Fiber optic sensors development as part of the DOE Advanced Sensors and Instrumentation program

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Programmatic framework

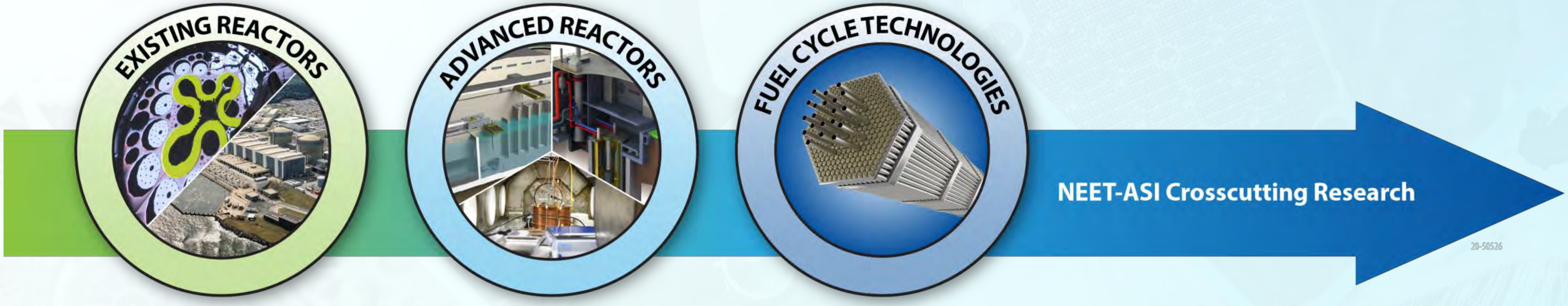
ASI Program Focus

Mission

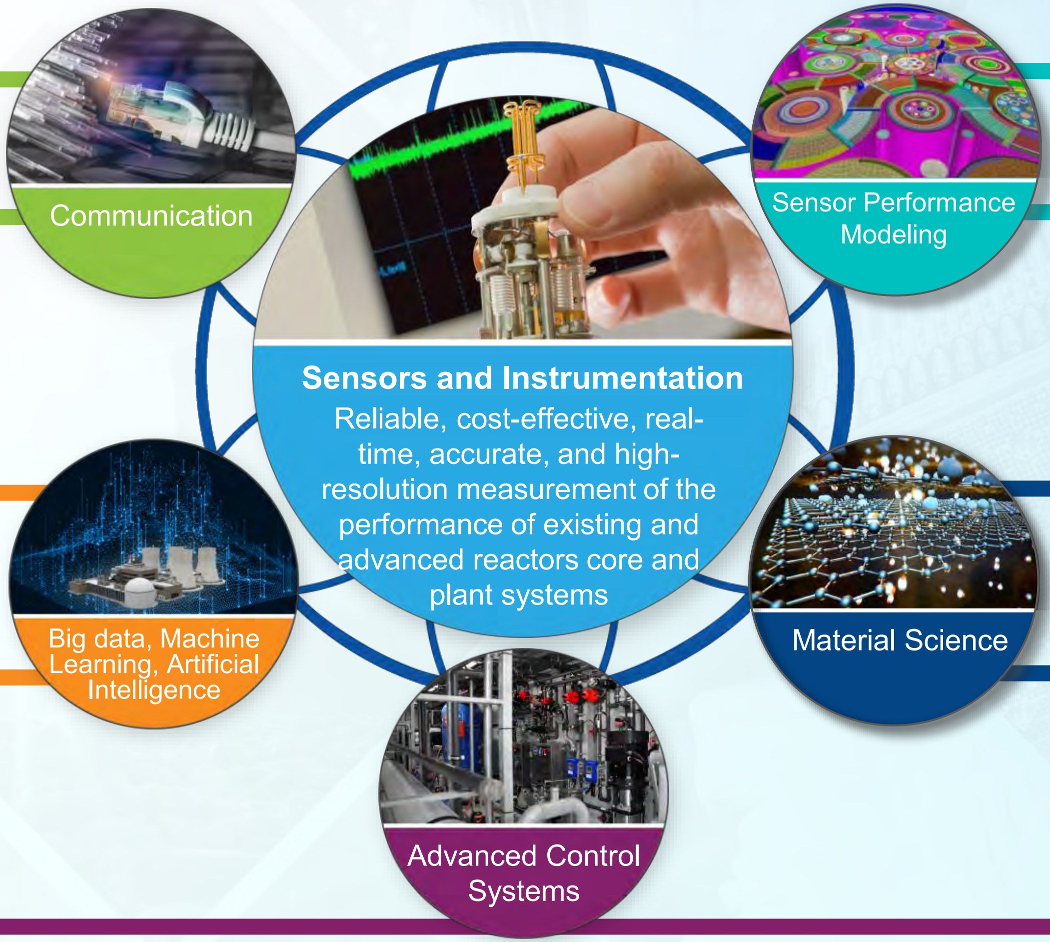
Develop **advanced sensors and I&C** that address **critical technology gaps** for monitoring and controlling existing and advanced **reactors** and supporting **fuel cycle** development

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**



ASI R&D Components



Sensors and Instrumentation

Reliable, cost-effective, real-time, accurate, and high-resolution measurement of the performance of existing and advanced reactors core and plant systems

