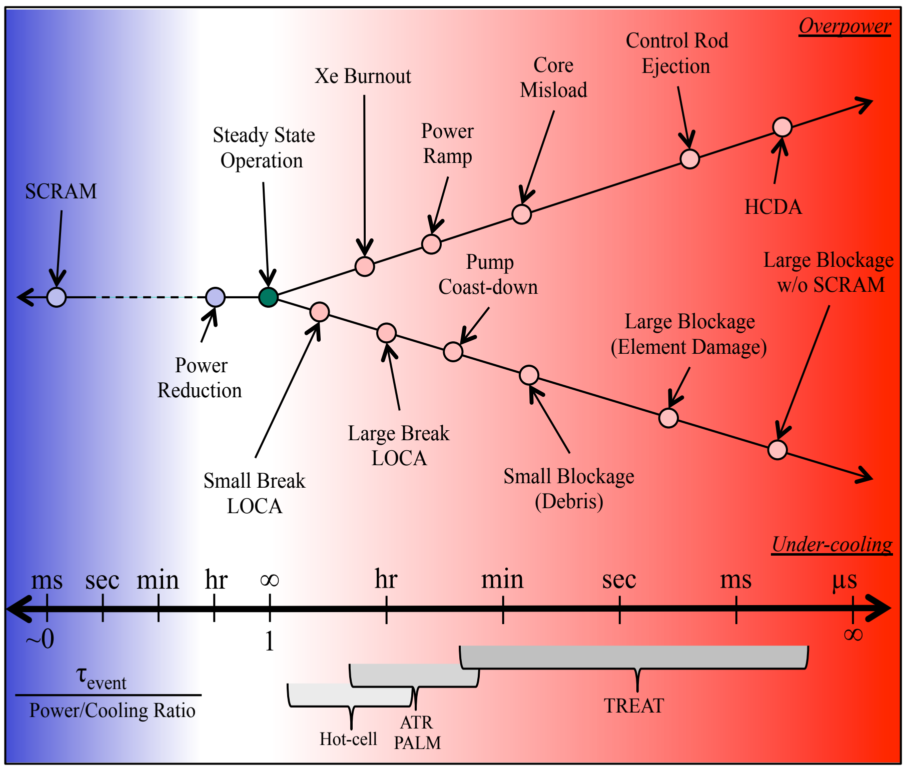
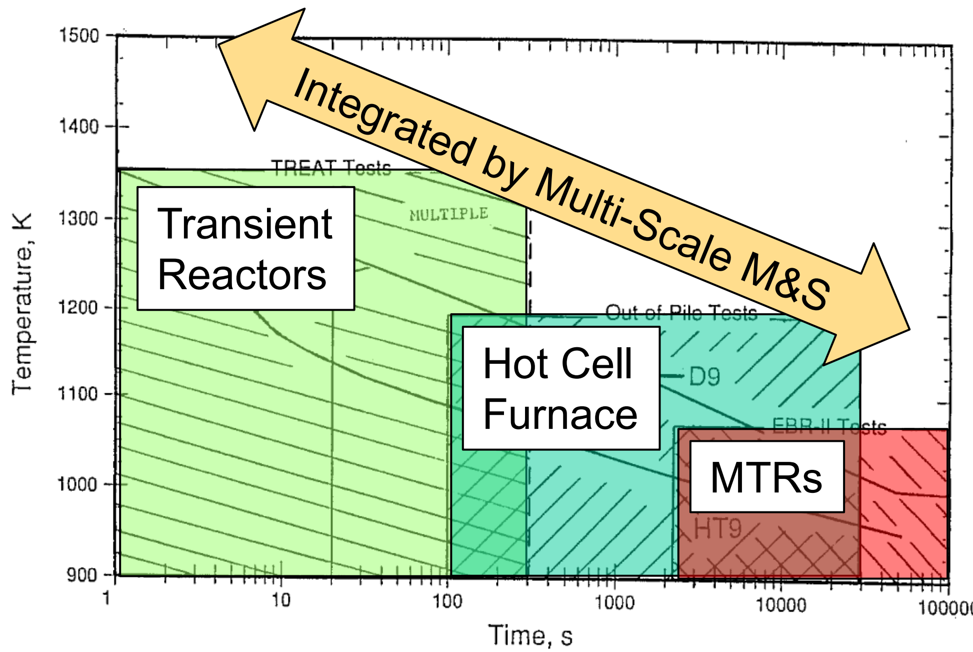
Idaho National Laboratory

Fuel Safety Research

- **Objective:**

  Conduct the experimental activities required to help the industry describe how fuel systems respond to relevant transients (both operational and off-normal)

