In-Pile Instrumentation Initiative: A Multidisciplinary Scientific Approach for Characterizing Fuels and Materials

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DOE-NE Sensors and Instrumentation Webinar
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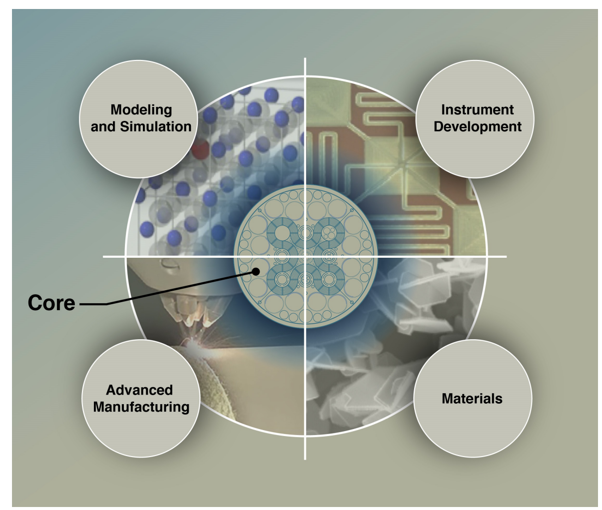

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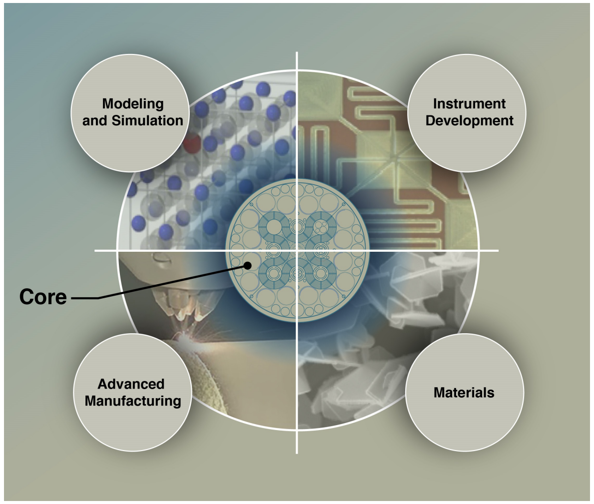
Science-based initiative for in-pile sensors and instrumentation development



Vision

- Provide real-time, accurate, spatially resolved information regarding performance of fuels and materials that can be tied to microstructure

Objectives

- Provide a multidisciplinary approach for characterization of fuels and materials
  - Material development
  - Advanced manufacturing & Integration
  - Device Modeling
  - Instrumentation development

Science-based initiative for in-pile sensors & instrumentation development

Outcomes

- New capabilities for in-pile measurement of materials behavior
- Reduced sensor development lifecycle
- Multi-mode instruments for improved accuracy and reliability
- Measure at smaller length scale to provide insight on irradiation-induced properties evolution
- Connect changes in material properties with microstructure and chemistry

Impact:

- Fuel cycle technologies
- Advanced reactor development
- Industry support
  - GAIN
  - Technology transfer

Extend Life, Improve Performance, and Maintain Safety of the Current Fleet

Enable New Builds for Electricity Production and Improve the Affordability of Nuclear Power

Science-based initiative for in-pile sensors & instrumentation development

Disruptive technologies with wide applicability

- Radiation resistant optical fibers
- Acoustic methods
- Power harvesting
- Wireless communication

