In-Pile Instrumentation program

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Idaho National Laboratory

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Program mission

Establish baseline and novel instrumentation for in-pile applications that can provide real-time, accurate, spatially resolved information regarding test conditions and the performance of fuels and materials during irradiation

The In-Pile Instrumentation Initiative received funds in FY17 and FY18 to establish the program structure, organization and research plan

Sept 2018

Program mission: provide real time measurements

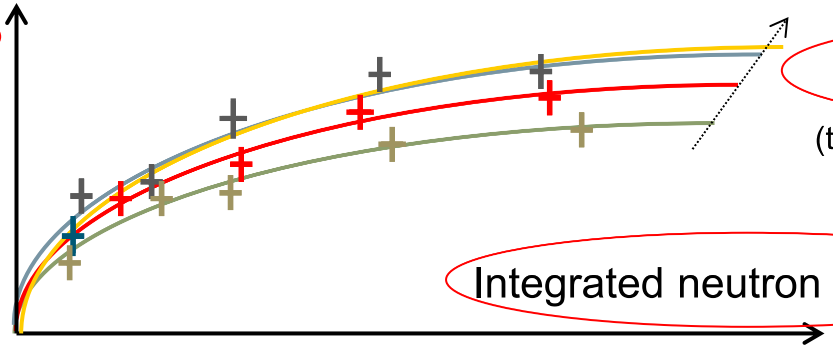
Real time in-pile measurements are essential to:

1. **Monitor the experiments**

Objectives of experimentation:
Assess / verify / increase the precision of behavior laws under irradiation

Studied property

(ex : fragility, cracking, corrosion, conductivity, etc.)



Influence parameter

(temperature, physicochemical conditions, etc.)

Integrated neutron flux / dose → Damages Burn-up

→ All these parameters must be accurately measured !

2. **Watch performance/safety parameters**

= check that some specified parameters stay in their acceptable range (e.g. : temperature, pressure, etc.)

Program mission: parameters of interest

Field properties (test conditions)

- Neutron flux / dose
- Temperature
- Pressure
- Physical chemistry
- Nuclear heating

Tensor properties (materials performance)

Thermal properties

- Thermal conductivity

Mechanical properties

- Creep testing (deformation vs mechanical loading)
- Crack growth / void formation
- Swelling

Chemistry

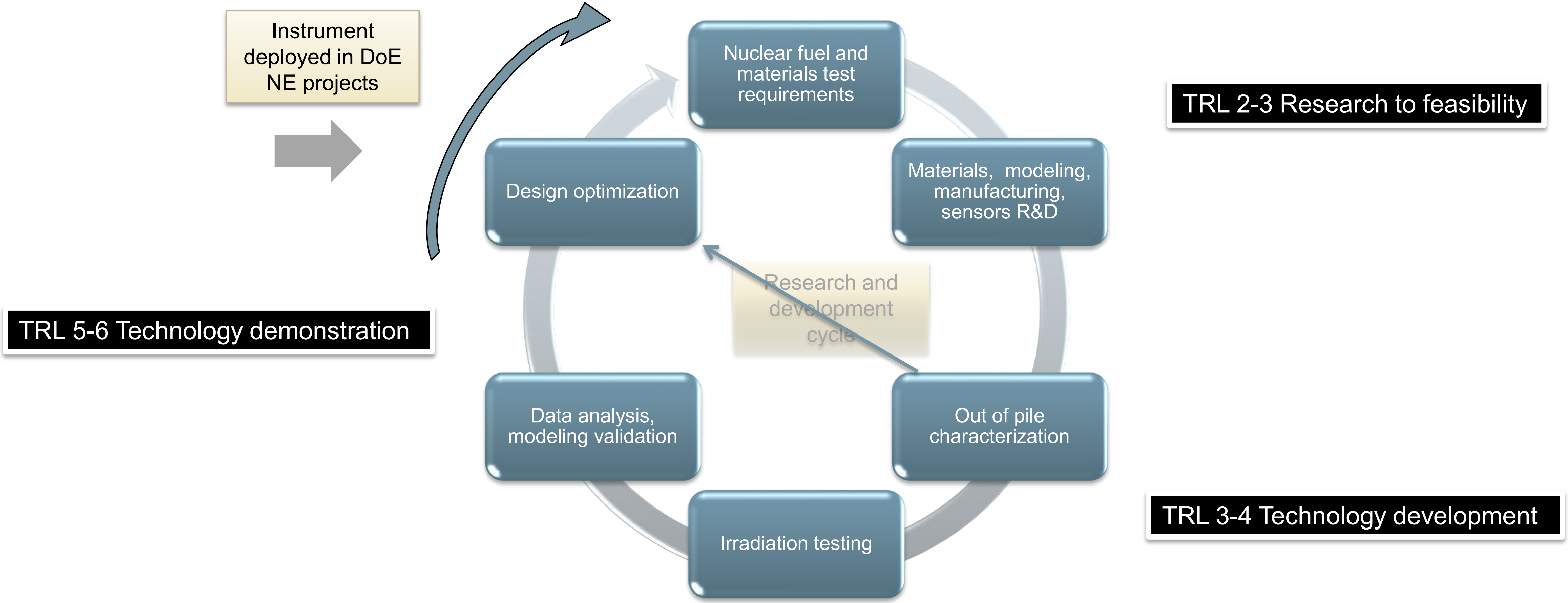
- Hydride formation and corrosion
- Crud build-up

