August 19, 2020

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Manager, Measurement Science Department

Advanced sensor technologies for real-time temperature measurement in nuclear reactors

With contributions from:
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Josh Daw, Austin Fleming, Kelly McCary, Troy Unruh

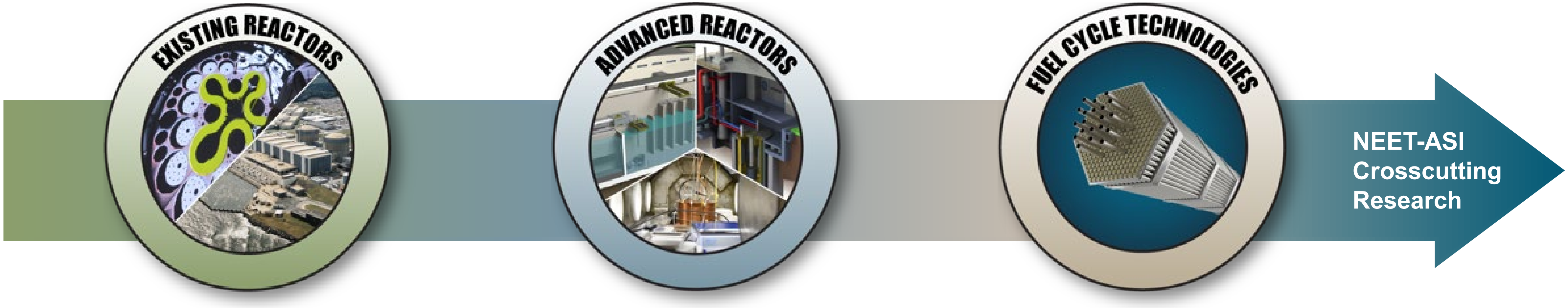
Idaho National Laboratory

Mission

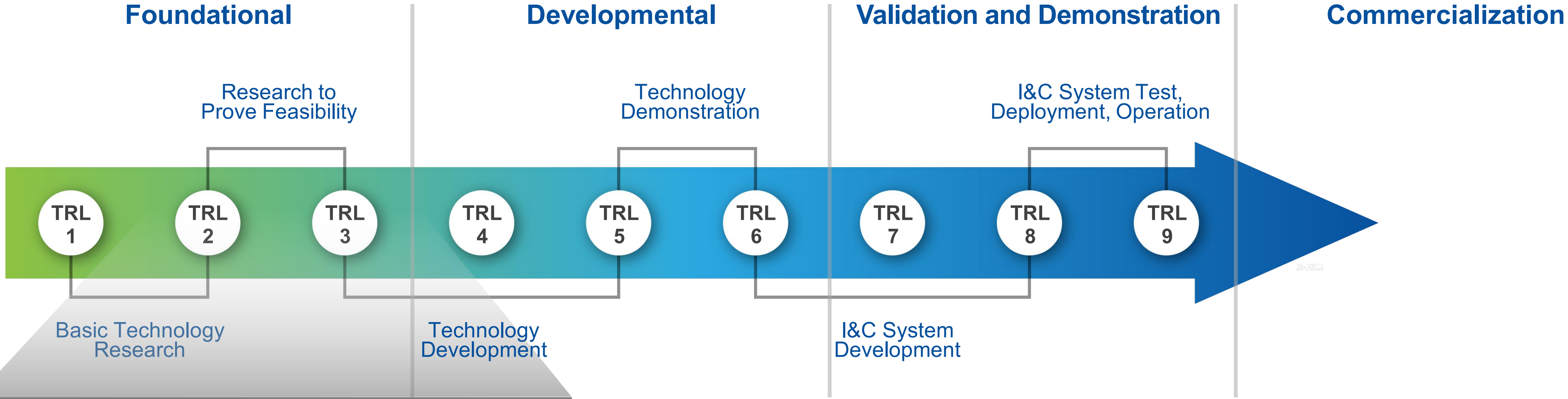
Develop **advanced sensors and I&C** that address **critical technology gaps** for monitoring and controlling existing and advanced **reactors** and supporting **fuel cycle** development

Vision

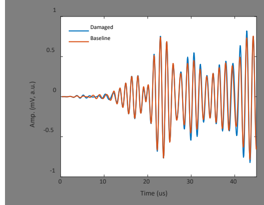
NEET ASI research results in advanced sensors and I&C technologies that are **qualified, validated, and ready to be adopted by the nuclear industry**

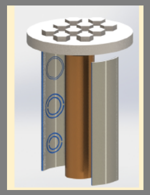


Irradiation experiments for sensors technology demonstration



CINR projects

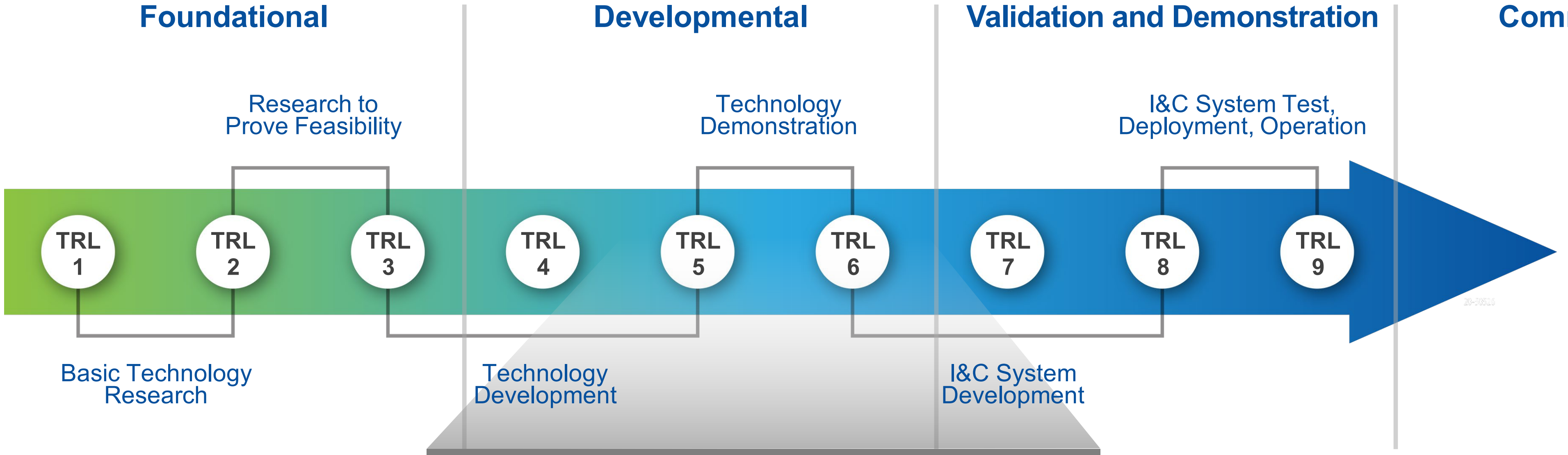




University projects | *SBIR* | *NSUF irradiation experiment*

- High Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle Systems (Xiaoning Jiang – North Carolina State University)
- Integrated silicon/chalcogenide glass hybrid plasmonic sensor for monitoring of temperature in nuclear facilities (Maria Mitkova – Boise State University)
- Development of Optical Fiber Based Gamma Thermometer to Infer Power Distribution (Tom Blue – Ohio State University)
- Irradiation Behavior of Piezoelectric Materials for Nuclear Reactor Sensors (Marat Kafizov - Ohio State University)

Irradiation experiments for sensors technology demonstration



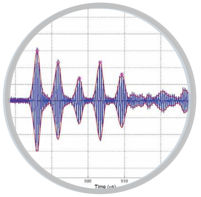
Irradiation experiments

Transient Reactor Test Facility (TREAT)

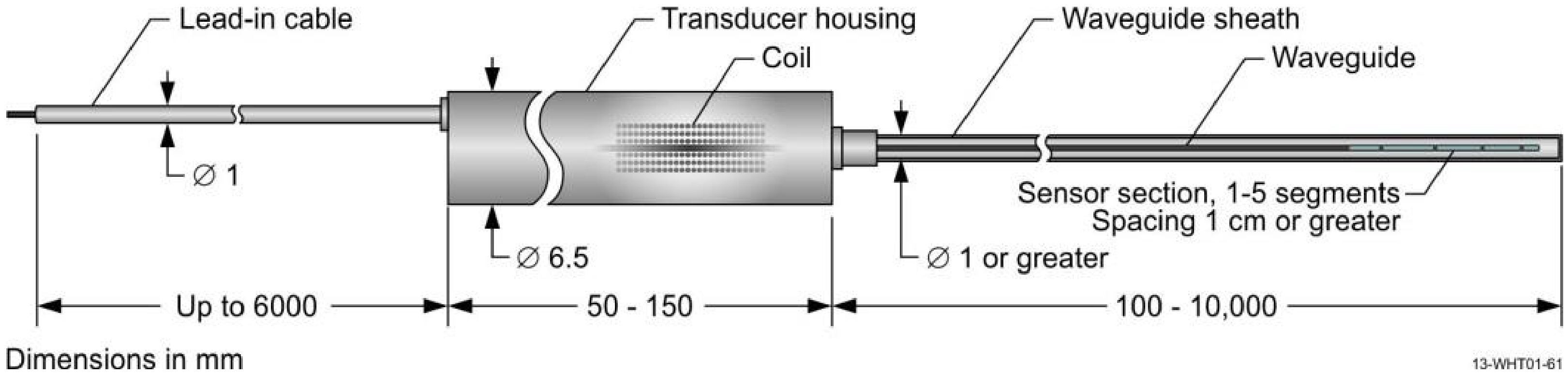
Advanced Test Reactor (ATR)

- Ultrasound Thermometers
- Fiber optic temperature measurement
- Passive monitors

