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Real Time In-core Instrumentation:

From Fuels and Materials Irradiation Tests to Advanced Reactor Demonstration

Advanced Sensors and Instrumentation Annual Webinar

November 5, 2020

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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

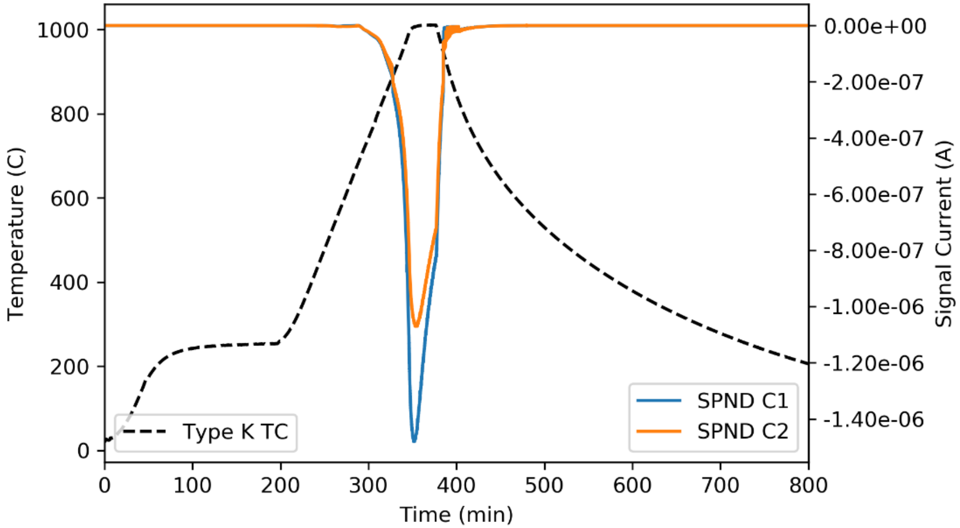
Milestone	Completed Date
Letter documenting installation completion of optical dilatometer installation and analysis procedure	6/25/2020
INL report summarizing analysis results of characterization of advanced manufactured Surface Acoustic Wave sensor for temperature measurement in nuclear applications	12/31/2020
Letter documenting fabrication completion of Ultrasound Thermometers (UT) for high temperature testing	2/20/2020
INL report summarizing test results of performing initial temperature testing of advanced manufactured melt wire package	3/26/2020
Letter documenting fabrication completion of Self Power Neutron Detectors for steady-state reactor operation (Rd-SPND)	6/26/2020
INL report summarizing test results of fabricated and tested out of pile a prototype optical fiber pressure sensor based on Fabry-Perot interferometry	9/10/2020

FY20 Milestones and Schedule

Milestone	Completed Date
INL report summarizing analysis results of identified technical solutions to allow optical fiber penetrations in irradiation experiments	7/24/2020
INL report summarizing analysis results of a test plan for the demonstration of wireless technology to nuclear applications	8/13/2020
INL report summarizing test of high temperature irradiation resistance (HTIR) thermocouples in the INL flowing autoclave system	9/2/2020
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	9/29/2020
INL report summarizing demonstrated performance of Self Power Neutron Detectors for steady-state reactor operation (Rd-SPND)	1/15/2021
INL report summarizing analysis results of characterized temperature sensors based on intrinsic fiber-optic sensor technology for reactor core applications	9/30/2020
INL report summarizing results from characterize out of pile long term drift of high temperature irradiation resistance (HTIR) thermocouples and compare with modeling results	1/29/2021

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.



