U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

ASI research activities overview

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 24 – 27, 2022

Pattrick Calderoni, ASI National Technical Director

Idaho National Laboratory

Stake-holders engagement

Program accomplishments

FY23 planned activities

Strategic Organizations Engagement

Domestic Government Engagement

Engagement with Domestic entities range from on-going conversations to active project collaborations.

NRC

- Industry standards for I&C – from LWRS experience to advanced reactors
- Artificial Intelligence applications for nuclear reactors (autonomous control)

EPRI

- Focus on high temperature Non-Destructive Examination (NDE) for advanced reactors

NEI

- Participation in Advanced Reactor forum meetings

NASA

- Fission Surface Power and Nuclear Thermal Propulsion (NTP) program
- High-temperature instrumentation development for structural health monitoring

DARPA

- Microsystems for Small Nuclear Reactors Virtual Workshop (June 15, 2022) sponsored by Microsystem Exploratory Council (MEC)

Regulatory aspects / advanced reactors I&C:

- ML/AI applications in nuclear
- Safety instrumentation: IAEA International Conference on Topical Issues in Nuclear Installation Safety: Strengthening Safety of Evolutionary and Innovative Reactor Designs

In-Core Real-time Mechanical Testing of Structural Materials (INCREASE) - INL/NRC/EPRI proposal to FIDES

NEI support of in-core instrumentation for ATF development

ASI roadmap presentation planned Dec 7, 2022

FSP Technology Maturation includes I&C task (INL, LANL) considering the use of ASI technologies for space reactors

Strategic Organizations Engagement

Foreign Government Engagement

Engagement with international research organizations as part of existing collaborative agreements

France - French Alternative Energies and Atomic Energy Commission (CEA)

Norway - Institute for Energy Technology (IFE)

Belgium - Belgian Nuclear Research Centre (SCK)

Japan - Japan Atomic Energy Agency (JAEA)

South Korea - Korea Atomic Energy Research Institute (KAERI)

Czech Republic - Technology Agency of the Czech Republic (TACR)

DOE/CEA bilateral agreement on Low Carbon Technologies

WG3.5 In-Pile Instrumentation:

- Neutron flux sensors: personnel and equipment exchange, test in TREAT and OSURR
- Collaborative activities on pyrometry measurement in water/steam environment planned in FY23
- OF INL compensation sensor included in TESCA experiment (SCK BR2)
- Significant scope extension discussed at SCM: dosimetry, in-core material properties characterization, thermocouples, LVDT

WG4 code development/validation:

- Instrumented test in NCSU PULSTAR for reactor multi-physics code validation

Strategic Organizations Engagement

DOE-NE Congruent Program Engagement

AFC/NEAMS

- Pursue common test (shared program milestones) for fuel code simulation development / Develop capabilities for fuel pin radial deformation measurement
- Consolidate and expand Transient Reactor Test Facility (TREAT) concurrent testing to support instrumentation development / Instrumented capsules

ART

- MSR: thermal conductivity probe development and test in Molten Salt Thermophysical Examination Capability (MSTEC) at INL / forced convection loop for ^{3}H transport characterization in flibe at INL, use as infrastructure for sensor test
- Sodium Fast Reactor: ANL Mechanisms Engineering Test Loop (METL) facility for sensor test
- Gas reactors materials (Sam Sham): in-core, miniaturized instrumentation (strain gauges)

NSUF

- Coordinated mid-year review of NSUF projects with ASI research (May 5, 2022)
- Supporting the Disc Irradiation for Separate Effects Testing (DISECT)
- SiC passive monitors process qualification and standardization effort

AMMT

- Development of advanced manufacturing techniques for sensors fabrication
- Characterization of structural material properties during neutron irradiation

LWRS/Cyber

- Data integration in the Nuclear Power Industry: the DIAMOND data model with Deceptive Infusion of Data (DIOD).

Cyber

- Coordinate work on wireless transmission of sensors and instrumentation data

NRIC/ARD

- Discuss opportunity to integrate instrumentation and digital twin capabilities into testbeds

DIAMOND = Data Integration Aggregated Model and Ontology for Nuclear Deployment

Industry & University Engagement

Through technology commercialization activities, ASI collaborates with industry providing I&C technology, examples include:

- Analysis & Measurement Services Corporation: Health monitoring of I&C systems, thermocouples
- X-Wave Innovations, Inc: Radiation hardened ultrasound transducers
- Idaho Laboratory Corporation: thermocouples and neutron flux sensors
- Curtiss-Wright: controls and plant monitoring
- Cleveland Electric Laboratories

ASI has extensive collaborations with Universities and related Organizations:

- INL National University Consortium
- Center for Advanced Energy Studies (CAES)
- Consortium for Nuclear Power – North Carolina State University (NCSU)
- Center for Reactor Instrumentation and Sensor Physics (CRISP) – Massachusetts Institute of Technology (MIT)
- CINR Awardees such as The Ohio State University (OSU) and North Carolina State University (NCSU) which are focused on lower TRL research

Strategic Organizations Engagement

Continuous dialogue with industries involved in the development of advanced reactors to assess I&C technology gaps and inform program strategy and priorities (ASI program roadmap)

BWXT Advanced Nuclear Reactor (BANR)

- In-core instrumentation for BANR-1 test in ATR

Terrapower Molten Chloride Fast Reactor technology

- Instrumentation for Molten Chloride Reactor Experiment (MCRE)

Westinghouse e-vinci micro reactor

- Fiber optic sensor development

Terrapower Natrium

Kairos Power FHR

Terrestrial Energy Integral Molten Salt Reactor

ThorCon power plant

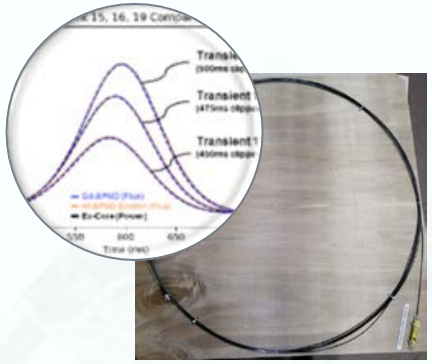
Seaborg compact molten salt reactor / Copenhagen technologies

Program accomplishments

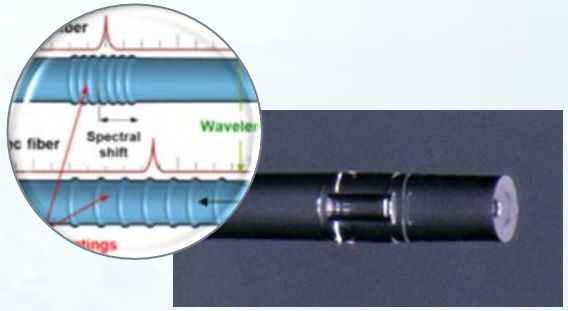
Ultrasound thermometer commercialization

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.