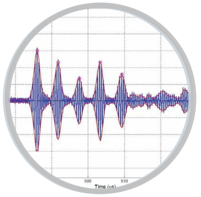
Ultrasound thermometers



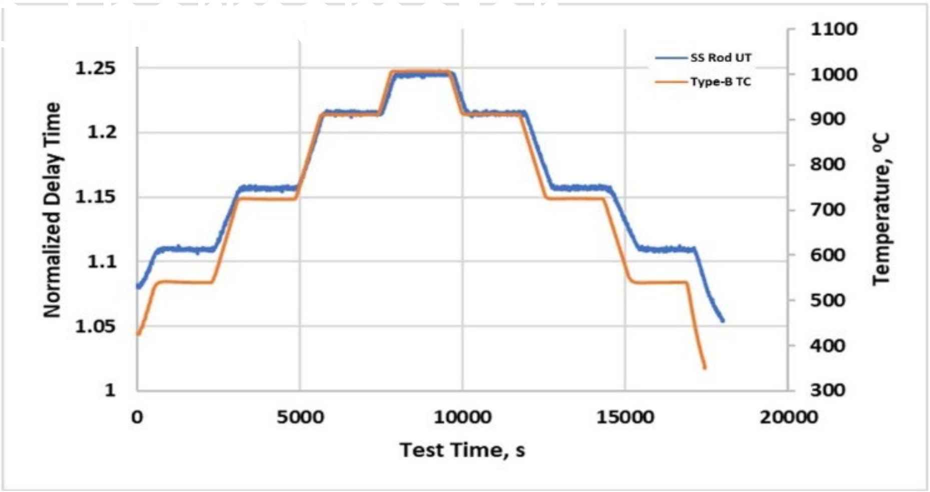
- Ultrasound based sensors allow distributed measurement of relevant operational parameters at temperatures beyond the capability of conventional instrumentation (up to 3000ºC)
- The use of specialized magneto-strictive materials in irradiation tests at MITR and ATR had demonstrated the feasibility of in-core temperature measurement using Ultrasound Thermometers based on waveguide design (UT)



Ultrasound thermometers

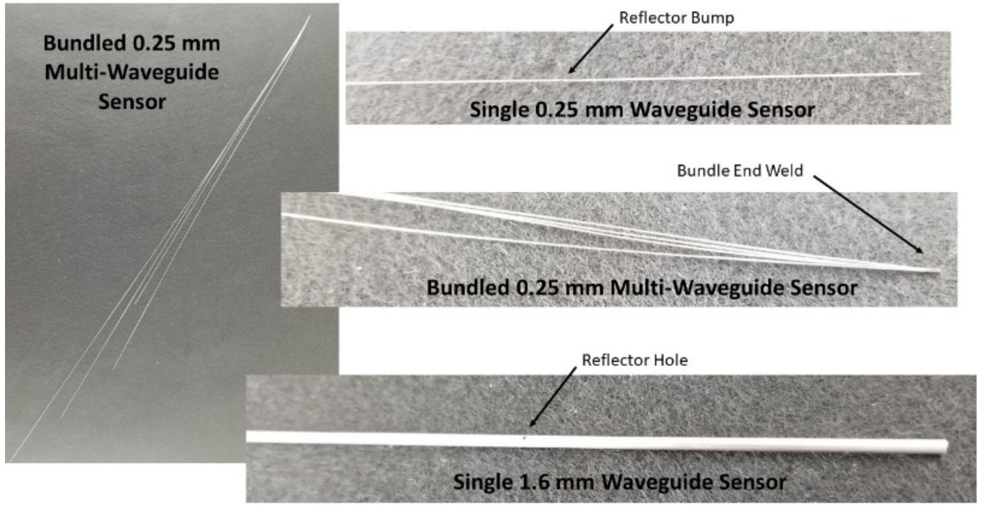


- Waveguide ultrasonic thermometer operational envelope testing
  - High temperature testing in vacuum furnace to find maximum operating temperatures
  - Pressure testing in static autoclave
    - No effect on signal to 2500 PSI and 325 ^{o}C
  - BSU developing FEA model of solid waveguide UT for performance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



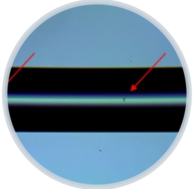
Normalized delay time to 1000 ^{o}C for 316-SS 1.6 mm UT

FEA model of 1.6 mm waveguide UT

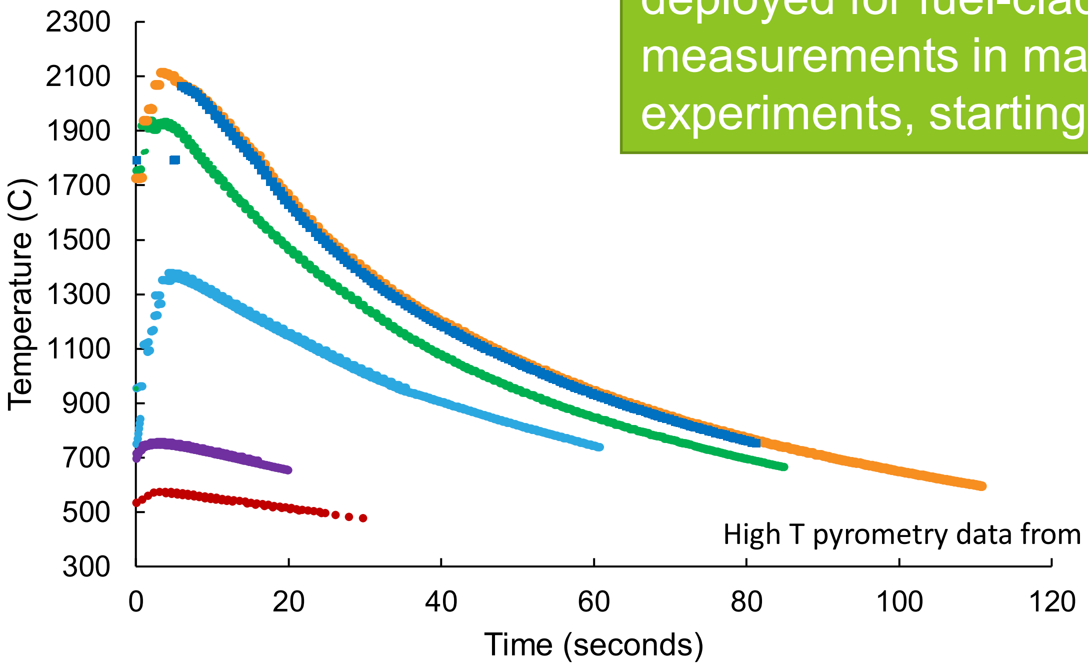


	Solid Rod			Multi-waveguide		
	SS-316	Mo	W	SS-316	La-Mo	Zirc-4
Max Demonstrated Temperature	1300 ^{o}C	2200 ^{o}C	2200 ^{o}C	1000 ^{o}C	1500 ^{o}C	800 ^{o}C
Limiting Factor	Onset of melting at ~1350 ^{o}C	Furnace limitation	Furnace limitation	Attenuation	Sticking	Attenuation / sticking

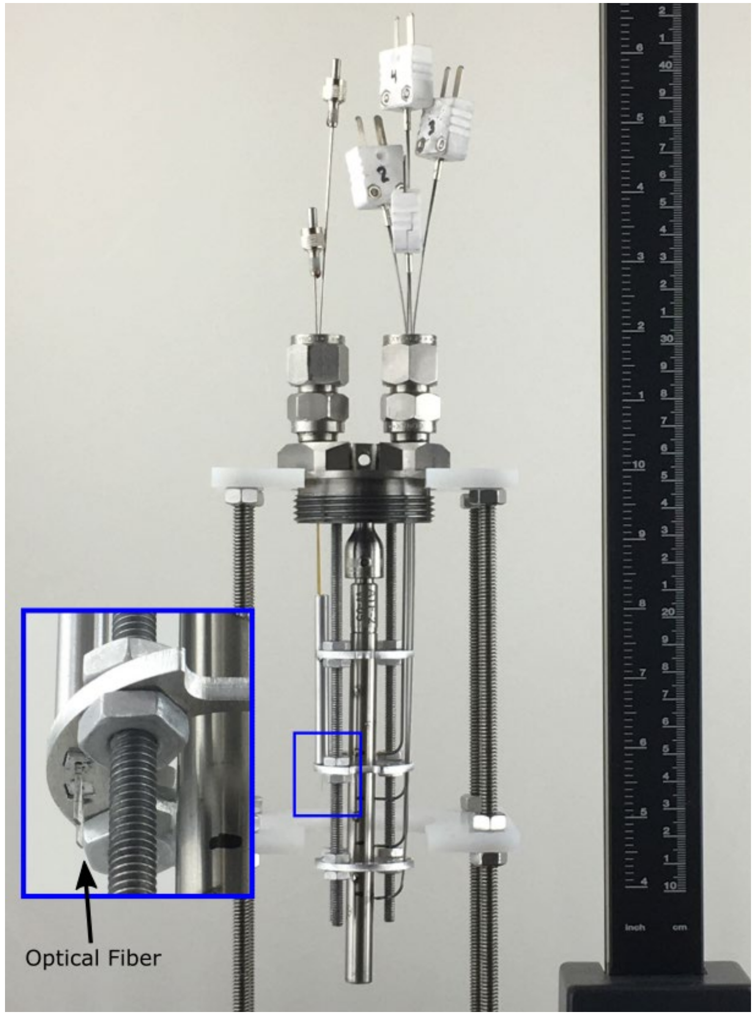
Fiber optic sensors



Fiber-optic Infrared-pyrometry with emissivity compensation has been deployed for fuel-cladding temperature measurements in many TREAT experiments, starting with the ATF-SETH

