U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

In-Pile Instrumentation program

Advanced Sensors and Instrumentation Annual Webinar

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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 (I3) received funds under NEET Crosscutting Technology Development (CTD) in FY17 and FY18 to establish the program structure, organization and research plan. The In-Pile Instrumentation (I^2) program is fully funded from FY19.

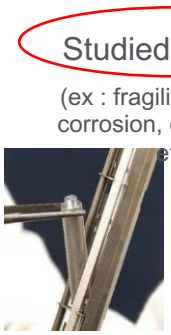
Sept 2018

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

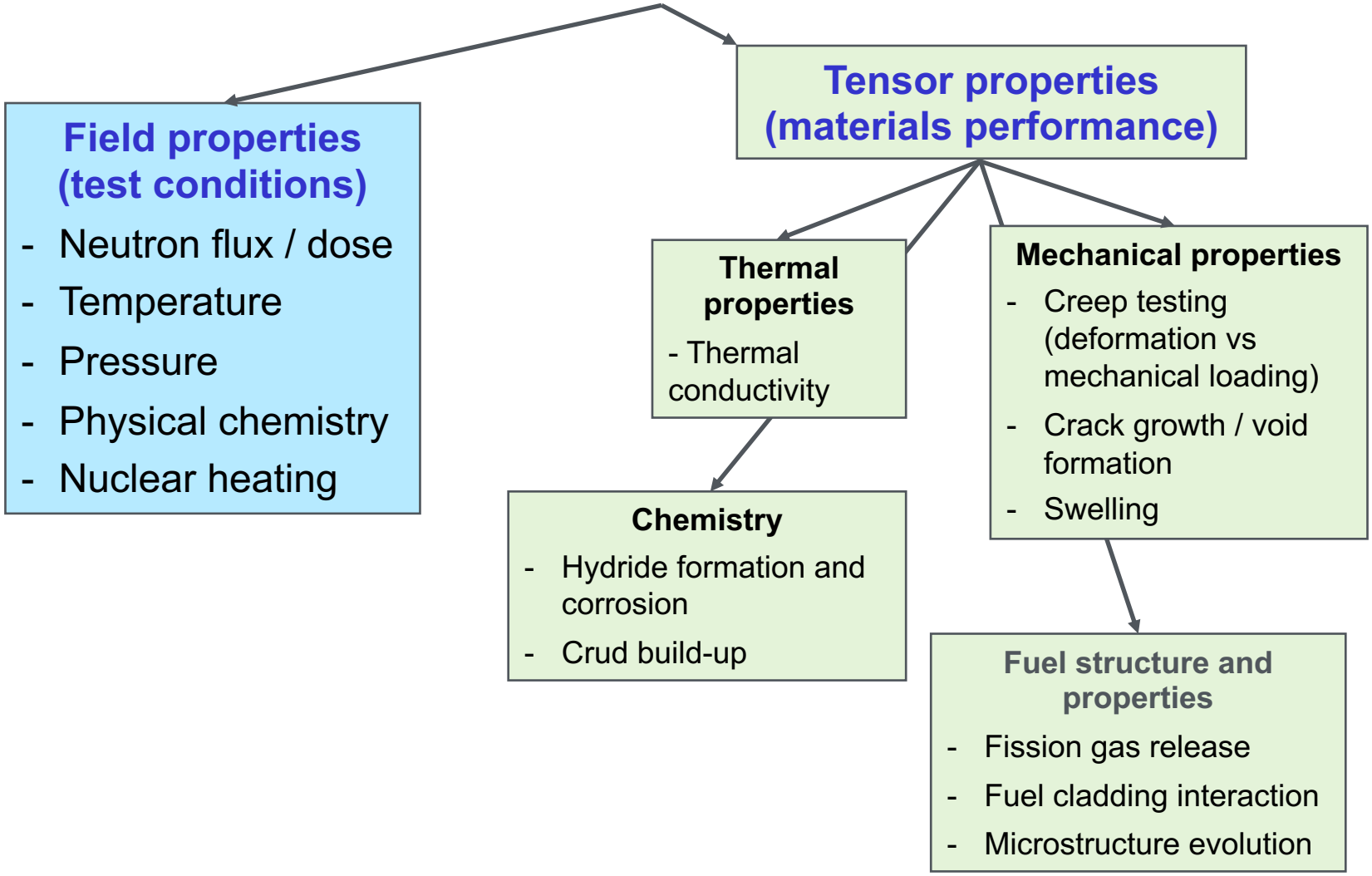


→ All these parameters must be accurately measured !