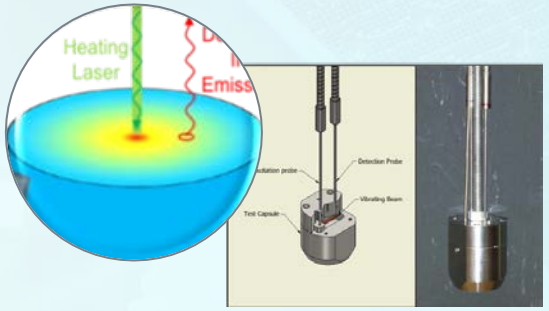
High Temperature Irradiation Resistant (HTIR) thermocouples



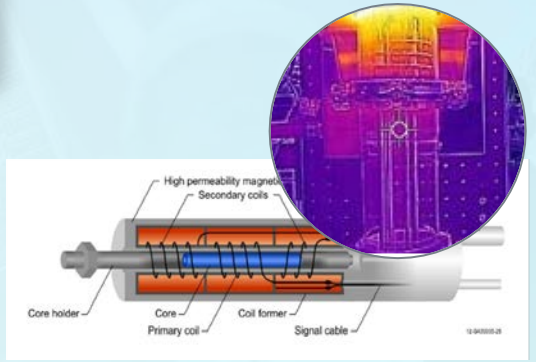
Self Powered Detectors and miniaturized Fission Chambers for local neutron flux measurement



Fiber optic sensors for nuclear applications



Real time measurement of fuel material properties in-core

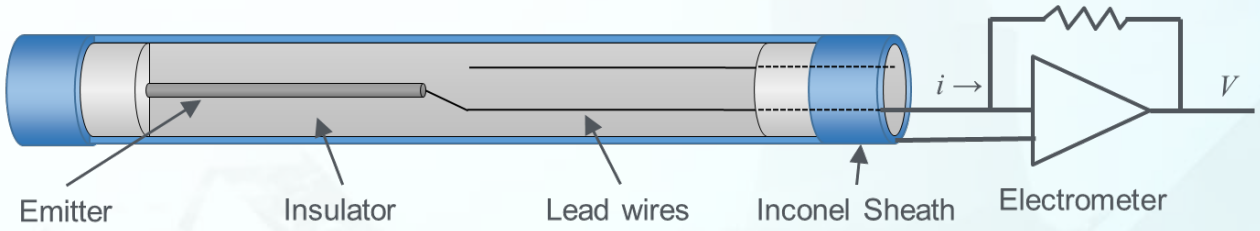


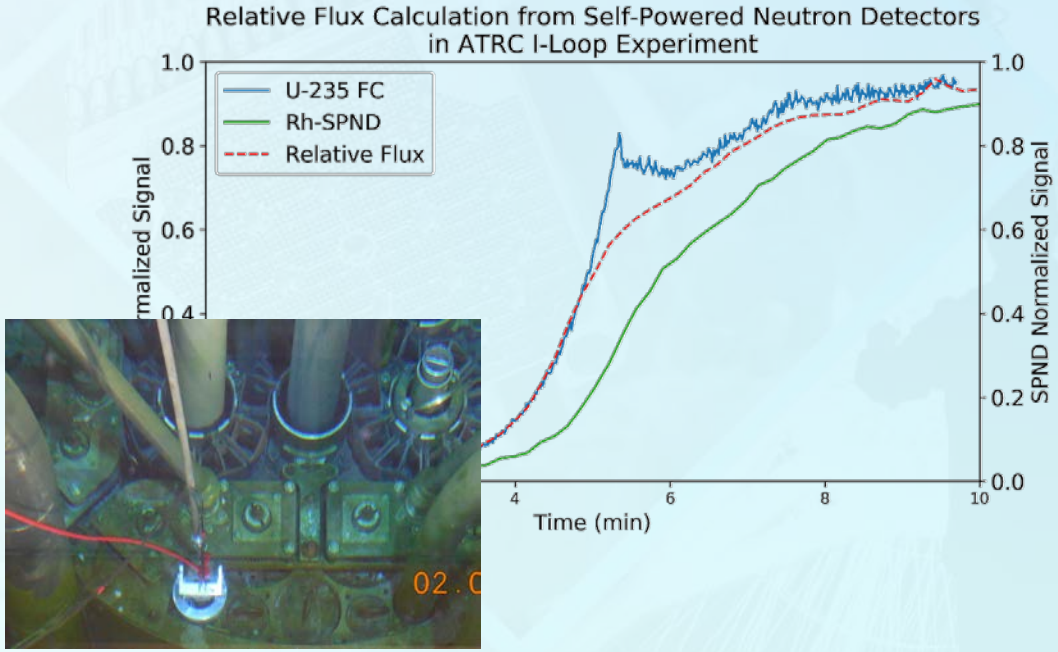
Linear Variable Differential Transformer (LVDT) for fission gas pressure measurement

Self Powered Detectors: temperature compensation

Two primary types of operation based on dominant emitter-neutron interaction

- Slow-response based on (n, β−) – Rh, V emitters
- Customized/commercial options tested in neutron irradiation heated experiments
- Objective: expanding temperature range of operation to 800 C