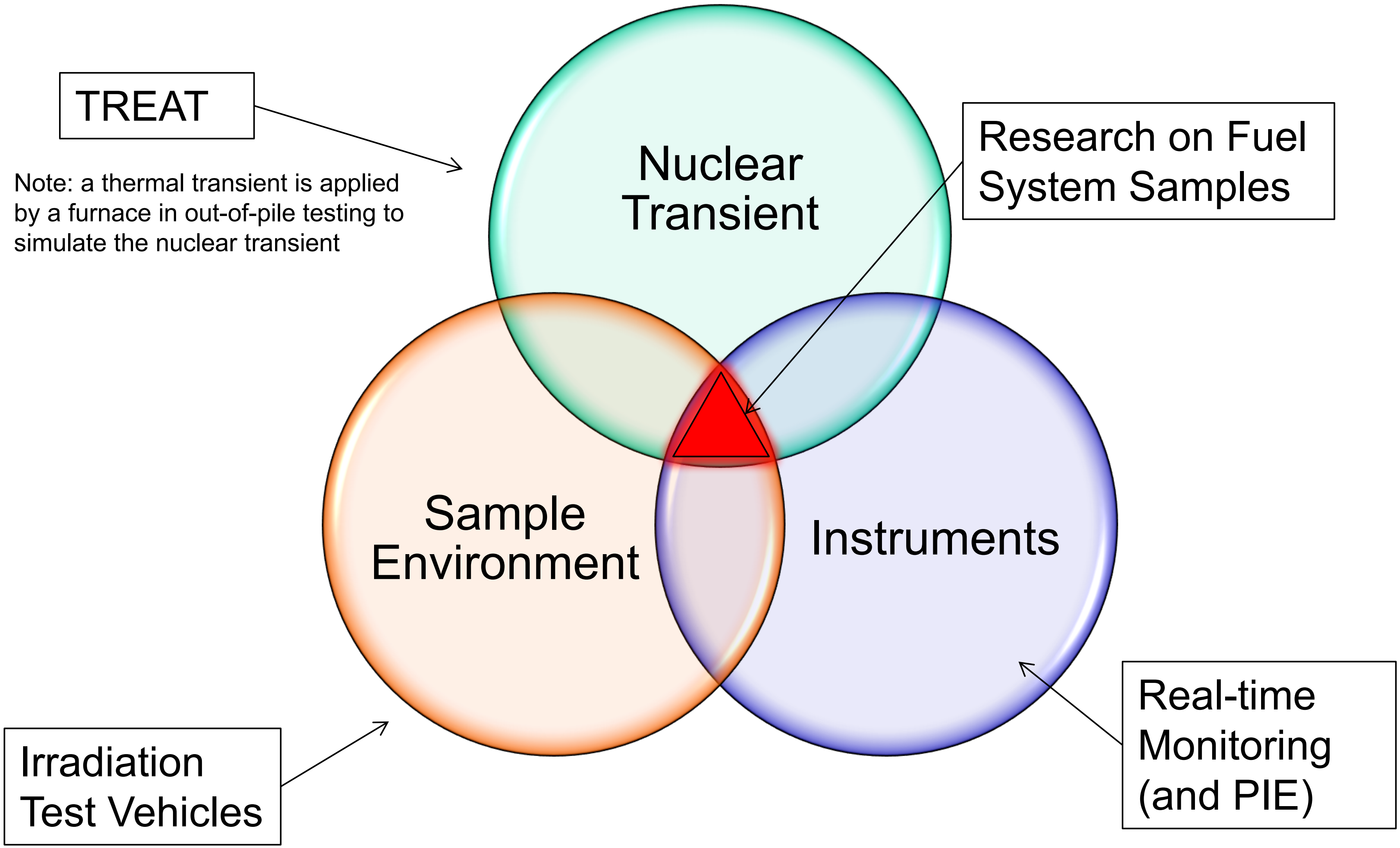




Active Fuel Safety Research Areas

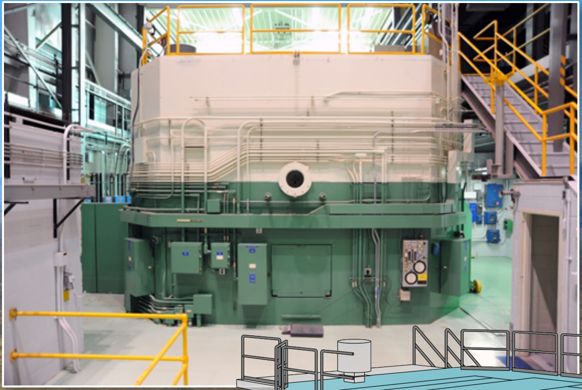
- Optimization of LWR Fuel Technology
  - Improved fuel safety criteria (power uprates, improved reactor protection strategies, …)
  - LWR fuel burnup extension
  - Accident tolerant fuels
- Enabling Advanced Reactor Technology
  - Establish fuel safety criteria for new reactor types including liquid metal, gas, or molten salt reactors for power production, neutron science, space propulsion, etc.
- Fuel Behavior Science
  - Separate effects tests to improve fundamental understanding of material behavior using short tem, dynamic irradiation

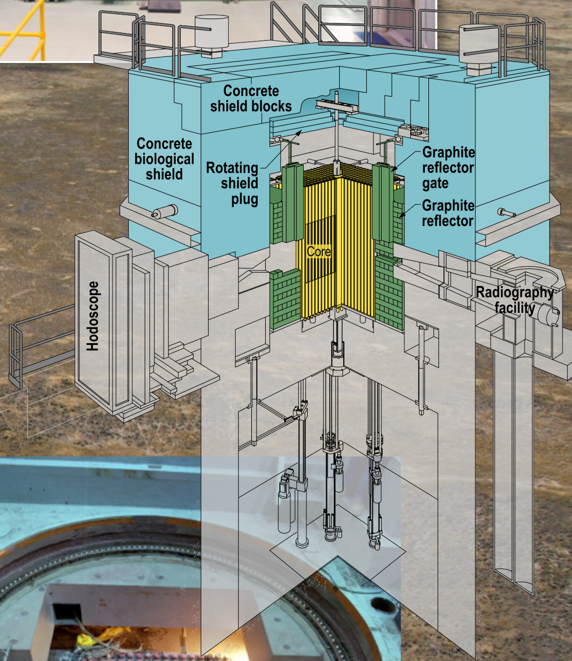
Scientific Instruments for Fuel Safety Research

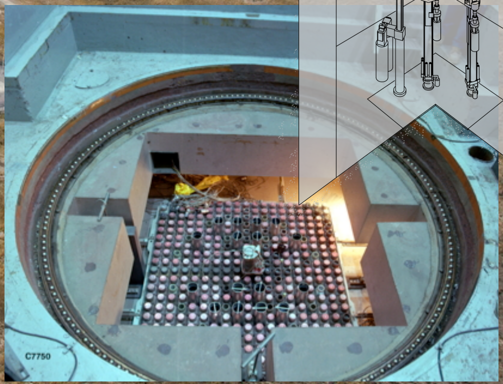


Transient Reactor Test Facility (TREAT)

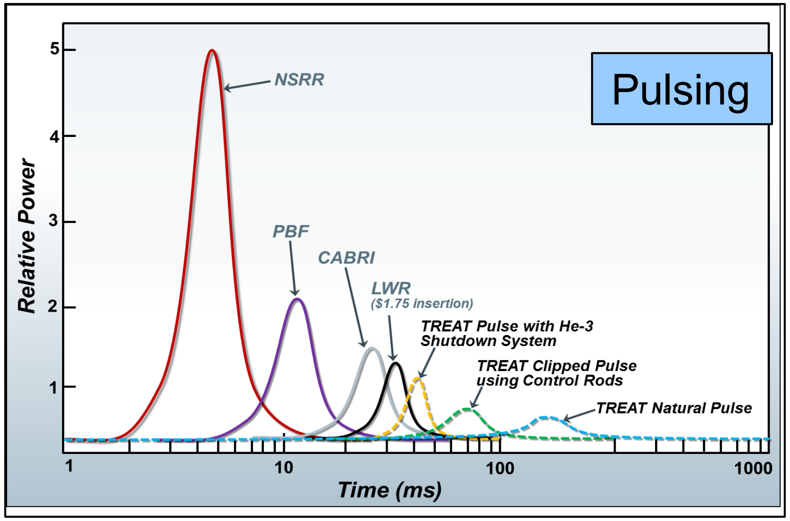
- **TREAT's unique design delivers the nuclear environment required to meet fuel safety research needs**
  - Core: ~1.2 m high x 2 m. diameter, 19 x 19 array of 10 x 10-cm. fuel and reflector assemblies
  - Fuel: 0.2 wt.% high enriched UO_2 dispersed in graphite
  - Instantaneous, large negative temperature coefficient (self protecting driver core)
  - Air-cooling system for decay heat removal (dry core)
    - 100 kW steady-state operation
    - Allows unique instrumentation access to the core
  - Computer controlled, hydraulically-driven transient rods
    - Allows for flexible power shaping delivery of 2500MJ max available core energy
- **Resumption of Operations**
  - TREAT put in operational standby in 1994 – ending 40 years of transient testing of nuclear fuels in U.S.
  - *'Mission Need Statement for Resumption of Transient Testing'* issued by DOE in January 2010
  - TREAT Selected as *'preferred option'* in February 2014 and restart activities were initiated at the beginning of FY15
  - Commitment to restart by the end of 2018 (to support the Accident Tolerant Fuels Program)
  - First operations anticipated in November this year!



