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The development of advanced nuclear instrumentation at the INL

Communication

Big Data,
Machine Learning,
Artificial Intelligence

Instrumentation
and Control

Joshua Daw

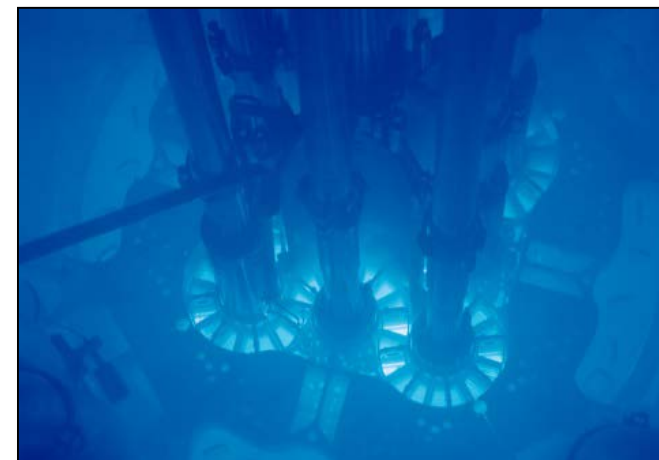
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June 19, 2019

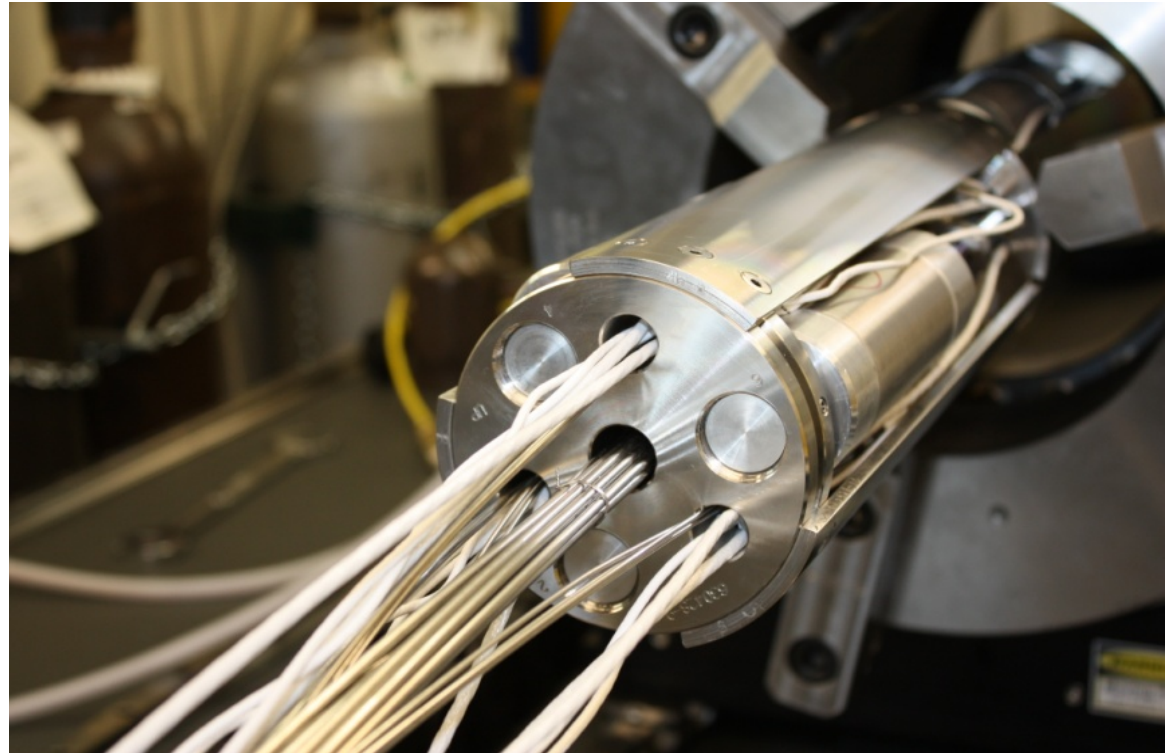
Motivation for Advanced Instrumentation Development

- NE has undertaken an approach that combines advanced PIE with multiscale and multi-physics fuel performance modeling. However, the desirable goal of completing the connection between measurement and predictive modeling will require dramatic advances in in-core instrumentation
- Advanced fuel and material development requires measurements of material behavior at smaller length and time scales during irradiation
- Support requests through the GAIN initiative to supply new technologies to industry, monitor critical process parameters, data transmission technologies, and monitoring systems for beyond design basis events
- Irradiation testing in a material test reactor is a complex and challenging measurement environment:
 - **Temperature and pressure extremes**
 - **Wide power and time scale extremes (TREAT vs. ATR)**
 - **Radiation effects**
 - **Feed-through limitations**
 - **Difficult geometries**



In-Core Instrumentation Design Requirements

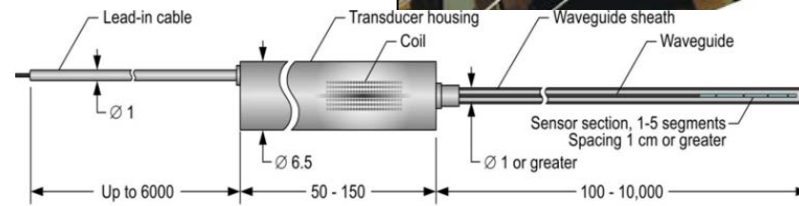
- Reliable
- Accurate
- Miniature
- High temperature resistant
- Corrosion resistant
- Neutron / gamma 'resistant'
- Non-intrusive
- "Low" cost



Instrumentation Capabilities and Development/Deployment*/Near Deployment**

- Temperature

- High Temperature Irradiation Resistant TCs*
- Silicon Carbide Monitors*
- Ultrasonic Thermometer**
- Optical Fibers**
- Melt Wires*
- Gamma Thermometer
- Self Powered Gamma Detector*
- Optical Pyrometer**