Fuel structure and properties

- Fission gas release
- Fuel cladding interaction
- Microstructure evolution

Program mission evolution

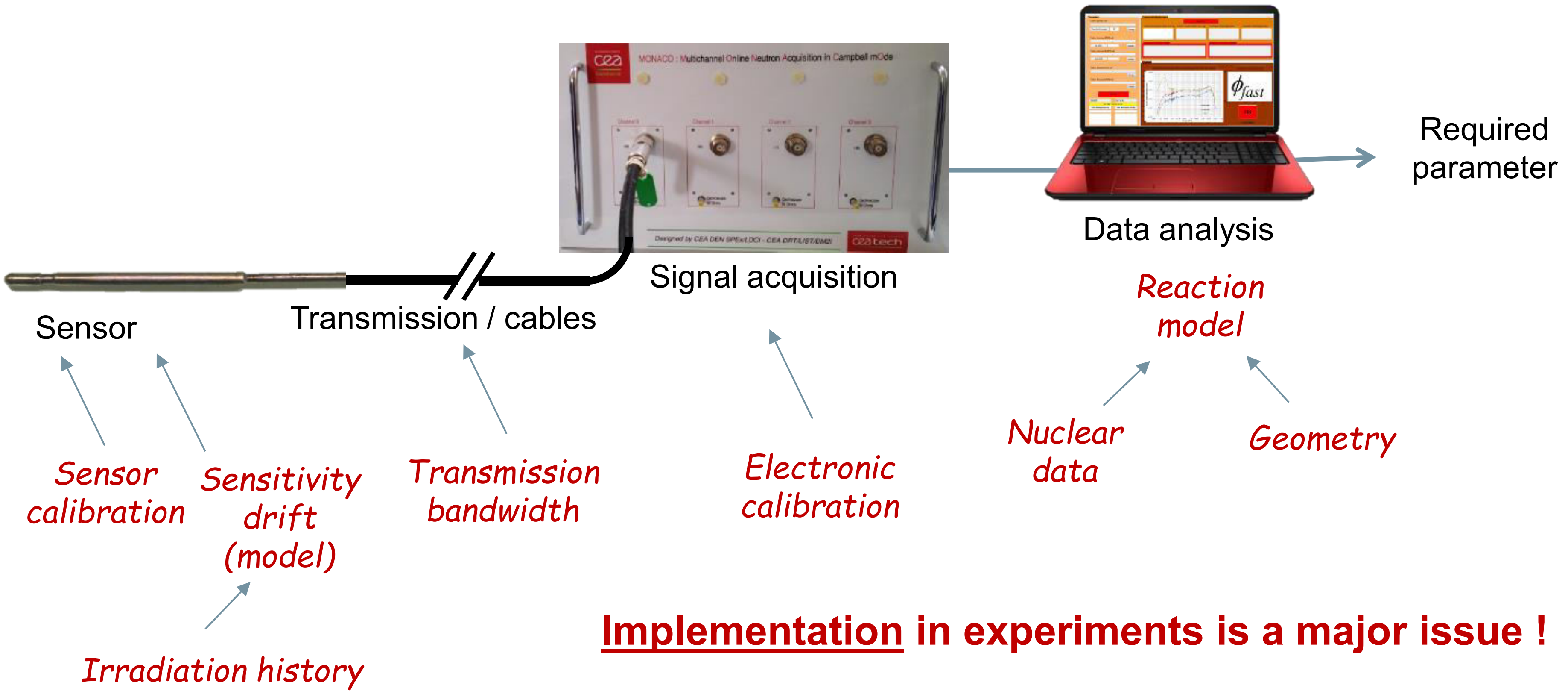
The In-Pile Instrumentation Initiative was conceived in response to weaknesses in the approach to nuclear instrumentation development in support of nuclear fuel and materials irradiation tests as part of DoE NE programs (2015 D. Petti / K. Pasamehmetoglu)



In-Pile Instrumentation requirements

- **High accuracy necessary** to meet scientific requirements

Many factors have an impact on measurement accuracy !



Implementation in experiments is a major issue !

In-Pile Instrumentation requirements

- **High accuracy necessary** to meet scientific requirements
- **High constraints** related to reactor conditions:
  - constraints due to irradiation (high neutron and gamma flux: material damages, composition changes, parasitic signal, etc.),

→ ***transmutations*** *: composition changes*

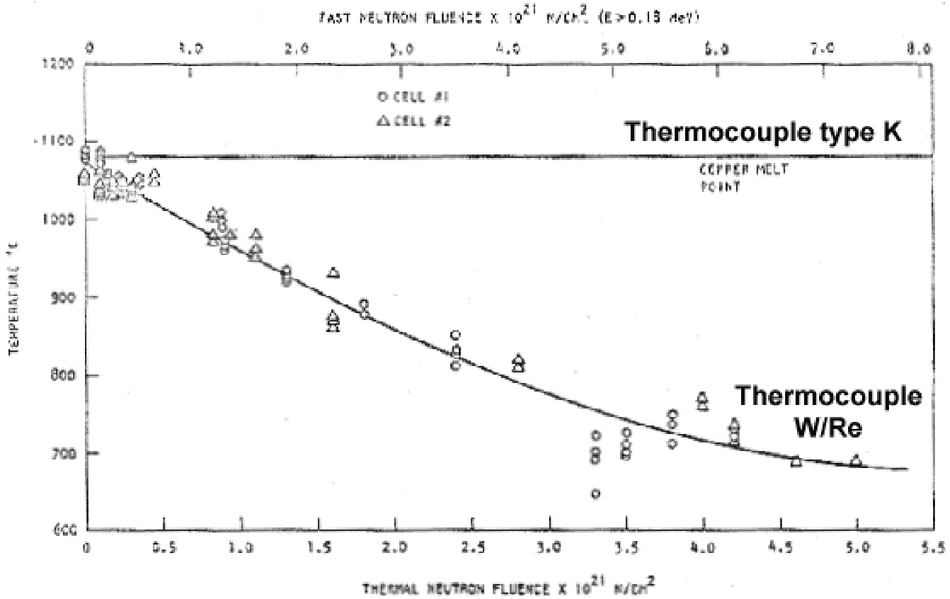
→ ***damages :***

- alteration of electric insulators

- change in material properties (mechanical, optical, electric, magnetic, thermal)

