Experiment Instrumentation for Transient Testing

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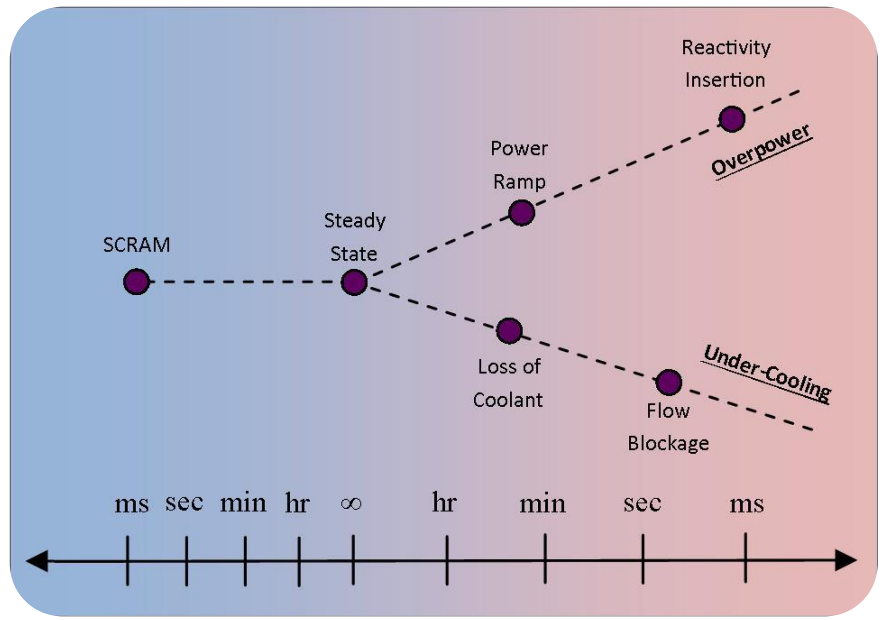
Introduction to Transient Testing, TREAT, and Current Experimental Efforts

What is Transient Testing?

- **Transient testing** is like car crash testing for nuclear fuel
  - Demonstrate **performance** phenomena and **limits** for fuel development and reactor design
  - Show consequences of hypothetical accidents for licensing

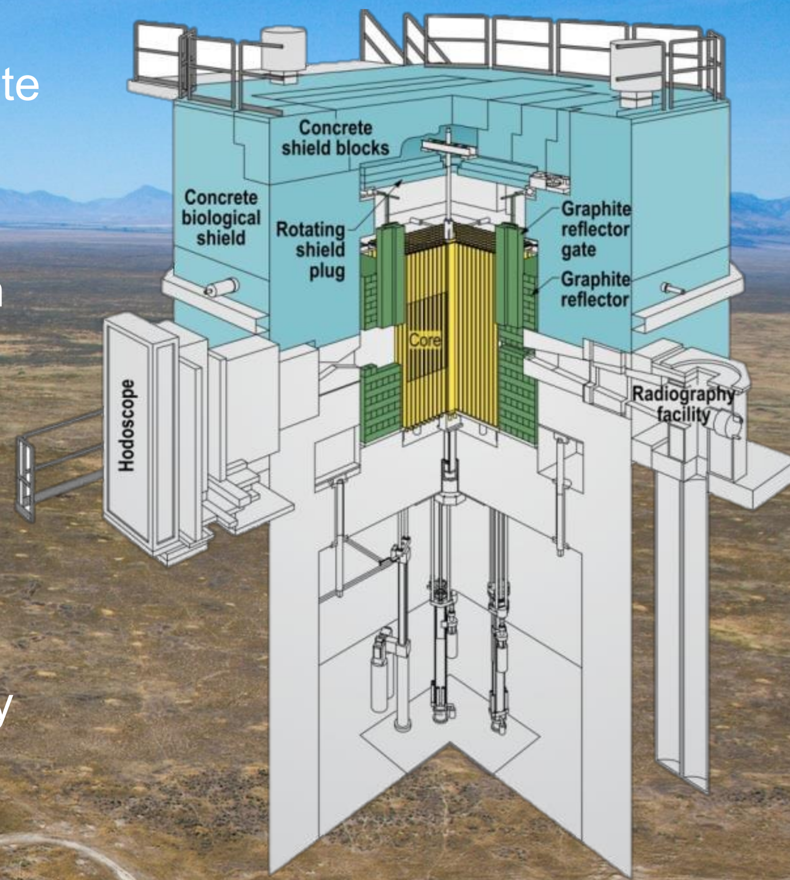
- Transient testing is the study of fuel and fuel system behavior under **power-cooling mismatch** conditions
  - Short timescale events need to be simulated with rapid nuclear heating
  - Nuclear heating provides prototypic heat transfer conditions

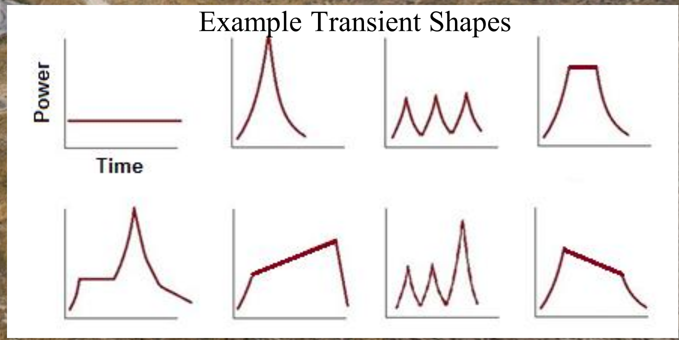


Slide Courtesy of Nicolas Woolstenhulme

Transient Reactor Test Facility (TREAT)

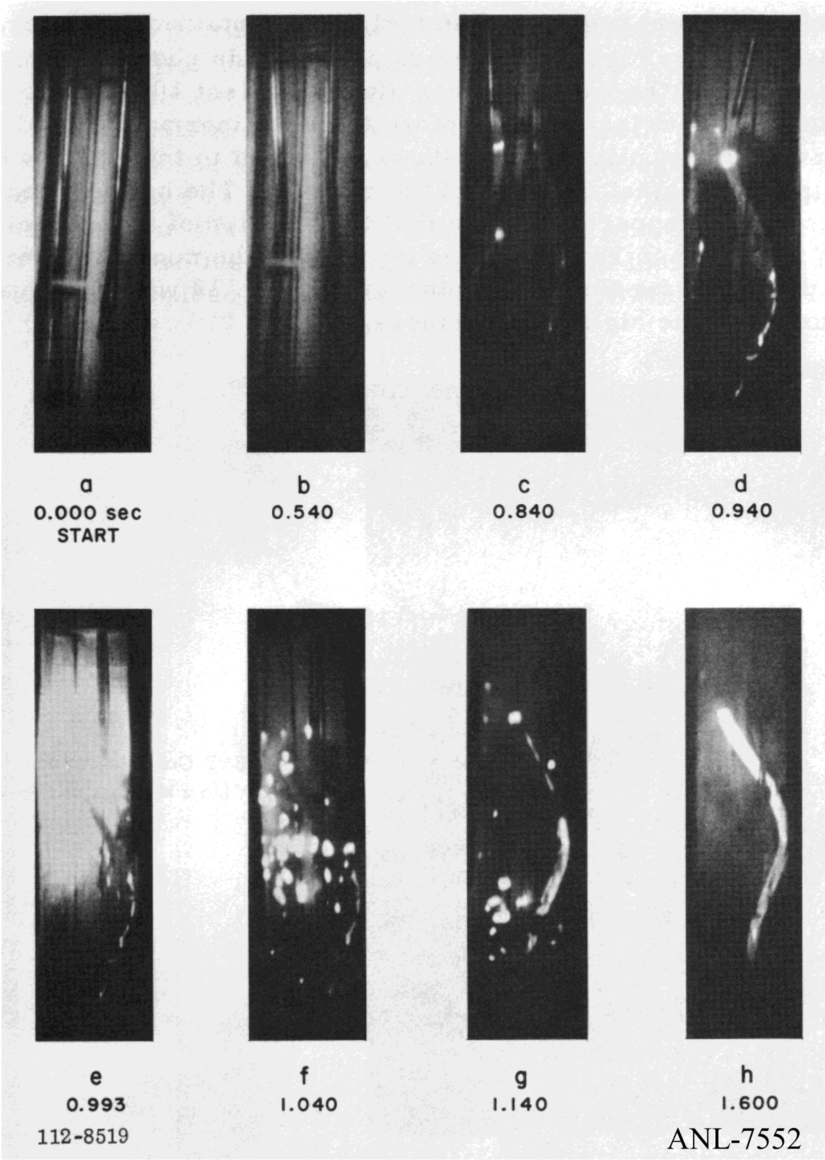
- TREAT core design:
  - Zircaloy-canned blocks of urania dispersed in graphite
  - Strong negative temperature coefficient, self-limiting
- Experiment displaces fuel assemblies
  - Each fuel assembly is 10cm × 10cm in cross section
  - 1.2m of active core length
- Air-cooling system for decay heat removal
  - 100kW steady-state operation
  - Not a required safety system
- 4 slots with view of core center, 2 in use
  - Fast neutron hodoscope, neutron radiography facility
- Hydraulically-driven transient rods
  - Allows for precise and flexible transient shaping
  - 2500MJ max core energy in prompt burst (<1 sec)
  - 2900MJ max core energy in shaped mode (up to ~5 min)
- On schedule for operation in 2018 and maybe sooner…