- Thermal Conductivity

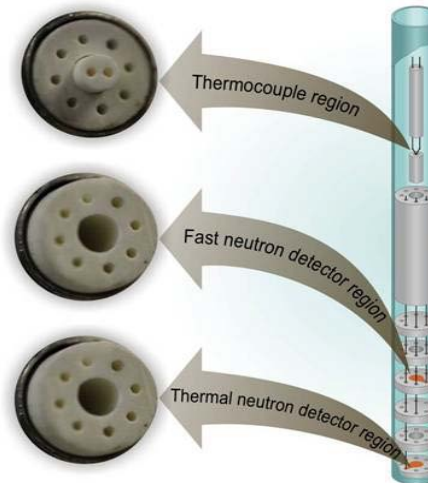
- Transient Hot Wire Method Needle Probe (USU, CEA, Halden)*

- Dimensional Changes

- LVDT-based (Halden)**

- Neutron Flux

- Self Powered Neutron Detector*
- Fission Chambers
- Flux Wires / Foils*
- Micro-Pocket Fission Detector (KSU, CEA)**



- Crack Growth

- Direct Current Potential Drop (MIT, Halden)*

- Self Powered, Wireless

- Thermoacoustic (TAC) Sensor**

- Void Sensor

- Boiling Detector



In-Pile Instrumentation Status

Establish baseline and novel instrumentation for in-pile applications that can provide real-time, accurate, spatially resolved information regarding test conditions and the performance of fuels and materials during irradiation

Baseline capability: qualify instrumentation for integration in irradiation test and demonstration plants

TRL 5-6 Technology demonstration

- Self-powered detectors (SPD) to measure neutron or gamma flux
- Thermocouples and passive monitors to measure local temperature
- LVDTs to measure deformation and pressure

Innovative sensors: develop disruptive technologies for nuclear applications

TRL 3-4 Technology development

- Impedance based sensors / Ultrasonic sensors / Fiber optics / Advanced Manufactured sensors

Single effect test: investigate in real time material science issues in-pile

TRL 2-6 Research to feasibility

- Thermal properties / Mechanical properties / Chemistry / Microstructure

Enabling capabilities

- Irradiation vehicles for instruments performance demonstration (TREAT, ATR, MITR, VTR)
- Out-of-pile system to enable re-instrumentation of irradiated fuel assemblies
- Expanded out-of-pile testing capabilities (HTTL, including flowing autoclave for PWR conditions)

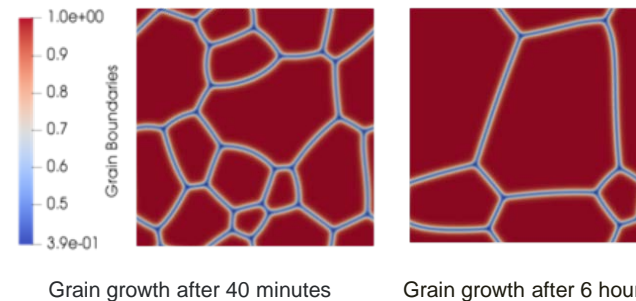
Thermocouples

- Real-time temperature measurement is a key parameter for validation of irradiations.
- Low-drift thermocouples for irradiation testing (HTIR-TCs) have been developed and commercialized
- Specialized cladding thermocouples with fast response are being developed to measure surface temperatures of new fuel claddings tested in TREAT

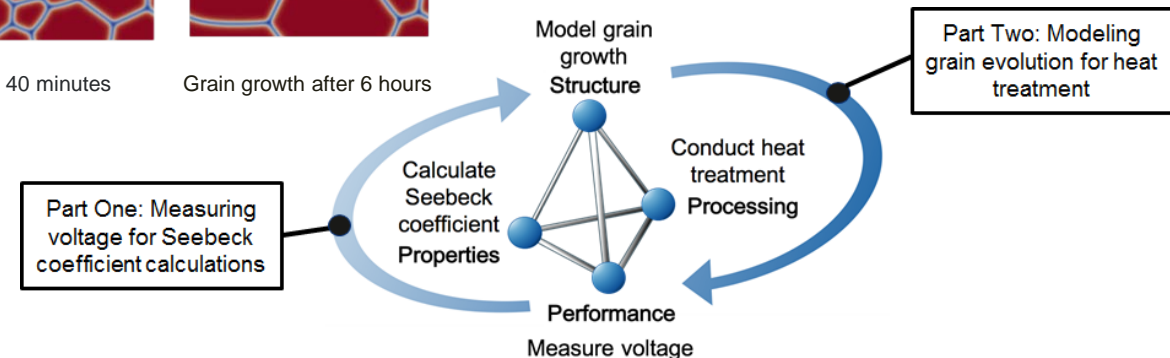
Thermocouple	Type K	Type B	Type N	HTIR-TC
Materials	Chromel vs Alumel	PtRh30% vs PtRh6%	Nicrosil vs. Nisil	Molybdenum vs. Niobium
Temperature Range	-270°C to 1260°C	0°C to 1700°C	-270°C to 1260°C	0°C to 1700°C
Cost	~\$30/ft	~\$250/ft	~\$50/ft	~\$250/ft
Radiation Tolerance	1/10 th	~1/100 th	1/4 th	1



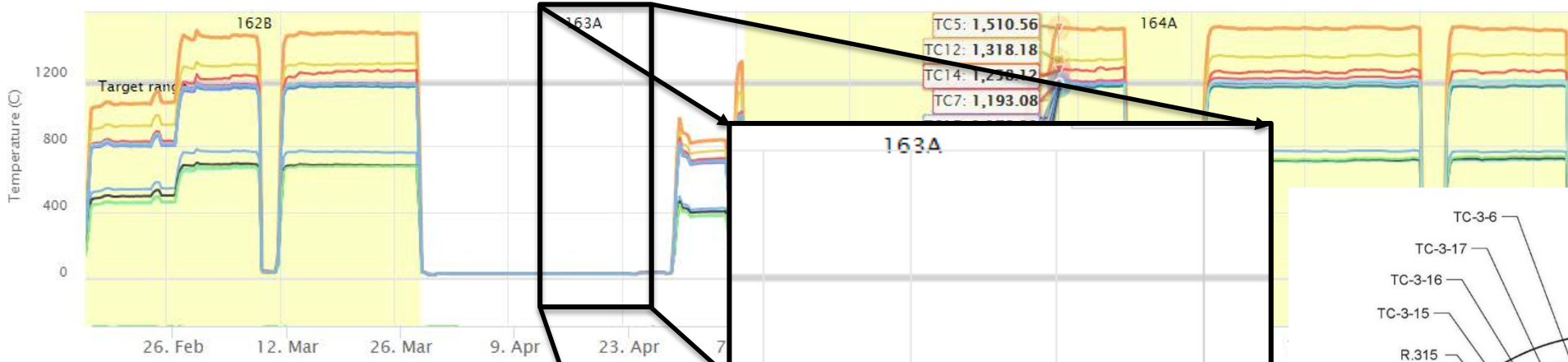
Characterization of Nb sheath ductility and optimization of heat treatment process