→ ***noise current*** *(EM, compton and photoelectric effects)*

→ ***heating***



Drift of thermocouple signal under MTR irradiation

In-Pile Instrumentation requirements

- **High accuracy necessary** to meet scientific requirements
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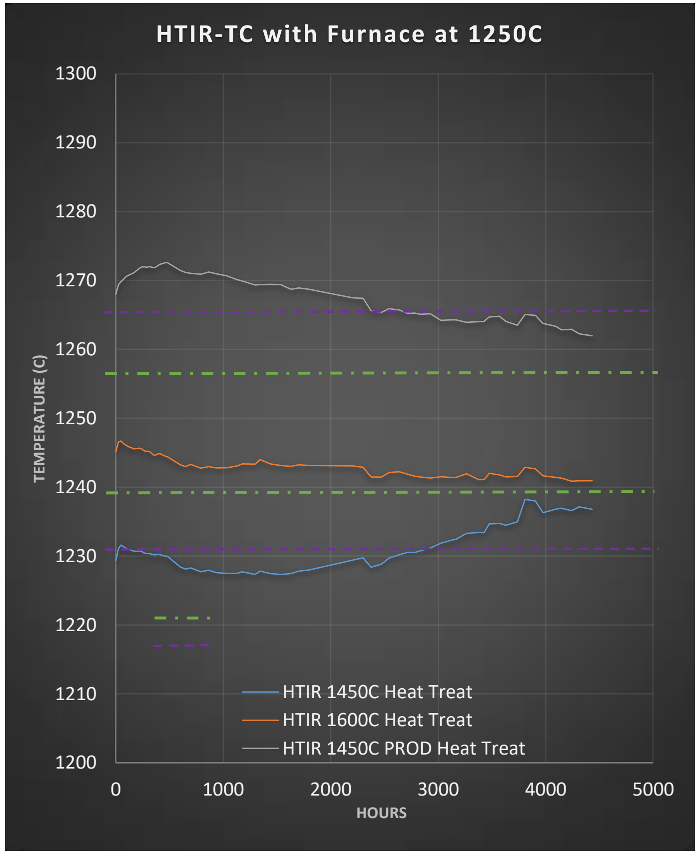
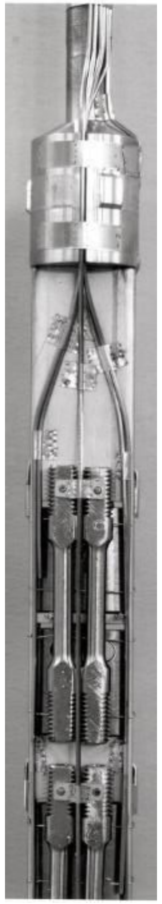
  - constraints due to irradiation (high neutron and gamma flux: material damages, composition changes, parasitic signal, etc.),
  - constraints due to physical chemical conditions in experiments (high temperature, pressurized water, liquid metals, etc.)