Furnace testing to 1000 °C for SPND signal deviation

	Emitter Dimensions (in.)	Emitter Insulation	Sensor OD
Design 1	0.030 OD x 3.5 L	Al2O3	0.102”
Design 2	0.018 OD x 3.5 L	MgO	0.080”

Procured SPND design specifications

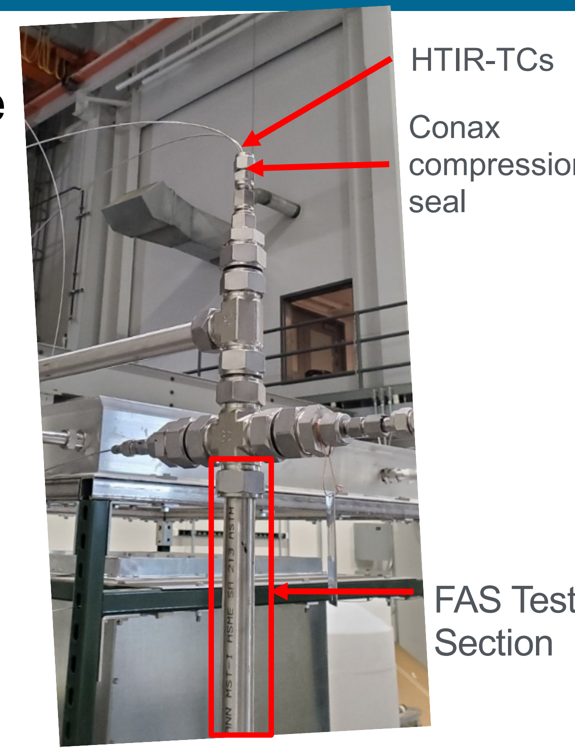
For more information: kevin.tsai@inl.gov

Technology Impact - SPND

- 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

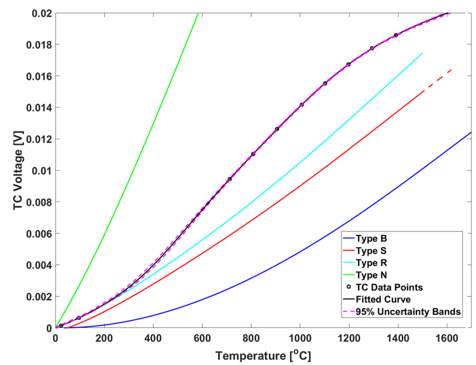
Accomplishments – High Temperature Irradiation Resistant Thermocouples

- High Temperature Irradiation Resistant Thermocouple (Molybdenum vs. Niobium)
  - Capabilities:
    - 0 °C to 1600 °C Temperature Range
    - High neutron flux ready 10^{15} n/cm²/s
    - 1% tolerance at high temperature
    - < 5% drift over long fluence of 10^{21} n/cm²

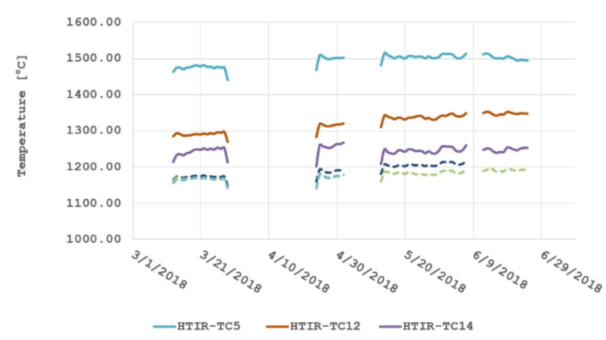


HTIR-TC during flowing autoclave testing

HTIR TC ready for shipment (Insert: 2019 R&D 100 Winner)



Calibration curve of HTIR-TC compared to other industry TCs



AGR 5/6/7 Results of HTIR-TC over 3 months time

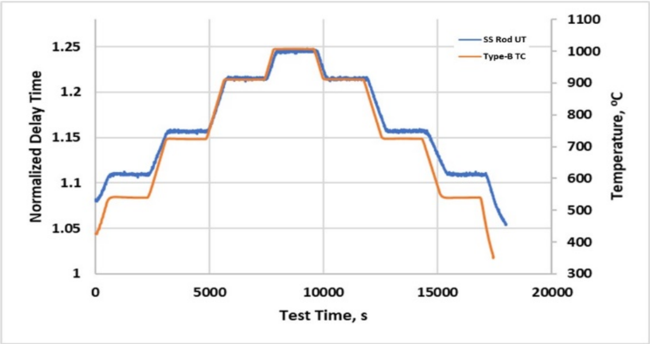
For more information: richard.skifton@inl.gov