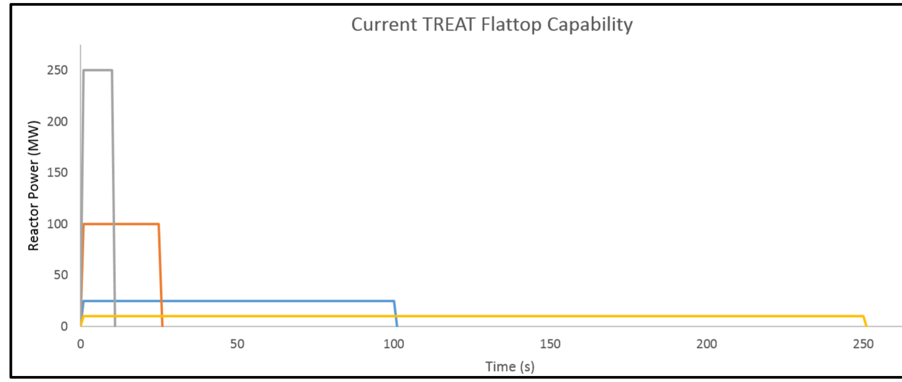




TREAT Power Transients

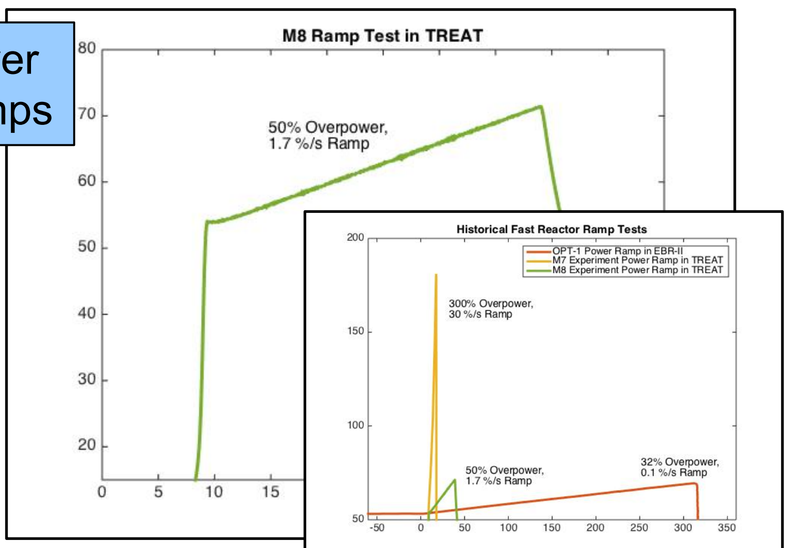


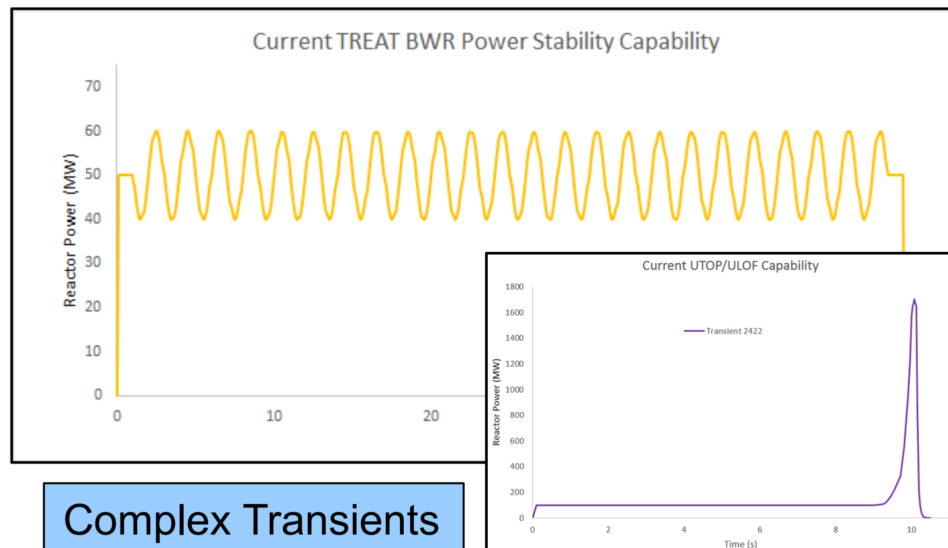
Pulsing



Continuous Power (e.g. 'Flattop')

Power Ramps



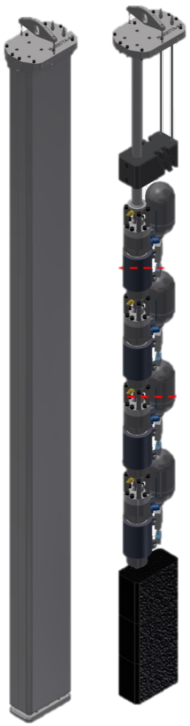


Complex Transients

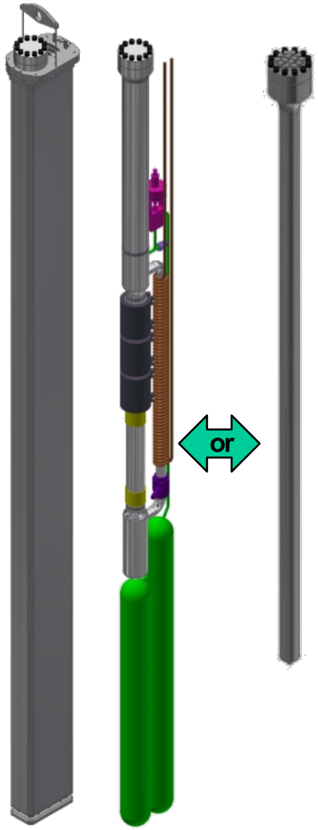
Fuel Safety Testing

Experimental Devices of the Next Generation

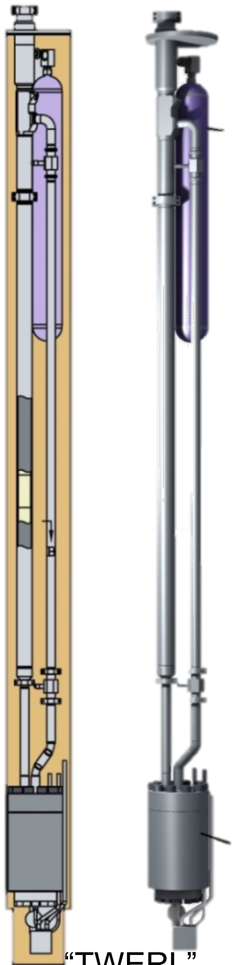
- Current TREAT device development



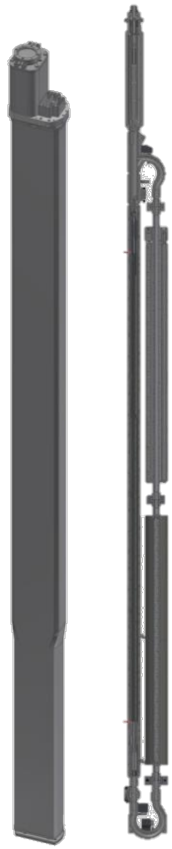
"Multi-SERTTA"
Multi-Vessel Static PWR water Capsule, Various coolants /thermal conditions



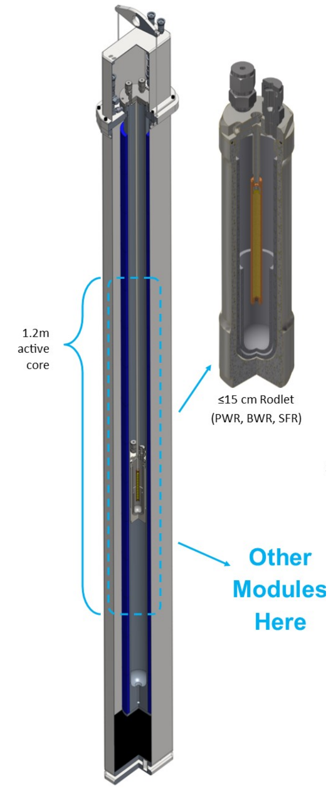
"Super-SERTTA"
Large, Single Vessel Capsule, RIA/LOCA, UTOP, Various coolants /thermal conditions



