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Nuclear Technology Research and Development

Advanced Fuels Campaign

In-Pile Instrumentation Overview

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Deputy Lead for Advanced Reactor Fuels

Advanced Sensors and Instrumentation (ASI)
Annual Review Webinar
October 23, 2019

Advanced Fuels Campaign

NTRD Nuclear Technology Research & Development

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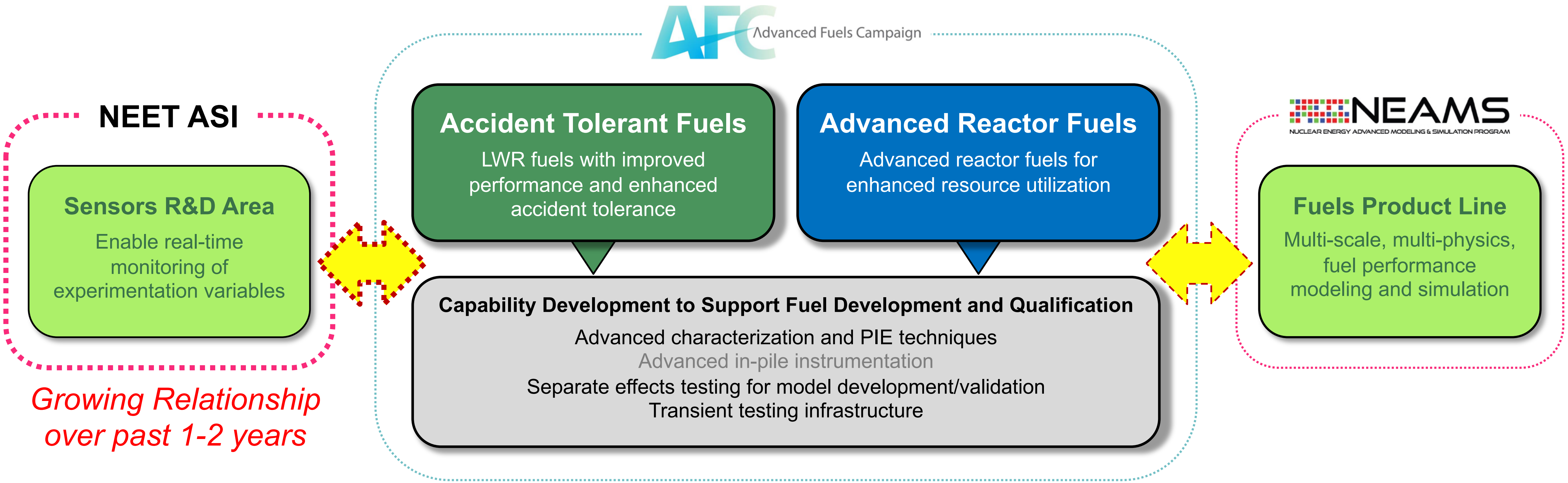
Advanced Fuels Campaign: Structure and Mission

- **Mission:**
  1) Support development of near-term **Accident Tolerant Fuel** (LWR) technologies
  2) Perform research and development on longer-term **Advanced Reactor Fuel** technologies



Industry-Led Development of ATF Concepts

Laboratory roles

- Develop and maintain fuel testing/ qualification infrastructure
- Perform uniform and independent testing of ATF concepts
- Support individual industry FOA teams as requested and approved.

ATF Industry FOA Awards

Framatome

- Cr-coated M5 cladding
- Doped UO_2 for improved thermal conductivity and performance
- SiC cladding.

General Electric

OAK RIDGE National Laboratory

- Coated Zr cladding
- Iron-based cladding
- (FeCrAl)
- ODS variants for improved strength.

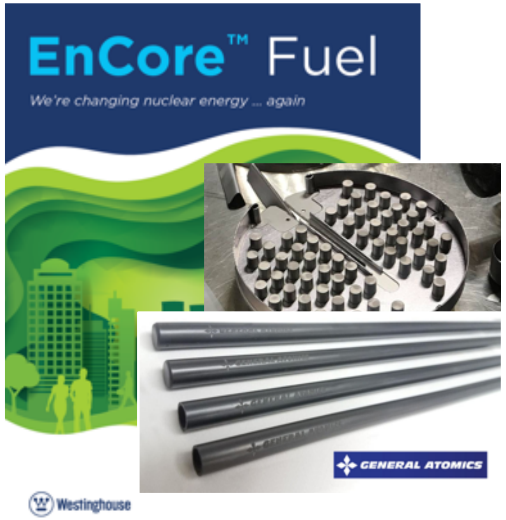
GE imagination at work

Westinghouse

INL Idaho National Laboratory

Los Alamos NATIONAL LABORATORY

- Cr-coated Zirlo cladding
- SiC cladding
- Alternative fuels with improved thermal conductivity and high density.



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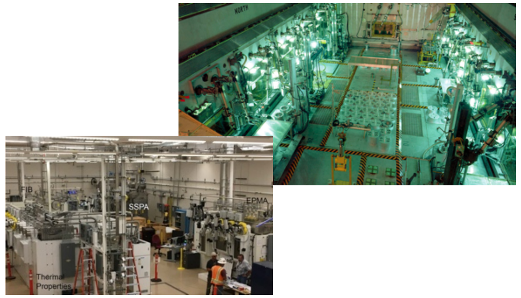
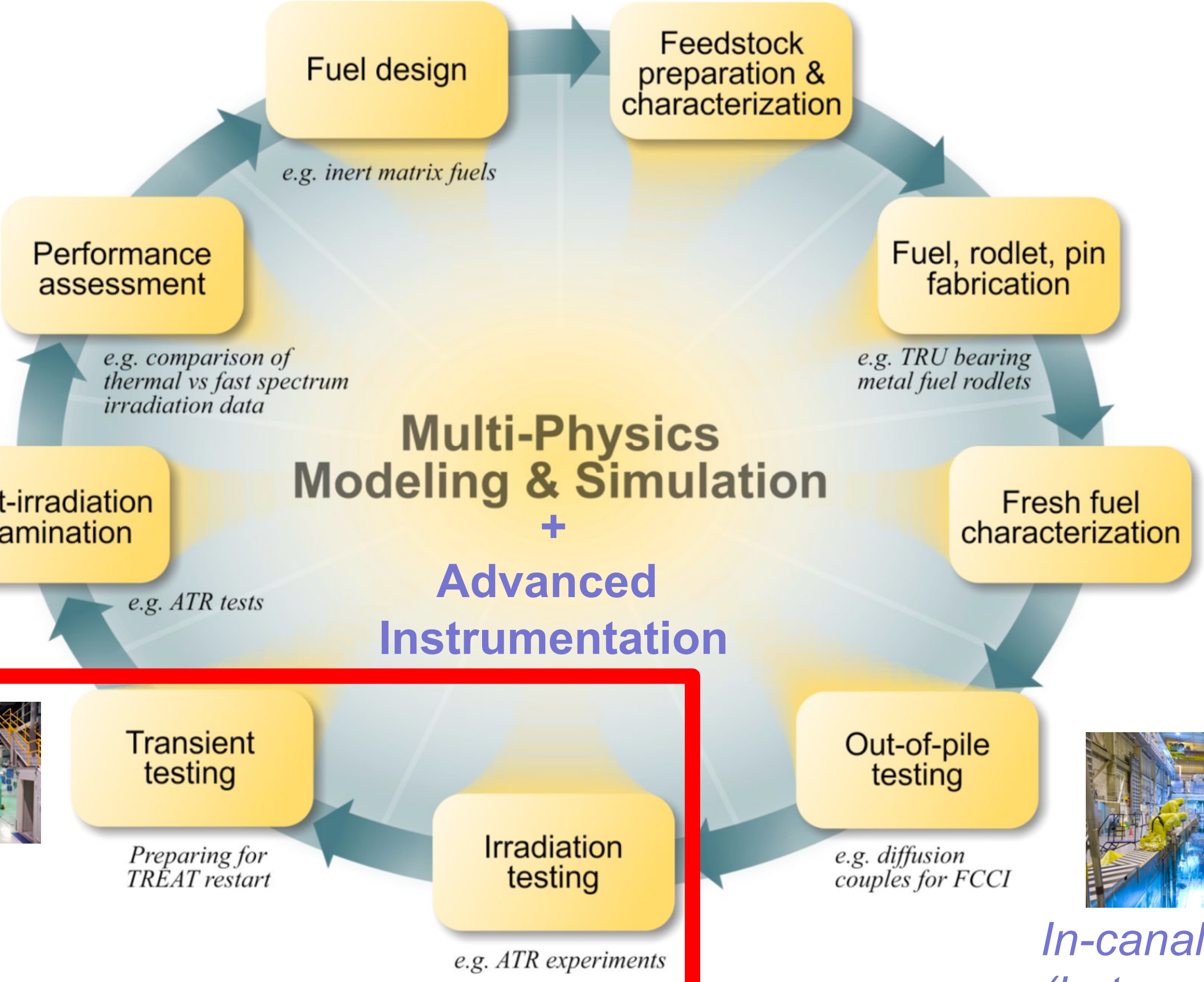
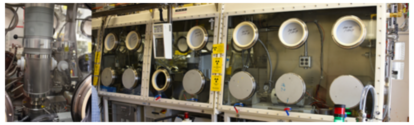
Key Elements of Fuels and Materials Development and Instrumentation Roles