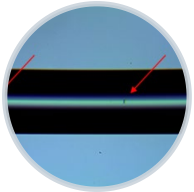


High T pyrometry data from the NASA SIRIUS experiment

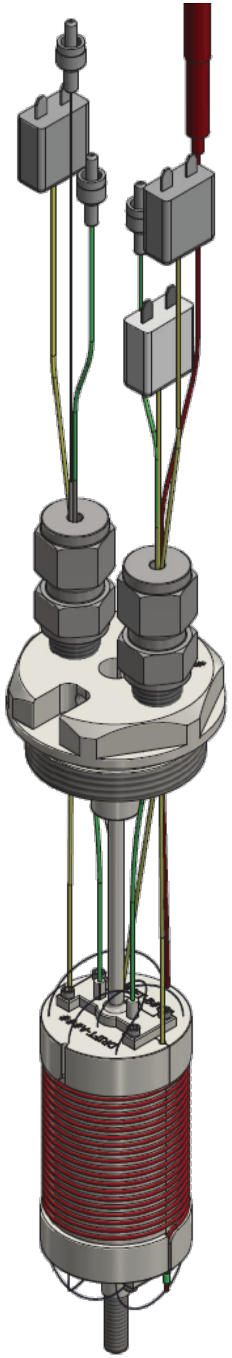


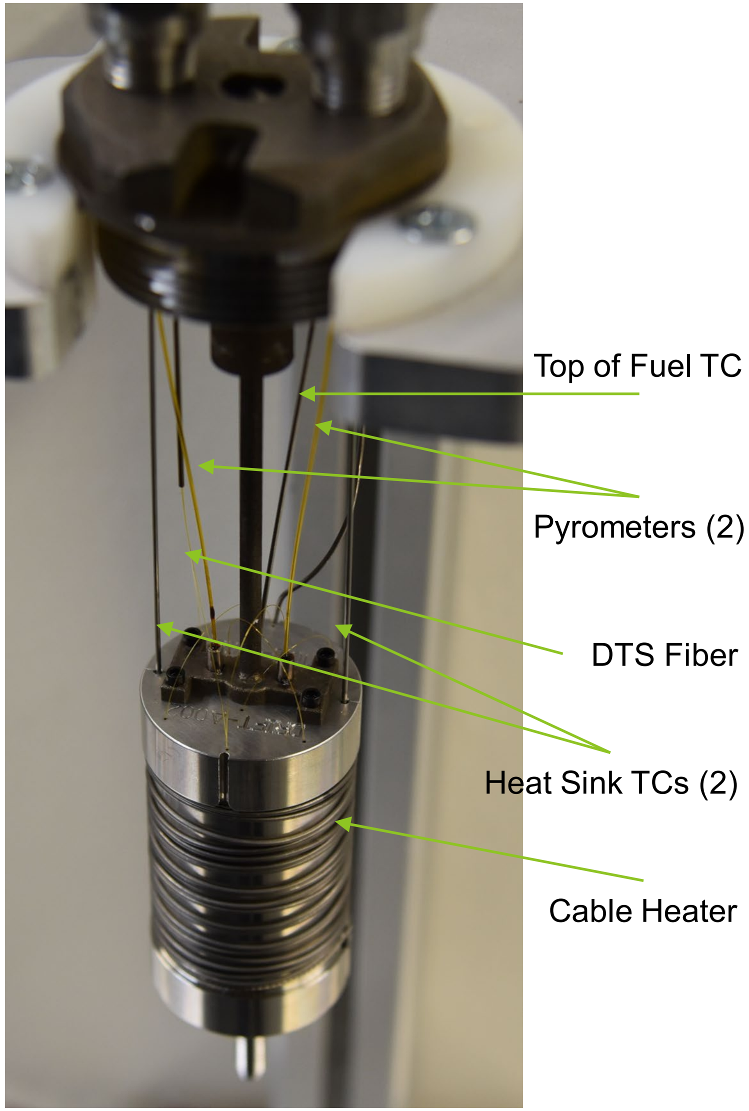
Austin Fleming
Nonlinear Photothermal Radiometry and its Applications to Pyrometry and Thermal Property Measurements (PhD Thesis)
Nonlinear heterodyne photothermal radiometry for emissivity-free pyrometry
Journal of Applied Physics **128**, 153101 (2020)

Fiber optic sensors

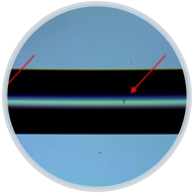


- DRIFT instrumentation package:
  - 2 Pyrometers viewing fuel pellet surface
  - 3 Thermocouples
    - 2 in the heat sink
    - 1 on the center of top pellet
  - 1 Distributed Fiber Optic Temperature Sensor
    - Routed throughout the heat sink
  - 1 Cable Heater (for preheating the experiment)

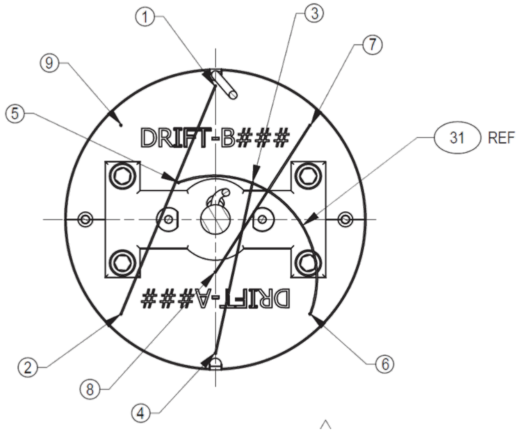


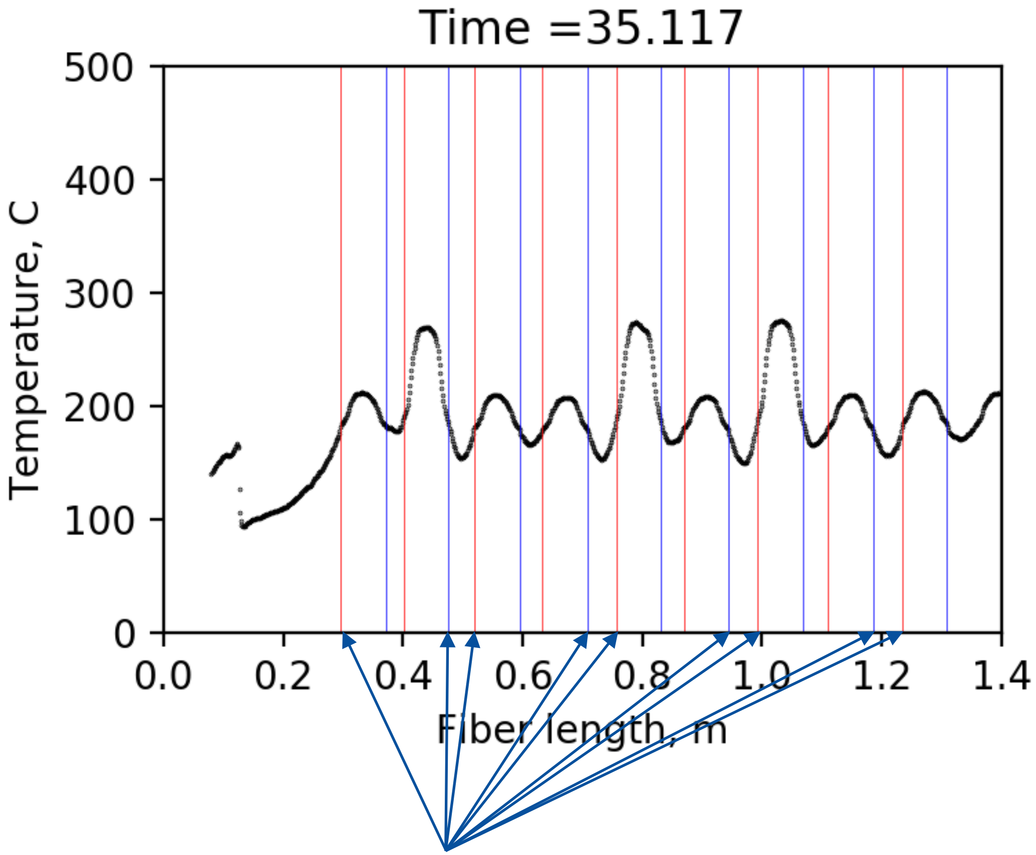


Fiber optic sensors



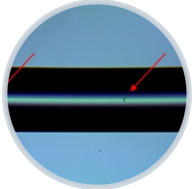
- Temperature profile along the length of a **single** fiber
- Segments between "inlet" and "outlet" of heat sink map the temperature profile and provide an indication of temperature at the top and bottom of capsule