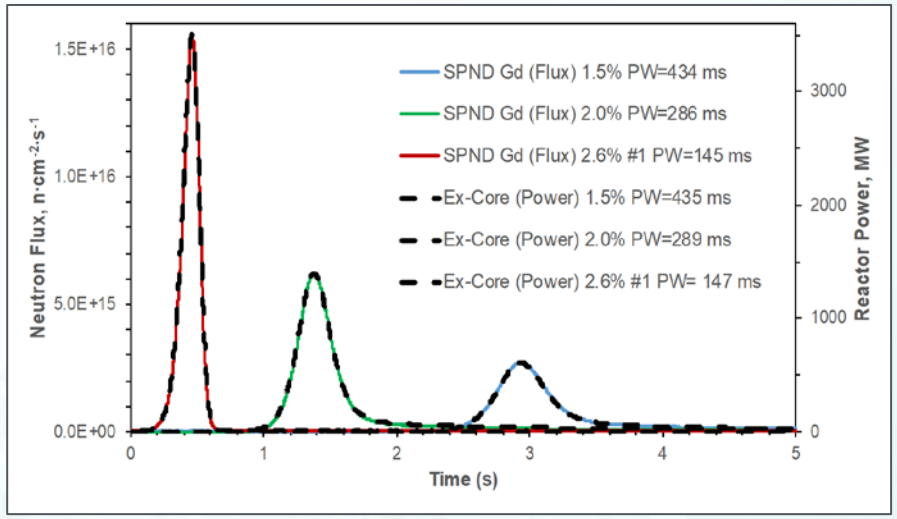




Self Powered Detectors: fast response

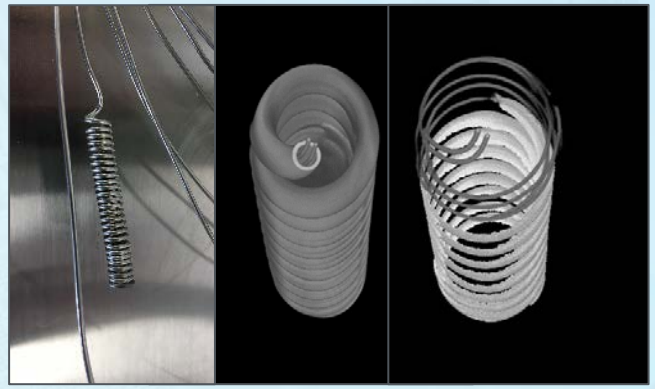
Two primary types of operation based on dominant emitter-neutron interaction

- Prompt-response based on (n, γ, e_{ce}) and (n, γ, e_{pe}) – Co, Gd, Hf



Transient measurement comparison of SPND with ex-core detector

The INL TREAT Reactor



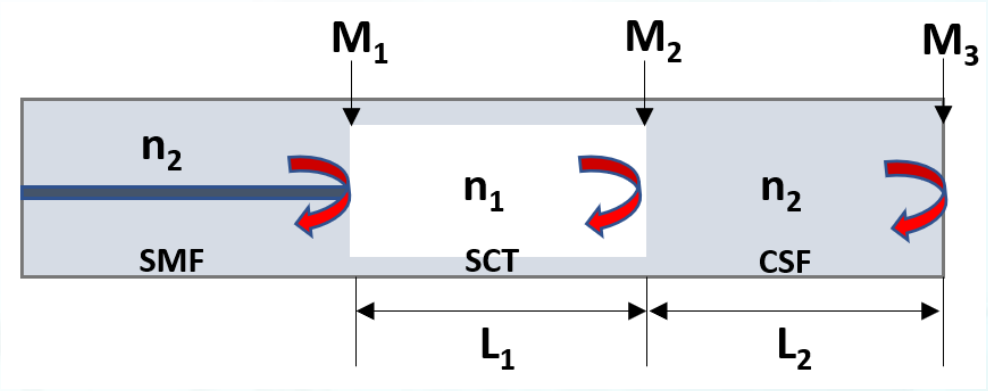
Physical and 3D Computer-Tomography image of a SPND

Synergistic activities:

- Miniaturized fission chambers test/development
- Self Powered Gamma Detectors development
- Fast SPNDs and spectrum unfolding capability

Optical Fibers: OF for nuclear applications

- Radiation-tolerant optical fibers
  - Pure silica core (PSC) fiber and fluorine-doped cladding
  - Both the core and cladding are fluorine doped
- Frequency based interrogations schemes (FBG, OFDR)
- Active compensation



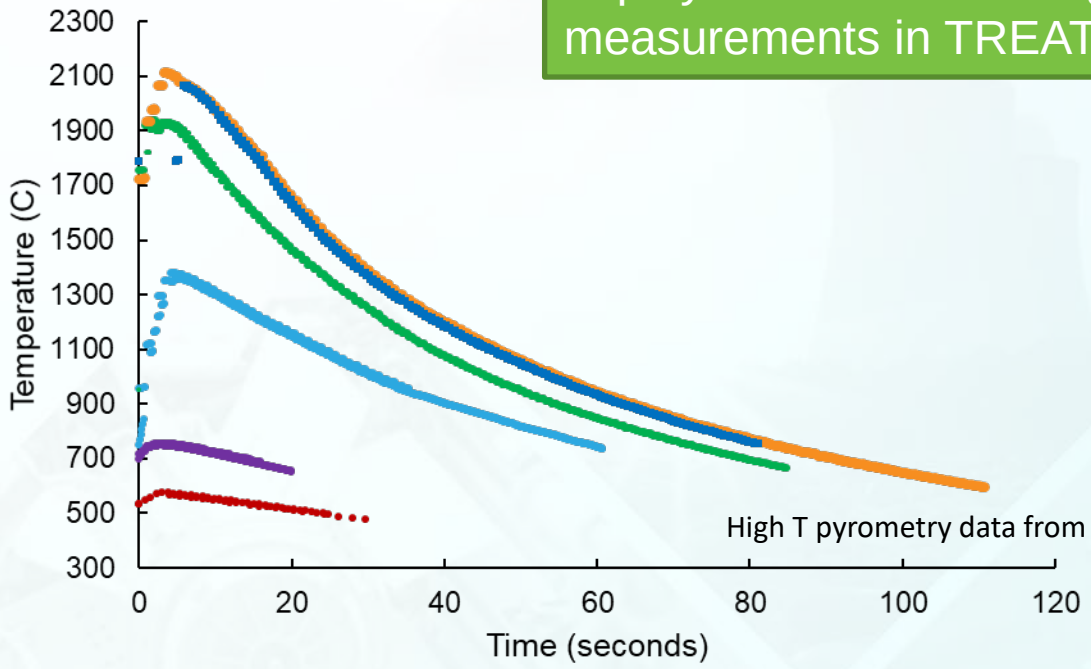
SMF – Single-mode fiber
SCT – Silica capillary tube
CSF – Coreless silica fiber
M_1, M_2, M_3 – Interface act as mirrors
n_1, n_2 – Refractive indices of air cavity, silica cavity
L_1, L_2 – Length of cavities