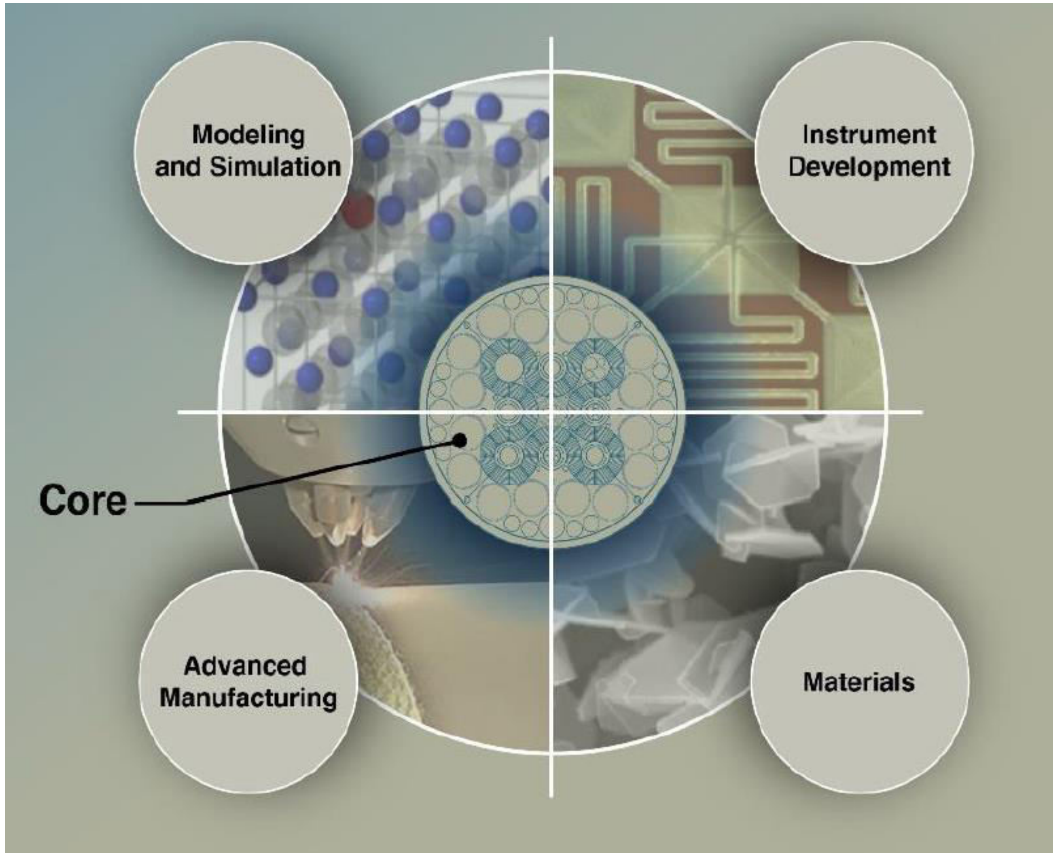
In-Pile Instrumentation requirements

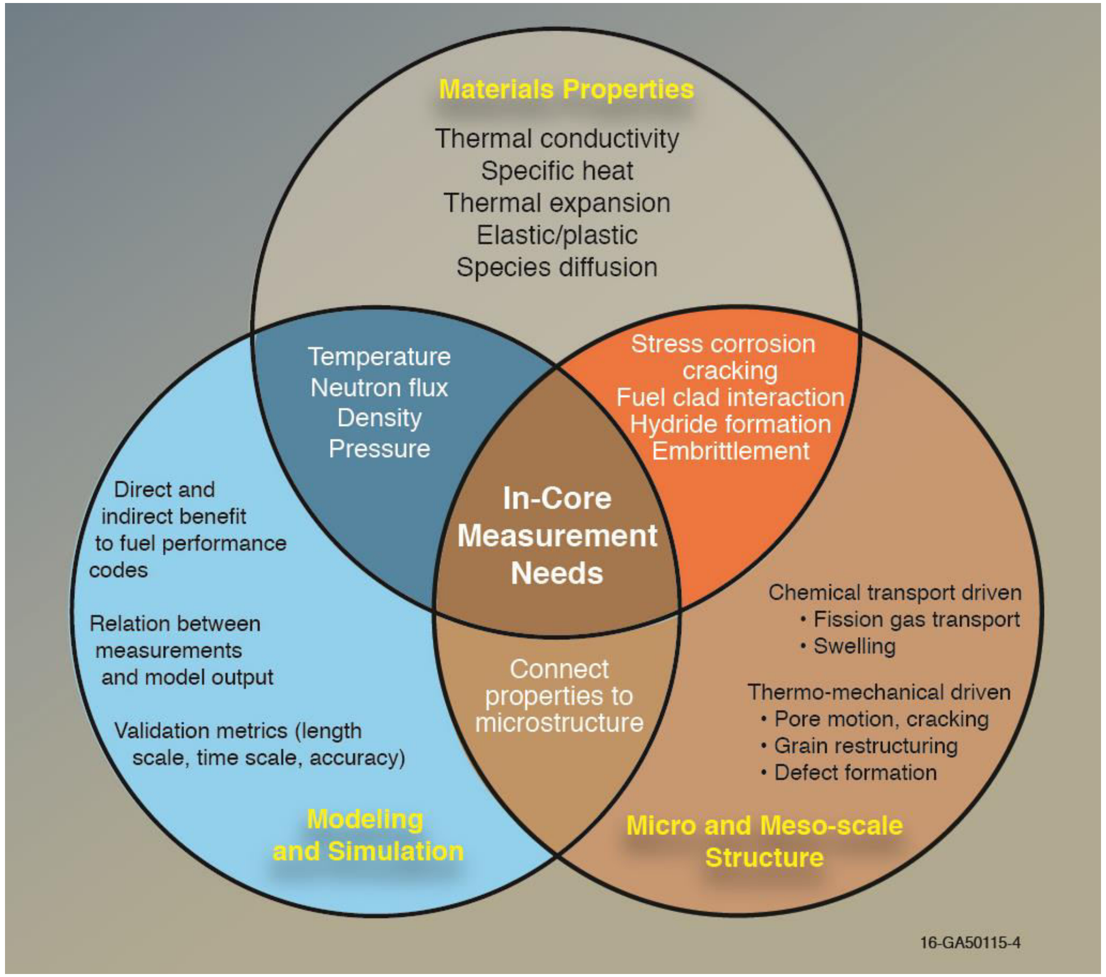
- **High accuracy necessary** to meet scientific requirements
- **High constraints** related to reactor conditions:
    - constraints due to irradiation (high neutron and gamma flux: material damages, composition changes, parasitic signal, etc.),
    - constraints due to physical chemical conditions in experiments (high temperature, pressurized water, liquid metals, etc.),
    - constraints due to integration (miniaturized sensors, long distance between sensors and electronics, etc.),
    - constraints due to operation (high reliability required because of difficult or impossible maintenance or replacement of irradiated instrumentation).



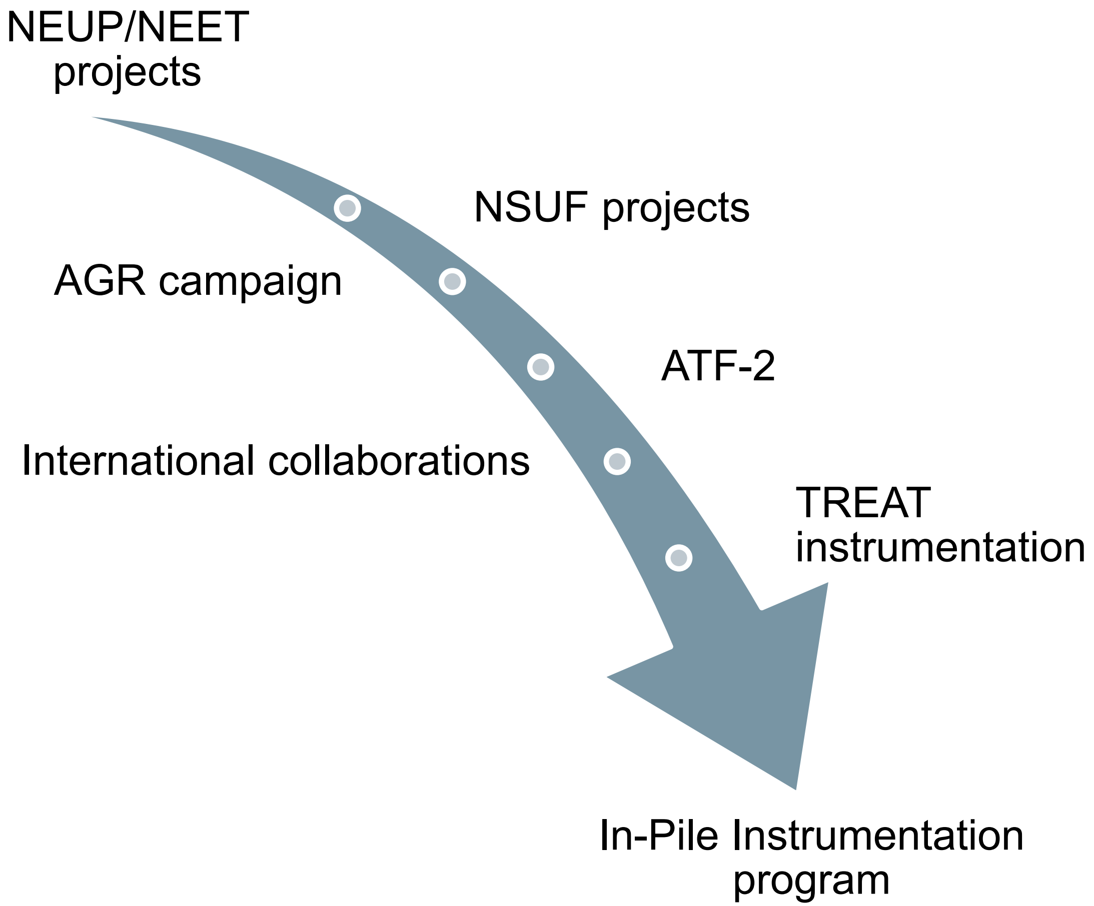
Program mission: science based approach for material properties

A science-based approach with emphasis on material science, advanced manufacturing and modeling and simulation was formulated to develop the Initiative technical plan (2016 B. Hallbert)



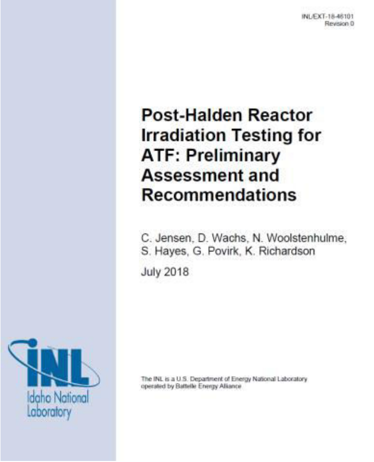


Program mission: DOE NE activities consolidation



The end of operation of the Halden Boiling Water Reactor (HBWR) creates an imperative to accelerate the support to DoE NE programs