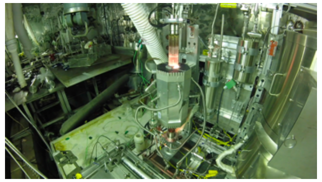


Advanced PIE Measurements





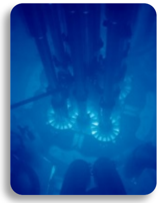
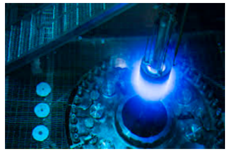
Material Properties and As-Built Data



Out-of-pile experiments (lab, glovebox, hot cell)

In-canal poolside (between cycles) exams

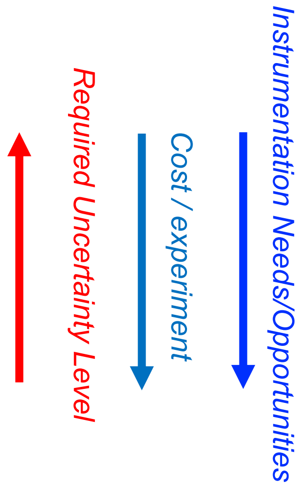
Presentation Focus

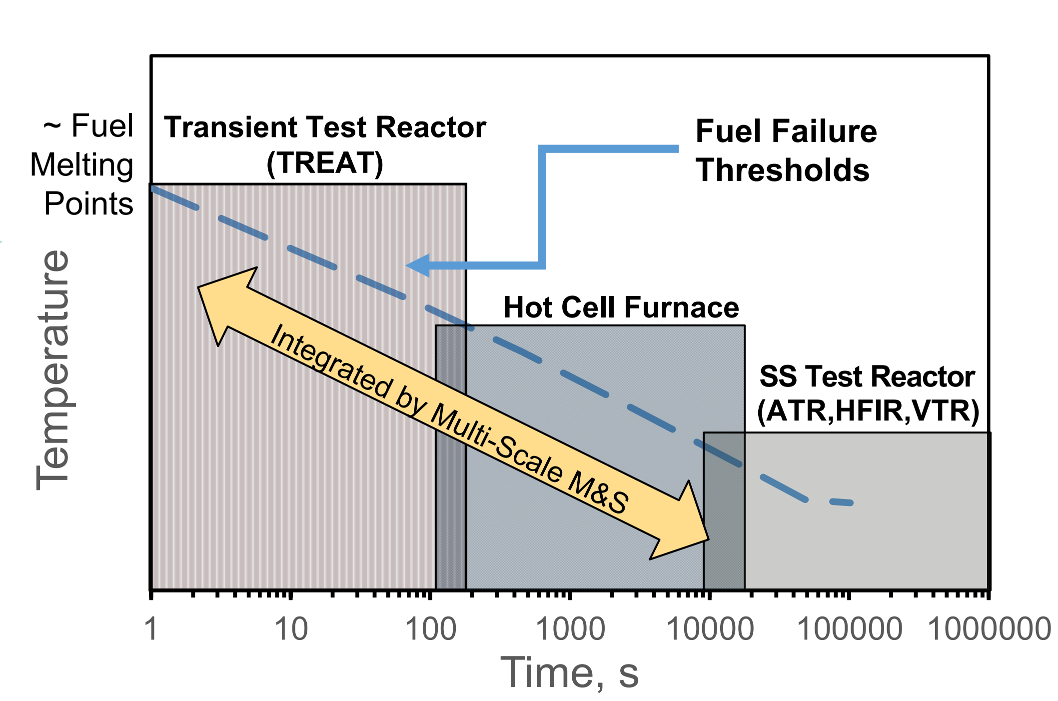




In-Pile Experiment Instrumentation

Experiment Classifications

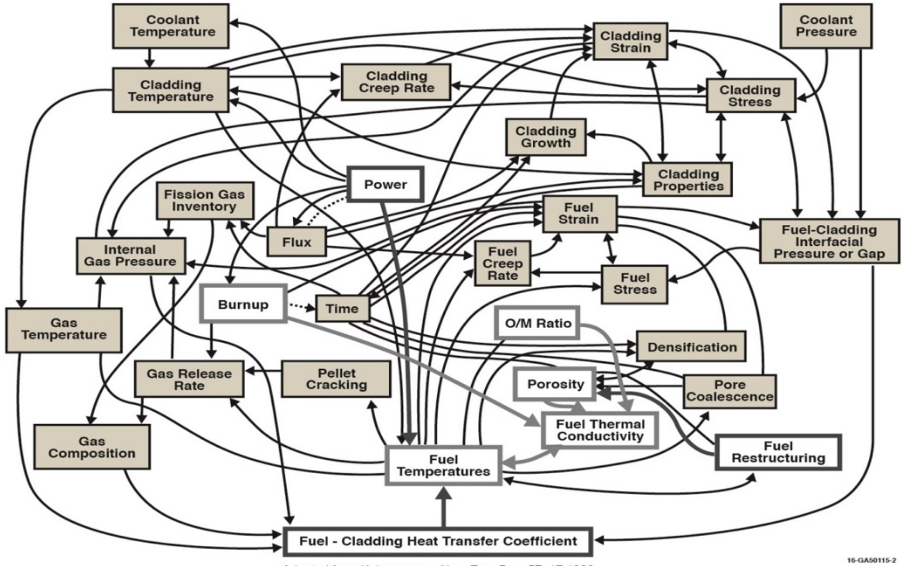
- **Fuels experiments span:**
  - time scales
  - length scales (micro to macro)
  - temperature scales (up to melting points)
  - neutron fluence
  - major irradiation facilities
  - reactor coolant environments, etc
- **Experiments require differing levels of instrumentation**
  - Screening evaluations – early technology evaluations
  - Analytic experiments - designed to target and measure very specific conditions and limits
  - Prototypic experiments – representative of application conditions
- **Objectives**
  - Develop predictive understanding of fuel behavior in normal and accident conditions
  - Identify and understand all life-limiting phenomena and potential failure mechanisms