Schematic of cascaded Fabry-Perot interferometer

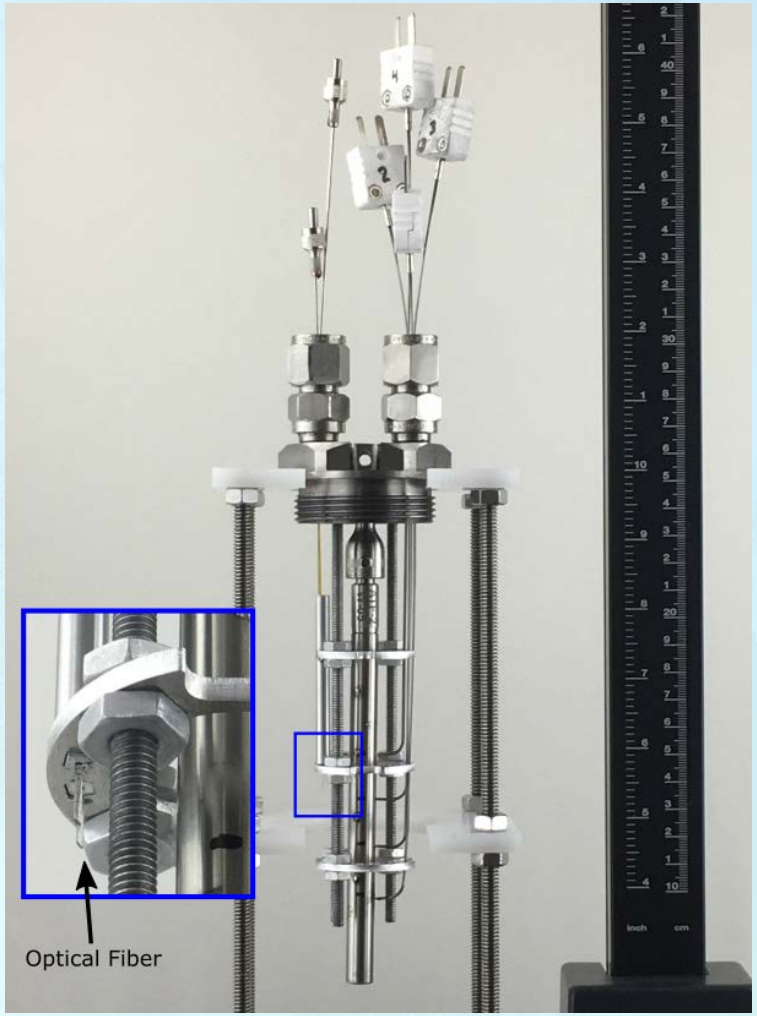
- First cavity (air) can be used to measure the length compaction, due to no change in the refractive index
- Assuming the same length change of both cavities, refractive index changes can be measured from the second cavity (silica)

Optical Fiber based pyrometer

Fiber-optic Infrared-pyrometry with emissivity compensation is routinely deployed for fuel-cladding temperature measurements in TREAT experiments

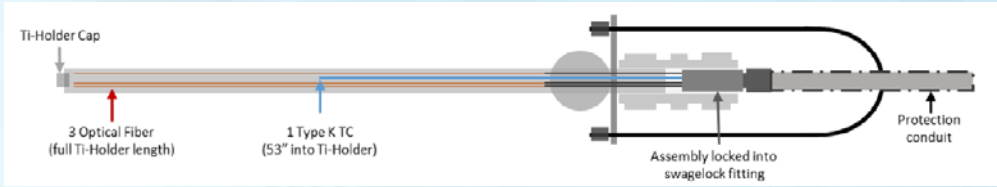


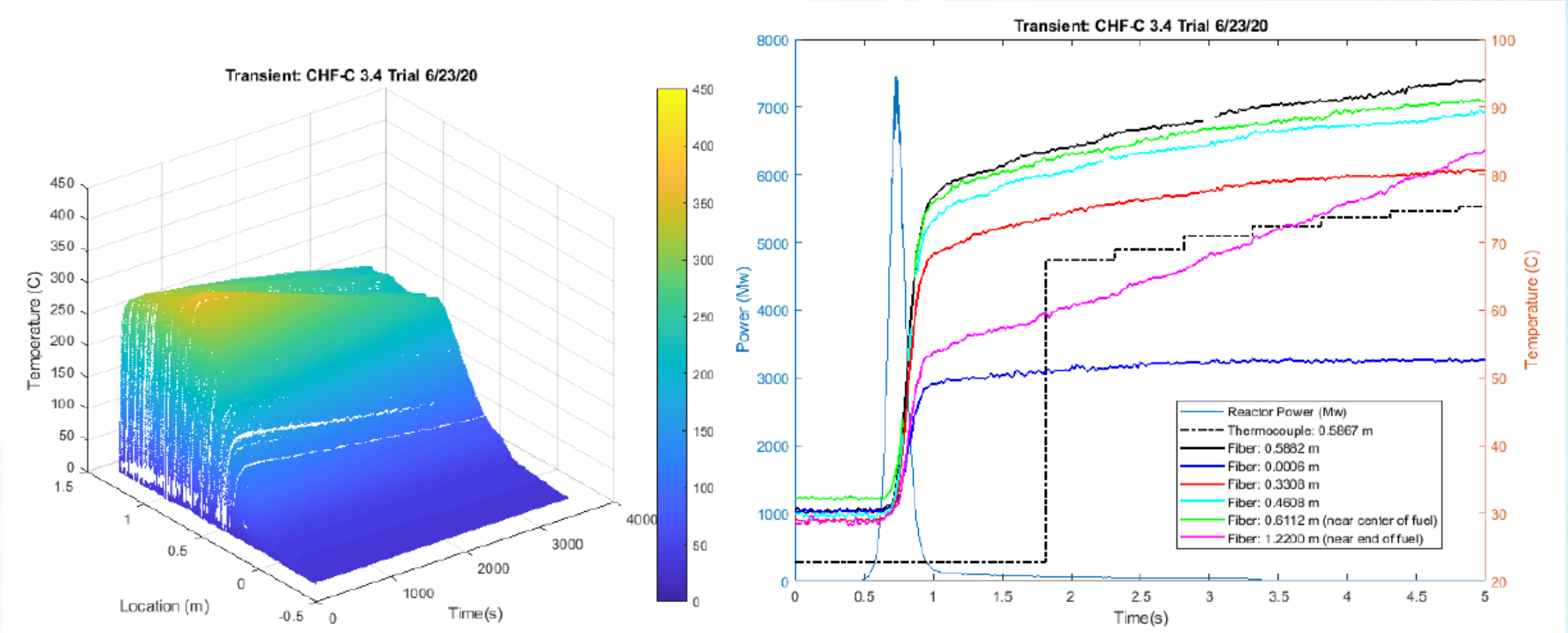
High T pyrometry data from the NASA SIRIUS experiment