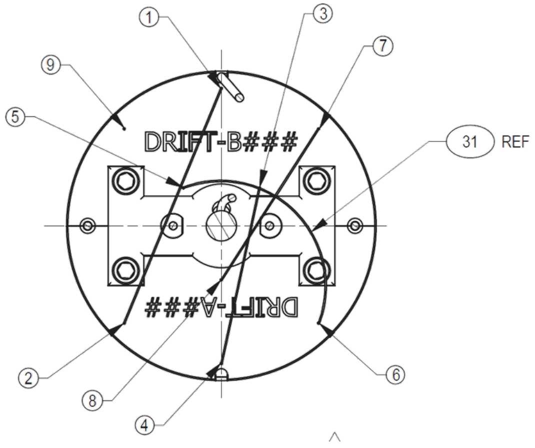


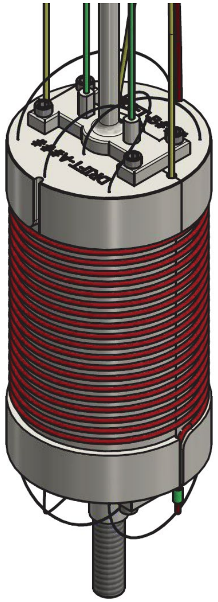
Top of heat sink

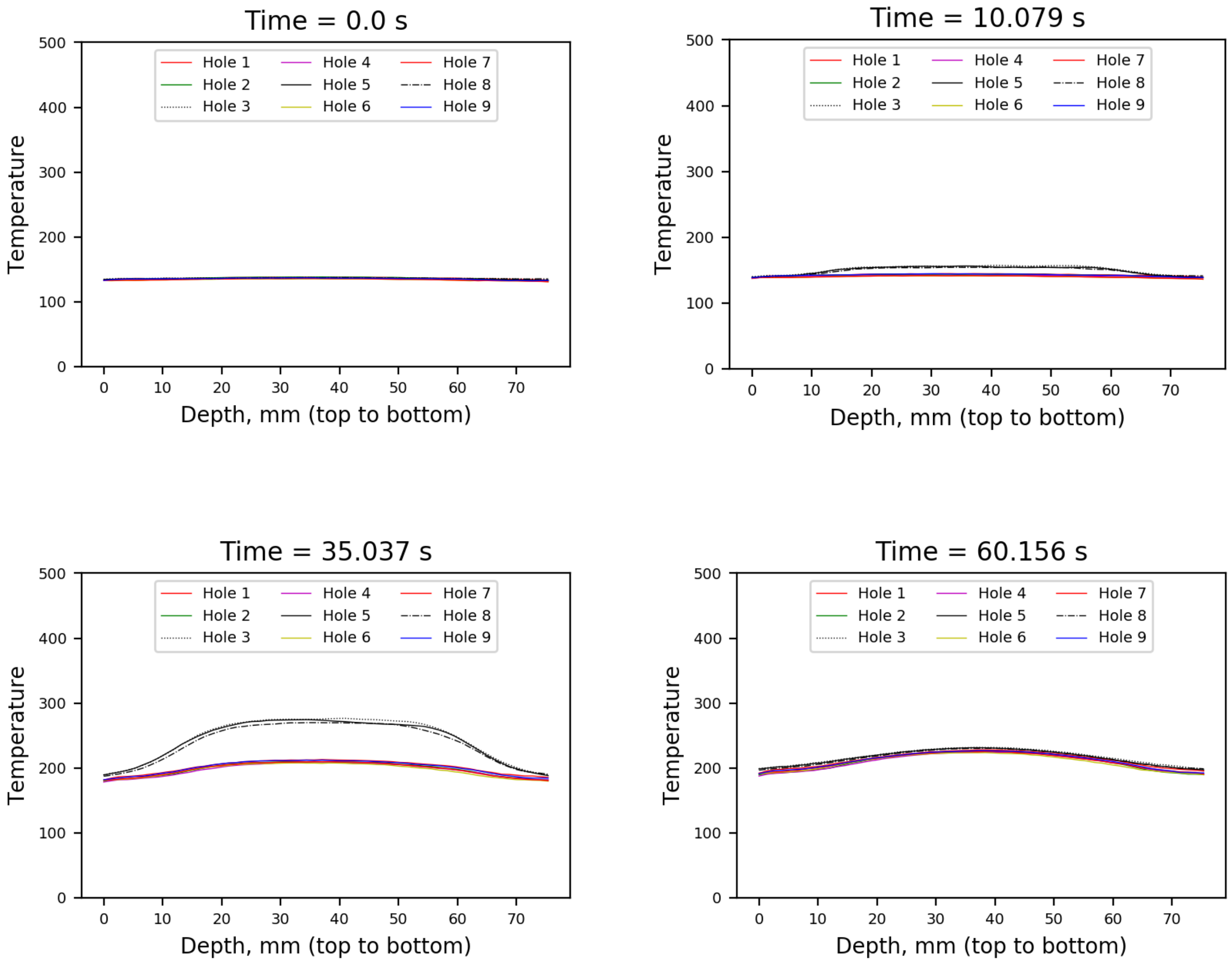
Fiber optic sensors



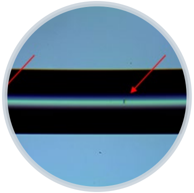
- Black traces (holes 3, 5, and 8) are radially closer to fuel
- Excellent axisymmetry
- ~1 minute end effects of heat sink become more important