Goals for Experiment Instrumentation

- **Goals for instrumentation**
  - Reduce uncertainty in key material behaviors and boundary conditions
    - In-reactor properties not the same as ex-reactor
    - Complex nature of fuel performance
    - Reduce quantity of required experiments with close support from modeling and simulation
  - Provide real-time evaluation of experiment performance – health and science



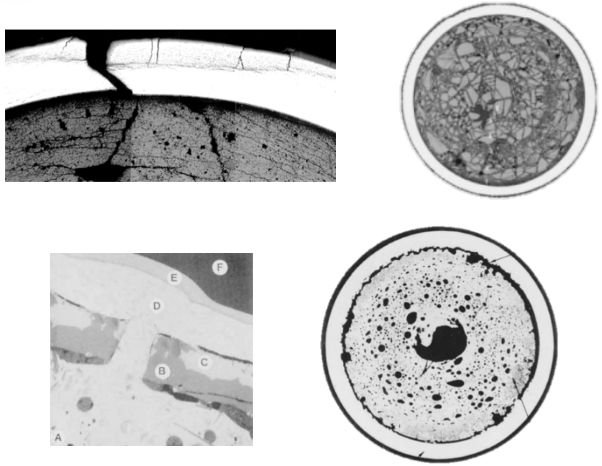
Adapted from K. Lassmann, Nuc. Eng. Des. 57. 17 1980

Pre-test

"State 1"

Post-Irradiation

"State 2"

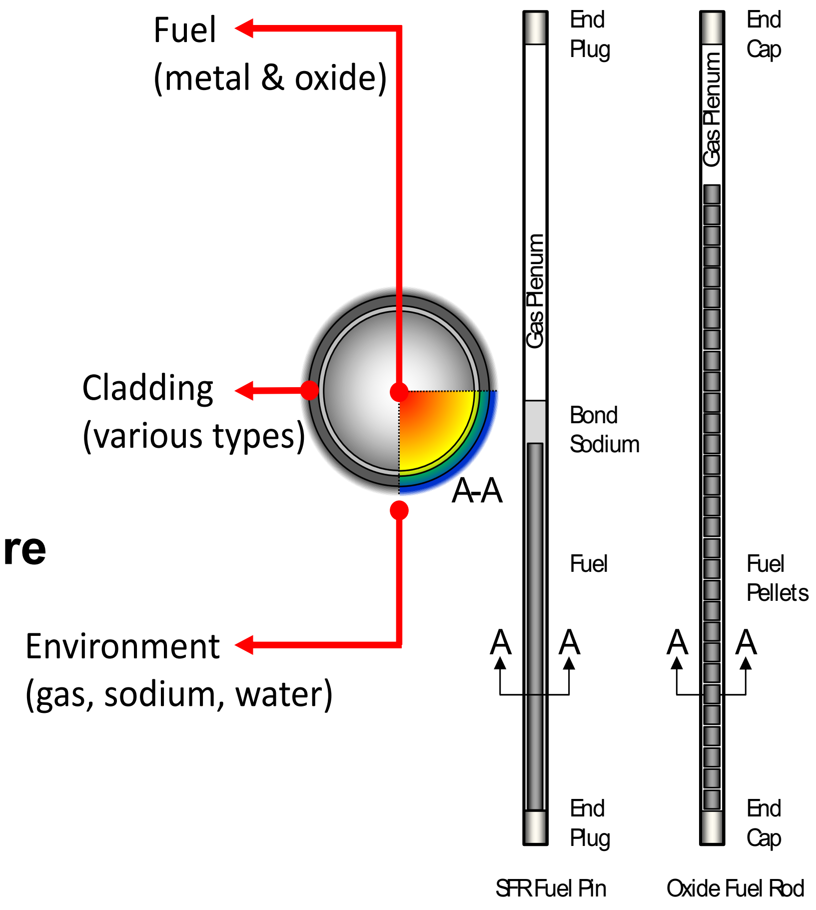


Desired Fuel Performance Measurements

Key Measurements supporting Fuel Technology Maturation

- Temperature is crucial independent parameter
  (… as well as composition and burnup)
- Dimensional changes
  - Swelling in cladding/fuel
  - Pellet Cladding Mechanical Interaction (PCMI)
  - Large scale deformation/fuel failure, dispersal
- Fission product behavior
  - Fission gas release (rod plenum pressure)
  - In-rod migration

- **And three primary boundary conditions: flux, temperature, pressure**
- **"Advanced" Opportunities: Chemistry, Microstructure, Properties**
  - Fuel Cladding Chemical Interaction (FCCI)
  - Constituent redistribution
  - Fuel restructuring
  - Thermal conductivity, etc
- *Later slide summarizes progress in many of these areas*



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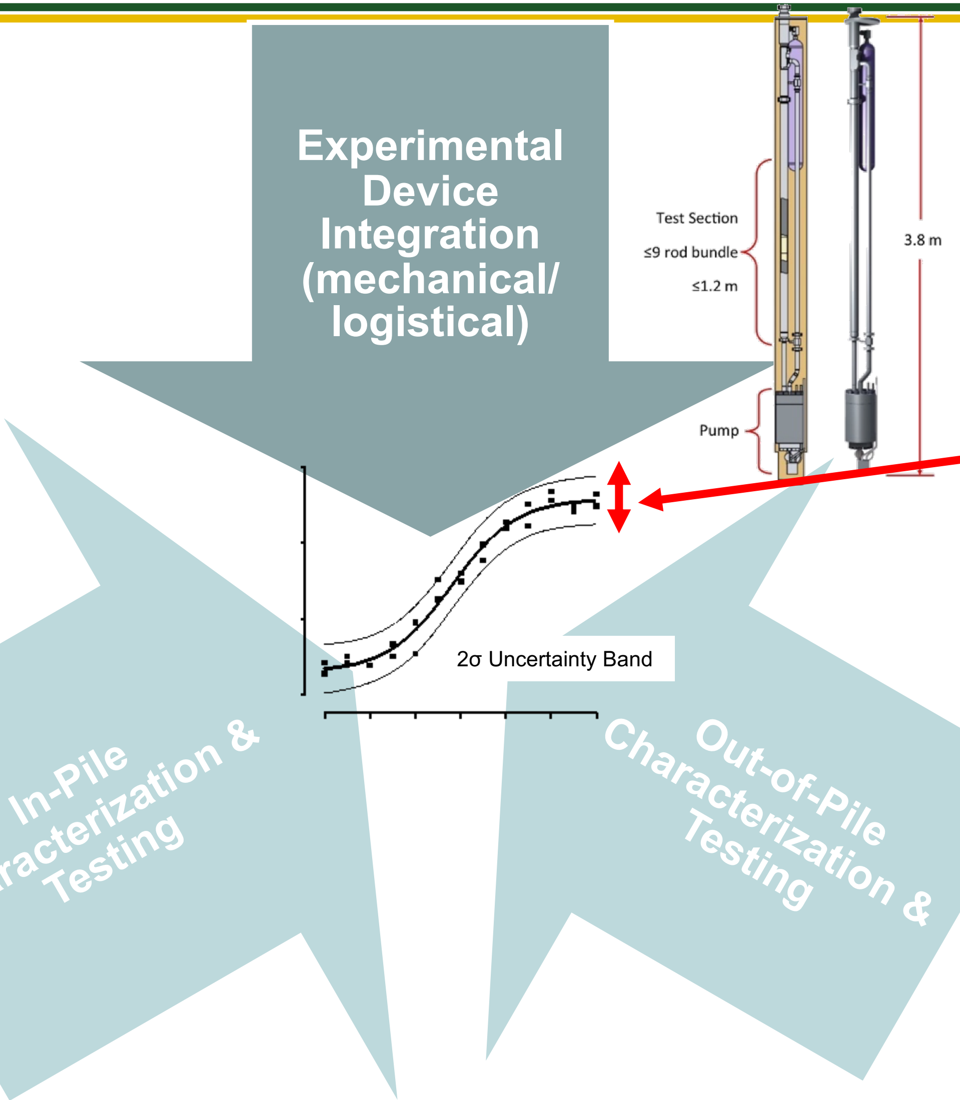
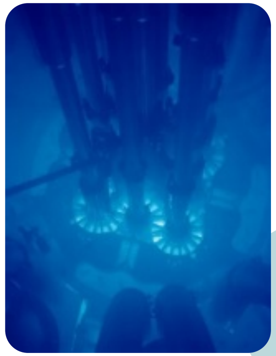
3 Instrument Qualification Focus Areas

