INTEGRATED SILICON/CHALCOGENIDE GLASS HYBRID PLASMONIC SENSOR FOR MONITORING OF TEMPERATURE IN NUCLEAR FACILITIES

2017 NEET-ASI
Award number
17-12633

PI Maria Mitkova, Boise State University

Project Objective – Applying additive technology to develop very low power consuming reversible and multiple time applicable devices, which can be deposited directly over the measured surface for real time temperature monitoring.

Accomplishments in the FY 2021

- Waveguides were produced and covered with chalcogenide glasses by thermal evaporation through a shadow mask or printing
- The waveguides were placed in a Grating coupling set up, established at Boise State for measurement of transmitted power as a function of temperature
- The light transmitted from the waveguides was captured and measured with the temperature increase past the crystallization temperature of the chalcogenide glass material, covering the waveguides
- Combination of waveguides with different compositions in an array created the opportunity for a real time measurement of the temperature and measuring the temperature profile of reactor’s cladding
- S-bend waveguide was designed and fabricated using electron-beam lithography.
- Chalcogenide glasses were deposited over the waveguides by thermal evaporation through a shadow mask or printing
- The light transmitted from the waveguides was captured and measured in a real-time with the temperature increase past the crystallization temperature of the chalcogenide glass material, covering the waveguides

- The radiation stability of the materials and devices has been studied after irradiation with neutrons, as well as with Xe-ions.
- Performed interface stress measurements of ChG on SiO_2 using KMOS tool.
- Reviewed requirements for packaging chip-based and fiber-optic sensors for deployment in nuclear facilities.
- Overview of the performed work on the project

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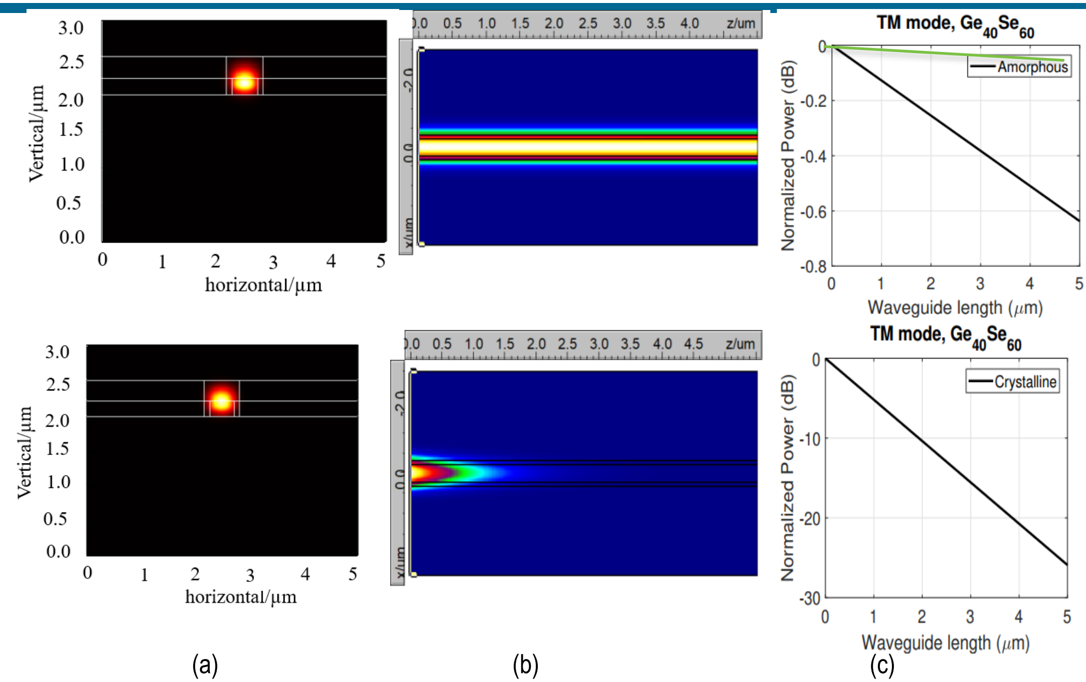
Simulation of the Si waveguide with $Ge_{40}Se_{60}$ covering

- The complex refractive index in two amorphous and crystalline phases is measured using ellipsometer.
- Si waveguide covered with in-house synthesized $Ge_{40}Se_{60}$ is simulated using PhotonDesign software.
- In amorphous phase of ink, fundamental TM mode is confined in Si core.
- At crystallization temperature of ChG, the phase of the glass is changed to metal phase.
- Fundamental TM mode in confined at the interface of Si and ChG.
- Higher loss in crystalline phase compared to amorphous phase of ChG.

Abrupt drop at the output power occurs at very well-defined temperatures (~$T=T_c$), monitoring of which provides information regarding the node temperature.



$Ge_{40}Se_{60}$ covering Silicon Waveguide.
Top row: Amorphous phase.
Bottom row: Crystalline phase.

a) Intensity profile of TM mode
b) Intensity distribution along the waveguide
c) Output power of TM mode as a function of the length of waveguide.

Measured refractive index

Composition	Refractive index		Temperature (˚C)		
	Amorphous	Crystalline	T_g(˚C)	T_o(˚C)	T_c(˚C)
$Ge_{40}Se_{60}$	2.63104+i0.00575	3.1099+i0.2211	343.7	446.6	472.3

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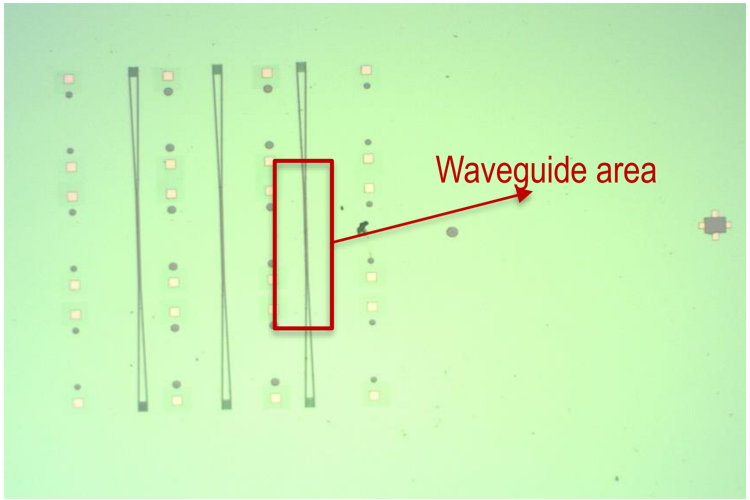
Temperature sensor fabrication

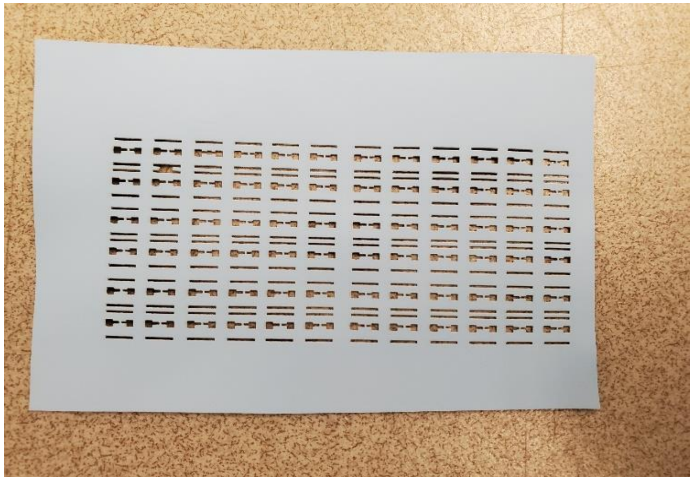
- The in-house synthesized ChG are used to cover the Si waveguides.
- Two different methods have been used for this:

  thermal evaporation of the chalcogenide glass film

  printing the chalcogenide glass film
- The thermally evaporated films were deposited over the waveguides using a shadow masks
- Printing of the chalcogenide glass films were achieved by creation of CAD files in the respective printers and direct printing over the waveguides.



Blank Si waveguides array



A shadow mask prepared at Boise State by laser cutting for direct chalcogenide glass evaporation over the waveguides

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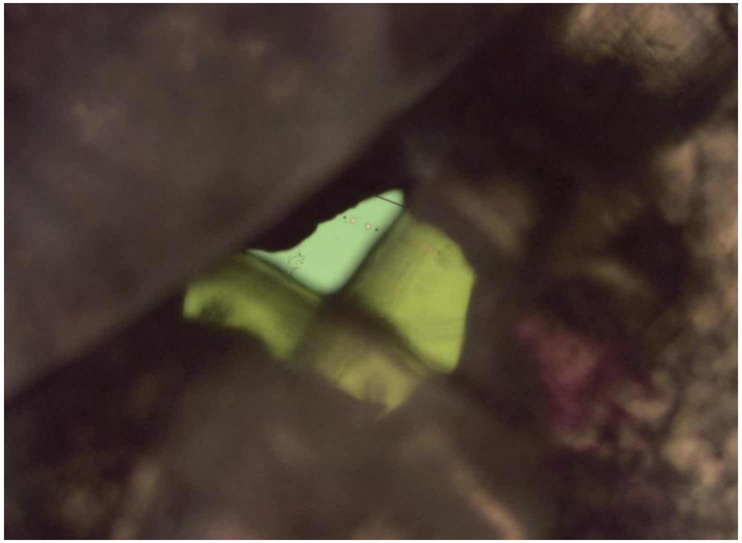
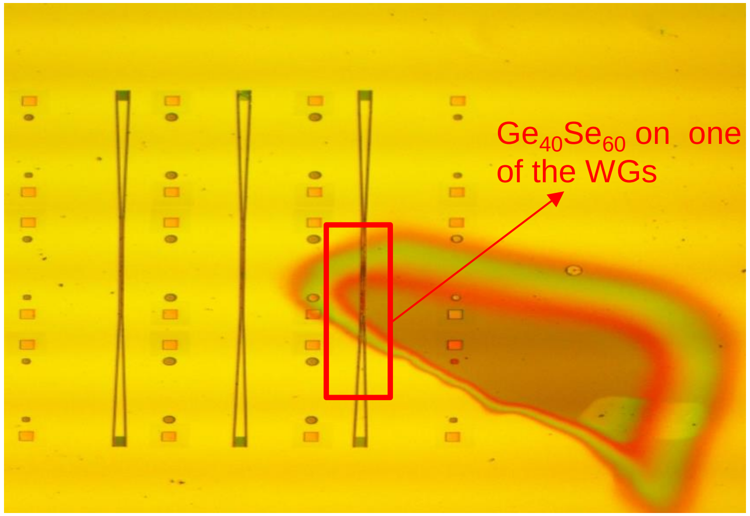


Waveguides covered with non-transparent shadow mask.

- The $Ge_{40}Se_{60}$ is deposited using thermal evaporation method on one of the array of waveguides.
- A photo-mask which covers whole chip with a small size hole (100 µm) is used in depositing process.
- The hole size in photomask is smaller than waveguide length.

The shape of the chalcogenide glass covered area is not well defined due to the distance between the mask and the waveguide. This can be prevented by direct printing of the chalcogenide glass over the waveguide.



$Ge_{40}Se_{60}$ covered Si waveguide

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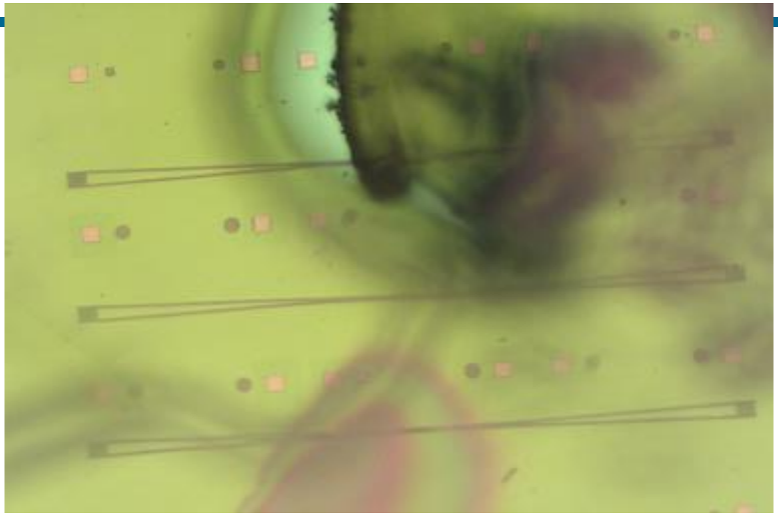
Temperature sensor fabrication details

Preparation for thermal evaporation

- Manually aligning of the samples were proven to be difficult with non-transparent mask.
- To ease the alignment process semi-transparent Kapton was used to cover the next waveguide.
- Instead of using a laser engraver to print a pinhole, a pin was used to put a pinhole on the shadow mask.
- The result was satisfactory. This means the process can be done manually and reduces the whole mask preparation and alignment time to 1-1.5hours, since the scheduling for work with the laser engraver is not necessary.



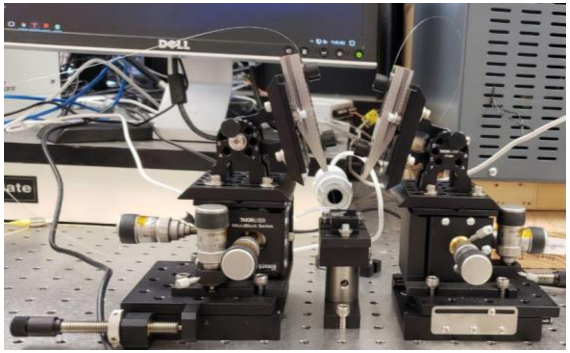
Waveguides covered with semi-transparent shadow mask.

$Ge_{30}Se_{70}$ covered Si waveguide

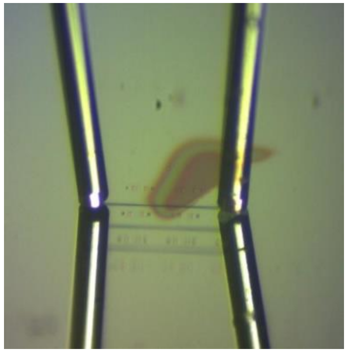
INTEGRATED SILICON/CHALCOGENIDE GLASS HYBRID PLASMONIC SENSOR FOR MONITORING OF TEMPERATURE IN NUCLEAR FACILITIES

Temperature sensor characterization and testing

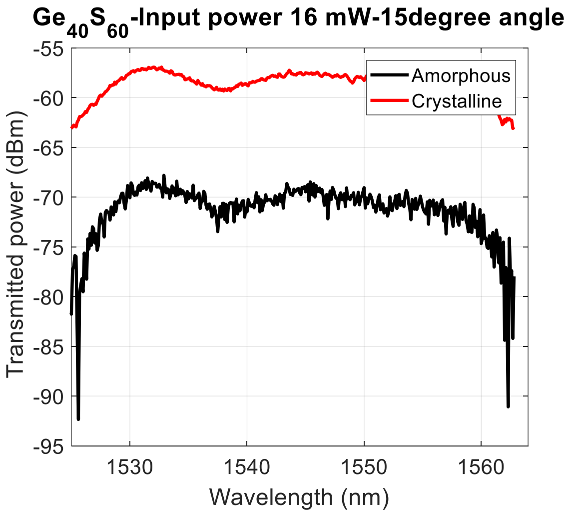
- The sensor is tested using grating coupler set up prepared at Boise State University.
- The temperature response of the device is measured in both - the amorphous and the crystalline phases of the $Ge_{40}Se_{60}$.
- First, the output power is measured in amorphous phase of the ChG.
- Second, the sample is removed and heating in enclosed heating stage up to crystallization temperature is conducted,
- Finally the output power at crystallization phase is measured.
- The measurements of the light output were performed with a laser emitting light at 1550 nm.



Grating coupling set up



Device under test

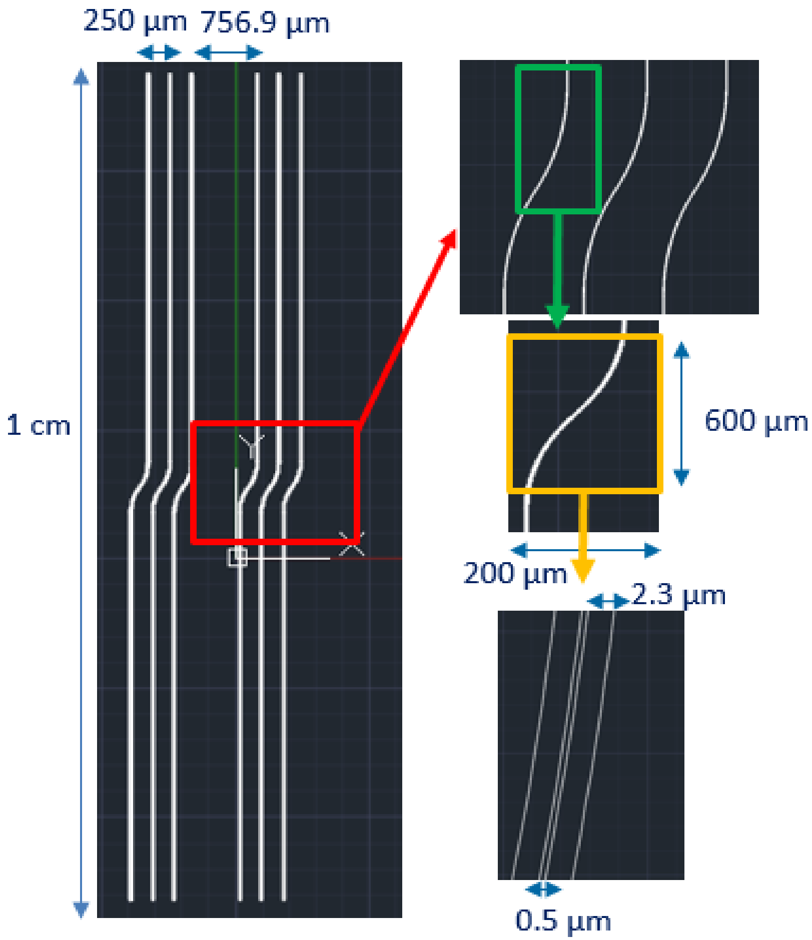


Transmitted power in amorphous and crystalline phases of the $Ge_{40}Se_{60}$

Wavelength (nm)-15degree incident angle	$P_{trans(amor)}$ (dBm)	$P_{trans(crys)}$ (dBm)	Normalize P_{crys} to P_{amor}
1550	-69.0448	-58.2739	10.7708

S-Bend waveguide Design

- The S-shaped bend is a bend waveguide connecting two lateral displaced parallel straight waveguides.
- S-bend waveguide can change the propagation direction by separating two or more output in the optical devices.
- The single mode S-bend Si waveguide is designed.
- The waveguide width is selected 500 nm and 2.3 µm border with 500 µm curvature radius which shows single mode characteristic.
- The ChG (temperature sensitive) can be deposited on this waveguide to act as a temperature sensor.
- The working mechanism of these sensors is based on changes in refractive index of ChG by increasing the temperature.
- Abrupt loss at output power is expected when the ChG crystalizes. The temperature at which this happens can be registered and IC added to the system can register the temperature and time frame in which this effect occurred.



AutoCad design of S- Bend waveguide

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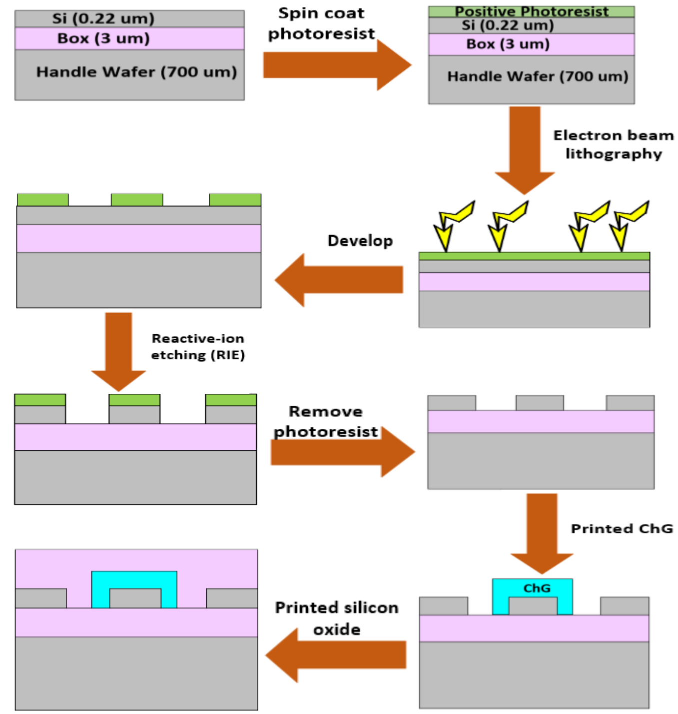
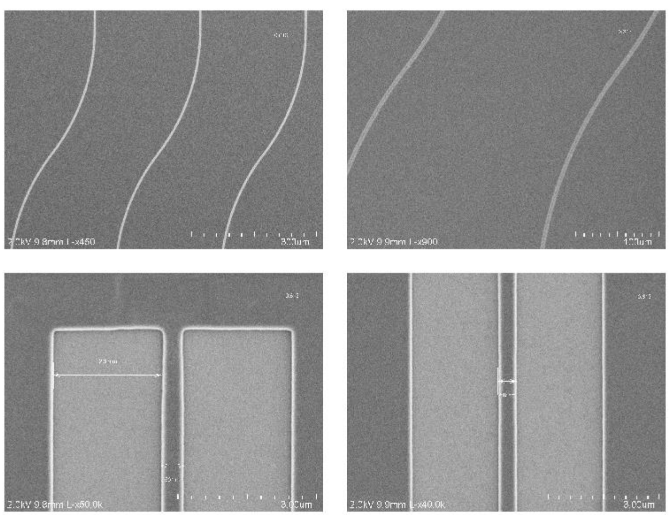
S- Bend Waveguide Fabrication

We have fabricated S-bend waveguide based temperature sensor on SOI wafer with 220 nm device layer and 3µmBox oxide layer.

- The positive photo-resist is exposed by electron beam .
- The exposed photoresist is developed using developer.
- The design structure is transferred on SOI wafer using Reactive ion etching.
- The photo-resist is removed.



Process flow for fabricating Hybrid Silicon:ChG Waveguide based Plasmonic Temperature Sensors



SEM image of an array of S-bend waveguide

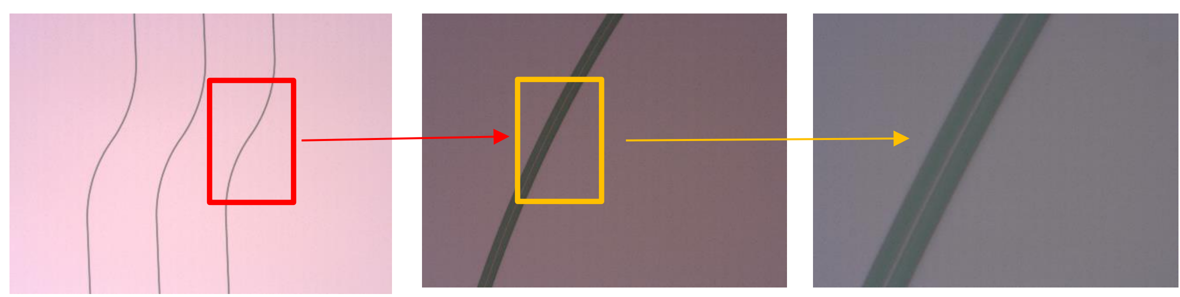
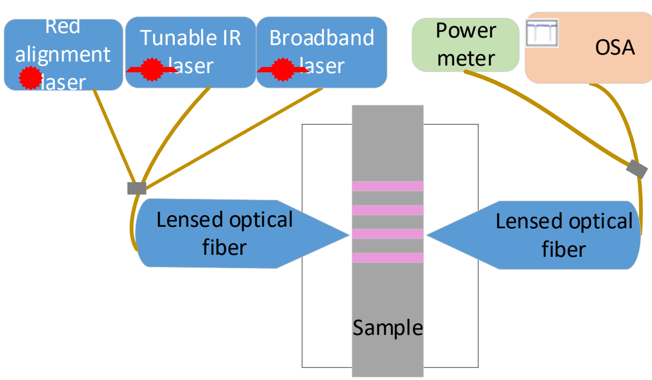


Image of the S-bend waveguide under microscope

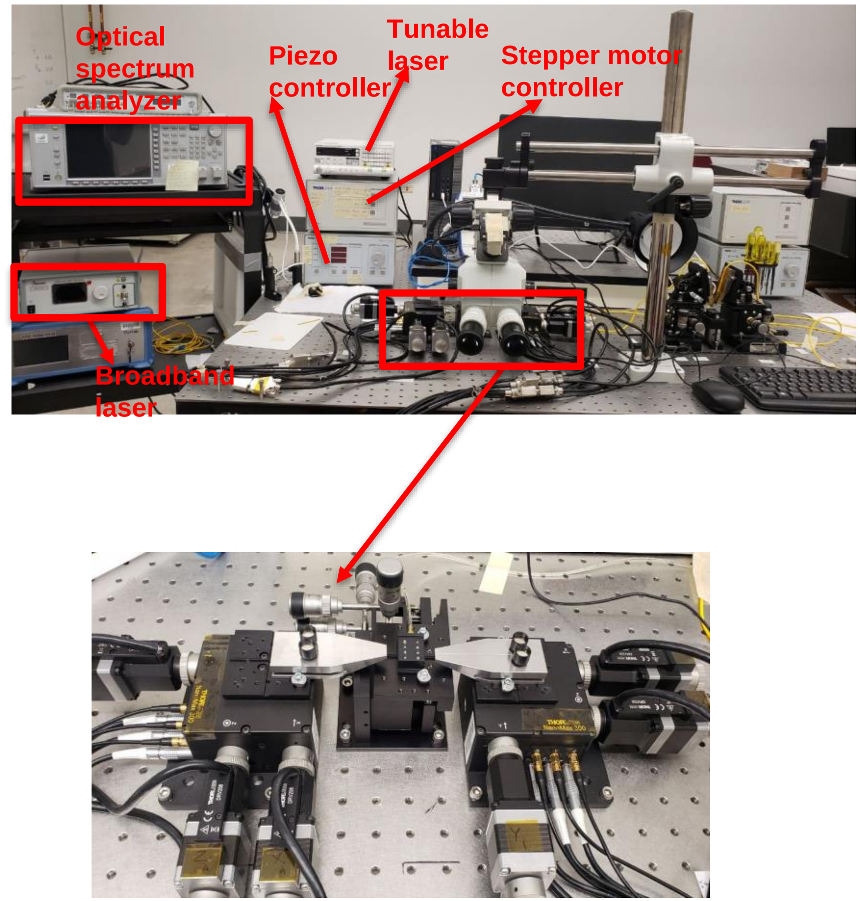
Edge coupling set up

Edge coupling set up is prepared to couple light through S-bend waveguide.

- The lensed optical fiber focuses the incoming light to the waveguide end-facet. The lensed fiber reduces the beam spot size to 2-3 μm while the mode field size of the single mode fiber (SMF) is about 8μm.
- Another lensed fiber is used as a detector fiber at output stage to collect the transmitted power at the output.
- The output power can be measured using power meter or optical signal analyzer (OSA).
- Fiber tip and waveguide edge under microscope are precisely aligned using piezo controller and stepper motors.



Edge coupling testing setup schematic



Edge coupling set up at Boise State University

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- The sensors are tested using grating coupler set up prepared at Boise State University.
- The temperature response of the device is measured in both - the amorphous and the crystalline phases of the $Ge_{40}S_{60}$.
- First, the output power is measured in amorphous phase of the ChG.
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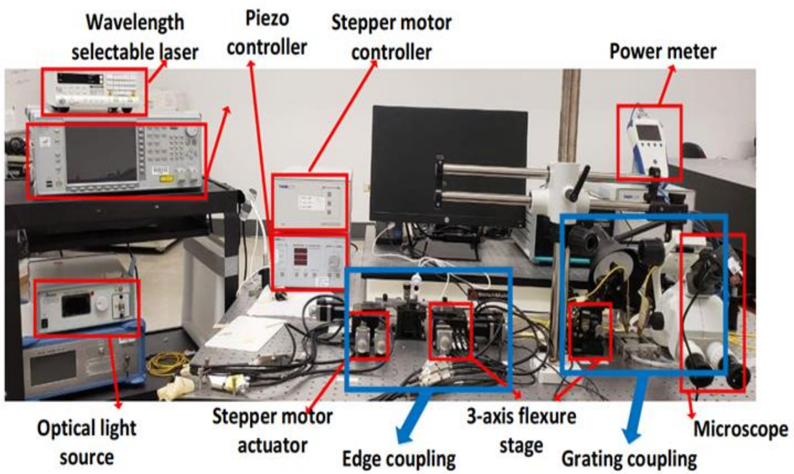
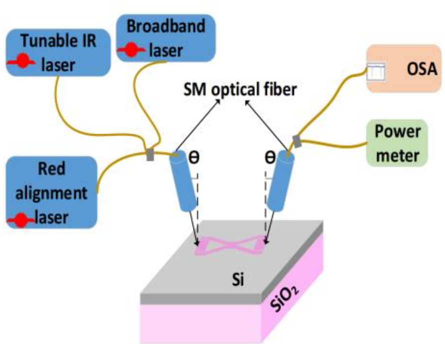
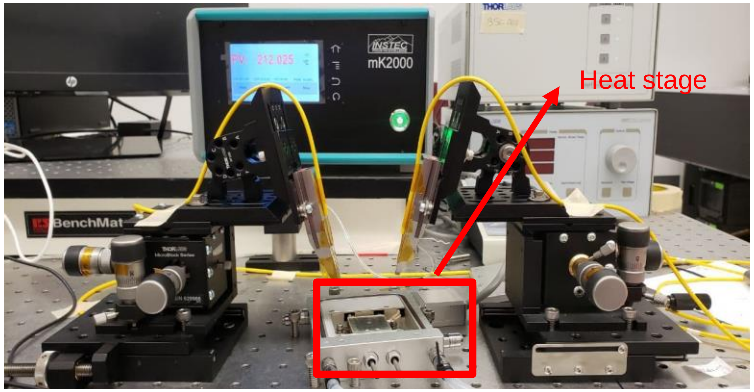


Waveguide characterization setup at Boise State University.



Waveguide grating coupling testing setup schematic.



Testing setup for characterization of the temperature response of the Si waveguide grating based temperature sensor.

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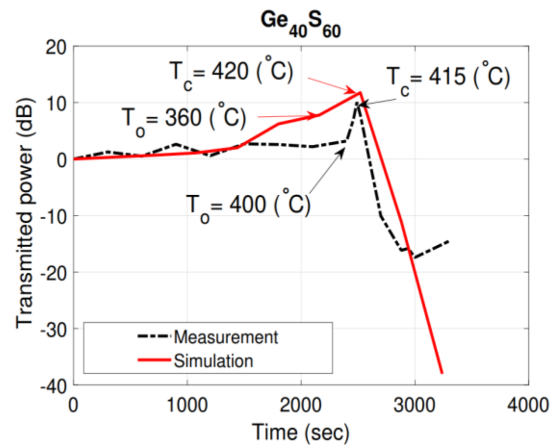
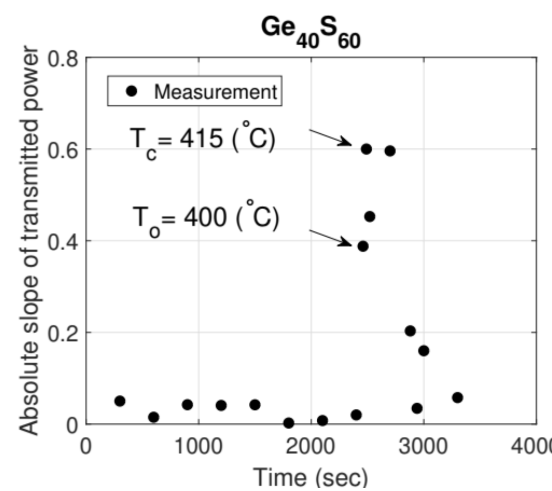
Real-time response of proposed Si waveguide based sensor

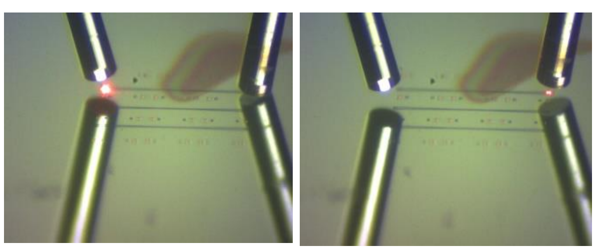
- Normalized transmitted power as a function of time in simulation and measurement with extracted refractive index profile from studying in-house ChGs are well matched.
- These sudden changes in transmitted power associated with temperatures can be efficiently extracted from the sensor data by plotting the slope as a function of time.
- This sudden change happens at well-defined temperature which indicates the ambient temperature.



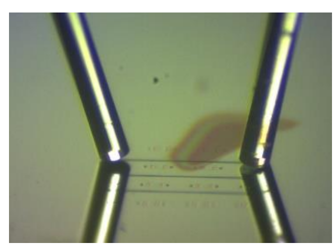
Simulated and measured optical spectra as a function of time with in-house synthesized $Ge_{40}S_{60}$ covered silicon waveguide.



Temperature response of evaporated $Ge_{40}S_{60}$ covered silicon waveguide based temperature sensor.

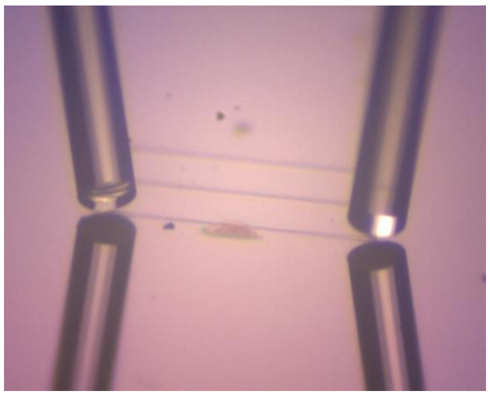


Use red light to find gratings

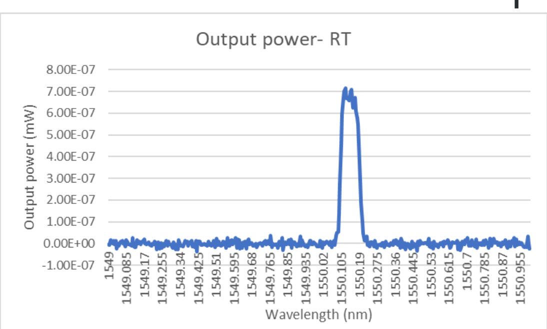


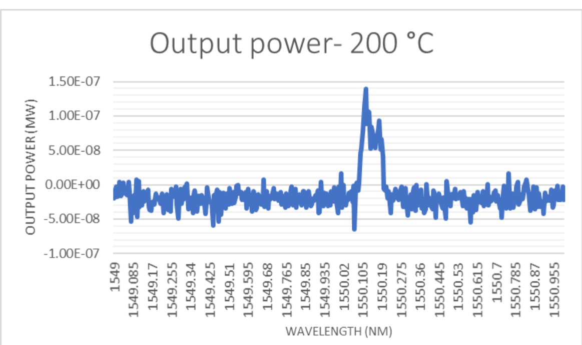
Device under test

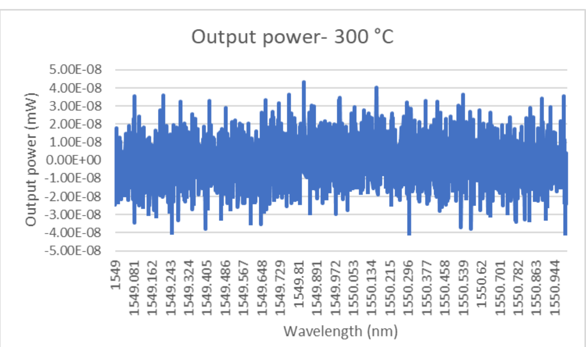
Tests of Temperature Sensors fabricated by printing of chalcogenide glasses over the waveguides



- The devices were crystallized (SET) by heating.
- In difference with the performance of the printed electrically measured devices and those based on dipped chalcogenide films on the tips of the fibers the printed devices performance is pretty weak and with increasing of the temperature the signal mixes with the noise. We suggest that the reason for this is that the material is much less dense compared to the thermally evaporated films, which prevents formation of well developed plasmonic effects.

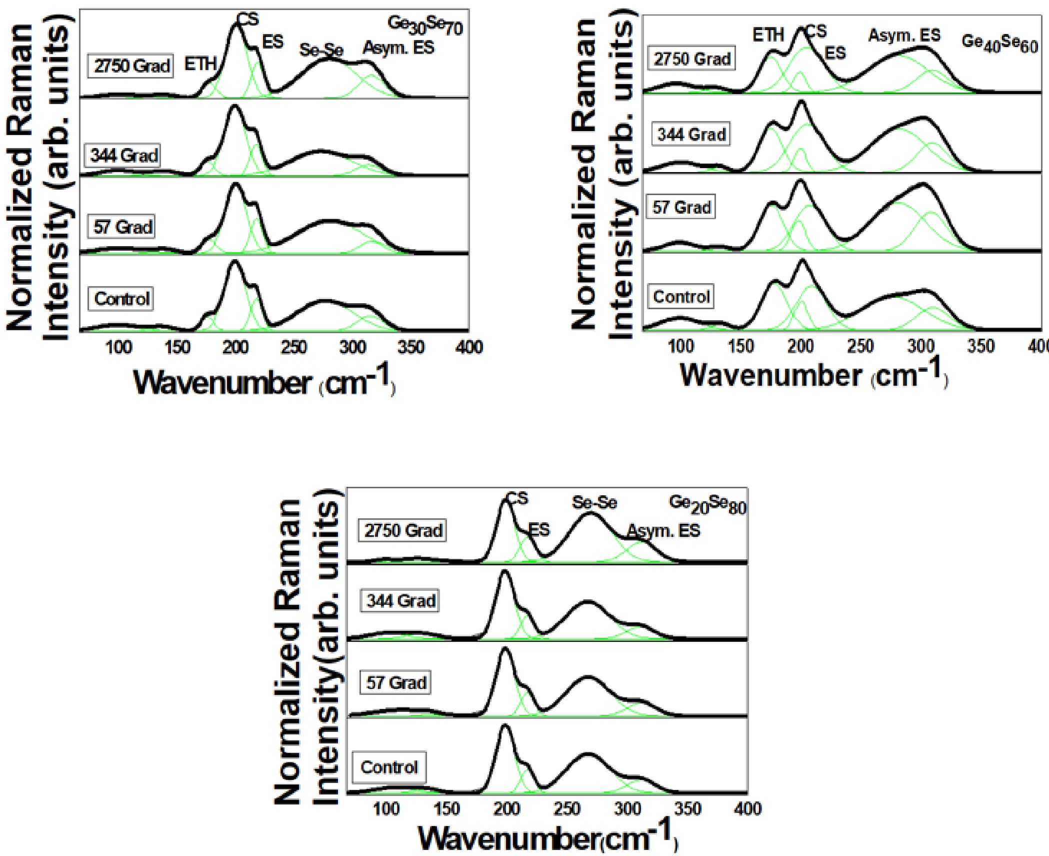






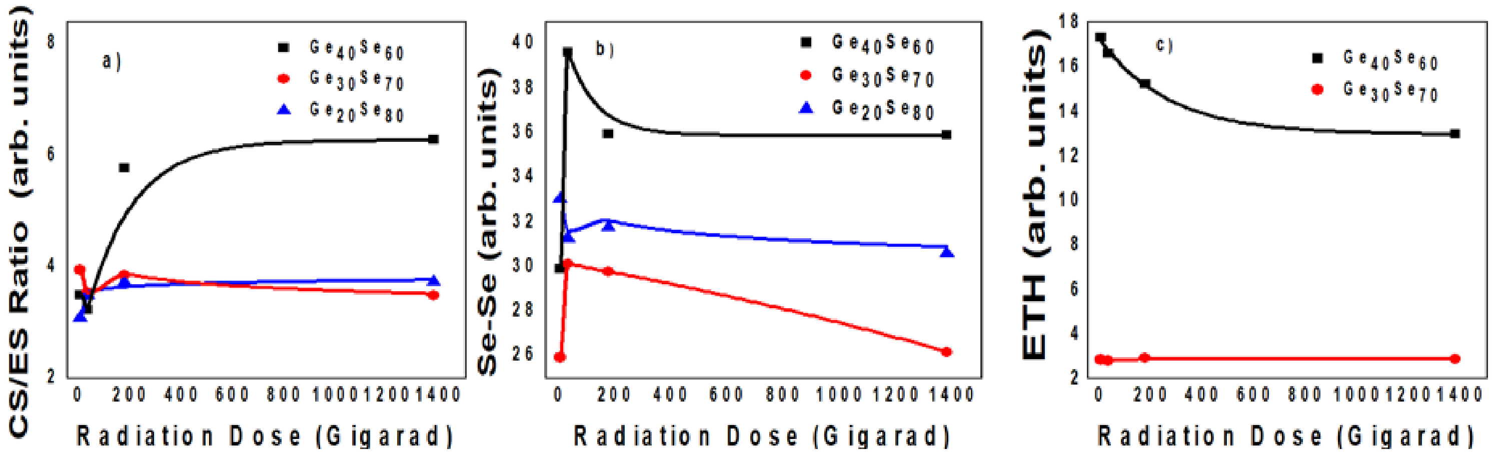
Raman Spectroscopy Structural Studies under Neutrons and Gamma Rays Irradiation

- Except for ETH units, $Ge_{30}Se_{70}$ (closest to stoichiometry with less homopolar bonds) does not show much change in structures.
- Even though neutron irradiation induces some change at lower dosage, in the presence of gamma ray most profound changes in the materials occur due to the additional interaction with the electromagnetic waves.



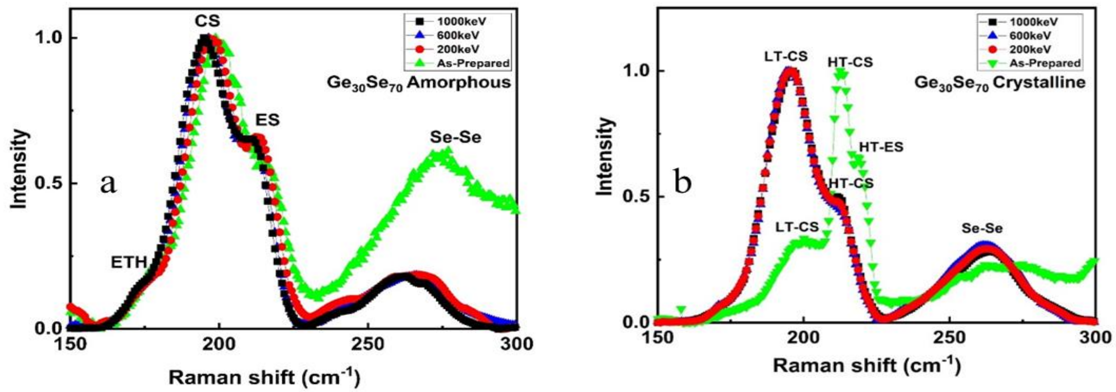
Raman spectra of neutron in presence of gamma rays irradiated ChG thin films $Ge_{30}Se_{70}$, $Ge_{40}Se_{60}$ and $Ge_{20}Se_{80}$.

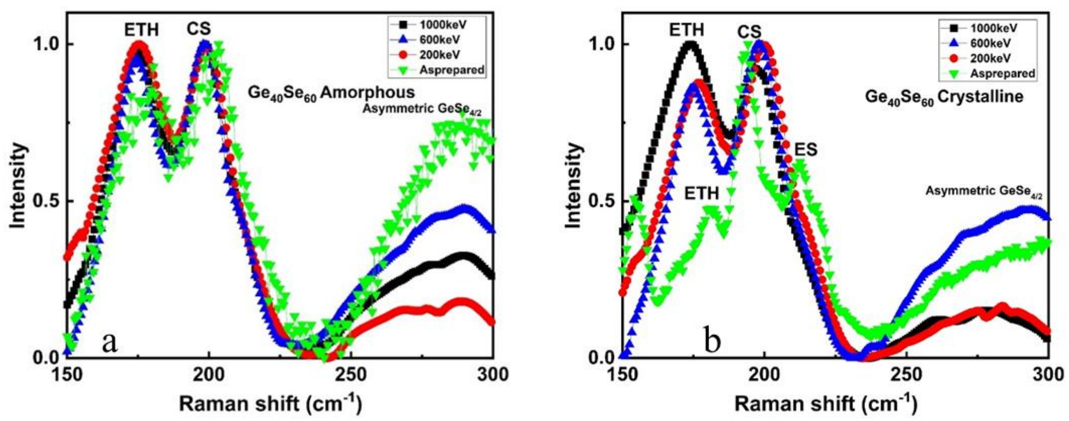
Raman Relative Structural Units Analysis



- Under irradiation with neutrons all the structures except for ETH (which is absent at x = 20) all compositions, show significant changes for low dose irradiation but the materials become less responsive to radiation as the dose increases.
- After prolonged irradiation the number of structural units is found to be very close to that of the unexposed thin films due to the fast recombination of the irradiation induced defects.
- It is seen that with neutron irradiation the CS/ES ratio for $Ge_{20}Se_{80}$ and $Ge_{30}Se_{70}$ is stable but undergoes significant change for $Ge_{40}Se_{60}$ due to availability of Ge-Ge bonding which is weak, it breaks and forms additional CS units

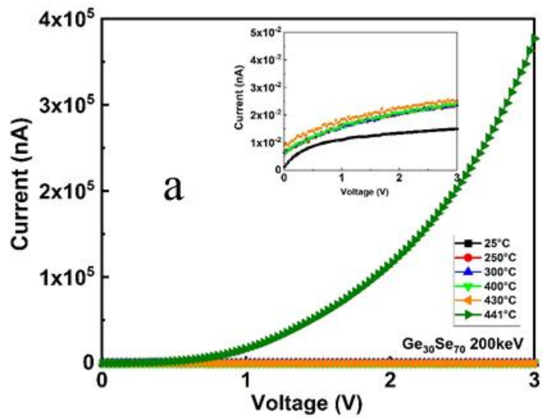
Raman Relative Structural Units Analysis under Xe Ions Irradiation

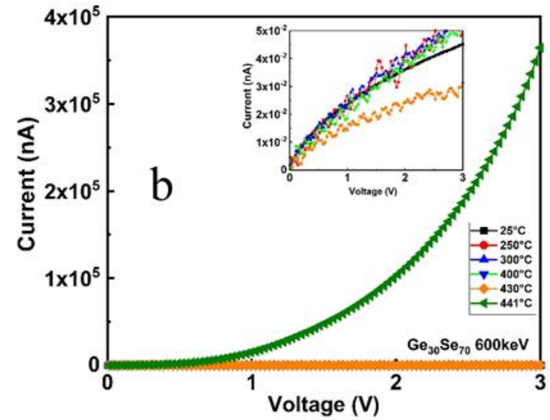




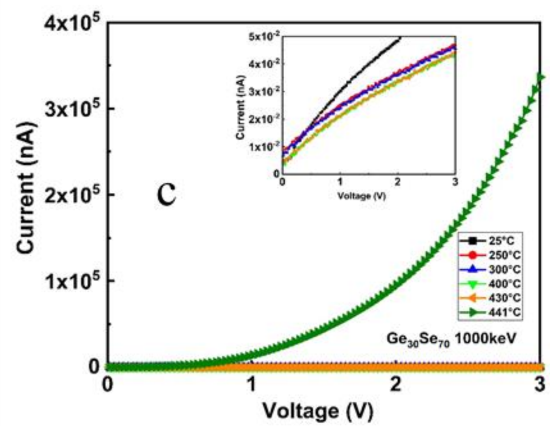
Irradiation with Xe ions, although introducing some small changes in the structure of the studied amorphous phases, they remain stable even at high irradiation energies. More expressed structural changes occur in the crystalline phases which in the course of irradiation change their structure from LT $GeSe_2$ to LT GeSe . This stabilizes it and opens up the structure reducing the damaging effects in it.