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

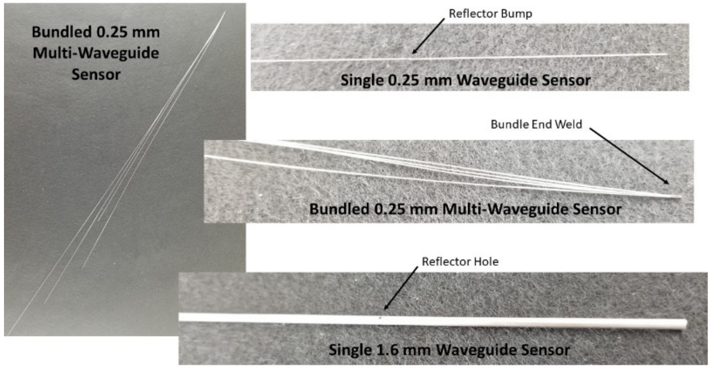
Accomplishments – Ultrasonic Thermometer

- 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



Normalized delay time to 1000 °C for 316-SS 1.6 mm UT

FEA model of 1.6 mm waveguide UT



	Solid Rod			Multi-waveguide		
	SS-316	Mo	W	SS-316	La-Mo	Zirc-4
Max Demonstrated Temperature	1300 °C	2200 °C	2200 °C	1000 °C	1500 °C	800 °C
Limiting Factor	Onset of melting at ~1350 °C	Furnace limitation	Furnace limitation	Attenuation	Sticking	Attenuation / sticking

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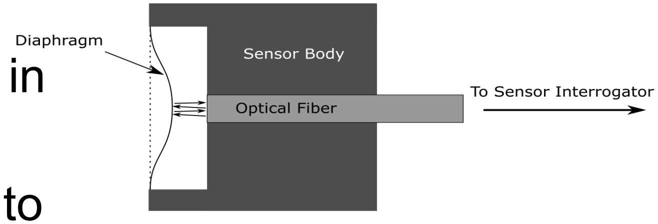
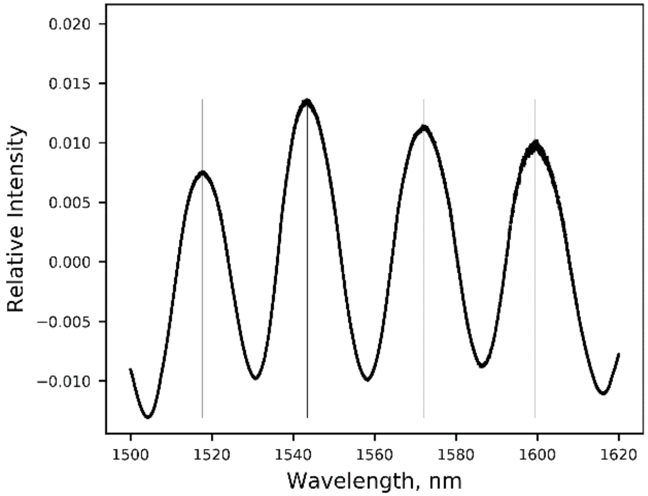
Technology Impact – Ultrasonic Thermometer