Qualification: science-based approach to show an instrument will operate in established limits for its intended purpose



- Geometry
- Feedthroughs
- Connectors
- Leads

Adequate definition = GOAL!

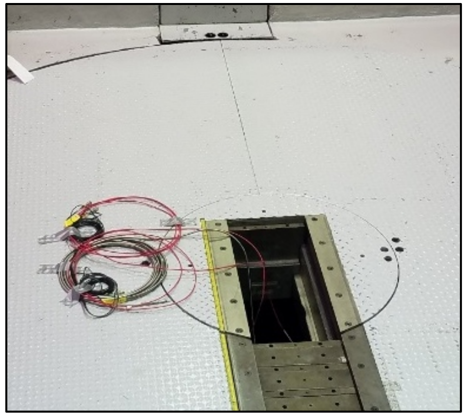


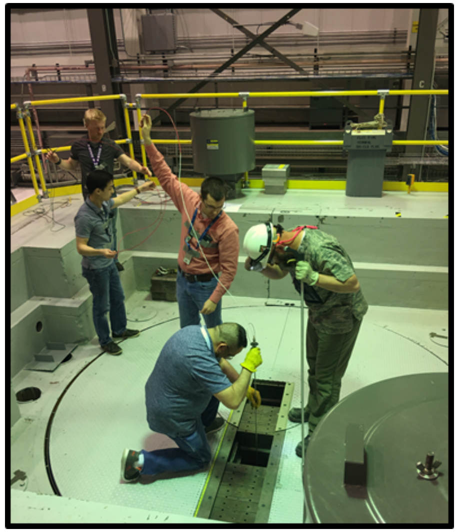
- Flux/fluence
- Electromagnetic environment
- Facility integration

- Temperature/Pressure
- Coolants
    - Chemistry/Flow
- Transient response

Continuous In-Pile Instrumentation Testing at TREAT

- **Sensors in pile since available in April 2018**
- **Developed flexible access approach - tremendous understanding gained over last 1.5 years**
- **Sensor insertion on the reactor top**
    - Optical Fibers – infrared pyrometers, distributed temperature sensors, Fabry-Perot sensors
    - Self-powered neutron/gamma detectors, miniature fission chambers
    - Thermocouples
    - LVDTs
    - Electrical impedance sensors





In-Pile Experiment Types

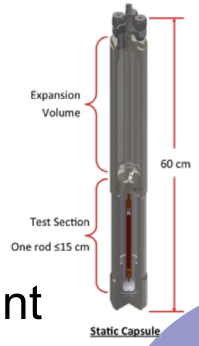
Reactors:

- ATR
- TREAT
- HFIR
- VTR (future)

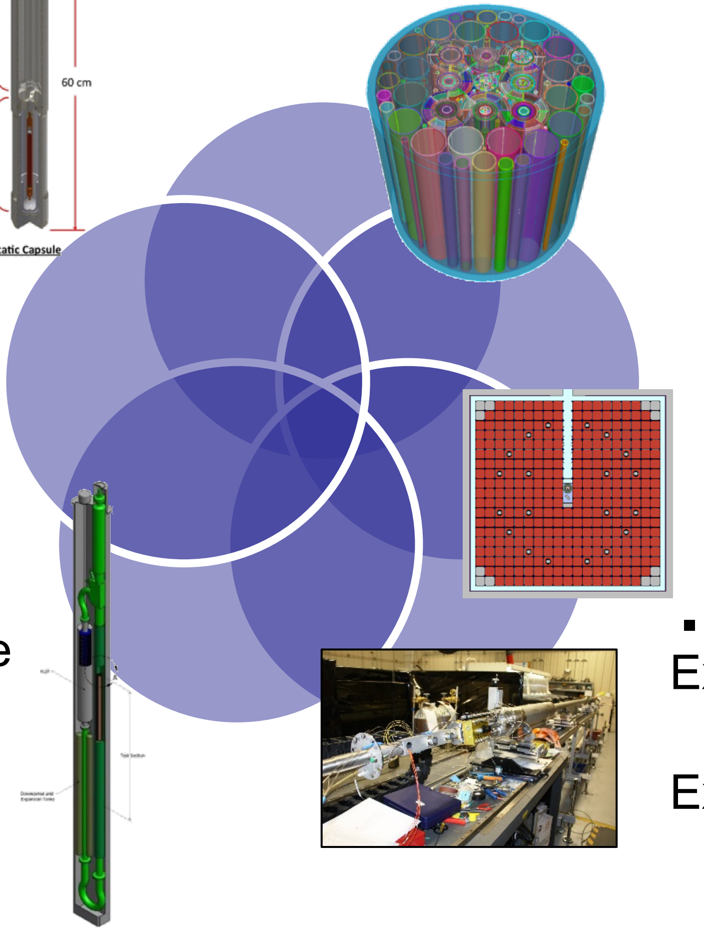
Environments:

- LWR
- SFR
- …

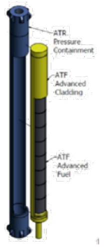
▪ Fuels
▪ Materials



▪ Static coolant
▪ Flowing coolant



▪ Steady-state (ATR, HFIR)
▪ Transient (TREAT)



▪ Drop-in device
▪ Integral TH system

▪ Prototypic Experiments
▪ Analytic Experiments

Fuels

- UO2, U3Si2
- U(Pu)Zr, UN, UC

Claddings

- Zirconium-based
- FeCrAl
- Silicon Carbide
- Austenitic Stainless
- HT9
- Many advanced alloys