Temperature $Ge_{30}Se_{70}$ Sensors Performance under Irradiation with Xe Ions a) 200keV;b)600keV; c) 1,000keV

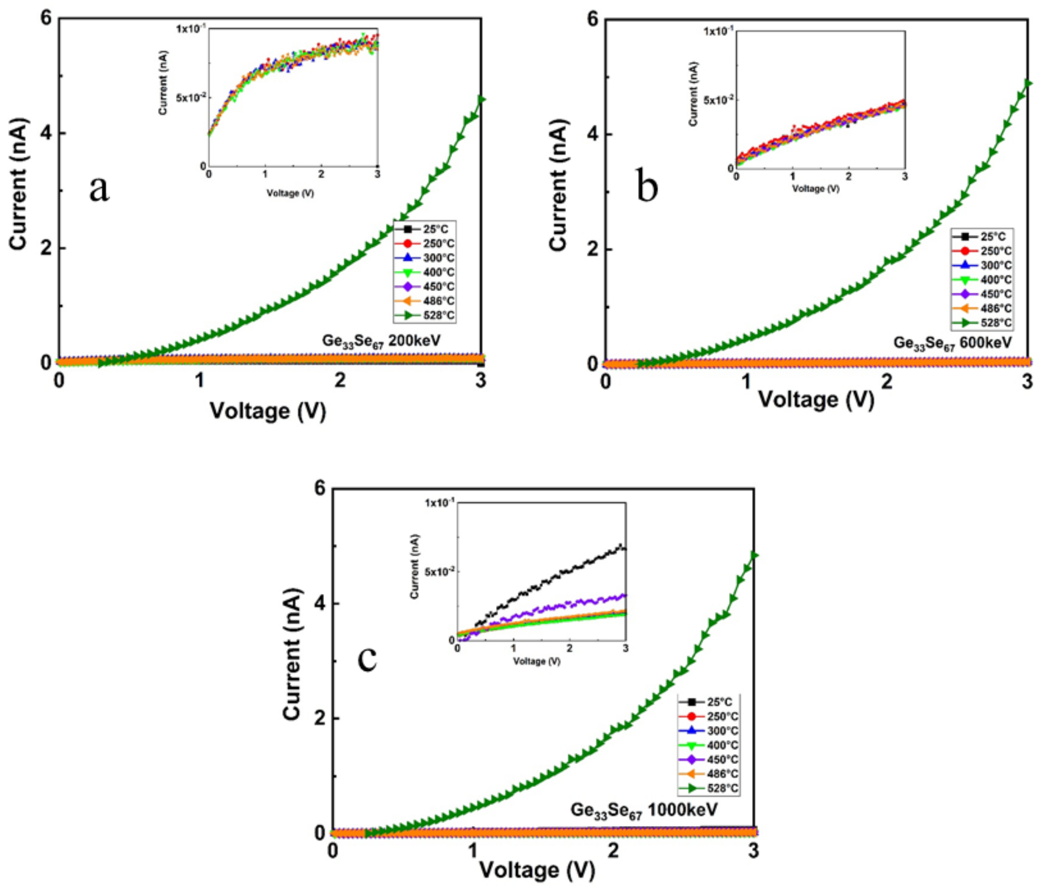




Device Structure

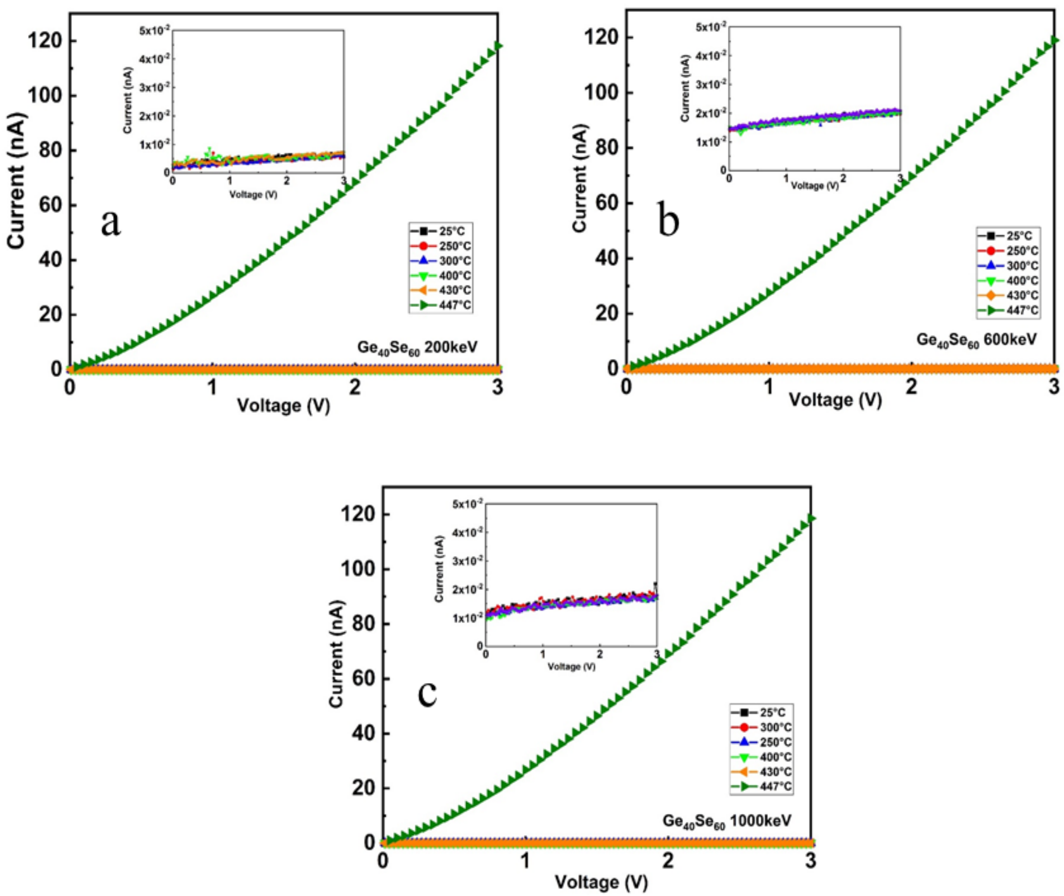


Temperature $Ge_{33}Se_{67}$ Sensors Performance under Irradiation with Xe Ions; a) 200keV;b)600keV; c) 1,000keV



- The devices were crystallizing (SET) by heating.
- The SET devices were irradiated with Xe ions with different energies.
- The devices performance is pretty stable and independent upon irradiation due to pinning of the Fermi level.

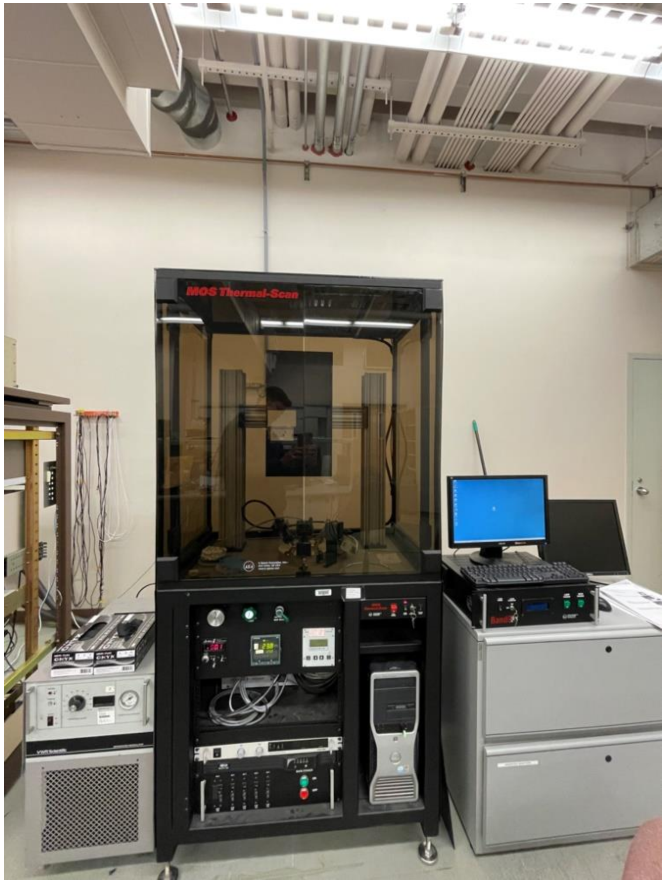
Temperature $Ge_{40}Se_{60}$ Sensors Performance under Irradiation with Xe Ions; a) 200keV;b)600keV; c) 1,000keV



- Composition $Ge_{40}Se_{60}$ shows reduction in current after irradiation.
- Although, 200 and 600keV ions are found to be impacting the device negatively, 1,000keV ions doesn't seem to affect the IV characteristics.
- We suggest this is because the 200 and 600 keV ions interact the most with the surface of the ChG thin film, on the other hand 1,000keV ions easily pass though the ChG layer and interact mostly underneath by which repulsions from the substrate occur which activate the recombination processes .

Strain measurement using KMOS tool

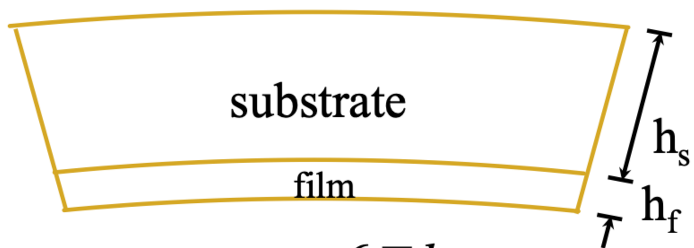
- Uses laser grid to measure the change in shape of a substrate



Theory

Measure thin film stress via wafer curvature

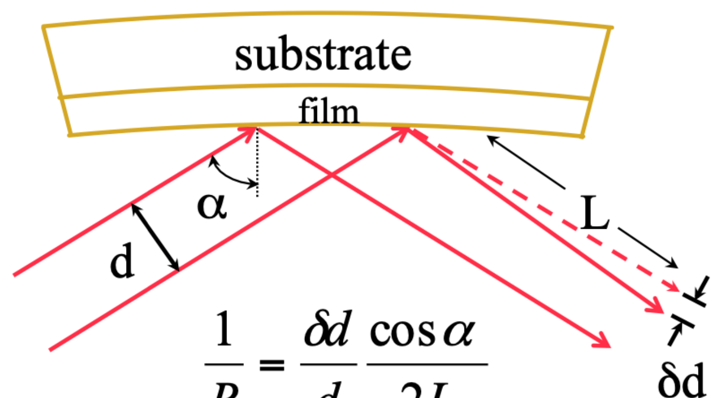
Stressed film bends the substrate
Stoney's equation



$$\kappa = \frac{1}{R} = \frac{6\bar{\sigma} h_f}{M_s h_s^2}$$

For multiple layers: $$\frac{1}{R} = \frac{6}{M_s h_s^2} \sum_i \bar{\sigma}_i h_i$$

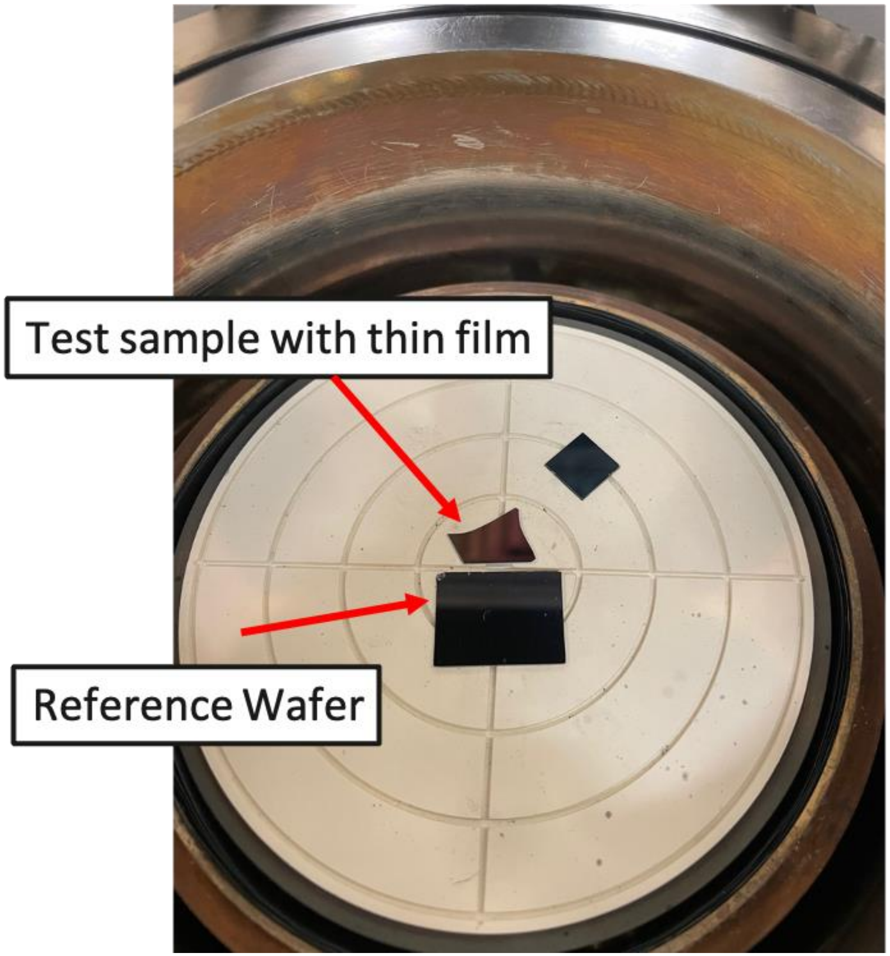
MOSS (multi-bean optical sensor)
Curved surface deflects
array of parallel beams

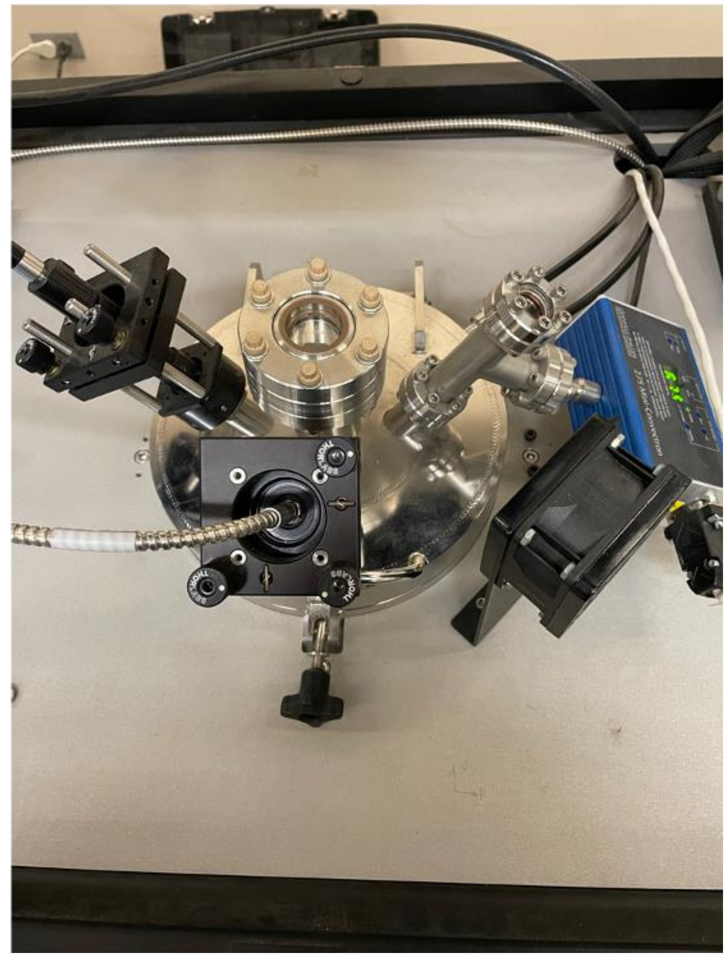


$$\frac{1}{R} = \frac{\delta d}{d} \frac{\cos\alpha}{2L}$$

Curvature measures product of average stress x thickness	$\bar{\sigma} h_f = \frac{\delta d}{d} \frac{M_s h_s^2 \cos\alpha}{12L}$

Experimental Setup





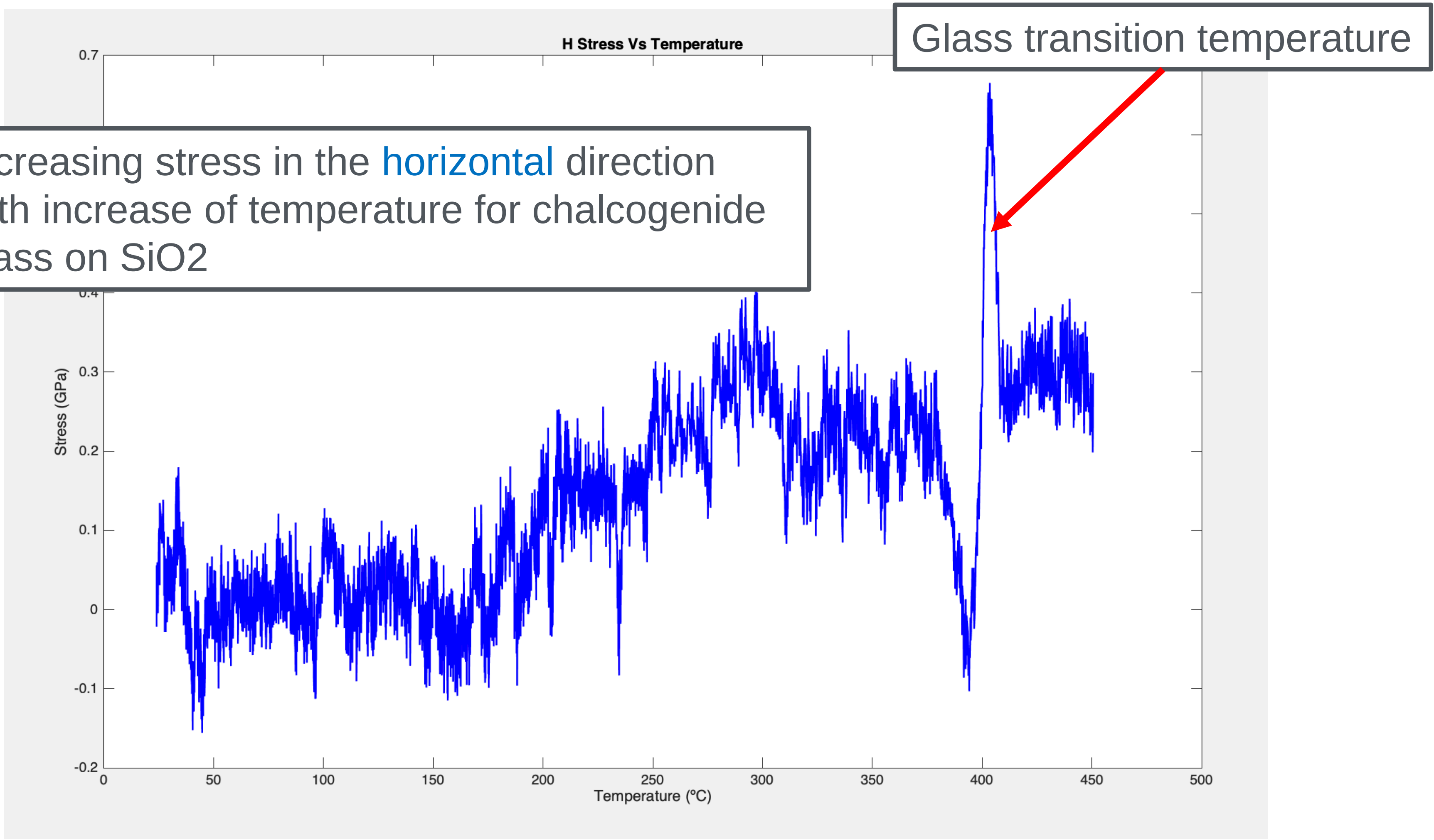
Experimental Setup

- Set up the temperature monitoring system; make sure the lasers are working and reflecting off the substrate studied for stress.
- Pump down the chamber by turning on the vacuum pump
- Read the data on the experimental

PJP Experimental set up.

PJP Experimental Setup

Increasing stress in the horizontal direction with increase of temperature for chalcogenide glass on SiO2

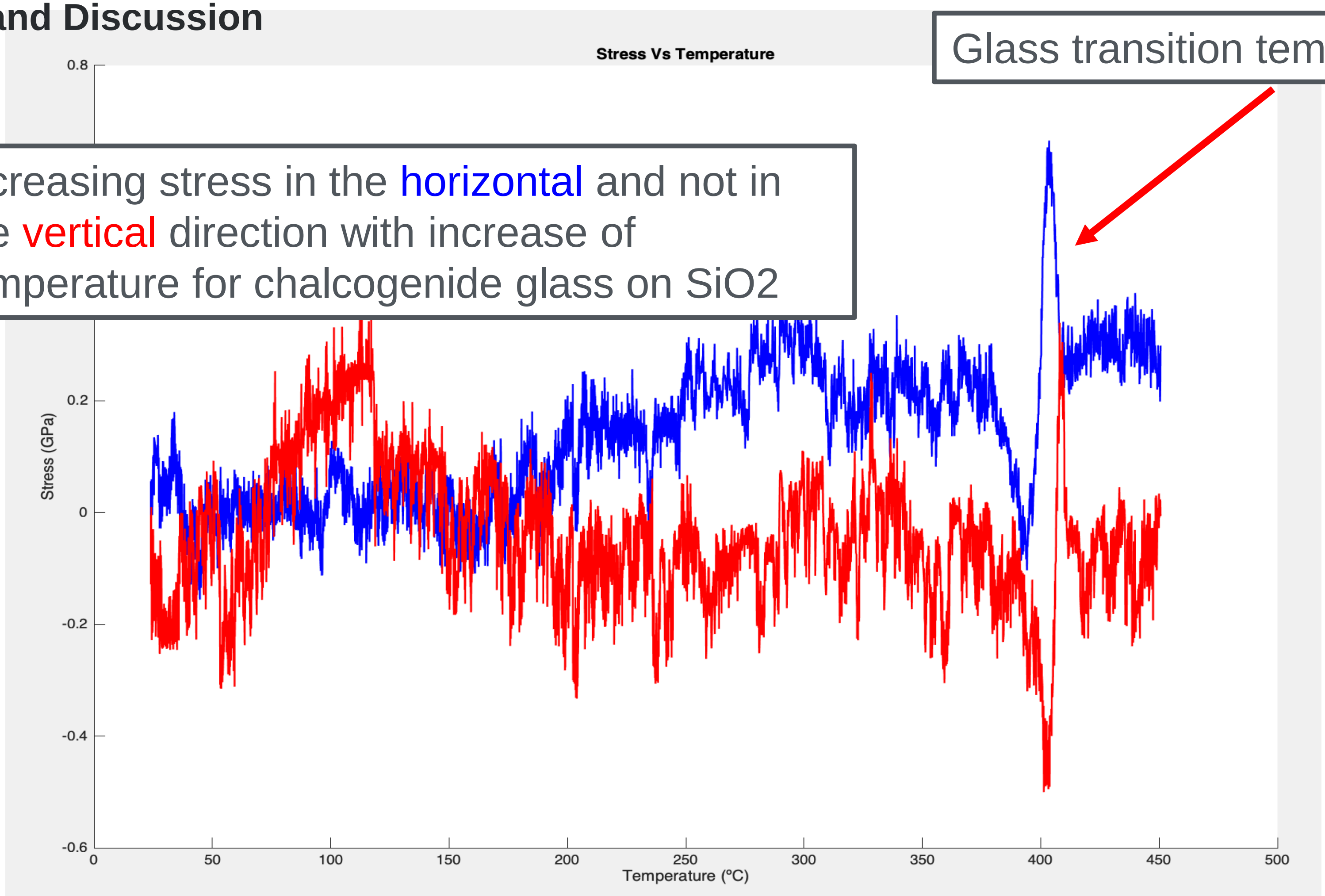


INTEGRATED SILICON/CHALCOGENIDE GLASS HYBRID PLASMONIC SENSOR FOR MONITORING OF TEMPERATURE IN NUCLEAR FACILITIES

2017 NEET-ASI
Award number
17-12633

PI Maria Mitkova, Boise State University

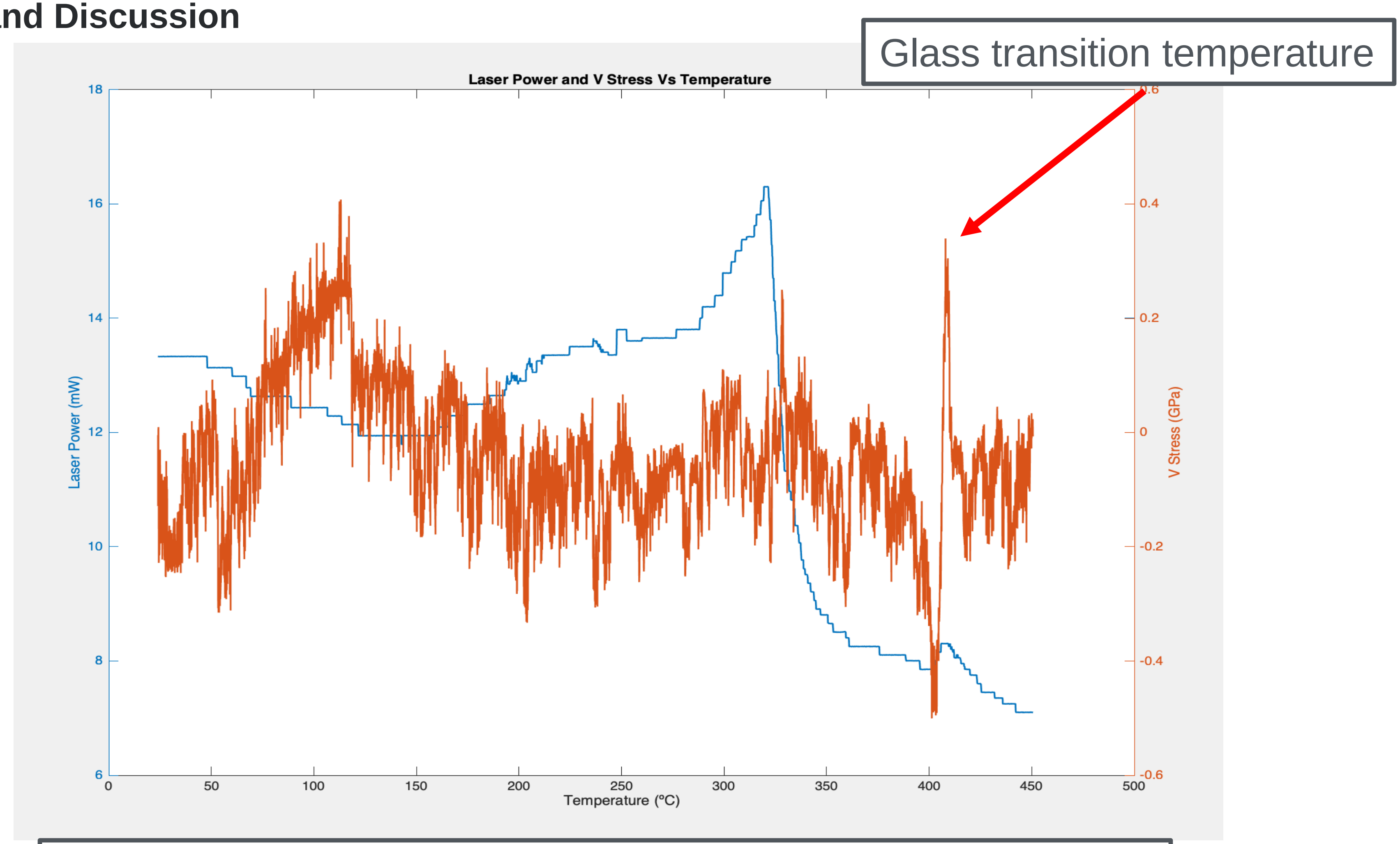
Results and Discussion



Glass transition temperature

Increasing stress in the horizontal and not in the vertical direction with increase of temperature for chalcogenide glass on SiO2

Results and Discussion



Laser power (blue line) can give information on the reflectivity of the sample as it increases in temperature and stresses

DOE award number DE-NE0008691

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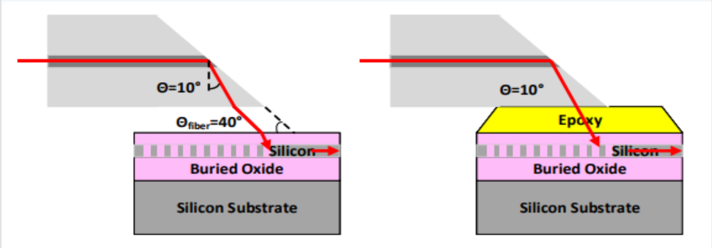
Silicon waveguide and fiber type chalcogenide based temperature sensor packaging:

- To minimize coupling loss caused by the second-order reflection, a grating coupler was designed to couple the light in/out with an angle (θ) off vertical direction.
- In packaging, the fiber must be polished with an angle (θ_{fiber}) that launches the light with totally internal reflected (TIR) light into the grating coupler.
- Angled polished input and output fibers should be placed into a silicon V-groove carrier.
- A red-light laser source can be used to align the fiber to a grating couplers.
- After completing the alignment, the fibers should be cured in the V-groove with UV-cured index matching epoxy.
- The distance between the fiber and the grating couplers should be studied to have highest transmitted power.
- To complete the packaging the chip should be mounted on a submount and attach the V-grooves to the same.

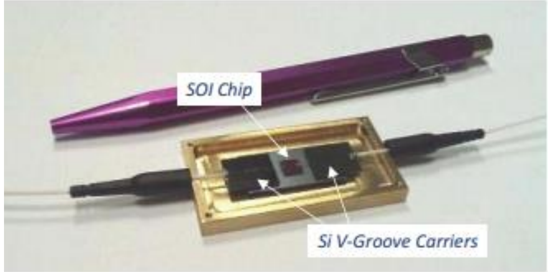


Using refractive index matching UV-cured epoxy to bond fiber to the Si waveguide device.

$$\theta_{fiber} = \frac{90^{\circ} - \theta}{2}$$

$$\theta_{TIR} = sin^{-1}\left(\frac{1}{1.4682}\right) = 42.930^{\circ} < \left(90^{\circ} - \theta_{fiber}\right)$$

This equation shows the limit of angles that can be used. This TIR equation is true only when the fiber facet is surrounded by air.



Completed package of fiber with epoxy and clean end-face [1].

[1] B. Snyder et al., "Packaging process for grating-coupled silicon photonic waveguides using angle-polished fibers." *IEEE Transactions on Components, Packaging and Manufacturing Technology 3*, no. 6 (2013).

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Optical fiber based temperature sensor packaging in harsh environment:

Implementing optical fiber sensors in harsh environments is challenging because they are small and fragile.

✓ There are several possible techniques.

- One potential solution is embedding optical fibers in a metal matrix and bonding the fibers to a metal substrate using epoxy.

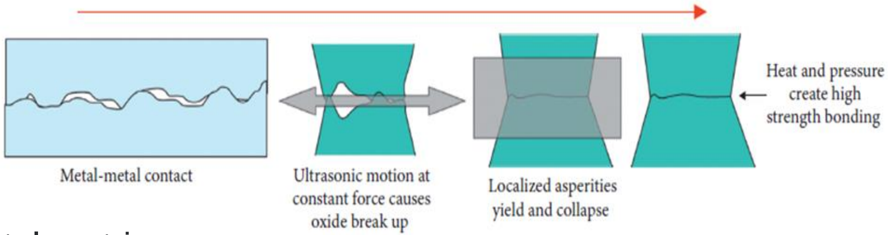
  - Embedding the fibers in metal also allows the entire sensor to be shielded from chemically harsh environments and increases the robustness of the overall sensor package.

- *Issues:*

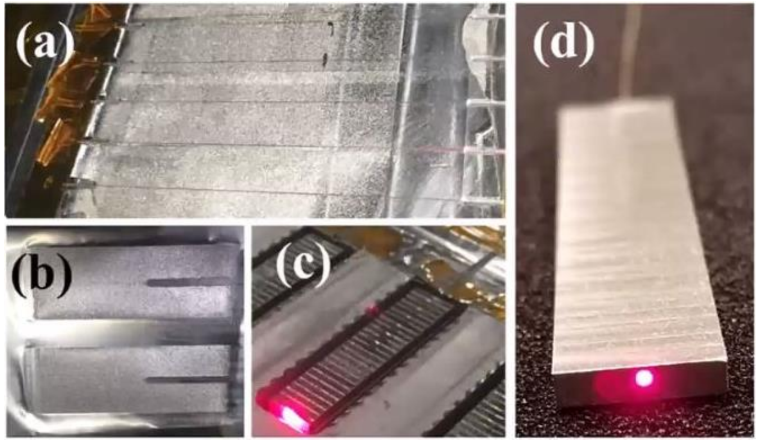
  - Conventional epoxies or adhesives cannot survive high temperatures or high doses of ionizing radiation.
  - De-bonding becomes an issue at higher temperatures and doses.

- *Solution:*

  - **Low-temperature ultrasonic additive manufacturing (UAM)** process can perform to bond fiber embed fibers directly within the metal matrix that can withstand in excess of 500 °C. It allows fibers to be embedded in metals without melting and without the use of epoxy.



Steps in attaining high-strength bonds via ultrasonic consolidation [1].



Process for UAM embedding of fiber optics [2,3].

[1] D. R. White, “Ultrasonic consolidation of aluminum tooling, "*Advanced Materials Processing*, vol. 161, pp. 64-65, 2003.
[2] C.M. Petrie et al., "Embedded metallized optical fibers for high temperature applications." *Smart Materials and Structures* 28, no. 5 (2019).
[3] C.M. Petrie et al., "High-temperature strain monitoring of stainless steel using fiber optics embedded in ultrasonically consolidated nickel layers*." *Smart Materials and Structures* 28, no. 8 (2019).

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Optical fiber based temperature sensor packaging-Cont'd:

Many metals greatly degrade in mechanical strength at higher temperature.

American Society of Mechanical Engineers for nuclear applications qualified 304 and 316 stainless steel, Incoloy 800 H, 2¼Cr-1Mo steel, and 9Cr-1Mo-V steel that can withstand above 550 °C [1].

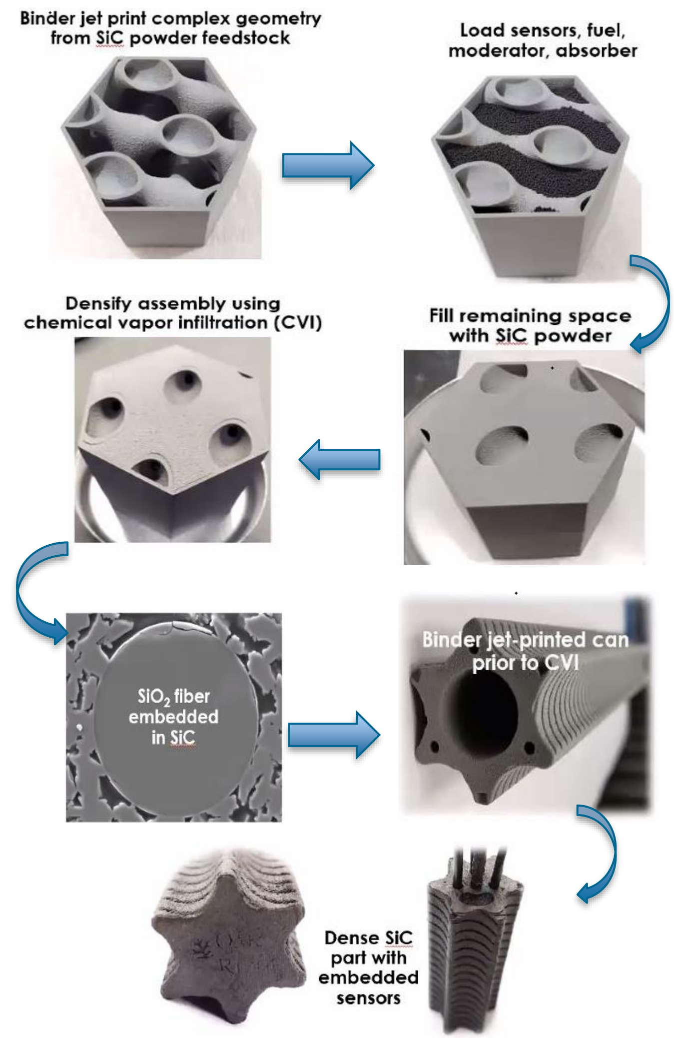
- For nuclear applications above 1000 °C refractory metals or ceramics can be used.
  - Ceramic materials such as silicon carbide (SiC): high-temperature strength retention approaching or exceeding 1000 °C, stability under neutron irradiation, and low neutron absorption.

Issue:

- Fabricating complex geometries using ceramic materials is challenging.

Solution:

- A binder jet printing process (3D printer) can be used to fabricate SiC components with complex geometries. The cavity in which the fiber sensor should be inserted can be printed using a 3D printer and then fix the fibers' location using chemical vapor infiltration process [2].



Process for binder jet printing for embedding of fiber optics [3].

[1] Section III Rules for Construction of Nuclear Facility Components: Division 5 High Temperature Reactors, 2019 ASME Boiler and Pressure Vessel Code, *The American Society of Mechanical Engineers*, New York, NY (2019).
[2] Terrani, Kurt, Brian Jolly, and Michael Trammell. "3D printing of high-purity silicon carbide." *Journal of the American Ceramic Society* 103, no. 3 (2020).
[3] C.M. Petrie et al., "Embedded sensors in additively manufactured silicon carbide." *Journal of Nuclear Materials* 552 (2021).

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Optical fiber based temperature sensor packaging-Cont'd:

Solutions-cont'd:

- Another solution to package optical fibers is using a printer to embed the fibers in ceramic components.

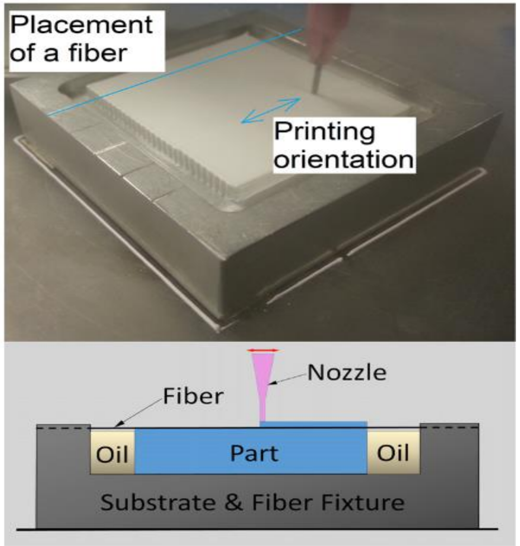
- An aqueous paste of ceramic particles is extruded through a moving nozzle to build the part layer-by-layer.

- Ceramic paste is extruded at controlled flow rates through a circular nozzle. The nozzle is attached to a motion system, which is capable of moving in X, Y and Z directions.

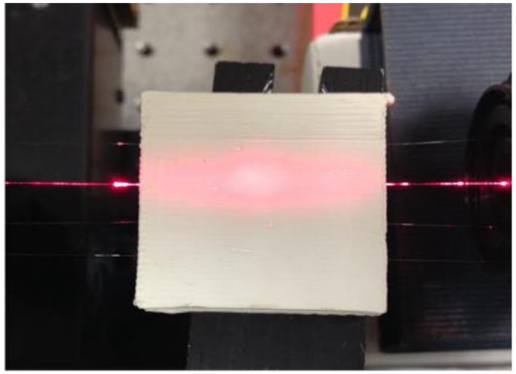
- In the case of sensor embedment, the fabrication process is halted after a certain number of layers have been deposited.

- The sensors are placed in their predetermined locations, and the remaining layers are deposited until the part fabrication is completed.

- Because the sensors are embedded during the fabrication process, they are fully integrated with the part and the problems of traditional sensor embedment can be eliminated.



An alumina block with embedded sensors during the fabrication process [1].



A signal in the visible spectrum passing through an embedded fiber (for demonstrative purpose) [1].

[1] A. Ghazanfari et al., "Advanced ceramic components with embedded sapphire optical fiber sensors for high temperature applications." *Materials & Design* 112 (2016): 197-206.

INTEGRATED SILICON/CHALCOGENIDE GLASS HYBRID PLASMONIC SENSOR FOR MONITORING OF TEMPERATURE IN NUCLEAR FACILITIES

Submitted publication this monthly period: B. Badamchi, A.A.A. Simon, M. Mitkova, H. Subbaraman "Ultra-Compact Silicon: Chalcogenide Optical Waveguide based High-Temperature Sensor" sent for publication in Journal *Optic Letters*

Project overview – all tasks have been fulfilled:

✓ Developed a ChG material suite with different Tcr and established the crystallization mechanism for each of the synthesized materia: One publication in *J. of Materials Science: Materials for Electronics*; One publication in preparation.

✓ Developed inks based on chalcogenide glasses – 2 patents applications and 2 Publications in *Microsocopy and Anlysis, presentation at IMA conference 2019*

✓ Characterised gold coated rad hard fibers fabricated by local fiber manufacturer – one Publication sent to *Optics Letters*

✓ Designed sensor architecture and simulate its performance – one publication in *Sensors, presentation at the ICANS conference 2019*

✓ Produced silicon-chalcogenide hybrid integrated plasmonic waveguide temperature sensor – details presented in 2 talks at the *NPIC&HNIT 2018*

✓ Produced chalcogenide coated rad hard fiber tip based temperature sensor - one publication in *Scientific Reports, presentation at the TMS conference 2020*

✓ Conducted experiments in nuclear facilities with neutrons and Xe ions irradiation for studies materials' and devices' radiation hardness–one publication in *Phys. stat. solidi*

INTEGRATED SILICON/CHALCOGENIDE GLASS HYBRID PLASMONIC SENSOR FOR MONITORING OF TEMPERATURE IN NUCLEAR FACILITIES

2017 NEET-ASI Award
Award number 17-12633
PI Maria Mitkova, Boise State University

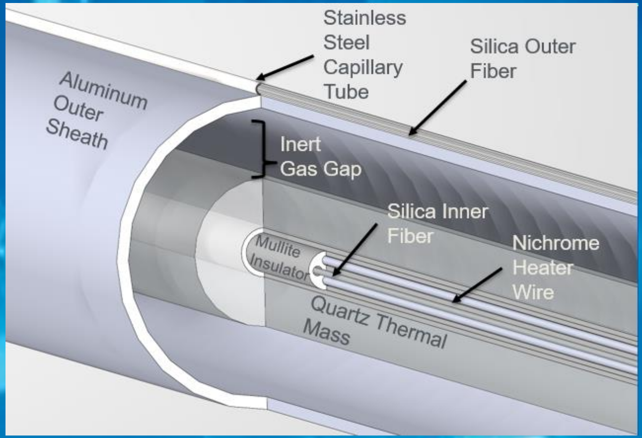
Objectives:

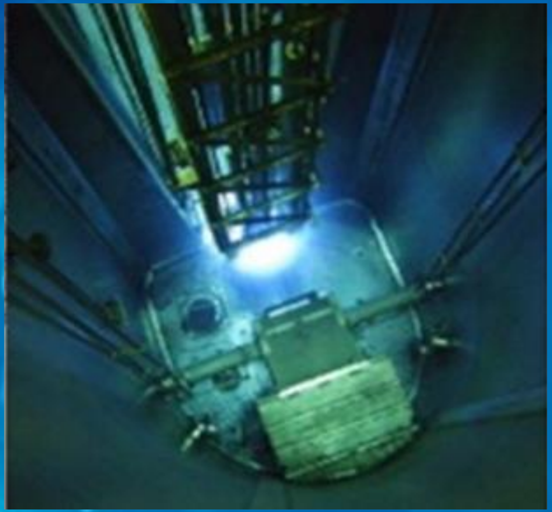
- ✓ Development of devices for real time temperature data collection
- ✓ Fabrication of very small sensors comfortable for integration in different structures of nuclear facility
- ✓ Very low power consuming device
- ✓ Reversible and multiple time application
- ✓ Additive technology for low cost thin films formation and better integration of the sensor
- ✓ Opportunity for a direct deposition of the device over the surface for measuring temperature

Outcomes:

1. Application of a new effect (Phase change amorphous/crystalline material) for temperature monitoring.
2. Application of additive technology for device formation and their integration in nuclear structure
3. Temperature sensing through plasmon formation and phase change characteristics of ChGs.
4. Educational benefits and familiarity with the nuclear facility important problems and solutions for two PhD and one master students and two undergraduate students.