Communication

Resilient, real-time transmission of sufficient amount of data for online monitoring and advanced data analytics

Sensor Performance Modeling

Modeling of instrumentation performance to enable predictive capabilities and integration in Digital Twins

Big data, Machine Learning, Artificial Intelligence

Machine learning and artificial intelligence processes to enable semi-autonomous operation and maintenance by design

Material Science

Innovative sensor materials and advanced manufacturing techniques applied to instrumentation design and fabrication

Advanced Control Systems

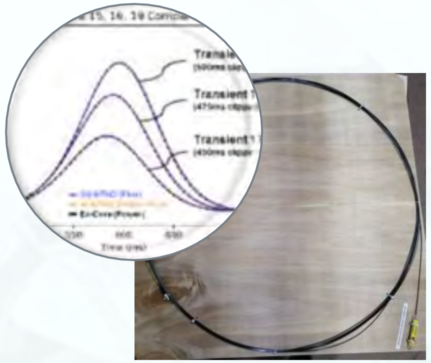
Enable near real-time control of plant or experiments process variables to enhance performance

Legacy achievements

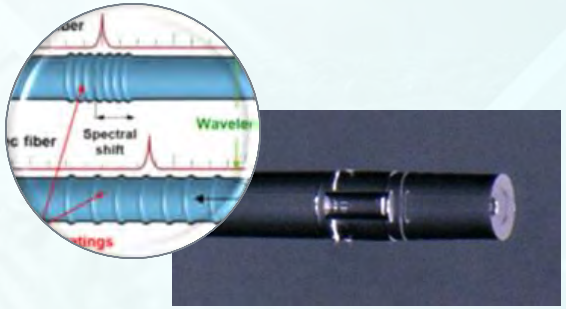
Ultrasound thermometer commercialization

Over the course of the last 11 years, the ASI program has fostered the development and commercialization of a wide range of technologies spanning the inception of novel sensing methods and the enhancement of instrumentation with a long history of commercial utilization. The program has funded over $58 million in RD&D which supports the US Department of Energy and the US DOE Office of Nuclear energy missions. Sensors developed under the ASI program have been used to support other DOE-NE programs and have been commercialized for nuclear industry adoption.

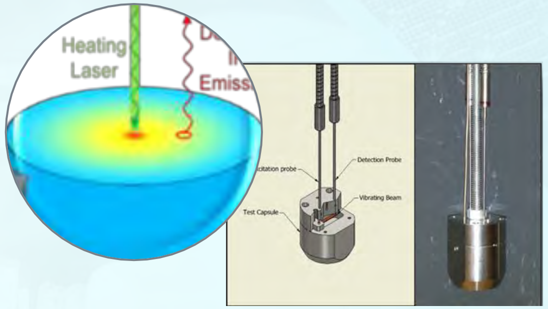
High Temperature Irradiation Resistant (HTIR) thermocouples



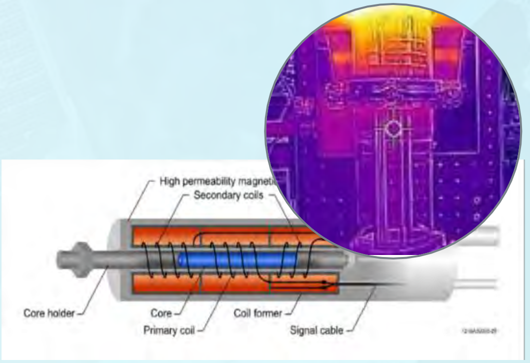
Self Powered Detectors and miniaturized Fission Chambers for local neutron flux measurement



Fiber optic sensors for nuclear applications



Real time measurement of fuel material properties in-core

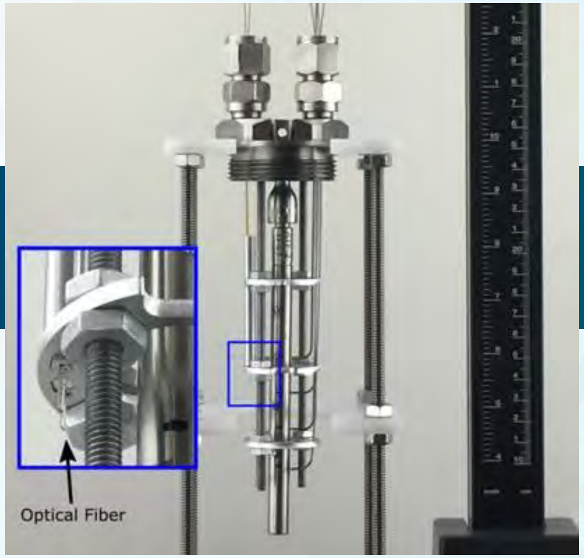


Linear Variable Differential Transformer (LVDT) for fission gas pressure measurement

Research focus areas

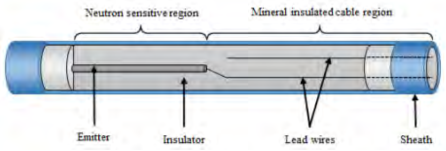
The ASI program activities have been structured into three main focus areas:

Sensors for Advanced Reactors

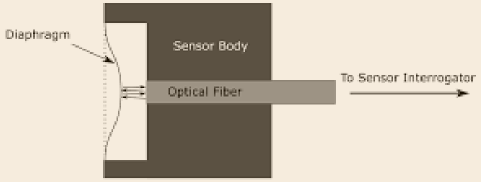


Sensors for
Irradiation Experiments

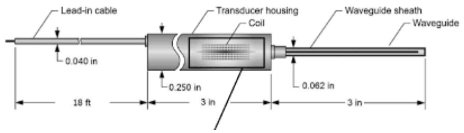
Sensors Integration



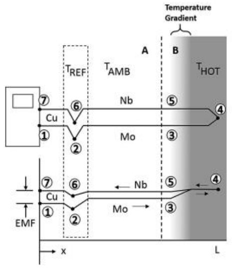
FLUX



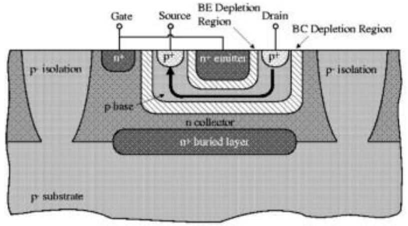
OPTICAL FIBERS



ACOUSTIC SENSORS



THERMOCOUPLES



RAD-HARD ELECTRONICS

DOE labs

- INL: Development of active compensation techniques
- INL: Development of FO pressure sensor
- INL: Benchmarking of Commercially Available Intrinsic Temperature Sensors
- INL: FO imaging
- ORNL: Assessment of FO sensors performance

DOE labs

- INL: High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors
- PNNL: Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control

University projects

- Virginia Tech: Non-Contact Strain and Displacement Monitoring via Single Crystal Sapphire Based Interferometry
- U Michigan: Irradiation of Optical Components of In-Situ Laser Spectroscopic Sensors for Advanced Nuclear Reactor Systems
- OSU (T. Blue): sapphire fibers, reactor power measurement
- Virginia Tech: Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring
- U Pitt: Radiation Effects on Optical Fiber Sensor Fused Smart Alloy Parts with Graded Alloy Composition Manufactured by Additive Manufacturing Processes
- U Pitt: High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle Systems

Sensor industry

- Luna: Fiber-Optic Multifunctional Sensor for Crack Monitoring in Harsh Environments
- Luna: Scaled Reduced Mode Sapphire Fiber Production Towards High Temperature Radiation Resilient Sensors
- Luna: Sapphire Single Mode Fiber Development Towards High Temperature Radiation Resilient Sensors

Nuclear Industry

- Westinghouse: e-vinci microreactor instrumentation

Int. collaborations

- CEA (France): pyrometer; FBGs, F-P extensometer

Documents (reports, review meetings presentations) available on ASI website:

[Advanced Sensors & Instrumentation (asi.inl.gov)](asi.inl.gov)

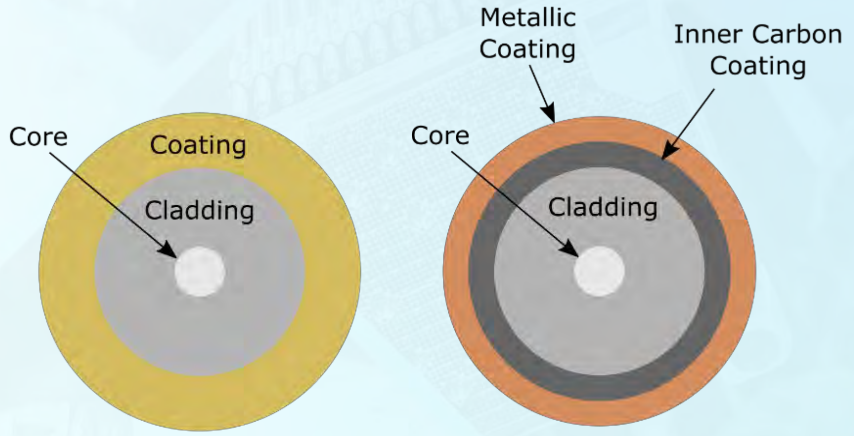
OF for nuclear applications

Challenges in the nuclear environment

- Temperature
- Radiation Effects
  - Radiation-induced Attenuation (RIA)
  - Radiation-induced Emission (RIE)
  - Radiation-induced Compaction (RIC)
- Mechanical Design Integration
  - Adequate Contact
  - Pressure Boundaries
  - Feedthroughs
- Sensor Deployment
  - Packaging

Temperature

- Focus on commercially available single-mode silica optical fibers:
  - 5–10 um core, 125 um cladding diameter: silicon dioxide with varying dopant concentrations
- Available coatings and maximum operating temperatures:
  - Acrylate (85° C)
  - Polyimide (350° C)
  - Aluminum (400° C)
  - Copper (~600° C)
  - Gold (~700° C)



