Real Time In-core Instrumentation:

From Fuels and Materials Irradiation Tests to Advanced Reactor Demonstration
Project Overview

• Objective
  – The real time in-core instrumentation element implements R&D activities to develop advanced sensors that address critical technology gaps for monitoring and controlling existing and advanced reactors and supporting fuel cycle development
  – Lead participants and collaborators
    • Troy Unruh -- TPOC and fission chamber PI, Kevin Tsai
    • Kevin Tsai – Self Powered Neutron Detector PI, Troy Unruh
    • Richard Skifton -- Thermocouple and flowing autoclave PI, Joe Palmer, Dave Swank, David Cottle
    • Joshua Daw – Ultrasonic Thermometer PI, Lance Hone, James Smith, Rob Schley, Zilong Hua
    • Austin Fleming -- Fiber Optic sensors PI, Kelly McCary, Lance Hone, Pattrick Calderoni
    • Additional University Collaborators
      – Boise State University – Lan Li, Ember Sikorski, Scott Riley, Dave Estrada, Dan Deng, Takoda Bingham, Nick McKibben, Shane Palmer, Brian Jaques, Nirmala Kandadai, Sohel Rana
      – The Ohio State University – Marat Khafizov
      – University of Pittsburg – Kevin Chen
## FY20 Milestones and Schedule

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Completed Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Letter documenting installation completion of optical dilatometer installation and analysis procedure</td>
<td>6/25/2020</td>
</tr>
<tr>
<td>INL report summarizing analysis results of characterization of advanced manufactured Surface Acoustic Wave sensor for temperature measurement in nuclear applications</td>
<td>12/31/2020</td>
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<tr>
<td>Letter documenting fabrication completion of Ultrasound Thermometers (UT) for high temperature testing</td>
<td>2/20/2020</td>
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<tr>
<td>INL report summarizing test results of performing initial temperature testing of advanced manufactured melt wire package</td>
<td>3/26/2020</td>
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<tr>
<td>Letter documenting fabrication completion of Self Power Neutron Detectors for steady-state reactor operation (Rd-SPND)</td>
<td>6/26/2020</td>
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<tr>
<td>INL report summarizing test results of fabricated and tested out of pile a prototype optical fiber pressure sensor based on Fabry-Perot interferometry</td>
<td>9/10/2020</td>
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<td>Milestone</td>
<td>Completed Date</td>
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<tr>
<td>INL report summarizing analysis results of identified technical solutions to allow optical fiber penetrations in irradiation experiments</td>
<td>7/24/2020</td>
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<tr>
<td>INL report summarizing analysis results of a test plan for the demonstration of wireless technology to nuclear applications</td>
<td>8/13/2020</td>
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<tr>
<td>INL report summarizing test of high temperature irradiation resistance (HTIR) thermocouples in the INL flowing autoclave system</td>
<td>9/2/2020</td>
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<tr>
<td>INL report summarizing analysis results of define operating window of Ultrasound Thermometers (UT) for reactor core applications with out of pile experiments and modeling activities</td>
<td>9/29/2020</td>
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<tr>
<td>INL report summarizing demonstrated performance of Self Power Neutron Detectors for steady-state reactor operation (Rd-SPND)</td>
<td>1/15/2021</td>
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<tr>
<td>INL report summarizing analysis results of characterized temperature sensors based on intrinsic fiber-optic sensor technology for reactor core applications</td>
<td>9/30/2020</td>
</tr>
<tr>
<td>INL report summarizing results from characterize out of pile long term drift of high temperature irradiation resistance (HTIR) thermocouples and compare with modeling results</td>
<td>1/29/2021</td>
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</table>
Accomplishments – Self Powered Neutron Detectors

- Rhodium-SPND design, fabrication, and testing
  - Design and procure Rh-SPND for steady-state operation
  - Non-nuclear furnace testing to evaluate SPND response at higher temperatures.
    - Identified signal deviation at approx. 450 °C.

For more information: kevin.tsai@inl.gov

<table>
<thead>
<tr>
<th>Emitter Dimensions (in.)</th>
<th>Emitter Insulation</th>
<th>Sensor OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>0.030 OD x 3.5 L</td>
<td>Al2O3</td>
</tr>
<tr>
<td>Design 2</td>
<td>0.018 OD x 3.5 L</td>
<td>MgO</td>
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</tbody>
</table>
SPNDs are an established technology for real-time neutron flux measurement in the control of operating reactors based on PWR technology.

Close relationship with SPND vendor enables customized instrumentation for irradiation experiments and advanced reactor demonstration as well as developing a new supply chain for existing plants.