Development of an Optical Fiber Based Gamma Thermometer





Project Number: 18-15086

Work Package ID: CA-18-OH-OSU_-0702-01

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Principle Investigator: Thomas Blue, PhD

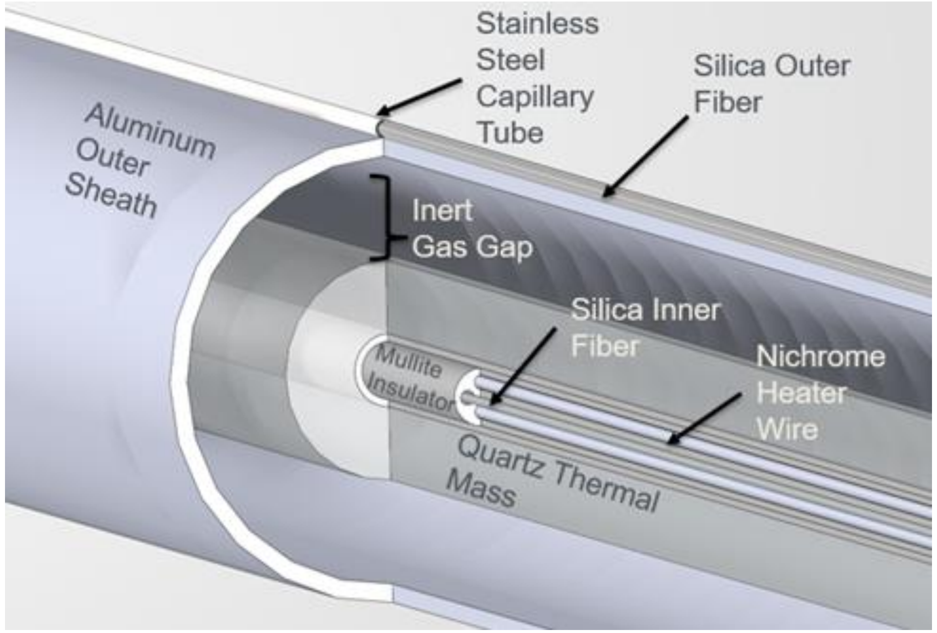
The Ohio State University
Texas A&M University
Idaho National Laboratory

Project Overview

- Objective: Develop an optical fiber-based gamma thermometer (OFBGT) in order to determine the power distribution in a reactor core by using statistical data analytic methods
  - An OFBGT measures the ΔT along the axial length of the sensor which can be used to infer core power distribution using response functions generated by MCNP (ΔT is measured by optical fiber)
  - We are demonstrating this measurement technique in both the Ohio State University Research Reactor (OSURR) and the Texas A&M (TAMU) TRIGA Reactor

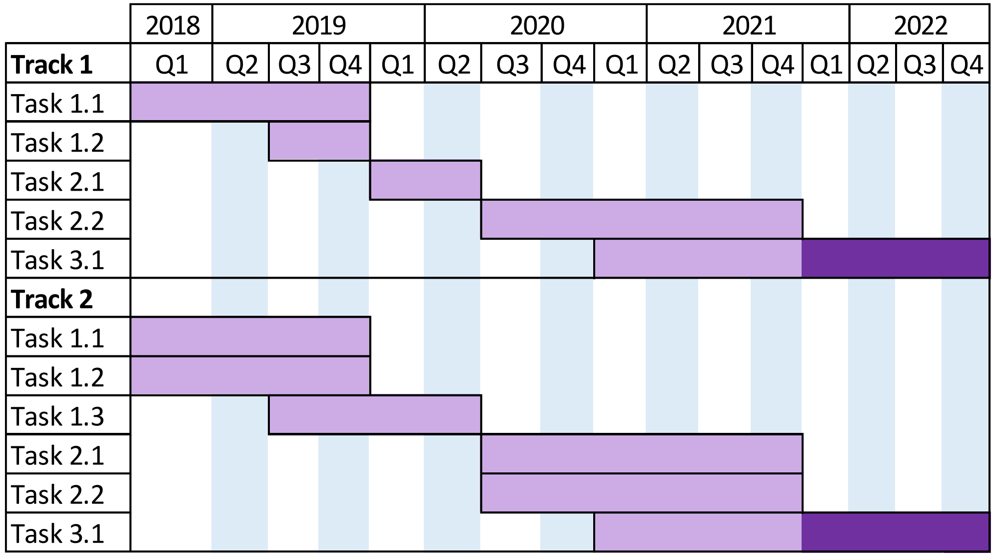
Participants:

The Ohio State University	Texas A&M University	Idaho National Laboratory
Thomas Blue (PI)	Pavel Tsvetkov (co-PI)	Diego Mandelli (co-PI)
Tunc Aldemir (co-PI)	Tyler Gates (Grad. Student)	
Anthony Birri (Graduated, PhD)	Noah Morton (Undergrad. Student)	
Joshua Jones (Grad. Student)		



Schedule and Status

- Track 1: Build OFBGTs and test them in a University Research Reactor
  - Year 1
    - Task 1.1: Design OFBGTs ✓
    - Task 1.2: Design and build irradiation test rigs ✓
  - Year 2-3*
    - Task 2.1: Construct OFBGTs ✓
    - Task 2.2: Test OFBGTs with silica fiber in OSURR and TAMURR ✓
  - Year 3-4*
    - Task 3.1: **Repeat Tasks 1.1 and 2.1 for a high temperature OFBGT and test in high temperature conditions (In progress)



- Track 2: Modeling and Data Analytics
  - Year 1
    - Task 1.1: Create modeled(MCNP and ANSYS) OFBGT data for irradiation facilities ✓
    - Task 1.2: Develop methods and algorithms to process OFBGT data using modeled data ✓
    - Task 1.3: Apply data analysis methods to MCNP OFBGT data to predict power distributions ✓
  - Year 2-3*
    - Task 2.1: Apply data analysis methods to test data for OFBGT with silica fiber ✓
    - Task 2.2: Refine the models and data analysis methods ✓
  - Year 3-4*
    - Task 3.1: **Repeat Tasks 2.1 and 2.2 for data for a high temperature OFBGT (In progress)

Notes * - Project delayed due to COVID-19 restrictions
** - Project direction change due to sapphire fiber research progress

Technology Impact

- The OFBGT allows one to obtain significantly more data points than previously implemented thermocouple GTs
  - This also enables the capability of power inferencing
  - As a more basic application, OFBGTs can be used to calibrate LPRMs in BWRs, instead of TIPs
- This work supports the DOE mission by addressing the demand for sensors for “big data” acquisition
- An array of OFBGTs in a commercial reactor would enable high fidelity 3D power monitoring
- The sensor could be commercialized by utilization of reactor qualified materials, laser welding, and drift correction techniques

LPRMs

TIP

OFBGT

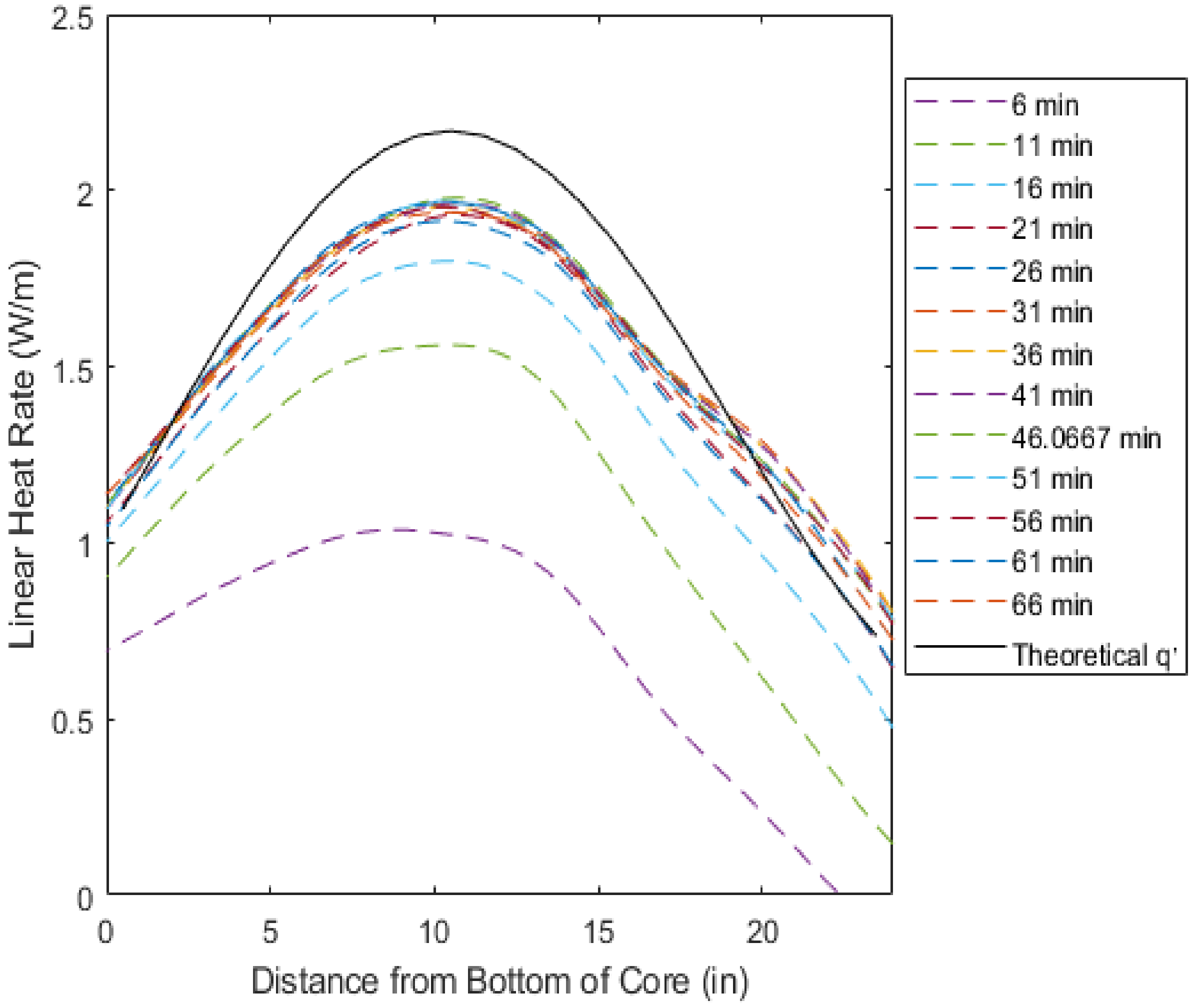
Results and accomplishments

- Track 1
  - A low temperature silica fiber based OFBGT was designed and tested in both the OSURR and TAMU TRIGA
  - Preliminary results were used to improve the design, and the device was re-tested
  - The (re)design phase for the high temperature OFBGT has begun and is in progress with FLUENT analysis
- Track 2
  - Algorithms for processing the OFBGT and MCNP data have been created
  - MCNP has been utilized to evaluate the low temperature OFBGT in both the OSURR and TAMU TRIGA
  - Test data from the OSURR and TAMU TRIGA has been analyzed with the developed algorithms
  - Modifications to the algorithms, to address nuances in the test data and expected conditions for long term operation in a higher power or higher temperature reactor, are being considered
- Miscellaneous accomplishments
  - Internally clad single crystal sapphire has been developed in collaboration with multiple external organizations
  - We have performed very high temperature testing with standard SMF-28 silica fiber using novel adaptive reference techniques being pioneered by ORNL

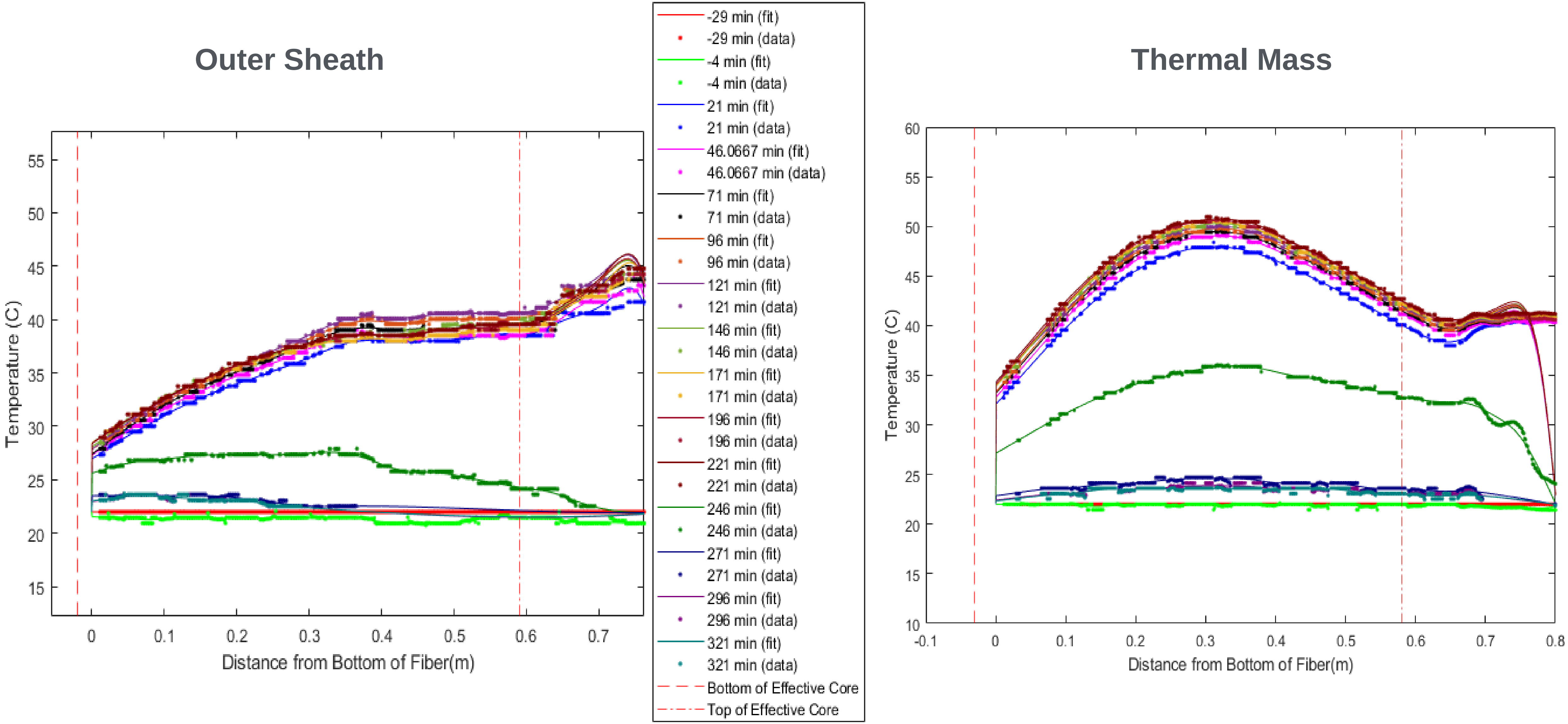
Results and accomplishments – OSURR Measurements

- OSURR measurements made in Dec. 2020 and Apr. 2021
  - Power level held at a constant 450 kW
  - Sensor installed in the Water Irradiation Facility (total neutron flux ~1e13 n/cm^2/s)
- Detrimental spacer effects appropriately addressed by modifications between tests
- Thermal mass temperatures reflect power profile of reactor
- Outer sheath temperatures reflect coolant temperature

Calibrated OFBGT Result

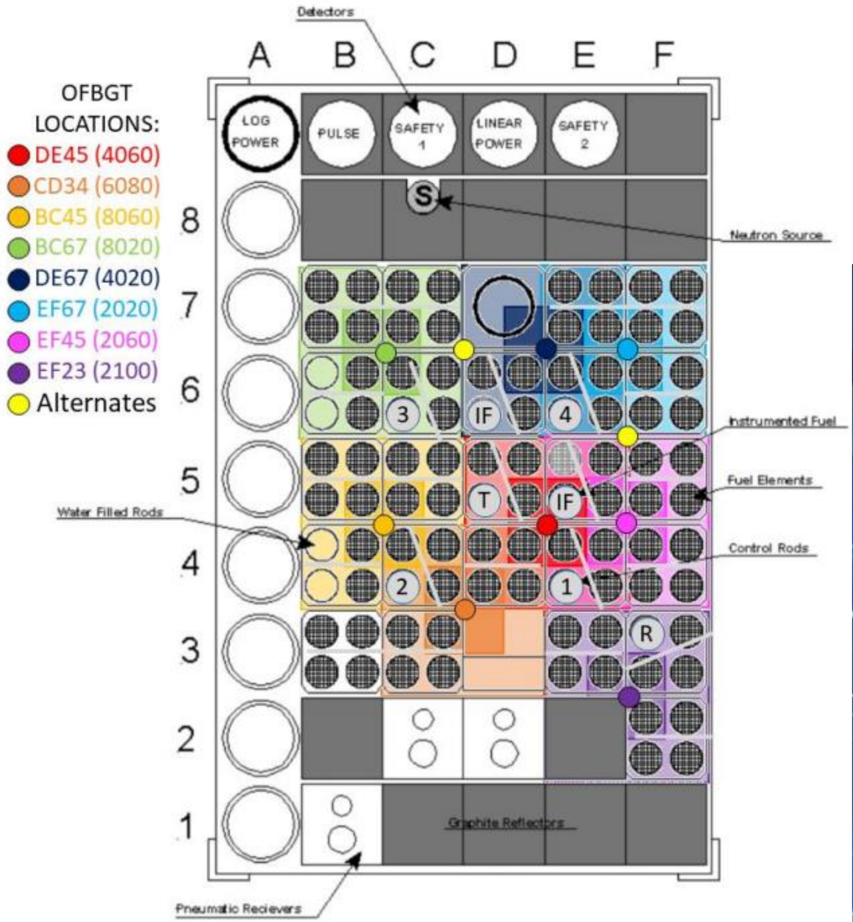


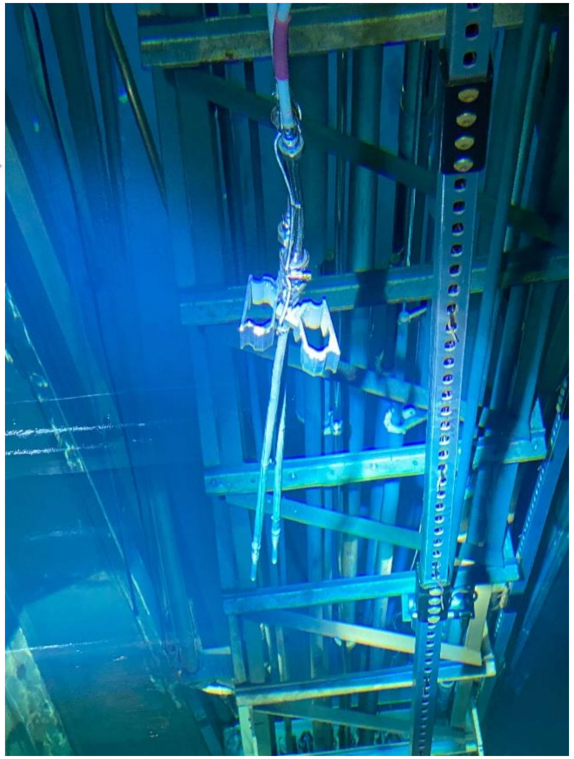
Results and accomplishments – OSURR Measurements



Results and accomplishments – TAMU TRIGA Measurements

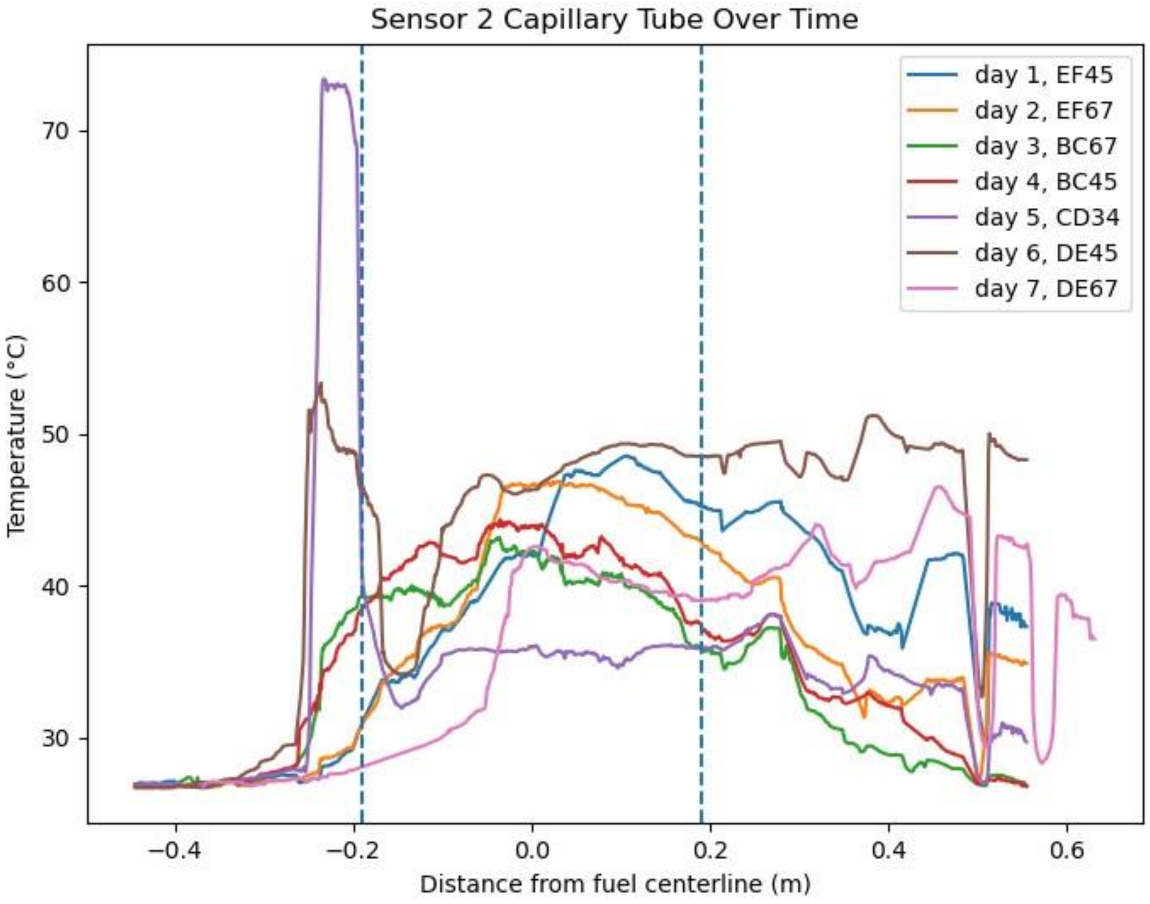
- 3rd Experiment TAMU TRIGA measurements made 8/16/2021 through 8/27/2021
  - Sensors repaired after failure during previous experiment
  - Power level held at 400 kW, then reactor operations were returned to normal
  - Data collected at 8 locations (tested individually on different days) with one stationary sensor as a benchmark
- TAMU data highlights practical concerns when using OFBGT
  - Vibration and sample rate
  - Changing flux and boundary conditions due to reactor operations
  - Sensor durability

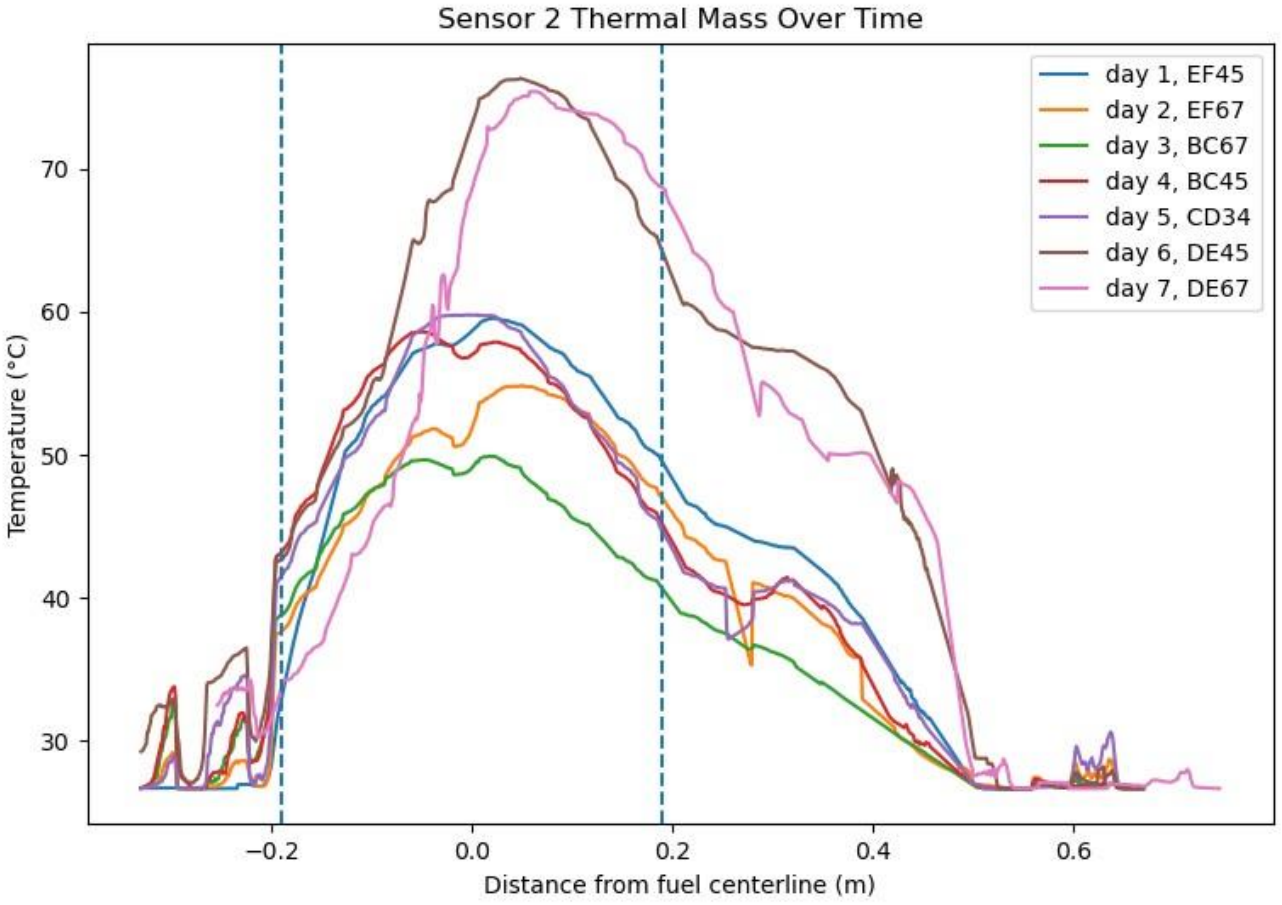




OFBGT-TAMU sensors before insertion in the NSCR Core.
The pool water thermocouple array can be seen to the right.

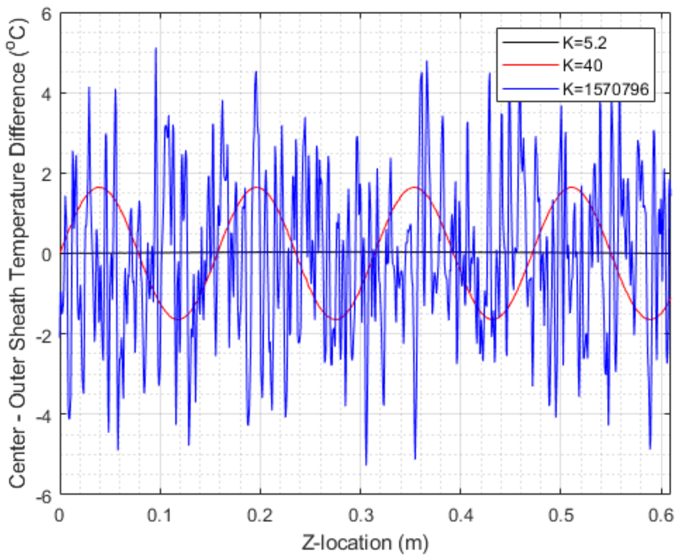
Results and accomplishments – TAMU TRIGA Measurements



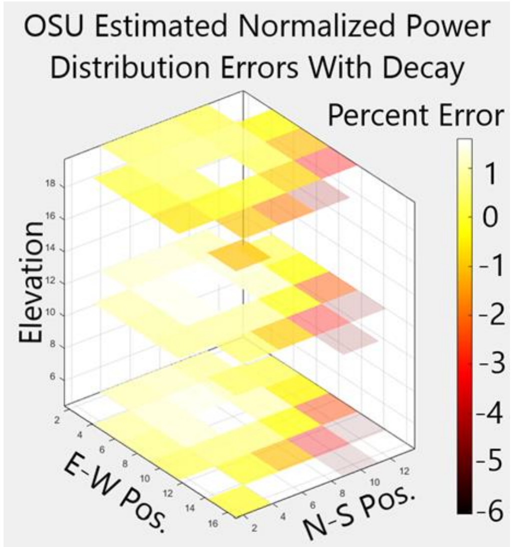


Results and accomplishments – Data Analytics Modifications

- Non-Uniform Temperature Boundary Condition
  - Boundary condition temperature variations do not translate fully into the thermal mass of a real device when axial spreading of energy is present
  - This failure to fully resolve boundary temperatures in the thermal mass causes errors in the OFBGT measurement



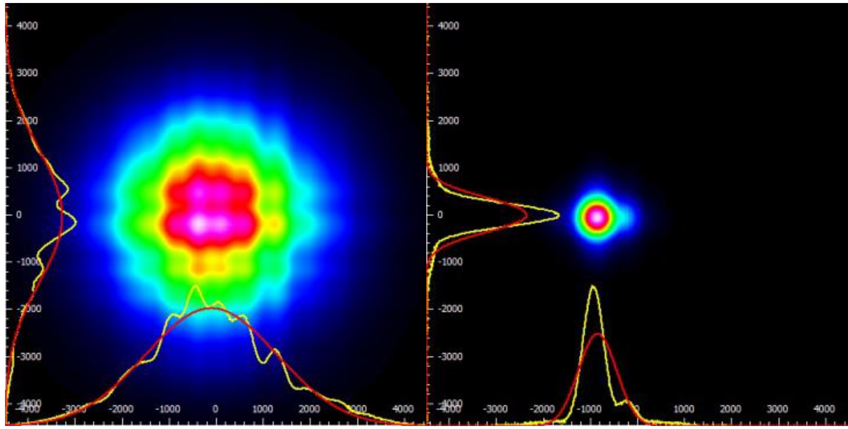
- Decay Product Effects
  - Gamma energy from daughter particle decay can contribute up to ~half of the OFBGT response if the reactor is operated for a sufficiently long time
  - Failure to account for the decay products results in errors in the normalized measurements taken by an array of OFBGT sensors
  - Solution is to use response functions that are consistent with the reactor operating history leading up to the measurement being taken

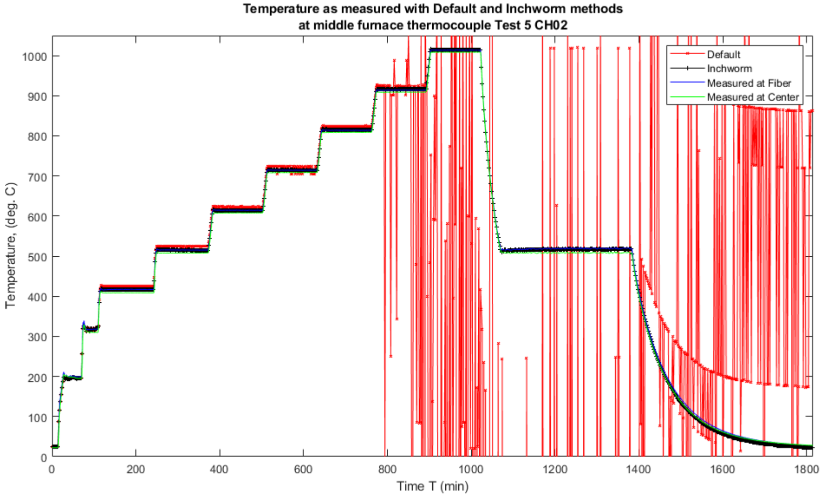


Results and accomplishments – Miscellaneous

- Sapphire Fiber Development
  - Work partnered with LUNA Innovations Inc. has led to improved, repeatable performance of internally clad single crystal sapphire fiber
  - Work partnered with INL demonstrated OFDR sensing in internally clad single crystal sapphire fiber up to 1600 ℃ with low neutron fluences
  - Work partnered with ORNL identified fundamental issues with sapphire irradiated at moderate temperatures with very high neutron fluences
  - Collectively, these results have led to the conclusion that, while internally clad single crystal sapphire fiber may fill an important role in extreme temperature distributed sensing, it is not appropriate for use in an OFBGT
- High Temperature Silica Measurements
  - Work partnered with ORNL has utilized adaptive reference techniques to measure temperatures using standard SMF-28 silica fiber operating up to 1000 ℃, when standard reference techniques fail at 700 ℃
  - Work partnered with ORNL identified that silica is an appropriate sensor material when exposed to very high neutron fluences
  - Silica fiber analyzed with adaptive reference techniques will be used in the high temperature OFBGT redesign

Original Clad Sapphire Fiber | **Improved Clad Sapphire Fiber**





Results and accomplishments – Products

- Publications (Published):
  - A. Birri, "The Development of an Optical Fiber Based Gamma Thermometer," Ph.D. Thesis, The Ohio State University, 2021
  - A. Birri, C. M. Petrie and T. E. Blue, "Analytic Thermal Model of an Optical Fiber Based Gamma Thermometer and its Application in a University Research Reactor," in IEEE Sensors Journal, vol. 20, no. 13, pp. 7060-7068, 2020
  - A. Birri, T.E. Blue, "Methodology for Inferring Reactor Core Power Distribution from an Optical Fiber Based Gamma Thermometer Array," Progress in Nuclear Energy, vol. 130, 103552, pp. 1-9, 2020
  - A. Birri, T.E. Blue, "The Development of an Optical Fiber Based Gamma Thermometer," Transactions of the American Nuclear Society, 121, 2019, pp. 662-665
  - A. Birri, T. Gates, J. Jones, P. Tsvetkov, T. E. Blue, "Data Analytic Methodology for an Optical Fiber Based Gamma Thermometer Array," Transactions of the American Nuclear Society, vol. 123, no. 1, pp. 549-552, 2020.
  - A. Birri, C. M. Petrie and T. E. Blue, "Parametric Analysis of an Optical Fiber–Based Gamma Thermometer for University Research Reactors Using an Analytic Thermal Model," Nucl. Technol., Published online: 03 Apr 2021.
  - A. Birri, C. M. Petrie, K. McCary, T. E. Blue, "Comparison of Calculated and Measured Performance of an Optical Fiber Based Gamma Thermometer," Transactions of the American Nuclear Society 124(1):263-266, 2021.
- Publications (In Review):
  - J. T. Jones, A. Birri, T. E. Blue, D. Kominsky, K. McCary, O. J. Ohanian, S. D. Rountree, "Light Propagation Considerations for Internally Clad Sapphire Optical Fiber Using the 6Li(n,a)3H Reaction," IEEE Journal of Lightwave Technology (Responded to Peer Review Comments 9/27/2021)
  - J. T. Jones, D. C. Sweeney, A. Birri, C. M. Petrie, T. E. Blue, "Calibration of Distributed Temperature Sensors Using Commercially Available SMF-28 Optical Fiber from 22 deg. C to 1000 deg. C," IEEE Journal of Lightwave Technology (Submitted for Peer Review 10/4/2021)
- Provisional Patent In Review

Conclusion – Project Summary

Overall project goal: The goal of this project was to design, build and test a distributed OFBGT using fiber optic sensing.

Accomplishments: The design, build and test process has been completed for a low temperature OFBGT. Appropriate data analysis methods have been devised to gather information from our sensor. Appropriate first steps have been taken for the redesign of the sensor for higher temperature and power conditions.

Products: 9 publications have been either published or submitted throughout the course of this project. 1 patent is in process for the technology.

Conclusion – Future Work

Future project work: As our project continues into 2022, we will continue to progress the high temperature redesign of the sensor through the design, build and test phases of development. The data analytics methods will continue to be modified as our knowledge of the sensor operation evolves.

Future non-project work: Our efforts in the development of internally clad single crystal sapphire fiber have reached a technically justified end for this project, but have made that technology more accessible for additional research. The OFBGT has inspired new sensor ideas based on the same operating principle, which will be investigated over the coming years.

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Questions?

ASI

Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

Advanced Sensors and Instrumentation (ASI) Program Research Overview

November 15 – 18, 2021

Pattrick Calderoni – National Technical Director

Measurement Science Department

Idaho National Laboratory

ASI FY21 Annual review meeting

ASI Advanced Sensors and Instrumentation

Webinar Agenda
Advanced Sensors and Instrumentation (ASI)
FY21 Annual Review meeting
(All Times are Eastern Standard Time)

Monday, November 15, 2021

10:00 am	Welcome and opening remarks (Suibel Shuppner, DOE)
10:10 am	ASI Program Overview (Dan Nichols, DOE)
10:40 am	ASI Research Activities Overview (Pattrick Calderoni, INL)
11:00 am	Nuclear Energy Sensor database

Session 1: Sensors for advanced reactors

11:30 am	Development of innovative sensors for advanced reactor concepts (Troy Unruh, INL)
12:00 pm	High temperature embedded/integrated sensors (HiTEIS) for remote monitoring of reactor and fuel cycle systems (Xiaoning Jiang, North Carolina State University)
12:30 pm	Development of Optical Fiber Based Gamma Thermometer and its Demonstration in a University Research Reactor Using Statistical Data Analytic Methods to Infer Power Distribution from Gamma Thermometer Response (Thomas Blue, Ohio State University)
1:00 pm	*Break*
1:15 pm	Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control (Michael Larche, PNNL)
1:45 pm	Development of Microwave Resonant Cavity Transducer for Flow Sensing in Advanced Reactor High Temperature Fluids (PI – Alexander Heifetz, Argonne)
2:15 pm	Demonstration and benchmarking of SPNDs for advanced reactor application (Kevin Tsai, INL)
2:45 pm	*Break*
3:00 pm	Optical fiber sensors (Austin Fleming, INL)
3:30 pm	Acoustic sensors (Josh Daw, INL)
4:00 pm	Nuclear Thermocouples (Richard Skifton, INL)
4:30 pm	Moderated discussion on Session 1 (Moderator: Troy Unruh, INL)
5:00 pm	*Adjourn*

r Agenda
l Instrumentation (ASI)
Review meeting
ern Standard Time)

INL)
trol (Kiyo Fujimoto, INL and
oshi, ORNL)
ques, Dan Deng, Dave Estrada,
g, Brian Jaques, BSU)
rials of Nuclear Components
Marat Kafizov, OSU)
in-pile power harvesting
Jovanovic, U of Michigan)
Optical Fiber Distributed
ry Loop Piping and
Sensor Devices, Packaging,
Nuclear Reactor Applications
inch Sensor Technologies and
asurements (Chad Kiger,

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Temperatures of SiC Passive
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Hua, INL)
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Reed, ORNL)
ated Electromagnetic
Measurement Services Corp.)
Inc.)
alibration (Tom Gruenwald,

ASI established as national program

Participating:

Idaho National Lab

Oak Ridge National Lab

Argonne National Lab

Pacific Northwest National Lab

Engaging in capabilities assessment:

Sandia National Lab

Livermore National Lab

Brookhaven National Lab

ASI Advanced Sensors and Instrumentation

Participating academic intitutations (lead only):

Arizona State University
Boise State University
Massachusetts Institute of Technology
North Carolina State University
The Ohio State University
University of Michigan
University of Notre Dame
University of Pittsburgh
Vanderbilt University
Virginia Tech

ASI established as national program

Participating:

Idaho National Lab

Oak Ridge National Lab

Argonne National Lab

Pacific Northwest National Lab

International Collaborations:

IFE Halden

DOE/CEA

SCK-CEN

KAERIOECD/NEA

IAEA

ASI Advanced Sensors and Instrumentation

Participating industry:

Alphacore
Analysis & Measurement Services
Blue Wave AI Labs
Dirac Solutions
Goldfinch Sensor Technologies and Analytics
GSE Systems
Hydromine
Intelligent Optical Systems
Operant Networks
Sporian Microsystems
Terrestrial Energy USA
ThorCon
Vega Wave Systems
X-wave Innovations

ASI stakeholders aligned with program enabling mission

Nuclear industry engaged through multiple avenues (GAIN, gap analysis, NSUF, ARDP):

BWX Technologies
Exelon
Flibe Energy
Framatome
Kairos Power
Oklo
NuScale
Radiant Nuclear
Southern Company
Terrapower
Terrestrial Energy
Westinghouse

ASI Advanced Sensors and Instrumentation

NE integrated planning:
AMMT, NEAMS, NSUF, LWRS, Cyber, SFR, HTGR, MSR, microR, NRIC, ARD, AFC

DOE agencies:
ARPA-E
NETL
Advanced Manufacturing Office
Artificial Intelligence & Technology Office

Government Agencies / other:
NRC
NNSA
EPRI
NIST

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

ASI technologies lifecycle to fulfill program vision

Basic research
- Design

Technology development
- Fabrication

Demonstration
- Test

Commercialization
- Tech transfer

Test reactor irradiation experiments and advanced reactors demonstration facilities

Transient Reactor Test Facility (TREAT)

MIT Reactor (MITR)

High Flux Isotope Reactor (HFIR)

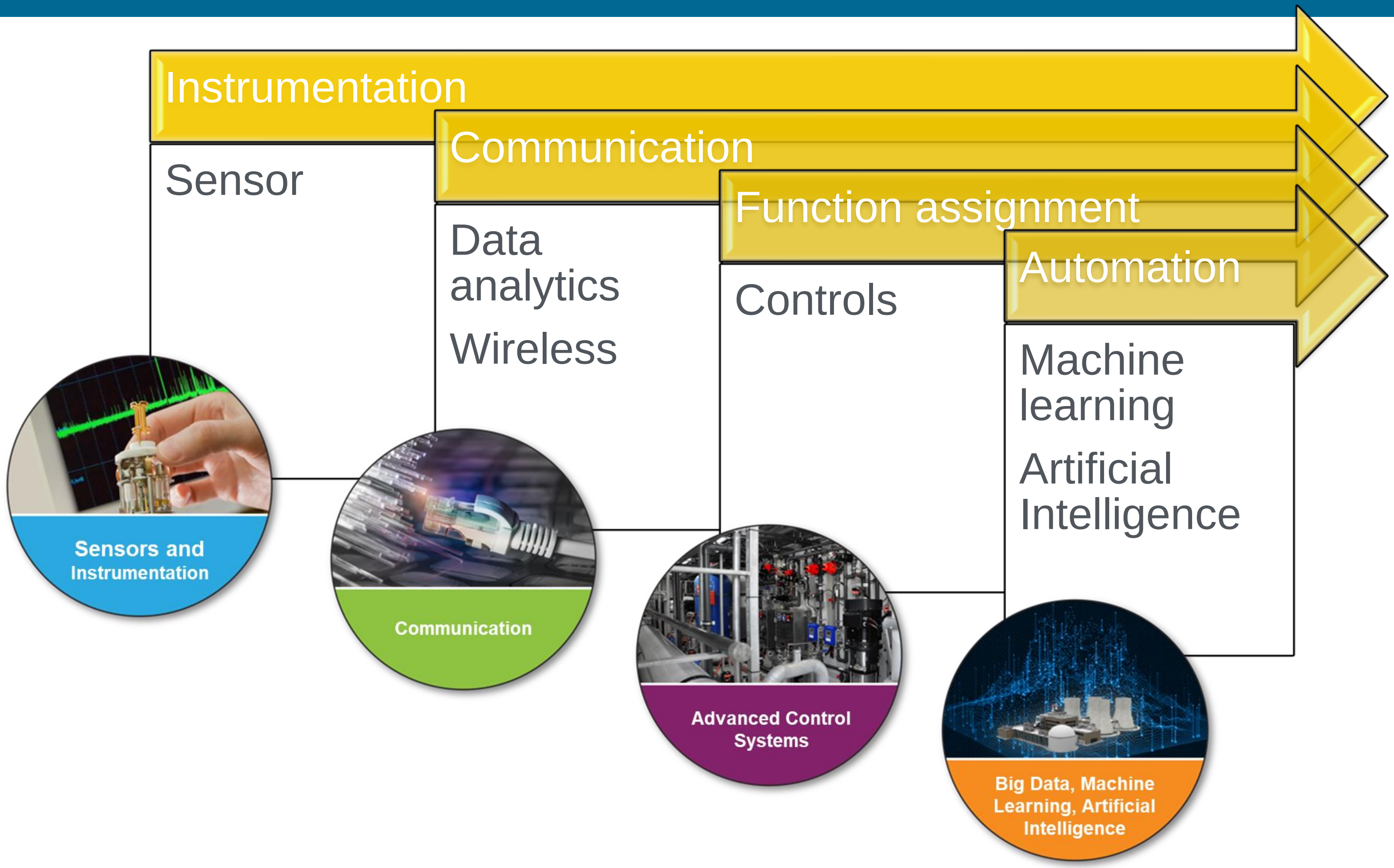
Advanced Test Reactor (ATR)

NRIC National Reactor Innovation Center

Why do we need a sensor development program as part of NE research portfolio?

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

Technology integration in plant I&C



Commercial Microreactors

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

Sensors for advanced reactors

5 year objectives

Develop advanced sensors (multi-mode; multi-point/distributed; miniature size and limited or no penetrations) and supporting technology (rad-hard electronics, wireless communication, power harvesting) for nuclear instrumentation	
Integrate advanced manufacturing technology in sensor fabrication process for performance improvement and cost reduction	
Develop modeling and simulation tools for sensors predictive performance	
Establish a supply chain for advanced reactor instrumentation (fabrication and services)	

BWX Technologies
Exelon
Flibe Energy
Framatome
Kairos Power
Oklo
NuScale
Radiant Nuclear
Southern Company
Terrapower
Terrestrial Energy
Westinghouse

Session 1: sensors for advanced reactors

ASI Nuclear Energy Sensor **(NES) database**

Development of optical fiber-based **gamma thermometer** (Thomas Blue, OSU)

High temperature embedded/**integrated sensors** (HiTEIS) for remote monitoring of reactor and fuel cycle systems (Xiaoning Jiang, NC State)

Acousto-optic Smart **Multimodal Sensors** for Advanced Reactor Monitoring and Control (Michael Larche, PNNL)

Development of Sensor Performance Model of **Microwave Cavity Flow Meter** for Advanced Reactor High Temperature Fluids (Alexander Heifetz, ANL)

FY22 activities

Neutron flux sensors	Temperature compensation for SPNDs
	Reactor power control - Assessment of options for advanced reactors power control, demonstration of fission chambers, gamma thermometer for core power mapping
Optical fiber sensors	Intrinsic temperature sensor
	Active compensation - modeling, data analysis
	Optical fiber imaging
	Fabry-Perot pressure sensor
Acoustic sensors	Ultrasound thermometers custom electronics / Data Acquisition development
	Ultrasound thermometer fabrication optimization
	Assessment of acoustic interrogation techniques for reactors operation and components health monitoring
Thermocouples	Intrinsic junction thermocouples for surface temperature measurement
	Performance assessment of commercial TCs for nuclear applications

Session 2: advanced materials and manufacturing methods for sensors applications

FY22 activities

Printed Sensors Technology for Harsh Environments	Bi-metallic melt wires for improved peak temperature resolution measurement Sensor robustness & quality control to ensure reliable operation in test reactors
High temperature materials and sensors predictive modeling	Development of high temperature materials for nuclear sensors and instrumentation Development of predictive models for sensors performance

NSUF irradiation projects

Irradiation Behavior of Piezoelectric Materials for Nuclear Reactor Sensors (Marat Kafizov, OSU)

High-performance nanostructured thermoelectric materials and generators for in-pile power harvesting (Yangliang Zhang, University of Notre Dame)

Irradiation of optical components of in-situ laser spectroscopic sensors (Igor Jovanovic, U of Michigan)

High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors (Kelly McCary, INL)

Irradiation of Sensors and Adhesive Couplants for Application in LWR Primary Loop Piping and Components (James Wall, EPRI)

Fiber Sensor Technology for Nuclear Power Applications: Radiation-harden Sensor Devices, Packaging, Sensor Data Fusion, and Instrumentation (Kevin Chen, U Pitt)

SBIRs

High Temperature Operable, Harsh Environment Tolerant Flow Sensors For Nuclear Reactor Applications (Jon Lubbers, Sporian Microsystems, Inc.)

Metamaterial Void Sensor for Fast Transient Testing (Mark Roberson, Goldfinch Sensor Technologies and Analytics LLC)

Health Monitoring of Digital I&C Systems using Online Electromagnetic Measurements (Chad Kiger, Analysis & Measurement Services Corp.)

Instrumentation for irradiation experiments

5 year objectives

Provide real time instrumentation and passive monitors to measure local operational parameters (neutron flux, temperature, pressure, mechanical solicitations) in TREAT, ATR, HFIR and MITR experiments

Develop methods to characterize nuclear fuel and material properties (thermal conductivity, microstructure, mechanical behavior) during irradiation

DOE NE programs:

AMMT

NEAMS

AFC

ARD

Session 3: instrumentation for irradiation experiments

Introduction of the **Center for Reactor Instrumentation and Sensor Physics** (CRISP)

SBIRs

Development of Radiation Endurance Ultrasonic Transducer for Nuclear Reactors (Uday Singh, X-wave Innovations, Inc.)

Advanced Laser Ultrasonic Sensor for Fuel Rod Characterization (Marvin Klein, Intelligent Optical Systems, Inc.)

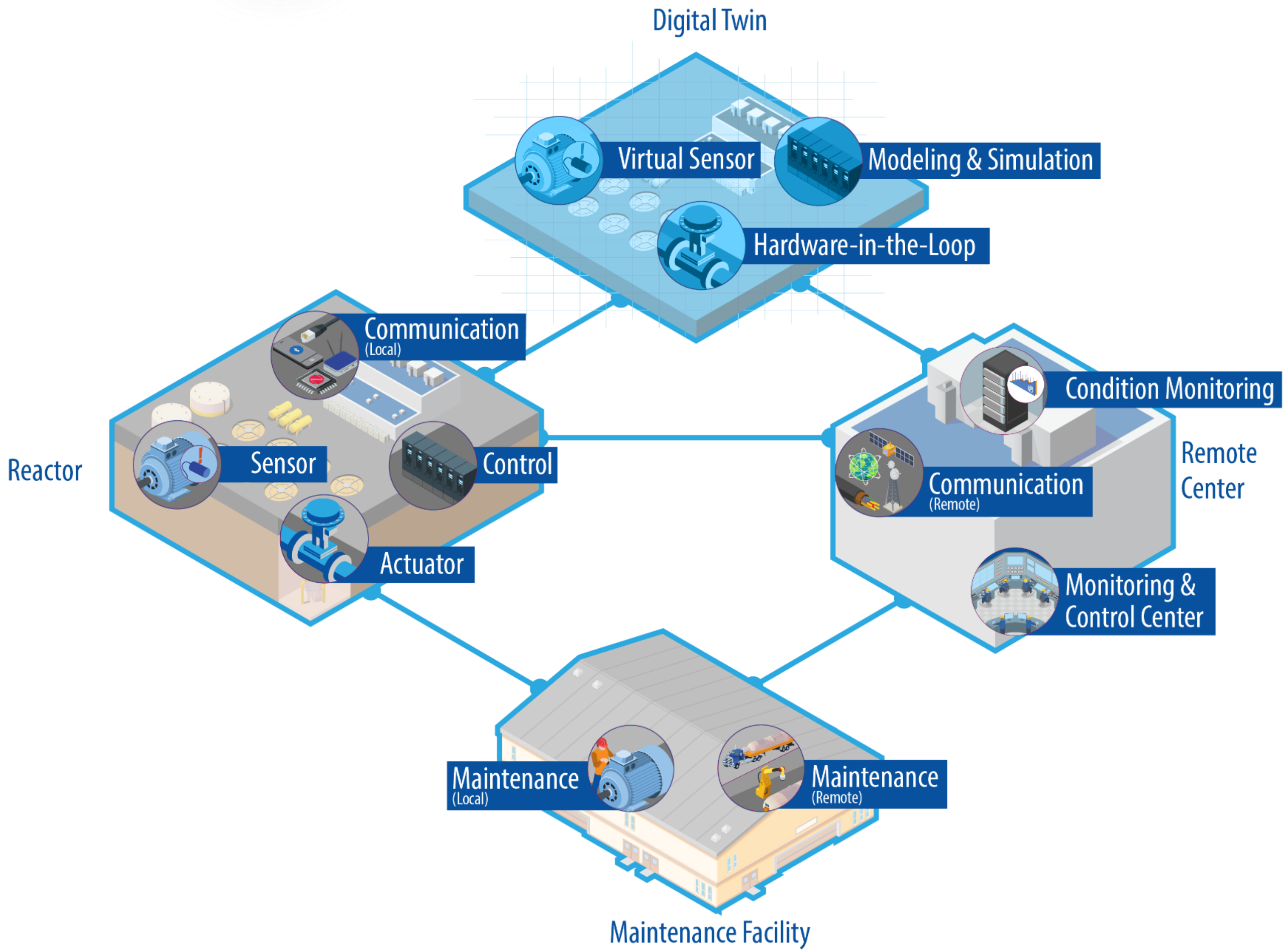
FY22 activities

Linear Variable Differential Transducers (LVDTs)	Design optimization, mod & sim development Supply Chain – test LVDTs purchased from US suppliers
Passive monitors	Develop options for printed melt wire arrays lines and encapsulation materials Silicon carbide monitors – complete demonstration of dilatometer measurements accuracy/sensitivity
Irradiation test	Heated test for neutron flux sensors calibration (NRAD, MITR) Retractable system for in-core instruments Gamma thermometer test in HFIR gamma facility Irradiated fuel instrumentation prototype
Mechanical properties characterization	Characterization of structural materials behavior in irradiation experiments Advanced manufactured strain gauges

Digital technology for advanced reactors

5 years objectives

- Develop Nuclear Digital Twins (NDT) with Hardware in the Loop simulation for **advanced controls demonstration**
- Develop technologies for anomaly detection, diagnostics, prognostics, and decision making that can **operate on streaming data**
- Develop modeling and simulation tools for **communication technologies** to support integration with predictive control systems
- Develop performance-based control algorithms to **enable autonomous operation**



Session 4: digital technologies for advanced reactors

The **approach to development** of digital technology for advanced reactors I&C (Craig Primer, INL)

Process Constrained Data Analytics for Sensor Assignment and Calibration (Rick Vilim, ANL)

Design of Risk-informed Autonomous Operation for Advanced Reactors (Michael Golay, MIT)

Analytics at scale of Sensor Data for Digital Monitoring in Nuclear Plants (Vivek Agarwal, INL)

Cost-Benefit Analysis through Integrated Online Monitoring and Diagnostics (Dave Grabaskas, ANL)

Develop Methods and Tools using NSUF Data to support Risk-Informed Predictive Analytics (Vivek Agarwal, INL)

Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance (Daniel Cole, University of Pittsburgh)

Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid (Roberto Ponciroli, Argonne)

Context-Aware Safety Information Display for Nuclear Field Workers (Pingbo Tang, George Gibson, ASU)

Rad-hard electronics for data communication and advanced controls – (Kyle Reed, ORNL)

SBIRs / iFOA

Fault Detection of Digital Instrumentation and Control Systems using Integrated Electromagnetic Compatibility and Automated Functional Testing (Greg Morton, Analysis & Measurement Services Corp.)