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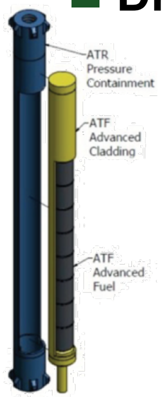
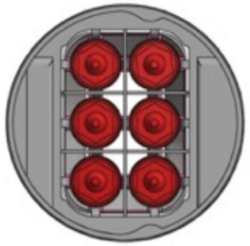
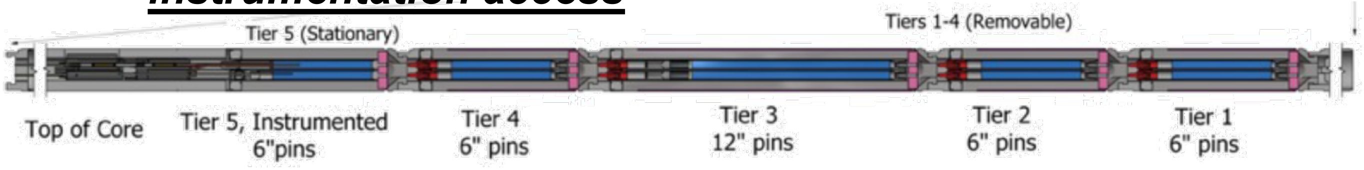
Primary ATR Experiments supporting LWR and Metallic Fuel Irradiations

- **Drop-in capsules in small-I and outboard A positions**
  - Early concepts, high throughput screening
  - Prototypic thermal and neutronic conditions
  - Scoping experiments for fuel and fuel-cladding interactions
  - ***No leadout*** instruments, passive instrumentation – SiC, melt wires
  - ATF-1 (LWR) and AFC (metallic fuel) experiments

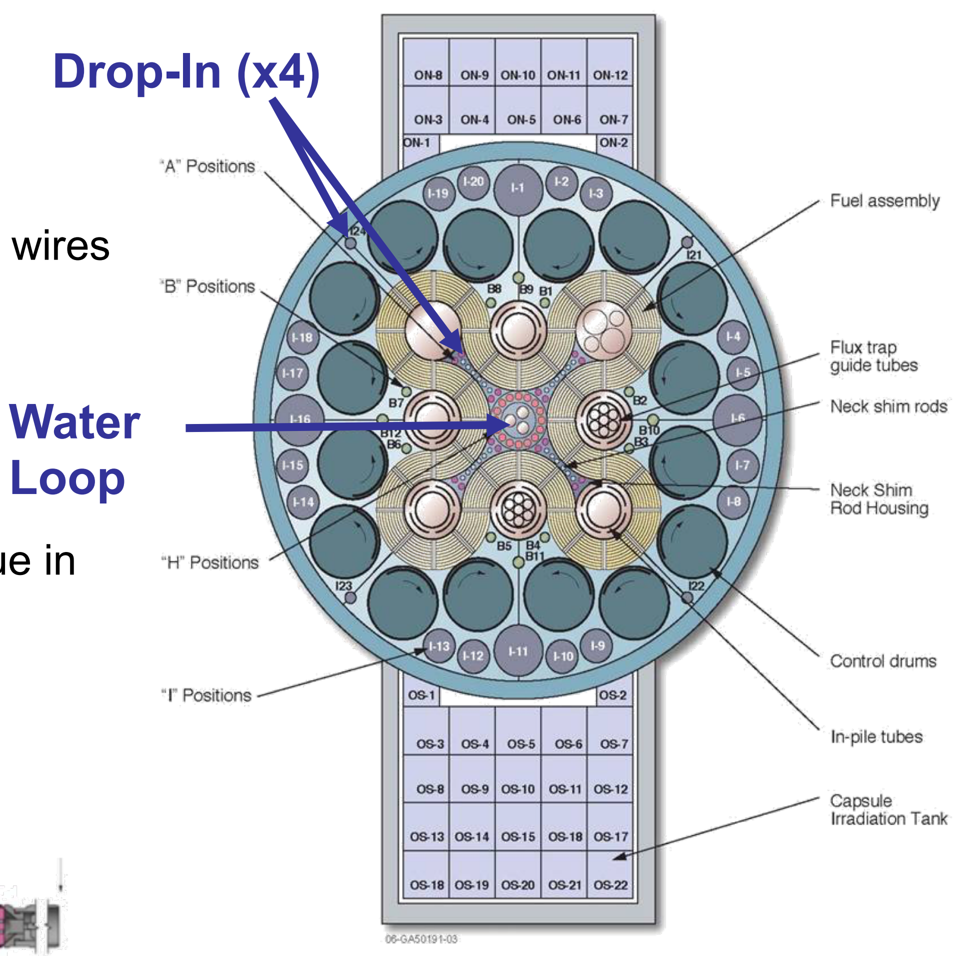


- **PWR flowing water loop in Center Flux Trap**
  - ATF-2 integral fuel tests
  - Prototypic thermal-hydraulic and neutronic conditions – unique in the western world!
  - High flux (~25-40 kW/m LHGR)
  - Prototypic experiments for confirmatory/qualification data
  - Currently 5 axial tiers, top tier designed to support ***online instrumentation access***





Advanced Test Reactor



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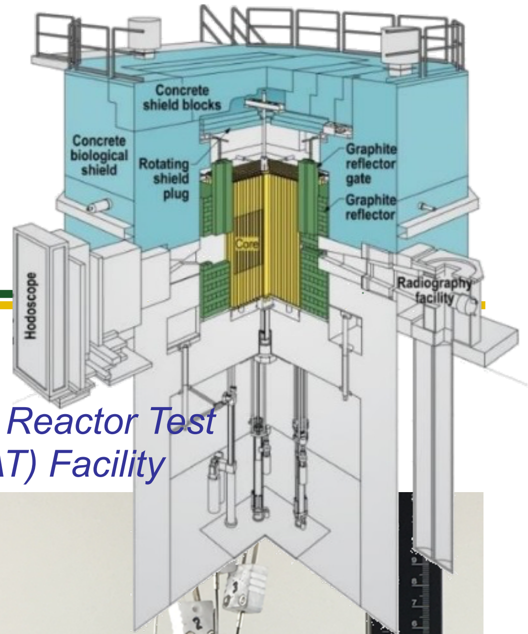
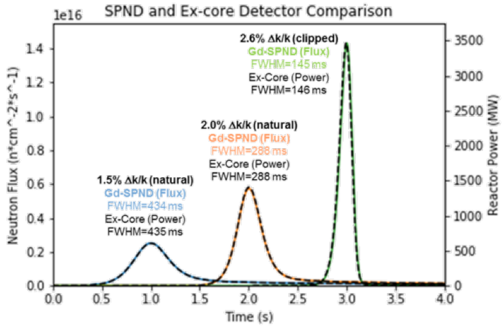
Recent TREAT Experiment Example