MOOSE phase field model to simulate Nb grain growth

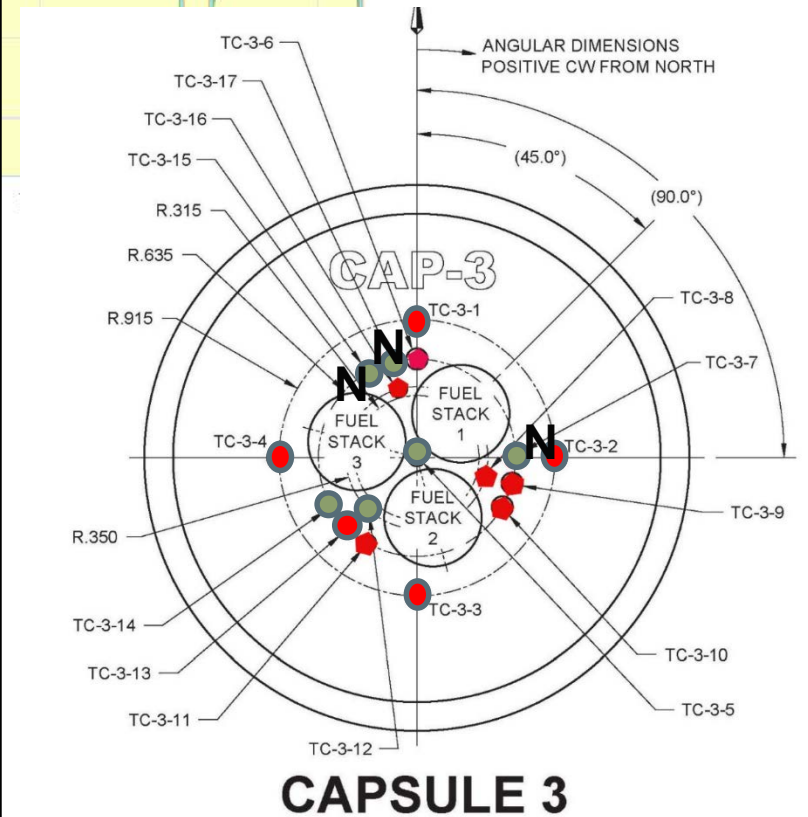
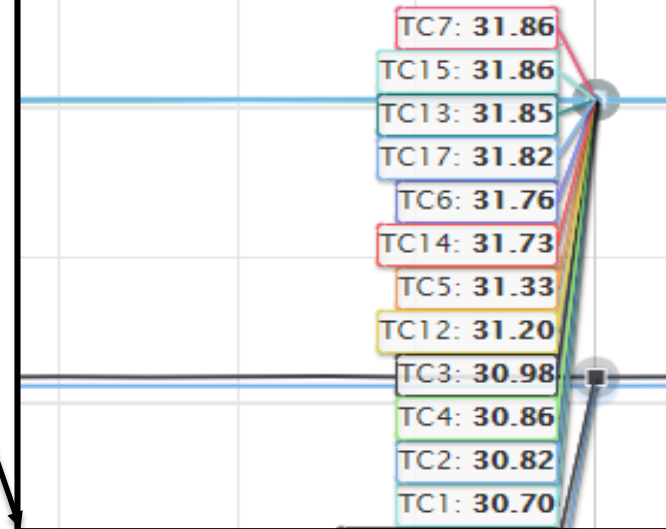


Thermocouples



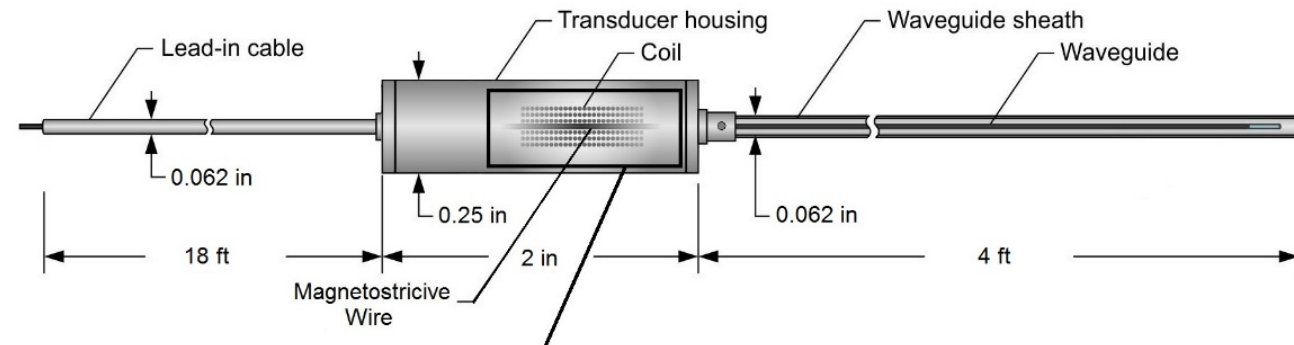
Palmer J., Performance of Custom-Made Very High Temperature Thermocouples in the Advanced Gas Reactor Experiment AGR-5/6/7 During Irradiation in the Advanced Test Reactor, Jun 21 (Fri) 10:00 Europa

- The AGR 5/6/7 fuels test was instrumented throughout the 5 capsules
- Capsule 3 has both Type N and HTIR TCs installed throughout the three (3) fuel bundles
- To our knowledge this is the highest temperature ever sustained in a nuclear test
- The ATR fluence for the duration of the test is ~10x more than a typical PWR reactor