Video Camera for Harsh Environments in Nuclear (Esen Salcin, Alphacore Inc.)

Machine Learning Enhancement of BWR Neutron Flux Measurement and Calibration (Tom Gruenwald, Jonathan Nistor, Blue Wave AI Labs)

Thank You!

ASI

Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Acoustic Sensors

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

Principle Researcher: Joshua Daw, Ph.D.

Idaho National Laboratory, Measurement Sciences

Project Overview

Acoustic and ultrasonic transducers can be used as a base technology in numerous sensors measuring a multitude of parameters, such as temperature, gas pressure, vibration, etc. The ability of some ultrasonic sensors to make spatially distributed and multiplexed measurements, sometimes without direct access to the sample to be measured, is highly valuable.

- Idaho National Laboratory (Joshua Daw) direct research primarily focuses on Ultrasonic Thermometry
- Boise State University (Dan Deng) research focused on development of multi-physics models of acoustic sensors, including piezoelectric SAW sensors and the waveguide based ultrasonic thermometer
- Ohio State University (Marat Khafizov) performing an assessment of sensors for pressure and acceleration measurement

Milestones:

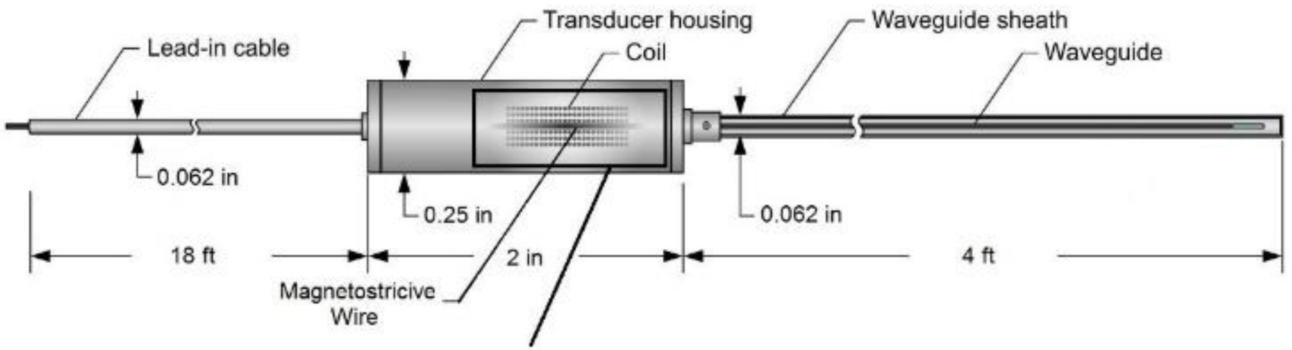
- M3CT-21IN07020110 - Perform characterization of advanced manufactured Surface Acoustic Wave sensor for temperature measurement in nuclear applications-Completed late: 04/22/2021
- M3CT-21IN0702017-Prototype new wave guides for Ultrasound Thermometers to minimize the effect of "sticking" wave guide to sheath-Completed on schedule: 8/26/2021
- M3CT-21IN0702018-Perform modeling activities for the development of damping system for wave guides of Ultrasound Thermometers-Delayed

Technology Impact

- Provide description of the technology application (i.e. where does it operate, who should be interested in this technology, and who are the stakeholders)
  - UT: In-core, multi-point temperature monitoring; Experiments in test reactors, core monitoring for high temperature advanced reactors
  - Acoustic Sensors: Too broad, depending on specific sensor they could be used anywhere
  - Stakeholders: Experimenters, Advanced Reactor Developers

- How does the technology support the nuclear energy industry?
  - UT: Accelerated development and acceptance of new fuels and materials through improved data density and testing in extreme conditions (ATF and High Temperature Concepts)
  - Acoustic Sensors (piezoelectrics, SAW): Enablement of online structural health monitoring of advanced reactors; wireless monitoring of temperatures, pressures, etc.; through vessel communications; etc.

Results and accomplishments-Background



UT Anti-sticking assessment

- FY-20 UT development work focused on establishing operational limits
- For sheathed UTs sticking was a primary failure mechanism

Below 1200 ℃: Type-C TC

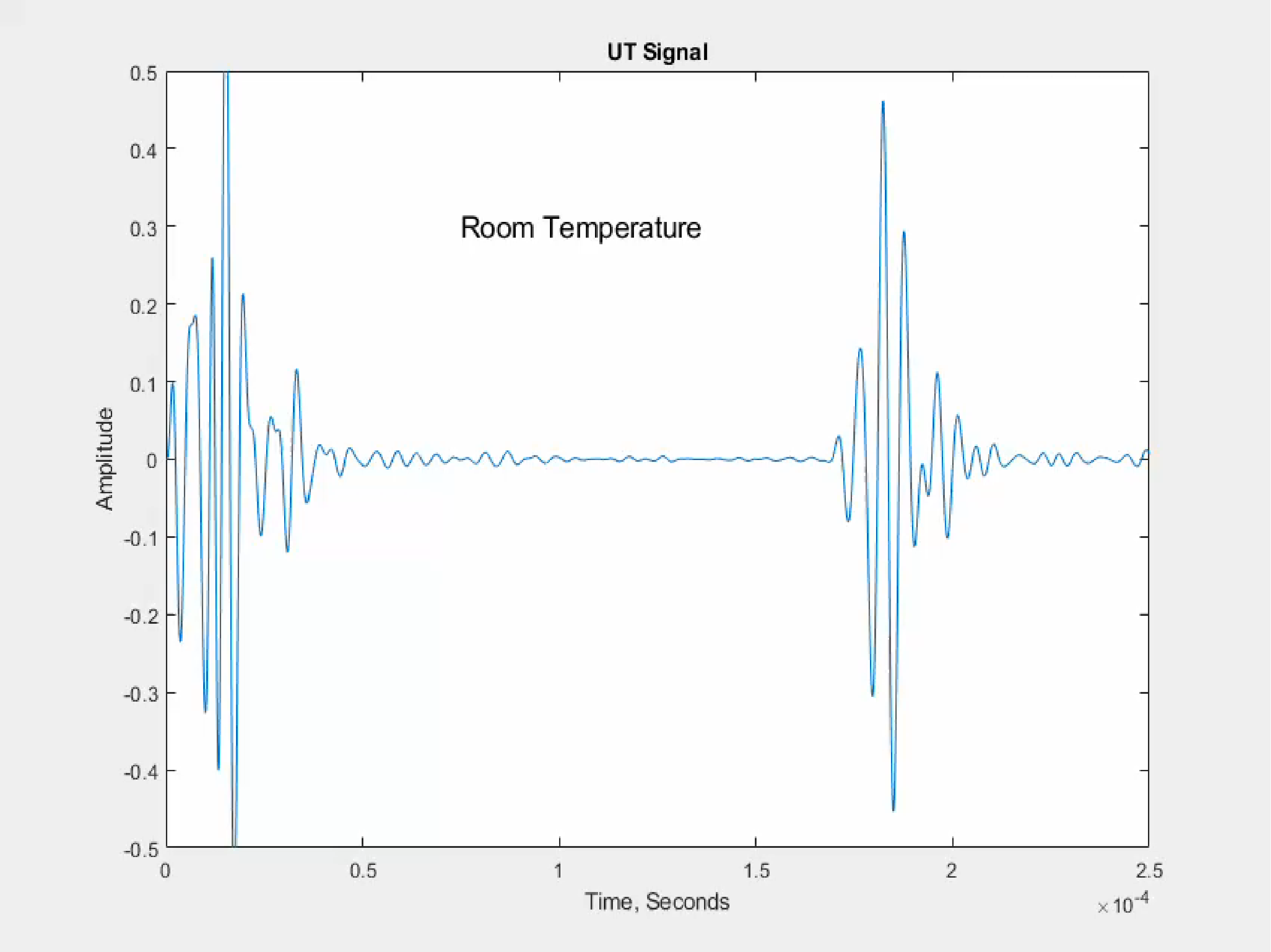
Above 1200 ℃: Pyrometer

	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

Results and accomplishments-Background

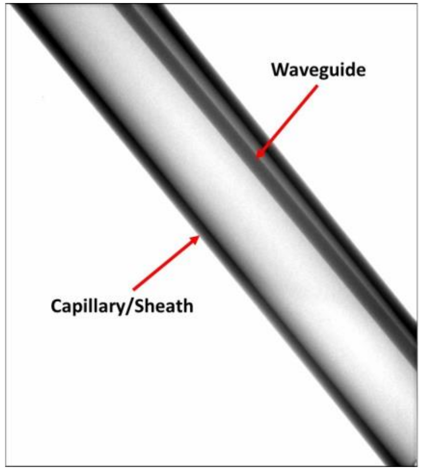
Sticking Example

- Data shown for discrete temperatures, not continuous
- Initial sticking effect can be ignored, but will progress while UT is at temperature
- Upon cooling, sticking is permanent and completely obscures signal

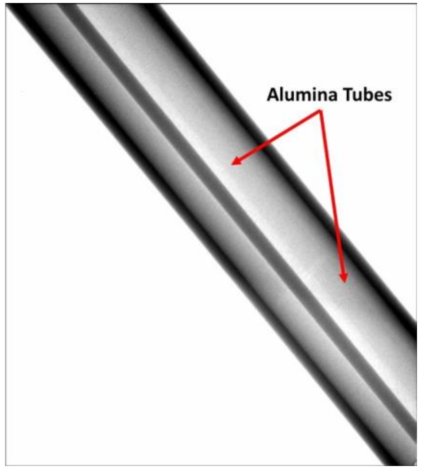


Results and accomplishments-Sticking

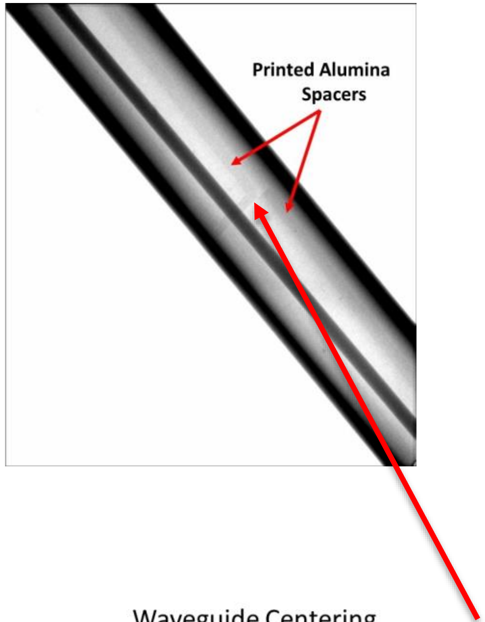
Option 1: Reference



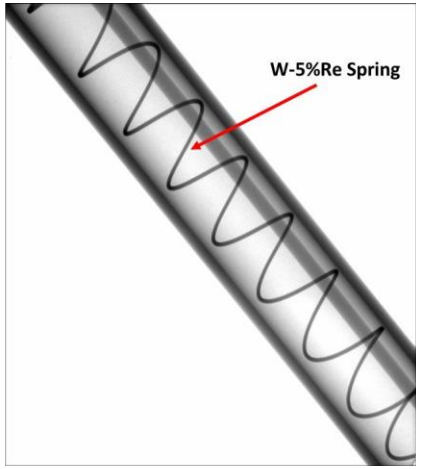
Option 3: Alumina Tube Standoff



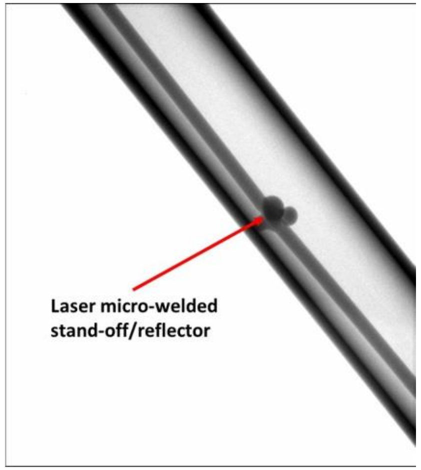
Option 6: Printed Standoff

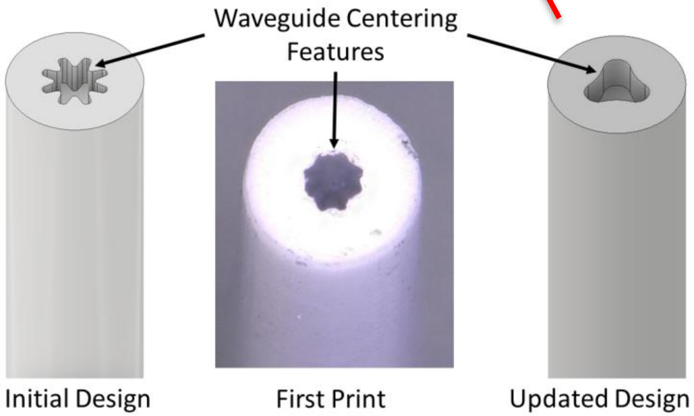


Option 2: Spring Standoff



Option 5: Reflector Standoff





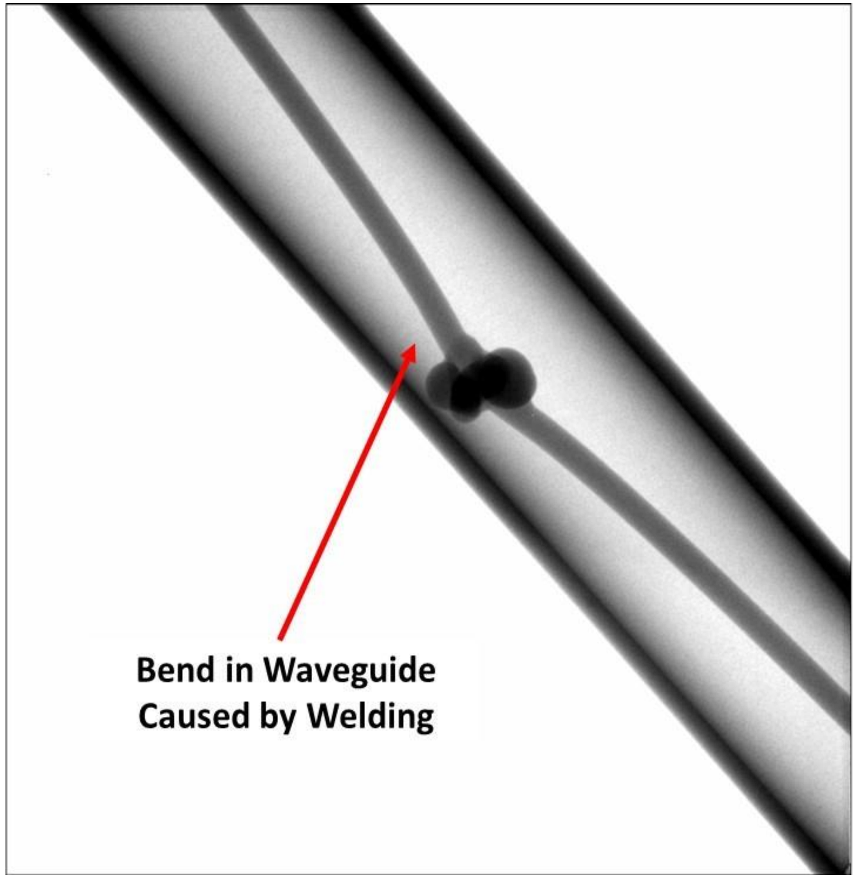
Material Combinations Tested

- **Zircaloy-4 Sheath and Waveguide**
- **Molybdenum Waveguide with Niobium Sheath**
- **Molybdenum Sheath with Molybdenum Waveguide**

Results and accomplishments-Sticking

Zr-4

Reference	Onset at 860 ℃
W-Spring	No sticking-Signal loss due to attenuation
Alumina Tubes	No Sticking-Signal loss due to attenuation
Welded Bump Reflector	Onset at 720 ℃



Mo-Nb

Reference	Onset at 1250 ℃
W-Spring	Onset at 1650 ℃
Alumina Tubes	Onset at 1900 ℃

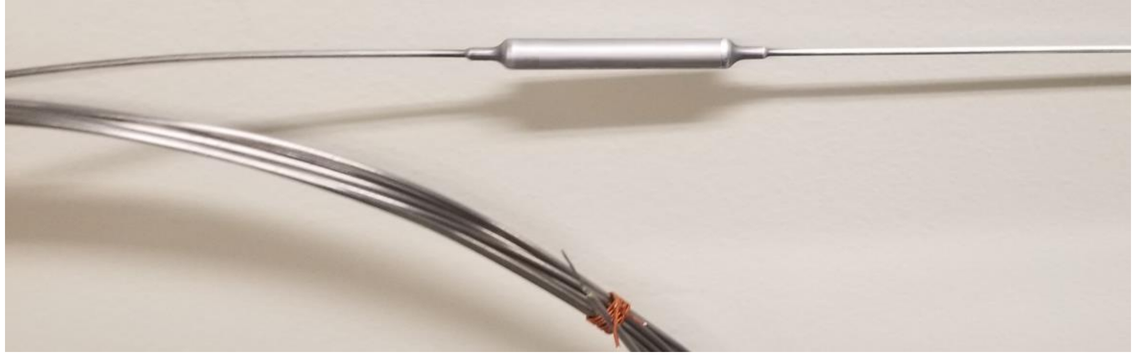
Mo

Reference	Onset at 1500 ℃
W-Spring	Onset at 1500 ℃
Printed Alumina Spacers	No sticking, melting of spacers at 2030 ℃

Results and accomplishments-Deployments

- Multiple UTs prepared for near term deployments/tests

- 5 UTs fabricated for PWR conditions
  - Stainless steel housing and waveguides
  - Autoclave testing
  - Deployment in ATR loop in CY 2022



- 2 UTs fabricated for DISECT irradiation
  - Separate transducer and sensor
  - Stainless steel housing and waveguides
  - Deployment in BR2 in CY 2022

UTs also being used in microreactor tests

- MAGNET/SPHERE: heat pipes (molybdenum waveguides in stainless steel sheath)
- Evinci: furnace test (molybdenum and Inconel 600 waveguides in Inconel 600 sheaths)

Results and accomplishments-Acoustic Sensor Planning

SAW sensor planning meeting held on June 22, 2021

Attendees

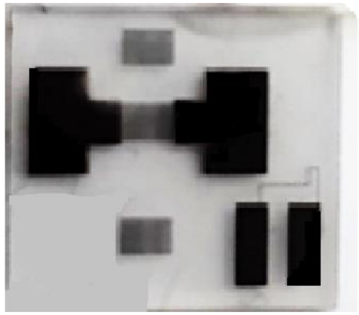
Joshua Daw	INL
Pattrick Calderoni	INL
James Smith	INL
Vivek Agarwal	INL
Pradeep Ramuhalli	ORNL
Morris Good	PNNL
Tim McIntyre	ORNL
Marat Kafizov	tOSU
Dan Deng	BSU
Dan Xiang	X-Wave
Dan Nichols	DOE
Melisa Bates	DOE

Main outcomes, priorities for study:

- Materials characterization and discovery:
  - LiNbO: Good performance, unproven under irradiation
  - AlN: High temperature and radiation tolerant, poor piezoelectric properties
  - Magnetostrictives: High radiation tolerance, limited bandwidth, can this be improved?
  - Corrosion not sufficiently understood
- Fabrication:
  - Integration into sensors, miniaturization, optimized design
  - Adhesion of electrodes
  - Printing vs classical methods
- Wired vs Wireless: Where can they be used

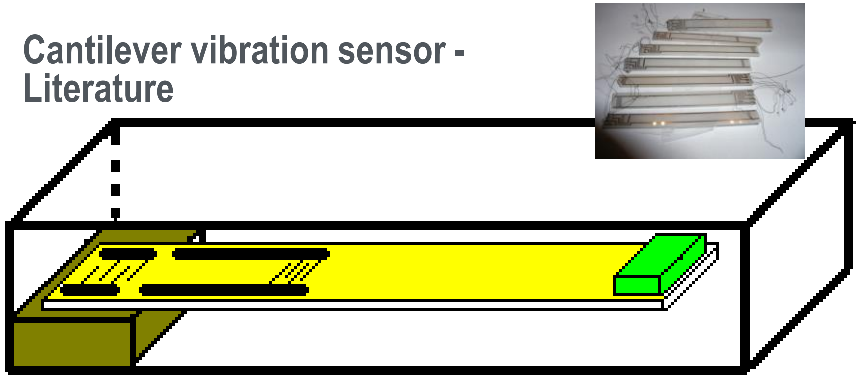
White paper draft to be issued for review shortly

Piezoelectric sensor development – Marat Khafizov (OSU)

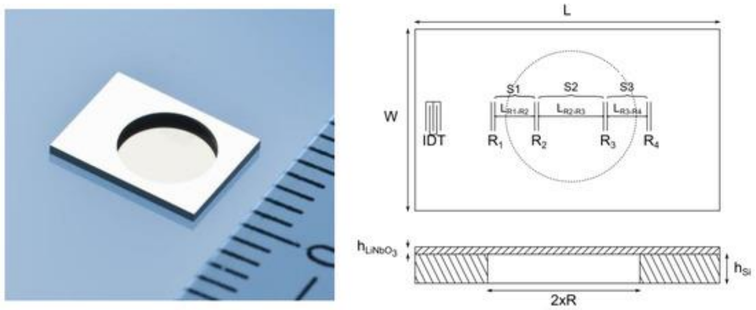


$LiNbO_3$ SAW temperature sensor with RTD

Cantilever vibration sensor - Literature



Membrane pressure sensor - Literature

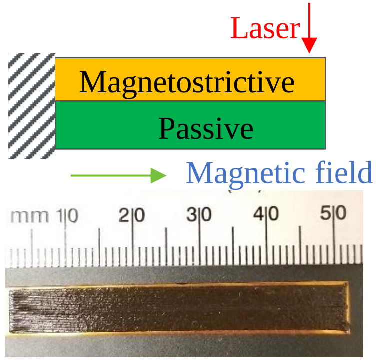


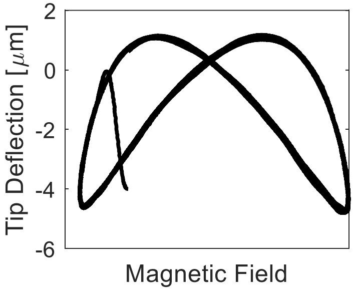
(a) (b)

- Traditional capacitive and resistive sensor are high impedance devices making electronic signal readout challenging
- Piezoelectric-based surface acoustic wave devices are explored as vibration and pressure sensors as an alternative
- Beam cantilever configuration for vibration sensing
- Membrane configuration for pressure sensing
- SAW sensors require temperature compensation
- Based on experience with piezoelectric SAW device irradiations, sensor will need to have gamma-ray heating compensation

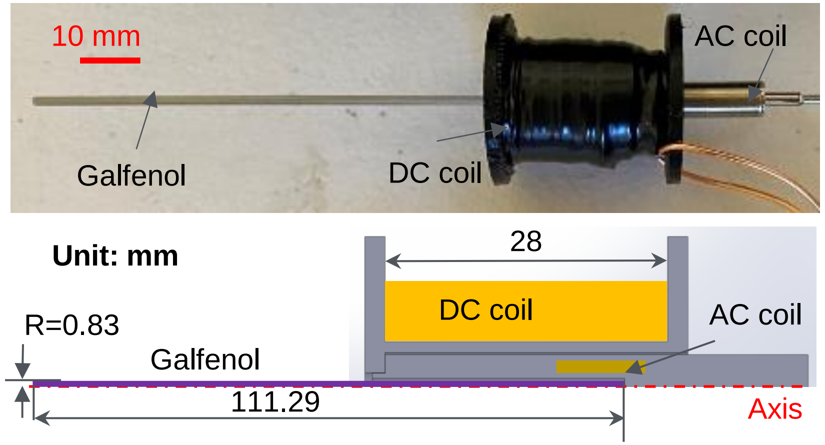
Multi-physics Model Development and AM– Dan Deng (BSU)

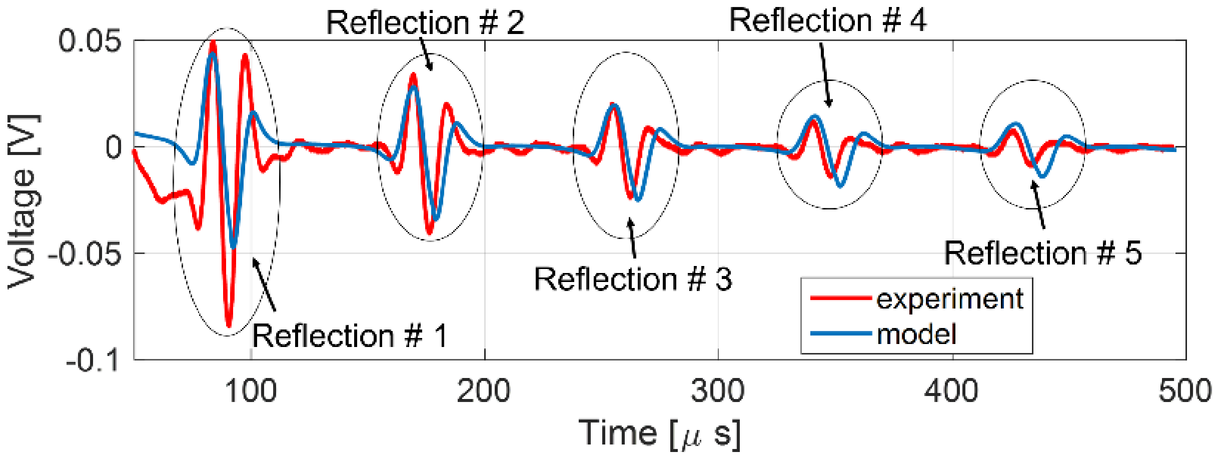
Advanced Manufacturing



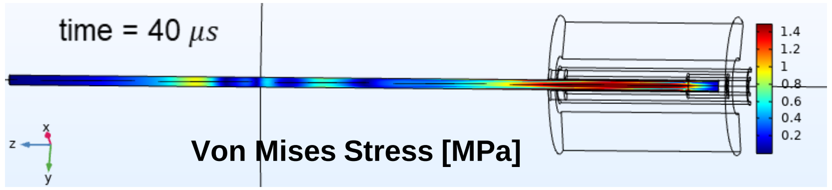


Experimental Validation





Multiphysics Simulation



Conclusion

- Summary of accomplishments
  - Tested several promising methods of mitigating sticking in UT waveguides
    - Printed ceramic spacers identified as most promising
  - Provided multiple UTs for deployments in ATR, BR2, and several non-nuclear experiments
  - Developing prioritized list of SAW sensor research activities
  - Assessing pressure and acceleration sensors (OSU)
  - Developed UT multi-physics model and developing SAW models (BSU)
- FY22 Work will include:
  - Optimizing fabrication of UT
  - Development of electronics specifically for UT
  - Assessment of SAW sensors for use in Mechanisms Engineering Test Loop (METL) demonstration (with ANL)
  - Assessment of Structural Health Monitoring technologies (with ORNL and PNNL)
  - Add UT development to ASI sensor database

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(208)-526-7114
ORCiD: 0000-0003-4377-6231

Questions?

ASI

Advanced Sensors and Instrumentation

Fiber optic sensors and enabling technology for Nuclear Energy applications

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Work Package Manager: Austin Fleming PhD

Idaho National Laboratory

Fiber Optic Sensor "Big Picture"

- Contributors
  - Kelly McCary (INL Graduate Fellow/Ohio State University)
  - Sohel Rana (INL Graduate Fellow/Boise State University)
  - Kevin Tsai (INL)
  - Ashley Lambson (INL)
- Technology has a high potential impact
  - Small size
  - Generally fast response
  - Strong electromagnetic noise immunity
  - Multi-point/multi-parameter sensing

Significant Ongoing research

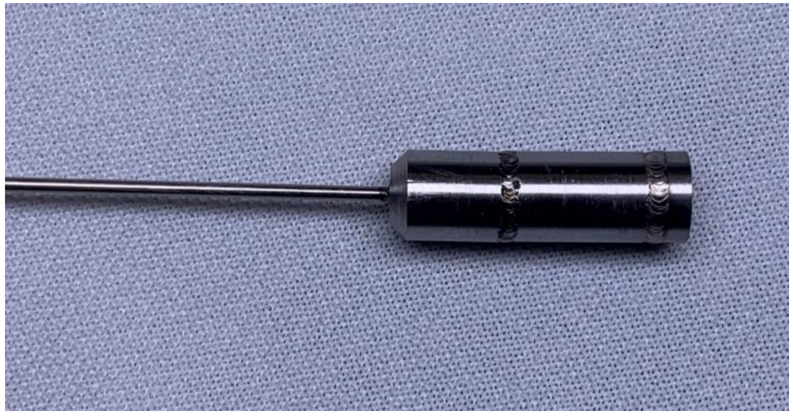
- Monday
  - 12:30 Development of Optical Fiber Based Gamma Thermometer and its Demonstration in a University Research Reactor Using Statistical Data Analytic Methods to Infer Power Distribution from Gamma Thermometer Response (Thomas Blue, Ohio State University)
- Tuesday
  - 2:00 Irradiation of optical components of in-situ laser spectroscopic sensors (Igor Jovanovic, U of Michigan)
  - 3:00 Fiber Sensor Technology for Nuclear Power Applications Radiation-harden Sensor Devices, Packaging, Sensor Data Fusion, and Instrumentation (Kevin Chen, U of Pitt)

Fiber Optic Activities

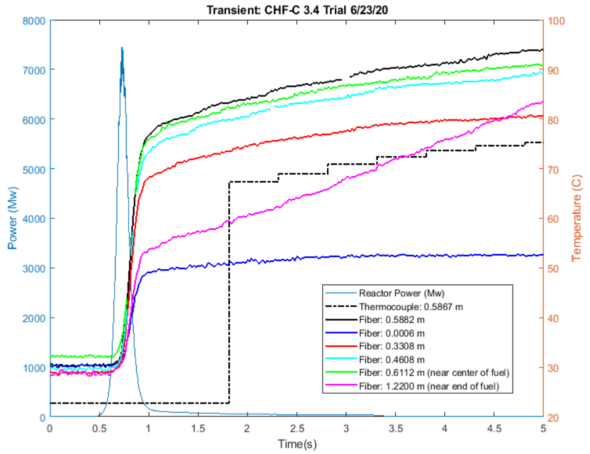
- Activities were prioritized by:
  - Impact to nuclear industry for
    - Applications in advanced nuclear reactors
    - Qualification of nuclear fuels & materials
  - Higher TRL
  - Straightforward path to development

Activities

- Fabry-Perot based pressure sensor
- Intrinsic temperature sensing
- **In-pile imaging** (fiber bundle based)
- **Active compensation** of Radiation Effect



Fiber optic pressure sensor



Fiber optic Intrinsic Temperature sensing

In-Pile imaging

- Motivation:
  - Quantitative and qualitative information about in-pile conditions, properties or state
    - DIC, PIV, etc;
    - Monitoring complex phenomena
    - Unexpected events
  - Diagnostics or control of systems
- Image bundles are commercially available “off-the-shelf” with up to 100,000 fibers, the fiber bundle used in this demonstration had 10,000 fibers
- Fiber bundles have the potential to be compatible with various experiments, as their feedthroughs and footprints are similar to those of other sensor types
  - Diameter 0.5 mm - 2 mm
  - Would not require facility modifications

Image during failed Space X landing

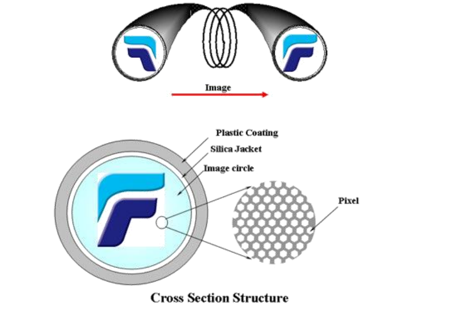
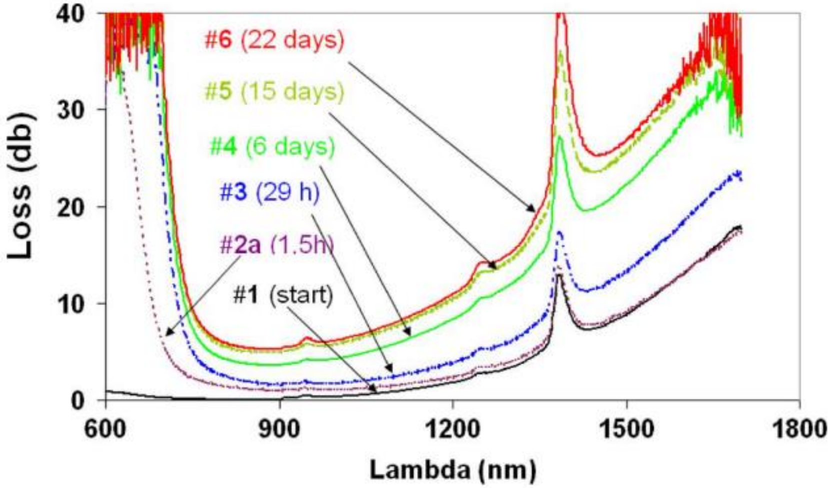


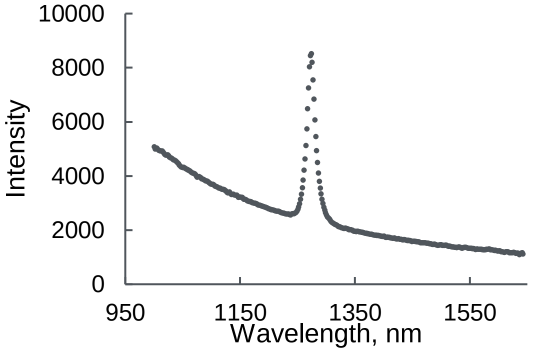
Image from fuel testing in TREAT requiring facility level modifications to obtain

Challenges (Fiber Optic Imaging)

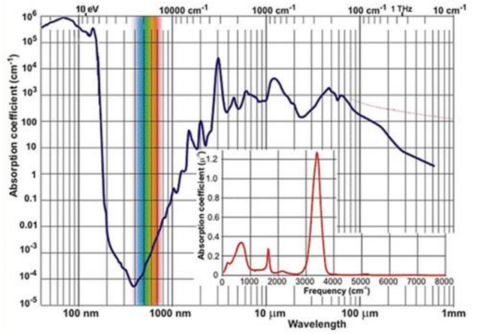
- Designing the distal lens system
  - Compatibility with the harsh environment (temperature & radiation)
  - Small footprint
- Radiation effects in the fiber
  - Radiation induced attenuation(RIA)
  - Radiation induced emission (RIE)
  - Both are heavily wavelength dependent
- Providing light for the imaging
  - Second fiber is necessary to send the light into the reactor
- The length of commercially available fiber bundles is limited



A measurement or radiation induced attenuation as a function of wavelength G. Cheymol et al, IEEE Transaction on Nuclear Science, Vol 58, No 4 pg 1895-1902

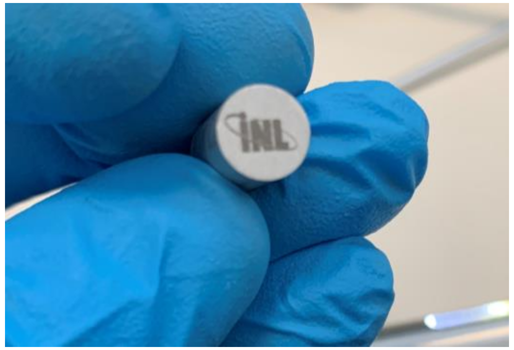


Cherenkov radiation induced in an optical fiber in TREAT, the peak at 1272 nm is the radioluminescence from interstitial O_2

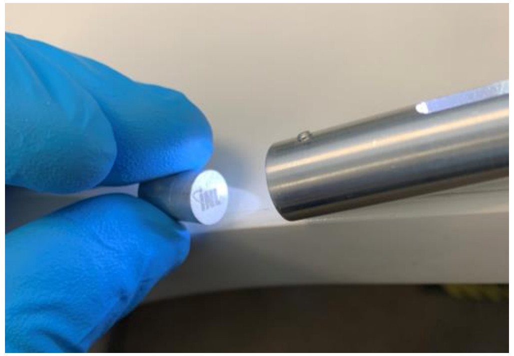


Water absorption spectrum. *Frontiers in chemistry* Vol 7, 48, 2019

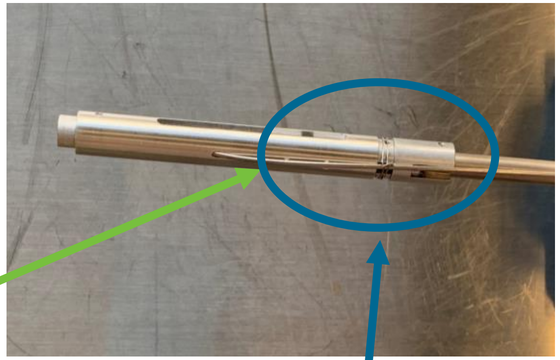
Setup and assembly



INL logo target used for imaging



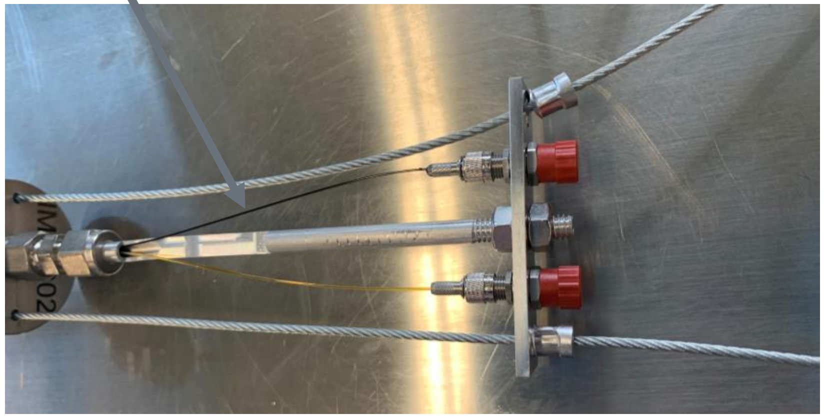
Target used for imaging



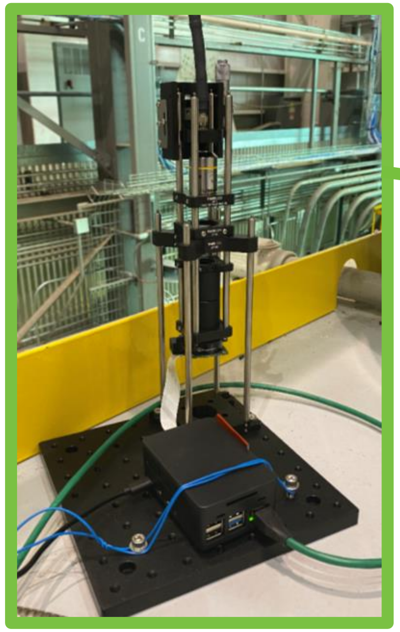
In-pile Lens assembly

Illumination fiber

Image Bundle

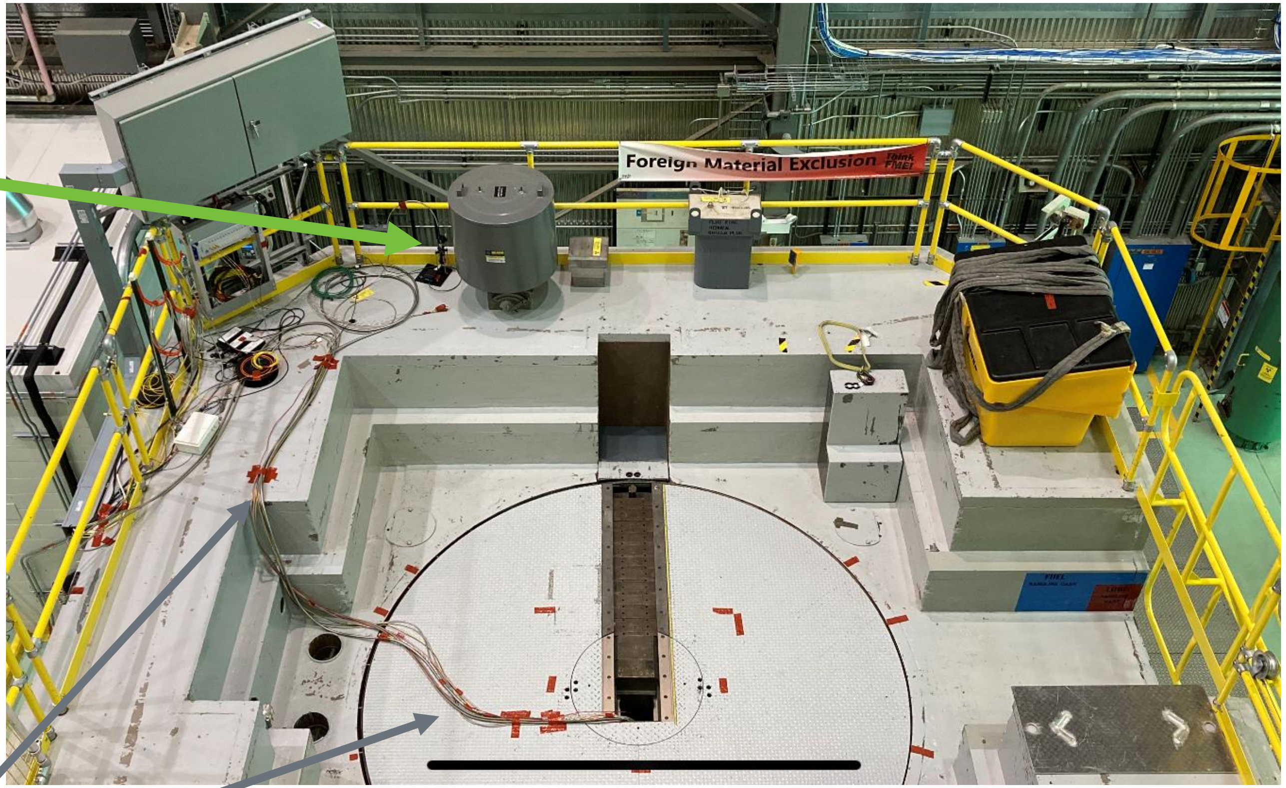


Installation at the reactor



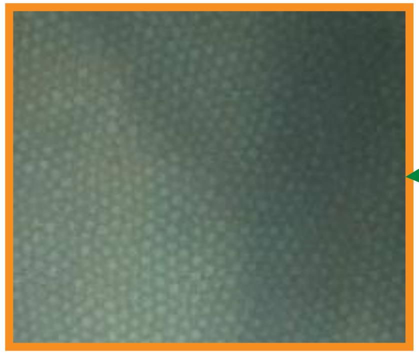
Computer, camera, and lens system for capturing the image from the fiber bundle

Armored imaging bundle running from camera to the test

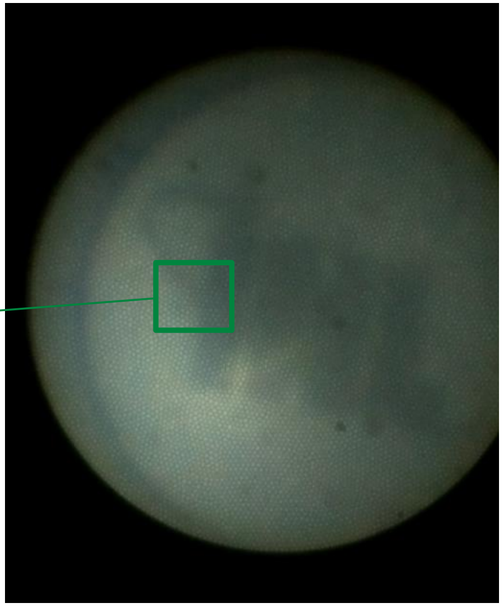


Installing the target and aligning pre-irradiation

Image taken adjacent to lens system viewing the target



Individual fibers in the bundle are visible

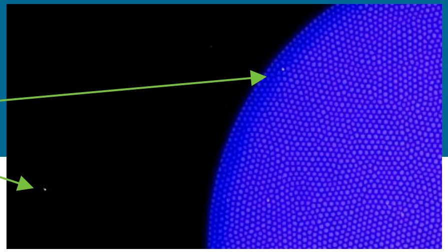


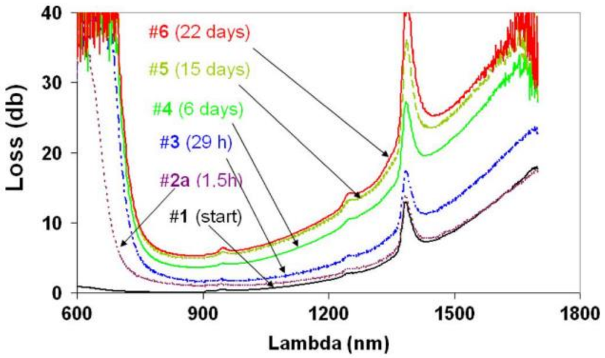
Still frame image through fiber bundle

Video taken during the installation of the target

Results of in-core test

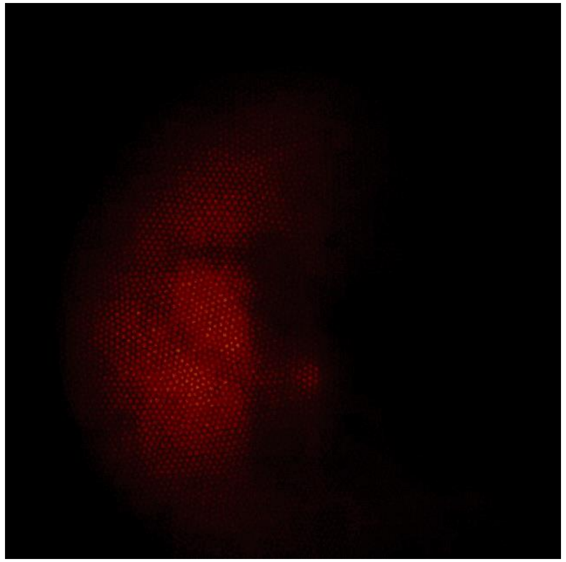
White speckles on image are the radiation effects on the camera directly. While noticeable, they have little impact





A measurement or radiation induced attenuation as a function of wavelength G. Cheymol et al, IEEE Transaction on Nuclear Science, Vol 58, No 4 pg 1895-1902

Before insertion into reactor, with led lighting ~50% power

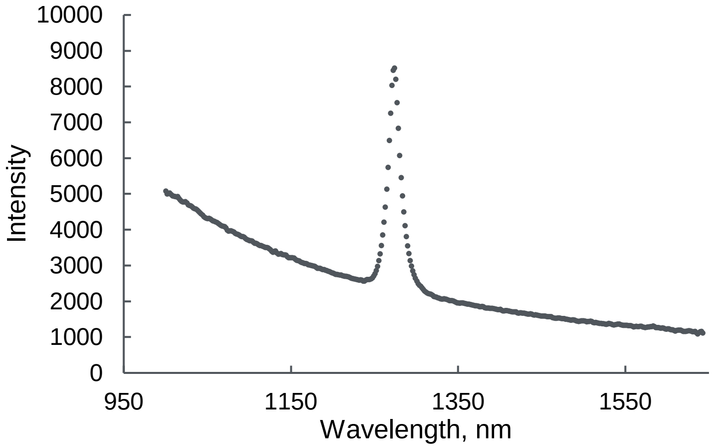


After insertion, at the initiation of transient

- RIA has significantly darkened the image even with LED at 100% power
- The red color is due to the greater RIA at shorter wavelengths