Characteristics of Transient Testing at TREAT

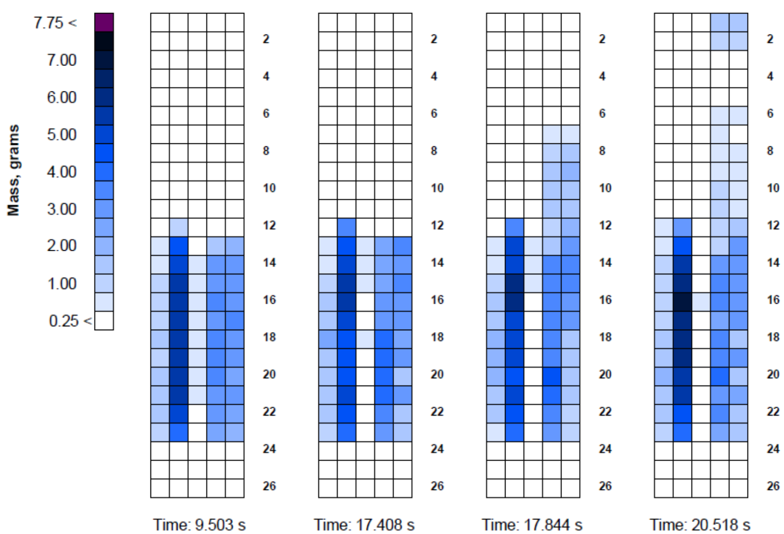
- Primary historical mission supported sodium-fast reactor testing
- TREAT is well suited to **self-contained drop-in test devices**
  - Installation, testing, and withdrawal in a matter of days - enables support for rapid transition between different-environment test devices (e.g. Na, H2O)
  - Effective approach to test many pins quickly and cost effectively
- Examples of instrument objectives: time and location of first cladding failure; time-dependent axial growth; fuel relocation; coolant temperature, dynamics, and pressure
- Transients evolved to shaped transients to simulate pre-transient thermal conditions in fuel, etc.
- **Experimental coupling** with the reactor - trigger reactor scram at failure or trigger power burst upon Na voiding using experiment instrumentation
- Fuel-motion monitoring
  - High-speed video in transparent capsule
  - Fast-neutron hodoscope (next slide)



Video still-frames of preirradiated UO_2, steel cladding (F1)

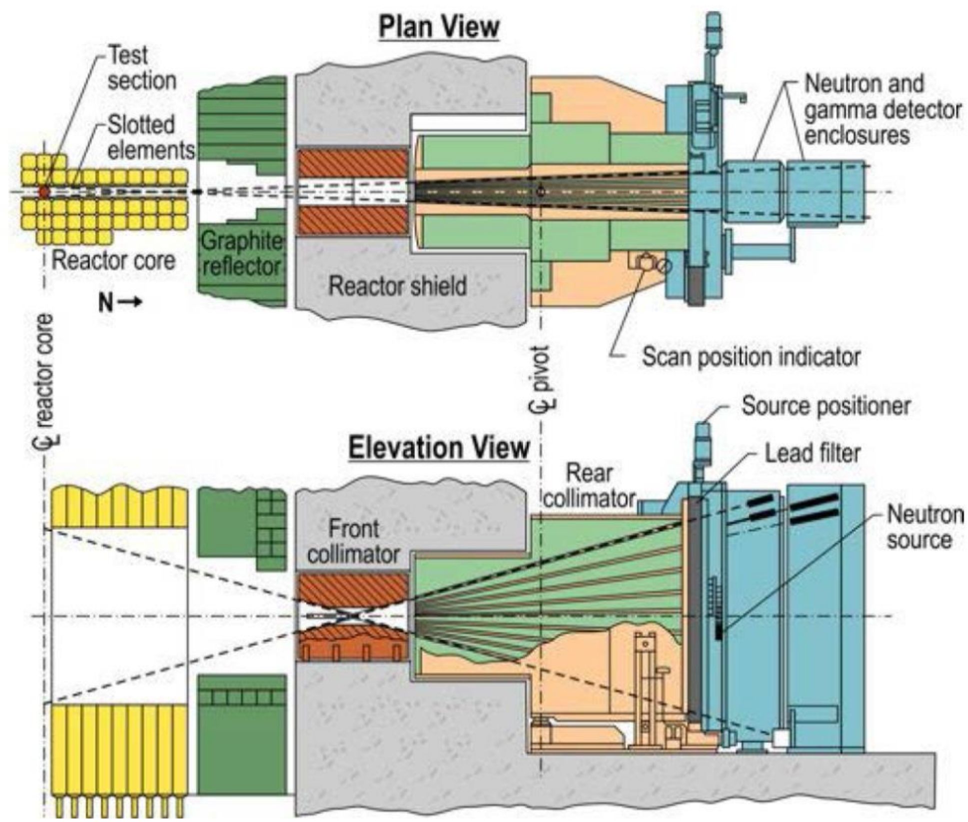
Fuel Visualization and Motion Monitoring

- Fast neutron hodoscope provides the key capability for monitoring fuel motion during the transient
- Fission-born fast neutrons emitted from specimen travel through vehicle's containment wall, through a collimator, and into detector array
- Provides pixelated view of fuel mass in each collimator slot



Snap-shot views of data from a Hodoscope experiment

This data shows the simultaneous response of two fuel pins to a transient. The pin on the right shows significant axial fuel relocation has occurred at 17.844 seconds. This observation establishes the failure point and the progression of fuel movement after the breach.



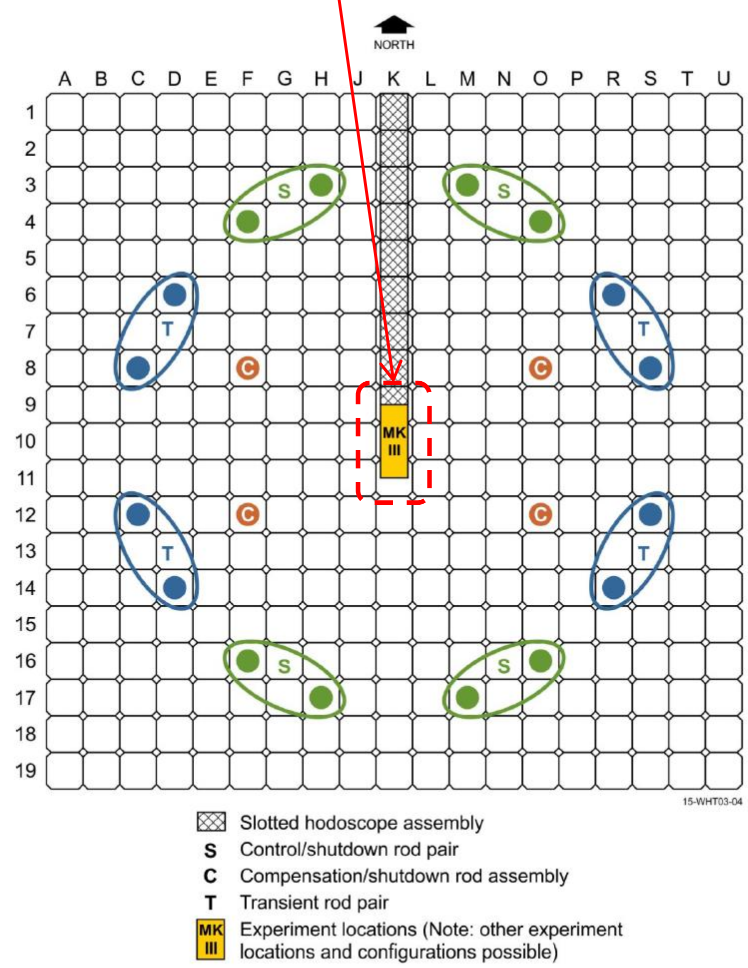
Slide Courtesy of David Chichester

Experiment Design

- TREAT provides neutrons
- The experiment vehicle (e.g. loop, capsule, etc.) provides:
  - Boundary conditions
  - Instrumentation
- Accident Tolerant Fuels (ATF) transient tests driving current experiment design (LWR)
  - TREAT spent the last two decades of its prior operation (~1970-1990) largely supporting fast reactor tests
  - Transient testing experiment team developing pressurized water test capabilities for TREAT
- Revitalization of sodium-environment irradiation vehicles underway
- Development of vehicles for “science-based” specimens also underway

Insert Experiment Here

(or anywhere else really)