2. **Watch performance/safety parameters**

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

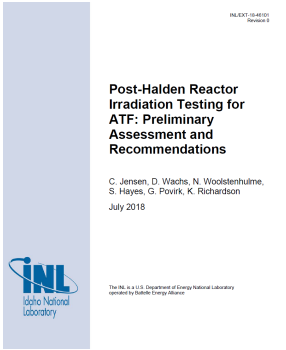
Program mission: parameters of interest



Recovery of HBWR capabilities

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



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 single effects 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, HFIR, 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)

In-Pile Instrumentation program timeline

Temperature – thermocouples (HTIR, cladding), melt wires, SiC monitors, ultrasonic thermometer (UT), LVDT, solid state thermistor, optical fibers (FBG, OBR)

Neutron, gamma Flux – SPDs, Fission Chambers, MPFD, Dosimeters

Fission gas pressure, composition – LVDT, optical fiber (FP, spectroscopy), acoustic sensor

Thermal Conductivity– Transient Hot-Wire Method (THWM) Needle Probe, photo thermal radiometry, line probe methods

Strain – Electrical gauges, optical fiber (FBG, OBR)

Microstructure evolution– Resonant Ultrasound Spectroscopy

Fuel elongation and radial deformation – LVDTs, diameter gauge, optical fiber (FP)

Chemistry –Electrochemical Impedance Spectroscopy, Electrochemical Corrosion Potential

Crack and macrostructure growth – Direct Current Potential Drop, IR thermography

Creep behavior – LVDT

FY12 FY14 FY16 FY18

Enhance irradiation instrumentation options to support DOE-NE programs

InPile Instrumentation program

Baseline Capability | Innovative technology | Vision

FY19: the Measurement Science Department is formed at INL as part of the NS&T Nuclear Fuels and Materials Division in direct support of the I² program

Real time measurement of test conditions

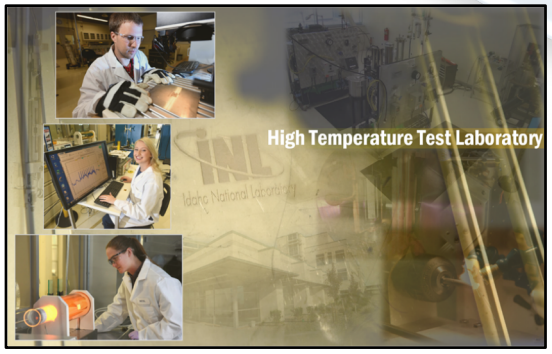
- Provide robust, high accuracy, high resolution sensors for nuclear fuel and materials irradiation test based on demonstrated technology
- Establish processes to fabricate, calibrate and deploy baseline instrumentation
- Develop capability to instrument irradiated fuel rods at INL (re-fabrication)

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

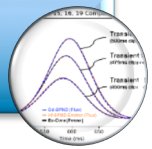
- Expanded capabilities to instrument irradiation test according to stakeholder requirements (NE programs, nuclear vendors)
- Technology transfers to industry for instrumentation fabrication and integration in advanced design concepts
- Instrumentation qualification user facility



Baseline instrumentation

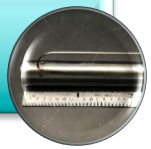
- Neutron and gamma detection
- Fast (Hf, Gd) and slow (Rd, Vd) response
- Established fabrication process at INL
- Performance demonstration in TREAT and AGR5/6/7

Self Power Detectors



- High Temperature Radiation Resistant (HTIR) for fuel centerline temperature (1200 - 1600 C)
- Fast response Type K for cladding temperature
- Performance demonstration in TREAT and AGR5/6/7