- 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

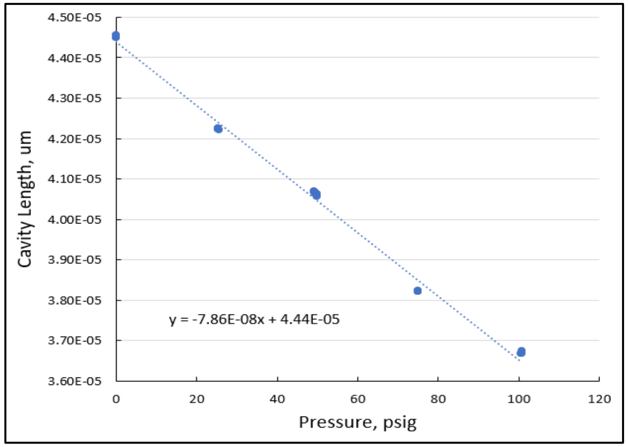
Accomplishments – Fiber Optic Pressure Sensor

- 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

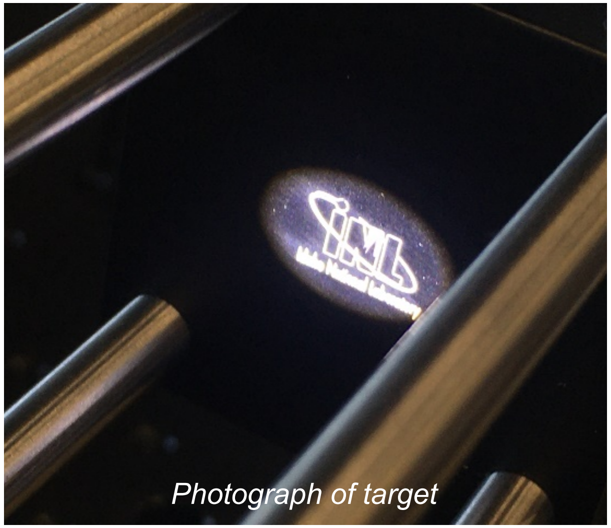


Cavity length vs reference pressure, used for calibration purposes

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



Photograph of target

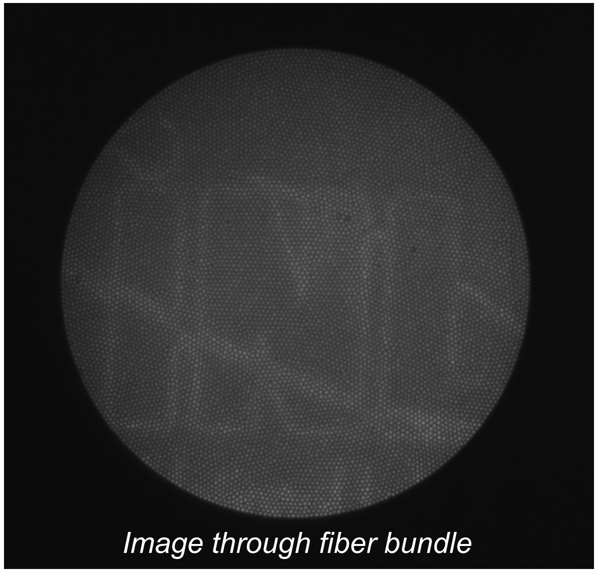


Image through fiber bundle

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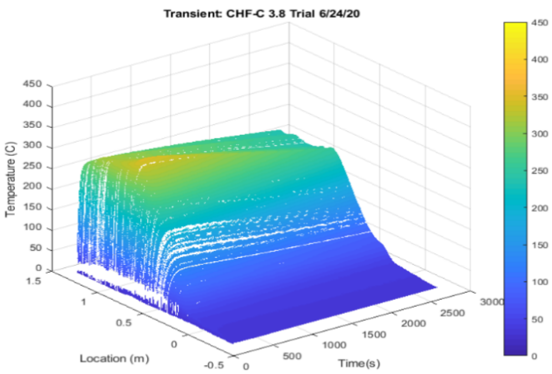
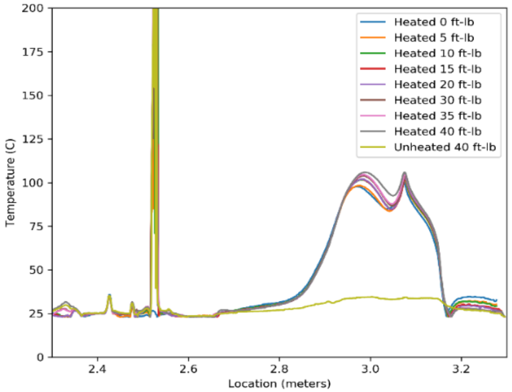
Accomplishments –Fiber Optic Intrinsic Temperature Sensing