Image during the peak of the Transient

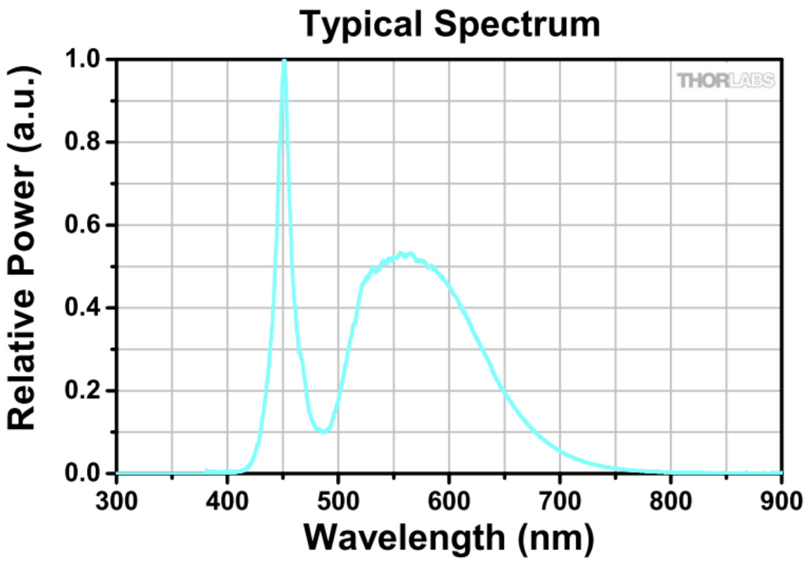
- The Cherenkov radiation is dominating and has washed out the image
- Due to the higher intensity at shorter wavelengths the Cherenkov radiation appears as blue, governed by Frank Tamm equation

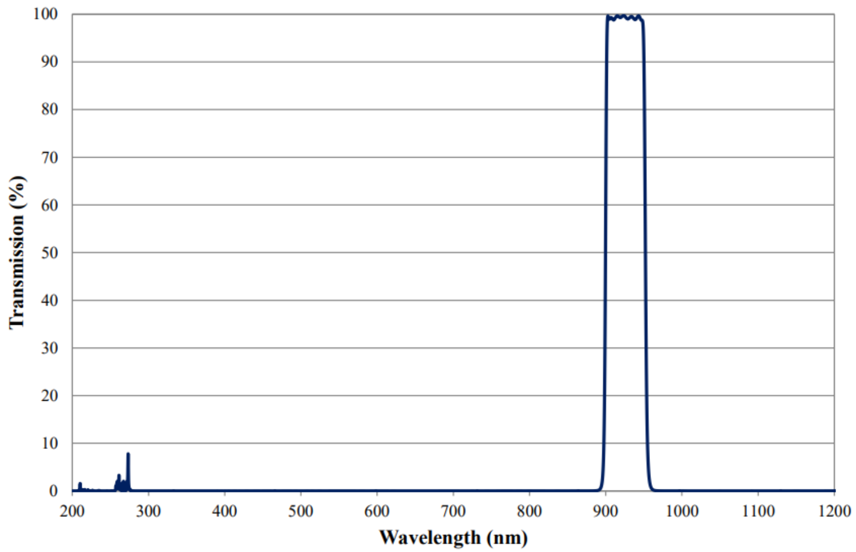


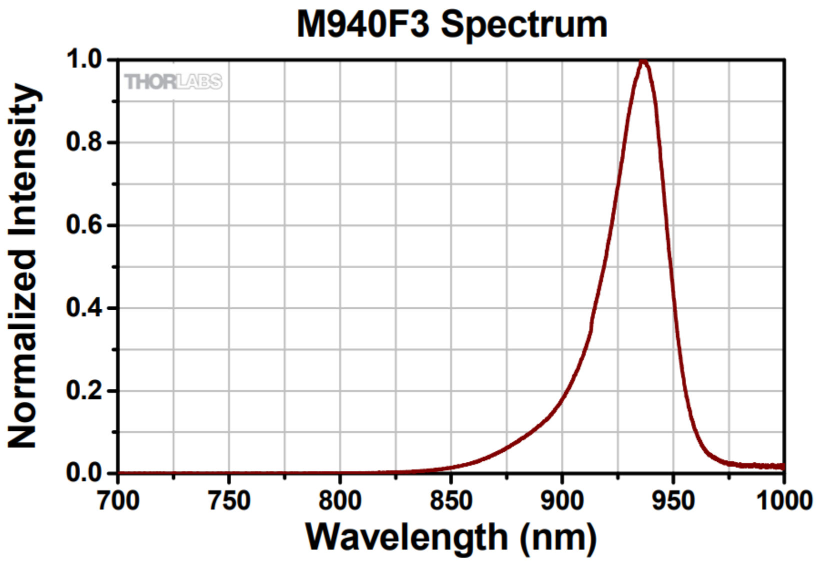
Cherenkov radiation induced in an optical fiber in TREAT, the peak at 1272 nm is the radioluminescence from interstitial O_2

Continued in-core testing

- Results from previous slide used broad visible light source with no filtering
- Recently (<week ago) irradiated a new configuration
  - IR light source
  - Corresponding filter to cut RIE







Active Compensation

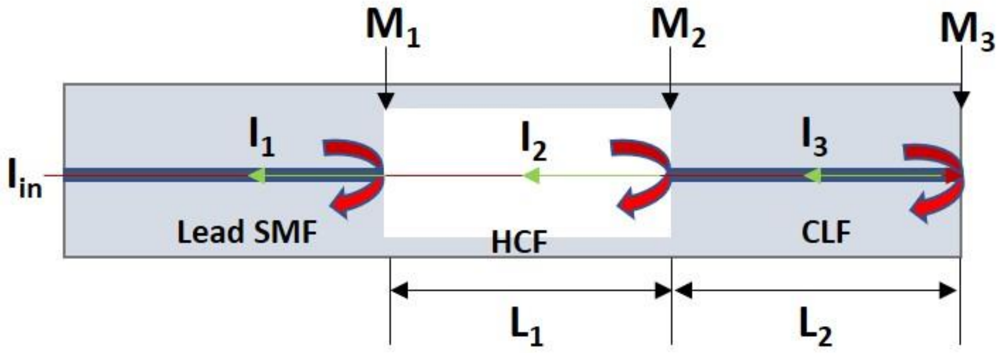
- Radiation effects on optical fibers can cause significant drift in sensor
  - Intrinsic fiber optic sensors are particularly susceptible
  - The sensor response is predominately determined by a geometry parameter and the fiber index of refraction
- Both of index of refraction and geometry can be impacted through radiation induced and attenuation (RIA) and compaction (RIC).
  - RIA leads to index of refraction changes through Kramers-Kronig relationship
  - RIC directly changes geometry and changes index of refraction through the Lorentz-Lorenz equation
- If we knew how the radiation was impacting the optical fiber, we can account for that and remove these effects

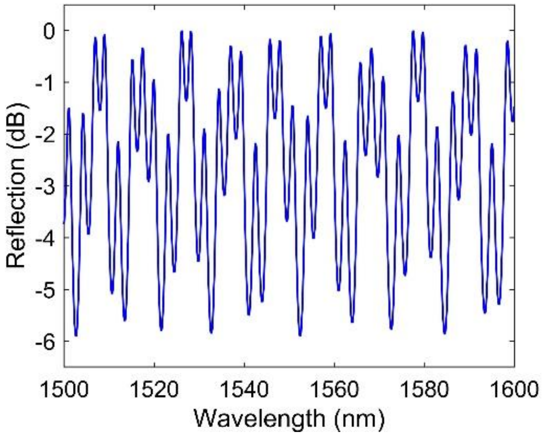
Active Compensation

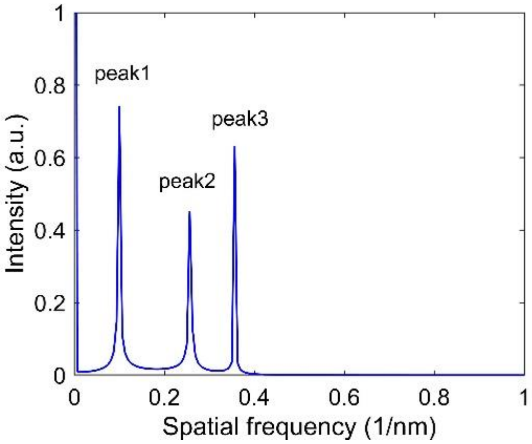
- Much research has been done on both RIA & RIC:
  - Depend greatly on dose, dose rate, irradiation temperature, fiber composition, etc;
  - Predictive models are under development, but are not fully mature
- Plan to exploit the multimodal capability of fiber optics
  - Develop a strategy to measure, in real time, the fiber index of refraction and compactions
  - Then use these measurements to compensation for the radiation effects on sensor performance

Active Compensation Structure

- Based on cascaded Fabry-Perot sensors
- Spectrum from the gas filled Cavity 1, provides information about fiber compaction
- Spectrum from cavity 2, provides a measurement of the index of







Active Compensation Prototype Sensor

Summary & Conclusion

- Four main activities are underway under this Fiber optic work package
  - Pressure sensor
  - In-pile Imaging
  - Intrinsic Temperature Sensors
  - Active Compensation for Radiation Effects
- Submitted 2 journal articles on active compensation
- A preliminary in-pile demonstration of fiber optic bundle based imaging has been conducted and is ongoing
- 1 Journal paper in preparation for pressure sensor results

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Questions?

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ASI Advanced Sensors and Instrumentation

Development of Microwave Resonant Cavity Transducer for Flow Sensing in Advanced Reactor High Temperature Fluids

CA-20-IL-AN-0702-02

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

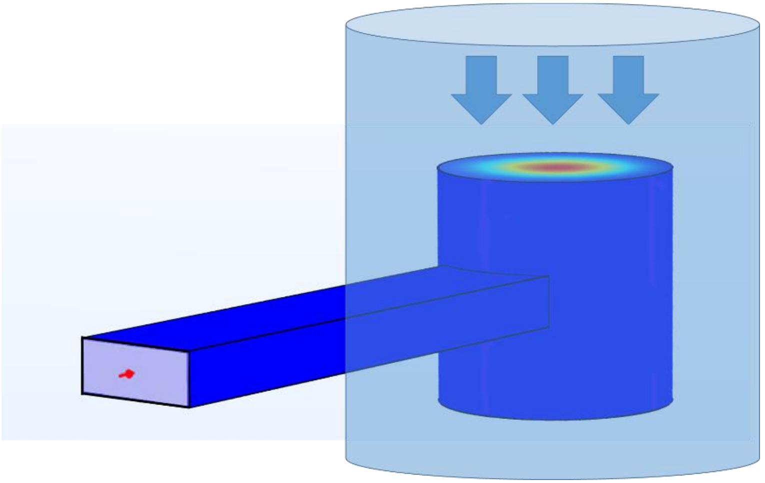
November 15 – 18, 2021

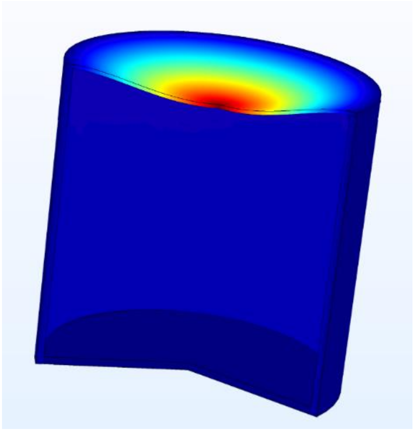
Alexander Heifetz, PhD
Principal Electrical Engineer

Argonne National Laboratory

Project Overview

- Objectives
  - Develop immersion flow meter for in-core sensing of high-temperature fluids
    - Sodium fast reactor (SFR)
    - Molten salt cooled reactor (MSCR)
  - Target operating temperature > 500^{o}C
  - Can made from material resilient to corrosion
    - SS316
- Sensor basic principles
  - Hollow metallic cylindrical microwave resonator with flexible membrane
  - Hollow rigid metallic microwave waveguide transmits RF signals and acts as insertion probe
  - Transduction through deflection of membrane due to dynamic pressure of flowing fluid
    - Microscopic deflections are sufficient for measurements
  - Cavity volume change shifts resonant frequency
  - Can be used as pressure and level sensor





Project Overview

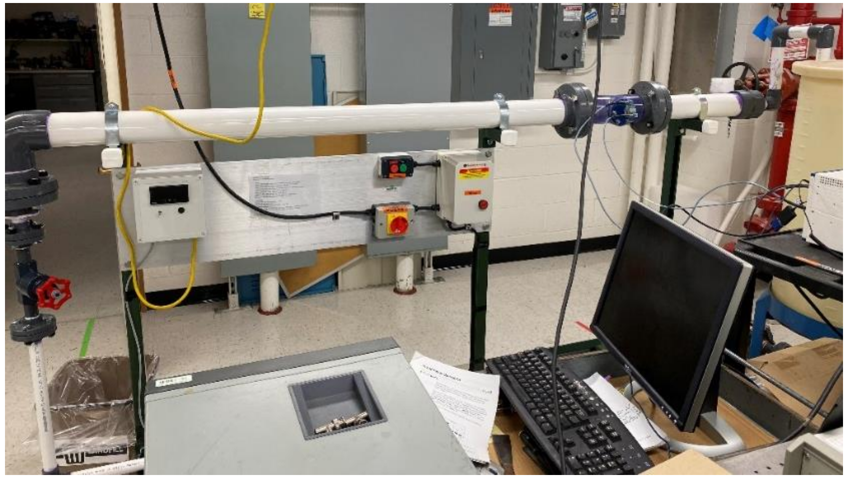
- Project Schedule

FY21

Sensor prototype design

FY22

Flow sensing in water



Current Status

FY23

Flow sensing in high temperature fluid

Project Overview

- **Participants**

Argonne National Laboratory

Alexander Heifetz (PI)
Sasan Bakhtiari
Eugene Koehl

Kairos Power

Anthonie Cilliers

Illinois Institute of Technology

Jafar Saniie

The University of Texas at San Antonio (UTSA)

Miltos Alamaniotis

- **Students**

Illinois Institute of Technology

Tianyang Fang

University of Illinois Urbana-Champaign

David Aronson

The University of Chicago

Dmitry Shribak
Victoria Ankel

Technology Impact

- Comparison of state-of-the-art in liquid sodium and molten salt flow sensing

	Ultrasonic	Electromagnetic	Microwave Resonant Cavity-Based
Sensing in which fluid	Liquid sodium & molten salt Based on detection of time of flight or Doppler frequency shift	Liquid sodium Take advantage of electrical conductivity of liquid sodium	Liquid sodium & molten salt Transduction is based on fluid-structure interaction
Immersion or external	External Two transducers in pitch-and-catch or transmission mode require direct line of sight	Immersion or external Measure rate of conducting flux passing through coil cross-section	Immersion Can be made as small as type-K thermocouple
Deployment challenges	Crystal can degrade due to exposure to high temperature and radiation	Permanent magnet could be de-magnetized. Coil requires large size DC power supply	Hollow stainless steel structure resilient to high temperature and radiation

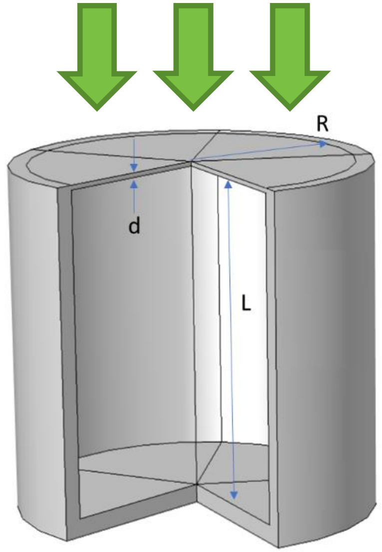
Results and accomplishments

- Chose right circular cylindrical design (L = 2R) to achieve highest Q-factor
- Derived equation for shift in resonant frequency due to membrane deflection
  - Used analytic closed form expression for deflection of radially constrained circular plate
  - First order term in Taylor series due to change in cavity length ΔL

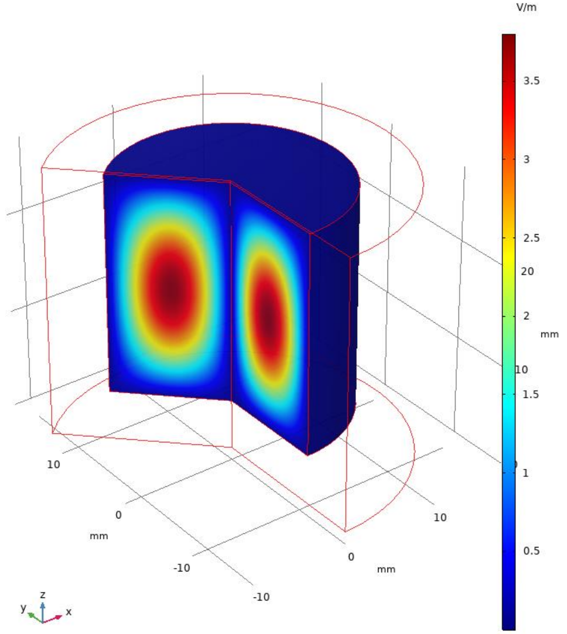
$$\Delta f_{nml} = \sqrt{\left(2X'_{nm}\right)^2 + \left(l\pi\right)^2}\,\frac{3\left(1-\nu^2\right)}{256E}\,\frac{cR^2}{d^3}\,\rho \mathrm{v}^2$$

$$P = \frac{1}{2}\rho \mathrm{v}^2$$

n,m,l = mode numbers
c = speed of light
X'_{nm} = n^{th} root of the derivative of the m^{th} order Bessel function
E = Young's modulus
ν = Poisson ratio
L = length
R = radius
d = membrane thickness
ρ = fluid density
v = fluid velocity



COMSOL RF Module simulations



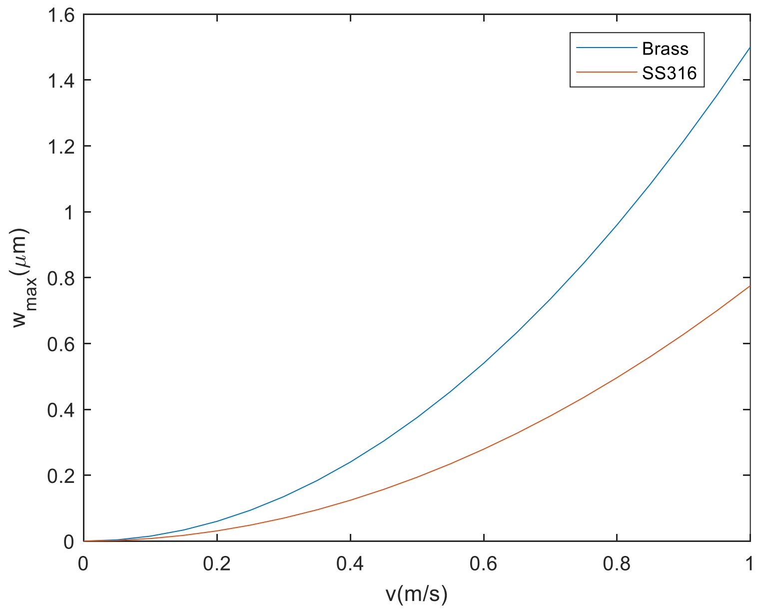
TE_{011} mode

Results and accomplishments

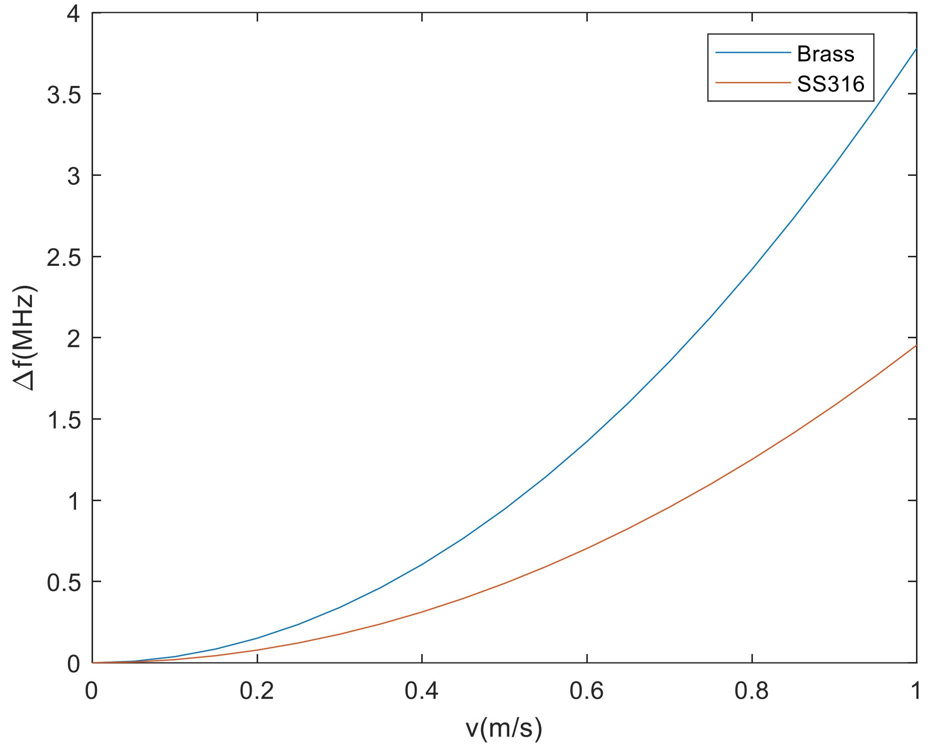
- Chose Brass as material for cavity prototype development for proof-of-principle tests in water

Material	E (GPa)	*v*
Brass	100	0.34
SS316	210	0.2

Maximum displacement of membrane



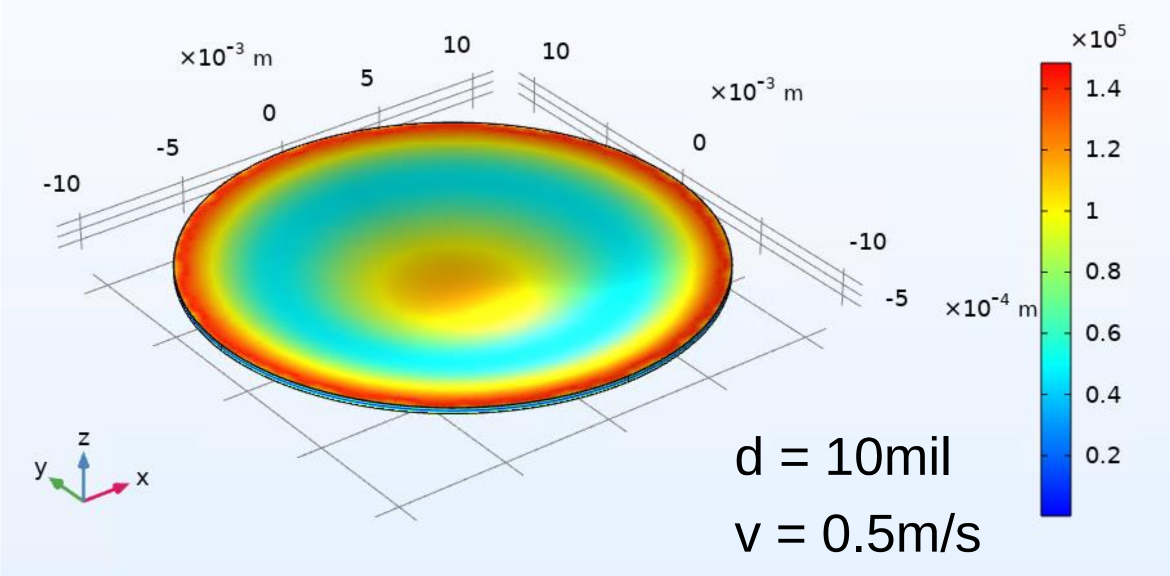
TE_{011} mode frequency shift

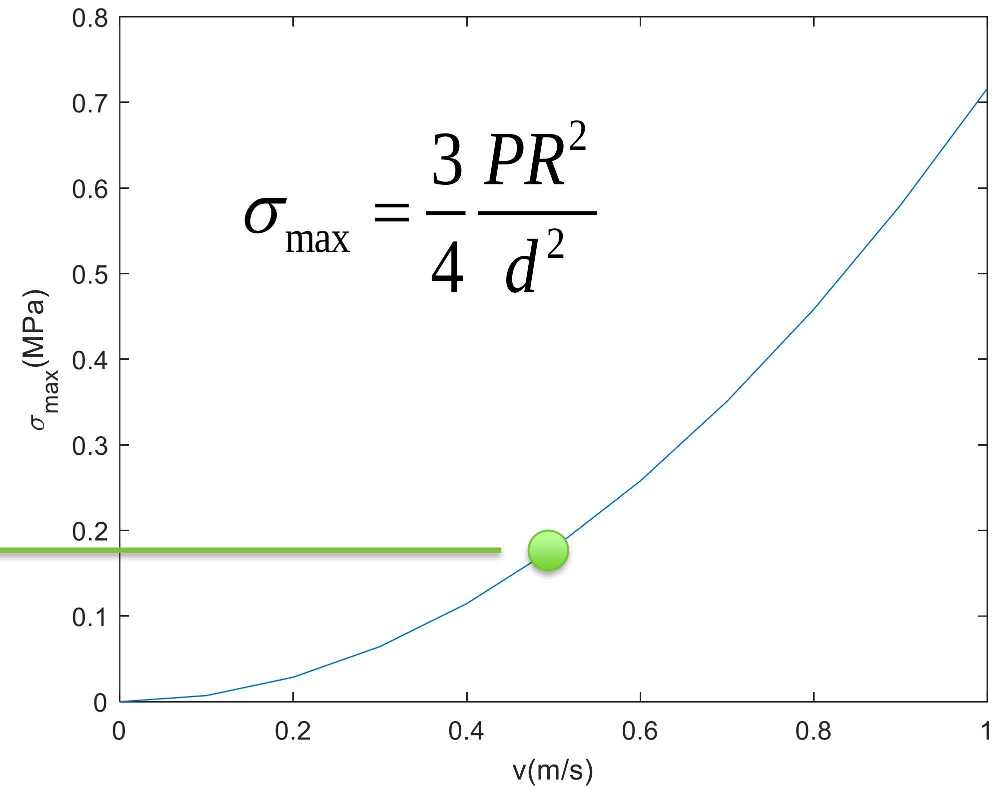


Results and accomplishments

- Analyzed mechanical integrity of membrane with computer simulations
  - Deflection of uniformly loaded radially constrained circular plate of thickness *d* and radius *R*
  - YS = 290MPa and UTS = 580MPa for SS316
  - Maximum stress at plate boundary

  - COMSOL calculation of von Mieses stresses for uniformly loaded radially constrained circular plate

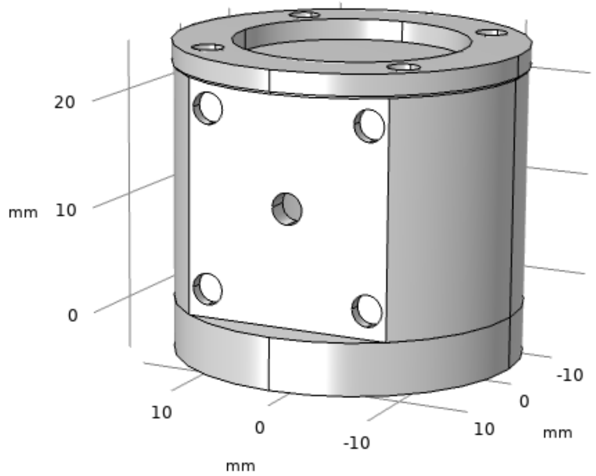


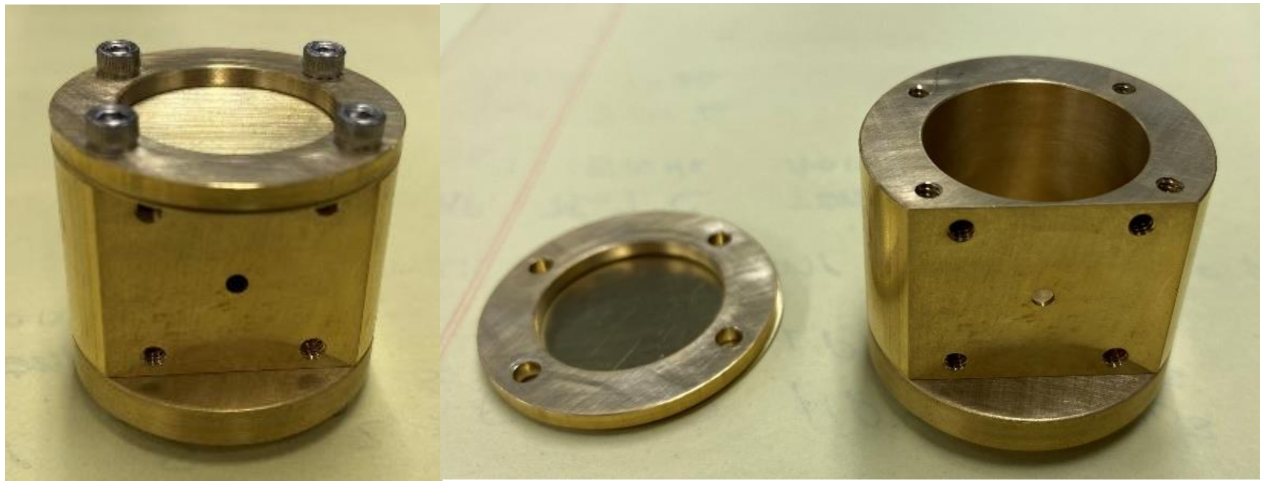


d = 10mil = 254μm

Results and accomplishments

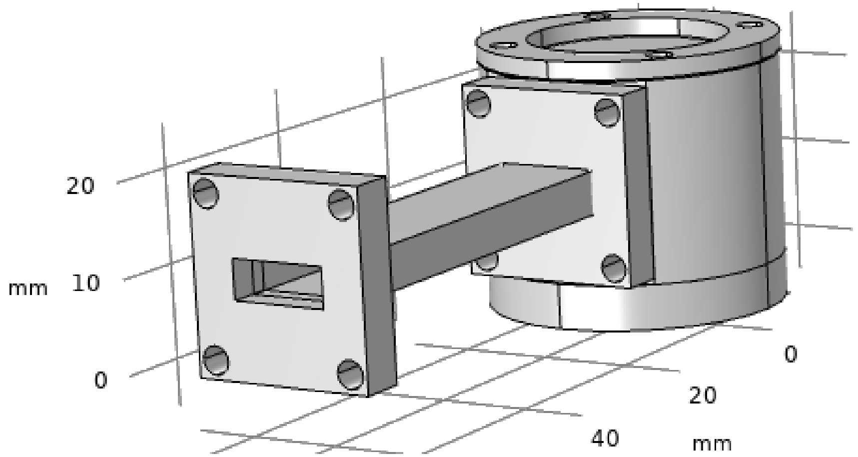
- Designed K-band (18-26.5GHZ) microwave cavity
  - Calculated frequencies of cavity modes with COMSOL RF module computer simulations
  - Cavity excited through subwavelength hole
  - Dimensions matched to commercial WR-42 microwave waveguide 22.2mm flange
  - Membrane thickness 8mil = 203µm
  - Fabricated Brass cavity prototype for initial testing in water

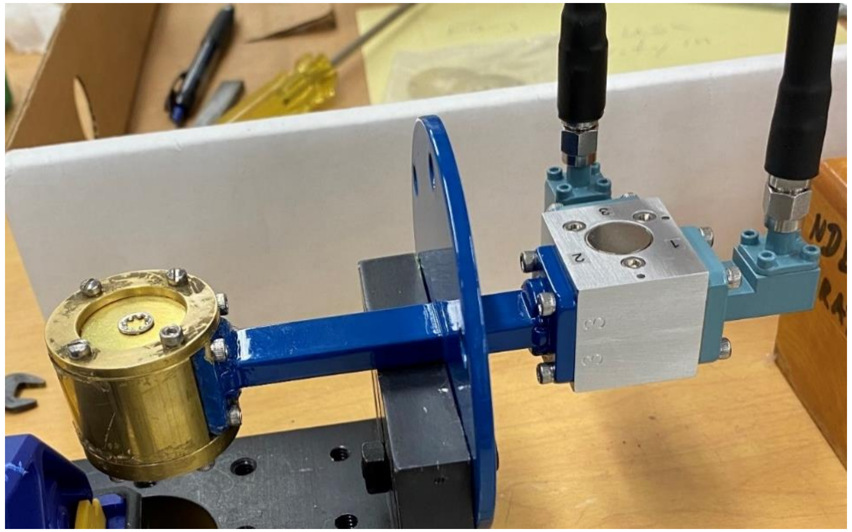


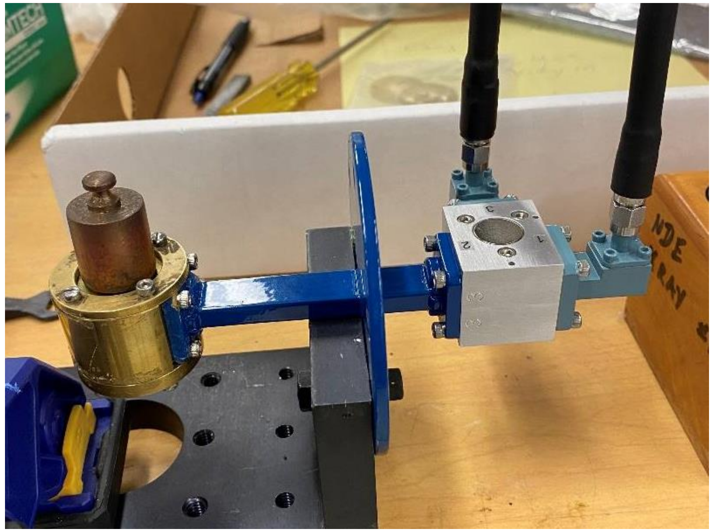


Results and accomplishments

- Cylindrical cavity coupled to commercial K-band WR-42 bulkhead waveguide
- Purchased and installed K-band microwave waveguide circulator for cavity readout
- Tested mechanical resilience of membrane with weights up to 500g

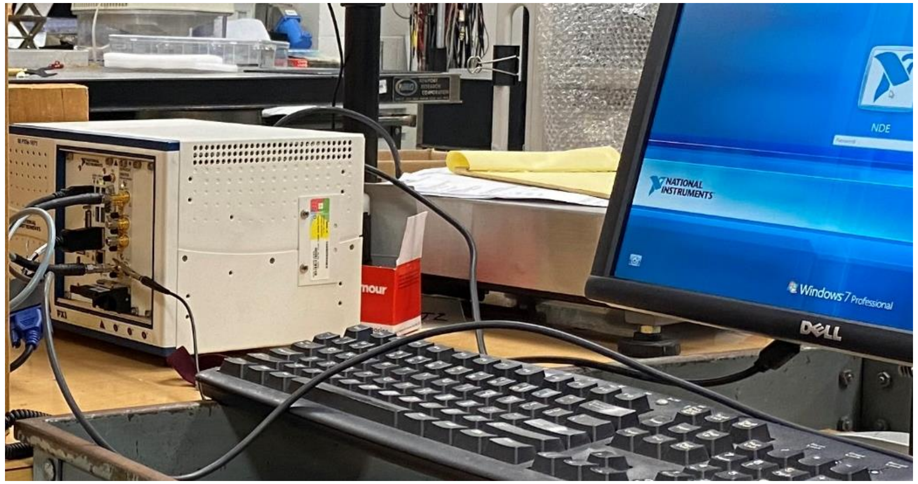






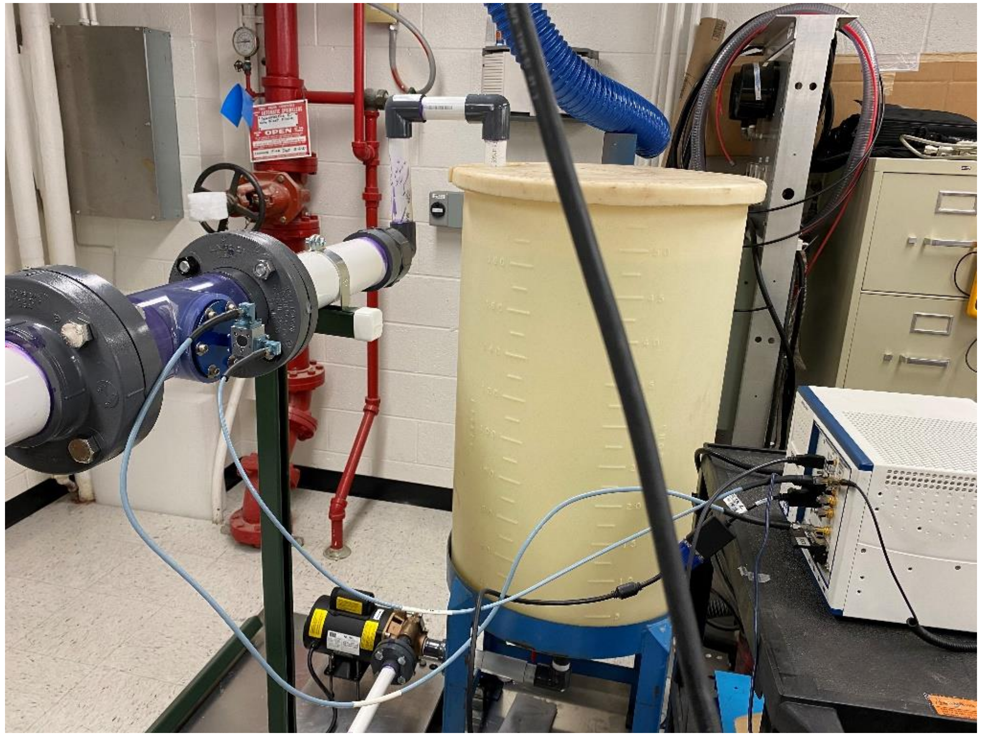
Results and accomplishments

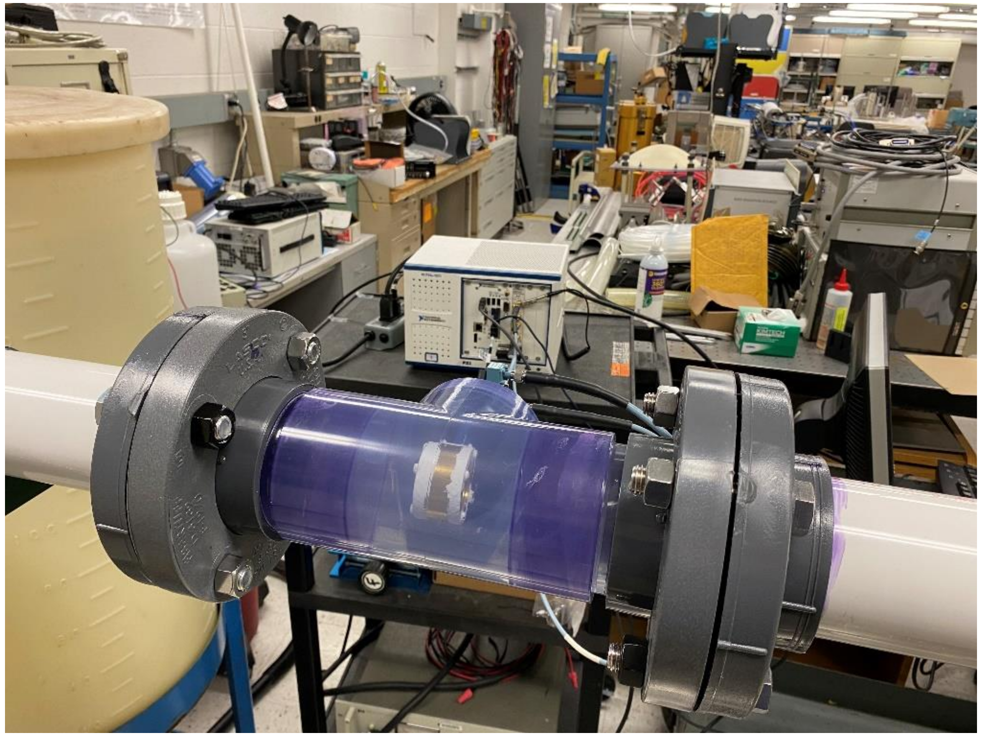
- Developed leak-proof test article
  - Size 3 piping tee
  - Designed and fabricated coupling components in ANL machine shop
- Developed measurement setup
  - PXIe chassis portable microwave vector network analyzer (VNA) with 26.5GHz bandwidth



Results and accomplishments

- Developed water flow loop for proof-of-principle flow sensing
  - Pump rated up to 50gpm flow rate at ambient pressure
  - Omega flowmeter installed for reference flow measurements

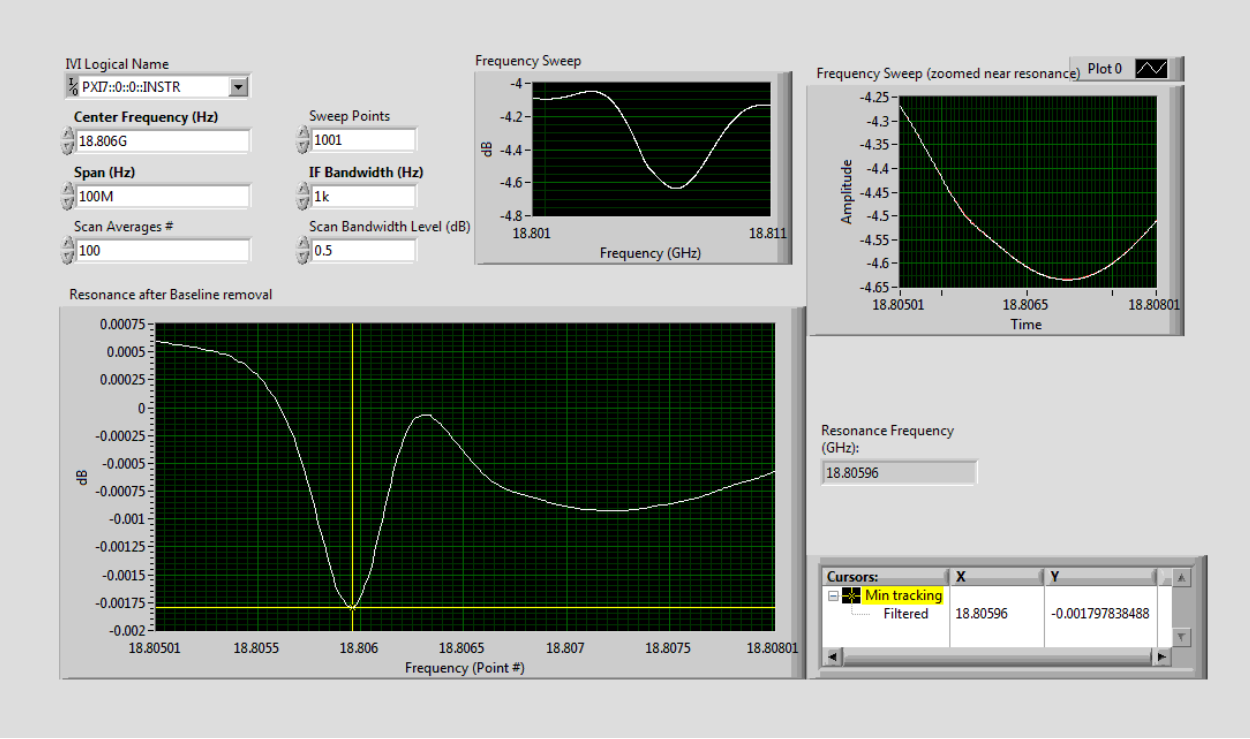




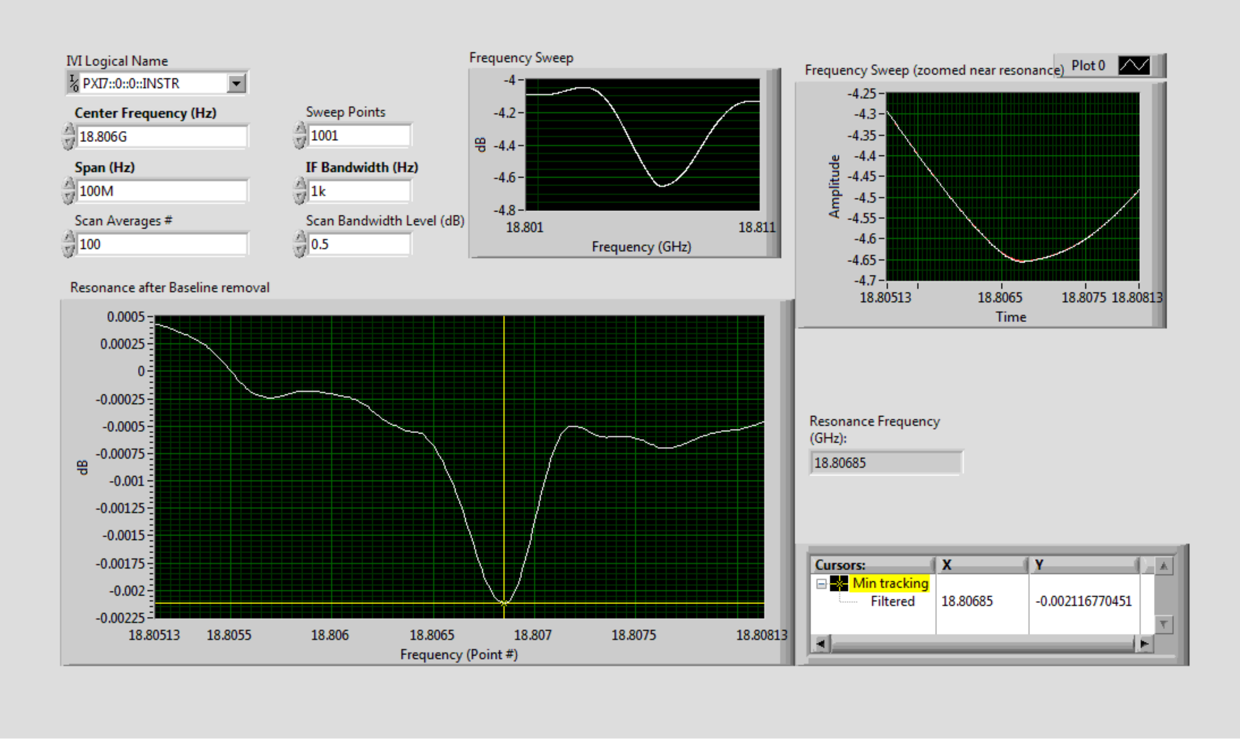
Results and accomplishments

- Developed Labview™ custom interface for data acquisition and processing

No flow



35gpm

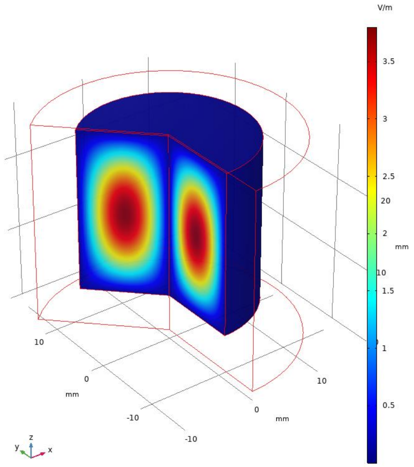


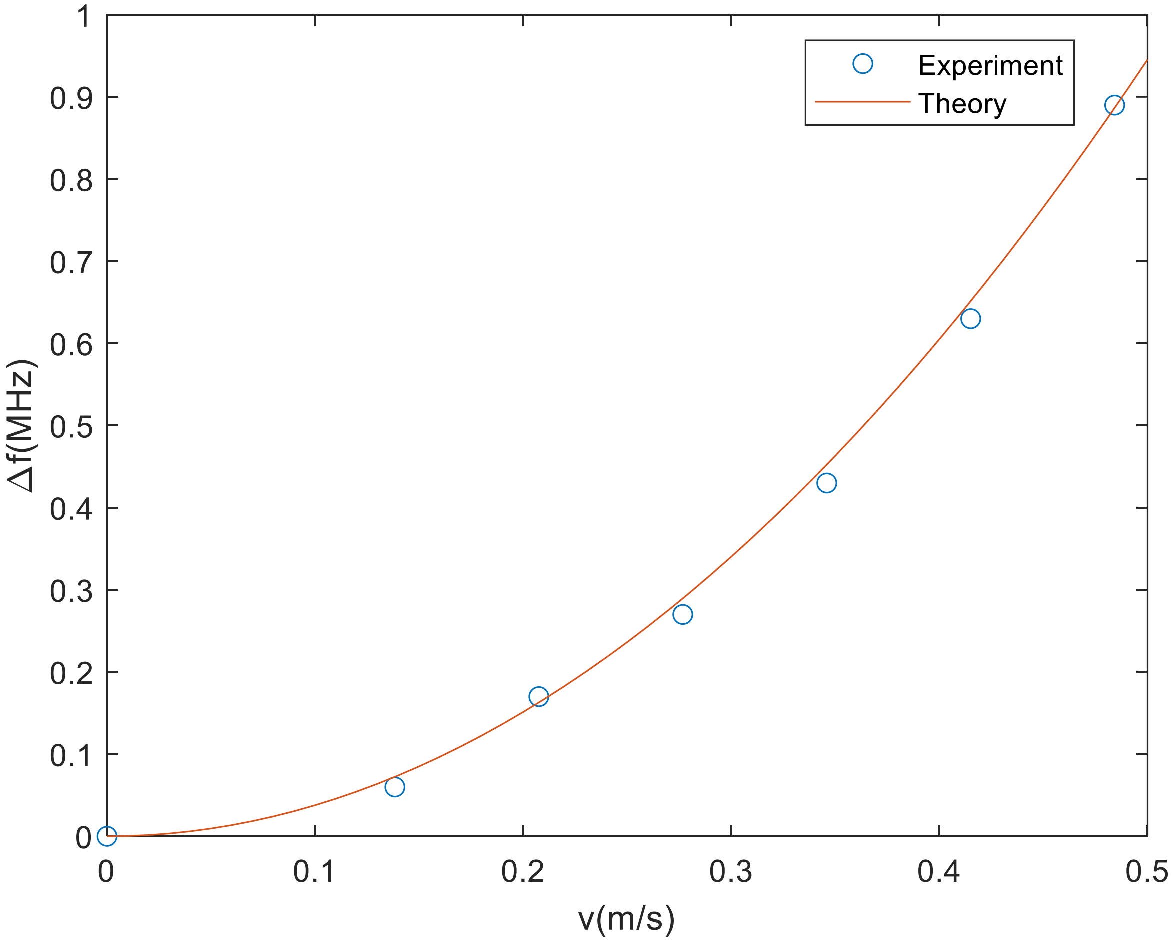
Results and accomplishments

- Measured flow rate using cavity response near 18.8GHz
- Assume response is TE_{011} mode
  - Based on calculations frequency of TE_{011} mode f = 17.8GHz
- Analytic expression for frequency shift

$$\Delta f_{011} = \sqrt{(2X'_{01})^2 + (\pi)^2}\,\frac{3(1-\nu^2)}{256E}\,\frac{cR^2}{d^3}\,\rho v^2$$

X'_{01}= 3.832





Conclusion

- Publications
  - A. Heifetz, V. Ankel, D. Shribak, S. Bakhtiari, A. Cilliers, “Microwave Resonant Cavity-Based Flow Sensor for Advanced Reactor High Temperature Fluids, *Proceedings 12th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 2021),* 232–238 (2021).
- Patents
  - A. Heifetz and S. Bakhtiari, “Microwave Resonant Cavity Transducer for High Temperature Fluid Flow Sensing,” IN-20-146, Argonne National Laboratory (2020).
- Reports
  - A. Heifetz, S. Bakhtiari, E.R. Koehl, D. Shribak, D. Aronson, T. Fang. J. Saniie, “First Annual Report on Development of Microwave Resonant Cavity Transducer for Fluid Flow Sensing,” ANL-21/49 (2021).
  - A. Heifetz, S. Bakhtiari, E.R. Koehl, D. Aronson, “Fabrication and Preliminary Demonstration of Microwave Resonant Cavity Transducer Performance,” ANL-21/38 (2021).
  - A. Heifetz, D. Shribak, S. Bakhtiari, E.R. Koehl, “Design of Microwave Resonant Cavity Transducer,” ANL-21/15 (2021).