Measurement of field properties

- Temperature
- Pressure
- Strain / elongation
- Neutron flux/energy

Thermal / mechanical properties

- Thermal conductivity
- Young, shear mod, UTS, v
- Density / porosity

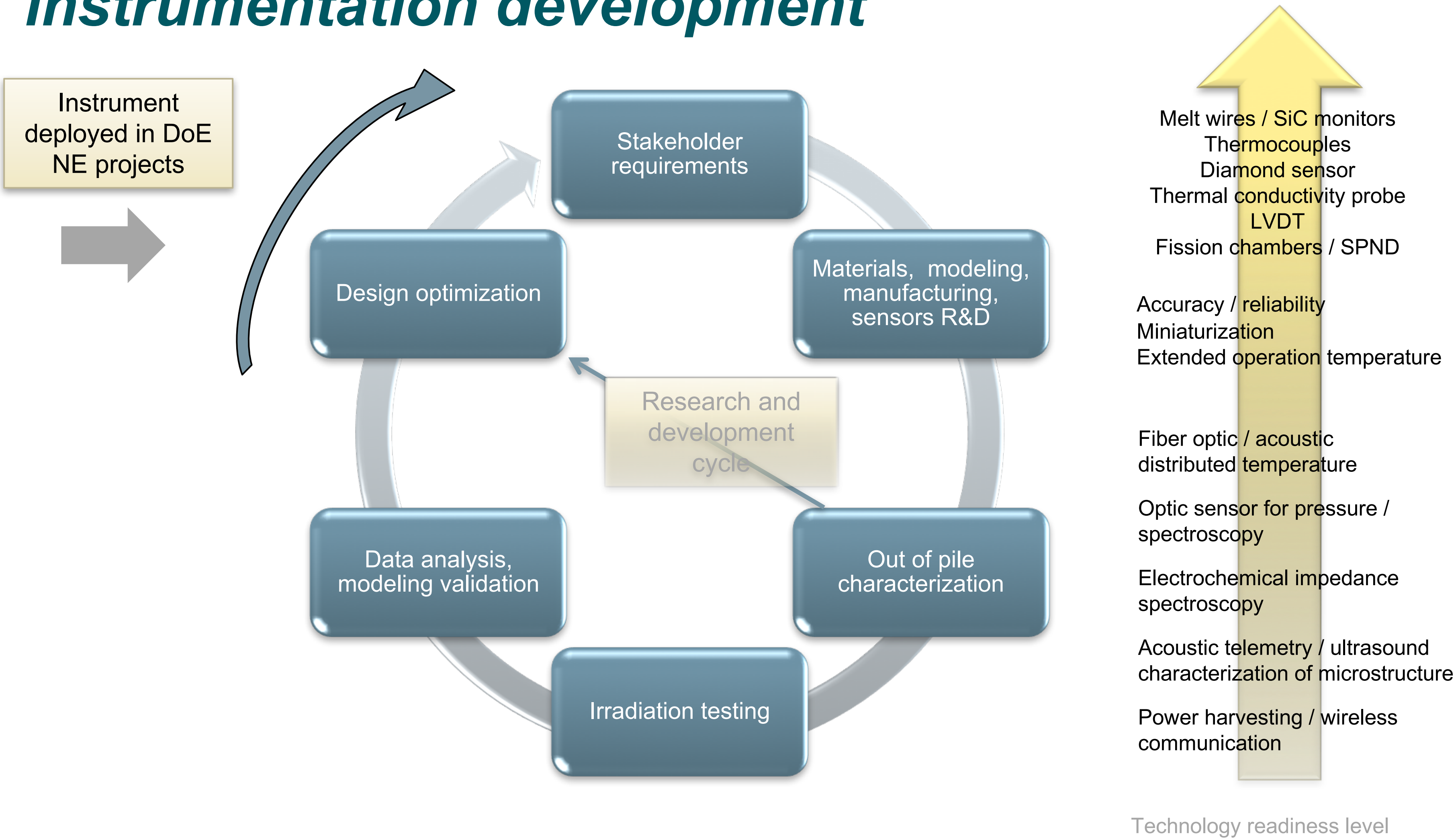
Solid-state chemistry

- Stoichiometry
- Species diffusion
- Fuel-cladding interaction
- Hydride formation / corrosion

Imaging/measuring structure

- Ultrasonic measurement
- Optical visualization
- X-ray diffraction / imaging
- Thermograph for crack formation