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.



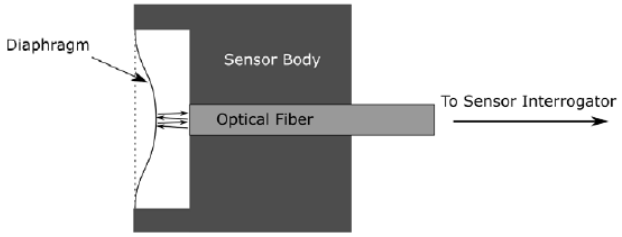


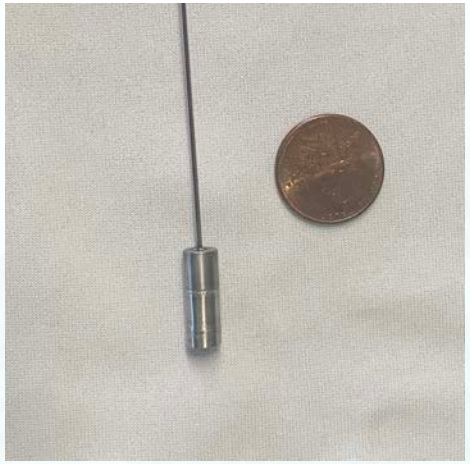
Response of PSC, F doped fiber to a 7000 MW, 200 ms pulse

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

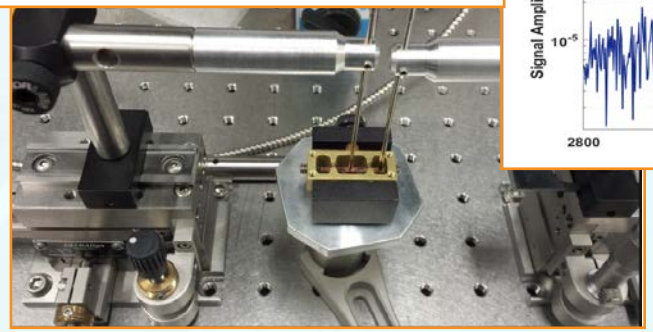
Optical Fibers: other applications

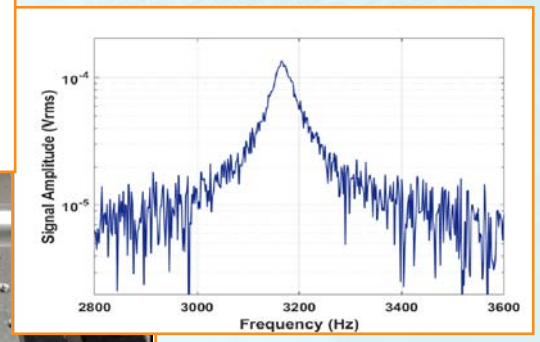
Pressure Sensor:
Extrinsic Fabry-Perot interferometry provides a flexible design for real-time pressure measurement in nuclear applications, including the detection of fission products in fuel pins



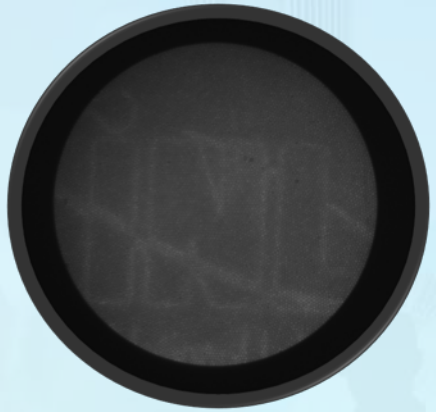


Resonant Ultrasound Spectroscopy – Laser (RUSL):
A 2019 TREAT experiment demonstrated the feasibility of detecting radiation-induced microstructural changes in cantilever beam samples by using an optical-fiber-based RUSL system. A free beam setup is being developed to characterize the impact of radiation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





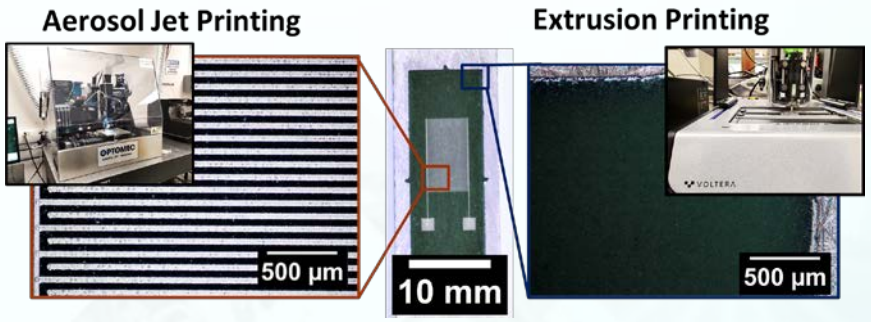
Visual and IR Imaging:
INL logo image reconstructed using an optical fiber bundle for in-core imaging and IR thermography for surface characterization