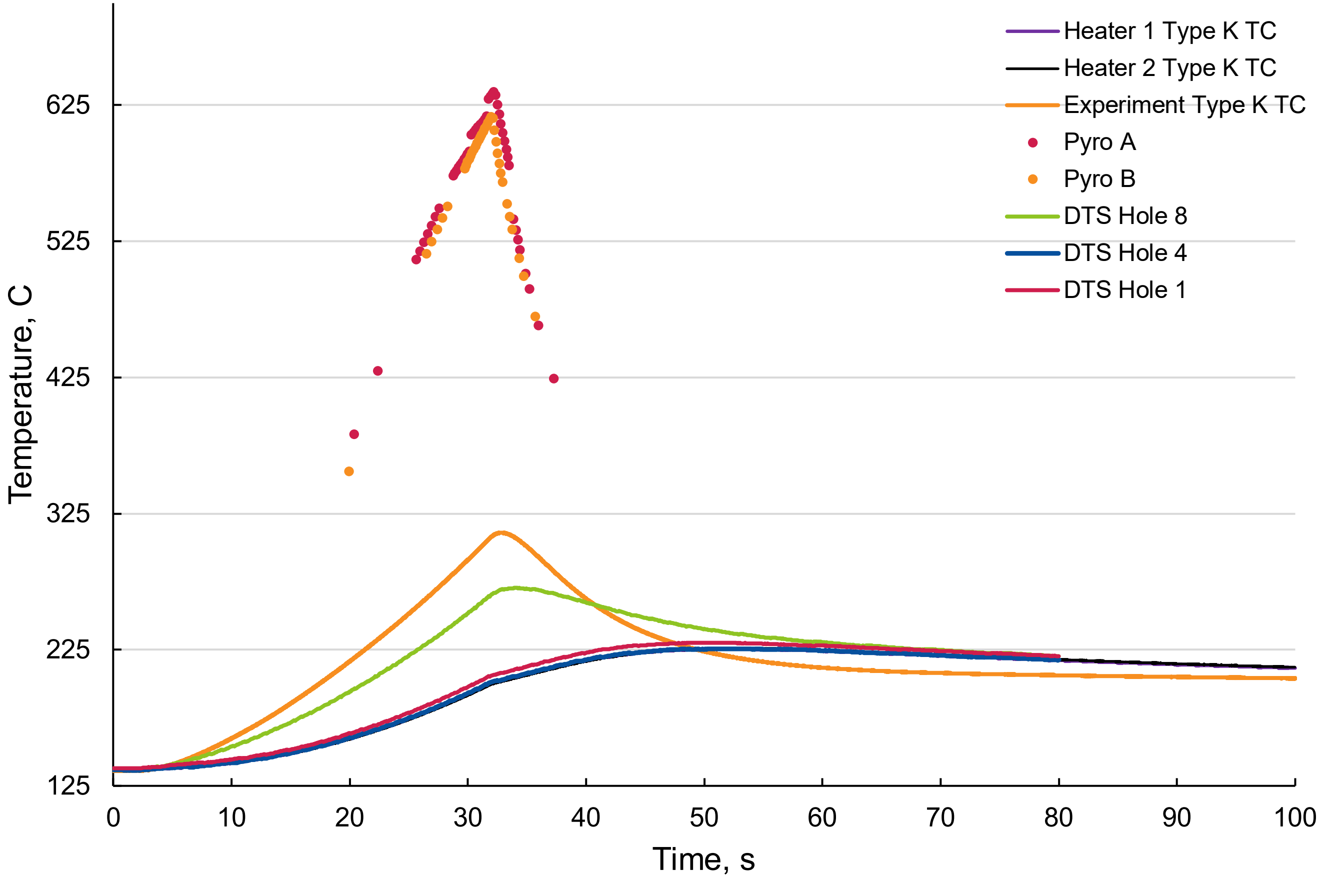


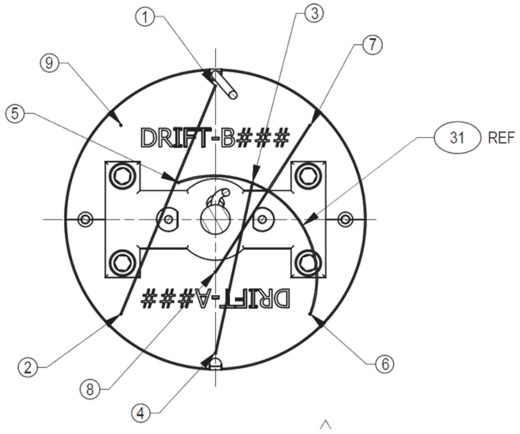


Fiber optic sensors

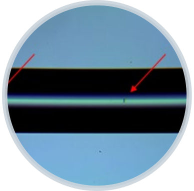


- Integrated data summary at experiment centerline



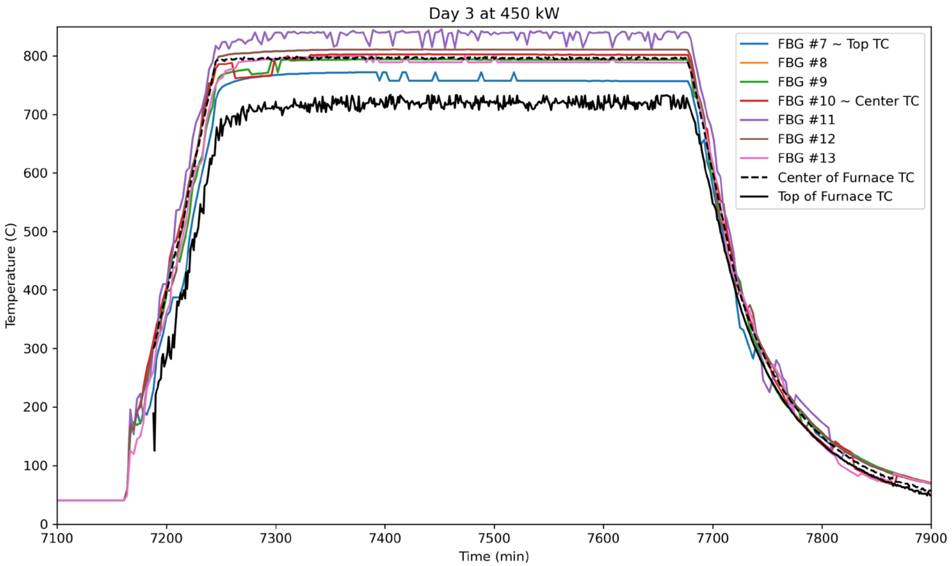


Fiber optic sensors

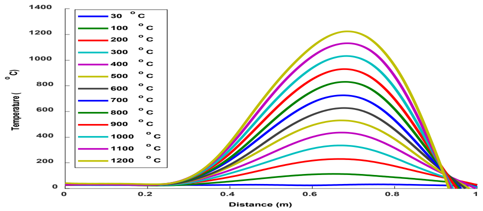


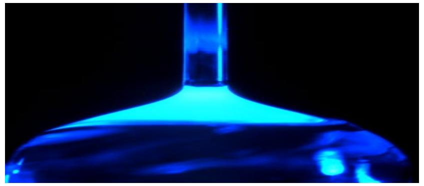
R&D activities to extend fiber reliability under high temperature and irradiation damage accumulation:

- Temperature and radiation compensation models for real time data analysis in silica fibers
- Advanced sensor inscription: laser enhanced Rayleigh scattering and intrinsic FP cavity arrays
- Development of laser based, coupled acousto-optic interrogation methods
- Industrial fabrication of cladded sapphire fibers by Laser Heated Pedestal Growth (LHPG)
- Test of reduced-transmission-mode sapphire fibers under irradiation (OSURR and MITR)

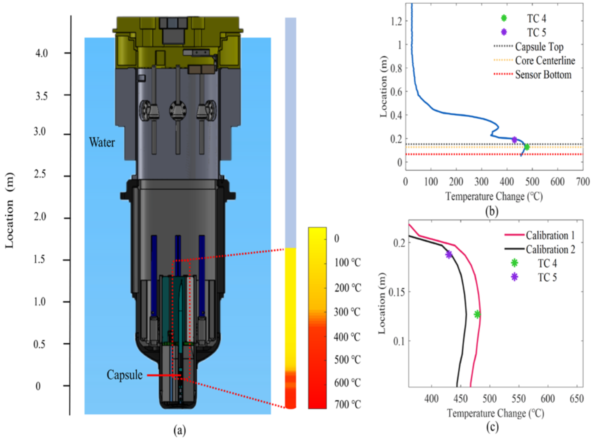


Sapphire optical fiber (75 um OD, clad via Li-6 method, with type-II FBGs) OFDR response at 800 °C and 450 kW reactor power (tested up to 1600 °C)

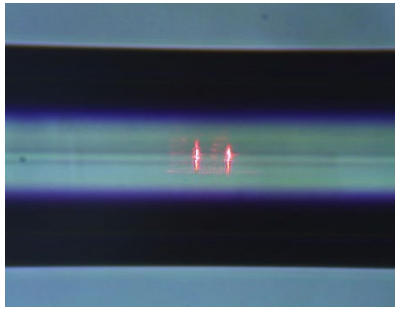




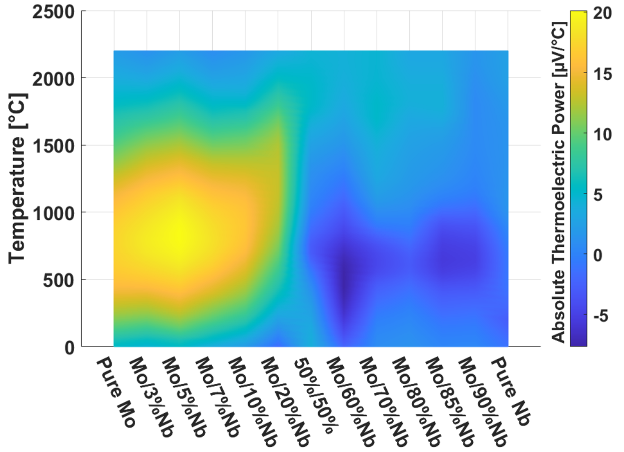
Michael Buric (PI), National Energy Technology Lab (Morgantown)



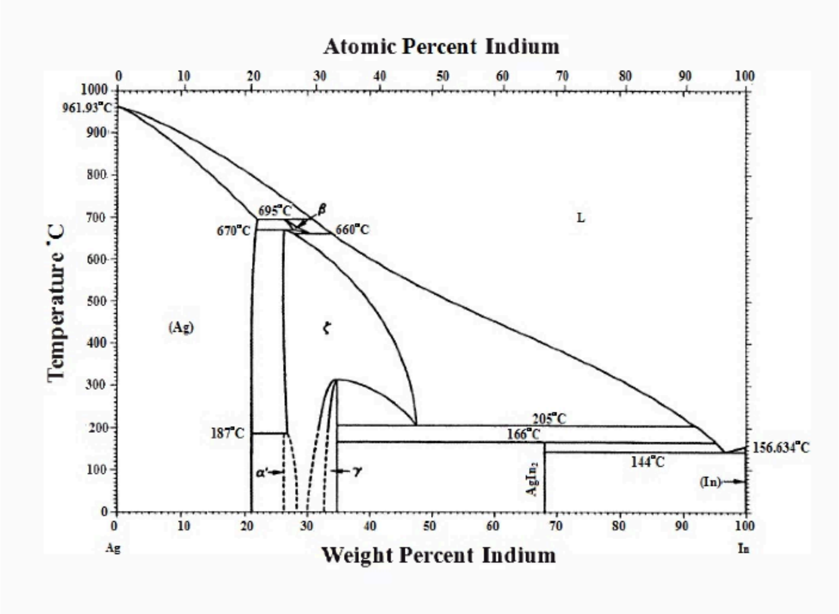
K. Chen (U Pitt) laser enhanced OFDR test in MITR and IFPI sensors fabrication

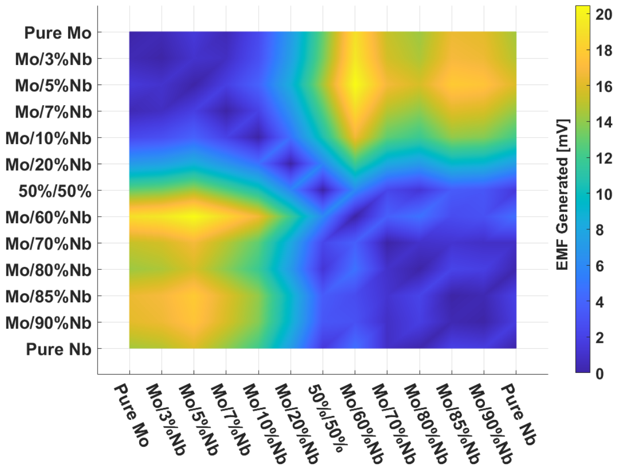


Advanced manufacturing methods for in-core sensors



Development of **bi-metallic ink** that are compatible with direct write technologies to produce highly sensitive, miniaturized and robust sensors for in-pile applications.