Thermocouples

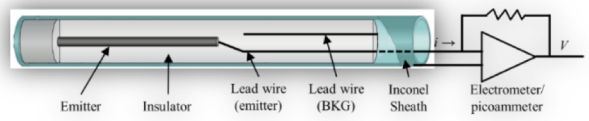


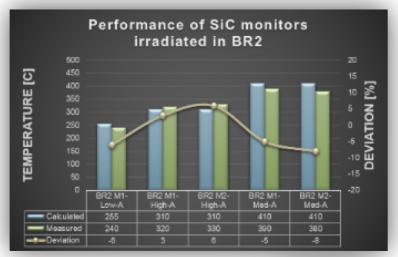
- Temperature and neutron flux validation in irradiation test without penetrations
- Data retrieved from PIE
- Melt wires and SiC monitors for peak irradiation temperature
- Dosimeters for neutron flux

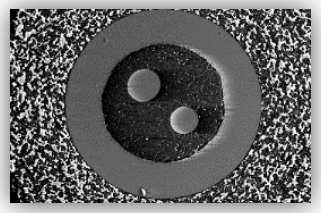
Passive monitors

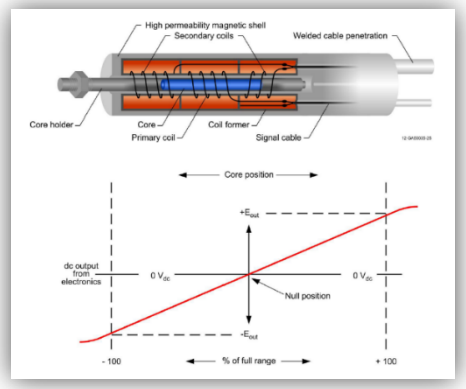
- Linear Variable Differential Transformer to detects the relative displacement of core/coils in 1D
- Integrated in standardized test rig can be used to measure fuel rod elongation, diameter changes, pressure and temperature

LVDTs





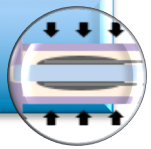




Innovative technologies: current activities

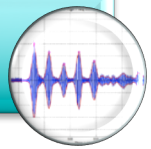
- Miniaturized fission chambers for neutron and gamma flux and energy distribution
- Mechanical sensors for strain, force, acceleration, vibration
- Solid state thermistors for temperature
- Impedance based sensors for deformation and phase change (void sensor)

Electrical sensors



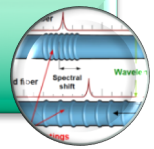
- Ultrasonic thermometers for distributed temperature
- Ultrasonic sensor for fission gas pressure and composition

Acoustic sensors



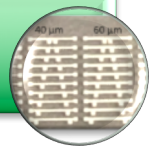
- Radiation tolerant optical fiber material/design (single mode)
- Intrinsic sensors (Fiber Bragg Gratings) and Optical Backscattering Reflectometry for distributed temperature and strain
- Extrinsic sensors (Fabry-Perot Interferometry) and spectrometry for deformation, pressure (composition)

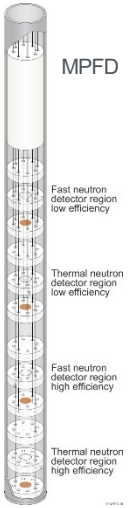
Optical fiber sensors

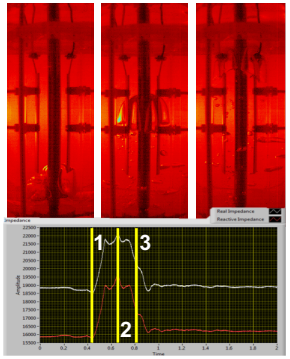


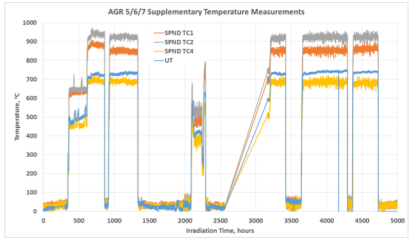
- Aerosol Jet Printing for the fabrication of nuclear instrumentation (ink development, process control)
- Combinatorial material science analysis for sensors design
- AM sensors: dosimeters strain gauges and thermal conductivity probes