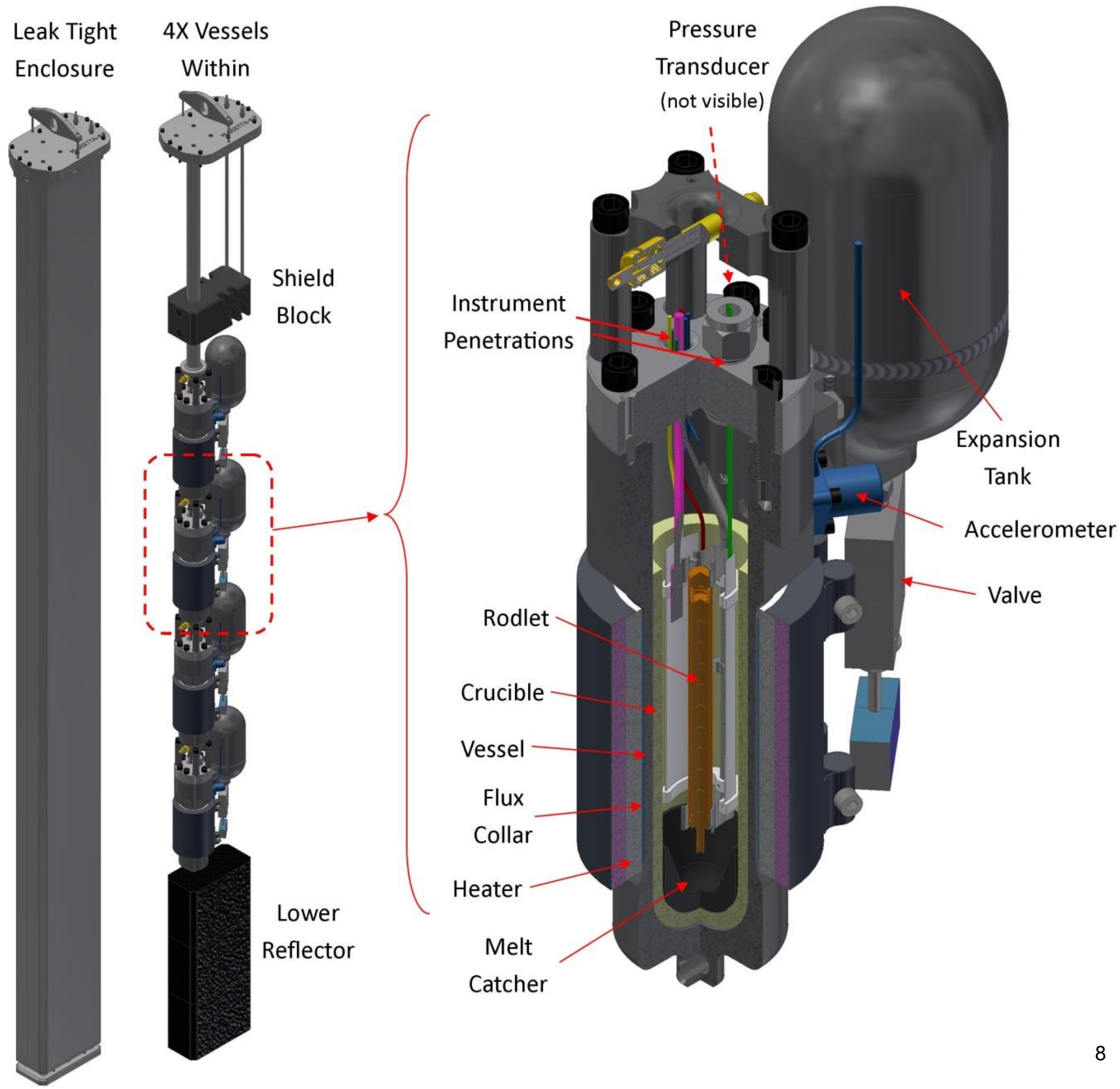


Slide Courtesy of Nicolas Woolstenhulme

Multi-SERTTA

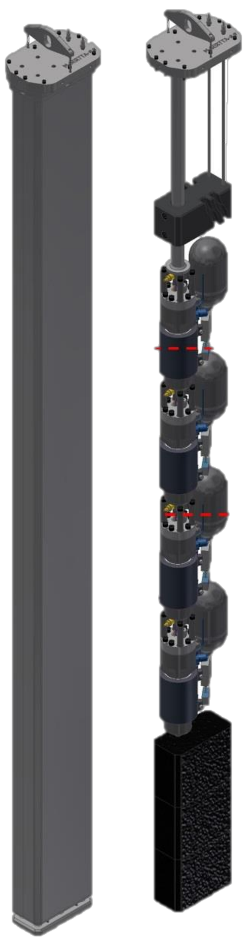
Static Environment Rodlet Transient Test Apparatus (SERTTA)

- General purpose device <u>without</u> forced convection
- Pre-pressurized and electrically heated
  - Liquid water up to PWR condition (300°C 15.5 MPa)
  - Inert gas or steam
  - Liquid sodium
- Planned to be the first "new" test to be used in restarted TREAT
- Includes a significant instrumentation package (later)



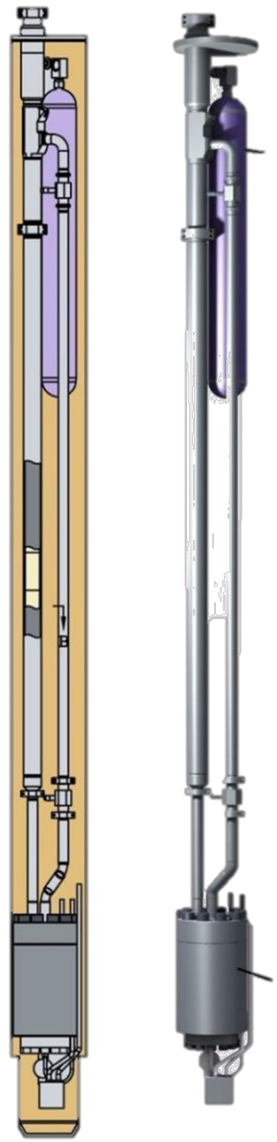
Conceptualized Experiment Vehicles

- Integral tests and separate effects studies in package-type "loops"

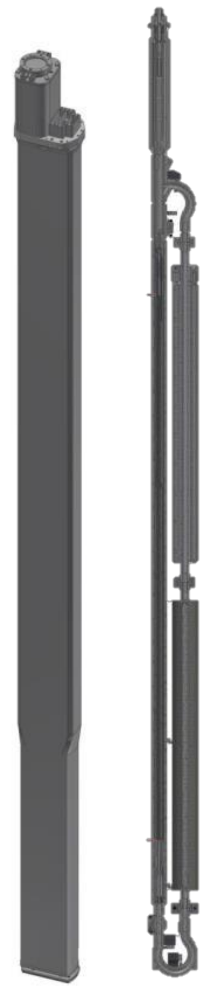


Multi-Vessel Static Capsule, Various coolants/thermal conditions

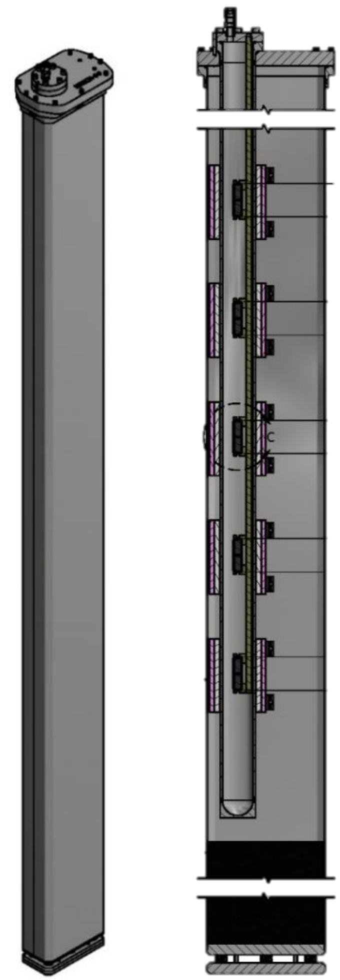
Large, Single Vessel Static Capsule, Various coolants/thermal conditions



PWR Flowing Water Loop



Flowing Na Loop (based on historical testing)

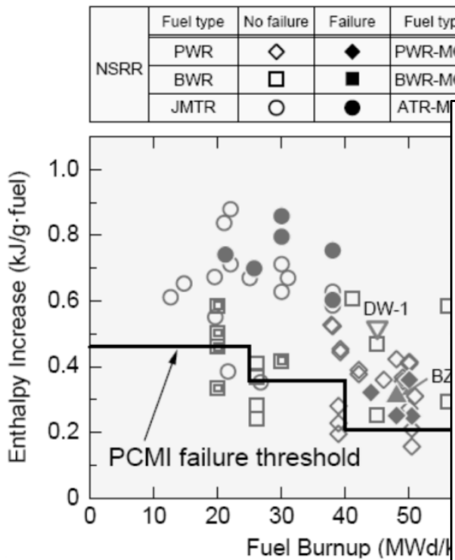


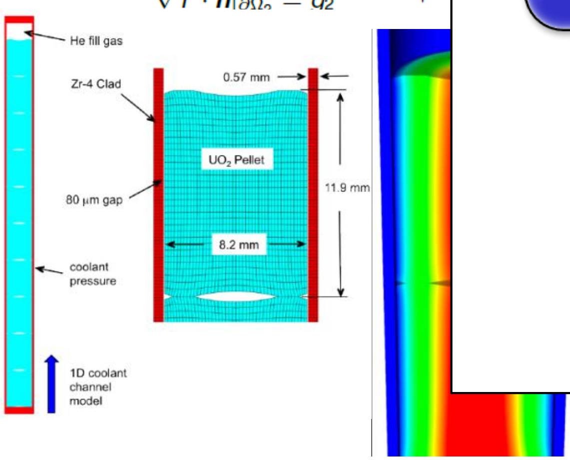
Multi-Vessel, Minimal-Activation Capsule