Geometry of common optical fiber structures

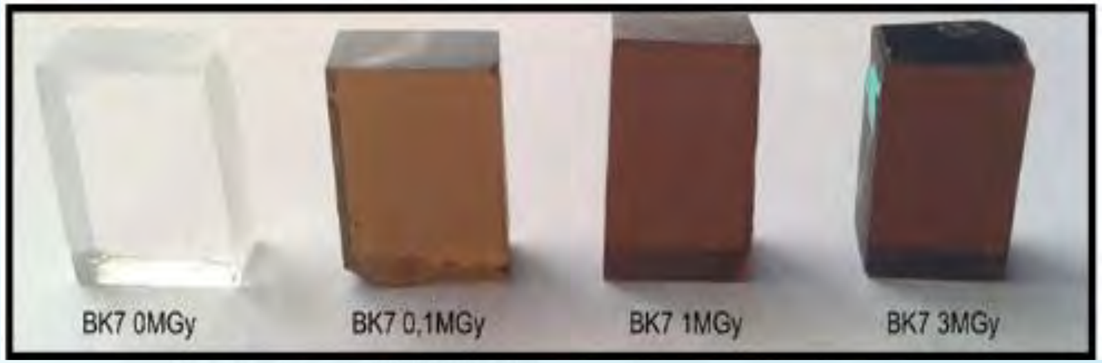
- Feasibility demonstration of the use of sapphire fibers for higher-temperature applications is ongoing
- Specific applications use different fiber configurations (e.g., pyrometer and imaging)
- Use of bare fiber is incompatible with most operating conditions

Radiation effects

- Radiation-induced Attenuation (RIA)
  - Occurs due to the creation of color centers
  - Degrades the fiber signal transmission capacity
  - Degrades the sensing range of distributed sensors
  - Changes the refractive index of the optical fiber

- Radiation-induced Emission (RIE)
  - Corresponds to light emission under irradiation
  - Increases the noise of a transmitted signal
  - Can be luminescence from pre-existing or radiation-induced point defects that are excited by the incoming particles

- Radiation-induced Compaction (RIC)
  - Causes changes in refractive index
  - Of primary importance when using optical fibers that are robust to RIA
  - Causes significant sensor drift



Macroscopic changes in silica after irradiation

Mechanical Design Integration

- Attachments for sensing applications:
  - Mounting a fiber optic in a ferrule or instrument mount (small axial length)
  - Bonding an optical fiber inside a capillary tube for distributed sensing (long axial length: >2 cm)
  - Hermetic feedthrough for fuel rod endcap or pressure vessel
- Common materials of interest:
  - Stainless Steel 304/316
  - Zirconium alloys
  - Nickel or nickel alloy low chromium (Haynes 230)
  - Silicon carbide
  - HT9
  - FeCrAl
  - Titanium alloy (Ti64)

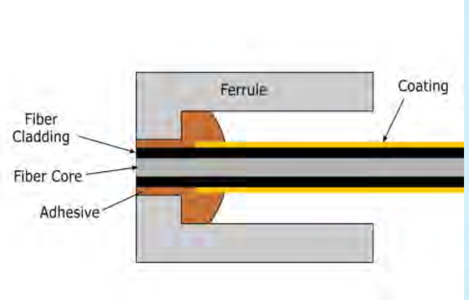


Diagram of a fiber optic mounted in a ferrule. The fiber optic is attached to the ferrule, then the fiber and ferrule end are polished until optically smooth

Aluminum-coated optical fiber soldered into a stainless-steel ferrule. This is the first step in fabricating a variety of fiber-optic-based sensors.

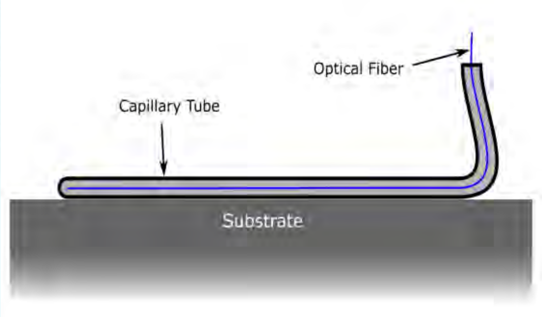
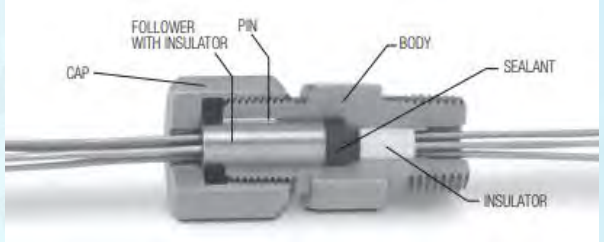


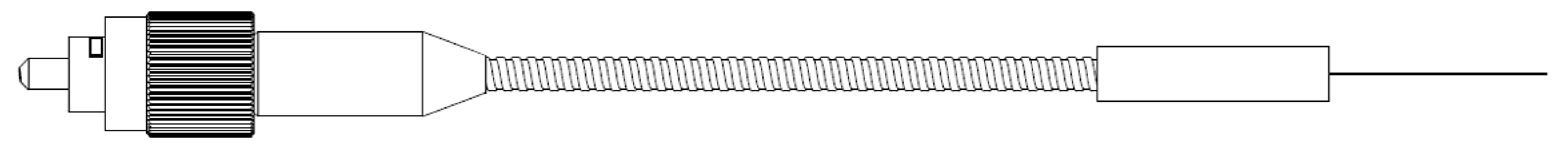
Diagram of an optical fiber embedded in a metallic sleeve and attached to a substrate of interest

Packaging

- Resilient fiber packaging is necessary to ensure the survival of optical fiber sensors during the assembly, transportation, and installation in a nuclear facility
- Each deployment will have different feedthrough requirements; however, successful deployments in the Advanced Test Reactor (ATR), the Transient Reactor Test (TREAT) facility, the High Flux Isotope Reactor and several University Research Reactors (MITR, OSURR) have all been achieved using similar packaging.