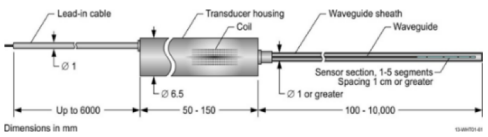
Advanced manufactured sensors



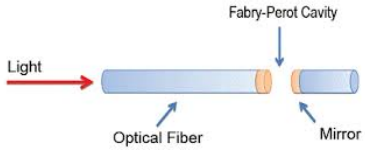


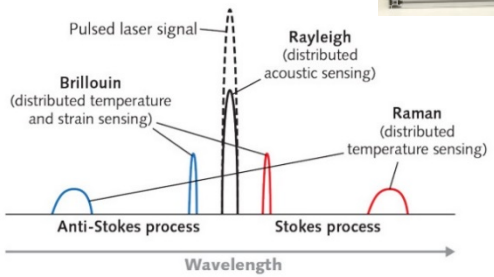


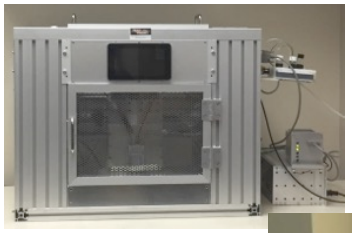


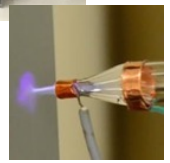


Multi-zone UT with High-Frequency Magnetostrictive Transducer

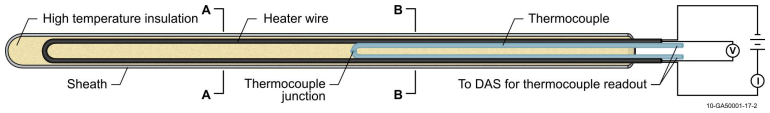








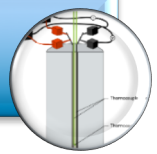
Integrated measurement systems



Transient Hot-Wire Method (THWM) Needle Probe

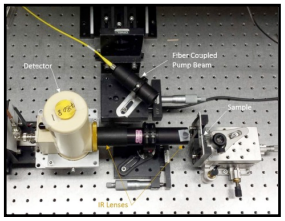
- Real time measurement of thermal conductivity during irradiation by photo thermal radiometry and line probe methods (needle probe, three-omega sensor)

Thermal properties

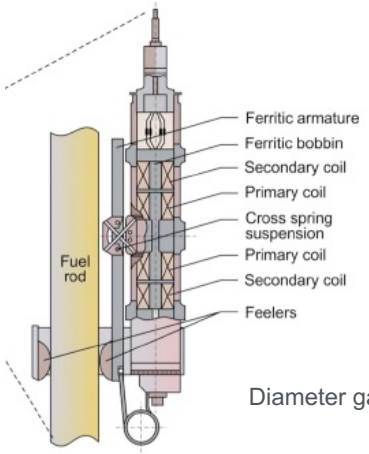


- Real time characterization of creep behavior during irradiation (LVDT test rig)
- Radial swelling (diameter gauge, impedance sensor)
- Crack growth, void formation (Direct Current Potential Drop, IR thermography)