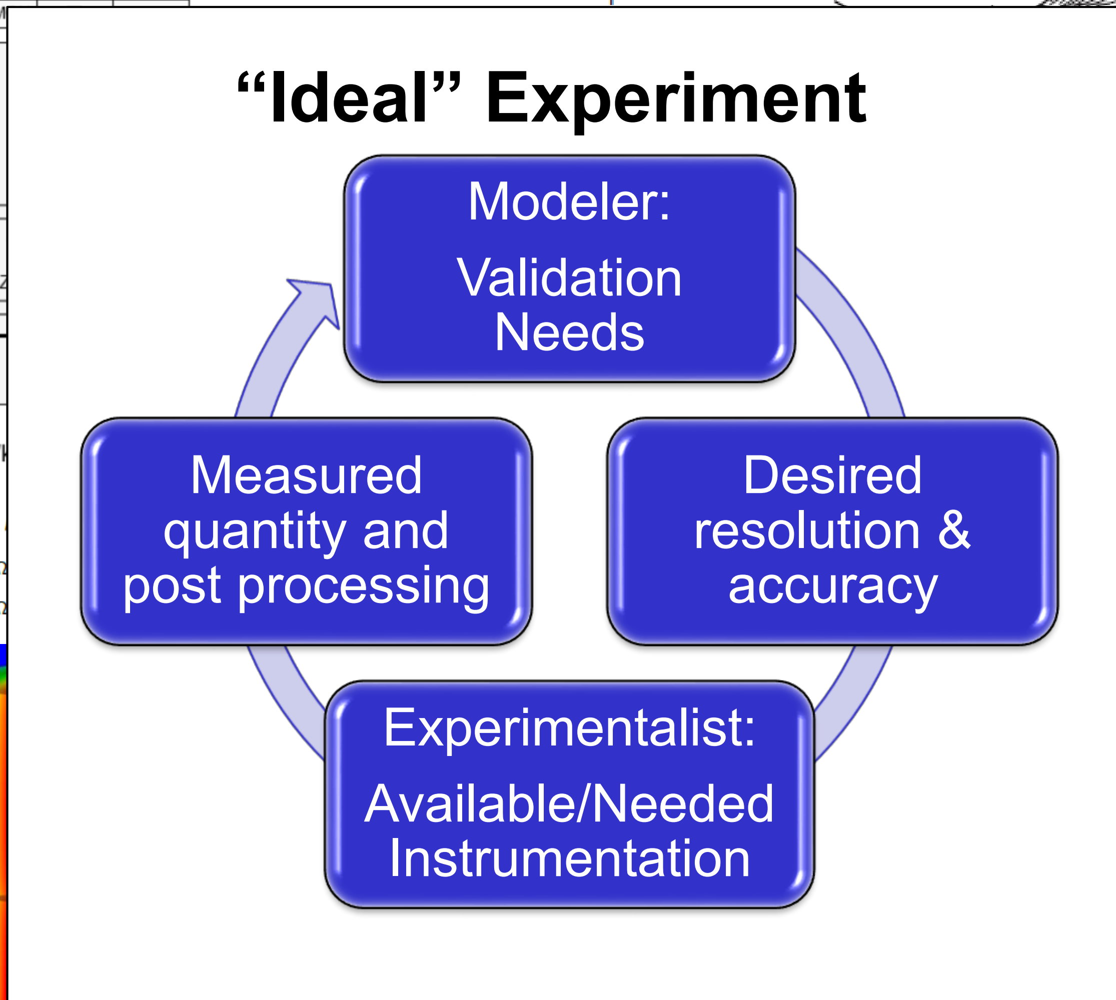
TREAT Instrumentation

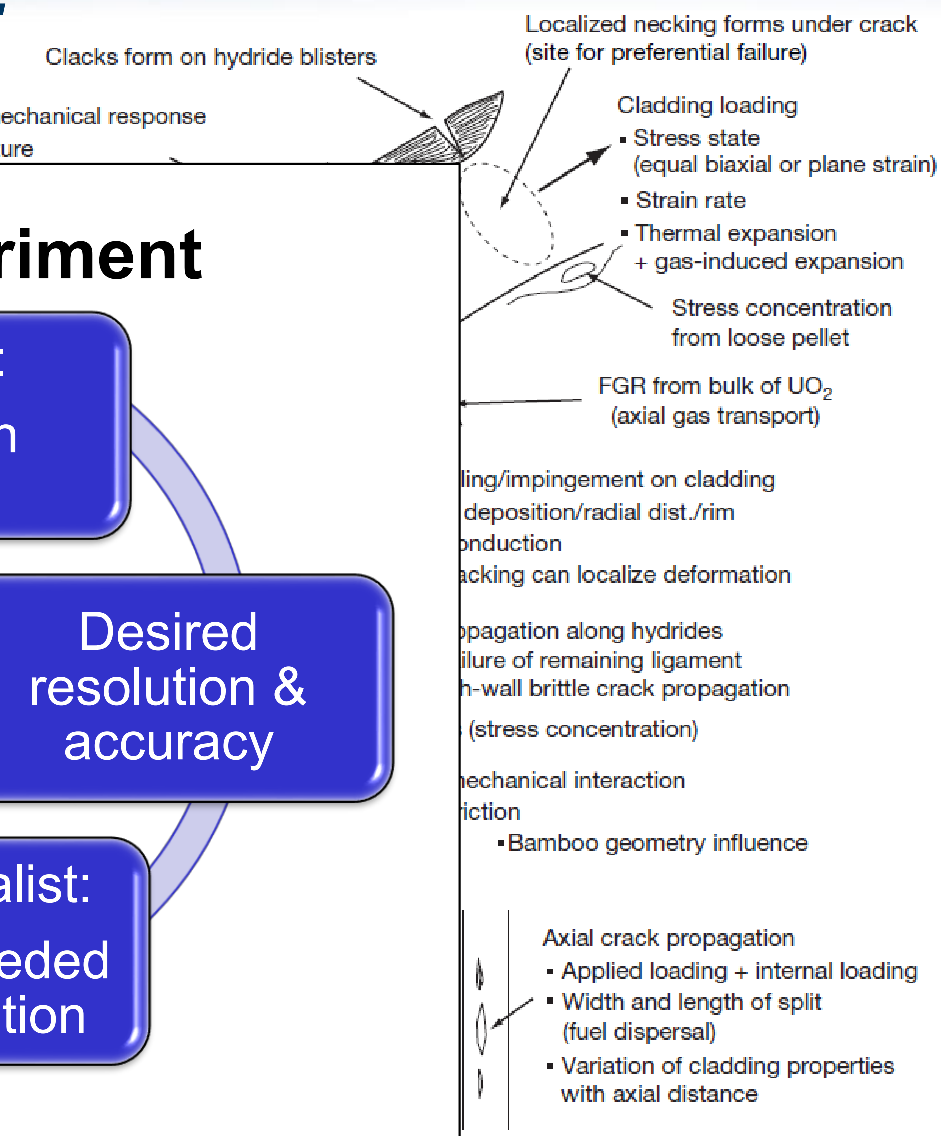
(In-Pile Experiments Focus)

Why Instrument in TREAT?







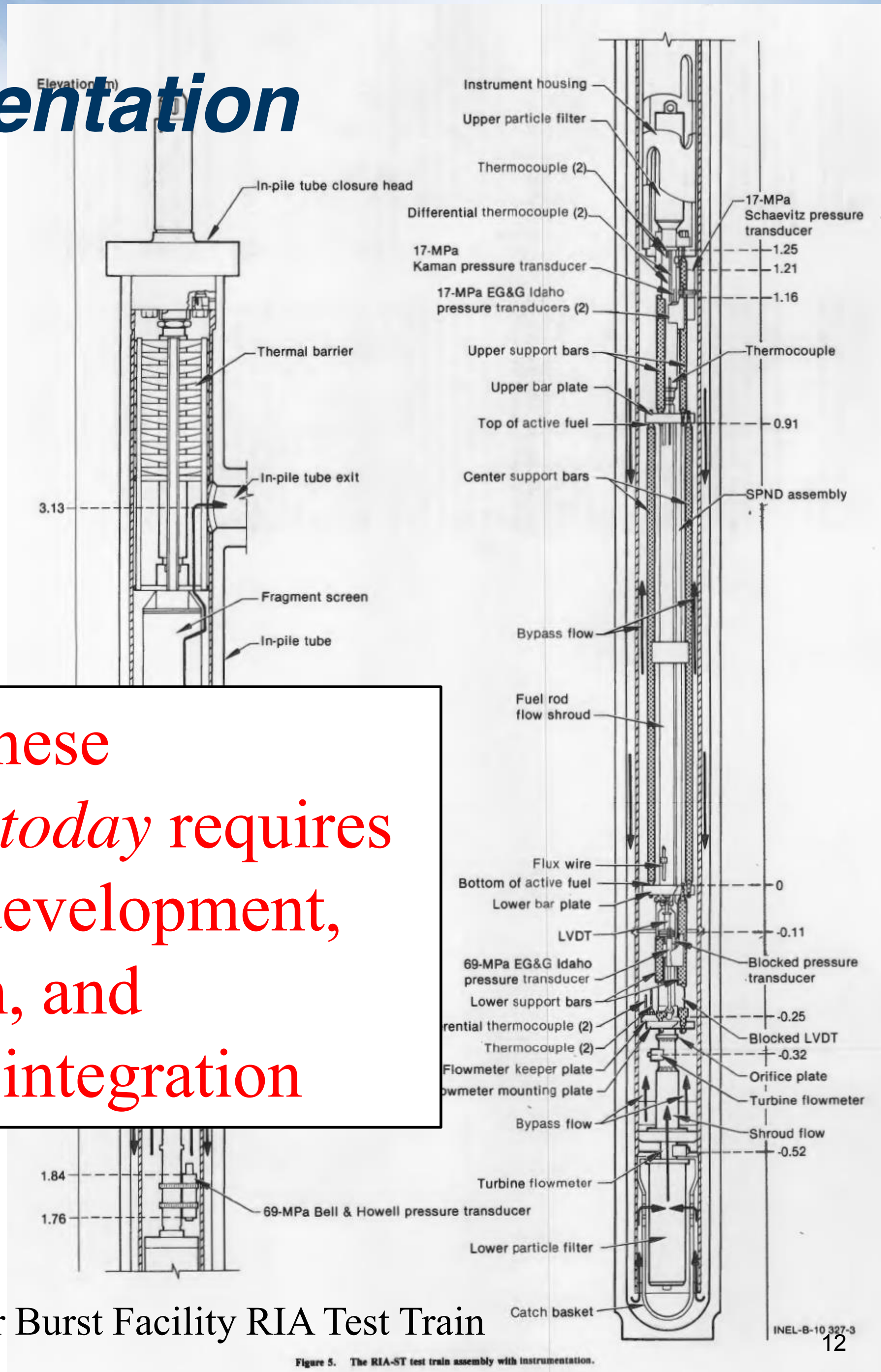


T. Fuketa, Comprehensive Nuclear Materials, Vol. 2, (2012) pp. 579-593

Historical Transient Instrumentation

- **LWR** (for example)
  - Thermocouples
  - Pressure transducers – coolant, rod
  - LVDT – elongation, pressure, flow rate
  - Strain gage
  - SPND, flux wires/foils, ion chambers
  - Ultrasonic thermometer
  - Acoustic sensors
  - Water column velocity
- **SFR** (for example)
  - Thermocouples
  - Pressure transducers
  - Flowmeters
  - Void sensor
  - Sodium column impact
  - Acoustic sensors