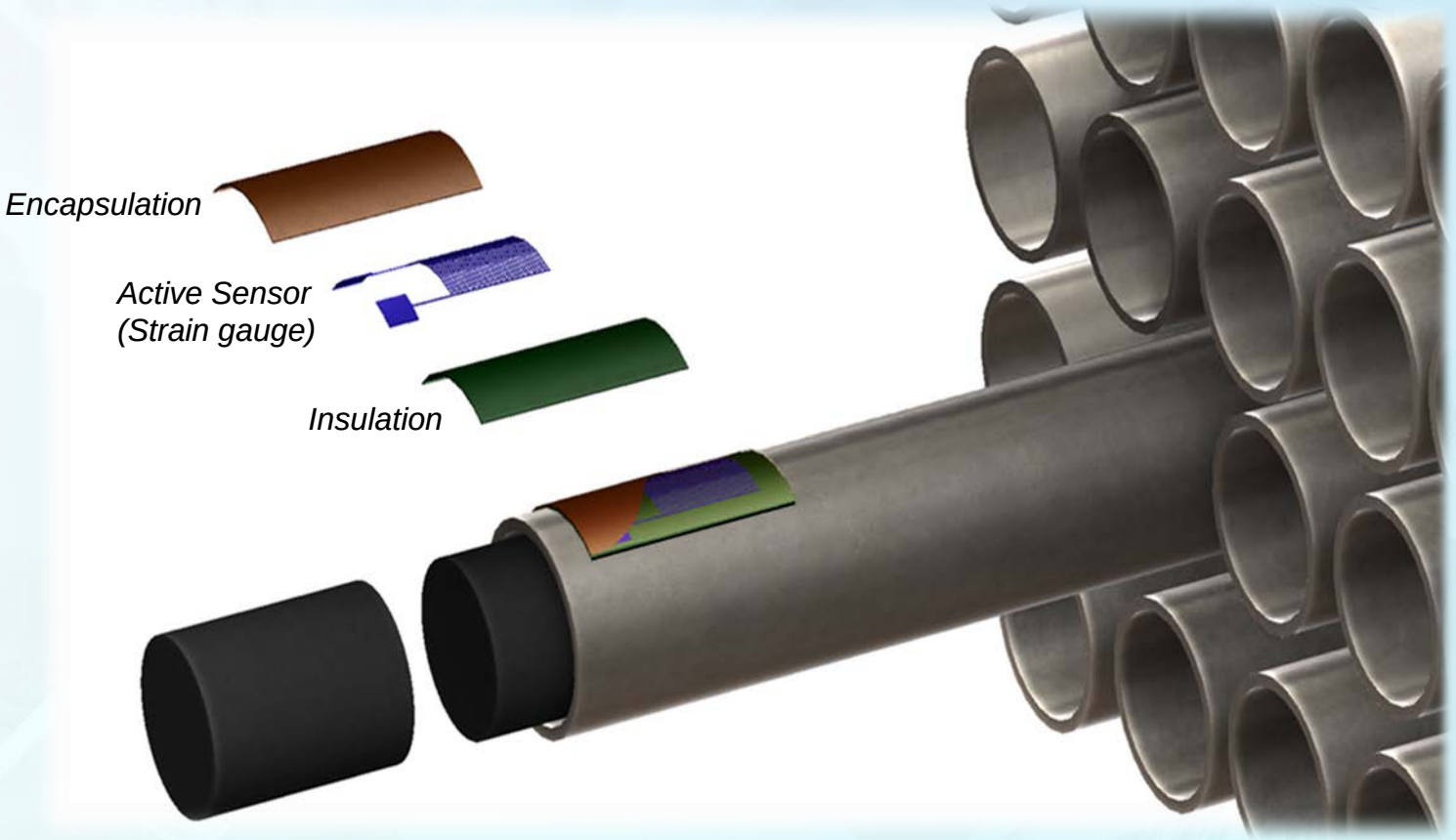


Additive manufacturing for sensor fabrication

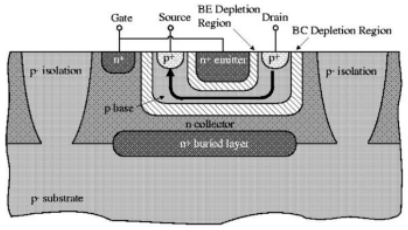
Printed Strain Gauge Advantages:

1) Reduce invasiveness
2) Direct fabrication on test article
3) Develop sensors with nuclear relevant materials