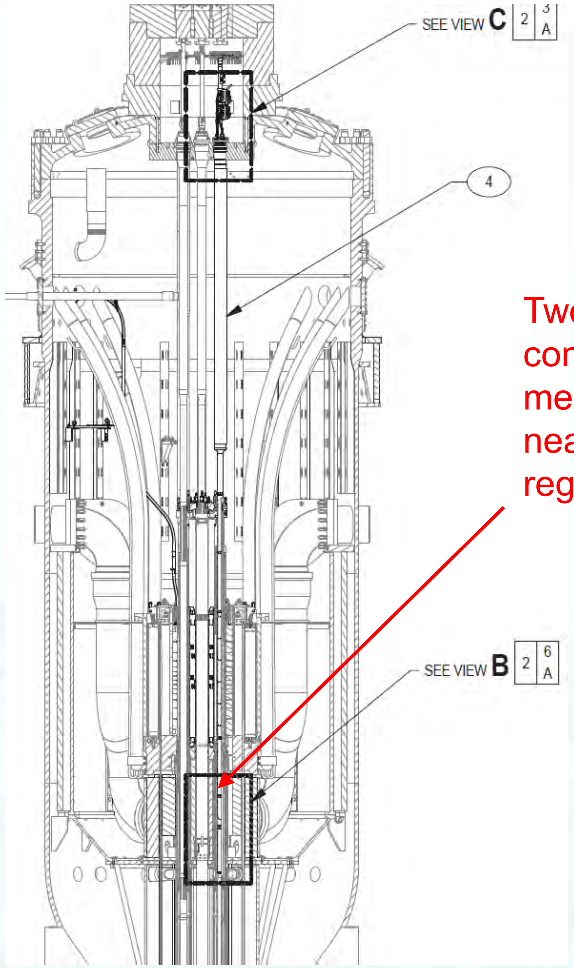
MHC-series Conax fitting [5]

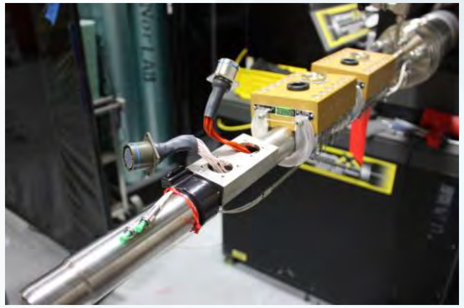


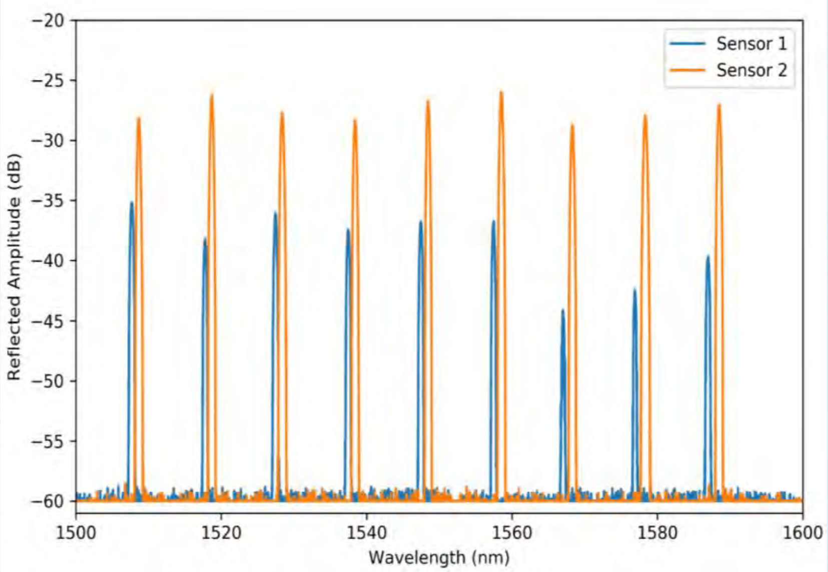
Armored fiber-optic extension and connector for reactor deployment

Example of OF deployment at INL

Temperature measurement by Fiber Bragg Gratings







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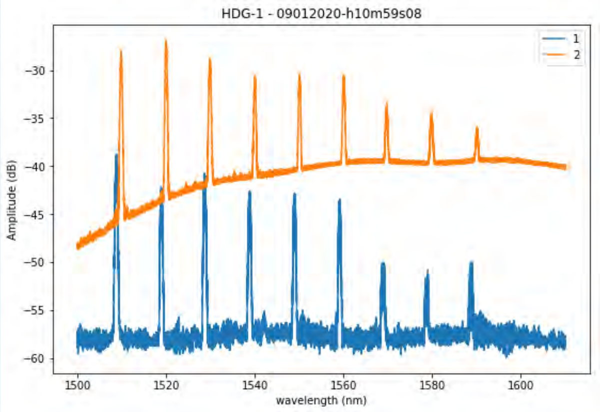