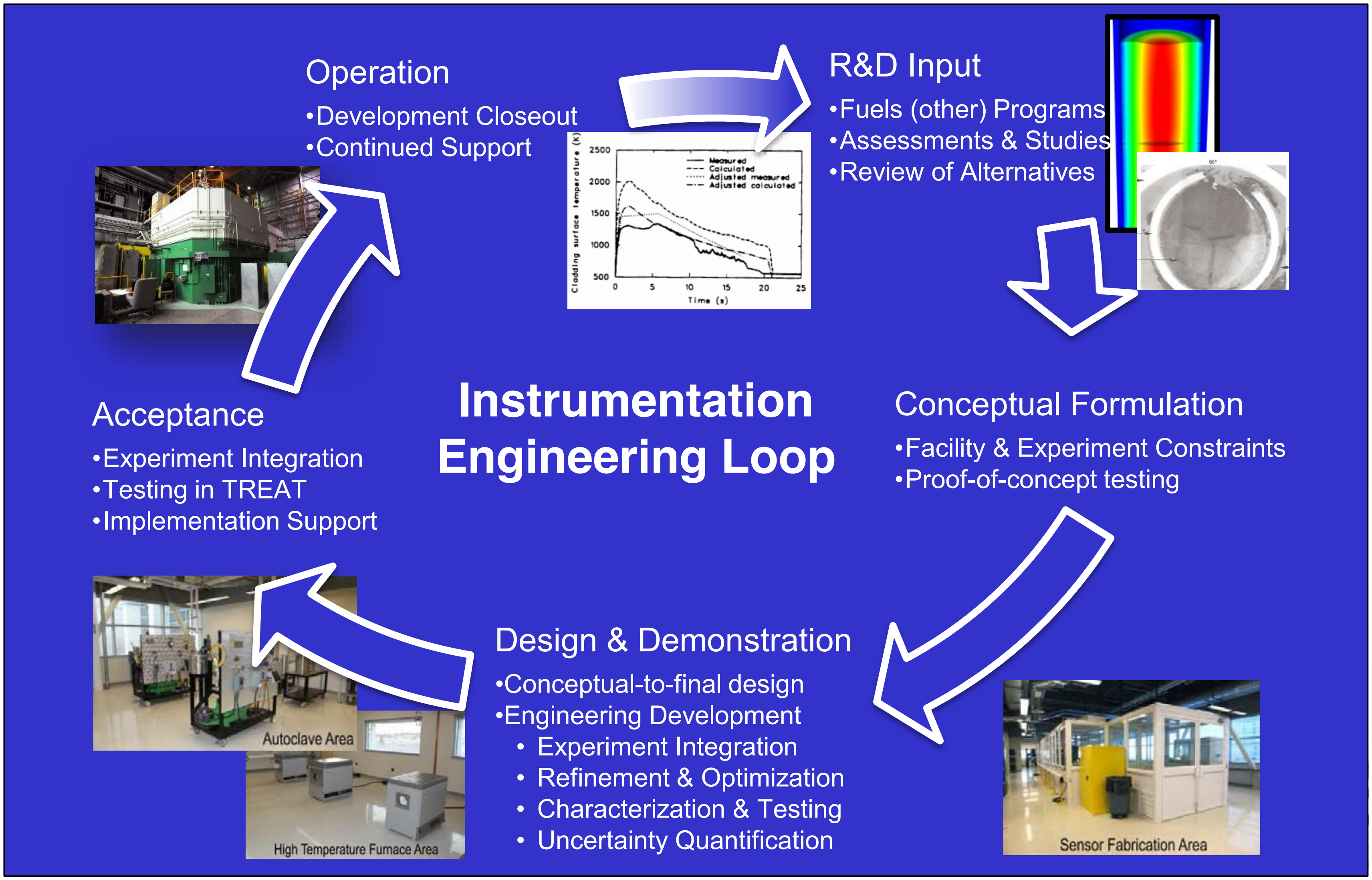
Deploying these instruments *today* requires significant development, qualification, and engineering integration



Example Power Burst Facility RIA Test Train

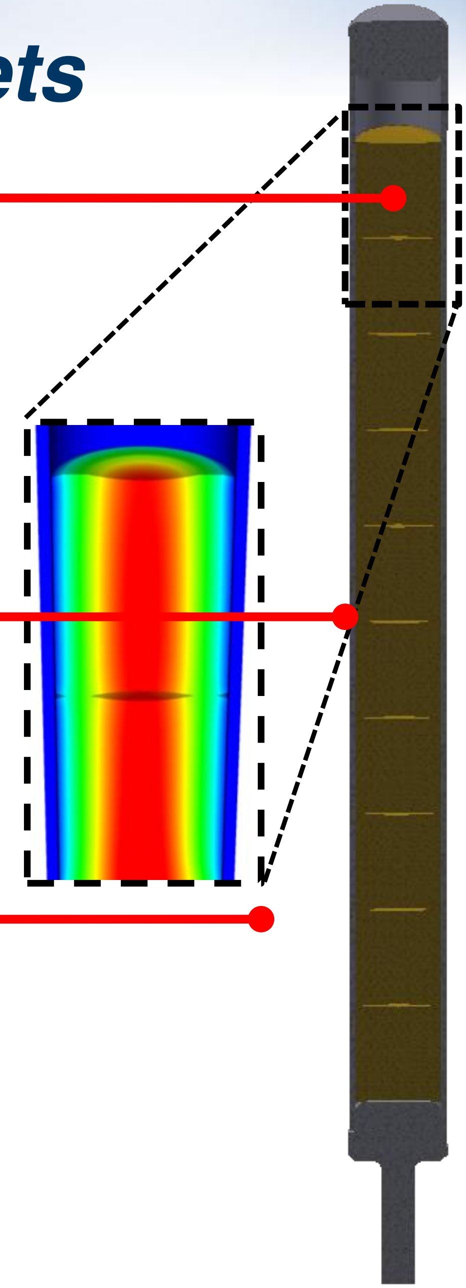
Instrument Development & Qualification

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



Transient In-Pile Instrumentation Targets

- **Fuel** – metal, oxide, (ATF)
  - Energy deposition - (dosimetry, micro-pocket fission detector), Temperature, Dimensional changes / mechanical behavior (hodoscope, LVDT), Microstructural / chemical behavior, Thermal / mechanical properties, Fission gas characteristics (pressure, composition) – (LVDT)
- **Cladding**
  - Temperature (TC, fiber-based IR radiometry), Dimensional changes / mechanical behavior (acoustic, LVDT), Microstructural / chemical behavior, Thermal / mechanical properties
- **Environment** – gas, water, sodium…
  - Temperature (TC), Pressure (transducer), Phase change (void sensor, acoustic), Mechanical behavior, Flow rate, Fission products, Chemical behavior