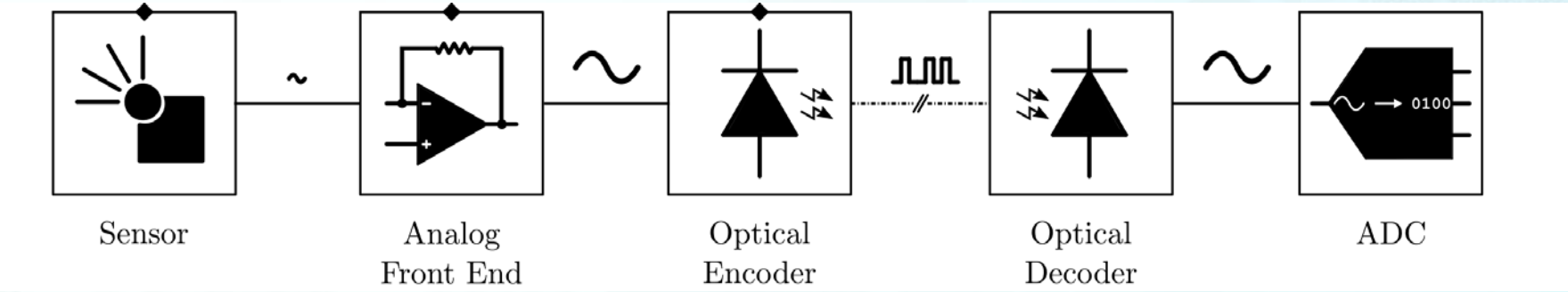
Radiation hardened electronics

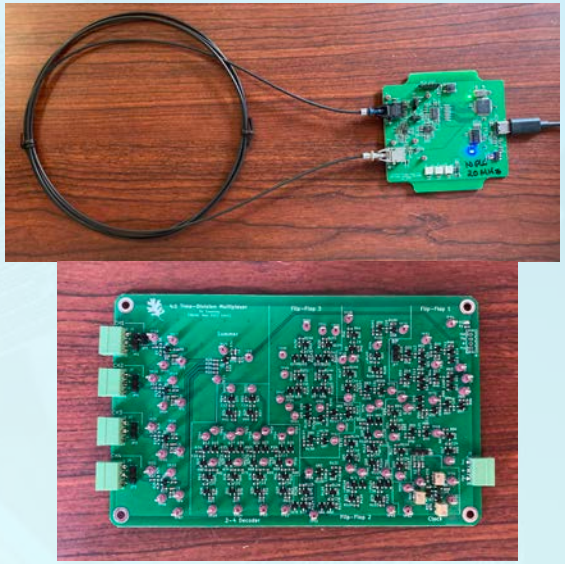


Use available JFET technology to demonstrate capability. Develop advanced material solutions (GaN, GaO2) for high temperature capability.

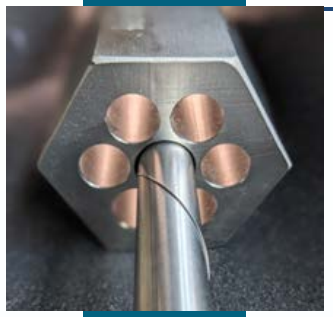
Demonstration objective: Front End Digitizer to read entire I&C suite at a single experimental location over one fiber optic cable (or cable bundle):

- Thermocouples, SPNDs, SPGDs, RTDs, fission chamber



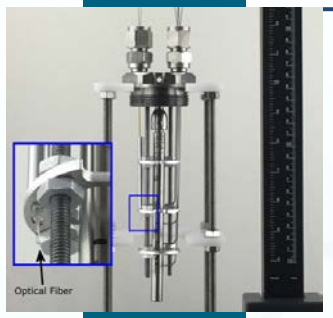


FY23 program directed research activities



Sensors for Advanced Reactors

Neutron flux sensors
Optical fibers
Acoustic sensors
Thermocouples
Rad-hard electronics



Sensors for Irradiation Experiments

LVDT
Passive monitors
Material properties
Sensor qualification

Digital Technology for Advanced Reactors

Advanced controls
Communication
Digital Twin

Competitively awarded projects (CINR, SBIRs, etc) address basic research and feasibility demonstration of innovative I&C technology.

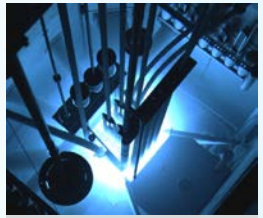
Directed research aims to increase maturity through testing in relevant conditions towards demonstration, to minimize risk of adoption to stake-holders.

Technology maturation using DOE testing infrastructure

Irradiation test requirements and technology maturity largely determine the appropriate facility for testing

Low sensor TRL Technology
Easier Access
Lower Cost Tests
Separate effects testing

OSUR
University Reactor



PULSTAR
University Reactor

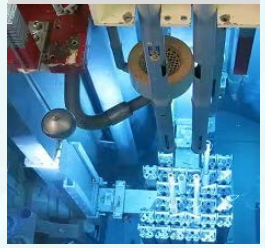
MITR
University Reactor

High sensor TRL Technology
Limited Access
Higher Costs, High Dose
Controlled Prototypic Environment

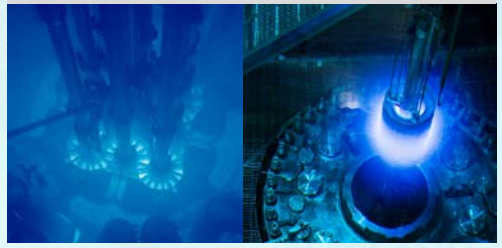
DEVELOPMENT → *PROTOTYPIC DEPLOYMENT*

TREAT (INL)

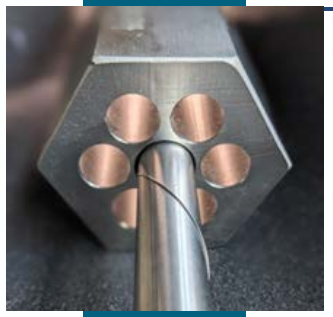
NRAD (INL)



ATR/HFIR (INL/ORNL)



FY23 program directed research activities



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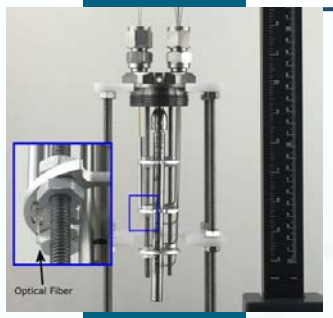

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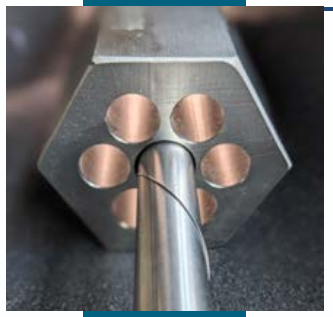
Directed research also provides coordination and ensures alignment with program objectives.

FY22 technical workshops and review meetings (Un, Labs, industry):

- Progress in the development of sapphire fiber optic sensors for nuclear applications (May 31)
- NSUF/ASI projects mid-year review (May 5)

https://asi.inl.gov/#/researchlibrary

FY23 Planned Activities



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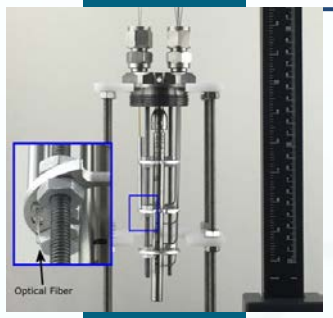

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Real time demo of temperature compensation tools for SPNDs

Power and reactivity control instrumentation for advanced reactors

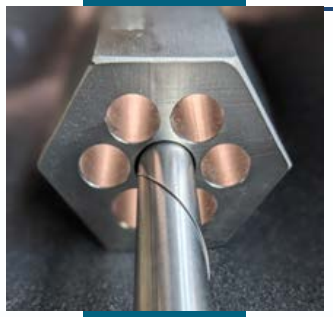
Power distribution inferencing with simulated sensor responses and a data analytic approach