- The HBWR capitalized on historical experience in U.S. test reactors, where dedicated instrumentation groups were key to the deployment of targeted irradiation experiments for nuclear fuel and materials development
- The HRP model is based on the seamless integration of a single, reliable instrument (LVDT) in standardized irradiation rigs focused on integral fuel pin tests in carefully monitored PWR conditions
- The development of infrastructure specific to targeted test facilities is an essential enabling component: the Initiative started with TREAT, need to expand to steady-state reactors (ATR, HFIR, MITR) and continue international collaboration (BR2, CEA)
- The success of the in-pile instrumentation program used at Halden is closely linked to their capability to remanufacture, instrument, repair, and recalibrate instrumentation on irradiated fuel rods


INL/EXT-18-46101
Revision 0

Post-Halden Reactor Irradiation Testing for ATF: Preliminary Assessment and Recommendations

C. Jensen, D. Wachs, N. Woolstenhulme, S. Hayes, G. Povirk, K. Richardson

July 2018

Idaho National Laboratory

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

Program mission

Establish baseline and novel instrumentation for in-pile applications that can provide real-time, accurate, spatially resolved information regarding test conditions and the performance of fuels and materials during irradiation

Sept 2018

The In-Pile Instrumentation Initiative received funds in FY17 and FY18 to establish the program structure, organization and research plan

In-Pile Instrumentation program structure

Baseline capability: qualify instrumentation for integration in standardized irradiation rigs — TRL 5-6 Technology demonstration

- Self-powered detectors (SPD) to measure neutron or gamma flux
- Thermocouples and passive monitors to measure local temperature
- LVDTs to measure deformation and pressure

Innovative sensors: demonstrate disruptive potential for in-pile application — TRL 3-4 Technology development

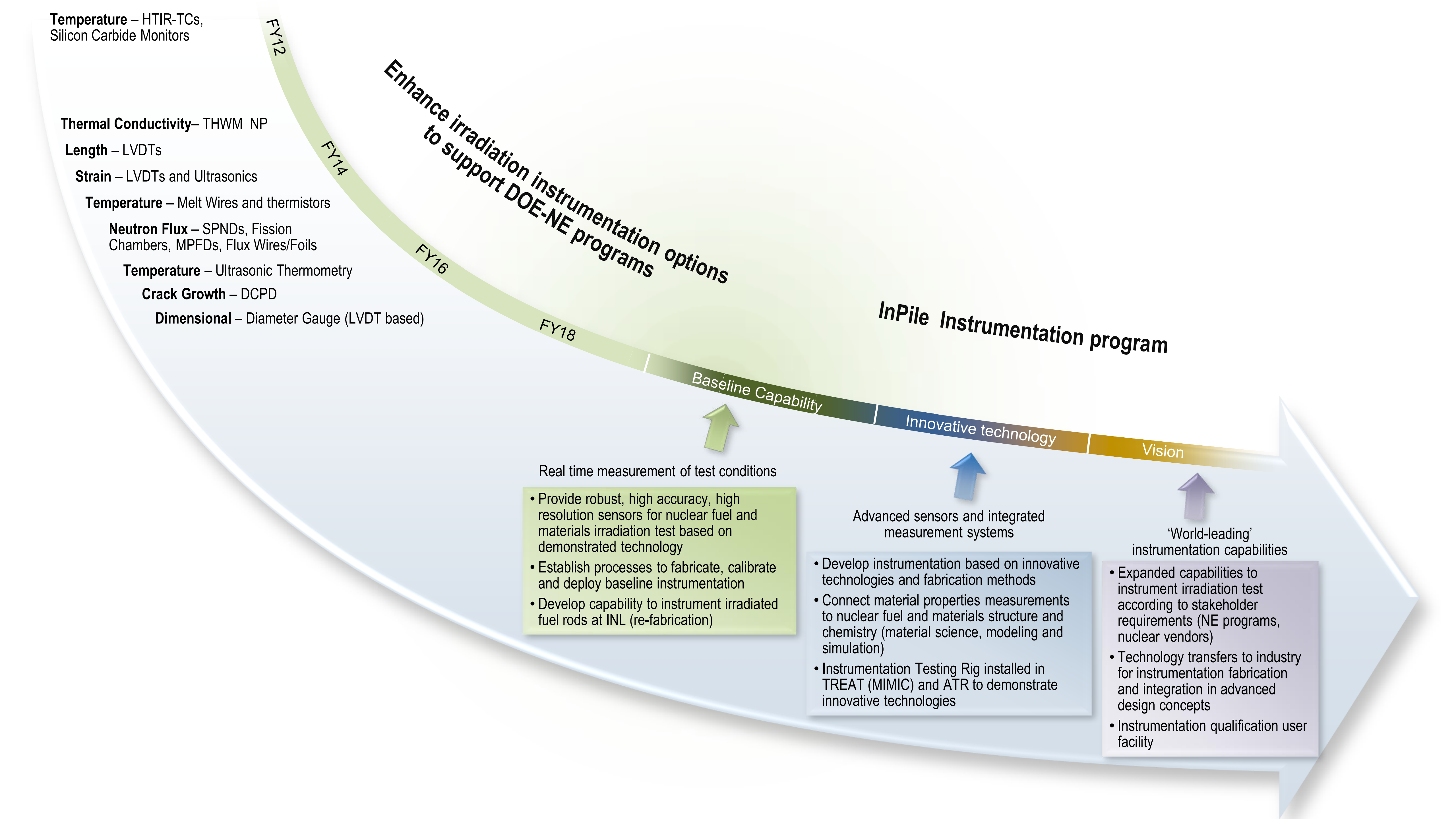
- Electrical sensors / Ultrasonic sensors / Fiber optics / Advanced Manufactured sensors

Integrated measurement systems: investigate in real time material science issues in-pile — TRL 2-6 Research to feasibility

- Thermal properties / Mechanical properties / Chemistry / Microstructure

Enabling infrastructure: demonstrate instrumentation performance and maintain expertise

- Irradiation vehicles for instruments performance demonstration (TREAT, ATR, MITR, VTR)
- Out-of-pile system to enable re-instrumentation of irradiated fuel assemblies
- Expanded out-of-pile testing capabilities (HTTL, including flowing autoclave for PWR conditions)