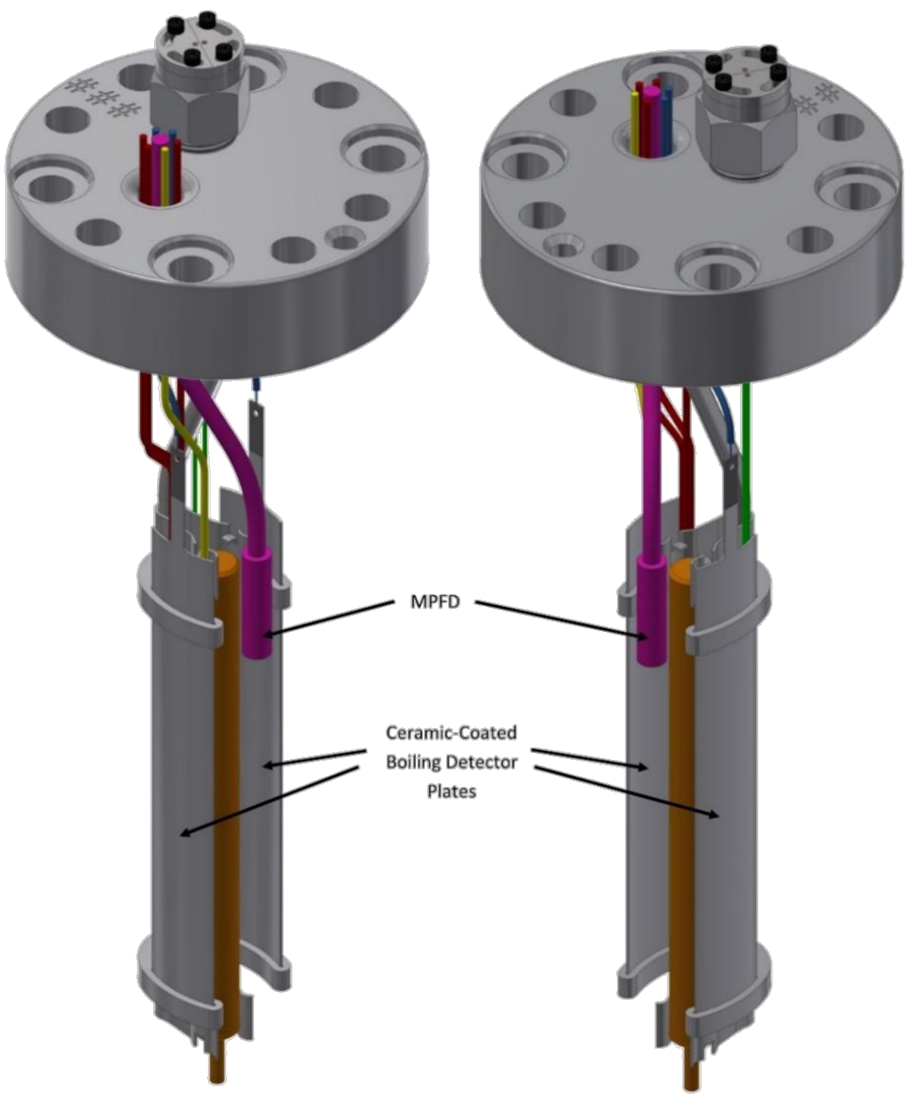


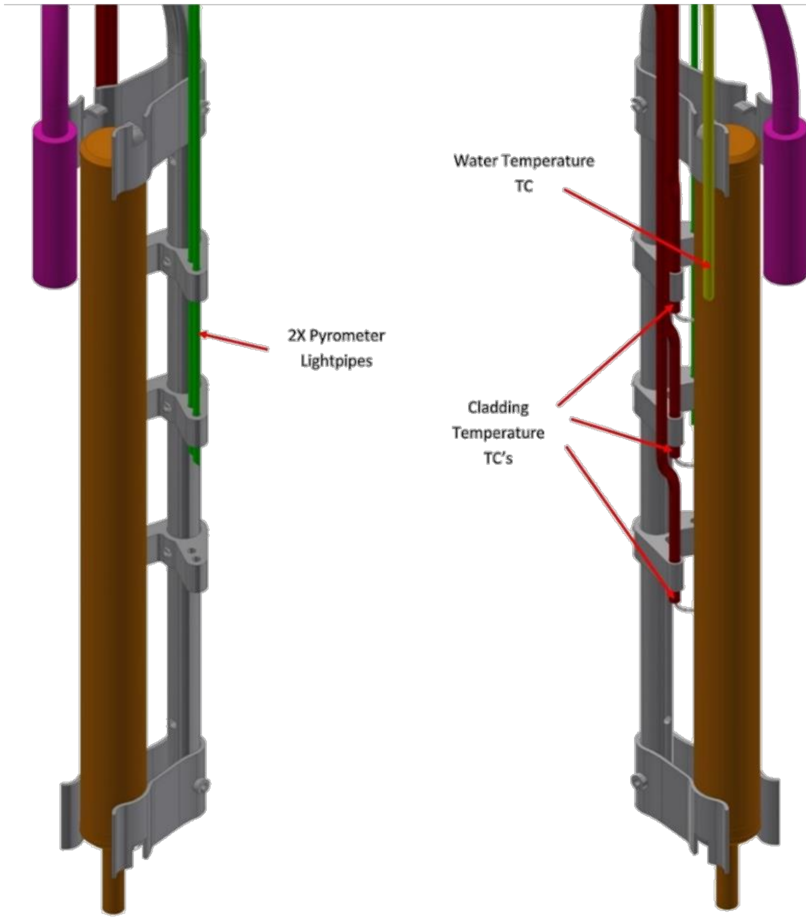
Instrument Challenges & Opportunities

- **Visualization** – imaging techniques; e.g. advanced hodoscope, visible & IR videography (e.g. boroscope technologies), under-sodium viewing (e.g. ultrasonics), microstructural visualization (e.g. SEM)
  - Hodoscope needs – see presentation by H. MacLean Chichester from NEET ASI Webinar 2015, "Advanced Fuels Program In-Reactor Instrumentation Overview"
- **Sensor miniaturization**
  - Less obtrusive
  - Increased spatial resolution/quantity
  - Located nearer to locations of interest (e.g. in fuel)
- **Electronics** – in-core options, signal conditioning, ADC, enable more signals to/from experiments
- **Feedthrough** technologies – wide range of temperatures and pressures
- Adaptation of existing technologies to experimental constraints
  - **Hot-cell** implementation considerations (non-contact, easy alignment, etc.)

Multi-SERTTA Instruments

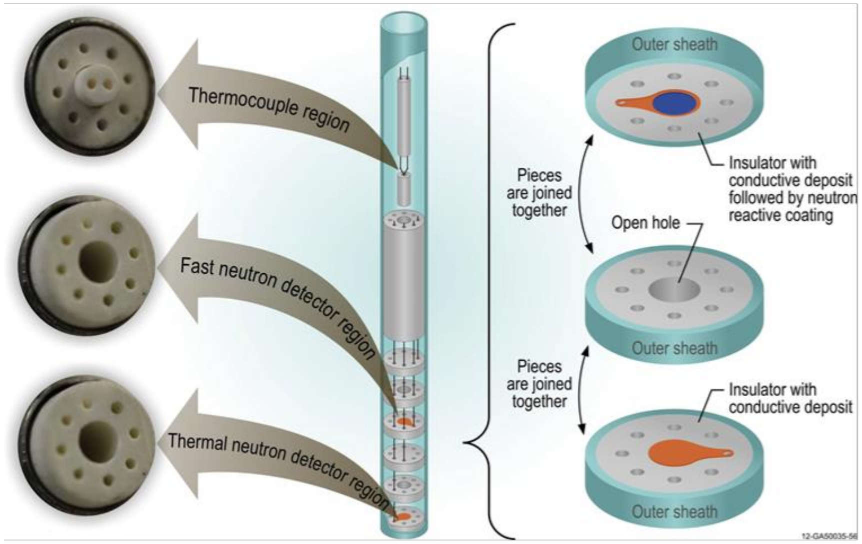
- PWR version of Multi-SERTTA
- Significant instrumentation capability
- Probable single test use instruments
- Current program development is focused on deployment of these instruments





Micro Pocket Fission Detector (MPFD)

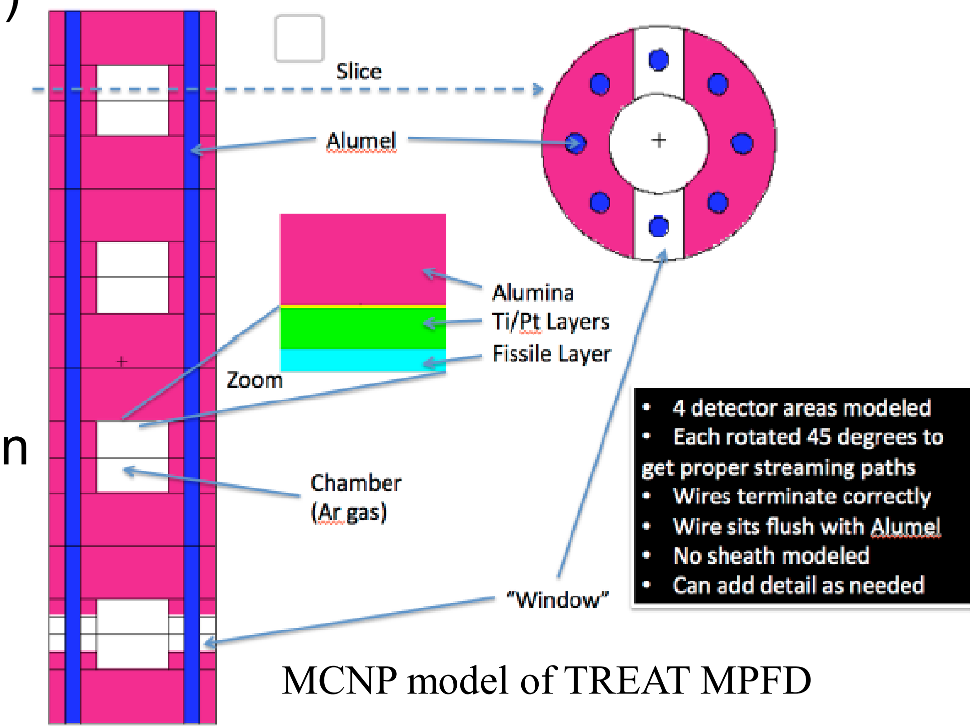
- Background: Specimen energy deposition is a key experiment output parameter
- Historical approach: Transient energy characteristics provided by combination of calibration tests (dosimetry) and reactor power measurements in TREAT biological shielding
- Goal: Provide real-time neutron flux measurement near test specimens
- Technology Need:
  - Compact size
  - High temperature and pressure resistance
  - Wide range of neutron flux while minimizing gamma influence
  - Spectral information
  - < ms response
- Approach:
  - Modify existing MPFD design



MPFD – Current Effort

- Modified MPFD design
  - 2 high and 2 low efficiency chambers
  - Thickened sheath (pressure boundary)
  - Chamber fissile material thickness to be tuned to desired flux level

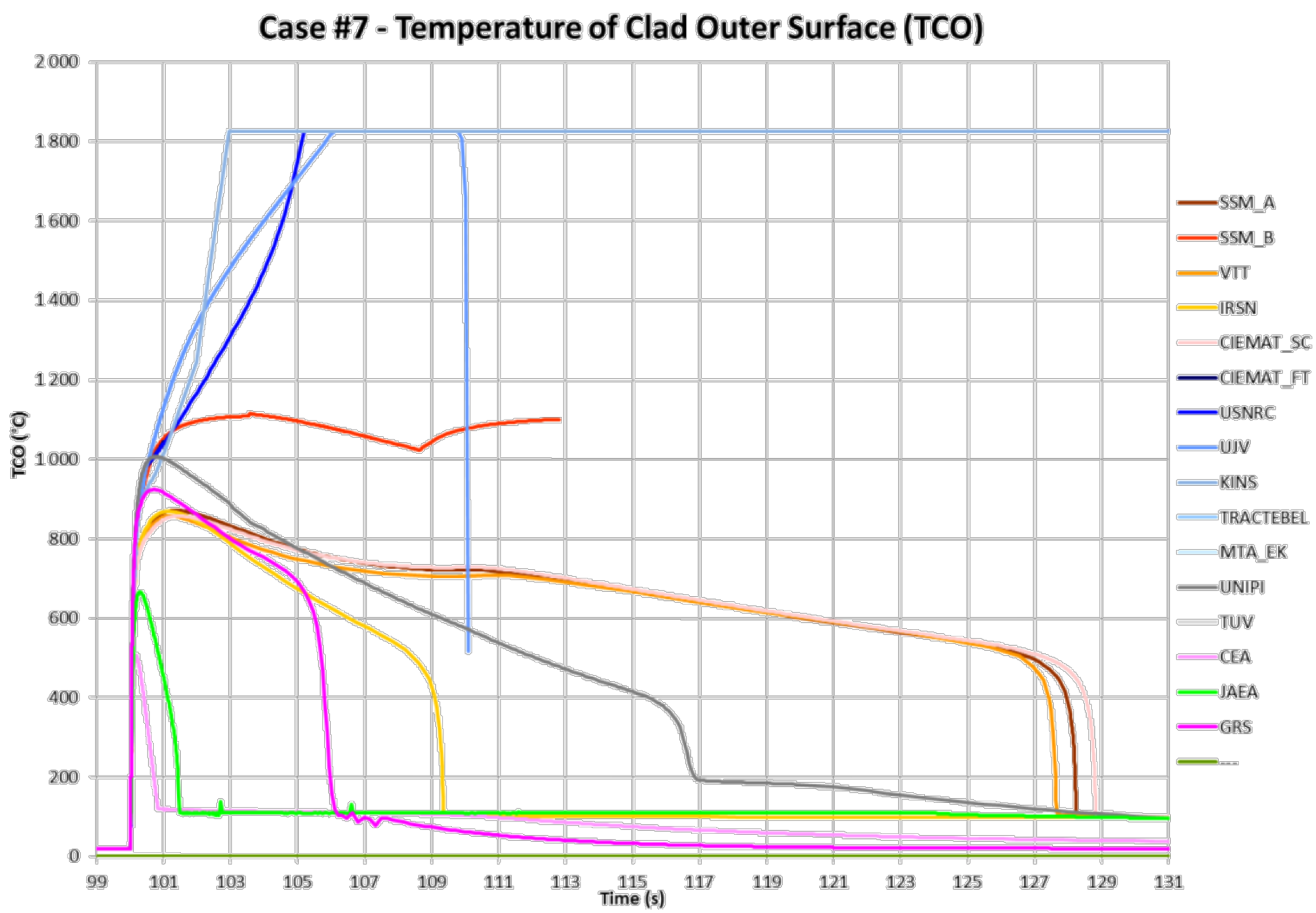
- Current status/progress:
  - Analysis supporting higher pressure sheath design
  - Analysis for optimal instrument location in experiment
  - Detailed MCNP model of sensor to better understand design response
  - Working through material quality requirements and procedures
  - Design and testing of specialized counting electronics at KSU