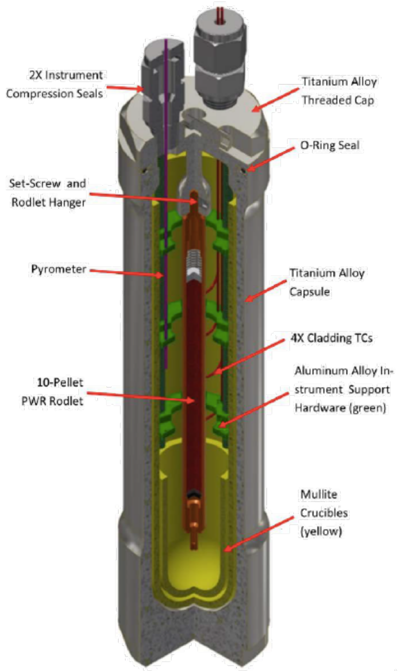
Transient Reactor Test (TREAT) Facility

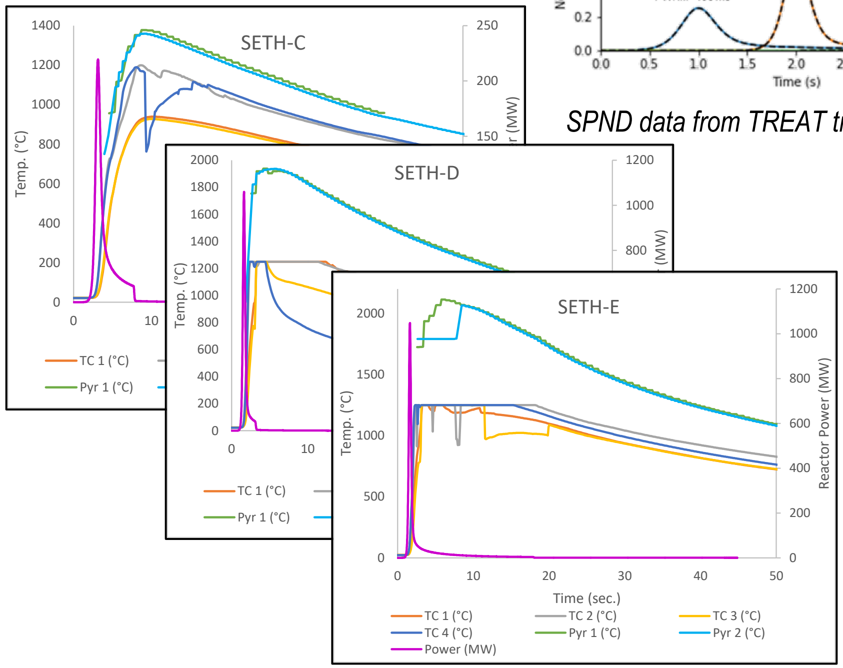
■ First fueled experiments in 2018, "SETH ATF" Experiments

- RIA fuel experiments in dry capsule
  - Thermocouples
  - Infrared pyrometer
  - Self-powered neutron detectors

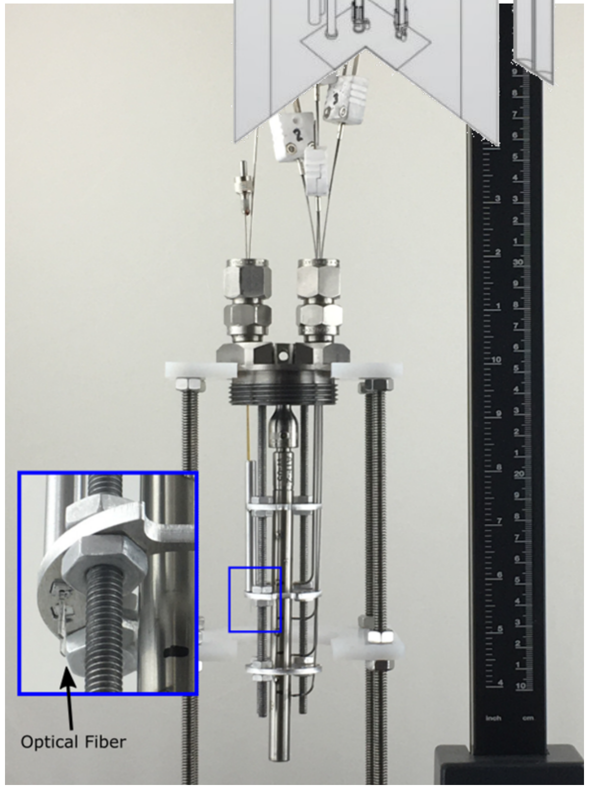


SPND data from TREAT transients





- ■ **650 J/g (SETH-C)**
- ■ **960 J/g (SETH-D):**
  - As intended, just barely reached cladding melting temperature (electronics-free calorimetry)
- ■ **1300 J/g (SETH-E):**
  - Really melted the cladding
- ■ **SETH-H & -I**
  - First U3Si2 pellet tests
  - PIE forthcoming, all indications are that fuel pellets were melted