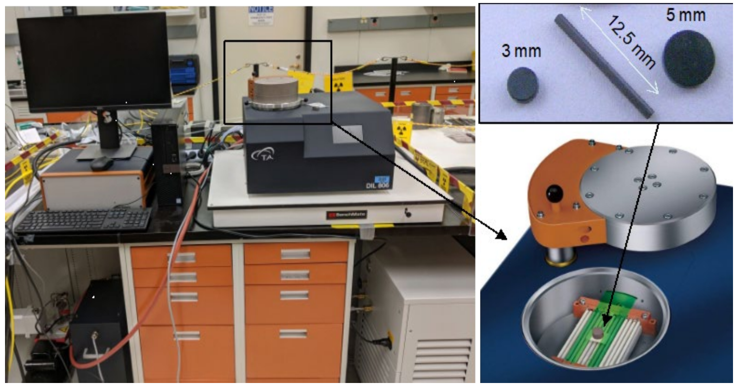


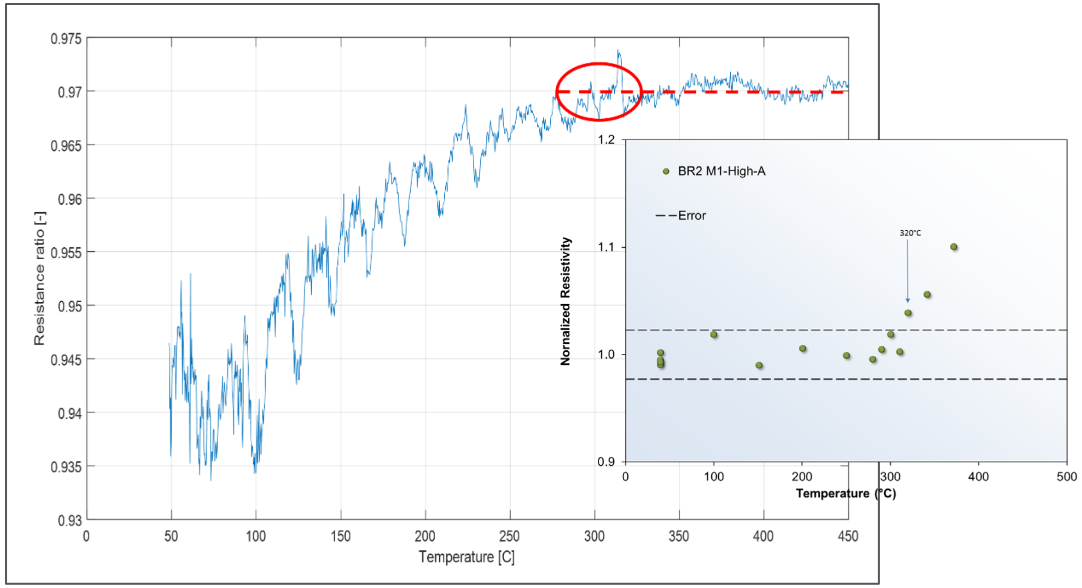


EMF from Mo/Nb alloys

HTIR sensitivity could be enhanced by AM fabrication

Passive monitors for peak irradiation temperature

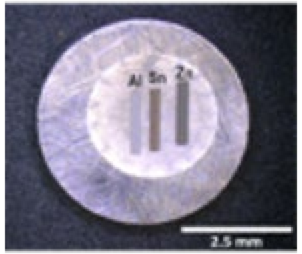


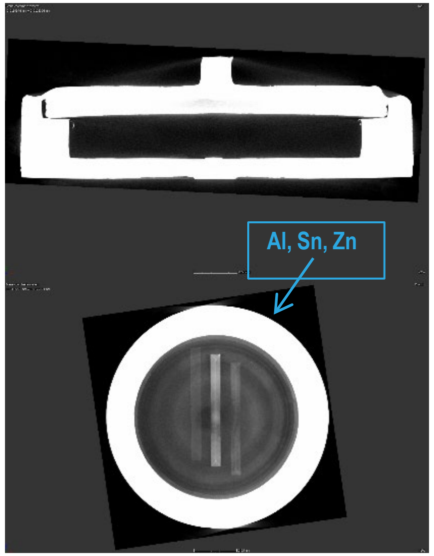


Continuous reading of SiC monitors in PIE after BR2 irradiation

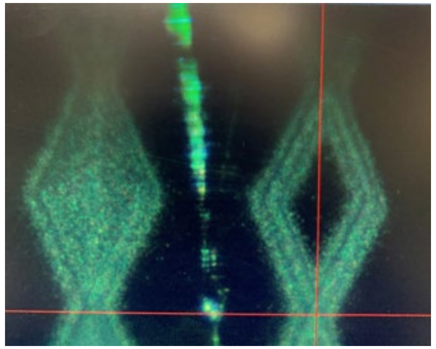
- Passive monitors are needed when real-time sensors are not practical or economical to install
- Specialized peak temperature and neutron fluence monitors and related analysis techniques for Post Irradiation Examination (PIE)
- Development focus on reliability and compatibility with standard material samples sizes (ie, 3 mm disc)

Passive temperature and flux monitors





CT scan of printed Sn, Zn and Al melt wires



Unique printing pattern to enhance melt wire sensitivity

Demonstration facilities for I&C system validation

Foundational | **Developmental** | **Validation and Demonstration** | **Commercialization**

- TRL 1 – TRL 2: Basic Technology Research
- TRL 2 – TRL 3: Research to Prove Feasibility
- TRL 3 – TRL 5: Technology Development
- TRL 5 – TRL 6: Technology Demonstration
- TRL 6 – TRL 8: I&C System Development
- TRL 8 – TRL 9: I&C System Test, Deployment, Operation

- High Temperature Irradiation Resistant thermocouples
- Microreactor Agile Non-Nuclear Testbed (MAGNET) heat pipe instrumentation

Technology Commercialization Fund (TCF)

Demonstration facilities

NRIC
National Reactor Innovation Center

Demonstration facilities – Microreactor Agile Non-Nuclear Testbed (MAGNET)

Distributed Thermocouples (TC):
- 10-point K-type thermocouple successfully demonstrated for measuring internal heatpipe temperature during startup

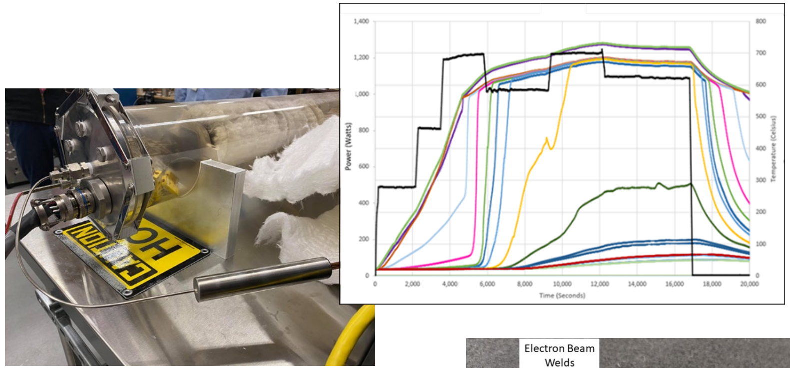
Ultrasonic Thermometer (UT)
- 7-point ultrasonic thermometer

Fiber Optic (FO)Temperature senor
- 9-point Type-II fiber bragg grating (FBG) FO calibrated and tested

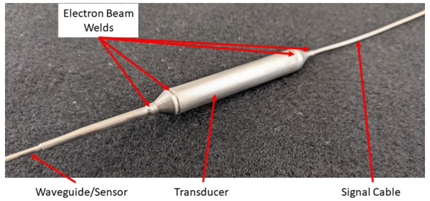
Embedded Sensors
- Spatially-distributed fiber-optic (FO) temperature and strain sensors and thermocouples (TCs) embedded in pipes and core blocks using ultrasonic additive manufacturing (UAM)

Digital Image Correlation (DIC)
- DIC for measuring strain and deformation at high spatial resolution as a non-contact, imager-based technique that can potentially be used to measure strain/deformation in 2D or 3D

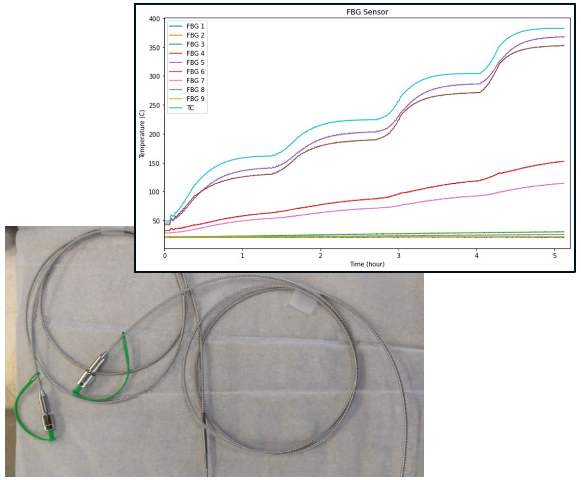
Microreactor Agile Non-Nuclear Testbed (MAGNET)