"TWERL"
PWR Flowing Water Loop



"Mark-IV"
Flowing Na Loop (based on historic TREAT design)



"MARCH"
Modular capsule system to support a variety of simpler, cheaper testing

Experiment Instrumentation

- Car crash testing analogy…

Pre-test

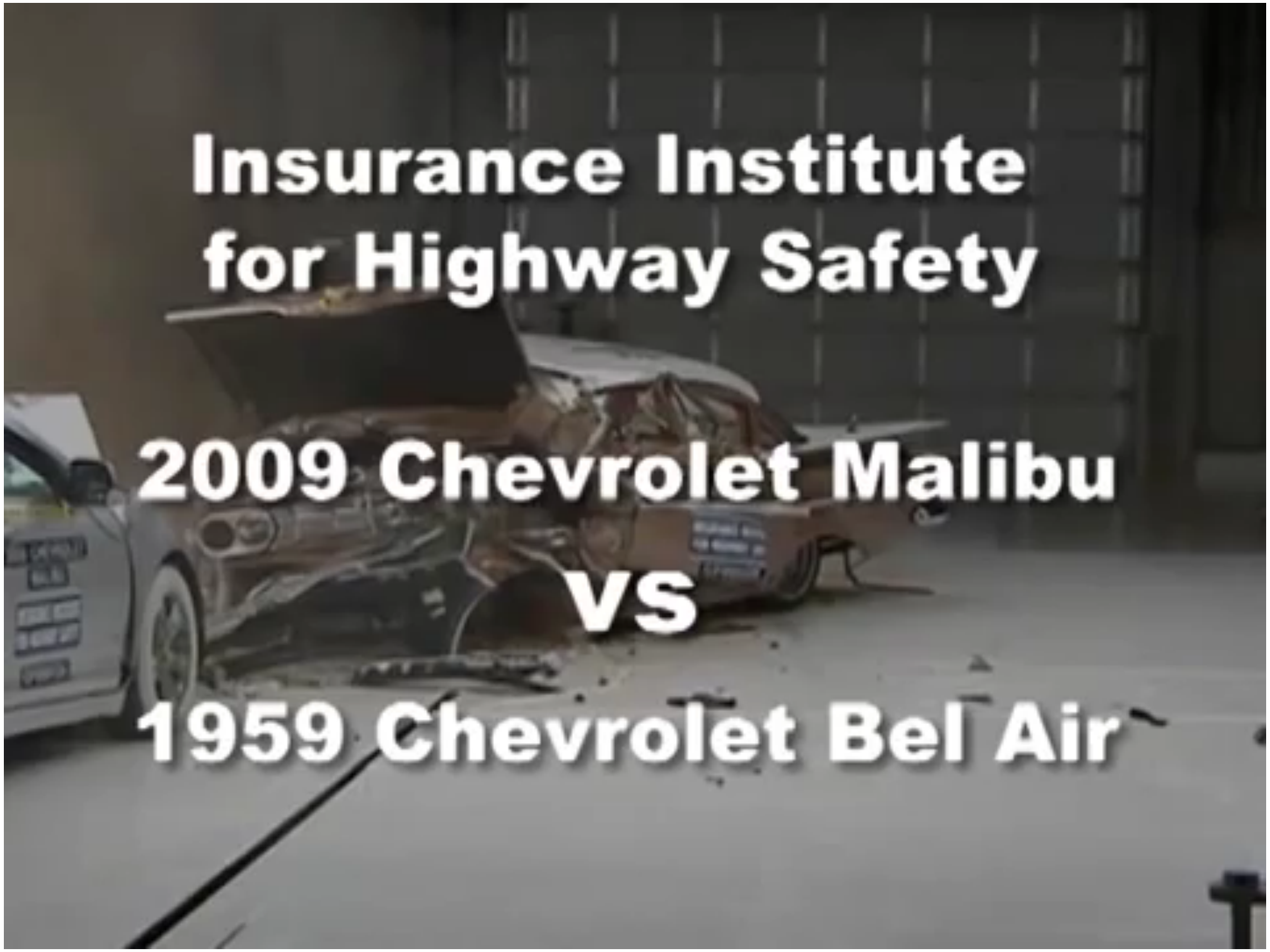
“State 1”

Post-Irradiation

“State 2”

Experiment Instrumentation

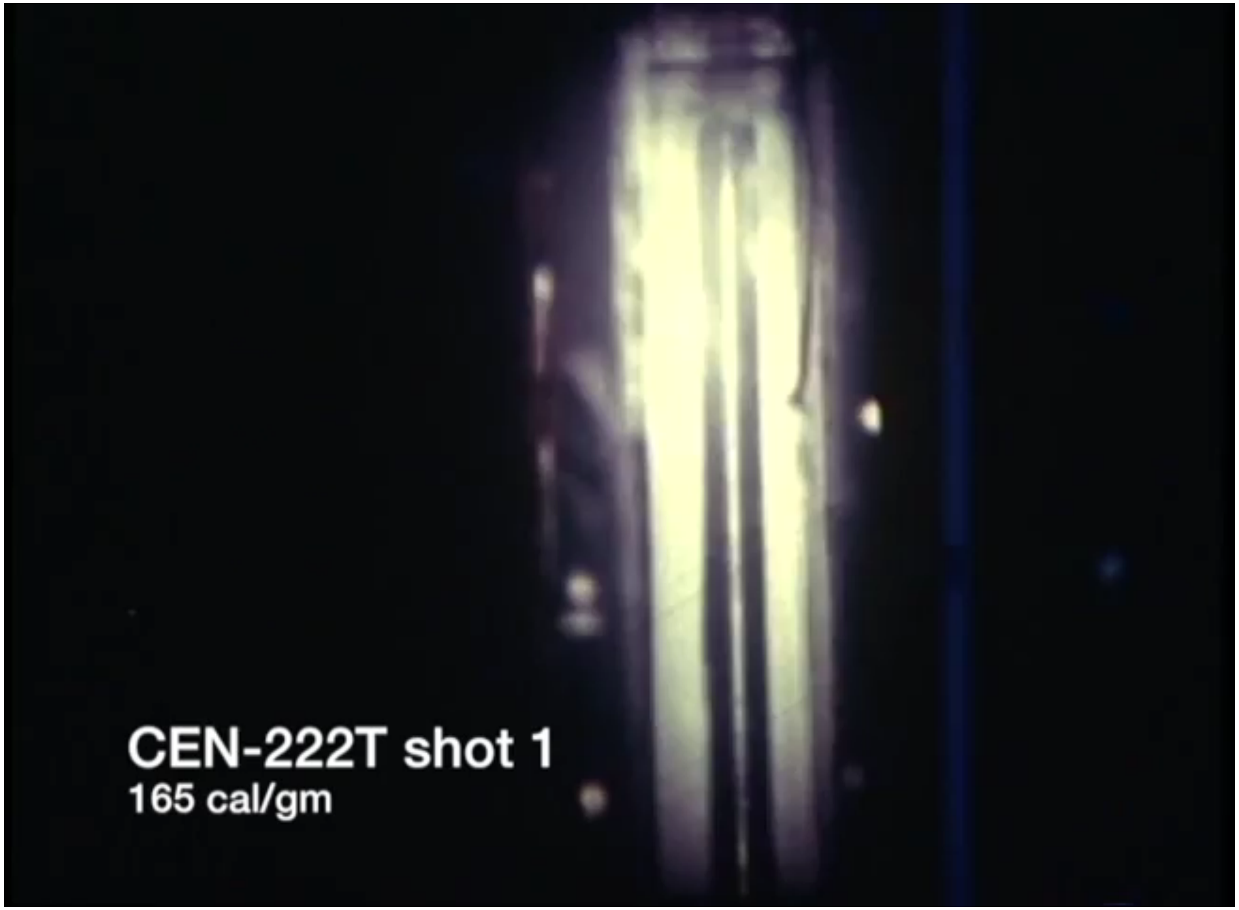
- Car crash testing analogy for transient testing