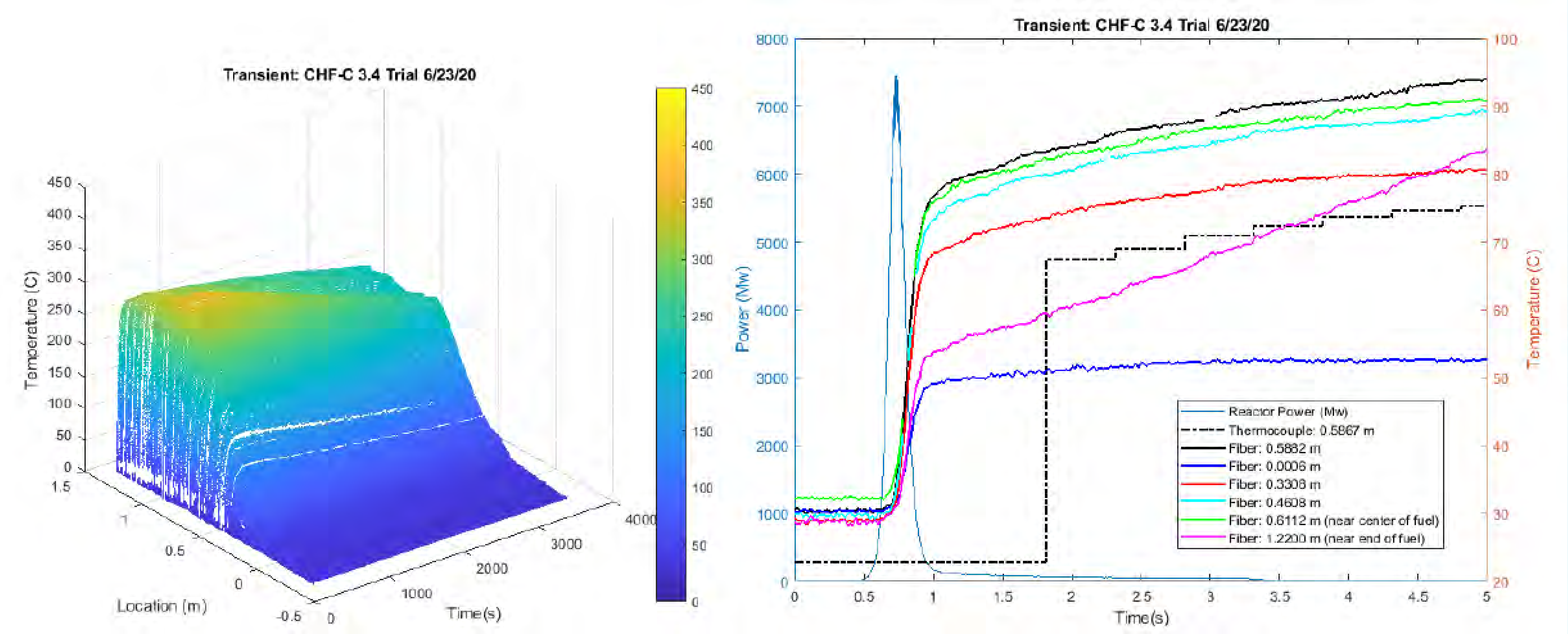
Two optical fibers and a comparison thermocouple measure temperatures near the top of the core region (approx. 530^{o}C)

HDG-1 (High Dose Graphite-1) began irradiation in ATR in August 2020

- Each fiber (pure silica core, fluoride-doped cladding) has nine type-II FBGs (fs-laser inscription) spaced 1 cm
- Lower amplitude (sensor 1) due to higher annealing temperature (750 vs. 650°C)
- Neutron flux varies along the fiber length

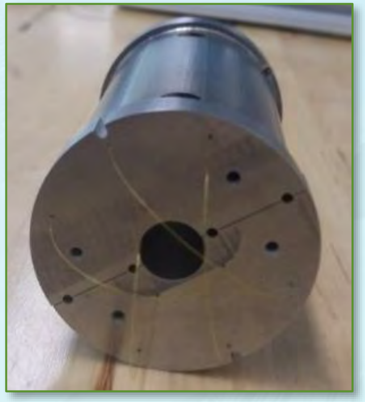
Temperature measurement by Optical Frequency Domain Reflectometry

The performance of several fiber types connected to a commercial OFDR interrogator (Luna ODiSI) was characterized in TREAT coolant channels using a titanium holder.