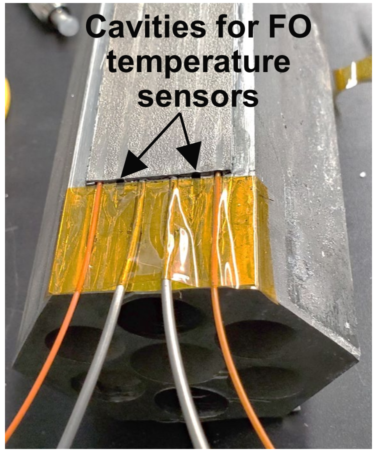
10-point TC installed and tested



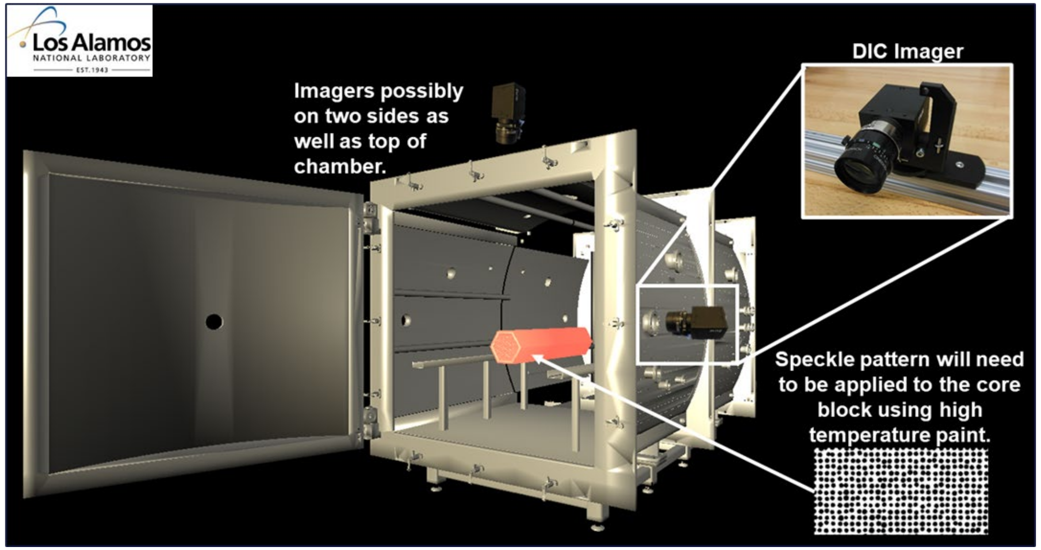
UT transducer



FBG sensors and calibration



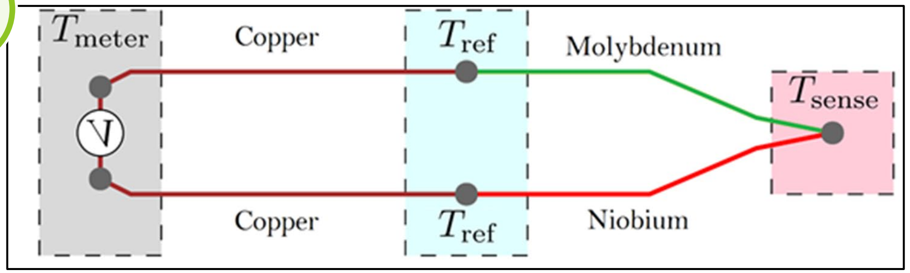
Core block with embedded sensors



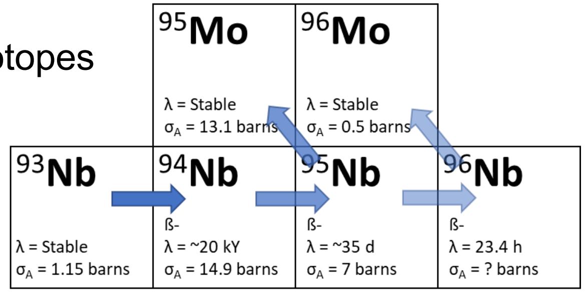
Digital Image Correlation Simulation

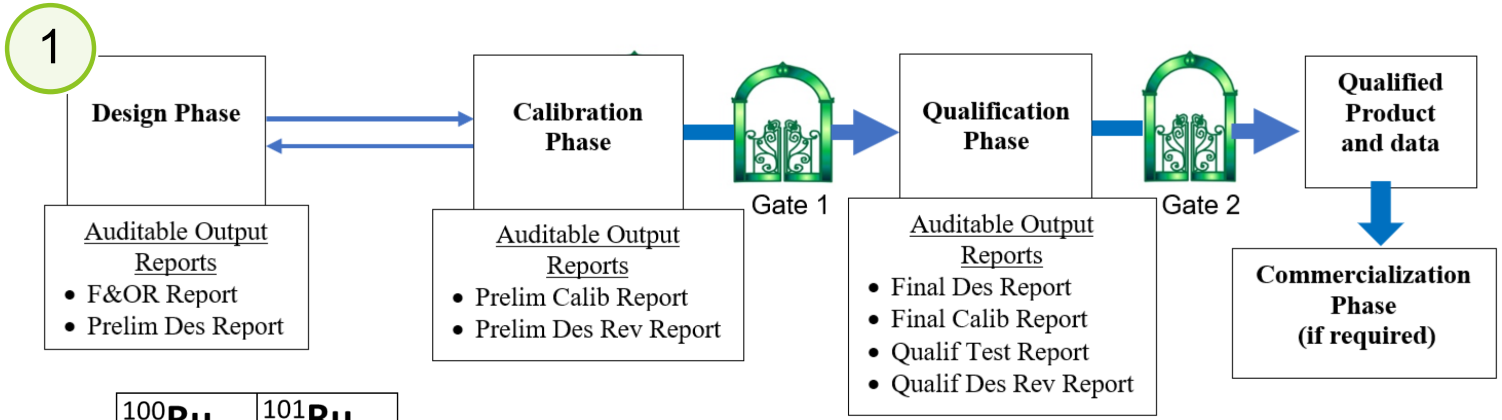
HTIR-TC development and qualification

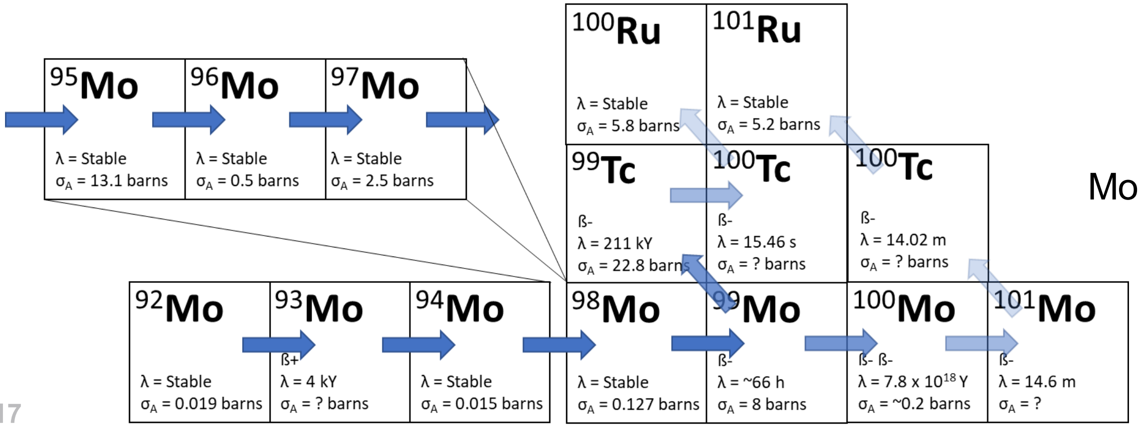
1



Niobium ß- decay to stable Mo isotopes





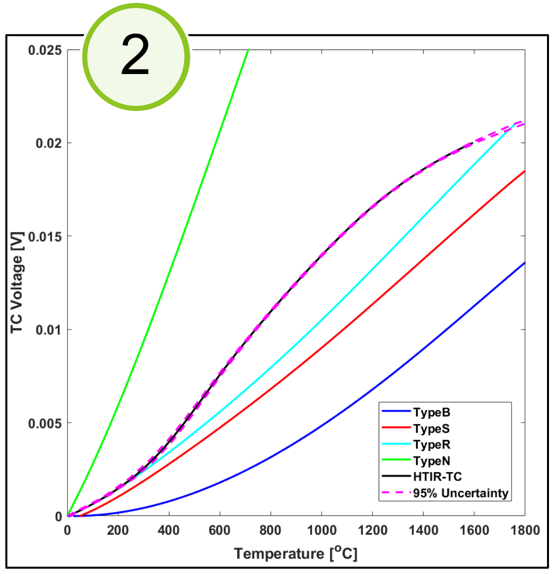


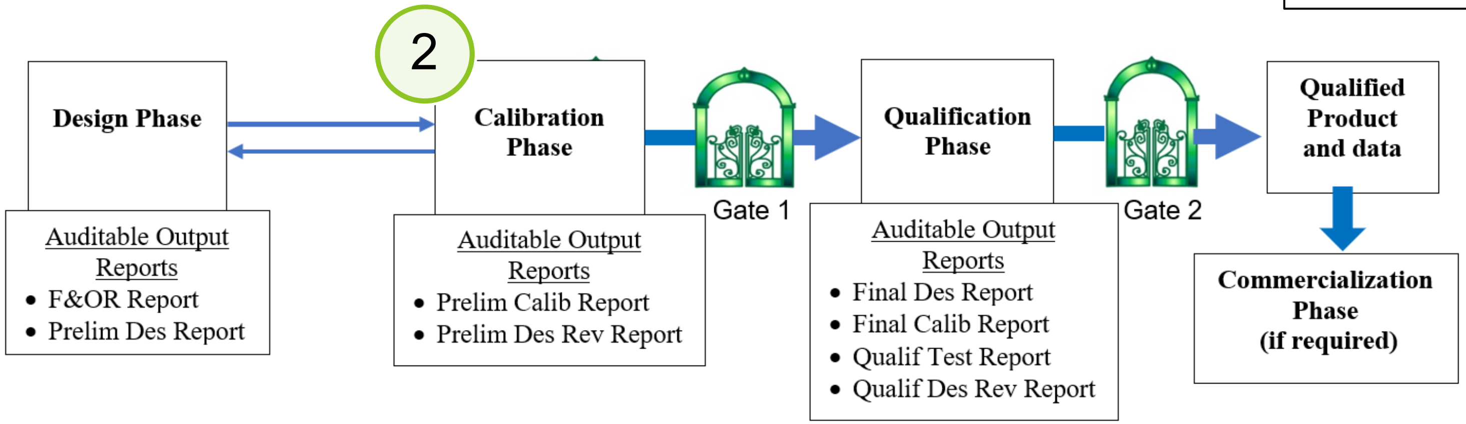
Mo ß- decay to stable ruthenium isotopes

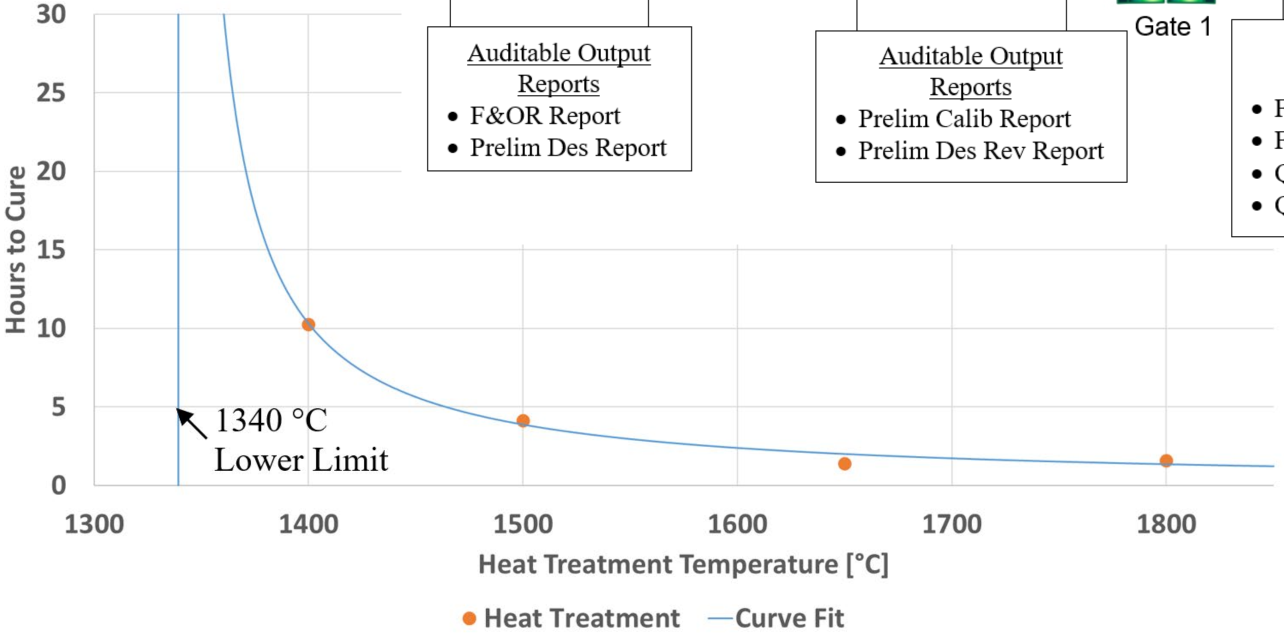
Richard Skifton #06-208
Optimized High Temperature Irradiation Resistant Thermocouple for Fast Response Measurements