https://www.youtube.com/watch?v=fPF4fBGNK0U

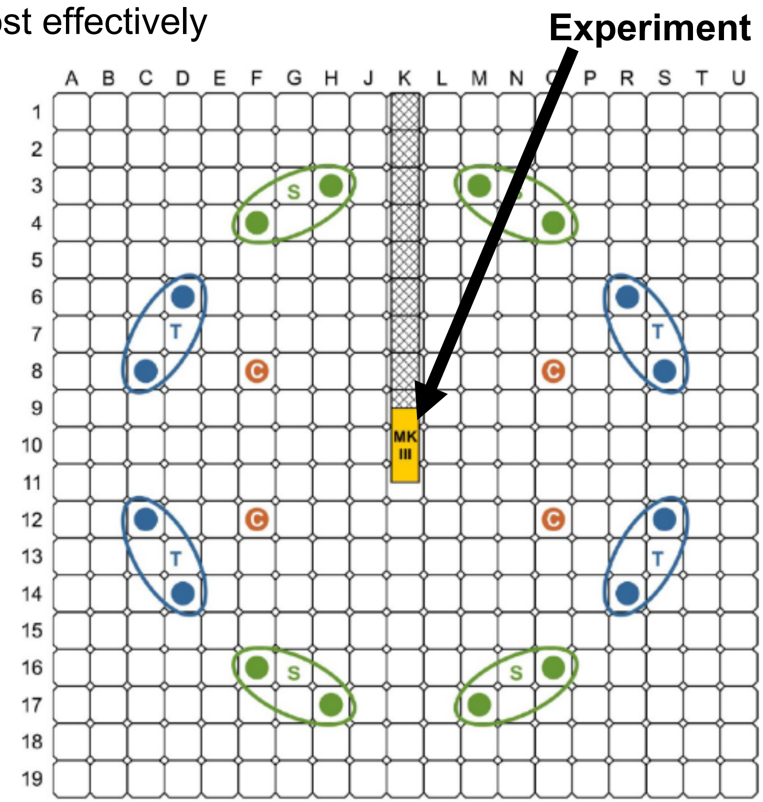
In-Pile Video of Fuel Behavior at TREAT

- Compare previous video with high speed video testing of LWR fuels in a windowed water capsule at TREAT from the mid-1960’s



Characteristics of Transient Testing at TREAT

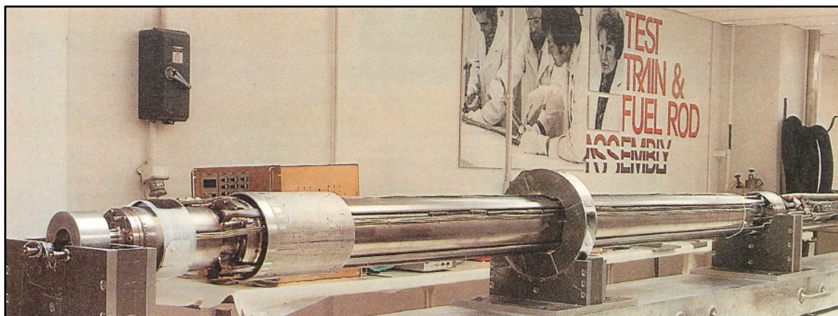
- Primary historical mission supported sodium-fast reactor testing
- TREAT is well suited to **self-contained, package-type, drop-in test devices**
  - Installation, testing, and withdrawal in a matter of days - enables support for rapid transition between different-environment test devices (e.g. Na, H_2O, gas)
  - Effective approach to test many pins quickly and cost effectively
- Examples of historical instrumentation objectives: time and location of first cladding failure; time-dependent axial growth; fuel relocation; coolant dynamics, phase, temperature, and pressure
- **Experimental coupling with the reactor** - trigger reactor scram at failure or trigger power burst upon Na voiding using experiment instrumentation
- **Fuel-motion monitoring critical to transient testing**
  - High-speed video in transparent capsule (previous slide)
  - Fast-neutron hodoscope (later slide)



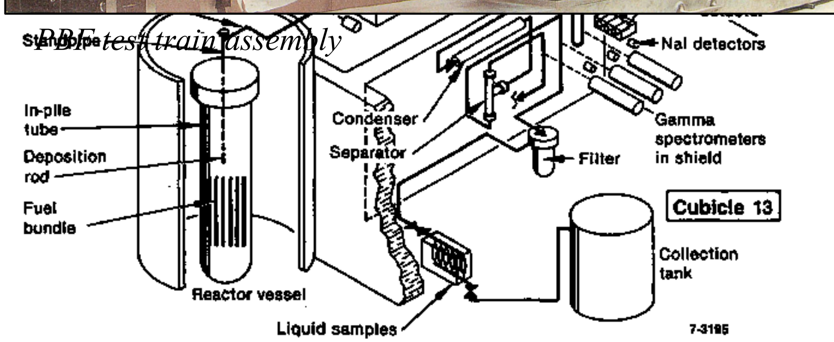
TREAT Core Layout

Experiment Instrumentation

- Experiment integration is non-trivial from:
  - Integral to experiment test trains
  - To externally integrated systems; for example, hodoscope (next slide), fission product monitoring