MCNP model of TREAT MPFD

Example of R&D need: Fast Transient Boiling

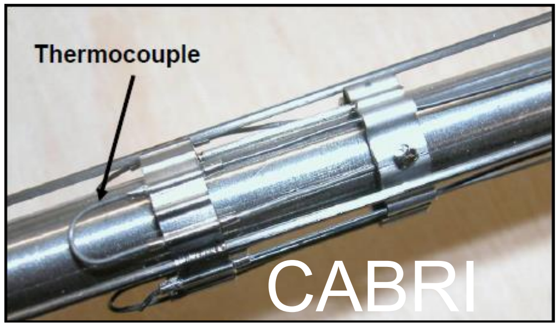
– Clad-to-coolant heat transfer remains an area of high uncertainty for modeling and simulation
  - → pyrometer and void sensor

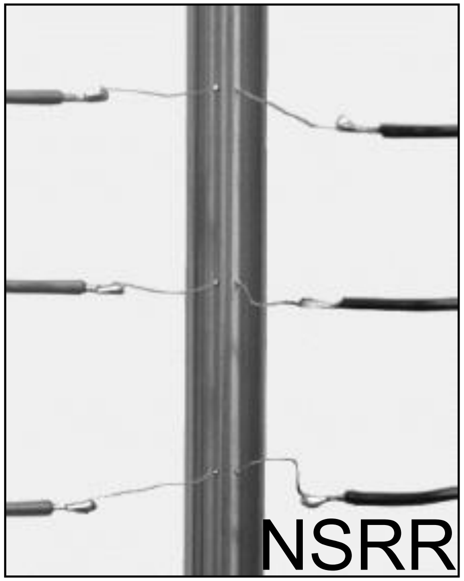


WGFS RIA Fuel Codes Benchmark Meeting 2015

Pyrometer

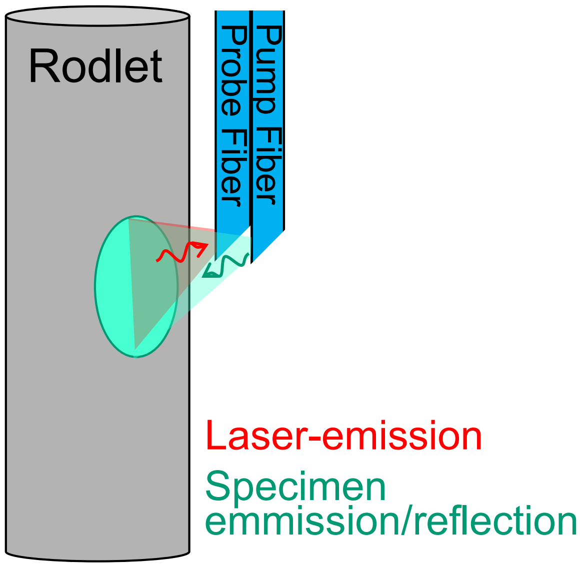
- Goal: Measure cladding temperature with time resolution adequate for RIA with minimal impact to cladding (non-contact)
- State-of-the-art cladding temperature measurement:
  - Thermocouple
    - Historical and contemporary standard (also in Multi-SERTTA)
    - Impacts - fin effects, gamma-heating, response time, cladding integrity
- Technology Need:
  - Response time ~ milliseconds
  - Non-contact
  - Use in multiple mediums, e.g. gas, steam, water
- Approach:
  - Off-the-shelf IR pyrometer system – customized fiber delivery
    - Characterize environmental effects
  - Complete custom pyrometer approach (Utah St)

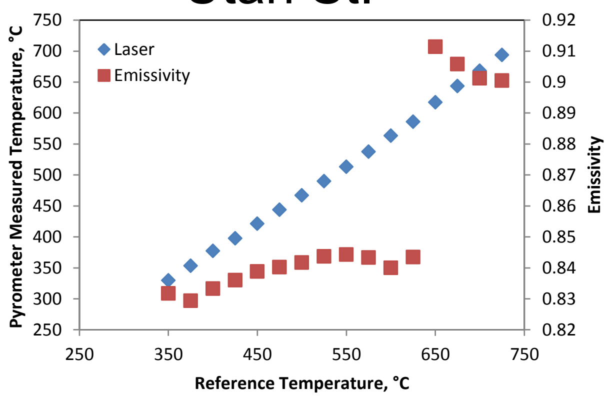




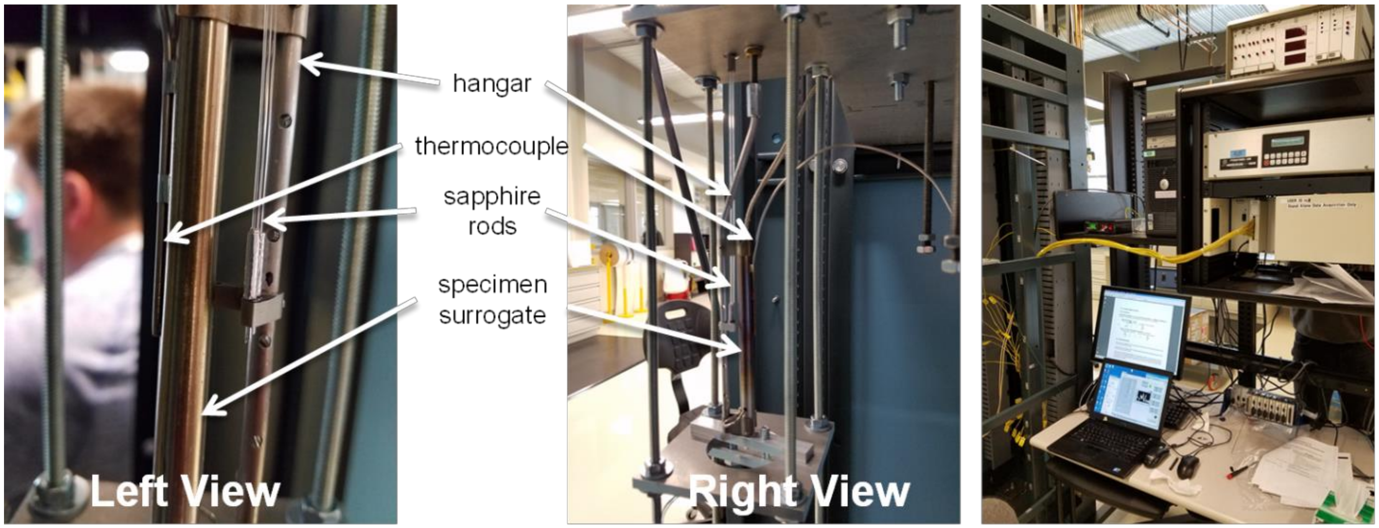
Pyrometer – Current Effort

- Emissivity-corrected, single-color, fiber-coupled pyrometer
  - Temperature range: 220-1600°C
  - Accuracy: ± 3°C
  - Temperature Resolution: ± 1°C
  - Spatial Resolution: ~ 2 mm
  - Temporal Resolution: ~ 8.3 msec
- Current status:
  - Instrument in HTTL
  - Testing underway
  - Custom design by Utah St.





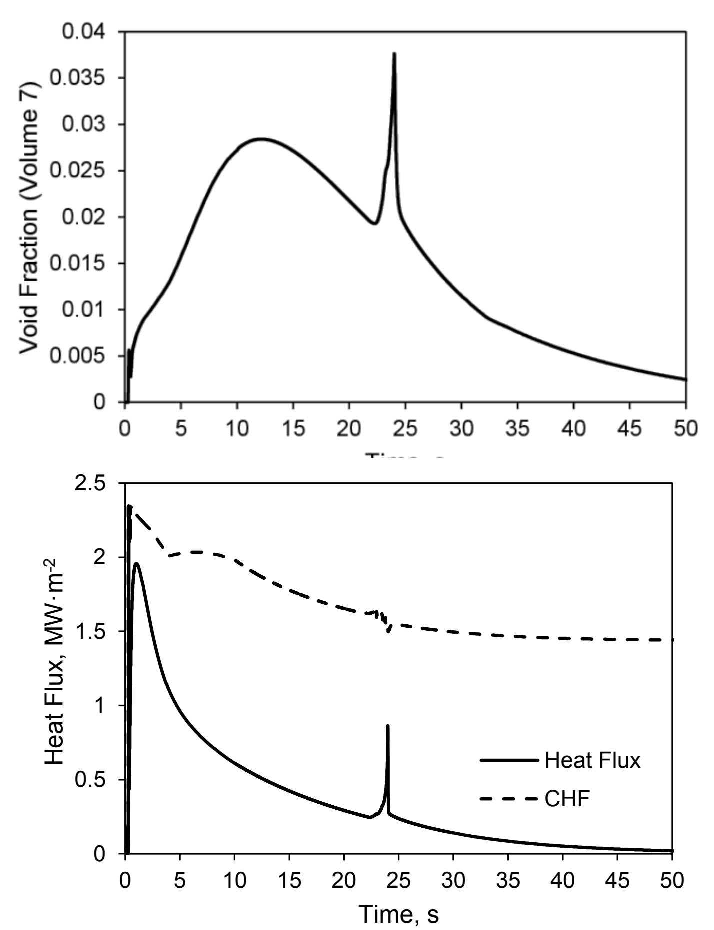
Preliminary testing results



Laboratory setup at HTTL

Void Sensor (Boiling Detector)