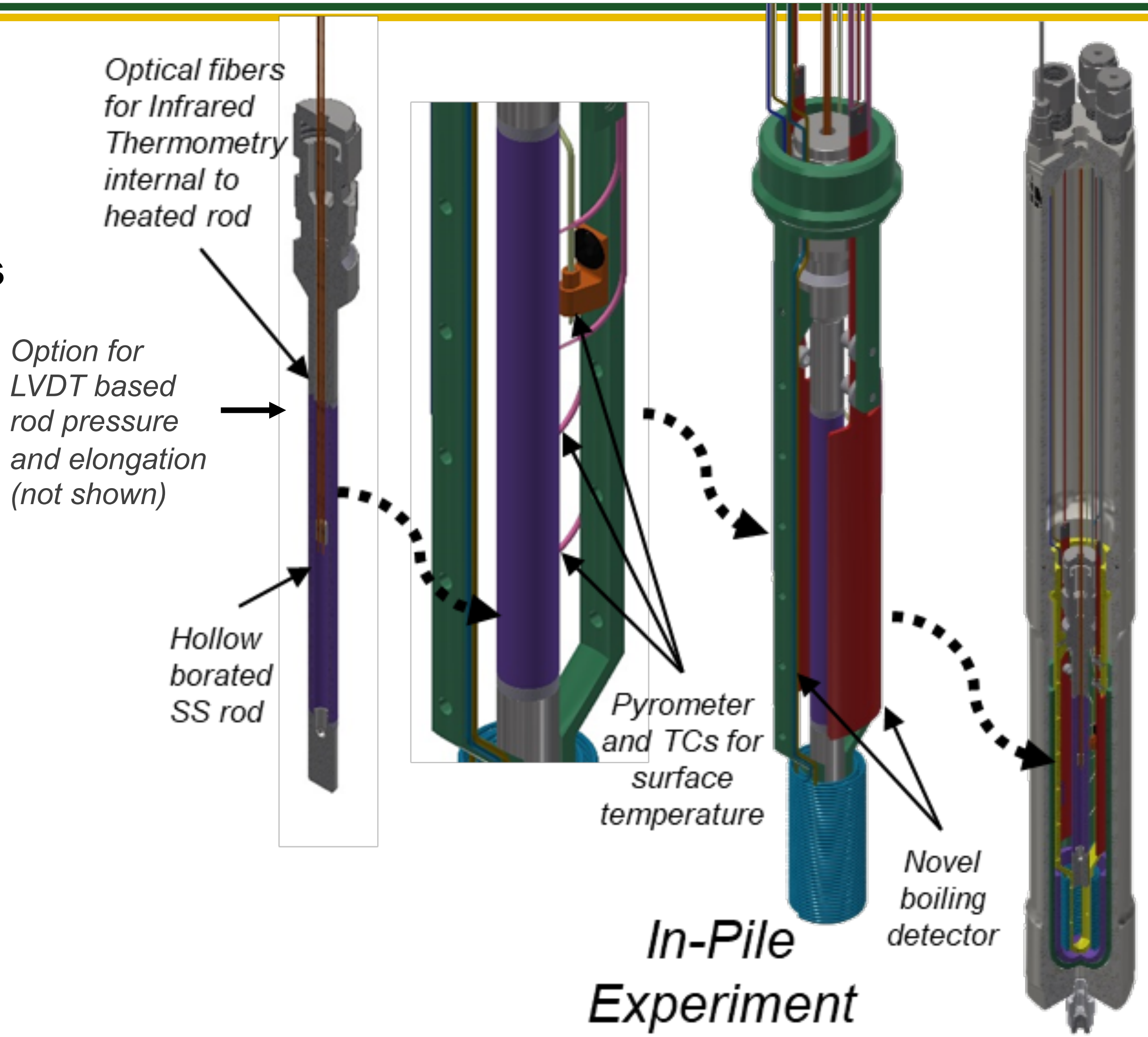


ATF SETH experiments: study specimen energy coupling with TREAT

TREAT Water Capsule Experiment Example

- **MARCH-SERTTA module for water-submerged rodlet testing**
- **Conaxes for up to 12X 1mm leads**
- **Current instrumentation package includes significant instrumentation**
  - Electrical-Impedance Boiling Detector
  - IR pyrometer
  - Surface thermocouples
  - Acoustic sensor
  - LVDT-based rod pressure/elongation
- **First experiments in December**

- **More devices on the horizon for flowing water and static and flowing sodium**



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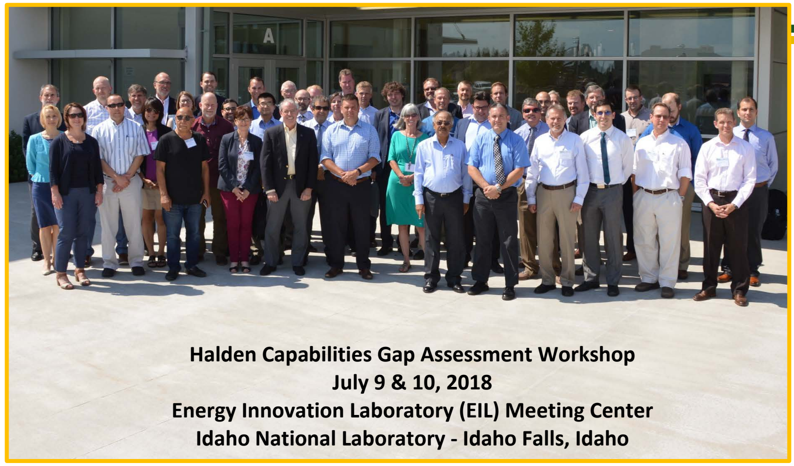
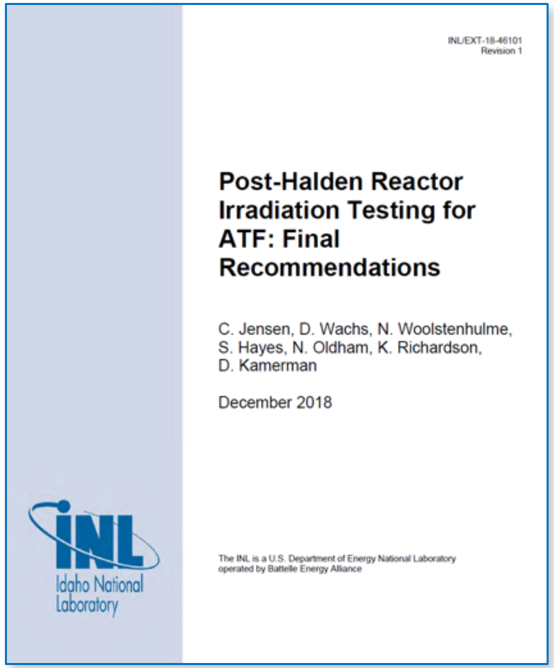
Halden Gap Assessment/Recommendations to Support ATF




INL/EXT-18-46101
Revision 1

Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations

C. Jensen, D. Wachs, N. Woolstenhulme, S. Hayes, N. Oldham, K. Richardson, D. Kamerman

December 2018

INL Idaho National Laboratory

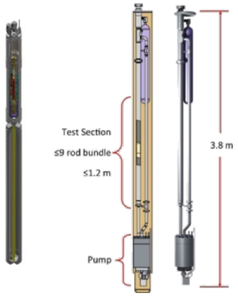
The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

RECOMMENDATIONS

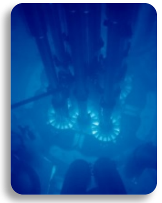
1) Accelerate LOCA testing capability at TREAT

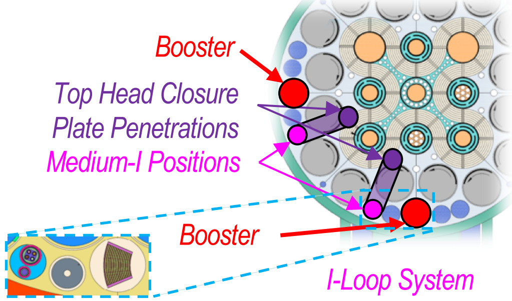
Devices for prototypic LWR design basis accident conditions

TREAT



2) Expand water loop capacity with ramp testing capability at ATR



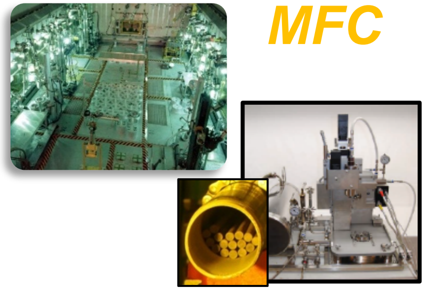


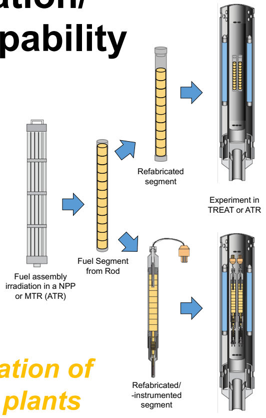
ATR

Prototypic environments for operational transient experiments to failure and BWR conditions