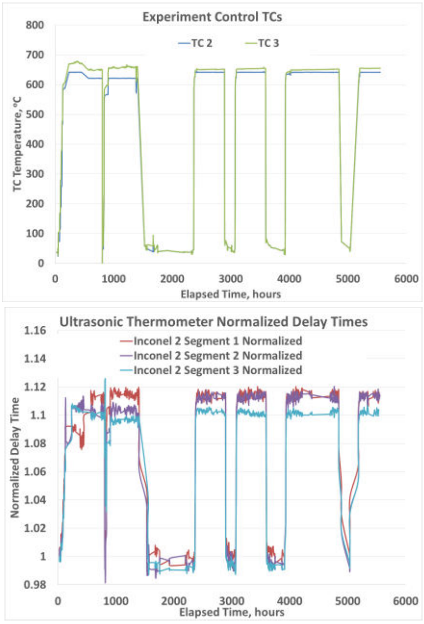

Temperature – HTIR-TCs, Silicon Carbide Monitors
Thermal Conductivity– THWM NP
Length – LVDTs
Strain – LVDTs and Ultrasonics
Temperature – Melt Wires and thermistors
Neutron Flux – SPNDs, Fission Chambers, MPFDs, Flux Wires/Foils
Temperature – Ultrasonic Thermometry
Crack Growth – DCPD
Dimensional – Diameter Gauge (LVDT based)
FY12
FY14
FY16
FY18
Enhance irradiation instrumentation options to support DOE-NE programs
InPile Instrumentation program
Baseline Capability
Innovative technology
Vision
Real time measurement of test conditions
• Provide robust, high accuracy, high resolution sensors for nuclear fuel and materials irradiation test based on demonstrated technology
• Establish processes to fabricate, calibrate and deploy baseline instrumentation
• Develop capability to instrument irradiated fuel rods at INL (re-fabrication)
Advanced sensors and integrated measurement systems
• Develop instrumentation based on innovative technologies and fabrication methods
• Connect material properties measurements to nuclear fuel and materials structure and chemistry (material science, modeling and simulation)
• Instrumentation Testing Rig installed in TREAT (MIMIC) and ATR to demonstrate innovative technologies
'World-leading' instrumentation capabilities
• Expanded capabilities to instrument irradiation test according to stakeholder requirements (NE programs, nuclear vendors)
• Technology transfers to industry for instrumentation fabrication and integration in advanced design concepts
• Instrumentation qualification user facility

Advanced acoustic and optical fiber instrumentation developed at INL and tested in the MITR-II

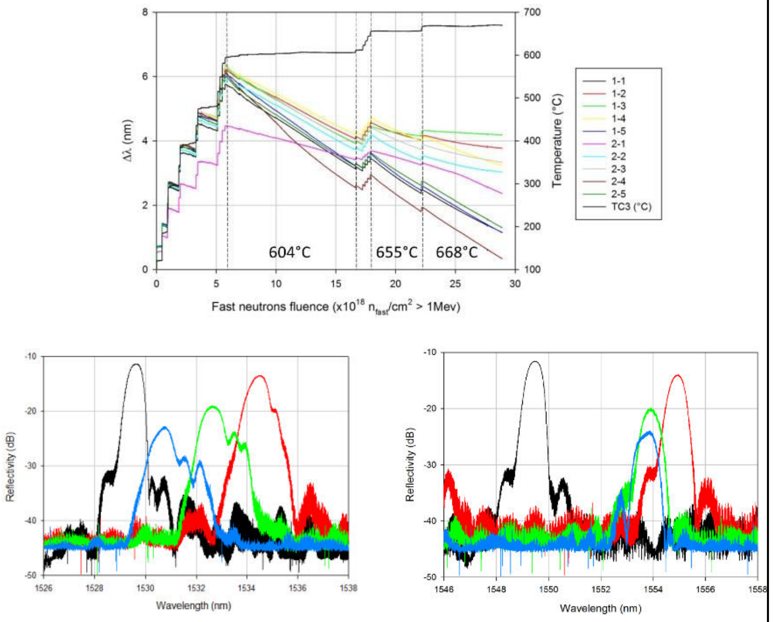
Acoustic and optical fiber sensors have demonstrated potential for in-pile online measurement:

- Radiation induced attenuation in silica fibers appears to reach a saturation level after ~50 days
- Optical fiber based sensors have shown high resolution, but de-calibrate due to radiation induced compaction
- Ultrasonic thermometers show minimal irradiation induced changes, but have lower resolution than fibers

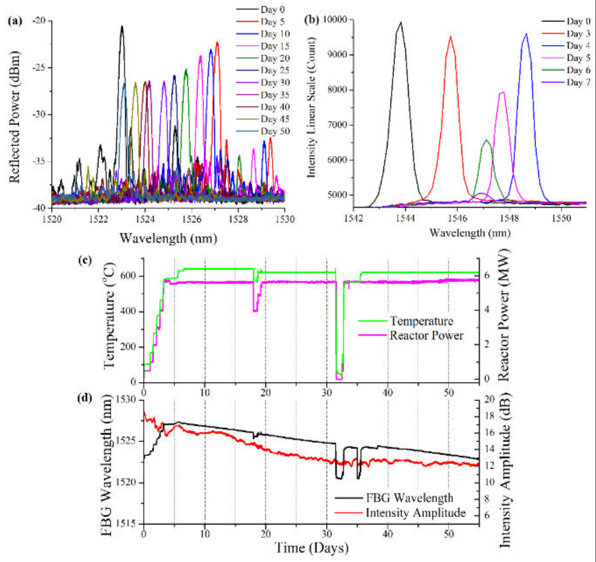
INL Multipoint Ultrasonic Temperature Sensors