Mechanical properties

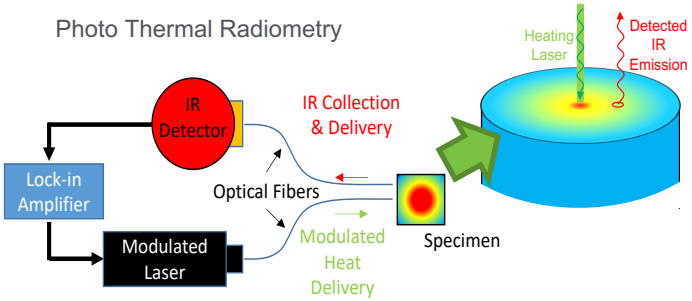


Benchtop setup

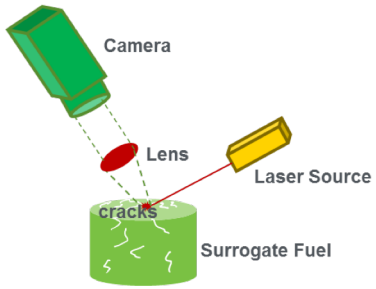


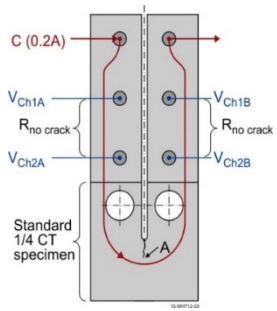
Diameter gauge

Photo Thermal Radiometry

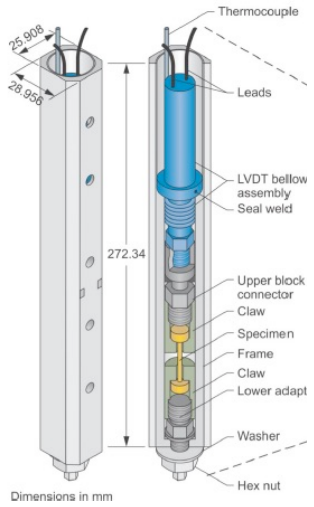


IR Thermography





DCPD



LVDT creep test rig

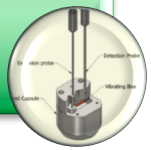
Integrated measurement systems

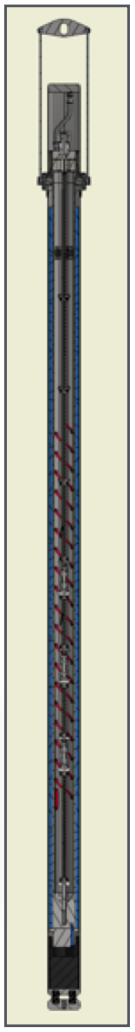
- Hydride formation and corrosion (Electrochemical Impedance Spectroscopy, Electrochemical Corrosion Potential)
- Crud build-up (diameter gauge)

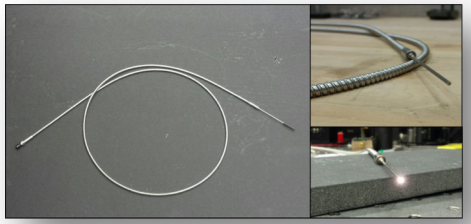
Chemistry

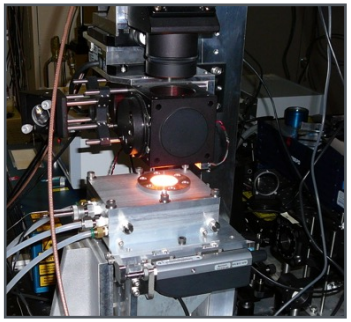
- Real time characterization of materials recrystallization during irradiation (Resonant Ultrasound Laser Spectroscopy)

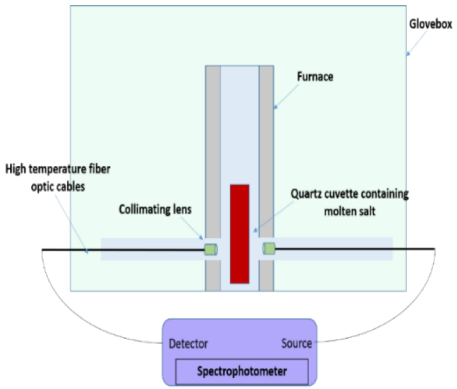
Microstructure









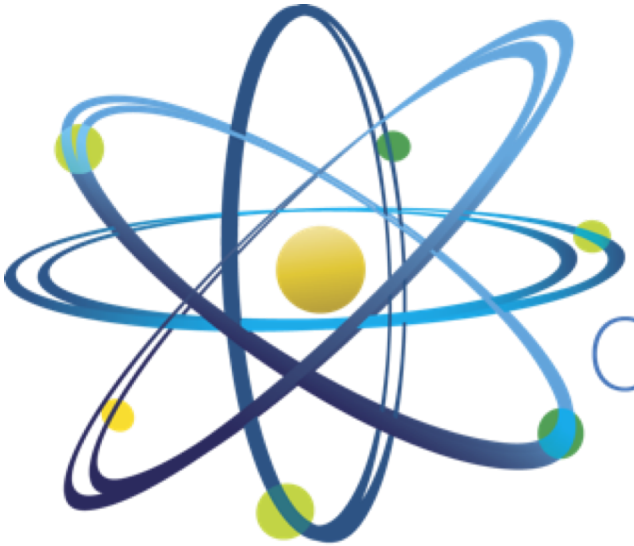


Schematic of the setup assembly

In-Pile Instrumentation 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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