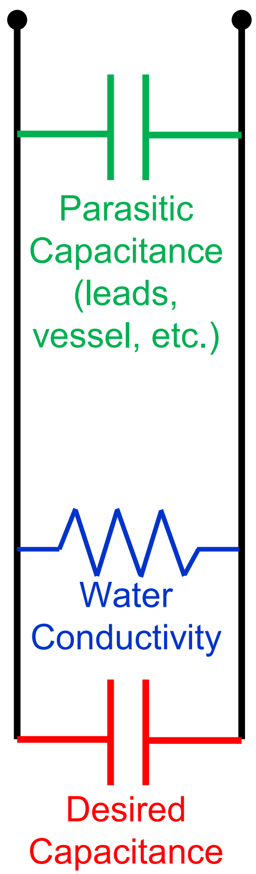
- Goal: Detect departure from nucleate boiling (DNB) – identify boiling regimes in PWR water
- State-of-the-art for phase change: CABRI – ultrasonics, acoustic sensors, temperature/pressure sensors
- Technology Needs:
  - Detect coolant event timing (ms response)
    - Sensitivity to DNB
  - Operate at STP -> PWR conditions
  - Void quantification
- Approach:
  - Build custom sensor based on known tech.
    - Effects of harsh environment
  - Design for in-pile use (signal acquisition)



Example of RELAP5 predicted heat void fraction and heat flux during RIA transient in Multi-SERTTA

Void Sensor (Boiling Detector) – Current Effort

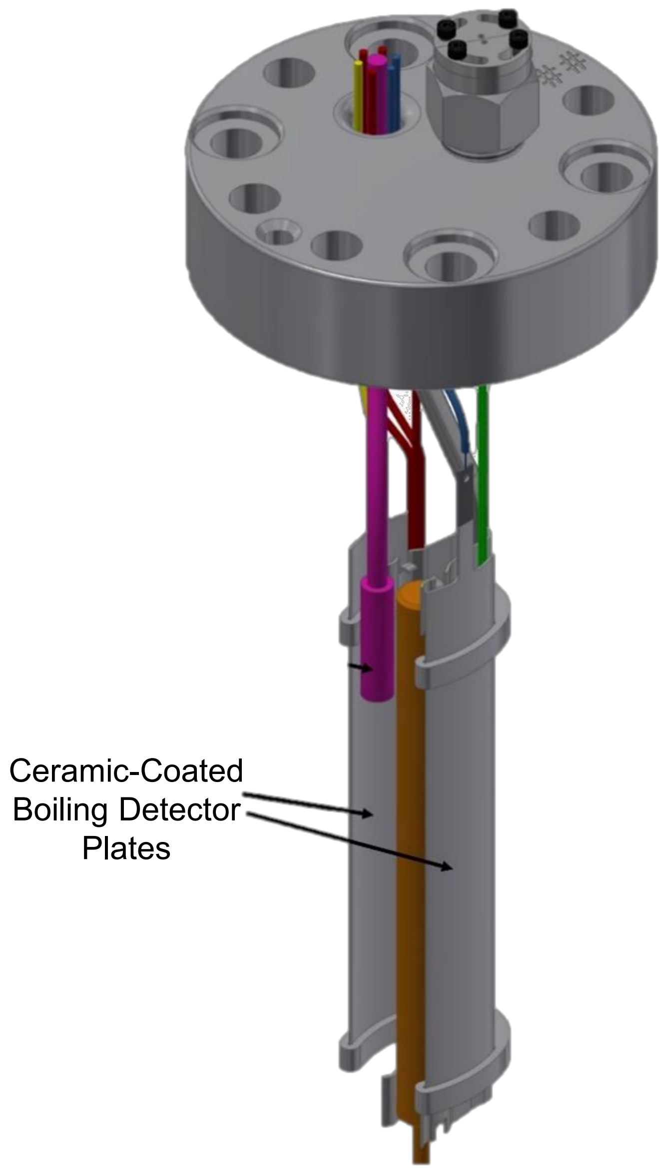
- Capacitive-based sensor
  - Two ceramic-coated electrodes
  - Single conductor MGO cabling from vessel
  - Signal conditioning outside core shielding



Measured impedance:

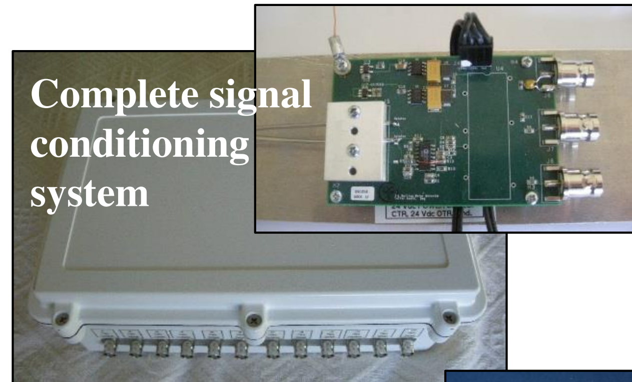
$$Z = \frac{V}{I}$$

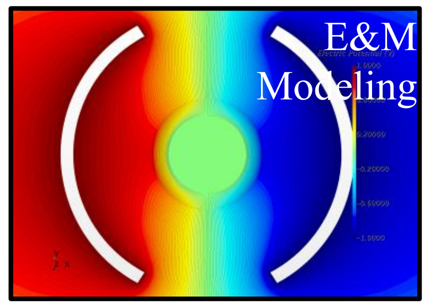
$$\frac{1}{Z_{eq}} = \frac{1}{R} + j\omega C$$



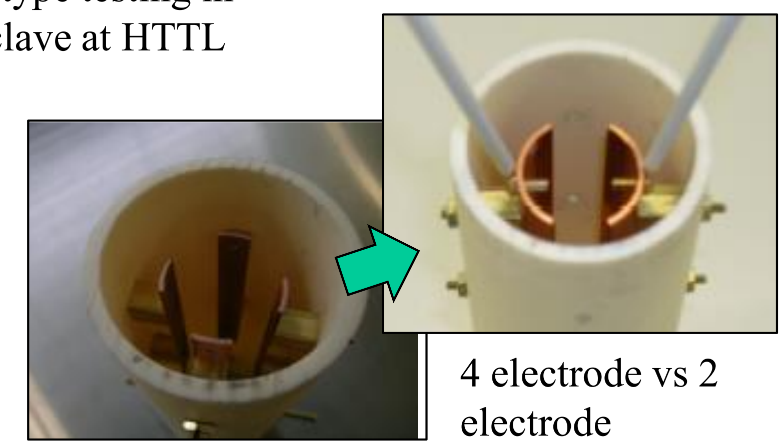
Void Sensor (Boiling Detector) – Current Effort

- Primary technical issues addressed to date:
  - Sensor-to-DAS leads/signal conditioning
  - Effects of component grounding
  - Optimal measurement frequency
  - Capacitor plate design (4 plate vs 2 plate)
  - Water quality effects
  - Capacitor plate isolation
  - PWR conditions

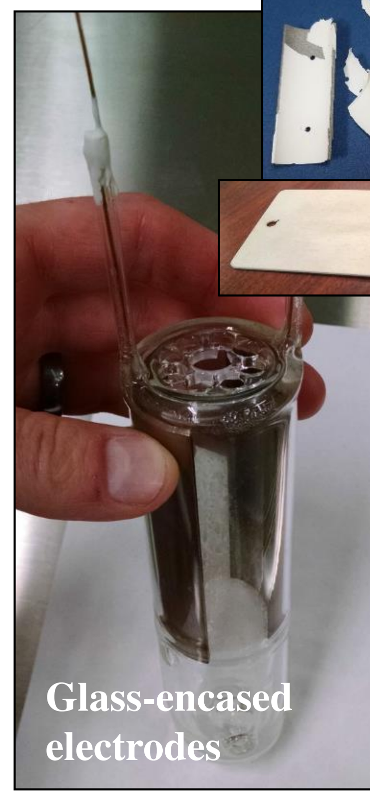




Boiling detector prototype testing in autoclave at HTTL



4 electrode vs 2 electrode configuration



Viable coating tested in PWR condition

Collaborations for Instrumentation

- NEUP Projects
  - Advanced Instrumentation for Transient Reactor Testing IRP (**UW**, **Ohio St, Kansas St, Idaho St**, INL)
  - Benchmarking for Transient Fuel Testing IRP – Task 3 Core Instrumentation Plan (**Oregon St, UMich, MIT**, INL)
  - A Transient Reactor Physics Experiment with High Fidelity 3-D Flux Measurements for Verification and Validation – **Kansas St**
- Instruments for Multi-SERTTA ATF-series
  - Thermocouples, pyrometer - **Utah St**
  - Void sensor – **Utah St, U of New Mexico**
- International collaborations
  - **CEA** (France) – CABRI/Sensors – optical fiber, pyrometer
  - **IRSN** (France) – CABRI experiments – pyrometer, ultrasonics, LVDT, sensor testing & qualification
  - **Halden** (Norway) – LVDT, pyrometer?
  - **NNC (Kazakhstan)** – IGR – In-pile instrument testing
- Continue to grow…

Summary

- TREAT has performed nearly 3000 transients and more than 900 experiments
  - Primary mission was transient fuel performance testing for SFR systems
  - Restart program underway with expected completion in 2018 (or sooner)
- Several test vehicle designs at various stages of development for LWR and SFR systems along with multiphysics modeling capabilities. Priority environments are:
  1. Light Water Reactor (PWR & BWR)
     - Reactivity Initiated Accidents (RIA)
     - Loss of Coolant Accidents (LOCA)
     - Variety of supporting separate-effects studies
  2. Sodium Fast Reactor
     - Transient Over Power (TOP)
     - Unprotected Loss of Flow (ULOF)
     - Variety of supporting separate-effects studies

Summary – Instrumentation

- 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
  - Recovering instrumentation capabilities of the past is an important and significant hurdle
- Looking (and developing) for next generation of sensors…
  - Instrument development underway since the beginning of FY16 for LWR applications – MPFD / IR pyrometer / Void sensor / TC design
- 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)

Acknowledgments

- Daniel Wachs – Scientific Coordinator for Transient Testing
- Nicolas Woolstenhulme – Experiment Design Lead
- Colby Jensen – Experiment Instrumentation Lead
- David Chichester – Hodoscope Lead
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  - Troy Unruh
  - Ashley Lambson
  - Eric Larsen
  - John Svoboda