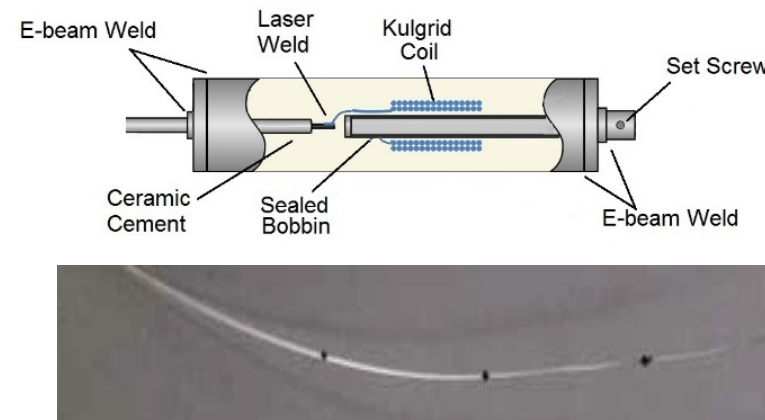
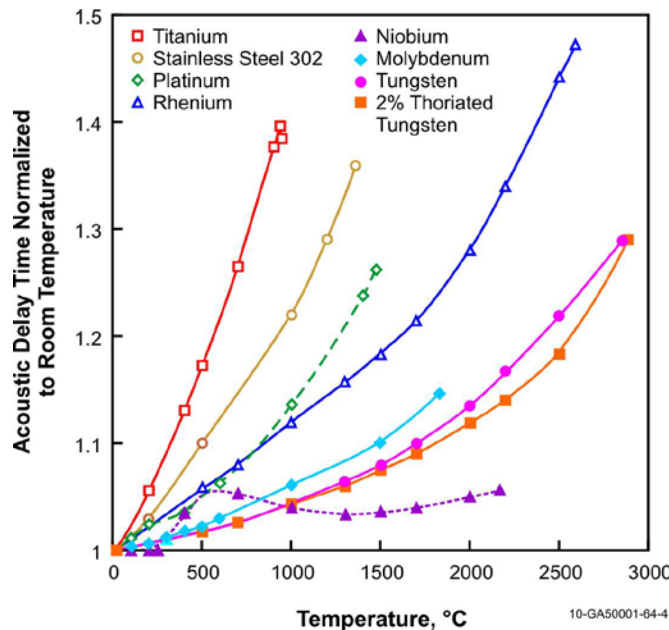


Ultrasonic Thermometer Development

- Ultrasound based sensors enable distributed temperature measurements up to 3000°C
- INL had demonstrated the reliability of magnetostrictive material transducers under irradiation
- Current research focuses on waveguide design optimization and unfolding signal response of distributed measurements



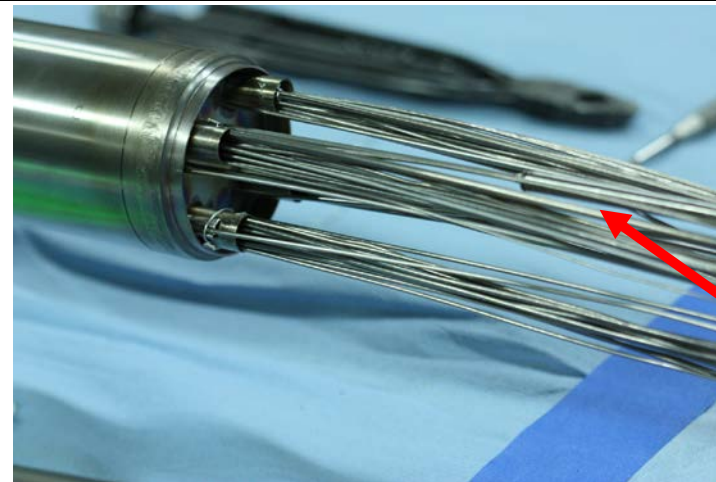
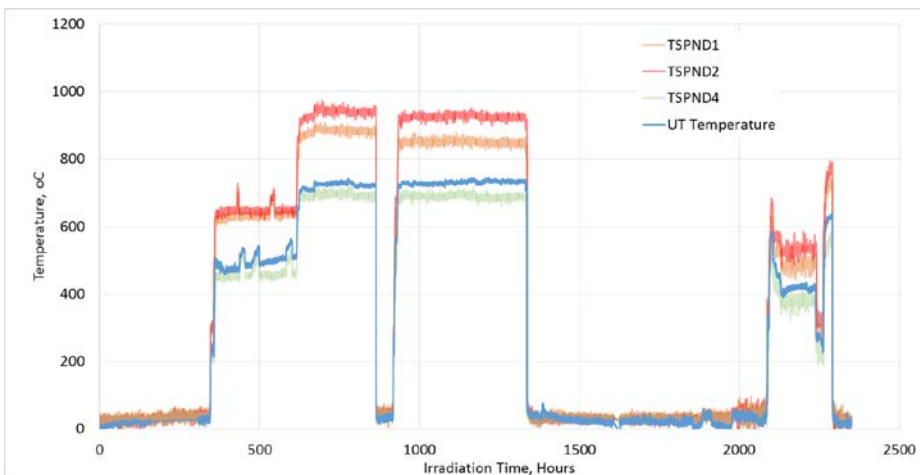
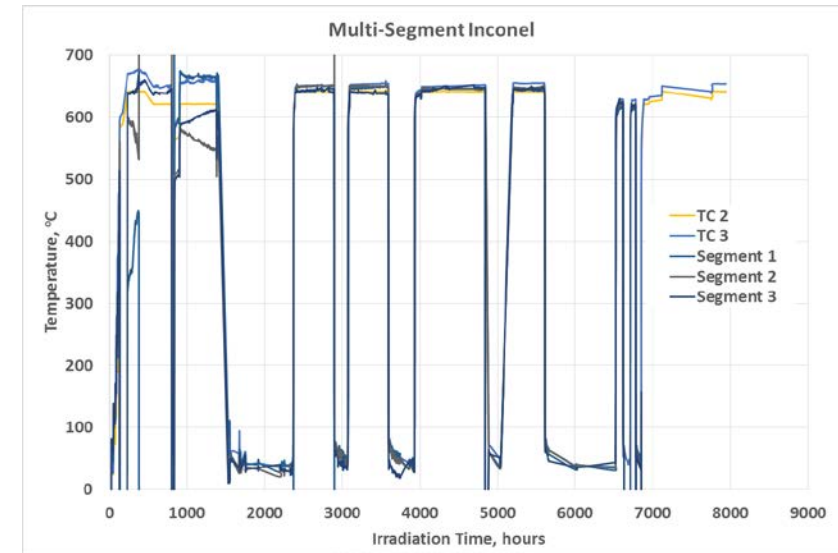
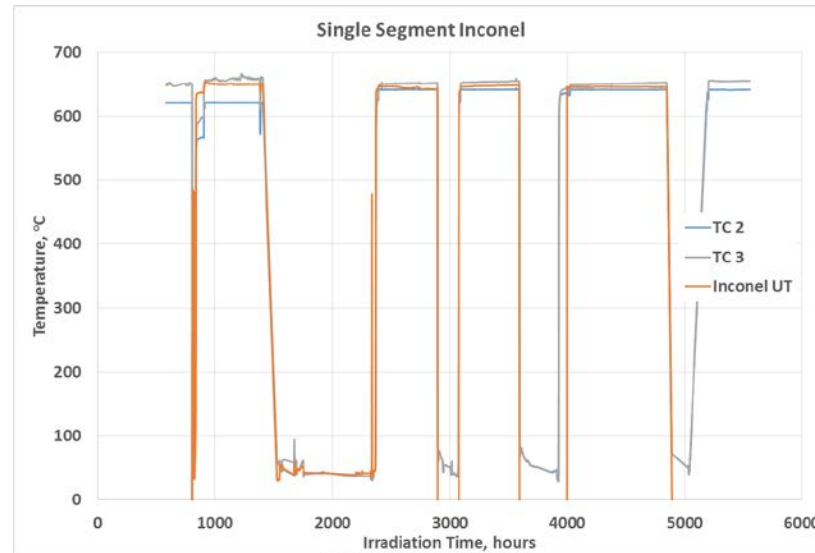
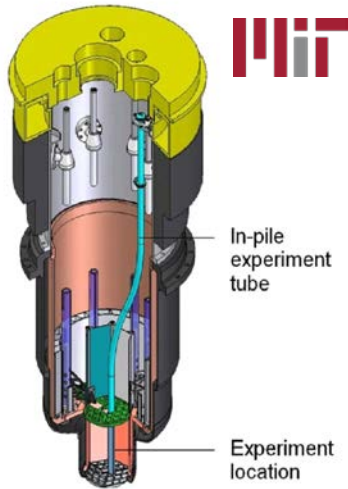
DISECT UT Diagrams