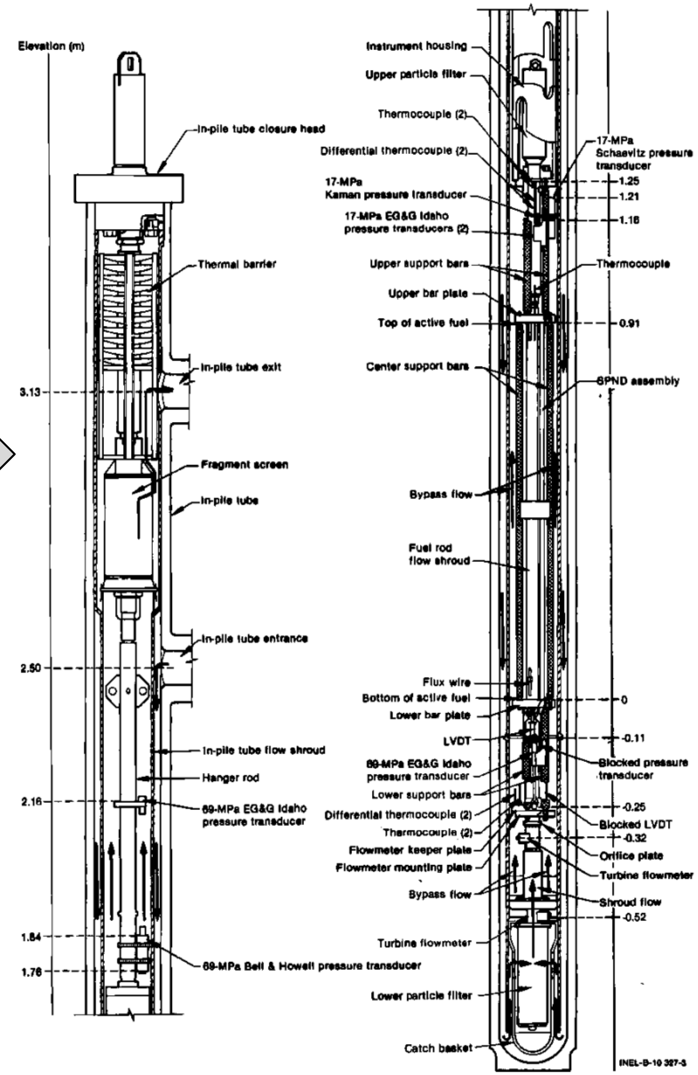


PBF test train assembly



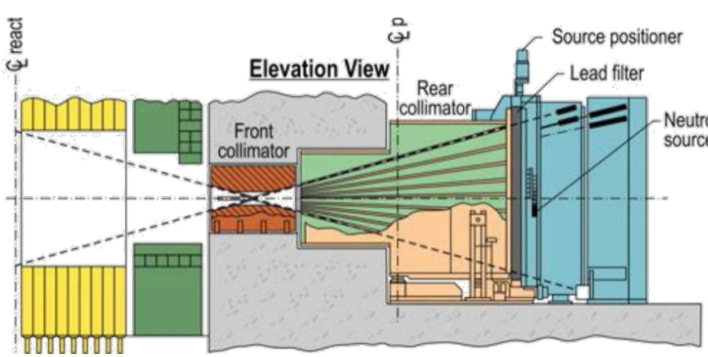
Fission product sampling and monitoring system from PBF

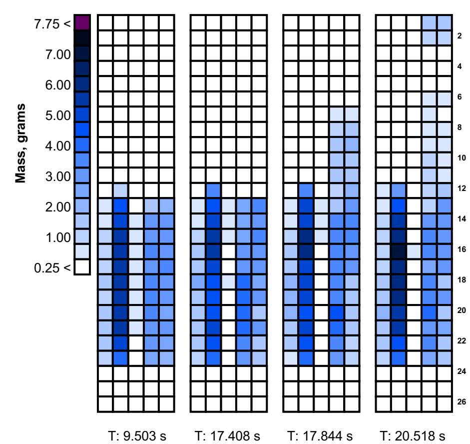
Instrumentation for PBF test train for LWR



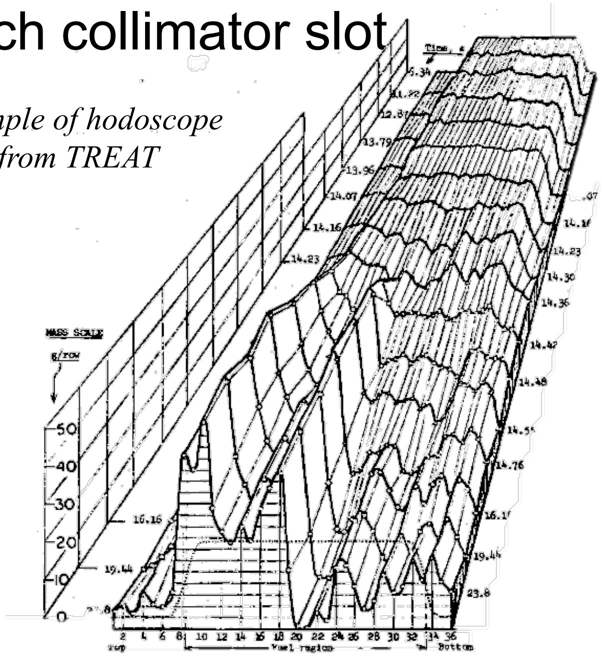
Experiment Instrumentation

- TREAT Fuel Visualization and Motion Monitoring
  - Fast neutron hodoscope is a key capability for monitoring fuel motion during a transient
  - Fission-born fast neutrons emitted from the specimen travel through the experiment containment wall, through a collimator, and into a detector array
  - Provides pixelated view of fuel mass in each collimator slot





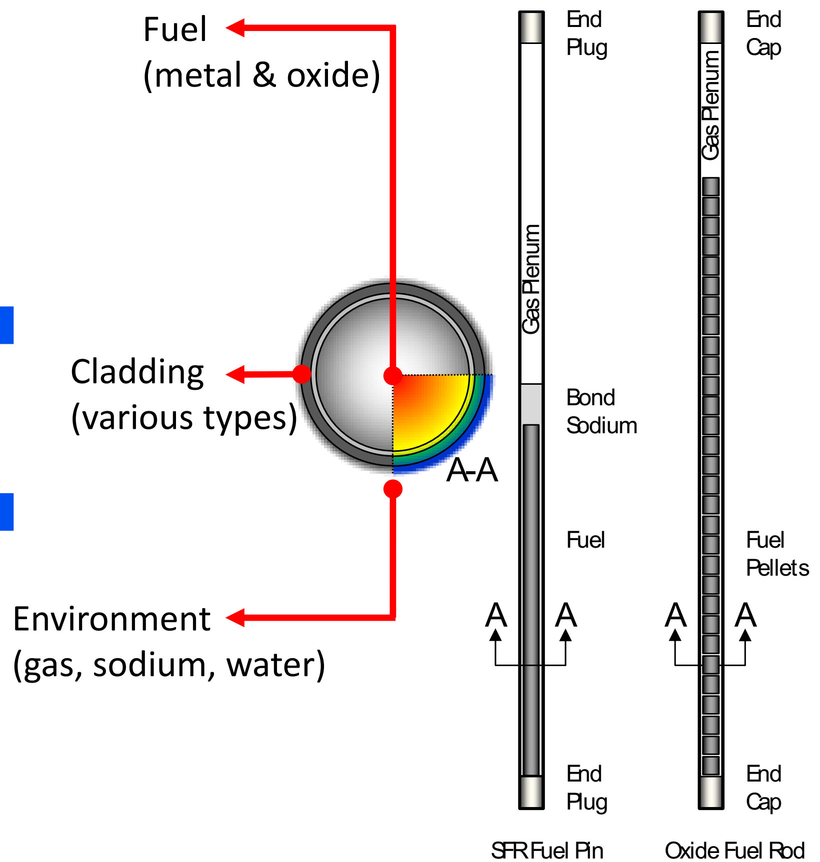
Example of hodoscope data from TREAT



Experiment Instrumentation

- Key measurement target areas:
  - Energy Deposition/Flux
  - Temperature
  - Mechanical Behaviors
    - Fuel deformation and movement*
    - Coolant dynamics
  - Fission Product Transport*
  - Material Properties
  - Microstructural/Chemical