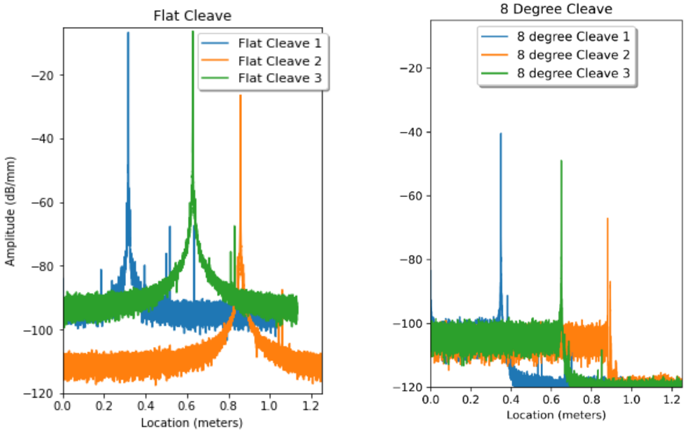
- A variety of intrinsic fiber optic temperature sensors were deployed in both high flux (TREAT) and high fluence (ATR) experiments
  - FBG & Rayleigh backscatter-based temperature sensors
- Addressed challenges associated with in-pile deployments for in-pile imaging
  - Feed through testing (disruption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