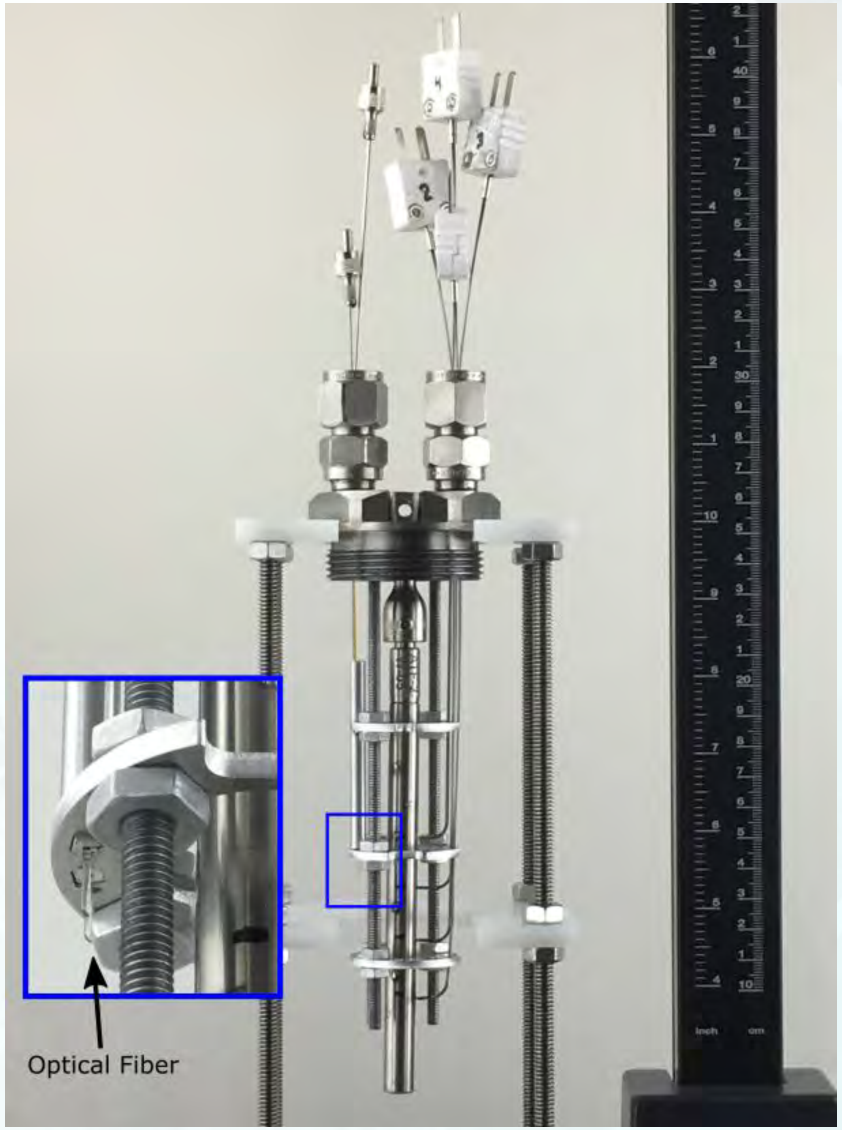


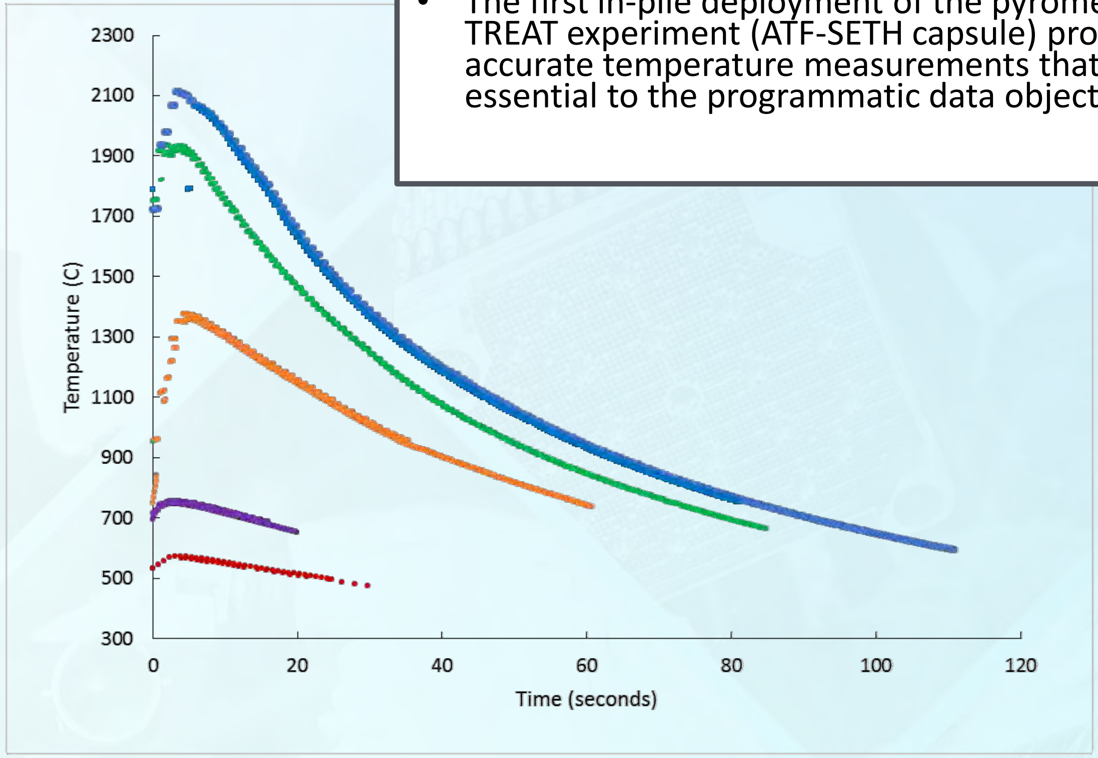
Response of PSC, F doped fiber to a 7000 MW, 200 ms pulse