*Priority target areas for instrumentation development



Instrument target locations for representative fuel designs for SFR and LWR systems

Instrumentation Challenges and Opportunities

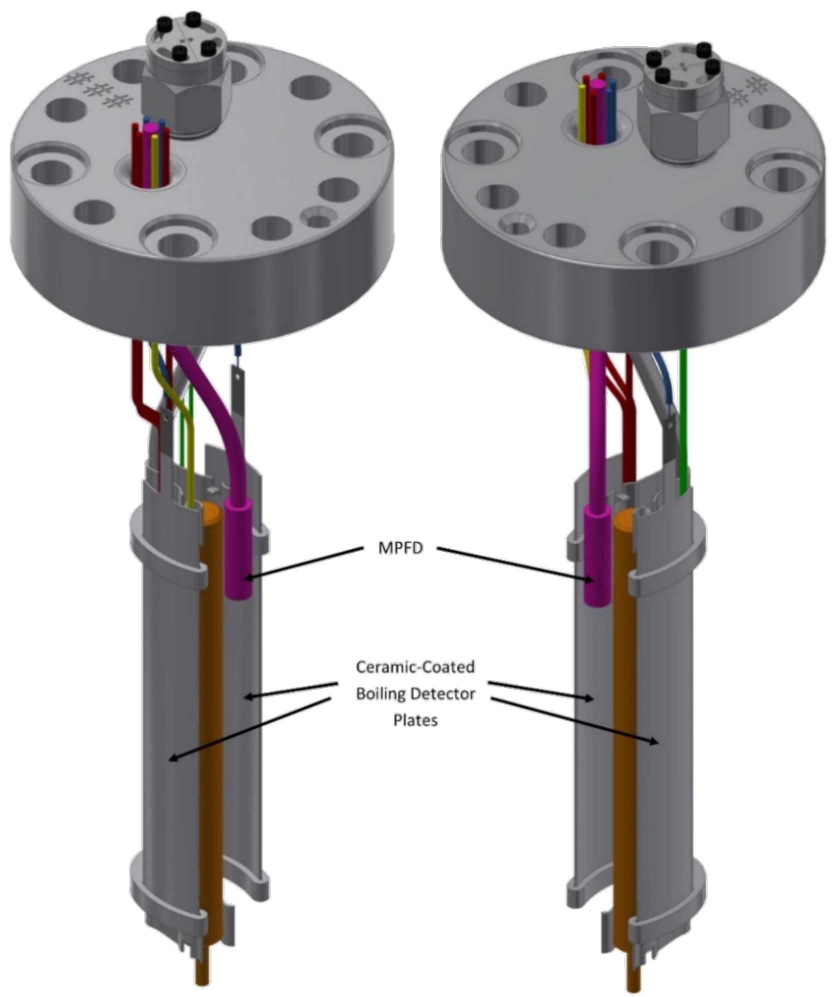
- **Visualization** – imaging techniques; e.g. advanced hodoscope, visible & IR videography (e.g. boroscope technologies), microstructural visualization
- **Environment resistance –** irradiation, temperature, pressure, material compatibility
- **Non-intrusive –** non-contact, non-destructive
  - **Miniaturization -** facilitates proximity to specimen and experiment integration
  - **Remote application –** facilitate installation onto pre-irradiated specimens
- **Electronics** – in-core options, signal conditioning, ADC, enable more signals to/from experiments
- Adaptation of existing technologies to experimental constraints
  - **Hot-cell** implementation considerations (non-contact, easy alignment, etc.)

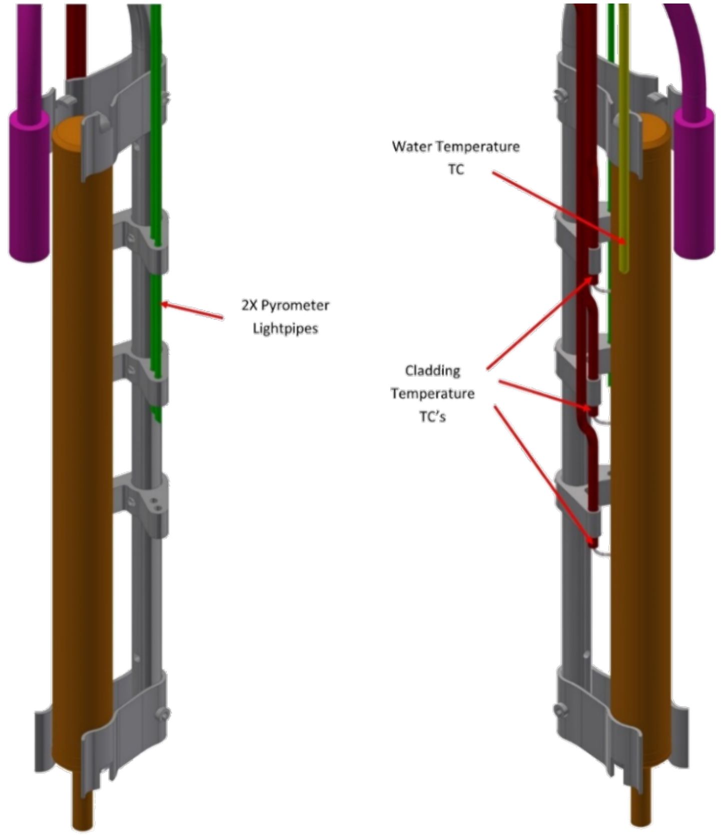
Critical Instrument Considerations

- Important differences from steady-state irradiation experiments (ATR, HFIR):
  - Neutron damage *nearly negligible* in transient testing
  - Gamma heating is very high during big pulses, volumetric fission heating can be enormous if sensor includes fissile material
  - Instrument response time (and data capture time) usually critical
  - TREAT provides easier access and more flexibility to the experiment location (dry core)
  - One-time-use instruments expected
  - Gamma background rather low, except when close to pre-irradiated experiment specimens (hot-cell implementation)
  - Instrumenting pre-irradiated fuel (hot-cell) is critical to transient testing programs
- Many of the same constraints still apply (not comprehensive):
  - Most test trains are severely limited on space, wire routing can be difficult, still a variety of options for wiring easier when integrated into initial experiment design, facilitated by "flexible wires" (fragile fibers difficult)
  - Must fit within the assumptions of experiment safety package
  - Hermetic penetration (and high-pressure/temperature penetration) common for anything passing into primary containment

Instrumentation Design for ATF RIA Experiments

- Static water capsule at PWR conditions
- Significant instrumentation capability
- Probable single test use instruments
- Current program development is focused on deployment of these instruments





Collaborations for Instrumentation

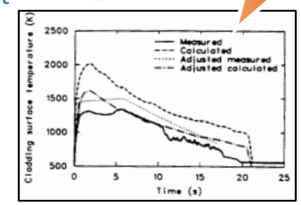
- NEUP/NEET Projects
  - Advanced Instrumentation for Transient Reactor Testing IRP – **UW, Ohio St, Kansas St, Idaho St**, INL
  - Benchmarking for Transient Fuel Testing IRP – **Oregon St, UMich, MIT**, INL
  - A Transient Reactor Physics Experiment with High Fidelity 3-D Flux Measurements for Verification and Validation – **Kansas St, UW**
  - Ultrasonic Sensors for TREAT Fuel Condition Measurement and Monitoring – **PNNL**, INL
- Programmatic Instrument Development
  - Pyrometer - **Utah St**
  - Void sensor – **Utah St, U of New Mexico**
  - Micro-Pocket Fission Detector (MPFD) – **Kansas St**
- International collaborations
  - **IRSN** (France), **CEA** (France), **Halden** (Norway), **NNC** (Kazakhstan)
- Continue to grow…