INL researcher installing fiber optic sensors in ATR experiment



Feed through testing of optical fibers using

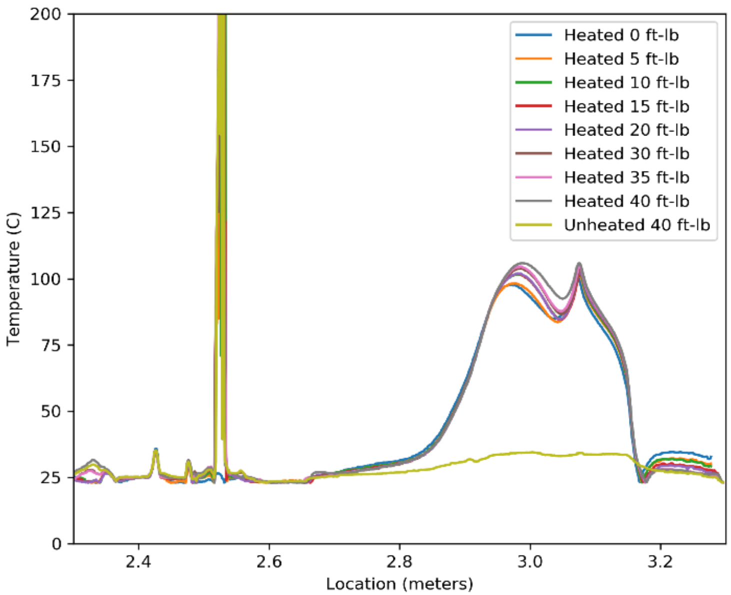


Measured back reflection of different end treatments of optical fibers

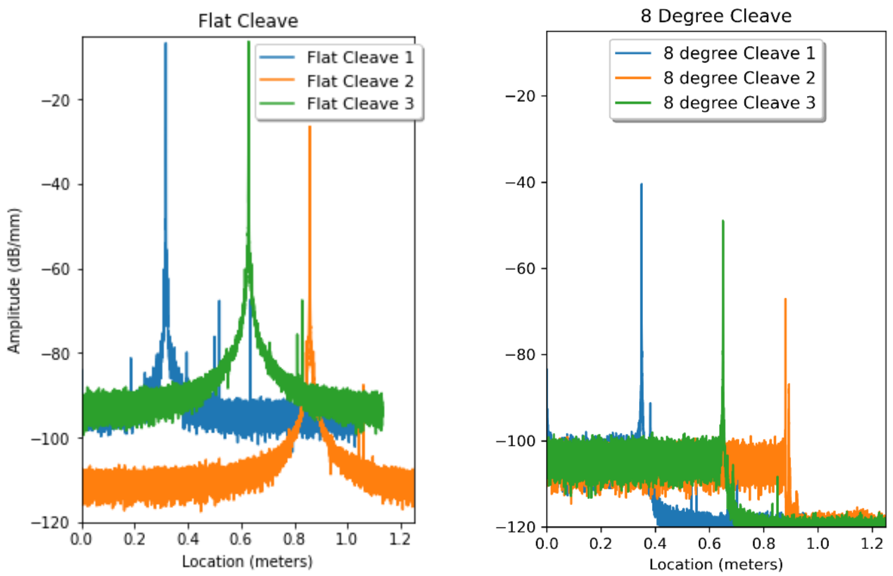
Summary & Accomplishments (FY20)

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



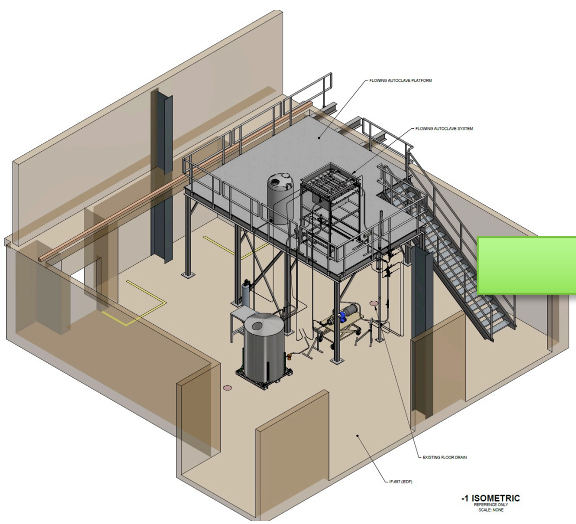
Measured back reflection of different end treatments of optical fibers

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)



Conceptual layout of Flowing Autoclave System (Isometric View)


360° view of the flowing autoclave system mezzanine support structure (finished Sept 2020)

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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 Milestones and Schedule

FY21 Real Time In-Core Instrumentation: From Fuel and Materials Irradiation tests to Advanced Reactor Demonstration Milestones	Due Date
INL report summarizing characterization of advanced manufactured Surface Acoustic Wave sensor for temperature measurement in nuclear applications	12/17/2020
INL report summarizing characterize out of pile long term drift of high temperature irradiation resistance (HTIR) thermocouples and compare with modeling results	1/22/2021
INL report summarizing HTIR performance in flowing autoclave for fuel center line temperature measurement in PWR conditions	9/30/2021
INL report summarizing In-core test of imaging technique based on optical fiber bundles	7/23/2021
INL report summarizing modeling activities for the development of damping system for wave guides of Ultrasound Thermometers	9/30/2021
INL report summarizing performance of Self Power Neutron Detectors for steady-state reactor operation (Rd-SPND)	1/14/2021
INL report summarizing prototype new wave guides for Ultrasound Thermometers to minimize the effect of "sticking" wave guide to sheath	8/26/2021
INL report summarizing the active compensation technique for radiation effects and degradation in optical fibers	9/15/2021
INL report summarizing the comparative assessment of neutron flux sensor technologies for advanced reactors	9/30/2021

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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