- Ten segment ultrasonic thermometer for DISECT irradiation planned in BR2
- Stainless steel waveguide with good sensitivity to ~1000 °C
- Transducer and sensor are separate parts

Ultrasonic Thermometer Demonstration

ULTRA2

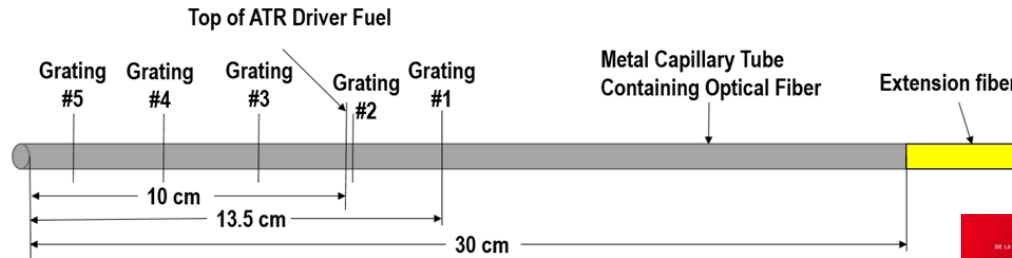


AGR5/6/7

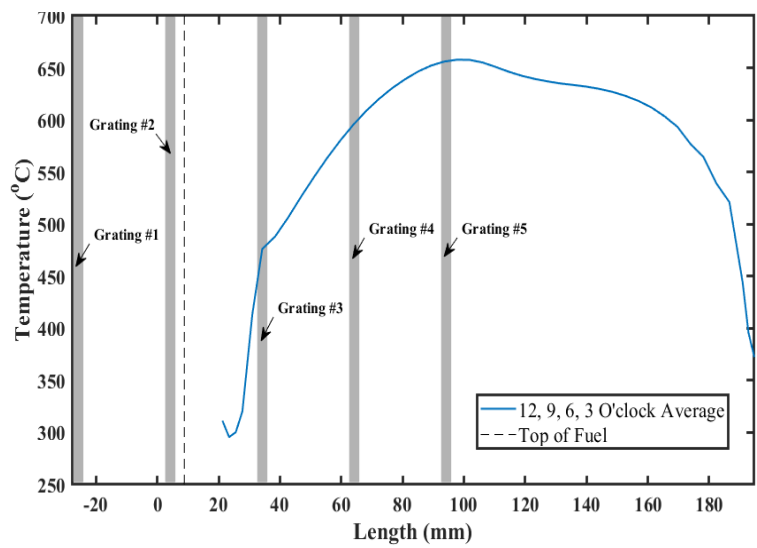
UT Transducer

Optical Fibers For Distributed Temperature Measurement

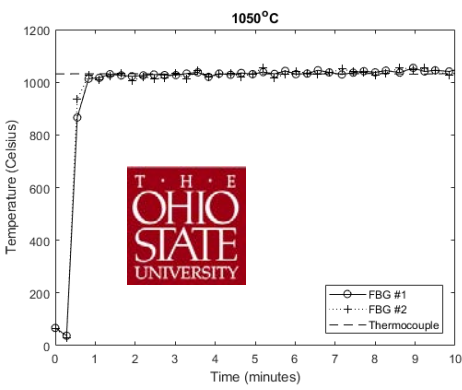
- Fiber optic based measurements are immune to electro-magnetic interference that can plague electrical based measurements
- Advanced sensor configuration and interrogation techniques enable distributed measurement with minimal invasiveness
- We are characterizing the limits of radiation induced degradation on specialized fiber materials, but OF have a role to play in irradiation test and nuclear plants operation