Conclusion

- Summary of presentation/accomplishments
  - Developed microwave K-band sensor prototype from Brass
  - Demonstrated initial performance in proof-of-principle test in water
- Future work
  - Deign sensor prototype for high temperature fluid environment
  - Demonstrate performance in high temperature fluid

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Questions?

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ASI Advanced Sensors and Instrumentation

High temperature embedded/integrated sensors (HiTEIS) for remote monitoring of reactor and fuel cycle systems

CA-17-NC-NCSU-0702-02

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

PI: Xiaoning Jiang, NC State University

TPOC: Vivek Agarwal, INL

Project Overview

- **Objective**

To develop and evaluate high temperature embedded/integrated sensor systems (HiTEISs) for applications in reactor and fuel cycle systems.

- **Participants (2021)**

PIs: Xiaoning Jiang, PI, NC State University (NCSU), **Mohamed Bourham**, Co-PI, NCSU, **Mo-Yuen Chow**, Co-PI, NCSU

Postdocs and Students: Howuk Kim, PostDoc, NCSU (HiTEIS integration and characterization, laser ultrasound), **Bharat Balagopal**, PostDoc, NCSU (wireless communication), **Sean Kerrigan**, PhD student, NCSU (corrosion resistance, mock-up structure), **Nicholas Garcia,** PhD student, NCSU (HiTEIS integration and characterization, laser ultrasound and mock-up structure)**, Sahil Deshpande,** PhD student, NCSU (wireless communication).

- **Schedule**

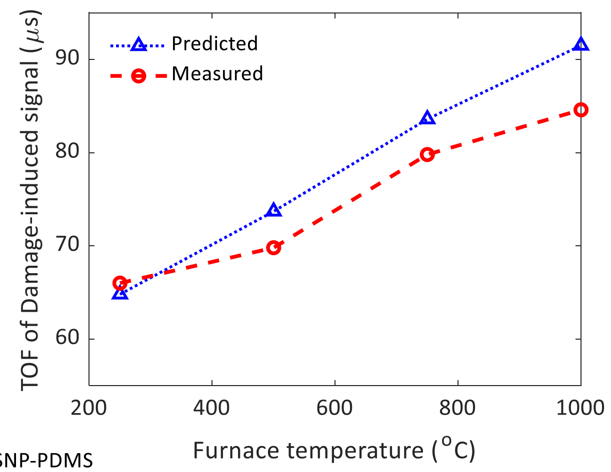
Year	Task	Role	Responsibility	Note
1 & 2	HiTEIS design and development	HiTEIS development	X. Jiang	NCSU
		Sensor material radiation resistance	L. Winfrey & M. Bourham	PSU/NCSU
2, 3 & 4	HiTEIS Integration and characterization	Wireless communication system	M. Y. Chow	NCSU
		HiTEIS integration & characterization	X. Jiang & M. Bourham	NCSU
2, 3, 4 & 5	Development of embedded sensors and laser ultrasound	Laser ultrasound transducer development	X. Jiang	NCSU
		Sensor radiation/corrosion resistance/mock-up testing	M. Bourham	NCSU
		Wireless communication for embedded sensors	M. Y. Chow	NCSU

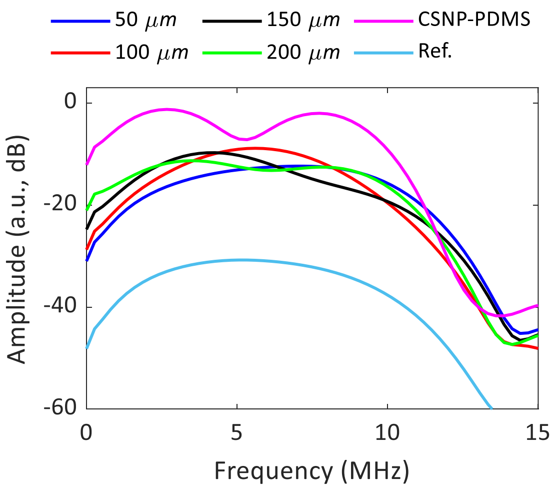
Summary of Accomplishments

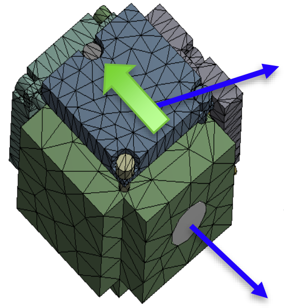
- Laser ultrasound assisted high temperature NDT
  – Laser ultrasound used in conjunction with Aluminum Nitride is useful for detecting defects at temperatures up to 1000 °C.

- Liquid metal laser ultrasound
  – Designed, fabricated and validated Field's Metal as a viable photoacoustic medium for high temperature laser ultrasound

- High temperature vibration 3D motion sensor
  – Demonstrated orthogonality of vibration sensing in x- y- and z-axes. Successfully assembled and validated fabrication of vibration motion sensor.



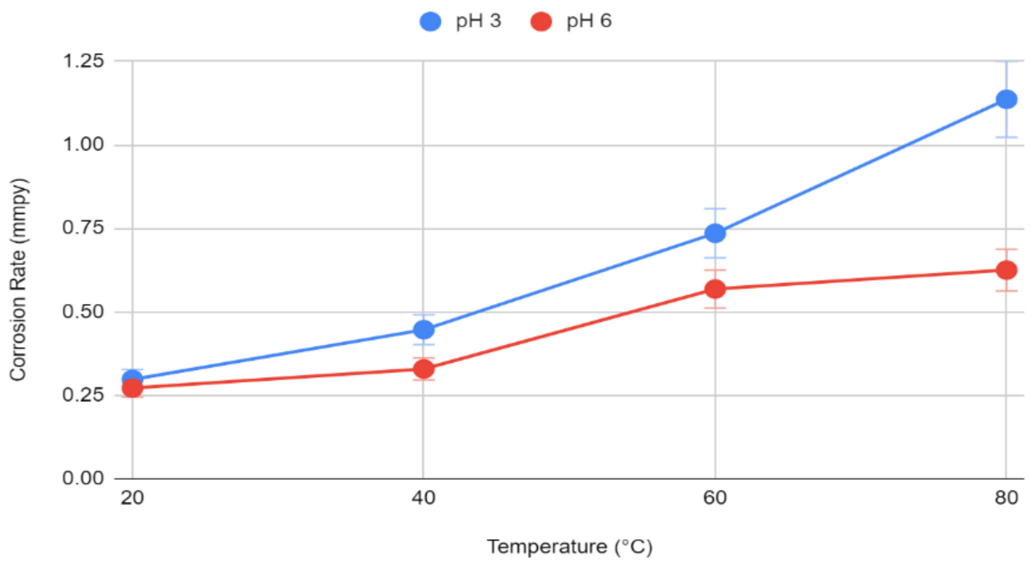




Summary of Accomplishments

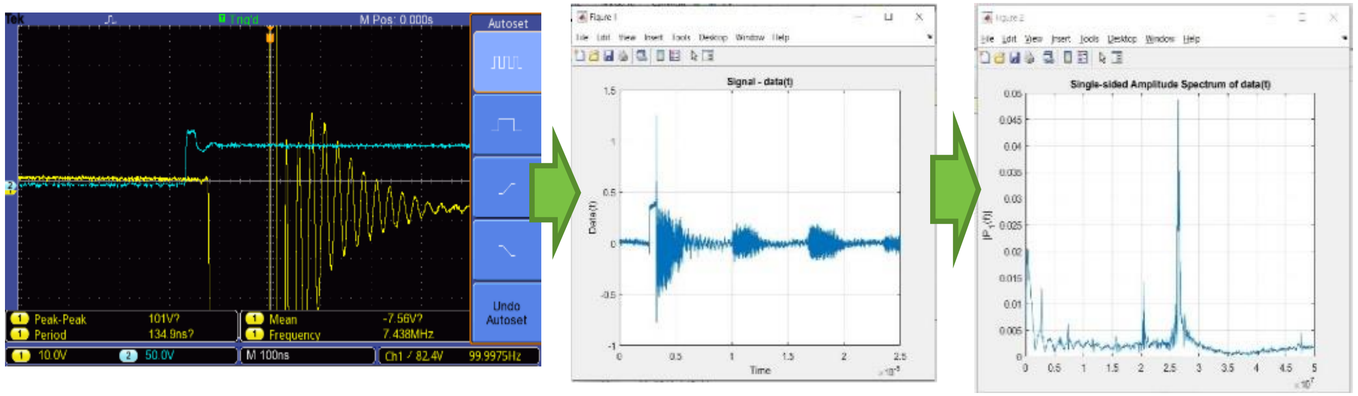
- Zirconium Oxide coated sensors:

  -The corrosion rate increased with decreasing pH (more acidic) and increasing temperature. Addition of a thin-film of ZrO_2 extended the lifetime by 2-5 years.



- Wireless Communication System

  -The conditioned data can be reconstructed on MATLAB for signal analysis. LabVIEW VI created to visualize the wirelessly transmitted signal remotely.



Technology Impact

- *Advances the state of the art for nuclear application*
  - ✓ Nonintrusive/embedded sensors under harsh environmental conditions utilizing innovative laser ultrasound generation techniques
- *Supports the DOE-NE research mission*
  - ✓ In-service monitoring of nuclear structures, ensuring nuclear energy supply with a reliable lifetime prediction
- *Impacts the nuclear industry*
  - ✓ Nonintrusive HiTEIS combined with wireless communication system for minimization of human influences
  - ✓ Laser ultrasound enabled remote structural health monitoring
- *Commercialization potential*
  - ✓ A liquid metal based HT laser ultrasound generator was prototyped and the technical feasibility has been demonstrated.
  - ✓ University technology transfer office will investigate business models for commercialization with the filed invention disclosure (patent). (current TRL: 4-5)

Conclusion

- Feasibility of laser ultrasound to detect surface damage on steel components at very high temperatures.
- An innovative liquid metal based photoacoustic transducer was investigated and characterized at HT conditions.
- 3D vibration motion sensor investigated via simulation and successfully fabricated.
- ZrO_2 thin film coated sensors can be more corrosion resistive.
- Wireless data communication system for HiTEIS has improved data acquisition, processing, and display.
- Next steps: During the extended project period, we will continue to improve the wireless communication system with time-of-flight feature extraction and graphic-user interface, together with a mockup test platform. We will also explore the capabilities of liquid metal laser ultrasound in high temperature NDT.

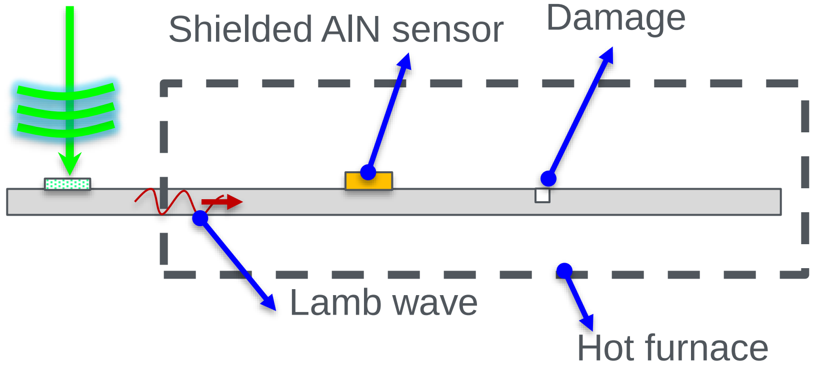
<u>Accomplishment 1:</u> Laser Ultrasound assisted high temperature damage detection (Task 3)

Purpose:

- To demonstrate proof-of-concept of high temperature laser ultrasound sensor and detect simulated damage at high temperature conditions (250 – 1,000 ^{o}C).

Methods:

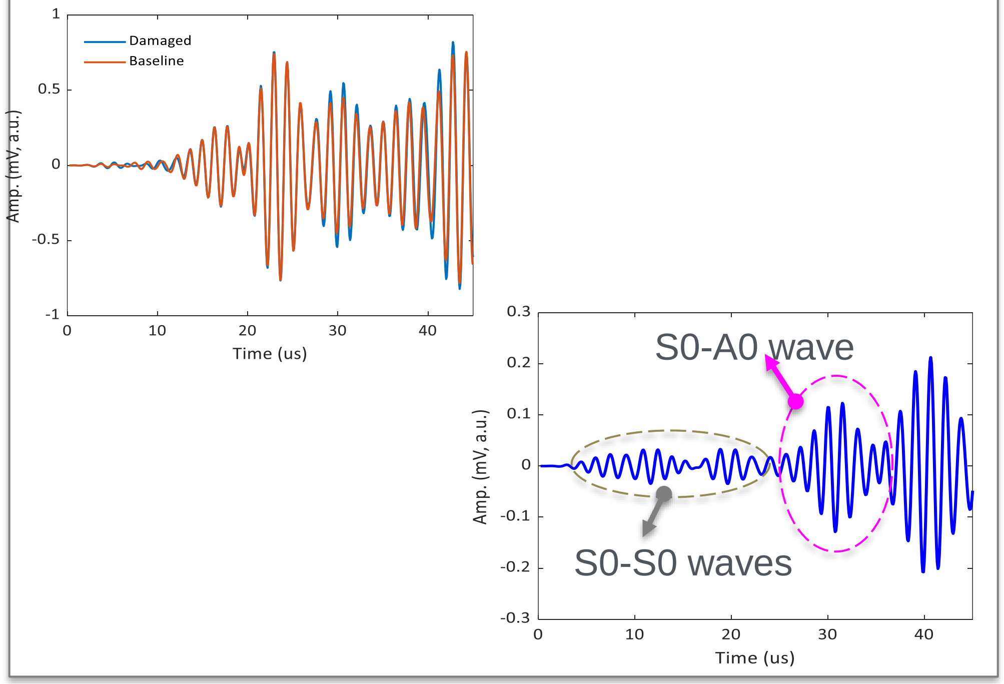
A. Concept and setup



Laser: **10 ± 0.5 mJ/cm^2**

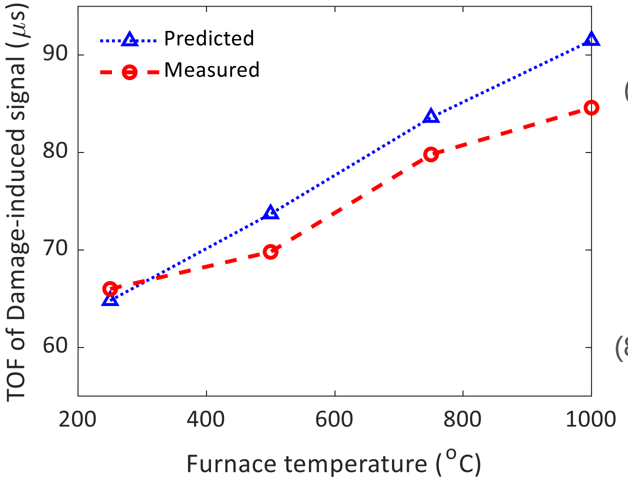
Furnace temp: **250 – 1,000 ^{o}C**

B. Simulation

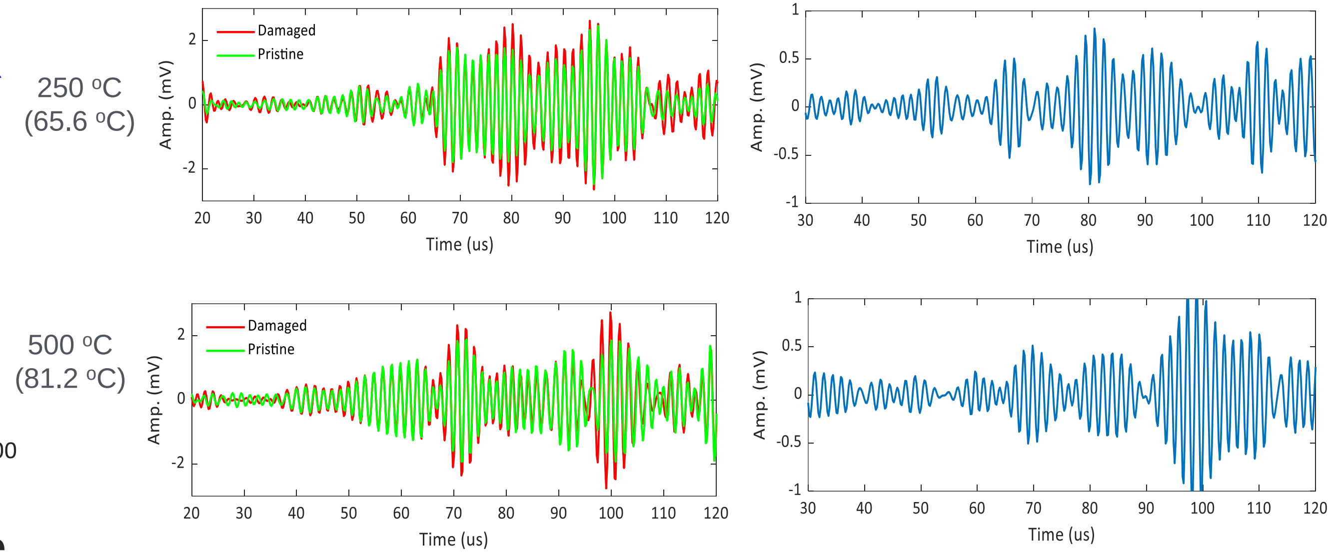


Accomplishment Details

Results:



Damage-induced wave signals are clearly detected.



Time-of-Flight of detection wave

Temp.(C)	Predicted (us)	Measured (us)	Error (%)
250	64.8	66	1.85
500	73.71	69.8	-5.30
750	84.645	79.8	-5.72
1,000	91.53	84.6	-7.57

Distance to damage and temp scaling factor

w/o Temperature Scaling		w/ Temperature Scaling	
Distance (mm)	Error (%)	Distance (mm)	Error (%)
56.73	3.47	56.73	3.47
63.91	17.81	55.12	0.24
82.78	55.55	57.43	4.85
91.84	73.67	53.95	-2.09

Conclusions:

- Demonstrated laser ultrasound at high temperature (up to 1000^{o}C) to detect surface damage on steel.
- S0-A0 lamb wave mode and temperature scaling factor can be used to accurately detect the defects.

Accomplishment Details

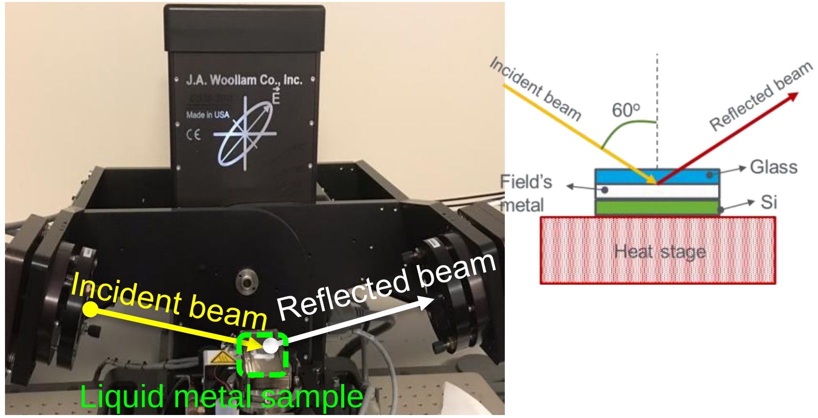
Accomplishment 2: **Liquid Metal Assisted Laser Ultrasound Transducer (Task 3)**

Purpose:

- To present a new PA transducer utilizing a liquid metallic material and to demonstrate the performance for the laser ultrasound generation.

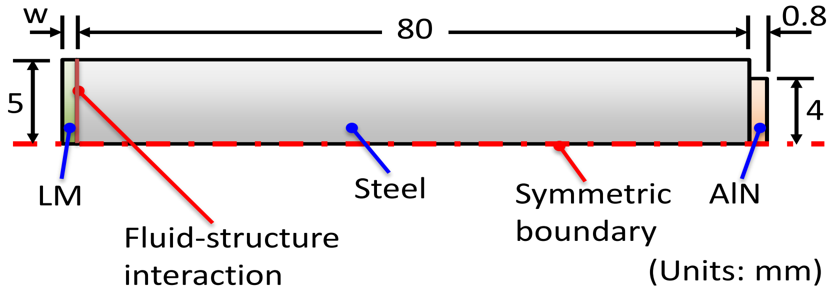
Methods:

A. Fields Metal Characterization



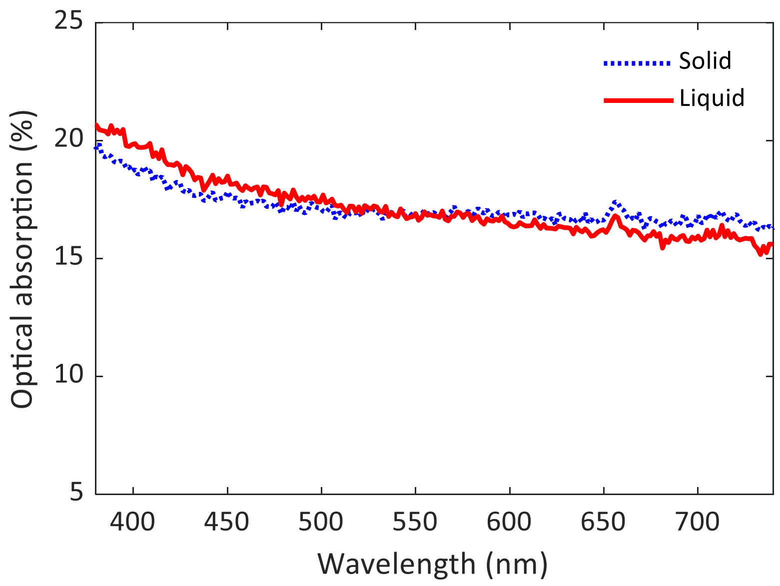
a. Optical ellipsometry (J.A. Woollam Co.)
b. Ratio of the optical reflection
c. Estimation of the optical absorption using the reflection data

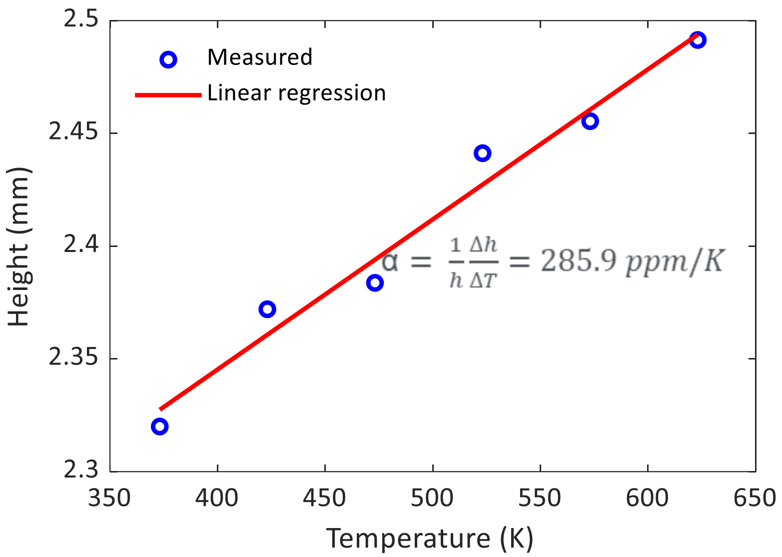
B. ANSYS Simulation

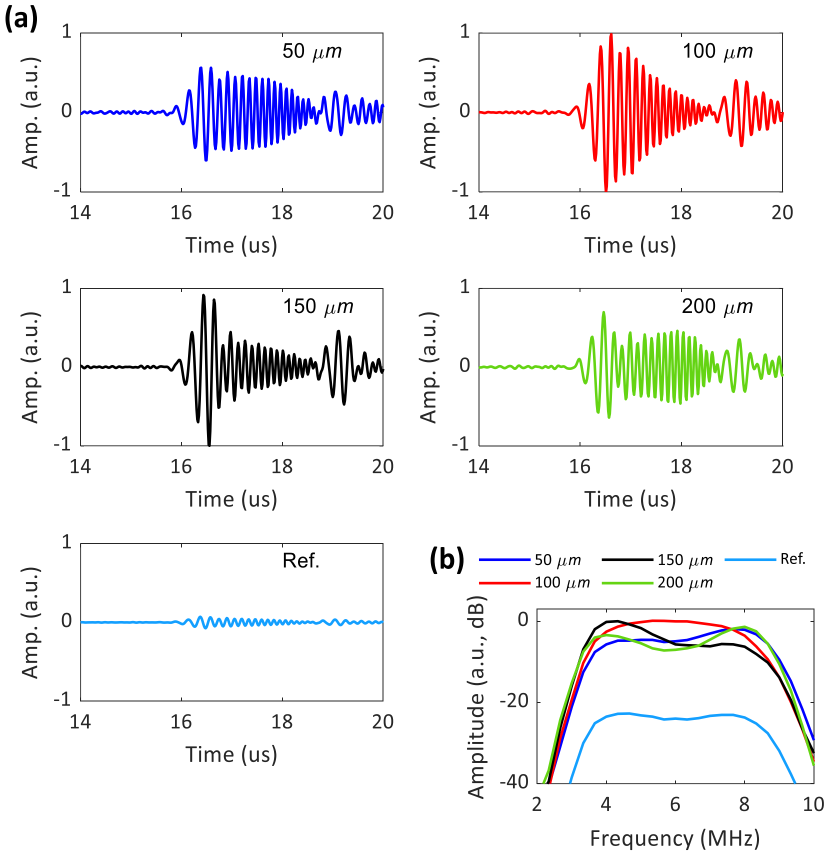


a. ANSYS Workbench (rel. 17.1)
b. Fluid-structure interaction condition between the steel and the liquid metal
c. Comparison LM with CSNP-PDMS at 100° C
d. Input condition: relative laser-induced pressures

Accomplishment Details







- A new modality utilizing liquid metallic material was investigated.
- Ensured the temperature stability of the liquid metallic materials in PA energy conversion.

Accomplishment Details

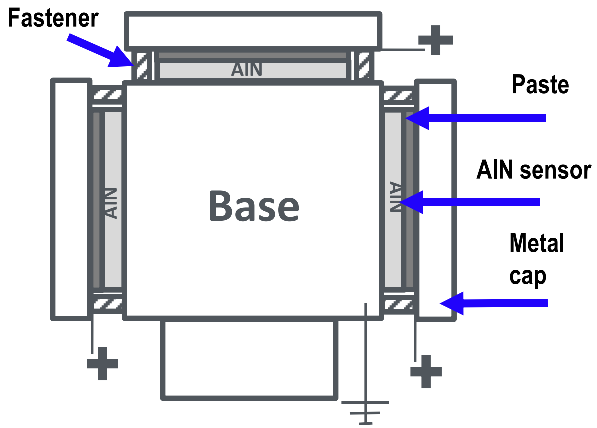
<u>Accomplishment 3:</u> High-Temperature Vibration Sensor fabrication and assembly (Task 2 & 3)

<u>Purpose:</u>

- To develop a HT 3D vibration motion sensor to detect normal and abnormal vibrations in the x-, y-, and z-directions for reactor components.

<u>Methods:</u>

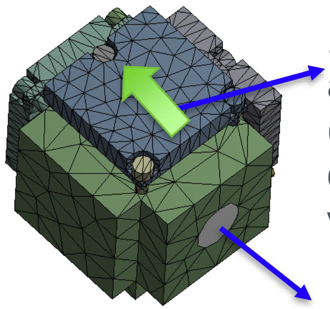
A. Sensor design and fabrication

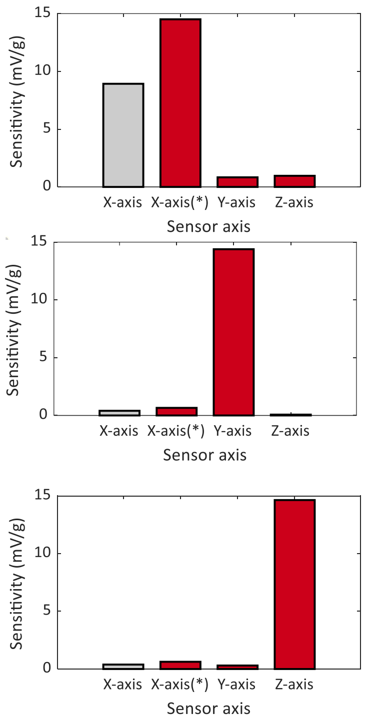


a. Compression type AlN (qty 3)
b. Base component acts as ground.
c. Insulating ceramic paste protects signal wires.

B. Simulation

a. Orthogonality among axes was confirmed.
b. Reliable (<3.5%) sensor response for any inclined vibration input.
c. ANSYS v. 17.1 (Cannonsburg, PA)
d. Frequency harmonic analysis

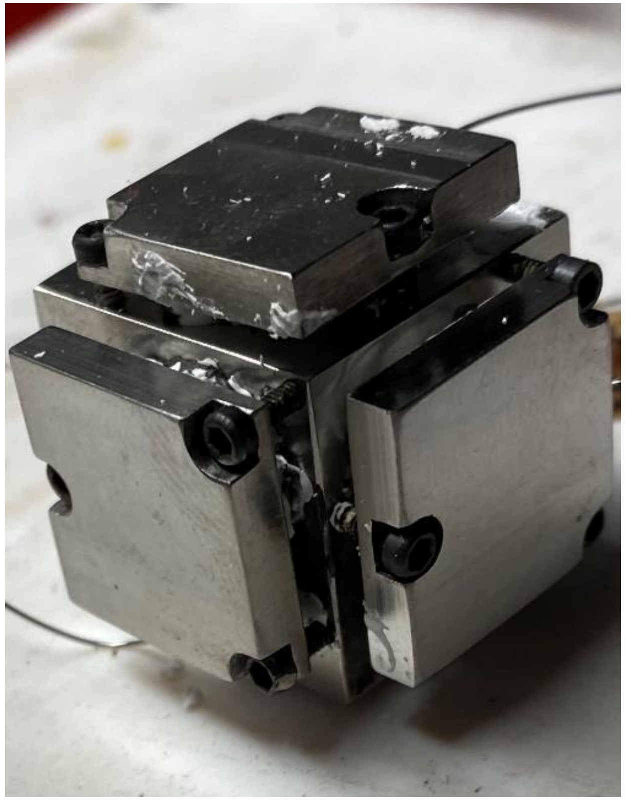




Accomplishment Details

Results:

	Pre-Fab	X-Axis	Y-Axis	Z-Axis
Capacitance (pF)	2.2	2.0	2.1	2.0
Dielectric Loss	0.022	0.020	0.018	0.019
Resonance (kHz)	640	640	640	640



- Successfully demonstrated orthogonality of vibration sensing in x- y- and z-axes.
- Successfully assembled and validated fabrication of vibration motion sensor.

Accomplishment Details

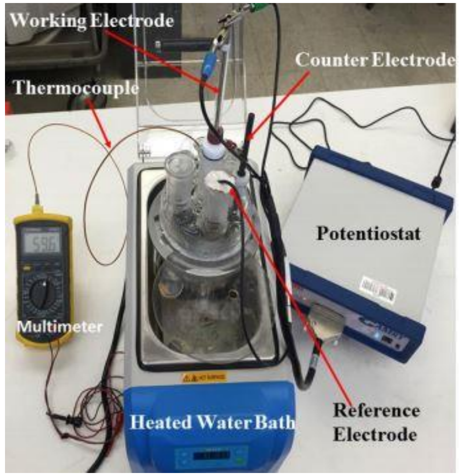
Accomplishment 4: Effect of Thin-Film Coatings for Enhanced Corrosion Resistance (Task 2 & 3)

Purpose:

- To measure the effectiveness of adding thin layers of ZrO_2 coatings to improve the sensor's lifetime in corrosive environments.

Methods:

A. Fabrication

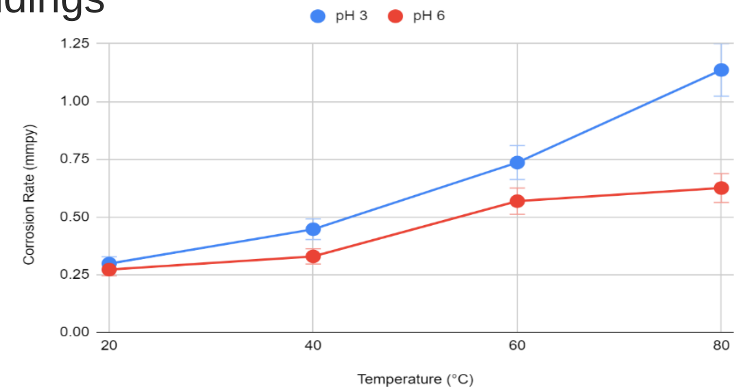


a. Thin-films (~100 nm) of ZrO_2 coated using Atomic Layer Deposition (ALD).
b. Cyclic polarization corrosion tests.
c. Solution of KNO_3 and H_2SO_4 at pH values of 3 and 6.

Results:

B. Corrosion rate findings

a. Addition of a thin-film of ZrO_2 extended the lifetime by 2-5 years.
b. Corrosion rate increased with decreasing pH (more acidic) and increasing temperature.
c. The corrosion resistance was improved by utilizing thin-film coatings.



Temperature	Lifetime (yr)	
	Bare	Coated
20 °C	8.3	12.9
40 °C	5.4	9.2
60 °C	3.7	5.9
80 °C	2.8	4.8

Accomplishment Details

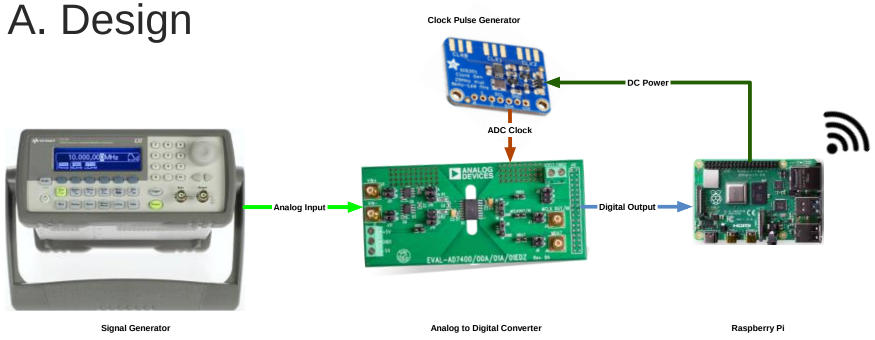
<u>Accomplishment 5:</u> Wireless Communication System (Task 2 & 3)

<u>Purpose:</u>

- To provide data relay from noninvasive sensor to the signal conditioning system and wirelessly communicate the data to be displayed on graphic user interface for the operator.

<u>Methods:</u>

A. Design

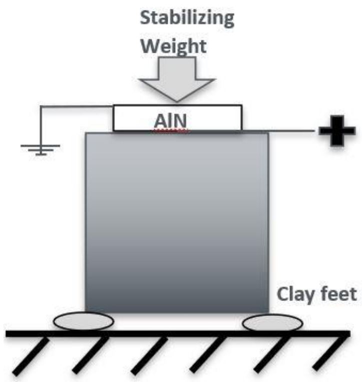


Block diagram of the test setup

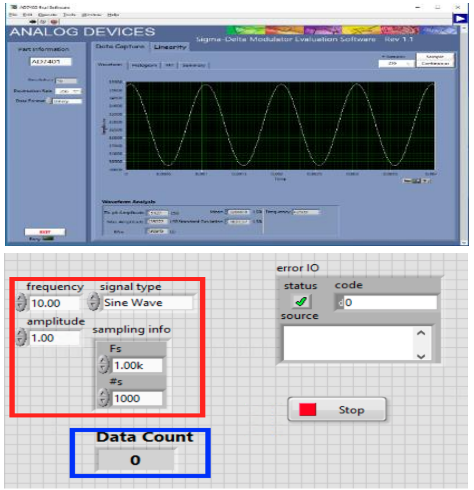
The AlN sensor output goes through the signal conditioning circuit and then the Analogue-to-Digital Converter (ADC) before it can be transmitted wirelessly.

The Output must be maintained under 300 mV to avoid damaging the WCS circuit.

B. Experimental setup



C. Simulation

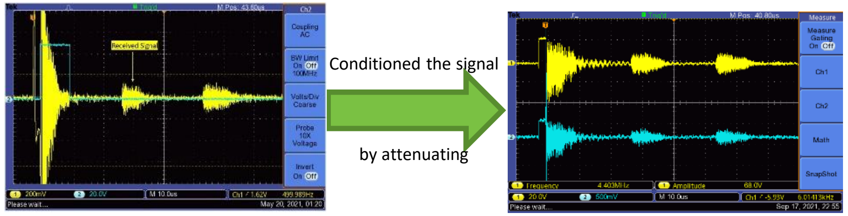


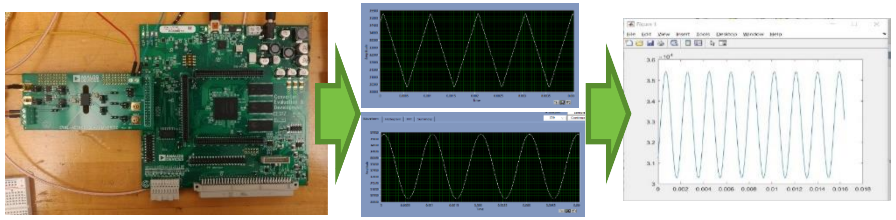
a. Test signal - Sine wave captured from EVAL-CED1Z board.
b. LabVIEW readout of virtual sensor data.

Accomplishment Details

Results:

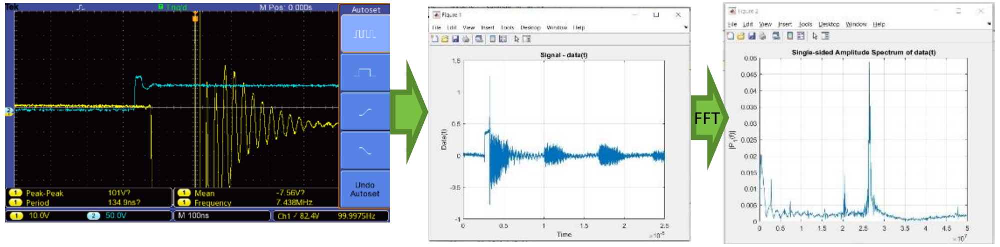
Stable, repeatable data acquisition



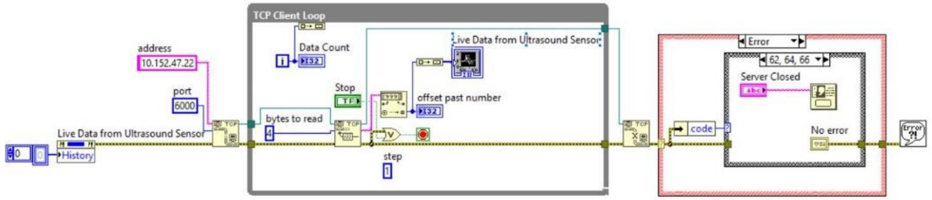


- ➢ The voltage attenuator appropriately scales AIN signal to a safe voltage to be read by the AD7400 ADC.
- ➢ The input signal after conditioning which has a frequency of 5 to 6 MHz with ~300mV amplitude is read by the AD7400 ADC.

Wireless Communication and Data Acquistion



Signal Data reconstruction on MATLAB to do FFT Analysis of the input signal



LabVIEW VI created to acquire wirelessly communicated data

- ➢ The conditioned data can be reconstructed on MATLAB to do FFT Analysis of the original signal.
- ➢ LabVIEW VI Created to visualize the wirelessly transmitted signal remotely.

Conclusions:

- The system can acquire and read the conditioned attenuated data from the ultrasound sensor with the ADC and the FPGA Board.
- The data can be visualized with a LabVIEW VI after transmitting it wirelessly.

Accomplishment Details

Publications:

A. Journal papers (4)

[1] Howuk Kim, Kyunghoon Kim, Nicholas Garcia, Tiegang Fang, and Xiaoning Jiang, "Liquid metallic laser ultrasound transducer for high-temperature applications", Appl. Phys. Lett. 118, 183502 (2021) https://doi.org/10.1063/5.0046052.

[2] Kim, T. H. Kim, and X. Jiang, “Laser ultrasonic defect localization using an Omni-arrayed candle soot nanoparticle patch“, Japanese Journal of Applied Physics, 2021.

[3] Peng, C., M. Chen, J. Spicer, and X. Jiang, “Acoustics at the nanoscale (nanoacoustics): A comprehensive literature review. Part I: Materials, devices and selected applications, Sensors and Actuators: A. Physical, 2021.

[4] Peng, C., M. Chen, J. Spicer, and X. Jiang, “Acoustics at the nanoscale (nanoacoustics): A comprehensive literature review. Part II: Nanoacoustics for biomedical imaging and therapy, Sensors and Actuators: A. Physical, 2021.

B. Conference papers and presentations (1)

[1] S. Kerrigan, H. Kim, M. Bourham, X. Jiang, “Effect of ZrO2 Thin-Film Coating on the Corrosion Resistance of AlN Piezoelectric Single Crystal Sensors,” *Advanced Sensors and Measurement Technologies*, Online presentation, pp. 406-415, 2021.

Contact: Dr. Xiaoning Jiang, xjang5@ncsu.edu; ORCiD: 0000-0003-3605-3801

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

ASI Advanced Sensors and Instrumentation

Acousto-Optic Multimodal Sensors for Advanced Reactor Monitoring and Control

CA-19-WA-PN__-0702-01

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Project Manager: Michael Larche
Co-Principle Investigators: Morris Good, Ph.D. and Yanming Guo, Ph.D.

Pacific Northwest National Laboratory
Signature Science and Technology Division

Project Overview

- Goal and Objectives:
  - The goal of this project is to design and develop a multimodal sensor for measurements of critical process parameters in advanced non-light water-cooled nuclear power plants (NPPs), for the early detection and characterization of atypical operating conditions.

  - Objectives
    - Develop an acousto-optic mechanism for measurement extraction from a Surface Acoustic Wave (SAW) device
    - Integrate a SAW and/or optical sensing-based mechanism for gas composition into a dual-mode SAW sensor
    - Develop algorithms for deconvolving the effects of temperature, pressure, and gas composition to extract three measurements from an integrated multimodal sensor
    - Test and evaluate the accuracy and reliability of the sensor.

Project Overview: Schedule and Participants

Year	Milestone/Deliverable	Description
1	M3CA-19-WA-PN -0702-014	Status Update of Multimodal Sensor Design
	M3CA-19-WA-PN -0702-015	Status Update of Evaluation Criteria for Assessing a Multimodal Sensor Concept and Data Analytics Deconvolution of Mixed Signals
	M2CA-19-WA-PN -0702-013	Year 1 FY20 Status Update of Smart Multimodal Sensor Design for Advanced Reactor Monitoring
2	M3CA-19-WA-PN -0702-018	Test Plan for Evaluating Sensor Concept Sensitivity
	M3CA-19-WA-PN -0702-019	Status update of Data Analytics Efforts for Isolating Measurement Parameters of Multimodal Sensor Data
	M2CA-19-WA-PN -0702-017	Year 2 FY21 Status Update of Smart Multimodal Sensors for Advanced Reactor Monitoring
3	M3CA-19-WA-PN -0702-0112	Status Update of Final Multimodal Sensor Design
	M3CA-19-WA-PN -0702-0113	Sensor Concept Testing/Evaluation and Analytics Update
	M2CA-19-WA-PN -0702-011	Final Report for (Project 19-17070) Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control

- Project Team
  - Pacific Northwest National Laboratory (PNNL)
    - Michael Larche (PI), Dr. Morris Good (Co-Pi), Dr. Yanming Guo (Co-Pi), Nicholas Conway, Dr. Michael S. Hughes, Dr. Hardeep Mehta, Dr. Mychailo Toloczko, and Ferdinan Colon
    - Student: Victor Aguilera-Vazquez
  - University of North Texas (UNT)
    - Co-Pi: Dr. Haifeng Zhang
    - Student: Chen Zhang (now employed at PNNL)

Technology Impact

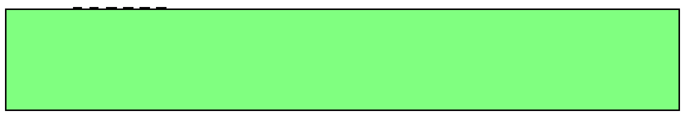
- *Advances the state of the art for nuclear application*: Work addresses technical gaps in temperature, pressure and gas composition sensing capabilities for advanced reactors.
- *Supports the DOE-NE research mission*: Work directly contributes to the DOE mission directives by developing enabling technology capable of reliable, higher-resolution process measurements for deployment of advanced reactors.
- *Impacts the nuclear industry*: The resulting multi-modal sensing platform will enable reduction of vessel penetrations in advanced reactors for condition monitoring sensors.
- *Commercialization*: Anticipated developments include deconvolving measurements affected by mixed parameters to measurements of parameters of interest, development of multimodal sensors for a variety of harsh condition measurements across the NE space and into other harsh environment applications (advanced reactors, petrochemical, sustained high temperature operation, etc.)

Results and accomplishments: Outline

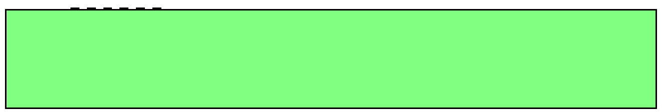
- Technical Outline:
  - Work performed at University of North Texas (UNT)
    - Modeling Surface Acoustic Wave (SAW) Generation and Interaction with Material
    - Design and Fabrication of SAW Resonator as Concept Pressure Sensor
  - Work performed at PNNL
    - Design and Fabrication of Multimodal SAW Sensor
    - Temperature and Pressure Test Setups and Unprocessed Data Format
    - Data analysis to reliably estimate Arrival Time
    - Temperature and Pressure Measurement Results

Work performed at UNT: Modeling of SAW Interaction with Material

- 2-D wave propagation modeling on LiNb03 and AIN
  - Wave is excited with AC voltage (@ saw resonator resonant frequency) supplied to the IDTs.
  - Wave is constrained in the surface area (with 1~2 wavelength) of the piezoelectric substrate.