Instrument Development & Qualification

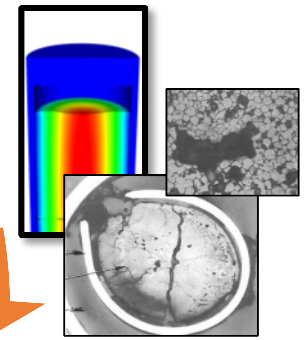
- High Temperature Test Laboratory (HTTL) is testbed
- Primary challenge is the integration of instruments into a test device and demonstration of interfaces and instrument performance

Instrumentation Engineering Process for TREAT Experiments

Operation
- Development Closeout
- Continued Support



R&D Input
- Fuels (other) Programs
- Assessments & Studies
- Review of Alternatives



Conceptual Formulation
- Facility & Experiment Constraints
- Proof-of-concept testing

Design & Demonstration
- Conceptual-to-final design
- Engineering Development
  - Experiment Integration
  - Refinement & Optimization
  - Characterization & Testing
  - Uncertainty Quantification

Acceptance
- Testing in TREAT
- Experiment Integration
- Implementation Support

Summary

- TREAT has a long history of performing transient irradiation experiments on nuclear fuels and materials and will soon be restarted (within months!)
- Priority test environments and experimental focus are currently overpower and undercooling events for Light Water Reactors and Sodium-cooled Fast Reactors.
- TREAT provides unique in-pile instrumentation access
  - Transient in-pile experiments employ *significant* instrumentation
  - *Wide* range of experimental configurations and environments
  - Fast response rate often required for instruments
  - Short-duration, high-peak neutron flux
  - Nuclear heating in materials can be significant
- Important near-to-medium-term challenges will be adaption/qualification of existing instrument technologies Next generation of sensors is needed
- INL's HTTL laboratory is the center of instrument development and qualification
- Encourage instrument testing in TREAT
- INL Transient Testing team can help! (needs & constraints)

Transient Testing Contacts:

- **Daniel Wachs – National Technical Lead for Transient Testing**
- **Nicolas Woolstenhulme – TREAT Experiment Design Lead**
- **Colby Jensen – TREAT In-Pile Instrumentation Lead**
- **David Chichester – Hodoscope Lead**

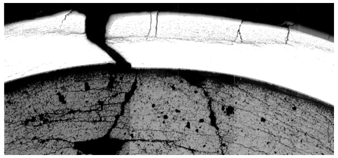
State-of-the-Art Instrumentation for Transient

Key Measurements	Transient Testing Instrumentation
Energy Deposition/Flux	passive dosimetry, SPND, miniature fission chambers
Temperature	thermocouples
Mechanical Behavior & Pressure	hodoscope, LVDT-based elongation and pressure transducer, strain-gauge pressure transducers, ultrasonics for boiling
Fission Product Transport	
Material Properties	
Microstructural/Chemical	

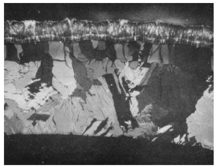
*Not ready for deployment in U.S.

Important Transient Fuel Behavior

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

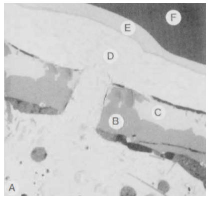


Cladding failure at hydride blister, NEA-6847

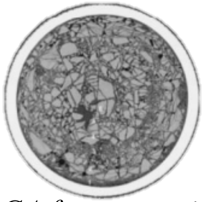


Cladding oxidized at LOCA conditions, NEA-6846

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



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

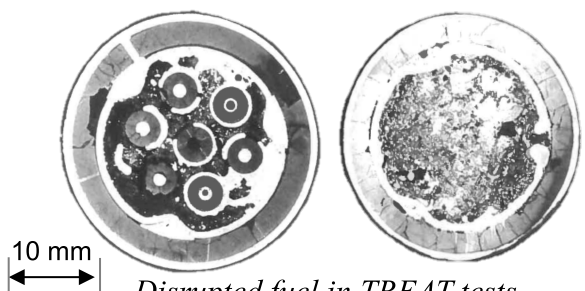


LOCA fragmentation, NEA/CSNI/R(2016)16

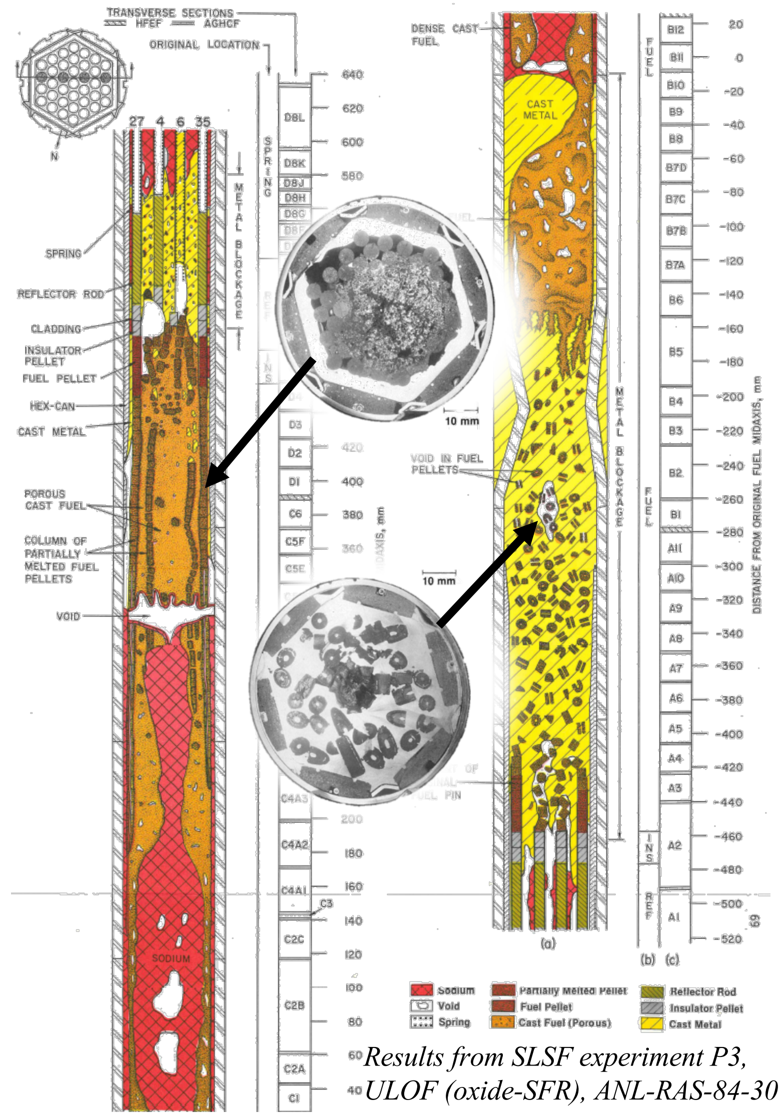
Important Transient Fuel Behavior

- 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