OFDR is used for temperature mapping of heat sink components of TREAT experiments



Temperature Measurement: Pyrometer



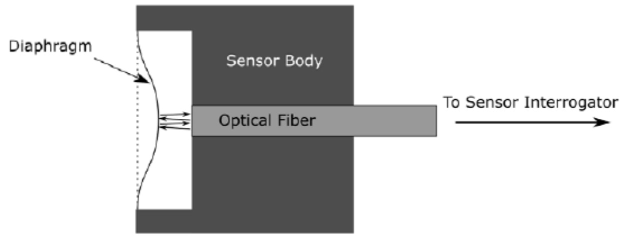


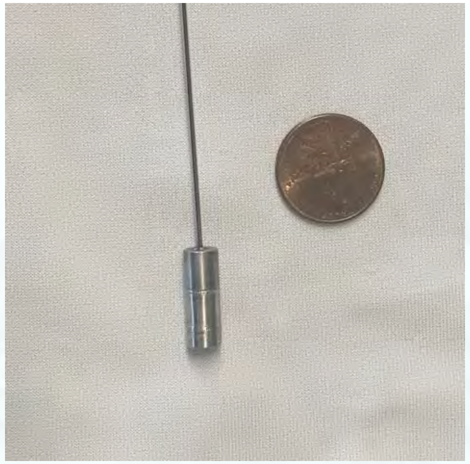
- The fiber-optic-based infrared pyrometry capability was established to support TREAT experiments because of its ability to provide noncontact, high-temperature, high-speed surface temperature measurements
- The first in-pile deployment of the pyrometer in a TREAT experiment (ATF-SETH capsule) providing accurate temperature measurements that were essential to the programmatic data objectives

Pressure Measurement and Other Applications

Pressure Sensor:

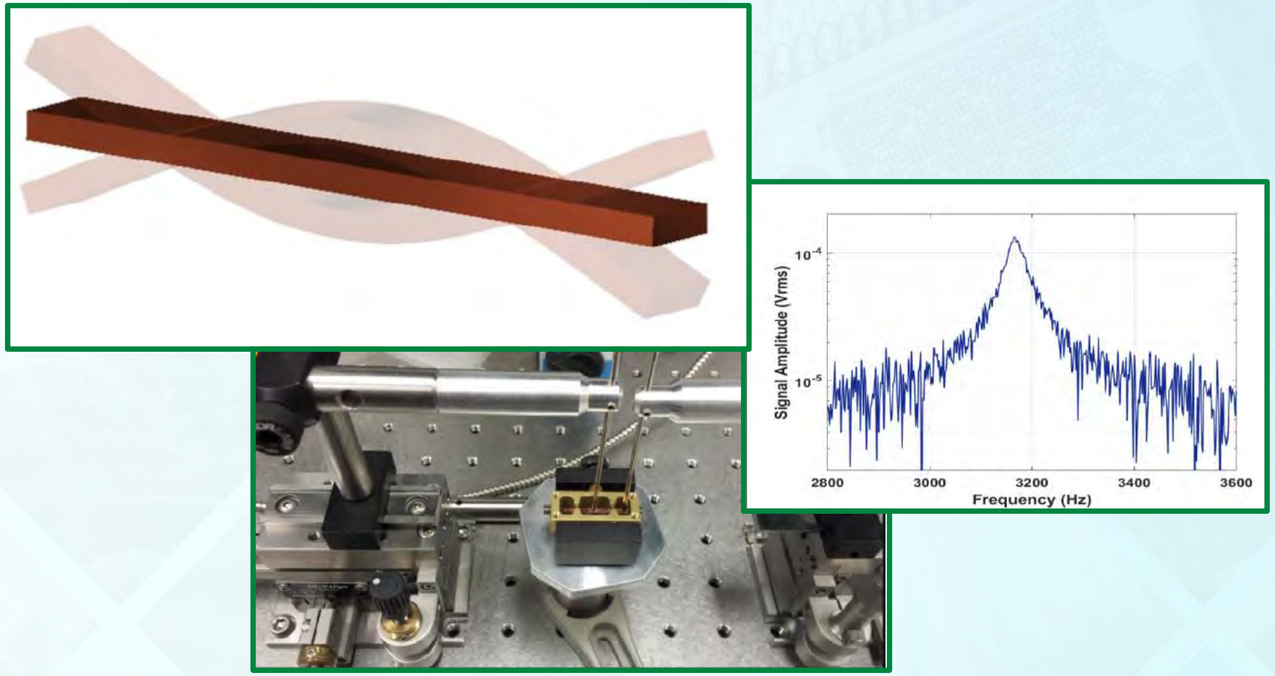
Extrinsic Fabry-Perot interferometry provides a flexible design for real-time pressure measurement in nuclear applications, including the detection of fission products in fuel pins





Resonant Ultrasound Spectroscopy – Laser (RUSL):

A 2019 TREAT experiment demonstrated the feasibility of detecting radiation-induced microstructural changes in cantilever beam samples by using an optical-fiber-based RUSL system. A free beam setup is being developed to characterize the impact of radiation on phase transitions in novel metallic fuel forms.



Visual and IR Imaging:

INL logo image reconstructed using an optical fiber bundle for in-core imaging and IR thermography for surface characterization

Thank You