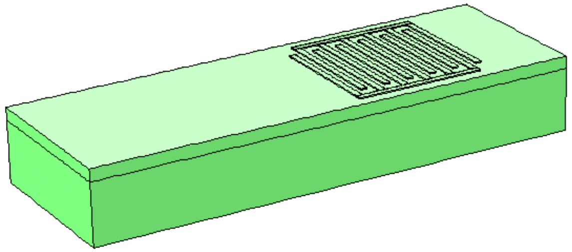


$LiNbO_3$

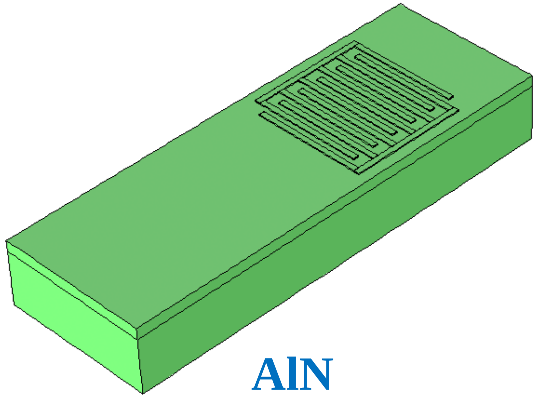


AlN

- 3-D wave propagation modeling on LiNb03 and AIN



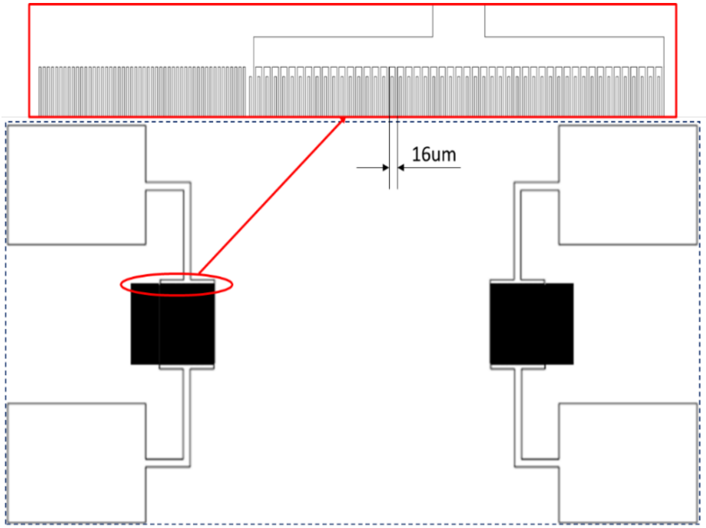
$LiNbO_3$



AlN

Work performed at UNT: Design and Fabrication of Pressure Sensor

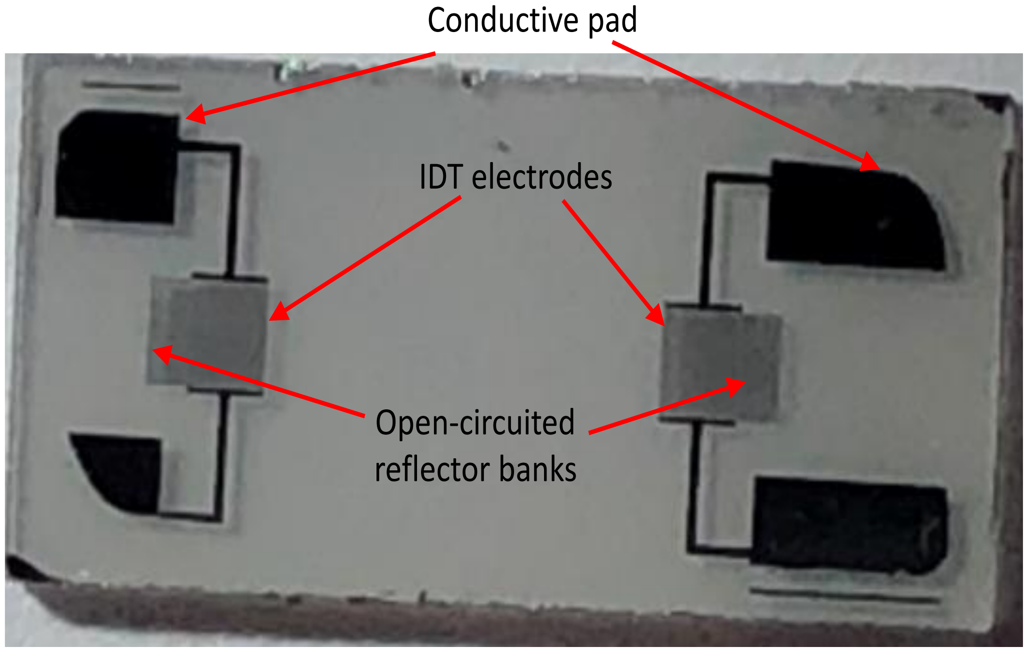
SAW Sensor Design



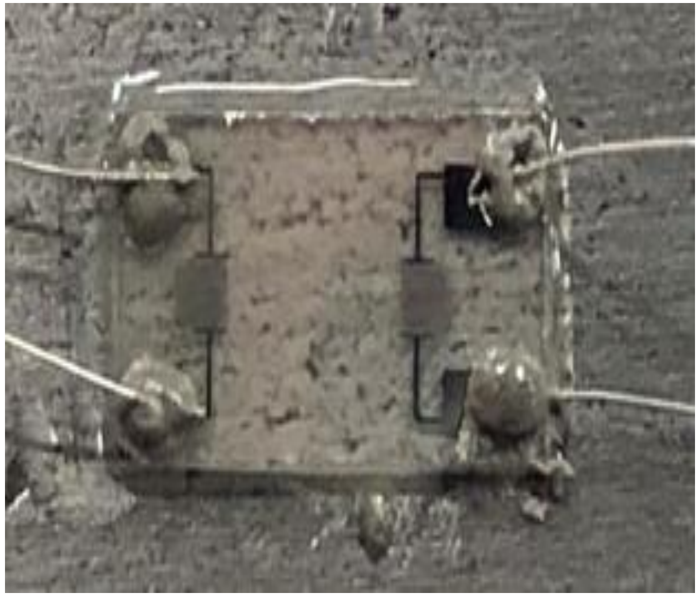
Design Features

- Two-ported SAW resonator
- 10 mm*5 mm*0.5 mm Y-cut LiNbO3 substrate
- 4 μm pitch size with reflector banks
- 16 μm wavelength
- Rayleigh wave velocity of 3560 m/s

Fabrication and Attachment to Beam for Strain to Mimic Pressure



- Positive Photolithography used to fabricate Interdigital Transducer (IDT) electrodes and Open-Circuited Reflector Banks

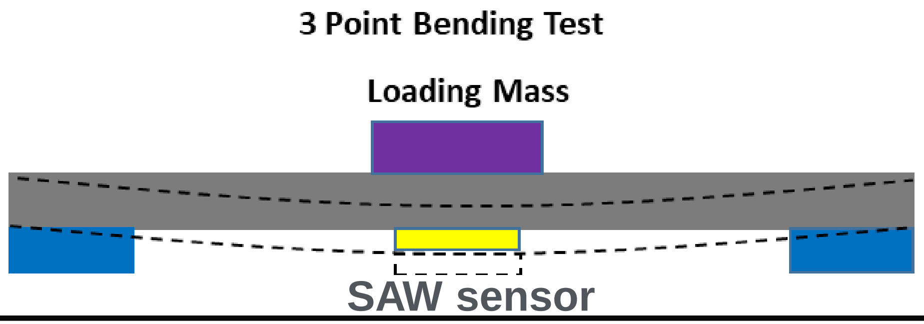


- Single wire attached on each electrically conductive pad
- Epoxy attached SAW sensor to surface of a carbon steel beam
- 3 Point Bending Test created strain that mimicked deflection caused by pressure

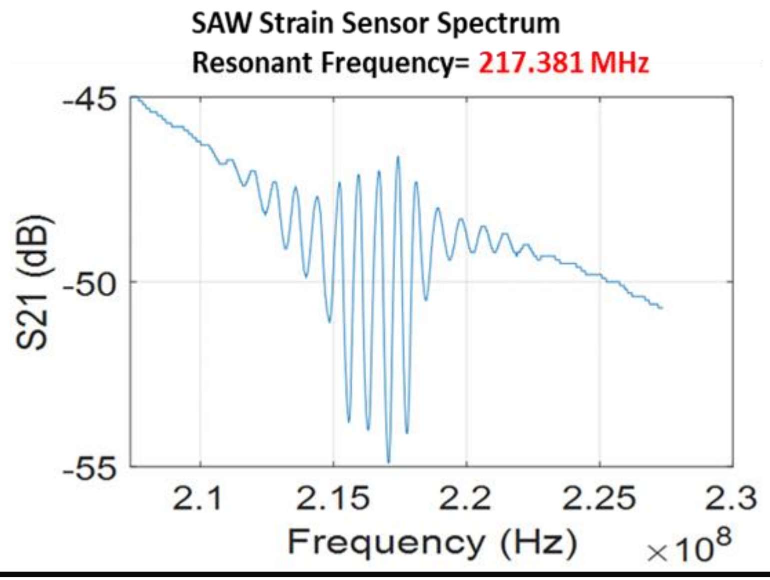
Work performed at UNT: Design and Fabrication of Pressure Sensor

- Test Setup for validation of the pressure sensor concept and typical data format of amplitude versus frequency

Test Setup:



Data Format: Amplitude versus Frequency for Two-Ported SAW Resonator



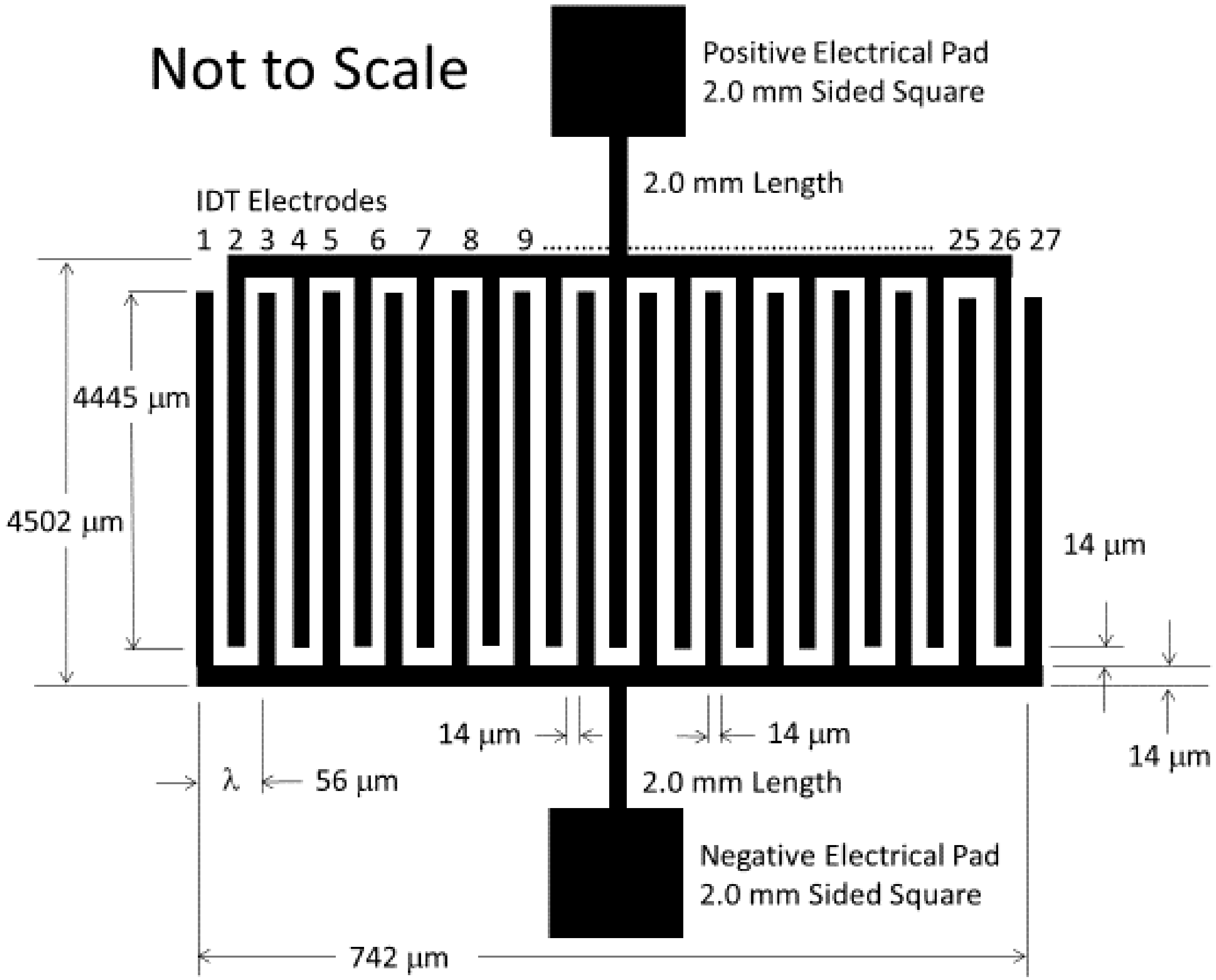
<u>Test Setup Parameters</u>

- Static tests with proof mass loading to simulate pressure
- Different loading levels at 0, 100, 200, and 300 g
- LiNbO2 substrate dimensions: 7.5 mm x 7.5 mm
- Beam dimensions: 220 mm x 12.5 mm x 0.6 mm
- Displacement between supports: 180 mm

Work performed at PNNL: Sensor Design #1

- PNNL Design #1: SAW IDT Design Parameters

  Transmitter-Receiver-0 with 27 IDT elements

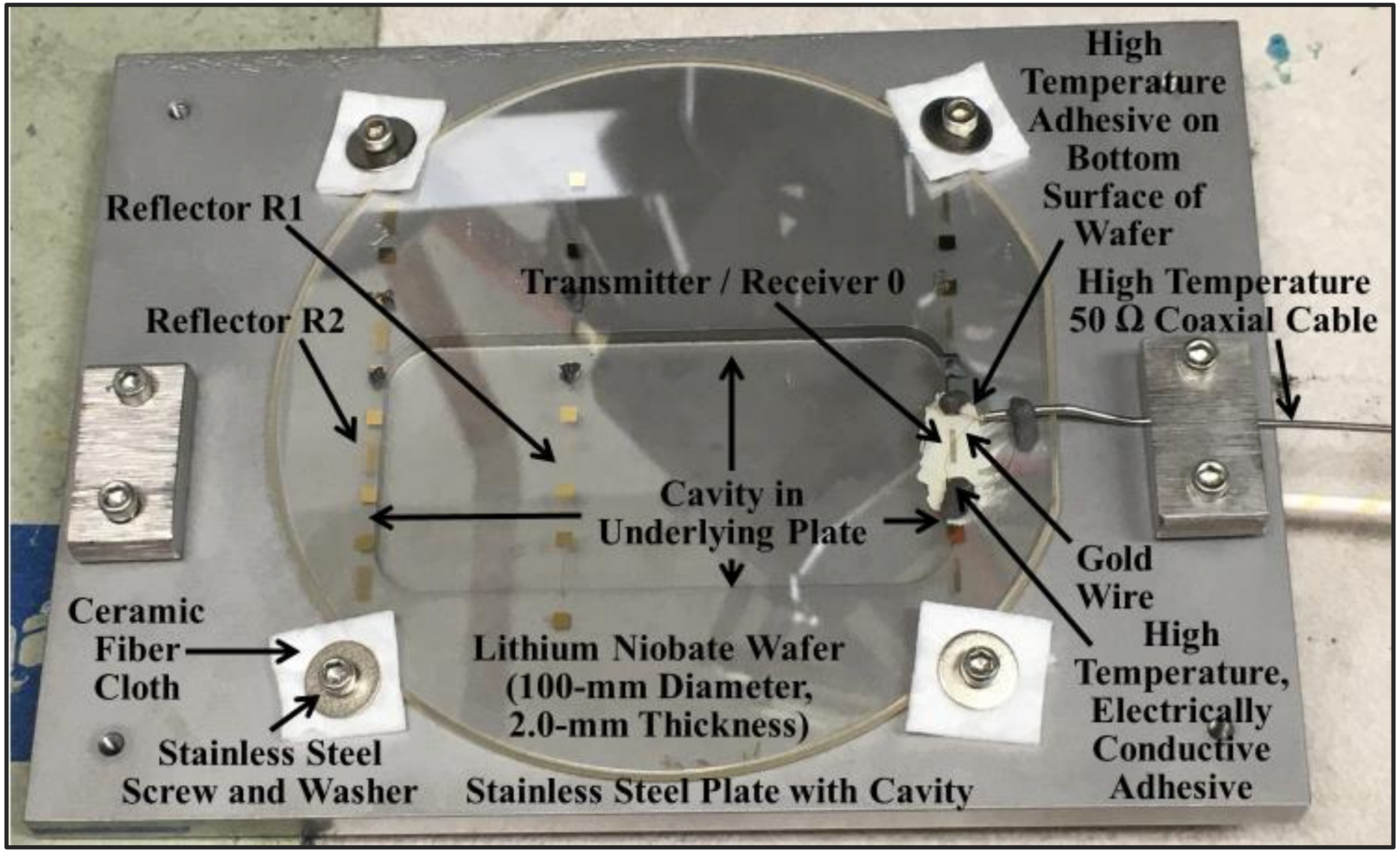


<u>Design Features</u>

- SAW with 1 IDT transmitter and multiple IDT reflectors
- Open reflectors: Enables response reception
- SAW design modified from temperature and pressure sensor (Hashimoto et al., 2008) to extend ranges
- Lithium Niobate (LiNbO3) Y-cut SAW grade wafers
  - Curie temperature: ~1200 °C
  - Diameter: 100 mm
  - Thicknesses: 2.0 and 0.5 mm
  - 70 MHz design
    - Facilitated fabrication with larger scaled features
    - Matched available instrumentation
    - Can be scaled to smaller versions at higher *f*
  - LiNbO3 is relatively economical: Design and Testing
  - Design transferable to material such as AlN: Curie temperature >2000 °C
  - Electrodes: 10 nm Chromium and 150 nm Gold
  - Used Lift-Off photolithography process.

Work performed at PNNL: Fabrication based on Sensor Design #1

- PNNL Design #1: SAW IDT Pattern on LiNbO3 Wafer for Initial Evaluations
  - T-R 0 is transmitter and receiver in pulse-echo mode
  - R-R 1 and R-R 2 are reflectors for pulse-echo mode and receivers for through-transmission mode.



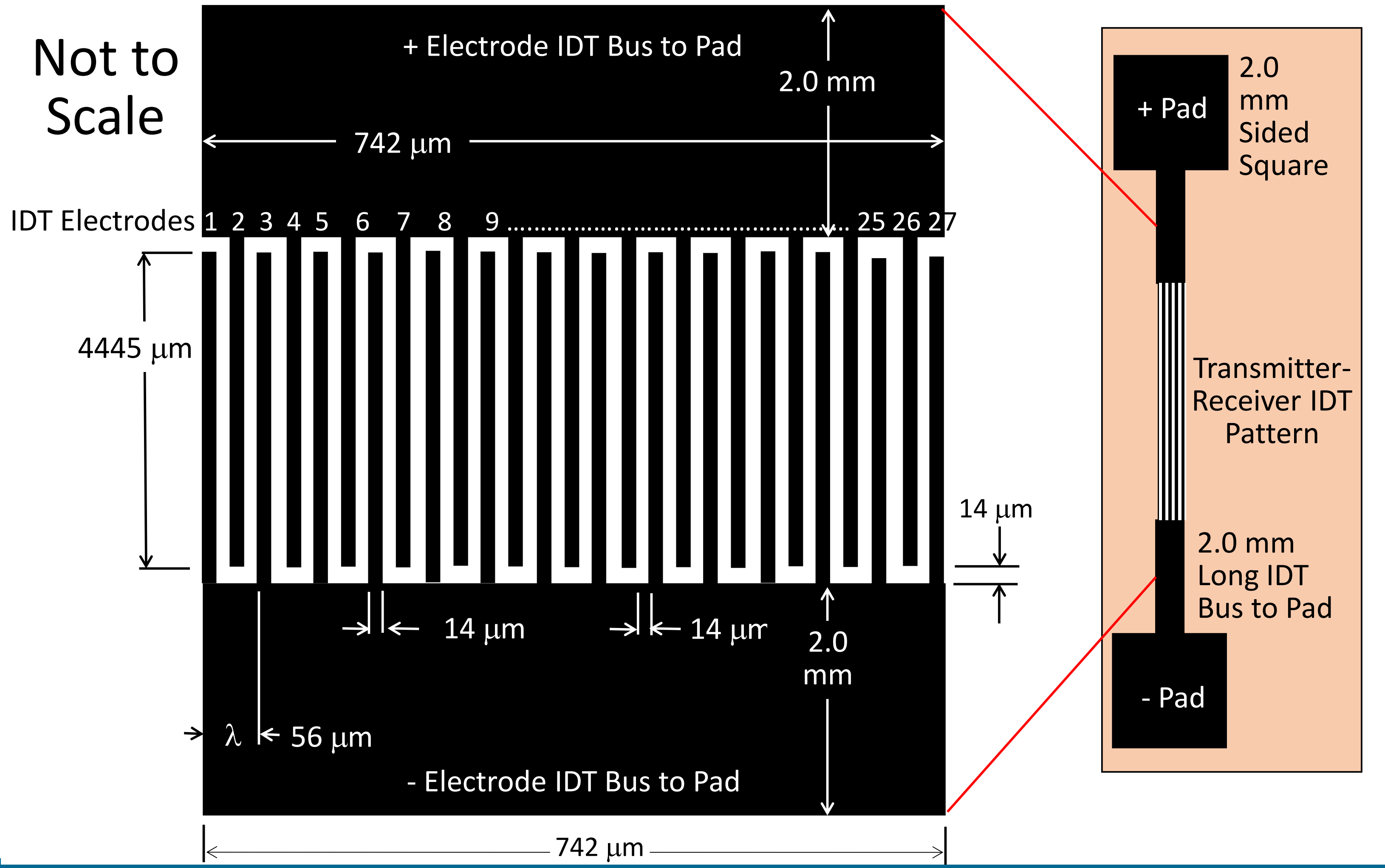
SAW Sensor Configuration

- Temperature Sensor
  - LiNbO3 wafer held in place on stainless steel plate
  - No Seal
- Temperature-Pressure Sensor
  - LiNbO3 wafer attached to stainless steel plate with epoxy
  - Seal between wafer and plate with underlying cavity forming a diaphragm
  - Temperature held constant for initial Pressure Test.

Work performed at PNNL: Sensor Design #2

➢ PNNL Design #2: SAW IDT Design Parameters

Transmitter-Receiver-0 with 27 IDT elements   Overall View

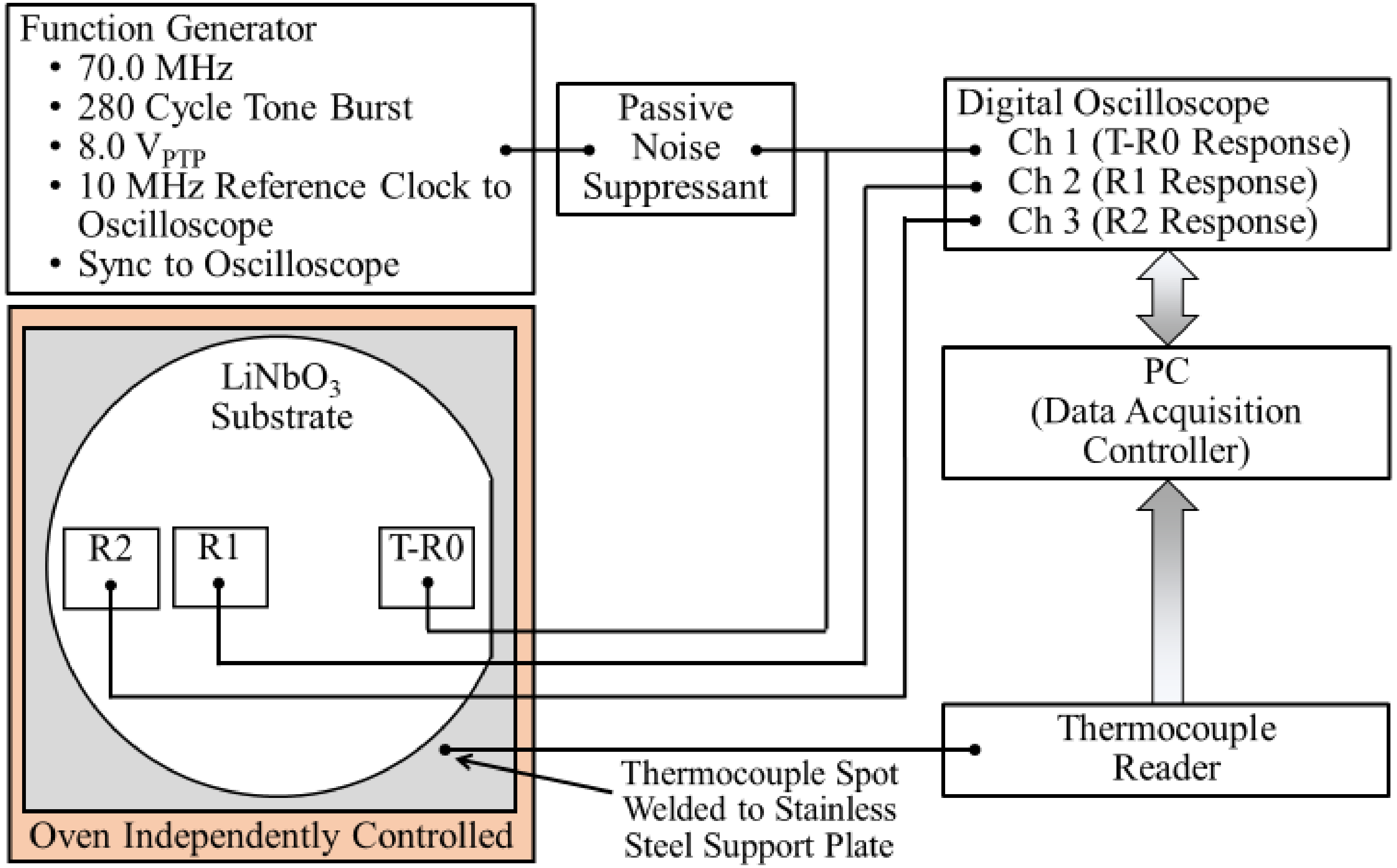


<u>Design Changes</u>

- SAW IDT Bus increased to width of IDT Pattern
- Reflectors:
  - Changed to Closed from Open
  - Both R1 and R2 IDT electrodes set to 11
- Electrodes: 10 nm Chromium and 200 nm Gold
- Moved transmitter and reflectors
  - Transmitter towards wafer center
  - Temperature reflector at left side
  - Temperature-pressure reflector at right side.

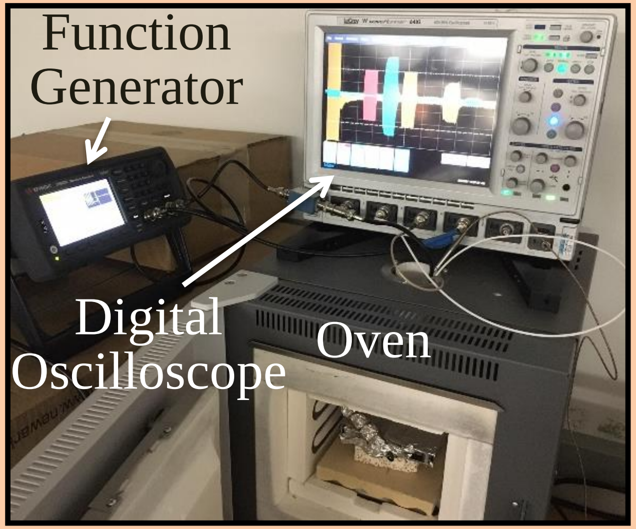
Work performed at PNNL: Temperature and Pressure Test Setups

➢ Temperature-Pressure Test Configurations



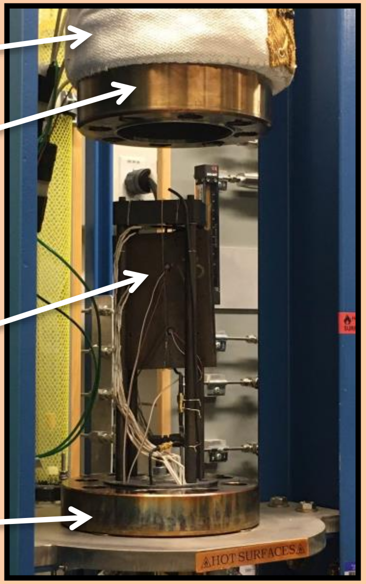
Oven Setup

- 25 - 700 °C
- Air
- 0 barg (0 psig)



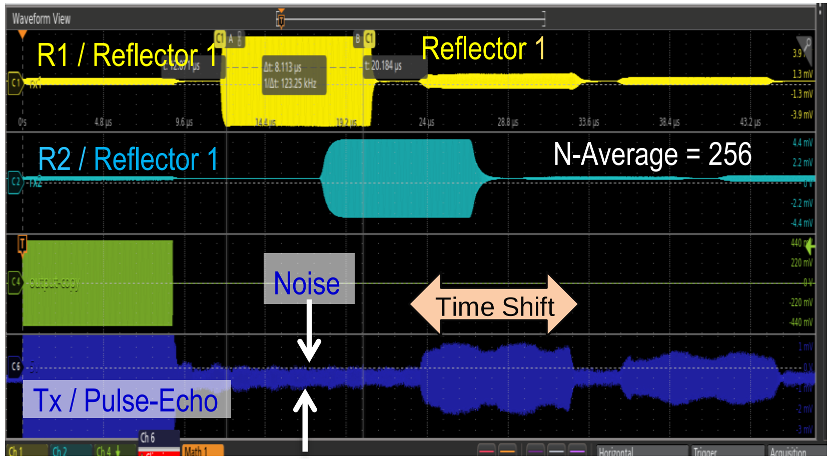
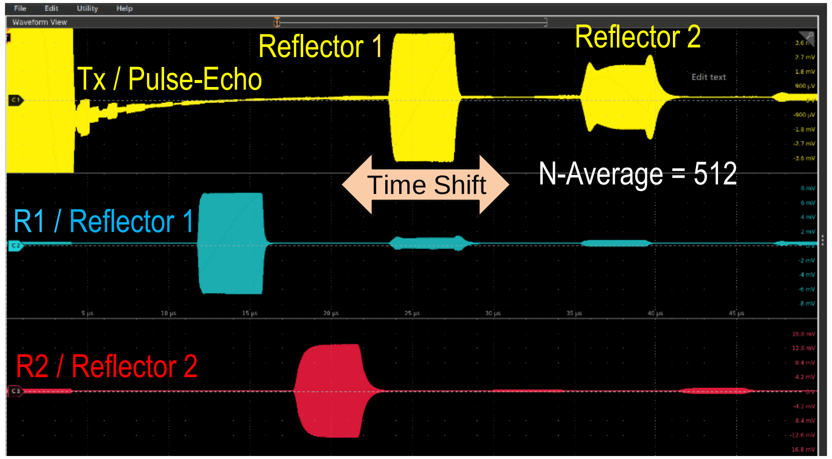
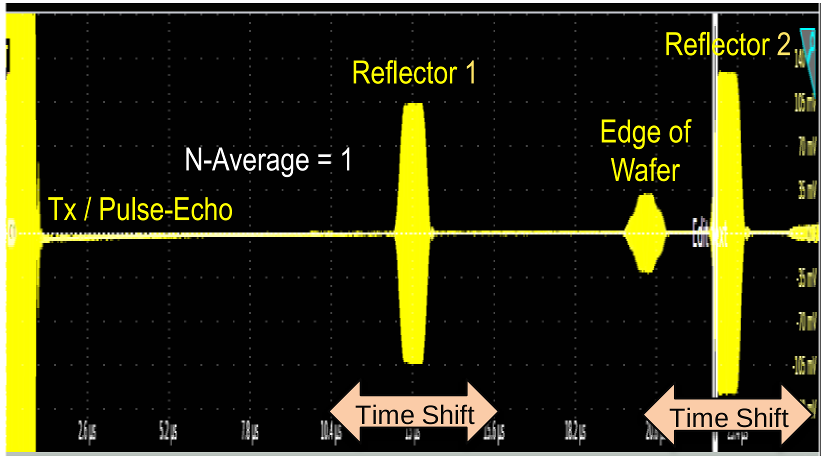
Autoclave Setup

- 25 - 360 °C
- Nitrogen
- 0 - 207 barg (0 - 3000 psig)



Work performed at PNNL: Unprocessed Data (Amplitude vs Time)

➢ Unprocessed Amplitude versus Time Data (RF Response) with Designs #1 and #2

Raw RF waveforms – Design #1	Raw RF waveforms – Design #1	Raw RF waveforms – Design #2
		

Initial Temperature Experiment

- Setup
  - Tone-Burst less than 1.0 V_{PP}
  - Average at 256 sweeps
- Noise of Pulse-Echo response required use of Open Reflectors as Receivers

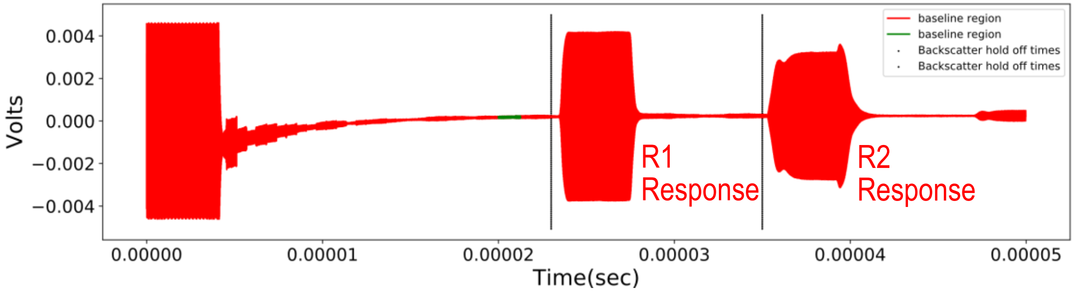
Second Temperature Experiment

- Setup Changes
  - Tone-Burst at 8.0 V_{PP}
  - Average at 512 sweeps
  - Used passive noise suppressant at Output of Function Generator
- Pulse-Echo signal-to-noise ratio (SNR) was markedly improved
- Interference apparent in Reflector 2 response

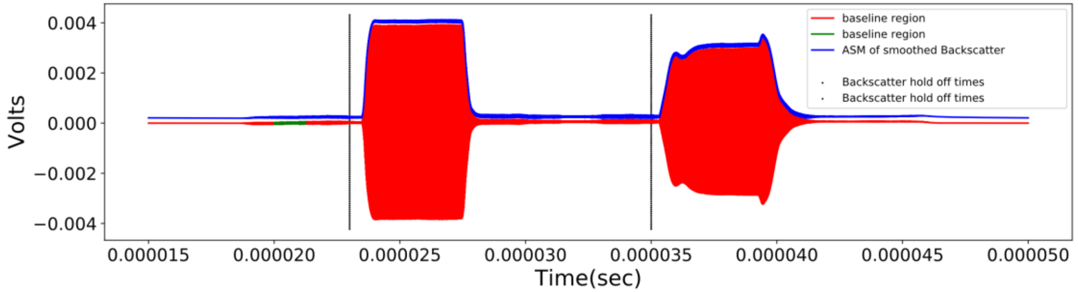
Pressure-Temperature Experiment

- Setup Changes
  - No averaging (1 sweep)
- Design #2 Improvements
  - IDT bus line width increased
  - Thicker gold layer
  - Transmitter between R1 and R2
- R1 – Temperature
- R2 – Temperature-Pressure with sealed cavity.

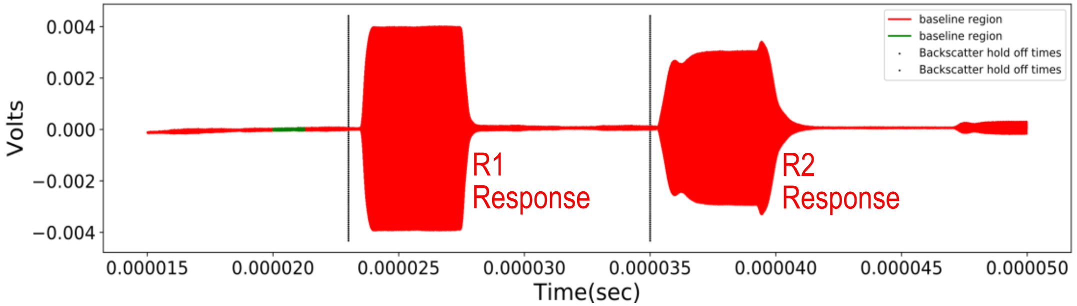
Work performed at PNNL: Data Analysis to Estimate Arrival Time



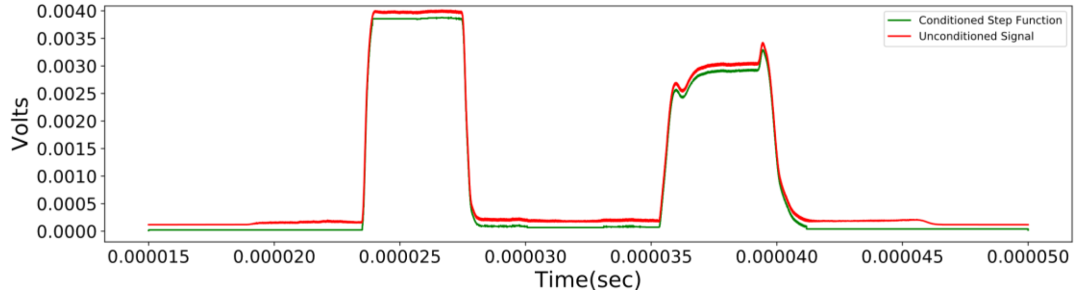
Unprocessed data used for Arrival Time versus Temperature



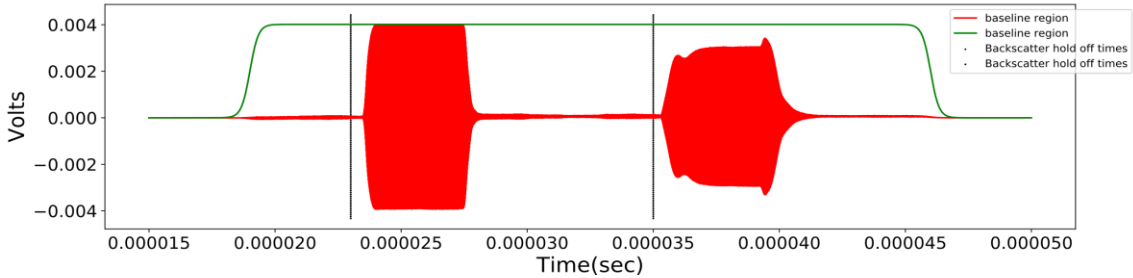
Analytic Signal Magnitude (Blue Plot) of Responses of R1 and R2



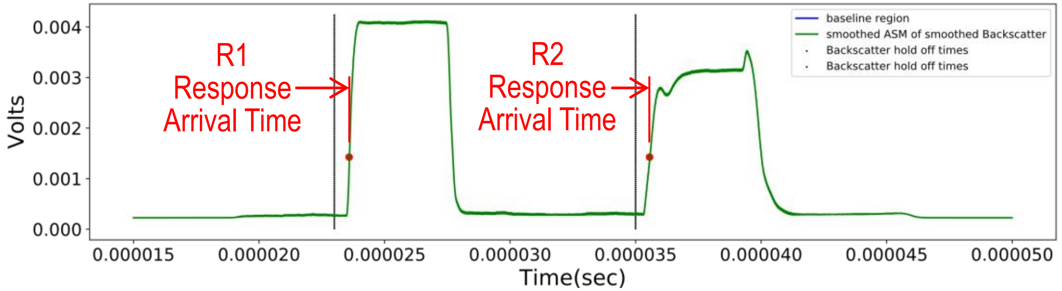
Gated Time Interval displayed



Smoothed Curve (Green Plot) of Analytic Signal Magnitude

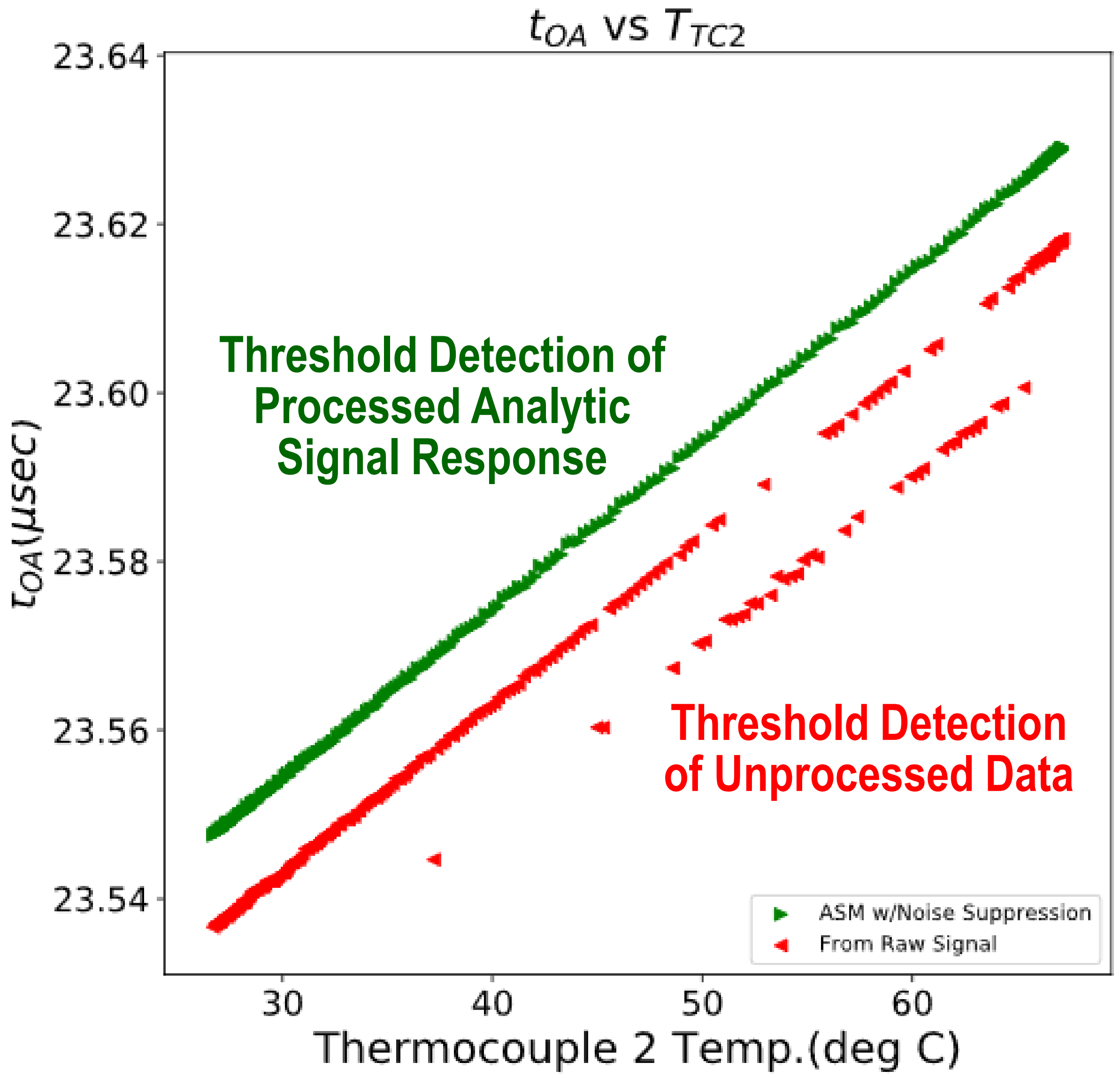


Window function and Hold-Off Times for Responses of R1 and R2



Threshold of 0.0015 V used to estimate Arrival Time of R1 and R2

Work performed at PNNL: Data Analysis Comparison



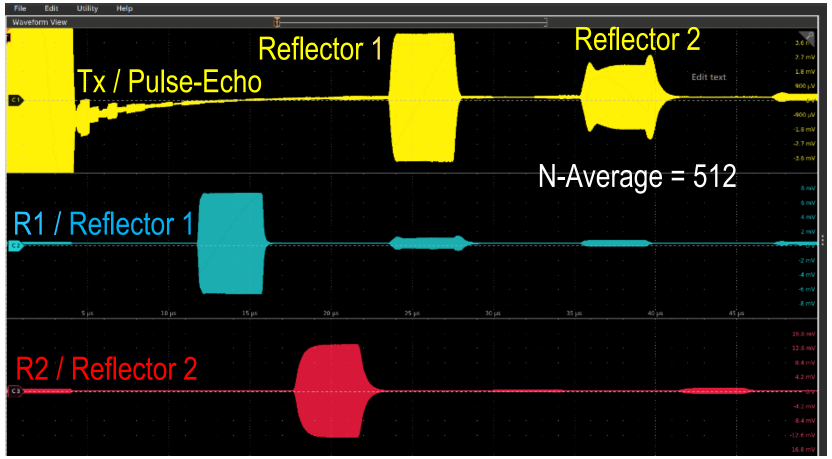
Observation

- Ambiguity is significantly reduced by use of the Analytic Signal Response and increases measurement reliability
- The ambiguity of unprocessed data is like the Phase Unwrapping Issue of Phase Detection and unwrapping multiple intervals of 2π radians.

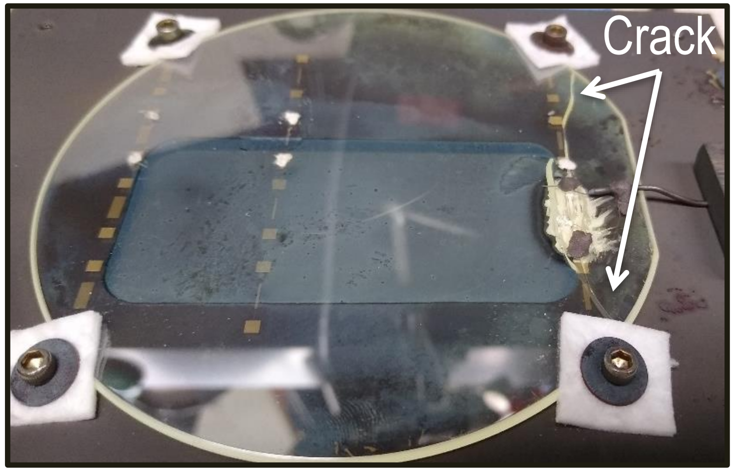
Results and accomplishments: Temperature Data with Design #1

➢ Temperature Test with Design #1

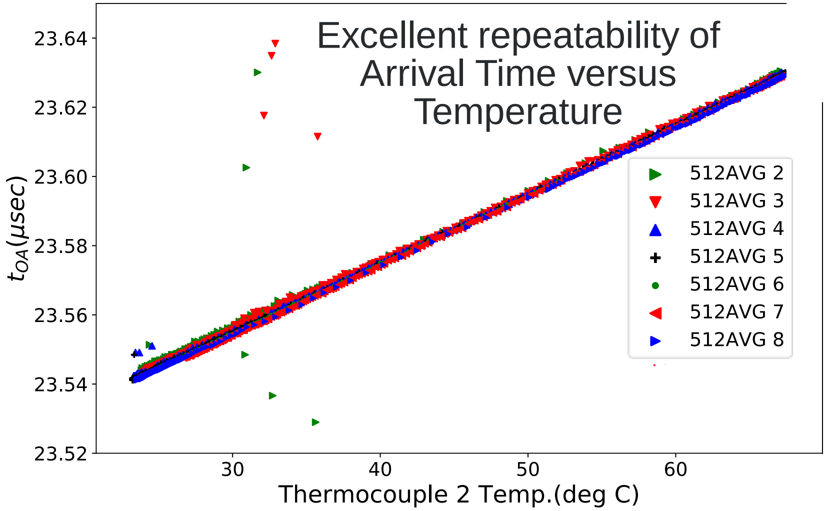
Raw RF waveforms



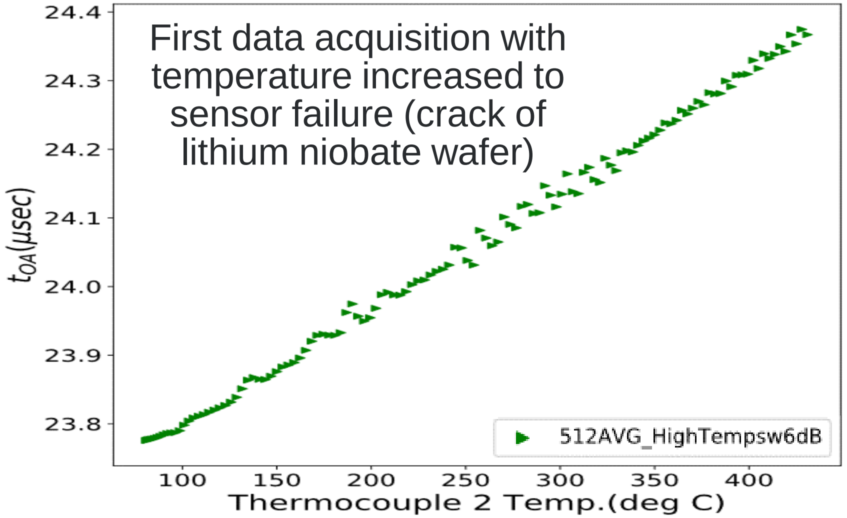
Failure Mode of Wafer: Temperature Ramp to 700 °C



Low temperature test results



High temperature test results



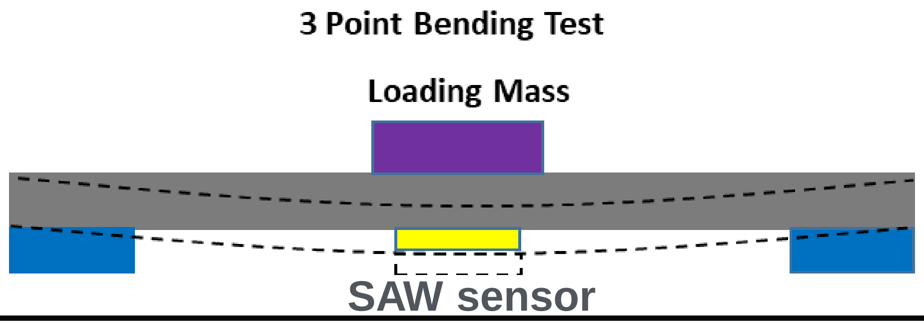
Observations

- Time-of-Flight change of Analytic Signal of Reflector 1 Response was proportional to Temperature
- Excellent Repeatability was demonstrated for numerous temperature ramps (up and down) between 23 - 68 °C
- A single high temperature ramp showed greater variability over 80 - 420 °C
- Decreased amplitude prevented meaningful measurements above 420 °C
- Design #2 was simplified by using a single reflector instead of paired reflectors.