Science-based initiative for in-pile sensors & instrumentation development



Field properties measurement

Develop instrumentation to characterize field properties during in-pile test of nuclear fuel and materials with adequate spatial and time resolution to satisfy the requirements of DOE NE programs (local, distributed measurements / online monitoring / fast response)

Neutron Flux

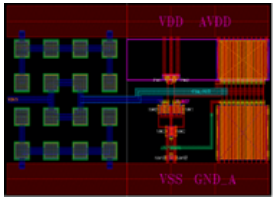
- Goal, and Objectives
  - Develop neutron and gamma flux instrumentation for real time, local in-pile measurement
  - Validate performance by testing in irradiation facilities
- Need
- The neutrons field establishes reactor operating conditions (temperature, pressure, strain) and is responsible for material properties degradation. Accurate characterization during irradiation test is required for performance characterization as well as validation of numerical models.
- Approach

Development strategy is based on application of innovative materials and fabrication processes towards the miniaturization of existing technologies. Near term activities include:

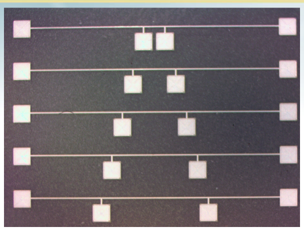
- **Passive neutron dosimeters (flux foils) fabricated by advanced manufacturing**

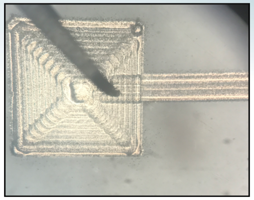
  Aerosol Jet Printing (AJP) prototyping, modeling for composition optimization, development of read-out system and enabling deployment in TREAT
- **Real-time, miniaturized flux detectors**

  Investigation of novel materials and fabrication processes towards the miniaturization of fission chambers (including the Micro-Pocket Fission Detector) and SPNDs
- **Nano-structured Materials for Solid-State Neutron Detection**



Temperature





- Goal, and Objectives
  - Develop instrumentation to measure real time, local temperature during nuclear fuel and materials in-pile test
  - Validate performance by testing in irradiation facilities
- Need

Virtually all nuclear material properties and performance parameters are temperature dependent. Accurate characterization during irradiation test is required for performance characterization. Temperature limits (as high as 2000ºC), gradients and power transients in fuel tests pose severe challenges to instrumentation development.

- Approach

Strategy is based on application of innovative materials and fabrication processes towards the miniaturization of existing technologies and the development of multi-sensor instrumentation. Near term activities include:

- **Advanced passive temperature monitors**

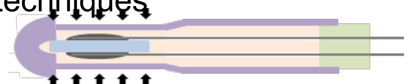
  Aerosol Jet Printing (AJP) prototyping of melt wire arrays / SiC monitors
- **Advanced thermocouples**

  High Temperature Irradiation Resistant (HTIR) Tc optimization (Mo/Nb elements) / innovative thermo-electric materials with focus on advanced manufacturing processes compatibility
- **Solid-state thermistors**

  Sensors based on diamond and sapphire crystals / SiC p-n junction diodes
- **Ultrasound temperature (UT) monitors**

  Based on magnetostrictive or piezoelectric materials for excitation and metal waveguide for distributed measurement / performance improvement thru AM processes for aluminum nitrade and other innovative materials
- **Optical fiber based temperature sensors**

  Fiber Bragg gratings (FBG) and long period grating fibers (LPGF) / Rayleigh backscattering techniques



Pressure and strain

- Goal, and Objectives
  - Develop instrumentation to measure fission gas products pressure (and composition)
  - Develop instrumentation to measure real time strain and deformation in fuels and materials
  - Validate performance by testing in irradiation facilities
- Need
- Accurate measurement of fission gas pressure and composition enables characterization and models validation for transport properties in fuel and materials. The measurement of strain and deformation is necessary to characterize mechanical properties.
- Approach

Strategy is based on application of innovative materials and fabrication processes towards the miniaturization of existing technologies and the development of radiation resistant optical fiber materials. Near term activities include:

- **LVDT deployment and miniaturization**

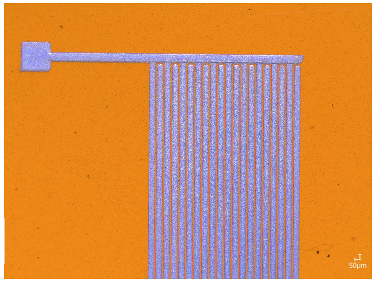
Establish LVDT deployment capabilities for irradiation test requirements / Reduce invasiveness (size, penetrations) of LVDT based in-pile instrumentation / Apply AM processes to LVDT components fabrication

- **Miniaturized strain and pressure gauges**

Aerosol Jet Printing (AJP) prototyping / development of radiation resistant piezoelectric materials

- **Optical fiber based deformation and strain sensors**

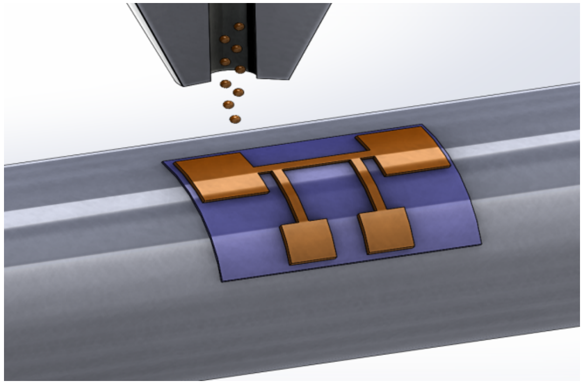
Fiber Bragg gratings (FBG) and long period grating fibers (LPGF) / Fabry-Perot interferometry techniques for deformation and pressure measurement

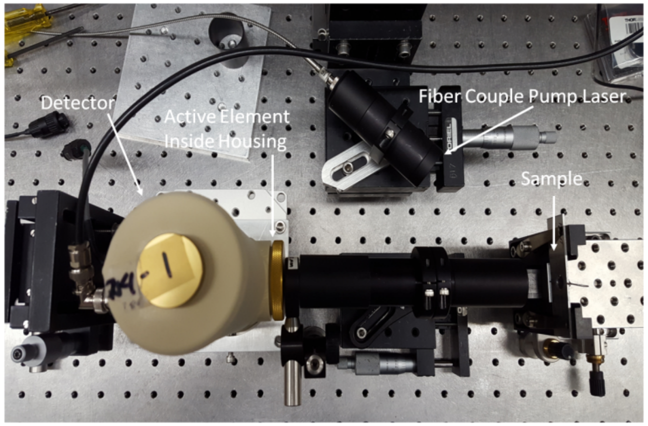


AJP printed strain gauge prototype

Thermal Properties

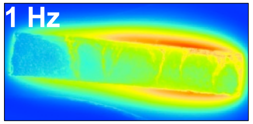
- Problem
  - Heat produced by fission must be transferred through and out of fuel
  - With increasing burnup, thermal transport properties degrade due to changes in microstructure brought about by neutron irradiation
  - Thermal conductivity of the fuel is a local property that depends on temperature and microstructure
- Goal
  - Measure thermal transport characteristics on length scales commensurate with microstructure heterogeneity (spatially resolved measurement of thermal conductivity)
- Approach
  - Develop laser-based techniques to measure local thermal conductivity and diffusivity (INL)
  - Develop enhanced needle probe with smaller thermal inertial (BSU)
  - Develop 3ω probe (Notre Dame)

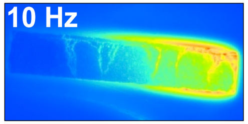


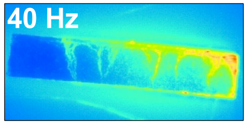


Large Scale Structure

- **Problem**
  - Large-scale structural changes to the fuel and cladding can a have profound influence on fuel performance and behavior
  - In ceramic fuels, fracturing of the ceramic pellets greatly influences the performance of the fuel
  - Fuel cladding interaction results in weakening of cladding and formation of low-melting point compositions in the fuel
- **Goal**
  - Remote imaging of large scale structure
- **Approach**
  - Develop cw and lock-in thermography techniques to image fuel cracking
  - Poolside imaging of fuel cladding gap using X-rays
- **Schedule & Outcomes**