AGR5/6/7



- 2 probes fabricated by CEA:
- 5 Type I FBGs in SMF28
 - Regenerative process for high-T operation
- 1 probe provided data up to 8000 hours of operation in ATR (8 cycles):
- up to 2.1×10^{21} n/cm² cumulated fluence
 - operating temperature between 300-650C
 - varying dose rates for each grating



TREAT

Preliminary test at OSURR (3 day test – up to 2×10^{18} n/cm²) confirmed Type II FBGs can accurately detect temperature transients (up to 1000 C) for TREAT test typical fluence even in SMF28 fibers

- Feasibility test ongoing for:
- SMF28
 - Pure Si core, F-doped clad
 - RAL
 - Commercial Type II FBGs

Optical frequency domain reflectometry
Tunable laser / OFDR

Optical Fibers Sensors Development

Develop advanced sensor configuration and interrogation techniques to measure:

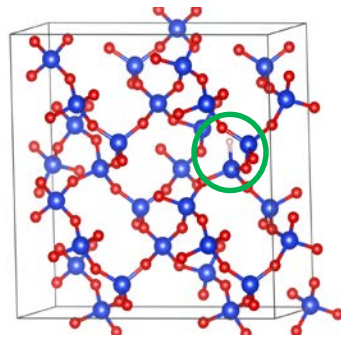
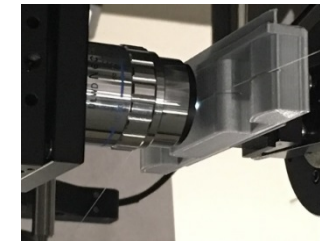
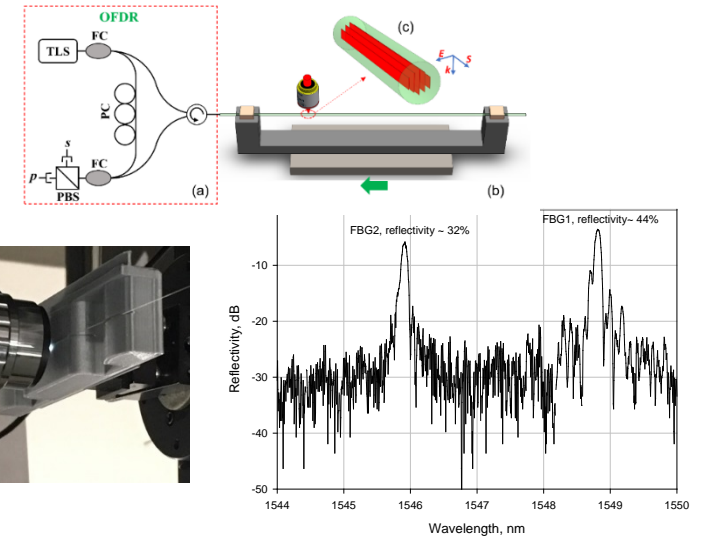
- Fission gas pressure and composition
- Flow induced vibration
- Microreactor core performance

Develop single mode sapphire fibers

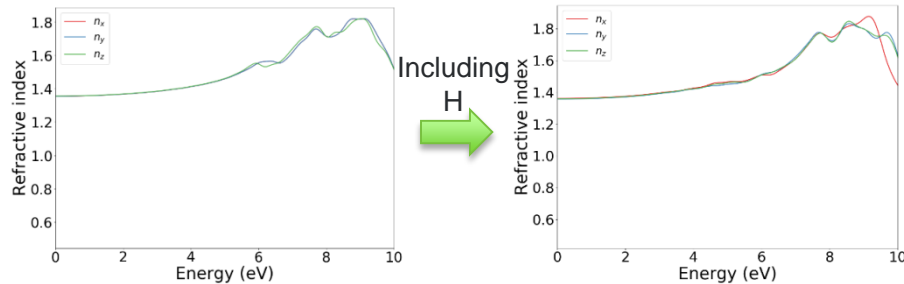
Develop modeling and simulation tools for fiber materials performance under irradiation

Type II FBGs fabricated by fs laser:

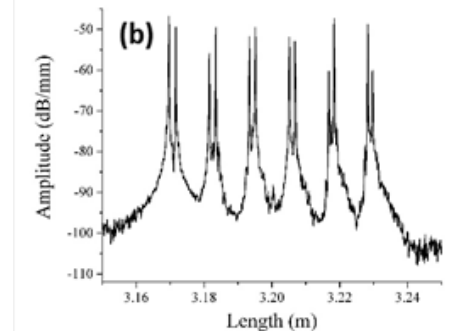
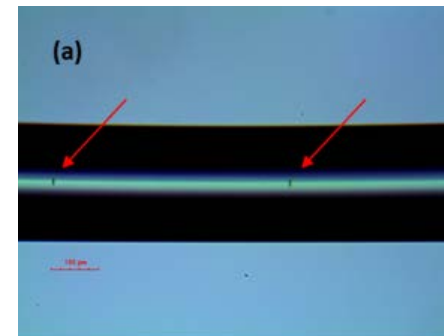
- Direct writing – point-by-point
- Phase mask



Modeling oxygen deficient centers (ODCs) and the effect of H dopant on refractive index