CEA Fiber-Bragg Grating Optic Temperature Sensors



University of Pittsburgh Fiber Optic Temperature Sensors

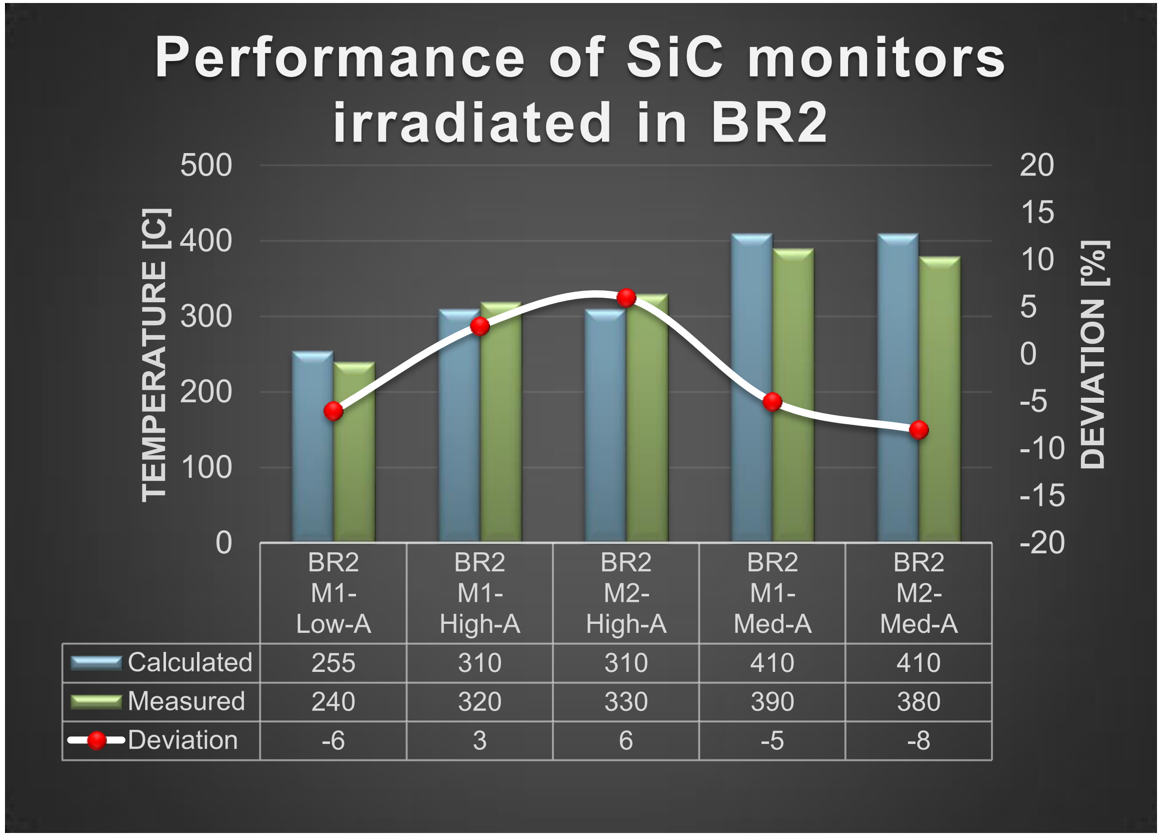


The validation of the performance of SiC monitors enables the measurement of irradiation temperature in ATR tests

- Passive temperature monitors are used to assess irradiation temperature in materials irradiation test not equipped with instrument leads

Silicon Carbide (SiC) rodlets and discs with required quality specifications are now available through the INL High temperature Test Laboratory (HTTL) for deployment in ATR test (NSUF, ATF-2)

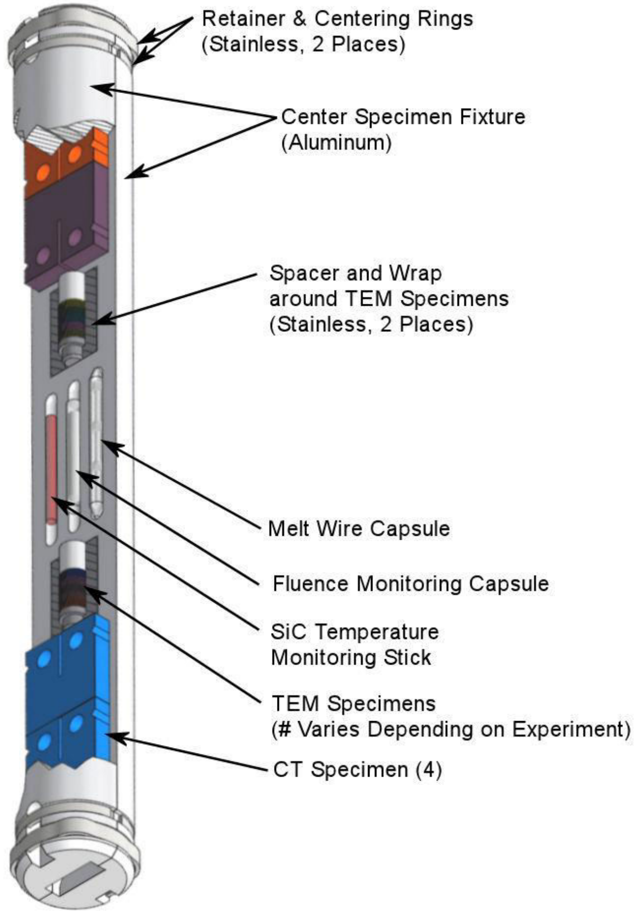
- Temperature is evaluated with a post irradiation annealing process that measures resistivity changes in SiC
- SiC monitors offer significant advantages compared to other passive methods (i.e., melt wires) in terms of reliability, accuracy and cost
- Development activities were funded by NSUF and carried out in collaboration with the SCK research center in Belgium, which irradiated samples in the BR2 reactor



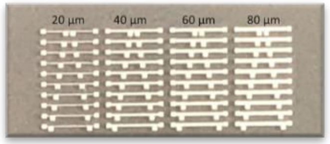
	BR2 M1-Low-A	BR2 M1-High-A	BR2 M2-High-A	BR2 M1-Med-A	BR2 M2-Med-A
Calculated	255	310	310	410	410
Measured	240	320	330	390	380
Deviation	-6	3	6	-5	-8

For more information: Pattrick.Calderoni@inl.gov

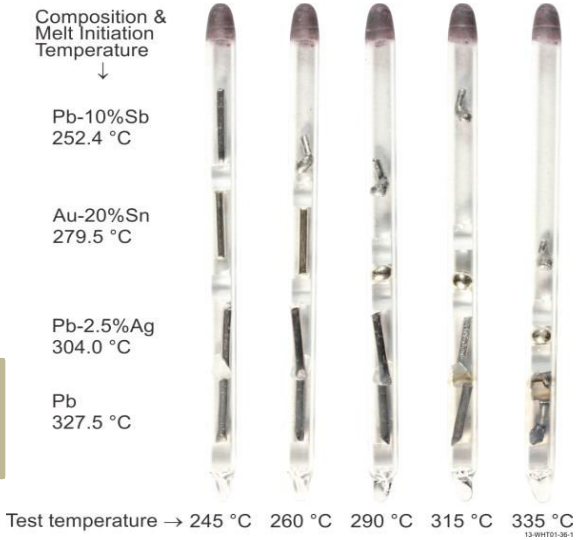
Instrumentation fabrication, testing and deployment: NSUF irradiation tests