Near	• Demonstrate high temperature crack detection in a surrogate sample via coherent fiber bundle thermography
Mid	• Construct and demonstrate bench top X-ray system for eventual insertion in the ATR canal
Mid+	• Develop test capsule integrating thermographic crack detection and begin irradiation plan

Microstructure

- **Problem**
  - Material science of fuels and materials is fraught with complexity due to large thermal gradients, nuclear reactions, and the continuous production of defects.
  - Large thermal gradients are a driving force for chemical transport, nuclear fission changes stoichiometry, and point defect production leads to the growth of voids and dislocations.
  - In the late stages of life, the fuel starts to swell due to bubble nucleation and growth; fission gas is released into the plenum, and the fuel and cladding start to creep.
- **Goal**
  - Develop traditional and non-traditional approaches to monitoring in-pile microstructure evolution
- **Approach**
  - Develop ultrasonic methods to monitor grain restructuring in ceramic and metallic fuels
  - Apply traditional measurement methods to monitor fuel microstructure
- **Schedule & Outcomes**

Near	• Investigate using resonant ultrasound to monitor grain restructuring using both free-standing and fixed-end geometries.
Near	• Tie experimental measurements of grain restructuring to phase field model of recrystallization
Mid+	• Develop test capsule integrating resonant ultrasound instrument and begin irradiation plan

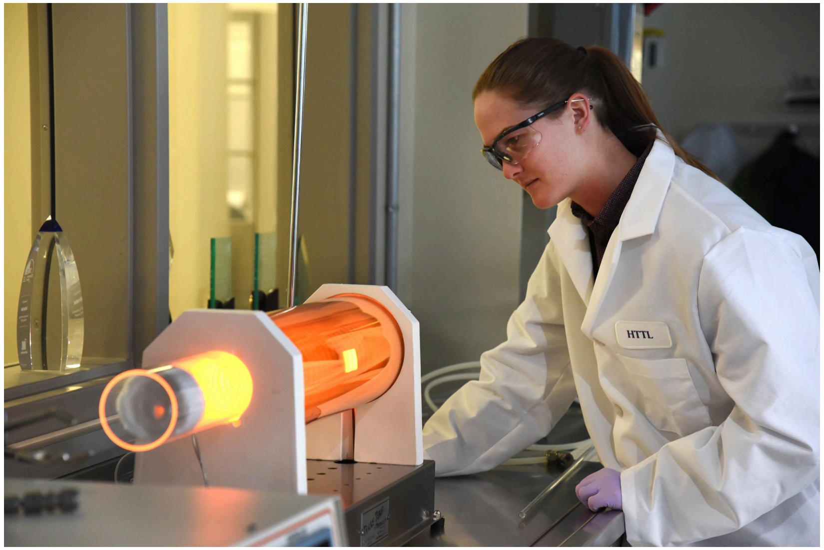
Chemistry

- **Problem**
  - In nuclear fuel, changes in chemistry over the lifetime of the fuel can have a significant impact on fuel performance.
  - In the mid stage of life, point defects start to diffuse; creating voids and causing dislocation growth, fission gas segregates to grain boundaries, and newly created fission gas bubbles start to form.
  - The structural integrity of the cladding is compromised by three primary mechanisms: (1) cladding embrittlement caused by pellet-cladding chemical interaction, (2) cladding embrittlement caused by hydride formation
- **Goal**
  - Develop unique tools to measure changes in solid-state chemistry
- **Approach**
  - Develop Electrochemical Impedance Spectroscopy to measure changes in stoichiometry, hydride formation and corrosion
- **Schedule & Outcomes**