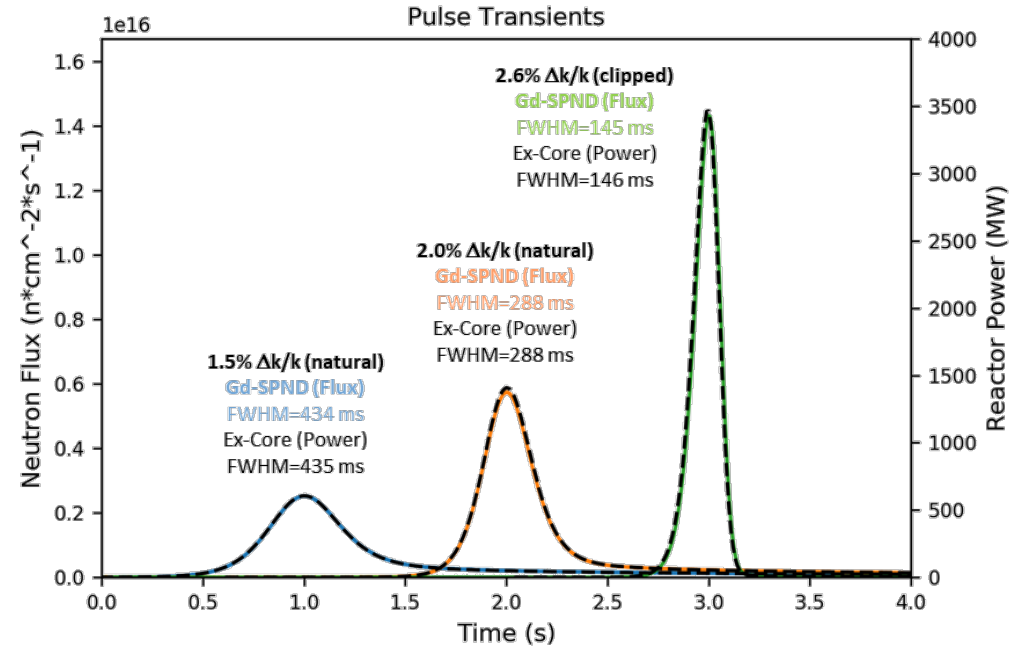


Intrinsic F-P cavities fabricated by fs laser

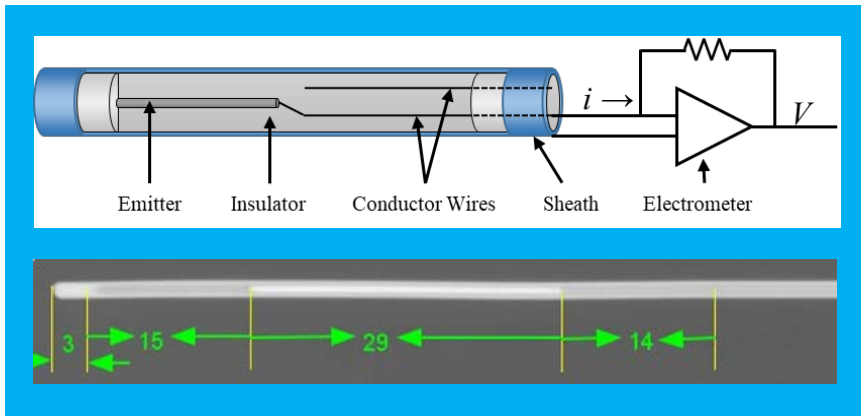


Self Powered Flux Detectors (SPD)

- Real-time neutron flux measurement with Self Powered Neutron Detectors (SPNDs) is widely used in reactors to monitor neutron flux and validate irradiations conditions
- Specialized SPNDs for steady-state and transient irradiation testing have been developed and fabricated at INL
- Characterization of fast response Gd SPNDs started in TREAT and will enable routine deployment in DOE test facilities



SPND performance in TREAT



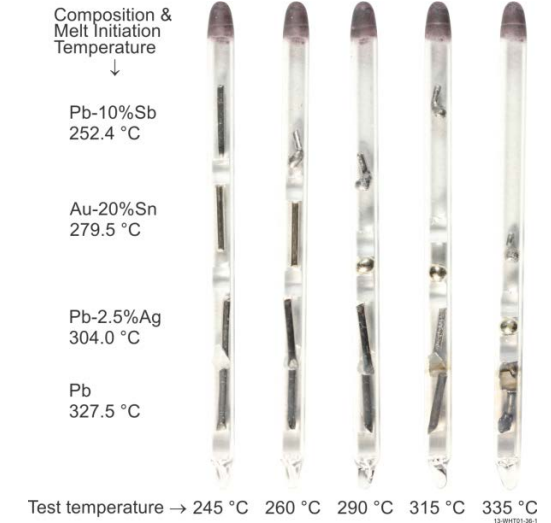
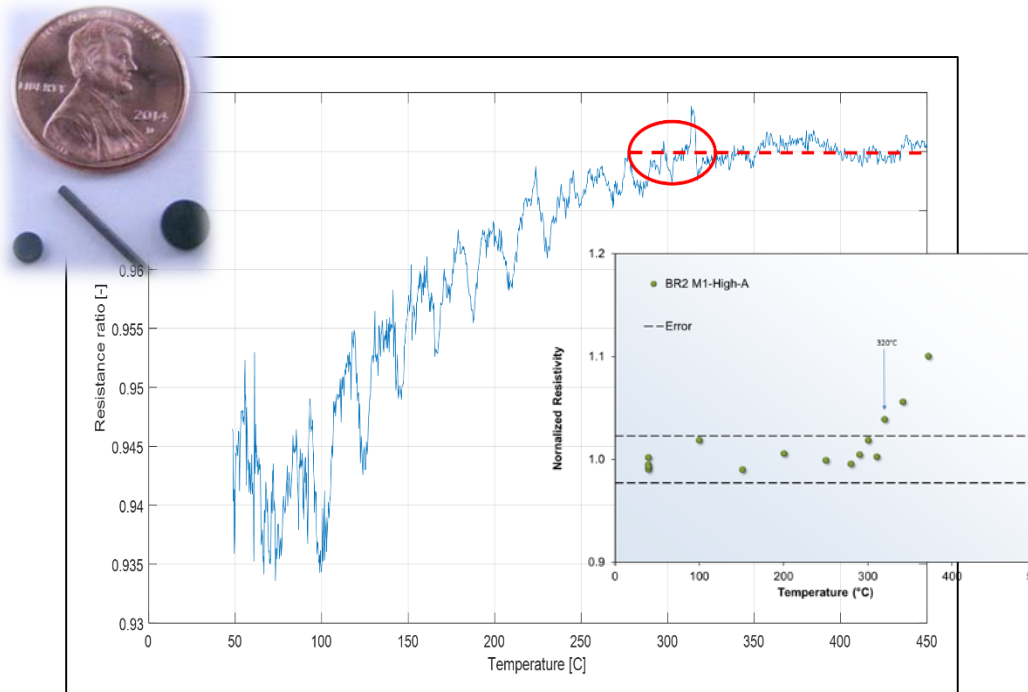
Unruh T., Neutron sensor developments at Idaho National Laboratory, #04-1399, Jun 20 (Thu) 15:40 Europa