Measure peak irradiation temperature during PIE with passive monitors for test with significant fluence (≥ 1 dpa) (enabling technologies – transformative thru advanced manufacturing)



Melt wire capsules with qualified materials (using DCS) in 85-1455 °C range

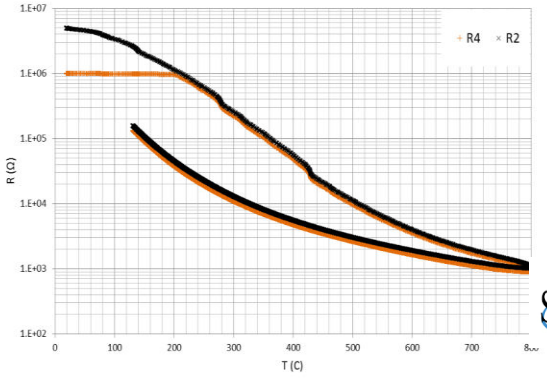


CVD SiC monitors - 4 point contact automated resistivity measurement

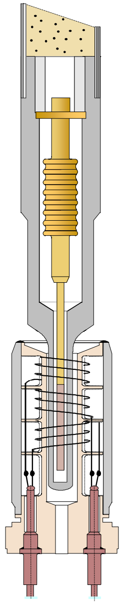
Automated Post-irradiation Examination of SiC Monitors for Peak Irradiation Temperature Measurement: Holder Design and Preliminary Results

Ahmad Al Rashdan, Troy Unruh, and Joshua Daw

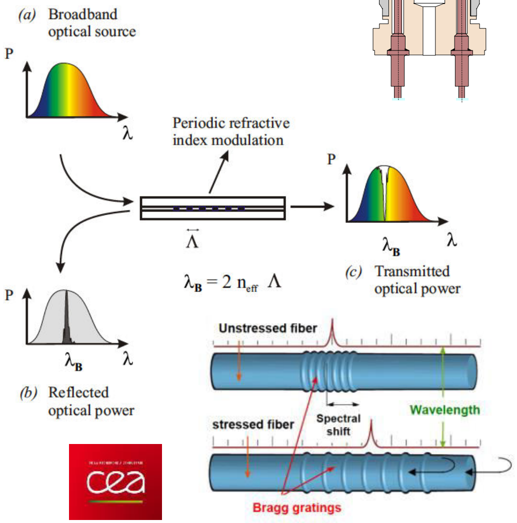
April 2017



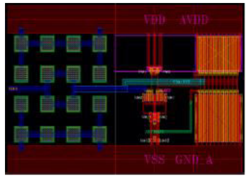
The High Temperature Test Laboratory: Service Center for instrumentation development



LVDT technology for fission gas pressure and creep measurement

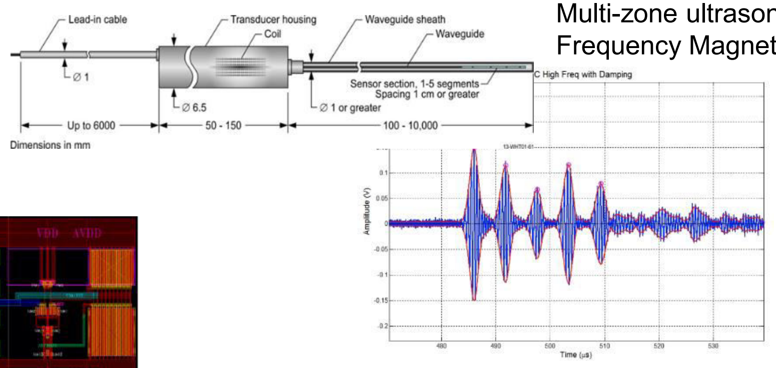


Regenerated (high-T) Fiber Bragg Gratings for temperature and strain/deformation

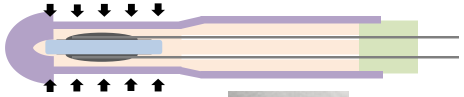


Radiation Hardened amplifier for MPFD

Korea Atomic Energy Research Institute (KAERI)



Multi-zone ultrasonic thermometer with High-Frequency Magnetostrictive Transducer

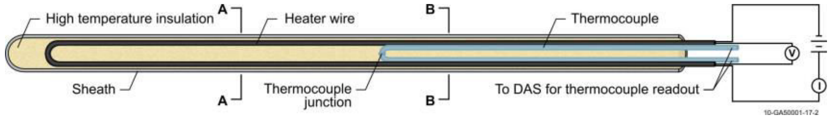



Diamond thermistor

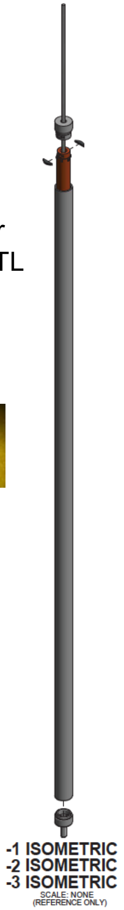
WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Precision laser welding at HTTL

UtahState University



Transient Hot-Wire Method (THWM) Needle Probe



ATF-2 SQT instruments pin assembly and thermal imaging during brazing process at HTTL

cea

Program vision

Vision: the U.S. leads the world in instrumenting irradiation experiments in material test reactor facilities

Direct support to:	Programs leveraging benefits:
Nuclear Technology Research and Development (NTRD) program: Accident Tolerant Fuels (ATF) and advanced reactor fuels under the Advanced Fuel Cycle program	Nuclear Energy Advanced Modeling and Simulation (NEAMS)
Advanced Gas Reactor Tri-structural Isotropic Fuel Development program	Consortium for Advanced Simulation of Light Water Reactors (CASL)
R&D needs of the U.S. nuclear industry including the GAIN program that supports LWR and advanced reactor companies, of particularly strategic importance in light of the closure of the Halden test reactor	Advanced Reactor Technology
Experiments supported by the Nuclear Science User Facilities (NSUF) program	LWR Sustainability
	DOE National Nuclear Security Administration's Material, Management, and Minimization program (low enriched uranium conversion)

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French alternative energies and atomic energy commission
Cadarache – F-13108 St Paul Lez Durance, France