Irradiation testing underway in steady-state and transient research reactors.
Accomplishments – High Temperature Irradiation Resistant Thermocouples

- High Temperature Irradiation Resistant Thermocouple (Molybdenum vs. Niobium)
  - Capabilities:
    - 0 °C to 1600 °C Temperature Range
    - High neutron flux ready $10^{15}$ n/cm$^2$/s
    - 1% tolerance at high temperature
    - < 5% drift over long fluence of $10^{21}$ n/cm$^2$

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Technology Impact - Thermocouples

• Real-time temperature measurement is arguably the most important operational parameter to measure for the characterization of irradiation experiments and the control of power plant systems
• Continued assessment of the reliability and performance of specialized low-drift thermocouples for operation in high neutron flux environments
• Commercialization strategy is well underway with R&D100 win and vendor relationship
Accomplishments – Ultrasonic Thermometer

- Waveguide ultrasonic thermometer operational envelope testing
  - High temperature testing in vacuum furnace to find maximum operating temperatures
  - Pressure testing in static autoclave
    - No effect on signal to 2500 PSI and 325 °C
  - BSU developing FEA model of solid waveguide UT for performance comparison

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• Ultrasound based sensors allow distributed measurement of relevant operational parameters at temperatures beyond the capability of conventional instrumentation (up to 3000ºC)

• The use of specialized magneto-strictive materials at INL had demonstrated the feasibility of temperature measurement using Ultrasound Thermometers based on waveguide design (UT)

• Potential for integration with fiber optic temperature sensors
Accomplishments – Fiber Optic Pressure Sensor

• Designed, built and benchtop tested a Fiber-optic based Fabry-Perot pressure sensor.
• Minor variations in sensor design accommodate a suite of pressure ranges (atm - 100 psi, atm - 500 psi, and atm – 1500 psi)
• Fully encased in stainless steel 316 enables its use in many harsh environments
• Fiber optic allows for multi-mode sensing capability to enable temperature compensation

Interference spectrum from pressure sensor identifying peak locations

Cavity length vs reference pressure, used for calibration purposes

For more information: austin.fleming@inl.gov
Accomplishments – In-Pile Imaging via Fiber Optics

- Lab-based testing of fiber optic bundle testing was conducted
  - Fiber bundle of 10k fibers
  - Compact custom lens system was designed and assembled to couple images into fiber bundle
  - Custom image coupler technology was established to enable image bundles to be connected
    - Length of continuous image bundles is limited and not long enough to enable in-pile applications

For more information: austin.fleming@inl.gov
Accomplishments – Fiber Optic Intrinsic Temperature Sensing

- A variety of intrinsic fiber optic temperature sensors were deployed in both high flux (TREAT) and high fluence (ATR) experiments
  - FBG & Rayleigh backscatter-based temperature sensors
- Addressed challenges associated with in-pile deployments for in-pile imaging
  - Feed through testing (disruption of Rayleigh backscatter at feed through location)
  - Tested backscatter associated with fiber termination techniques

For more information: austin.fleming@inl.gov

INL researcher installing fiber optic sensors in ATR experiment

Measured back reflection of different end treatments of optical fibers
Intrinsic Temperature Sensing

• Addressed challenges associated with in-pile deployments for in-pile imaging
  – Feed through testing (disruption of Rayleigh backscatter at feed through location)
  – Tested backscatter associated with fiber termination techniques

Feed through testing of optical fibers using

Measured back reflection of different end treatments of optical fibers
Technology Impact – Optical Fiber sensors

• Optic fiber based sensors offer small footprint, high sensitivity, immunity to electromagnetic noise, high-speed, and multiplexed sensing capability
• Straightforward path to development (little to no R&D, mostly engineering)
• Focus development on impact to the nuclear industry (prioritize measurements with higher impact)
• Data already received from optical fiber sensors deployed in TREAT and ATR experiments will be used to characterize performance and develop active compensation techniques for data analysis to reduce uncertainty of known irradiation degradation effects
Accomplishments – Flowing Autoclave for Sensor Testing

• Flowing Autoclave System
  • Capabilities:
    • Water | 50 gal/min | 320 C | 2200 PSI
    • 4 ft length | 1.5 inch OD | or build to suit
    • Reynolds, Prandtl, or Nusselt number matching
    • Water chemistry control (pending construction)

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Technology Impact – Flowing Autoclave

• Non-nuclear full sensor system “shakedown” evaluations are a necessity for advanced instrumentation deployment and rapid testing of nuclear fuels and materials in support of the US advanced nuclear technology industry

• The early part of sensor development can be done outside of the reactor environment, but full technical readiness requires maturation from a staged approach in prototypic environments

• Customers usually have only one opportunity to conduct their irradiation experiments, so preparation is vital
## FY21 Real Time In-Core Instrumentation: From Fuel and Materials Irradiation tests to Advanced Reactor Demonstration Milestones

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<td>INL report summarizing HTIR performance in flowing autoclave for fuel center line temperature measurement in PWR conditions</td>
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<td>INL report summarizing In-core test of imaging technique based on optical fiber bundles</td>
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<td>INL report summarizing modeling activities for the development of damping system for wave guides of Ultrasound Thermometers</td>
<td>9/30/2021</td>
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<td>1/14/2021</td>
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<td>INL report summarizing prototype new wave guides for Ultrasound Thermometers to minimize the effect of &quot;sticking&quot; wave guide to sheath</td>
<td>8/26/2021</td>
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<td>INL report summarizing the active compensation technique for radiation effects and degradation in optical fibers</td>
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<td>INL report summarizing the comparative assessment of neutron flux sensor technologies for advanced reactors</td>
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Real-time In-core Instrumentation Summary

• R&D activities underway to develop, deploy and commercialize nuclear instrumentation that address critical technology gaps for monitoring and controlling existing and advanced reactors and supporting fuel cycle development

• Developmental technologies are employed in irradiation test and demonstration facilities to progress their Technical Readiness Level and enable stakeholders to adopt them with minimal risk

• Questions?

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