HTIR-TC development and qualification

- Calibration fit using both low and high temperature ranges
- 5th order polynomial works best
- Comparable output to other commercially available TCs
- Linear region between 700 °C and 1500 °C



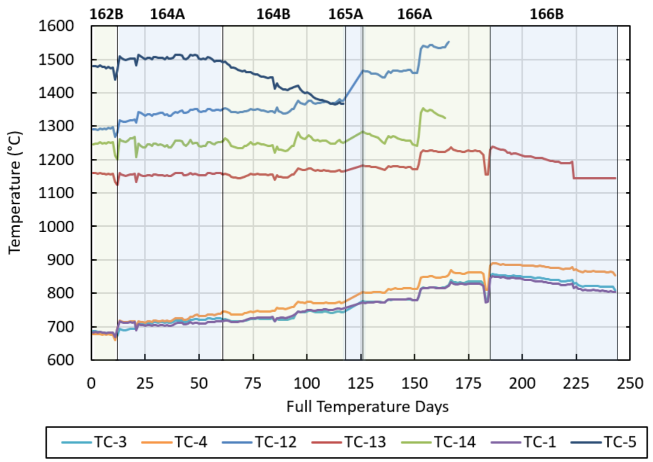




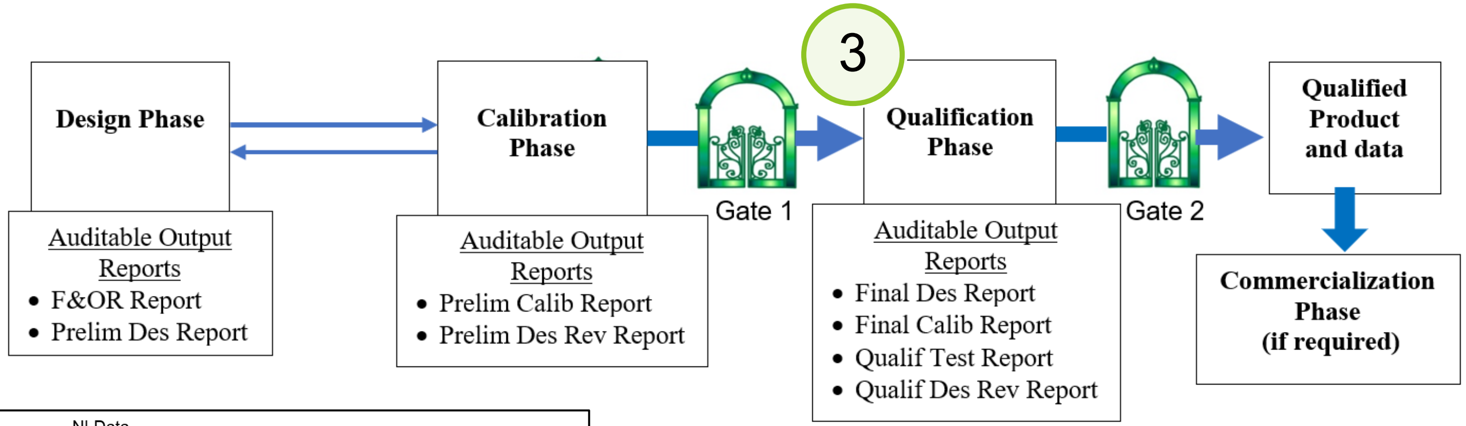
- Heat treatment necessary for stable calibration
- Time and temperature dependent with a 1/x law
- Must reach higher than ~1340 °C to take effect
- Minimum timeframe at around 2.5 hours

HTIR-TC development and qualification

Joe Palmer #04-196
Summary of Thermocouple Performance in the Advanced Gas Reactor Experiment AGR-5/6/7 During Irradiation in the Advanced Test Reactor



AGR5/6/7 Capsule 3 data



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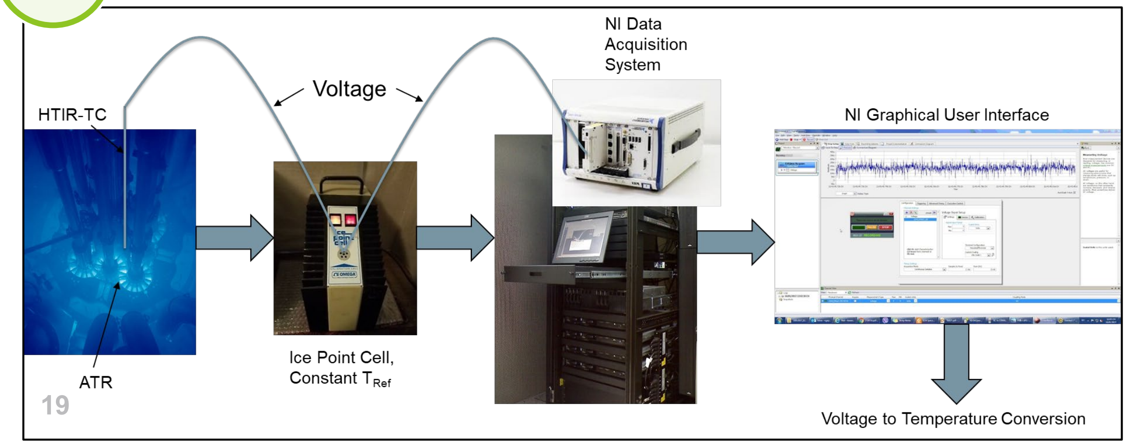


HTIR-TC development and qualification

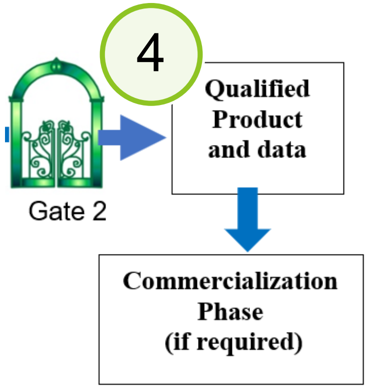
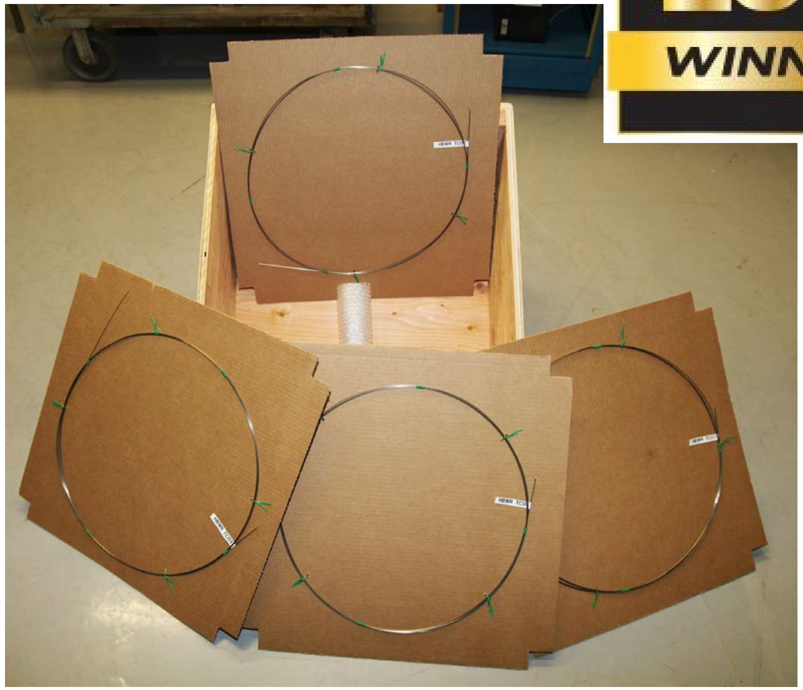


Table 1: Summary of performance parameters for the HTIR-TC

Performance Parameter	Performance Requirement Fuel Test Application	Performance Requirement Stand-Alone Application
Temperature Range	**Room Temperature - 1600°C**	**Room Temperature - 1600°C**
Accuracy	Not Specified	±1%
Drift	**3% for 4.5 x 10^{21} nvt (thermal)**	**3% for 4.5 x 10^{21} nvt (thermal)**
Life	**4.5 x 10^{21} nvt (thermal), or 10 thermal shocks (room temperature to 1600°C)**	**18 months or 4.5 x 10^{21} nvt (thermal)**
Mechanical Ruggedness:		
Rugged Junction	Rugged mechanical junction design	Rugged mechanical junction design
Bend Radius	Minimum of 0.5 inch	Minimum of 0.5 inch
Thermal Shock	5 sudden startups and 5 sudden shutdowns—each causing a thermal shock on the order of room temperature up to 1600°C	100°C/hr
Response Time	<0.5 seconds	<0.5 seconds



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