INL Gd SPNDs



Passive Temperature And Flux Monitors

- Passive monitors for temperature and neutron fluence are needed when real-time sensors are not practical or economical to install in an irradiation test
- Specialized peak temperature and neutron fluence monitors and related analysis techniques for Post Irradiation Examination (PIE) have been developed at INL in collaboration with ORNL
- Focus is placed on reliability and compatibility with standard material samples sizes (ie, 3 mm disc)

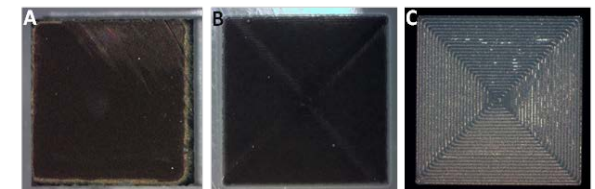
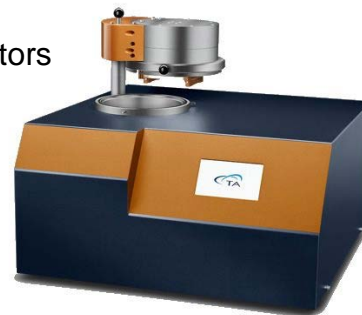


Melt wires for peak temperature evaluation

Automated post-processing of irradiated SiC rods



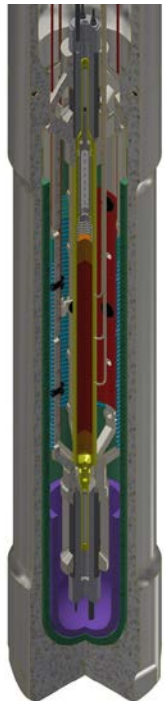
High-T optical dilatometer for disc monitors



Printed dosimeters for neutron flux

Linear Variable Differential Transformers

- For decades, Linear Variable Differential Transformer (LVDT) technology has demonstrated excellent performance under irradiation in test reactor environments
- The Halden Reactor Project (HRP) has optimized LVDT sensor technology and applications
- With the closure of HBWR the INL is working to recover HRP capabilities for DOE programs and the US nuclear industry



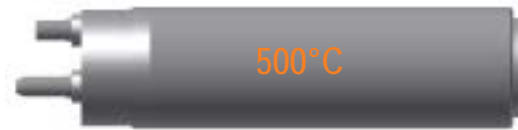
TREAT MARCH SERTTA

- Cladding elongation
- Pressure sensor

Fleming A., The Development and Testing of Instrumentation for the Transient Reactor Test Facility, #04-1491, Jun 21 (Fri) 11:20 Europa



Standard type 5 LVDT, O.D. 12 mm, Length 55mm Measuring range ± 2.5 mm



Short type 5 LVDT, Ø4mm hole, O.D. 12 mm, Length 46 mm, Measuring range ± 2.5 mm
6 Due in May



Small dia. type 5 LVDT, O.D. 9.0 mm, Length 46 mm Measuring, range ± 2.5 mm



Bellows type 3 LVDT, O.D. 13.4 mm, Length 26 mm, Measuring range ± 1.5



LVDT driver & processing, 3 Channel, Expansion to 10 Operating @ 2500 Hz. (1 ms response time)



Miniature type 2 LVDT, O.D. 8.3 mm, Length 22 mm, Measuring range ± 1.5 mm



LVDT evaluations in horizontal and vertical tube furnace

HIGH TEMPERATURE TEST LABORATORY



High Temperature Furnaces



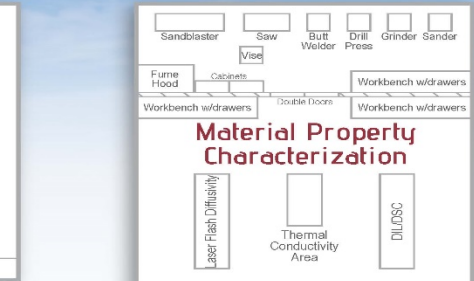
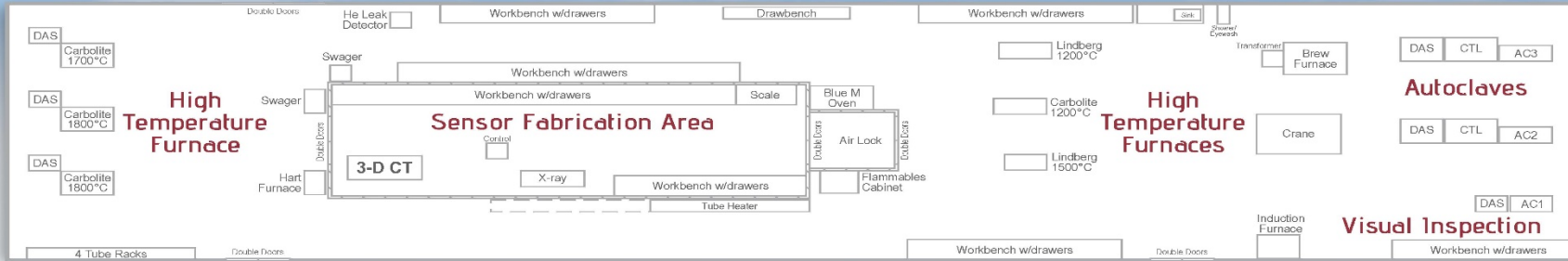
Sensor Fabrication



Autoclaves



Material Property Characterization



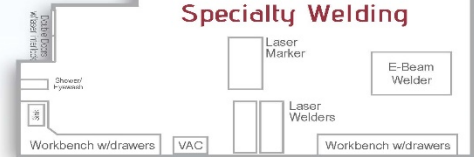
3-D Computed Tomography



X-Ray



Specialty Welding



Visual Inspection



High Temperature Furnaces





Idaho National Laboratory