3) Establish re-fabrication/ instrumentation capability

MFC

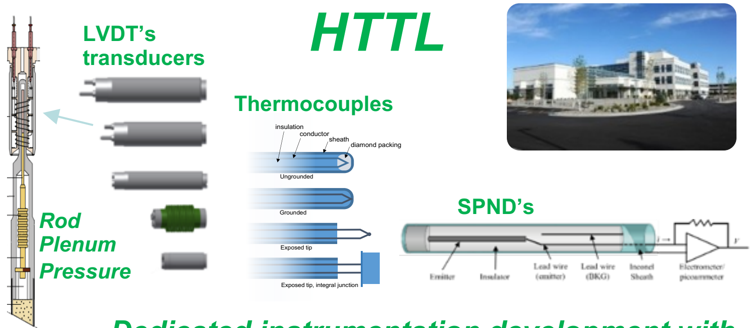




Refabrication and reinstrumentation of fuel irradiated in nuclear power plants

4) Deploy reliable advanced in-pile instrumentation

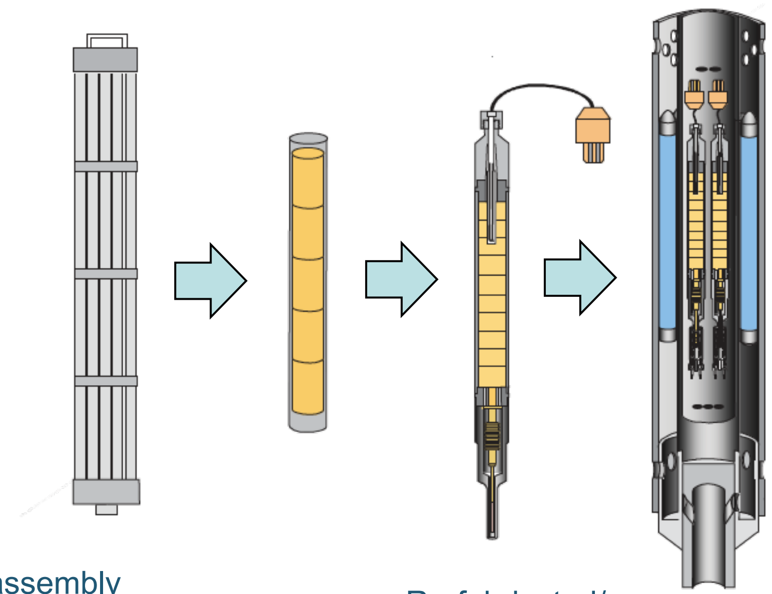
HTTL



Dedicated instrumentation development with specific focus on in-pile test reactor deployment

Instrumenting Highly Irradiated Fuels and Materials

- **Fuel rod reinstrumentation capability is the <u>KEY</u> to make this work**
  - Well established approach for LWR fuels
  - Not done in the U.S. DOE laboratories in > 3 decades
  - Target specific segments and resize rods for further testing
  - Ability to add instrumentation to high burnup materials
  - Adding instruments allows measuring fuel performance parameters late in life under steady state conditions, i.e. centerline temperature, fission gas release
  - Perform experiments to evaluate operational and off-normal transient conditions, i.e. ramp testing, cladding liftoff, power to melt, RIA, LOCA
- **Working with NEET ASI to establish domestic capability as a result of post- Halden recommendations**



Irradiated UO2

What instrumentation is working for AFC?

- **Passive, leadless methods – melt wires, SiC, flux wires**
  - Gap – always looking for ways to get more from these approaches
- **Thermocouples – cladding surface, fuel centerline, coolant**
  - Gap – reliable in-core, fuel-rod feedthrough, preirradiated fuel application
- **Self-powered neutron detectors – local power/flux**
  - Gap – limited use in ATR to date, affordable source for nonstandard emitter types
- **LVDT-based sensors – fuel & cladding elongation, rod pressure**
  - Gap – limited use in ATR to date, Halden is primary supplier to date, preirradiated fuel application
- **Optical fibers – non-contact temperature measurement, distributed temperature sensor, Fabry-Perot sensors**
  - Gap – further establish high fluence reliability, delicate handling logistics, versatile feedthrough options, preirradiated fuel application
- **Electrical Impedance Sensor – coolant phase change, cladding deformation**
  - Gap – In-pile performance evaluations in TREAT
- **Variety of commercial sensors – acoustic, pressure, temperature at TREAT** – gap in-pile evaluation in TREAT

- **Other current direct interests (not comprehensive)**
  - Diameter gauge (similar to Halden) – still desire less-intrusive approach to measure fuel rod radial deformation for TREAT and ATR
  - Sodium flow meters for small loops and flow tubes in TREAT
  - High speed (<1ms), high temperature (500C), in-core pressure transducers for TREAT
  - High temperature fuel centerline (to UO2 melting point) – UT sensor?
  - "Experiments designed as measurement systems" – unique designs to enable advanced measurements
- **Close integration with NEET ASI development on many related topics**
- **Development opportunities? specified on next slide**

Challenges and Opportunities

- **Environment resistance** – irradiation (fluence – ATR, flux – TREAT, temperature, pressure, material compatibility)
- **Non-intrusiveness** – non-contact, non-destructive application
- **Miniaturization** - facilitates proximity to specimen and experiment integration
- **Remote application** – facilitate installation onto pre-irradiated specimens, reinstrumentation technique
- **Connectors and feedthroughs** – required by long leads, complicated logistics, pressure/hermetic boundary penetrations
- **In-core electronics** – wireless connectors, in-core options, signal conditioning, ADC, enable more signals to/from experiments
- **High resolution in space and time**
- **Reliable calibration with practical implementation**
- **Handling and transport of experiments** – not as gentle as one may hope

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Summary

- **Close relationship to in-pile instrumentation with ongoing development**
  - ATR
    - Drop-in capsules for LWR & SFR fuels – Passive (no leads) point or integral monitors
      - Instrumented SFR capsule desired (currently lacking resources)
    - Current LWR loop experiments with options for fuel temperature, rod internal gas pressure, fuel and cladding elongation – others possible needing some additional qualification testing
    - Planned LWR loop experiments to focus on enabling instrumentation access and integration with fuel rod refabrication and reinstrumentation capabilities
  - TREAT
    - Wide range of devices under development and deployed in capsule devices
    - Planned LWR loops, SFR capsules and loops
    - Fuel Motion Monitoring System (Hodoscope) is working and is crucial to transient experiment objectives
- **Primary challenges and gaps for in-pile instrumentation are integration into experimental devices, assembly and logistics, and in-pile environments.**
- **Working closely with industry R&D partners to establish needs and the NEET ASI program to leverage x-cutting technologies that support test objectives and instrument maturation**

Contact for AFC in-pile instrumentation:

Colby Jensen, colby.jensen@inl.gov

Reactor Characteristics for Instrumentation

- **ATR (Steady-state test reactor)**
  - Environments span range of LWR and SFR needs
  - Instrumentation integrated in experiment test train, must pass through pressure boundary feed through
  - Dimensionally constrained to small circular cross-sections consistent with fuel rod diameters ~5-10mm and ATR positions ~15-38mm (test train hardware further limits space)
  - Max fluence (10^{20}-10^{23} n/cm^2) currently typical objective (alleviated for instrumentation by refabrication)
  - Peak flux ~ <10^{15} n/cm^2
  - Experiment logistics are non-trivial – removals and reinsertions likely required
  - Lead wire access to from vessel to core requires support structure
  - Limited to ~25 lead wires
  - Generally expect more greater overall effort/cost to integrate into a very complex and high performance system

- **TREAT (Transient test reactor)**
  - Dry core (air) design provides variety of options for access with many ports around the core
  - Experiment environments may be quite harsh (postulated reactor accident conditions) and varied (gas, liquid; H2O, Na, ..)
  - Experiments typically arrive in packaged-devices with instrumentation, inserted into center core location; integration of instrumentation into experiment devices is generally non-trivial (feedthroughs, size constraints, etc.)
  - Peak neutron flux ~ <10^{17} n·cm^{-2}·s^{-1}
  - Max neutron fluence ~ <10^{16} n·cm^{-2}
  - Gamma heating may be very high (~150 ΔK for stainless steel)
  - Response time and data acquisition rates are crucial for many experiment objectives
  - Relatively short wire runs (~10-20 m)
  - Design features provide flexible platform for in-pile instrumentation R&D