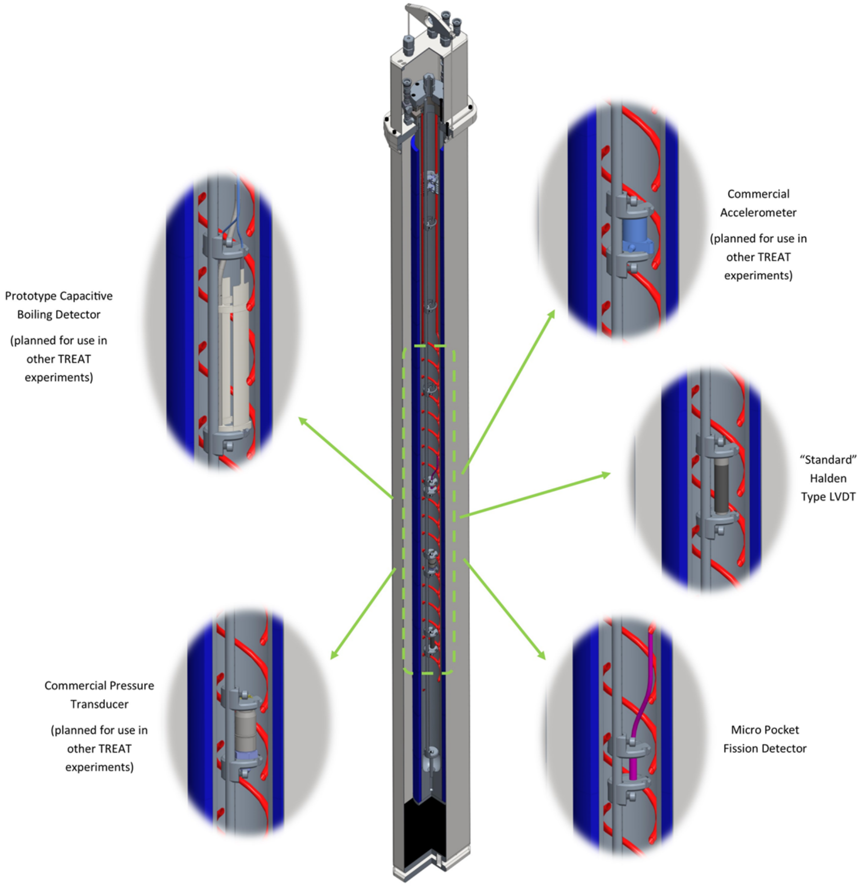
Early	Complete the construction of high temperature electrochemical cells with separately controlled gas atmospheres to anode and cathode for hydride formation and hydride dealloying study; (2) complete the acquiring of 8-channel potentiostat that can be used for future combinatorial testing; and (3) complete the development of finite element (FE) model for dielectric response of porous media.
Mid	Complete the kinetic study of hydride formation and associated microscopic characterization and mechanism study.

Innovation and deployment

Testing CEA optical fiber FBGs temperature sensors at HTTL

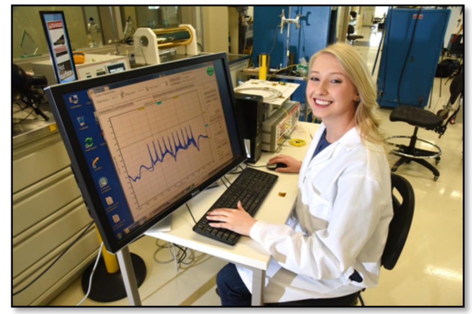


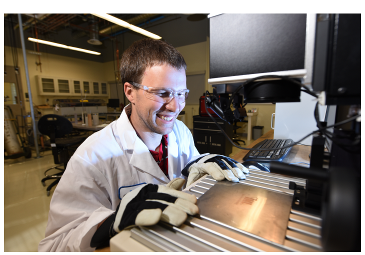
TIMMIE capsule for instrumentation testing in TREAT



Establishing measurement science capabilities and expertise for nuclear applications

Researchers and international collaborations





University fellowship and internship programs