Data analytics of SPND from WIRE-21 irradiation

Idaho National Laboratory

OAK RIDGE National Laboratory

FY23 Planned Activities



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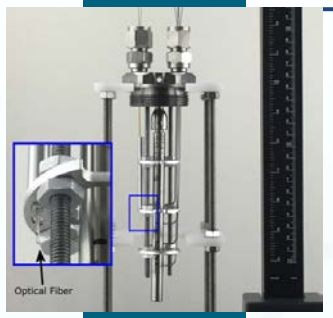

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Development of active compensation optical fiber

Fiber optic pressure sensor

Data analytics of fiber optics from WIRE-21 irradiation

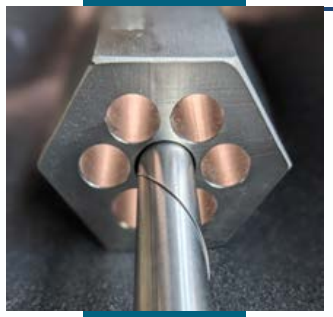
Benchmarking commercial intrinsic temp sensors

In-pile imaging of gas environments

Idaho National Laboratory

OAK RIDGE National Laboratory

FY23 Planned Activities



Sensors for Advanced Reactors

Neutron flux sensors
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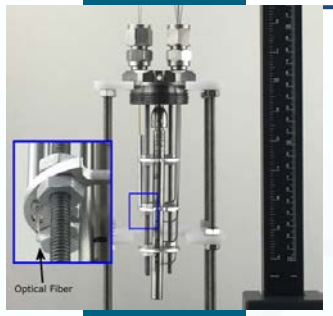
Rad-hard electronics

- **Ultrasound thermometer**
- **Ultrasound pressure sensor**
- **Acoustic emission/vibration sensor**



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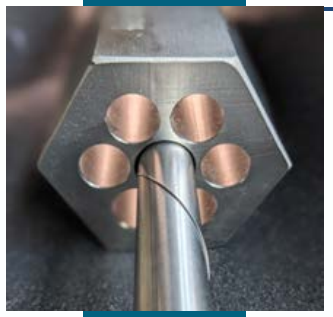
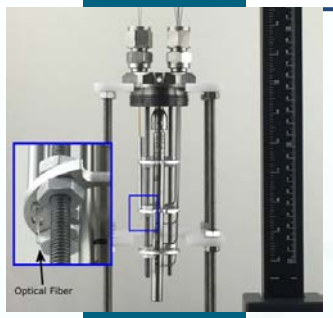
Digital Twin

FY23 Planned Activities



Sensors for Advanced Reactors

Neutron flux sensors
Optical fibers
Acoustic sensors
Thermocouples
Rad-hard electronics



Sensors for Irradiation Experiments

LVDT
Passive monitors
Material properties
Sensor qualification

Digital Technology for Advanced Reactors

Advanced controls
Communication
Digital Twin

Real time drift compensation models

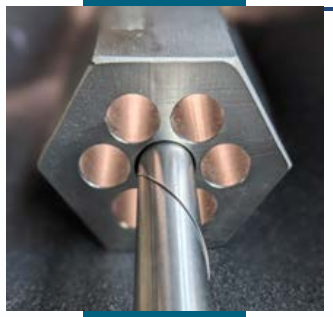
Intrinsic junction TC compensation

Front end digitizer (FREND) for analog to optical converter

Idaho National Laboratory

OAK RIDGE National Laboratory

FY23 Planned Activities



Sensors for Advanced Reactors

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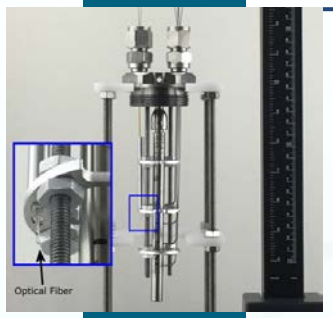

Sensors for Irradiation Experiments

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LVDT Supply Chain Evaluation – Low dose irradiation testing

Passive monitors advanced readout capabilities

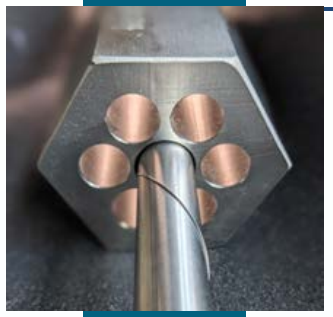
Data analytics of SiC from WIRE-21 irradiation

Additive manufactured strain gauges

Idaho National Laboratory

OAK RIDGE National Laboratory

FY23 Planned Activities



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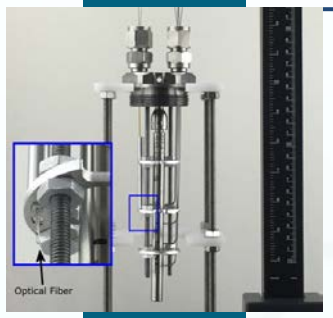

Sensors for Irradiation Experiments

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Temperature and neutron flux qualification device – transient – concurrent testing

Temperature and neutron flux qualification device – design and analysis for low dose

Digital Technology for Advanced Reactors

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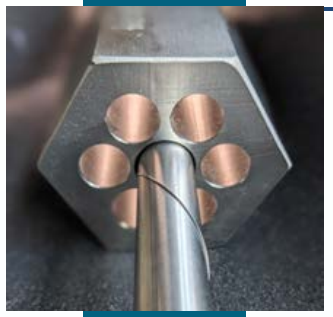
FY23 Planned Activities



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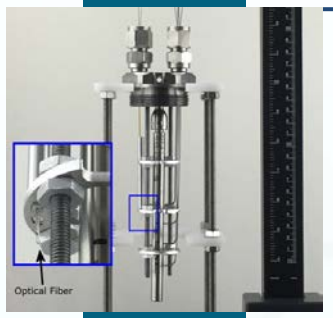

Sensors for Irradiation Experiments

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Digital Technology for Advanced Reactors

Advanced controls
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Develop multi-band wireless
Technology demonstration at METL
Simulation platform for digital, high performance, and AI-assisted controls
NES maintenance and expansion

Thank You

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