Results and accomplishments: Applied force to Mimic Pressure

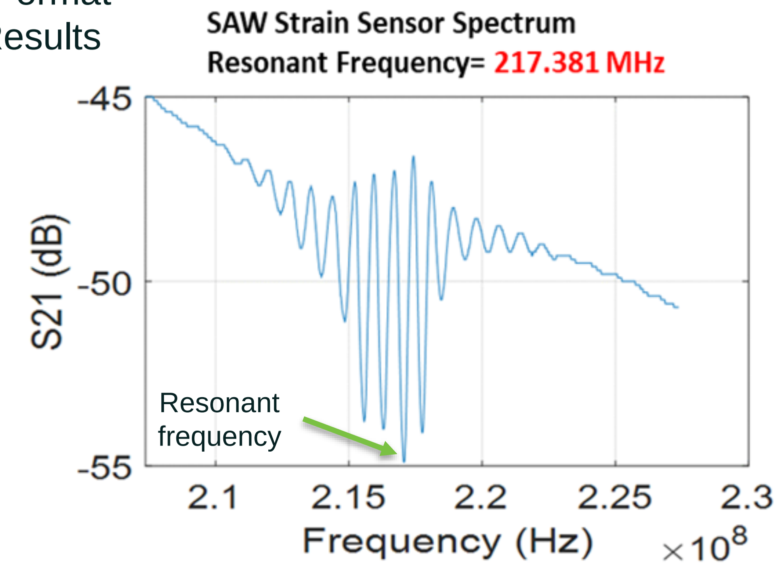
➢ Validation of the pressure sensor concept using a LiNbO3 SAW sensor and applied force to mimic pressure

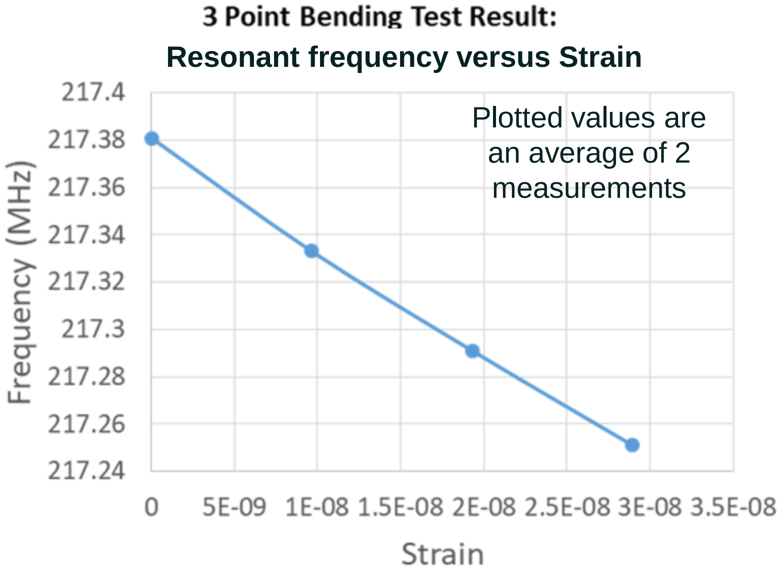
Test Setup:

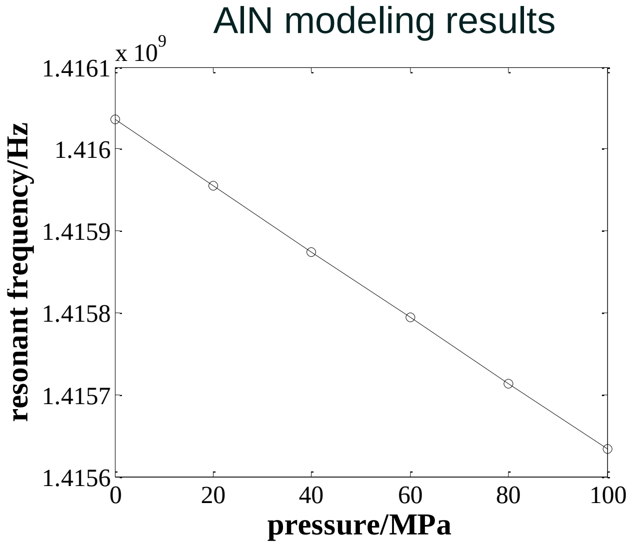


- Static tests with proof mass loading to simulate pressure
- Different loading levels at 0, 100, 200, and 300 g

Data Format and Results







Conclusions

- Temperature tests with a one port, 70 MHz SAW sensor demonstrated a linear relation with excellent repeatability over the 23 – 68 °C interval. One temperature run tracked temperature up to 420 °C.
- Threshold detection of the Analytic Signal provided reliable detection of changes in arrival time that tracked temperature. This will aid future sensor parameter measurements that depend on accurate measure of arrival time.
- The sensor can be configured to be sensitive to pressure by formation of a diaphragm with the SAW wafer acting as a membrane deformed by a pressure change.
- A two port SAW resonator was validated as a pressure sensor concept with an inverse relation between force and resonance frequency. A 3 Point Bending Test induced force to mimic strain incurred from a pressure change.

Conclusions

- Future work in FY 2022 includes the following:
  - A laboratory prototype of a bimodal temperature-pressure sensor was designed and is being fabricated; tests expected in November.
  - Data analytics will address deconvolution of temperature and pressure from the temperature-pressure sensor to estimate both temperature and pressure.
  - Gas composition will be addressed separately and after sensor concept validation integrated into the multimodal SAW based sensor.
    - Select gases of interest
    - Select coatings robust to high temperature, sensitive to selected gases, and reversible to track an increase and decrease in concentration of the selected gas
  - Expand the temperature range of the one port SAW sensor to a temperature such as 700 °C.

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Pacific Northwest National Laboratory
Michael.larche@pnnl.gov
W (509)-372-4143

Questions?

ASI | Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Advanced Sensors and Instrumentation (ASI) Program Overview

November 15 – 18, 2021

Daniel Nichols – Federal Program Manager

Office of Nuclear Energy

U.S. Department of Energy

Intent of Webinar

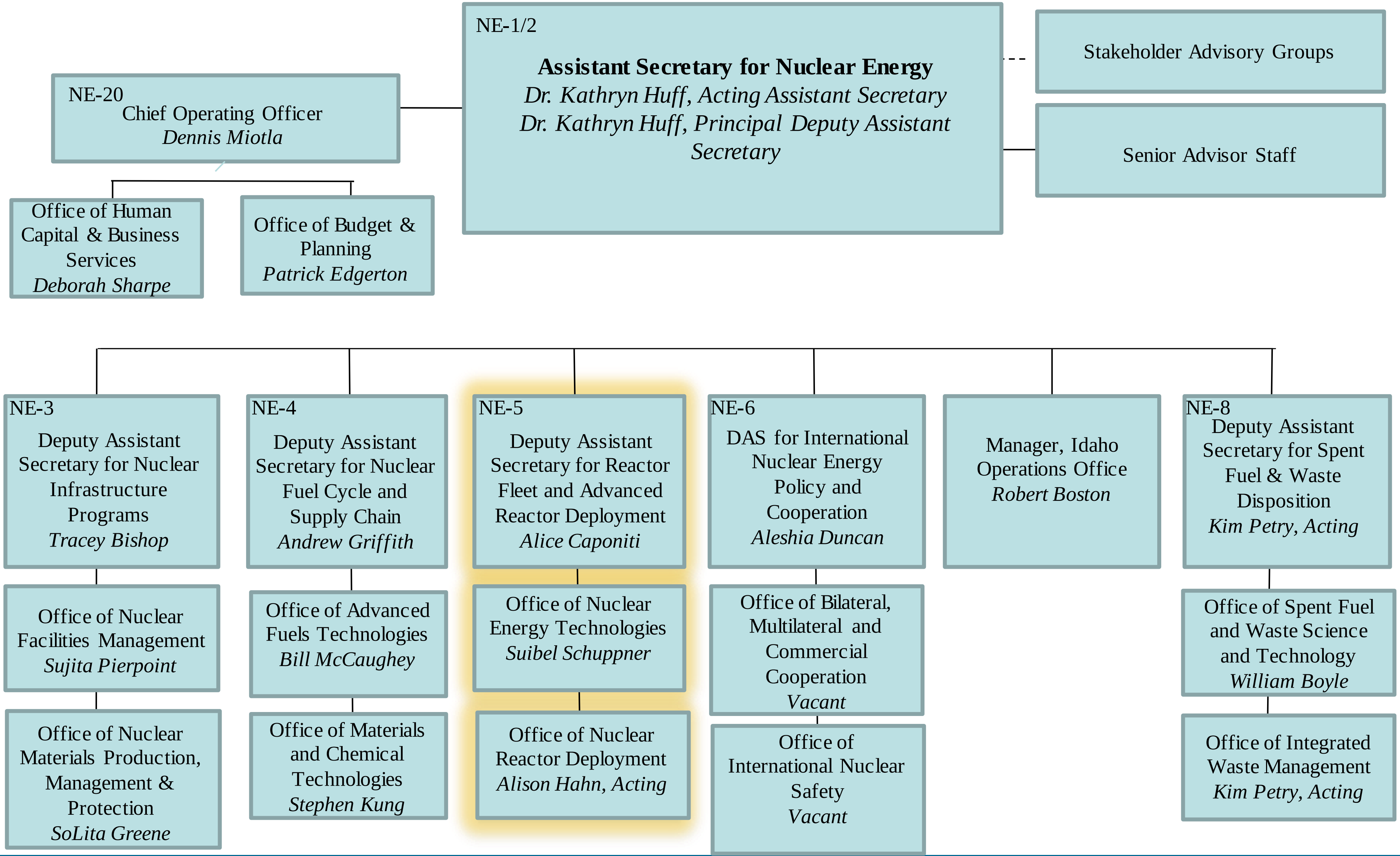
Goals:

- Complete Annual Review of all ASI program projects
- Provide broad programmatic information for stakeholders throughout NE industry
- Provide detailed project status presentations to information NE community of progress

Expected Outcomes:

- Allow for productive dialogue about ongoing work
- Ongoing projects gain visibility with NE industry stakeholders
- Receive feedback from NE community on the ASI program and projects

Office of Nuclear Energy



Reactor Fleet and Advanced Reactor Deployment (NE-5)

NE – 5
DAS for Reactor Fleet and Advanced Reactor Deployment

Alice Caponiti, Deputy Assistant Secretary

Michael Worley, Associate Deputy Assistant Secretary

Tim Beville, Program Director (ARDP)

NE – 51
Office of Nuclear Energy Technologies

Suibel Schuppner, Director

NE – 51.1
Enabling Technologies Team

Melissa Bates, Team Leader

- Advanced Sensors and Instrumentation (ASI) – D. Nichols
- Advanced Materials and Manufacturing Technologies (AMMT) – D. Cairns-Gallimore
- Nuclear Energy Advanced Modeling and Simulation (NEAMS) – D. Henderson
- Nuclear Science User Facilities (NSUF) – T. Selekler
- High-Performance Computing (HPC) – T. Selekler

NE – 51.2
University and Competitive Research Team

Aaron Gravelle, Team Leader

- Nuclear Energy University Program (NEUP) – J. Payne
- University Nuclear Leadership Program (UNLP) – J. Payne
- Research Reactor Infrastructure (RRI) – A. Gravelle
- Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) – C. Wade
- Gateway for Accelerated Innovation in Nuclear (GAIN) – C. Wade
- Advanced Nuclear Industry Funding Opportunity (IFOA) – C. Wade
- Technology Commercialization Fund (TCF) – C. Wade

NE – 52
Office of Nuclear Reactor Deployment

Alison Hahn, Acting Director

NE – 52.1
Reactor Optimization and Modernization Team

Alison Hahn, Team Leader

- Light Water Reactor Sustainability (LWRS) – A. Hahn, B. Walsh, S. Lesica, J. Marcinkoski
- Advanced Small Modular Reactor R&D – B. Onuschak
- Integrated Energy Systems (IES) – J. Marcinkoski
- Nuclear Cybersecurity – B. Onuschak
- Advanced Reactors Safeguards (ARS) – A. Hahn

NE – 52.2
Advanced Reactor Development Team

Janelle Eddins, Team Leader

- Sodium-Cooled Fast Reactors (SFR) – B. Robinson
- High-Temperature Gas-Cooled Reactors (HTGR)/TRISO Fuel – D. Prevost, D. Li
- Molten Salt Reactors (MSR) – B. Robinson
- Microreactors -D. Li
- National Reactor Innovation Center (NRIC) – J. Eddins
- Advanced Reactor Regulatory Development – J. Eddins

Advanced Sensors and Instrumentation Leadership

Federal Program Manager: Daniel Nichols

daniel.nichols@nuclear.energy.gov

National Technical Director: Pattrick Calderoni

pattrick.calderoni@inl.gov

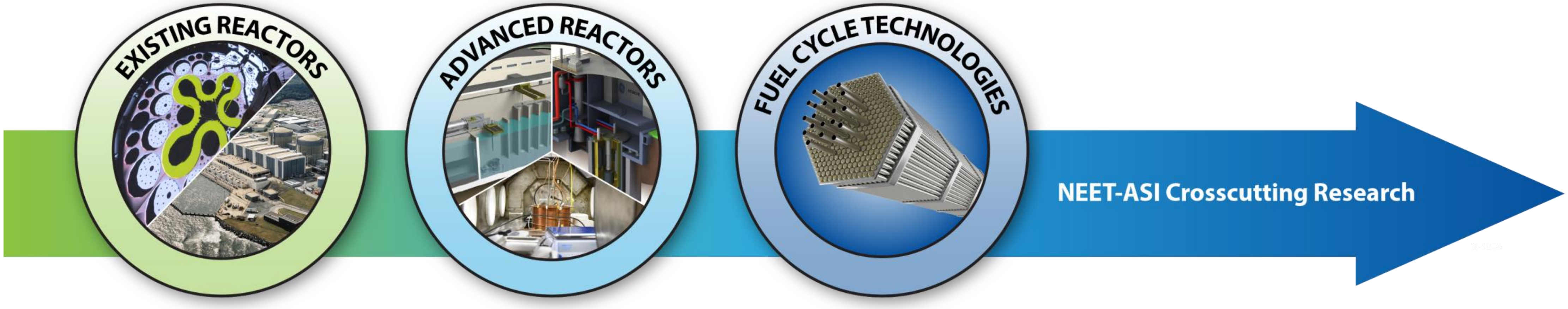
ASI Program Focus

Mission

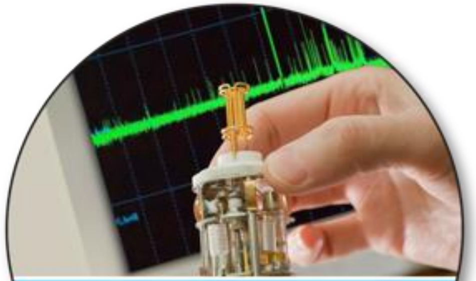
Develop **advanced sensors and I&C** that address **critical technology gaps** for monitoring and controlling existing and advanced **reactors** and supporting **fuel cycle** development

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**



Program Development Categories



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

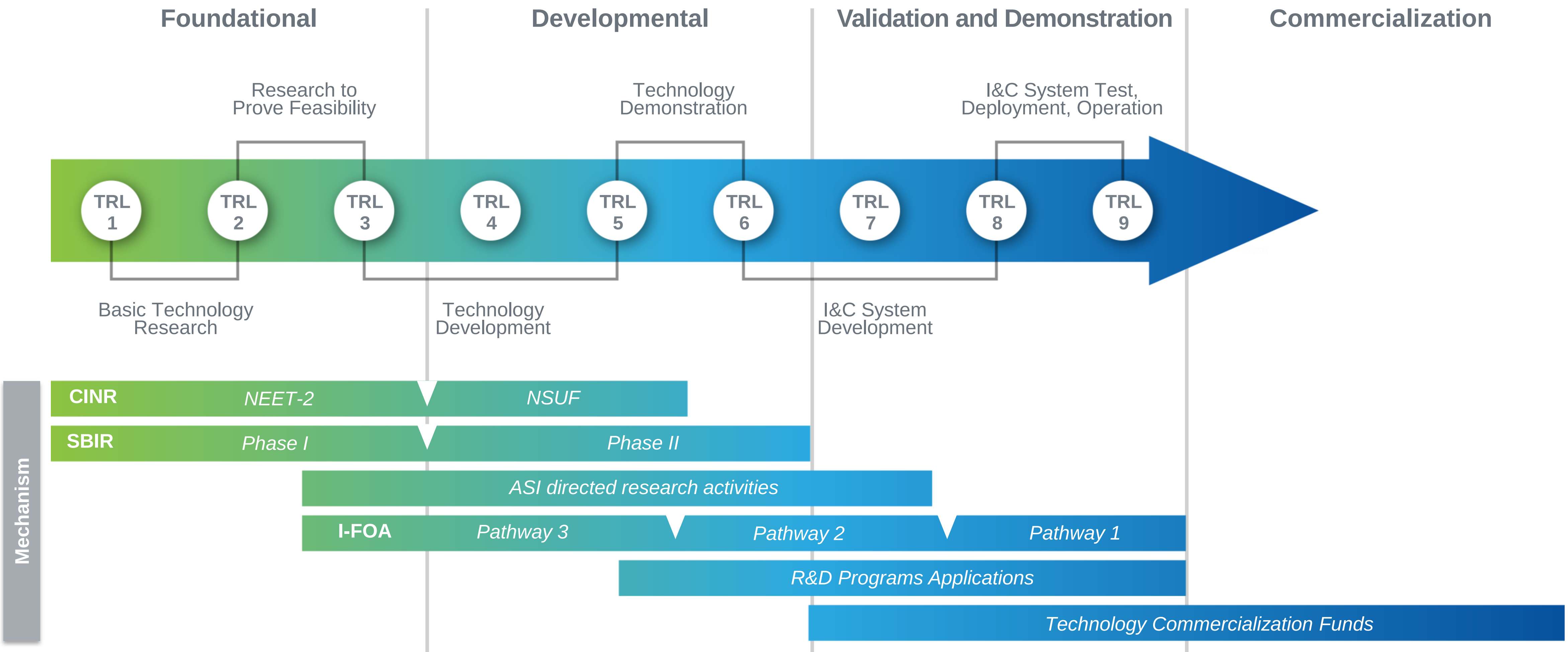
Big Data, Machine Learning, Artificial Intelligence

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

Advanced Control Systems

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

Methods and Metrics of ASI Research



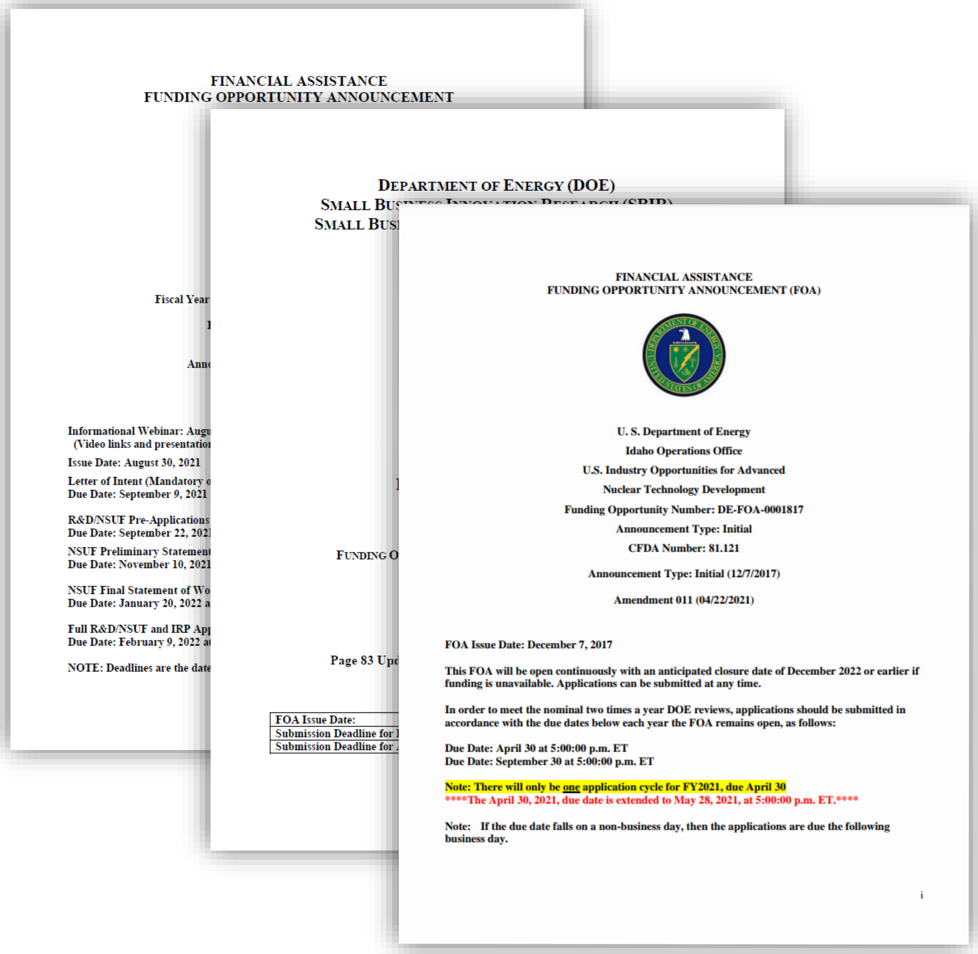
NE Funding Opportunities

- **Consolidated Innovative Nuclear Research (CINR)**
  - Competitive awards with university leads only
  - Nuclear Energy University Program (NEUP)
  - Nuclear Energy Enabling Technologies (NEET)
  - Nuclear Science User Facilities (NSUF)

- **Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR)**
  - Competitive awards for small businesses only
  - Advanced Technologies for Nuclear Energy

- **U.S. Industry Opportunities for Advanced Nuclear Technology Development (DE-FOA-0001817)**

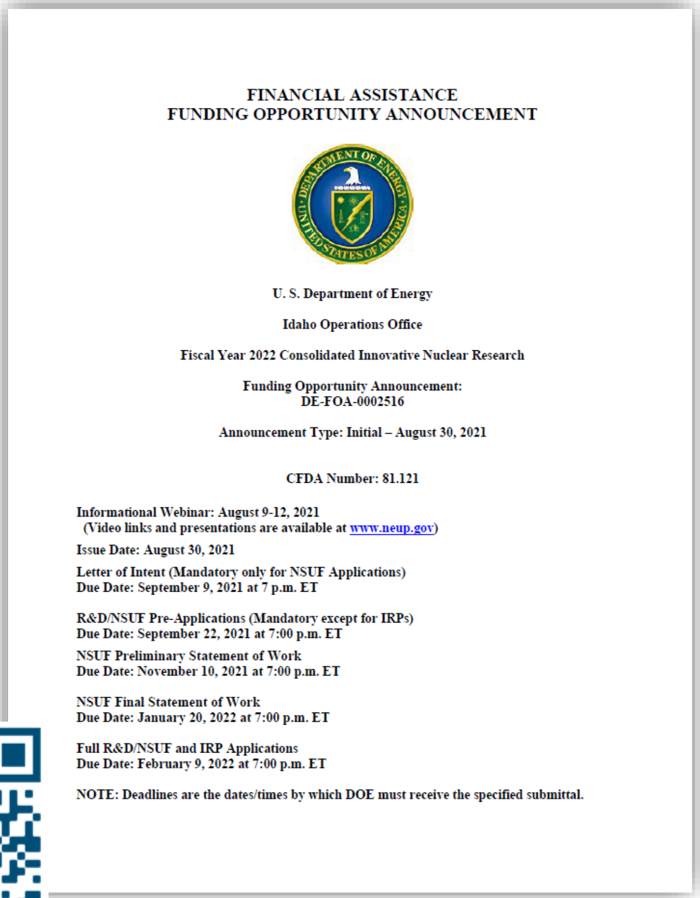
- **Gateway for Accelerated Innovation in Nuclear (GAIN) Vouchers**



Gateway for Accelerated Innovation in Nuclear

Important Upcoming Dates: CINR

- ***CINR Schedule (7 PM ET):***
  - **January 20, 2022:** NSUF Final Statement of Work
  - **February 9, 2022:** Full R&D Applications
  - **February 9, 2022:** IRP Applications


FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy

Idaho Operations Office

Fiscal Year 2022 Consolidated Innovative Nuclear Research

Funding Opportunity Announcement:
DE-FOA-0002516

Announcement Type: Initial – August 30, 2021

CFDA Number: 81.121

Informational Webinar: August 9-12, 2021
(Video links and presentations are available at www.neup.gov)

Issue Date: August 30, 2021

Letter of Intent (Mandatory only for NSUF Applications)
Due Date: September 9, 2021 at 7 p.m. ET

R&D/NSUF Pre-Applications (Mandatory except for IRPs)
Due Date: September 22, 2021 at 7:00 p.m. ET

NSUF Preliminary Statement of Work
Due Date: November 10, 2021 at 7:00 p.m. ET

NSUF Final Statement of Work
Due Date: January 20, 2022 at 7:00 p.m. ET

Full R&D/NSUF and IRP Applications
Due Date: February 9, 2022 at 7:00 p.m. ET

NOTE: Deadlines are the dates/times by which DOE must receive the specified submittal.

NEET-ASI Current CINR Awards

FY	Project Title	Principal Investigator / Location
2017 (Completed)	Integrated silicon/chalcogenide glass hybrid plasmonic sensor for monitoring of temperature in nuclear facilities	Maria Mitkova / Boise State University
	High temperature embedded/integrated sensors (HiTEIS) for remote monitoring of reactor and fuel cycle systems	Xiaoning Jiang / North Carolina State University
	3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures	Douglas Adams / Vanderbilt University
	Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring	Gary Pickrell / Virginia Tech
	Ultrasonic Sensors for TREAT Fuel Condition Measurement and Monitoring	Andrew Casella / Pacific Northwestern National Laboratory
2018	Development of optical fiber-based gamma thermometer	Thomas Blue / The Ohio State University
	Analytics-at-scale of Sensor Data for Digital Monitoring in Nuclear Plants	Vivek Agarwal / Idaho National Laboratory
	Process-Constrained Data Analytics for Sensor Assignment and Calibration	Richard Vilim / Argonne National Laboratory
2019	Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control	Michael Larche / Pacific Northwestern National Laboratory
	Design of risk informed autonomous operation for advanced reactor	Michael Golay / Massachusetts Institute of Technology
	Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics	David Grabaskas / Argonne National Laboratory
	Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance	Daniel Cole / University of Pittsburgh
	Context-Aware Safety Information Display for Nuclear Field Workers	George Gibson / Arizona State University
2020	Development of Sensor Performance Model of Microwave Cavity Flow Meter for Advanced Reactor High Temperature Fluids	Alexander Heifetz / Argonne National Laboratory
	Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid	Roberto Ponciroli / Argonne National Laboratory
2021	Gallium Nitride-based 100-Mrad Electronics Technology for Advanced Nuclear Reactor Wireless Communications	Milton Ericson / Oak Ridge National Laboratory

NSUF CINR Awards with ASI R&D Funds

FY	Project Title	Principal Investigator / Location
2017 (Completed)	Additive manufacturing of thermal sensors for in-pile thermal conductivity measurement	David Estrada / Boise State University
	Radiation Effects on Optical Fiber Sensor Fused Smart Alloy Parts with Graded Alloy Composition Manufactured by Additive Manufacturing Processes	Kevin Chen / University of Pittsburgh
2018	Irradiation Behavior of Piezoelectric Materials for Nuclear Reactor Sensors	Marat Khafizov / The Ohio State University
	High-performance nanostructured thermoelectric materials and generators for in-pile power harvesting	Yanliang Zhang / University of Notre Dame
2019	Irradiation of Optical Components of In-Situ Laser Spectroscopic Sensors for Advanced Nuclear Reactor Systems	Igor Jovanovic / University of Michigan
	High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors	Joshua Daw / Idaho National Laboratory
2020	Irradiation of Sensors and Adhesive Couplants for Application in LWR Primary Loop Piping and Components	James Wall / Electric Power Research Institute
2021	Understanding irradiation behaviors of ultrawide bandgap Ga2O3 high temperature sensor materials for advanced nuclear reactor systems	Ge yang / North Carolina State University
	Deployment and In-Pile Test of an Instrument for Real-Time Monitoring Thermal Conductivity Evolution of Nuclear Fuels	Zilong Hua / Idaho National Laboratory

Important Upcoming Dates: SBIR/STTR

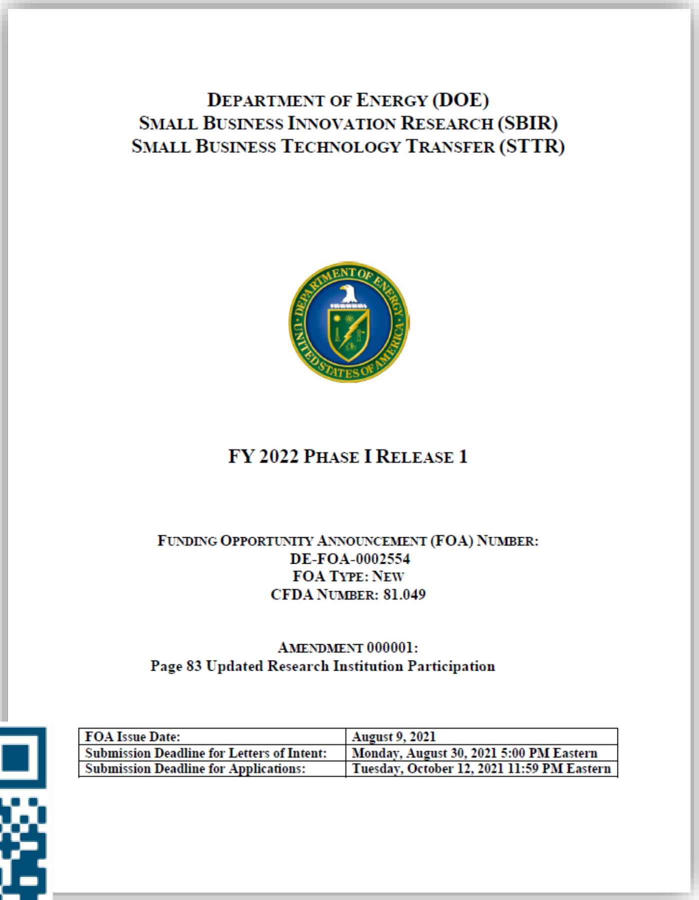
- ***SBIR/STTR Schedule:***

– ***Phase I Release 1:***
- **January 3, 2022:** Award Notification
- **February 14, 2022:** Projected Grant Start Date

– ***Phase I Release 2:***
- **December 13, 2021:** FOA Issued
- **January 3, 2022:** Letters of Intent (LOI) Due
- **January 24, 2022:** Non-responsive LOI Feedback Provided
- **February 22, 2022:** Full Applications Due
- **May 16, 2022:** Award Notification
- **June 27, 2022:** Projected Grant Start Date

– ***Phase II Release 1:***

****Only Phase I awardees are eligible***
- **December 7, 2021:** Applications Due
- **February 22, 2022:** Award Notification
- **April 4, 2022:** Projected Grant Start Date



DEPARTMENT OF ENERGY (DOE)
SMALL BUSINESS INNOVATION RESEARCH (SBIR)
SMALL BUSINESS TECHNOLOGY TRANSFER (STTR)

FY 2022 PHASE I RELEASE 1

FUNDING OPPORTUNITY ANNOUNCEMENT (FOA) NUMBER:
DE-FOA-0002554
FOA TYPE: NEW
CFDA NUMBER: 81.049

AMENDMENT 000001:
Page 83 Updated Research Institution Participation

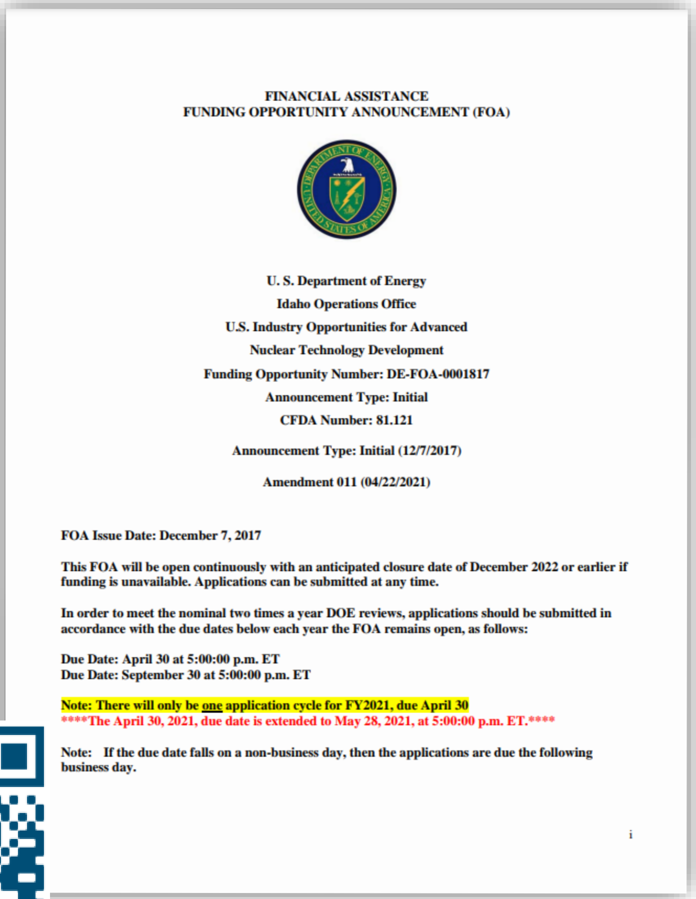
FOA Issue Date:	August 9, 2021
Submission Deadline for Letters of Intent:	Monday, August 30, 2021 5:00 PM Eastern
Submission Deadline for Applications:	Tuesday, October 12, 2021 11:59 PM Eastern

SBIR/STTR Awards

Phase	FY	Project Title	Principal Investigator / Location
II B	2019	High Temperature Operable, Harsh Environment Tolerant Flow Sensors For Nuclear Reactor Applications	Jon Lubbers / Sporian Microsystems, Inc.,
II		Metamaterial Void Sensor for Fast Transient Testing	Mark Roberson / Goldfinch Sensor Technologies and Analytics LLC
II		Health Monitoring of Digital I&C Systems using Online Electromagnetic Measurements	Chad Kiger / Analysis & Measurement Services Corp.
II		Fault Detection of Digital Instrumentation and Control Systems using Integrated Electromagnetic Compatibility and Automated Functional Testing	Greg Morton / Analysis & Measurement Services Corp.
II	2020	Video Camera for Harsh Environments in Nuclear	Esen Salcin / Alphacore Inc
II		Development of Radiation Endurance Ultrasonic Transducer for Nuclear Reactors	Uday Singh / X-wave Innovations, Inc.
II		Advanced Laser Ultrasonic Sensor for Fuel Rod Characterization	Marvin Klein / Intelligent Optical Systems, Inc.
I	2021	Integration of Wireless Sensor Networks and Battery-free RFID for Advanced Reactors	Faranak Nekoogar / Dirac Solutions Inc.
I		High Penetration Wireless Networking for Nuclear Power Plant Sensing	Randall King / Operant Networks Corporation

Important Upcoming Dates: IFOA & GAIN

- ***IFOA Schedule (5 PM ET):***
  - **February 28, 2022:** 1st Round Proposals Due
  - **June 30, 2022:** 2nd Round Proposals Due
  - **October 31, 2022:** 3rd Round Proposals Due
- ***GAIN NE Vouchers Schedule (5 PM ET):***
  - **May 2, 2022:** Proposals Due



FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT (FOA)

U. S. Department of Energy
Idaho Operations Office
U.S. Industry Opportunities for Advanced
Nuclear Technology Development
Funding Opportunity Number: DE-FOA-0001817
Announcement Type: Initial
CFDA Number: 81.121

Announcement Type: Initial (12/7/2017)

Amendment 011 (04/22/2021)

FOA Issue Date: December 7, 2017

This FOA will be open continuously with an anticipated closure date of December 2022 or earlier if funding is unavailable. Applications can be submitted at any time.

In order to meet the nominal two times a year DOE reviews, applications should be submitted in accordance with the due dates below each year the FOA remains open, as follows:

Due Date: April 30 at 5:00:00 p.m. ET
Due Date: September 30 at 5:00:00 p.m. ET

Note: There will only be one application cycle for FY2021, due April 30
****The April 30, 2021, due date is extended to May 28, 2021, at 5:00:00 p.m. ET.****

Note: If the due date falls on a non-business day, then the applications are due the following business day.

i

GAIN Gateway for Accelerated Innovation in Nuclear

Industry Awards

FY	Industry-FOA Project Title	Recipient
2019	Machine Learning for Enhanced Diagnostic and Prognostic Capabilities of NPP Assets	Blue Wave AI Labs, Inc.
	Passive Radio Frequency Tags and Sensors for Process Monitoring in Advanced Reactors	Dirac Solutions Inc.

FY	GAIN Voucher Title	Recipient / Location
2017	Radiation Aging of Nuclear Power Plant Components	Analysis and Measurement Services Corp / Knoxville, TN
	Human Factors Engineering for the Move to Digital Control Systems – Improved Strategies for Operations	GSE Systems Inc / Sykesville, MD
2018	Advancement of Instrumentation to Monitor IMSR® Core Temperature and Power Level	Terrestrial Energy USA / New York, NY
	Electroanalytical Sensors for Liquid Fueled Fluoride Molten Salt Reactor	ThorCon / Stevenson, WA
2019	Testing of Instrumentation and Control Sensors and Cables for Small Modular Reactors	Analysis & Measurement Services Corp. / Knoxville, TN
2020	On-Line Lead/Water Heat Exchanger Sensor/System Feasibility	Hydromine, Inc. / New York, NY
2021	Radiation Testing for High-Resolution, Radiation-Hardened Camera Systems	Vega Wave Systems, Inc / West Chicago, IL

Principal Investigator: Dr. Nance Ericson (Oak Ridge National Laboratory)

Summary: Circuits carefully designed and fabrication in a Gallium Nitride (GaN) based fabrication process will enable high temperature (>400° C), high total ionizing dose (>100 Mrad TID) and high neutron fluence (>10^{15} n/cm^2) electronics for communications in advanced reactors. A demonstration system will be designed and fabricated for wireless interfacing with two GaN-based dual sensor transmitters with a viable path forward towards increasing the number of sensors per transmitter, and transmitters per centralized receiver. Irradiation studies will be carried out for gamma (>100 Mrad (GaN)), neutrons (>10^{15} n/cm^2), mixed gamma/neutrons, and elevated temperatures up to 400° C. The sensor platform will wirelessly link to a software defined radio (SDR) receiver for data collection, processing, and networking. The expected outcomes of this research are GaN-based sensor and electronics technologies which extend beyond the thermal and radiation limits of Si-based systems, to enable sensing and wireless communications electronics systems suitable for integration into reactor facilities (in-vessel and/or near-vessel) that has been advanced to a TRL-4 status.

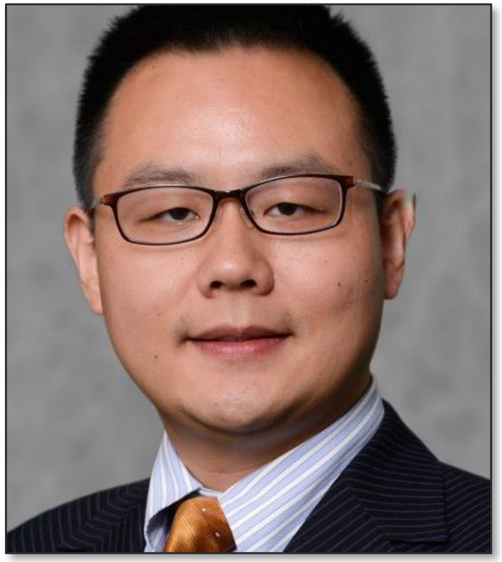
Project Period: 10/1/2021 – 9/30/2024

OAK RIDGE National Laboratory

Understanding irradiation behaviors of ultrawide bandgap Ga_2O_3 high temperature sensor materials for advanced nuclear reactor systems

NSUF-1.1: Testing of Advanced Materials or Advanced Sensors for Nuclear Applications

Principal Investigator: Dr. Ge Yang (North Carolina State University)

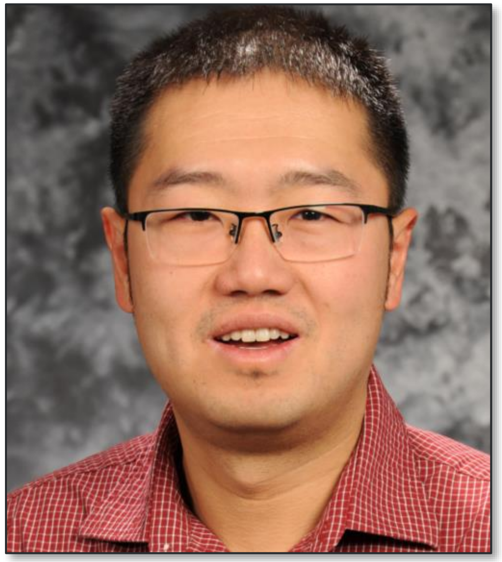


Summary: The proposed research will focus on two key parts to achieve the proposed project objective: (1) performing systematic neutron irradiation and positron annihilation lifetime spectroscopy (PALS) and Doppler broadening spectroscopy (DBS) analysis at NCSU's PULSTAR Nuclear Reactor; and (2) conducting targeted post irradiation examination (PIE) at CAES to measure the changes of microstructures, compositions and functional properties of Ga_2O_3 sensor materials. Special emphasis will be put on the evaluation of the impact of irradiation and temperature on Ga_2O_3, i.e., clarifying the neutron influence-rate dependence of Ga_2O_3 performance at different working temperature. Such efforts will help understand the occurrence and evolution of radiation-induced materials defects, especially vacancy-related ones, and their effects on the sensing performance of Ga_2O_3, thus providing key information regarding Ga_2O_3 sensors' use in intense irradiation and high temperature environment. The scientific output of this project will provide key fundamental knowledge to promote Ga_2O_3's nuclear instrumentation applications for next-generation nuclear energy systems.

Project Period: 10/1/2021 – 9/30/2024

NC STATE UNIVERSITY

Principal Investigator: Dr. Zilong Hua (Idaho National Laboratory)



Summary: This project will deploy a recently-developed fiber-optic-based instrument in the MIT Research Reactor (MITR) to perform in-reactor thermal conductivity measurements of nuclear fuels. Based on photothermal radiometry (PTR), this instrument is capable of performing thermal conductivity measurements in a temperature range commensurate with reactor operation in a remote and non-contact manner, and is highly tolerant to environmental noise and fuel surface deterioration. The MITR is the ideal collaborative facility to validate the in-reactor performance of this PTR instrument as programs for in-core testing of advanced ultrasonic and fiber-optic sensors for high temperature use are ongoing. The high technical readiness of the equipment combined with the extensive personnel expertise will be key to the success of this work. The real-time performance of using this instrument to measure thermal conductivity will be documented. PIE test will be performed to examine the survivability of the instrument. Finally, a draft protocol to use the instrument for regular, in-reactor thermal conductivity measurements will be provided.

Project Period: 10/1/2021 – 9/30/2024

Idaho National Laboratory

Summary

- Improvements and advancements in ASI technologies will
  - enable advances in nuclear reactor and fuel cycle system development
  - enhance economic competitiveness for nuclear power plants, and
  - promote a high level of nuclear safety
- NEET-ASI research produces concepts, techniques, capabilities, and equipment that are or can be demonstrated in simulated or laboratory test bed environments representative of nuclear plant systems or fuel cycle systems
- Innovative and crosscutting research is funded through competitive, peer-reviewed, solicitations and directed work

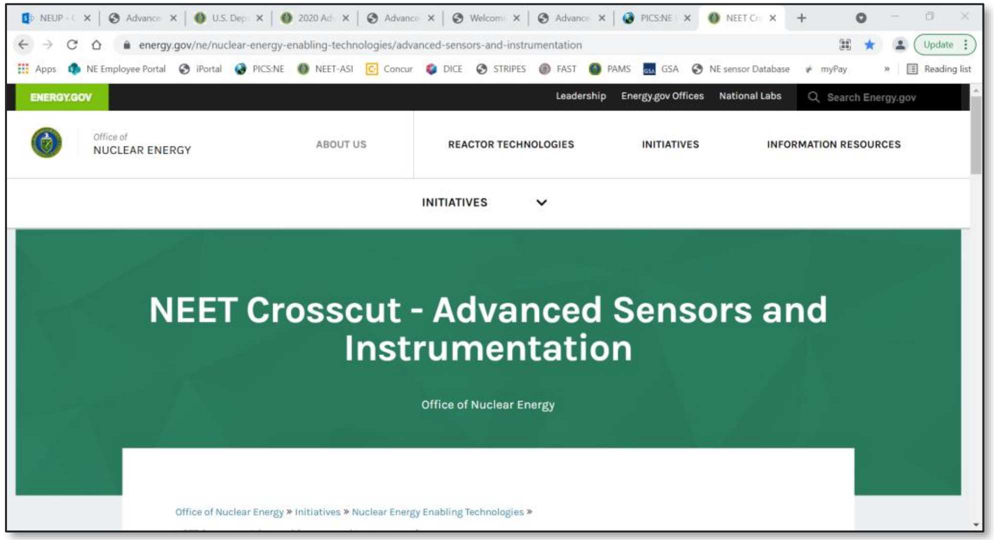
Advanced I&C technologies are an integral component for advanced reactors to provide safe, clean, and reliable power

ASI Resources

For more information:

Visit the DOE-NE website:

https://www.energy.gov/ne/nuclear-energy-enabling-technologies/advanced-sensors-and-instrumentation

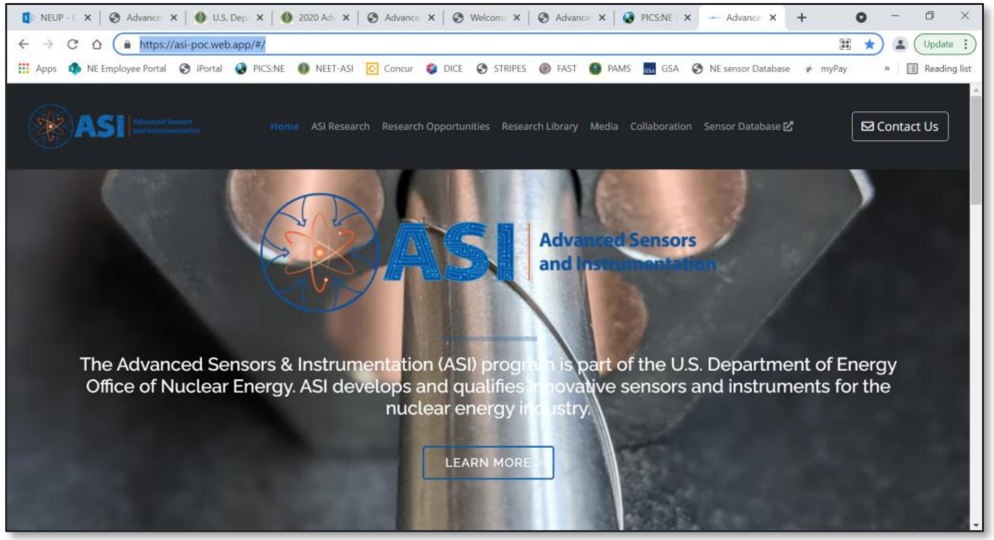


Or

Checkout the new ASI website:

[asi.inl.gov](asi.inl.gov)

(coming soon)



Thank You!

ASI | Advanced Sensors and Instrumentation

Nuclear Thermocouples

CT-22IN070204 - Thermocouples

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

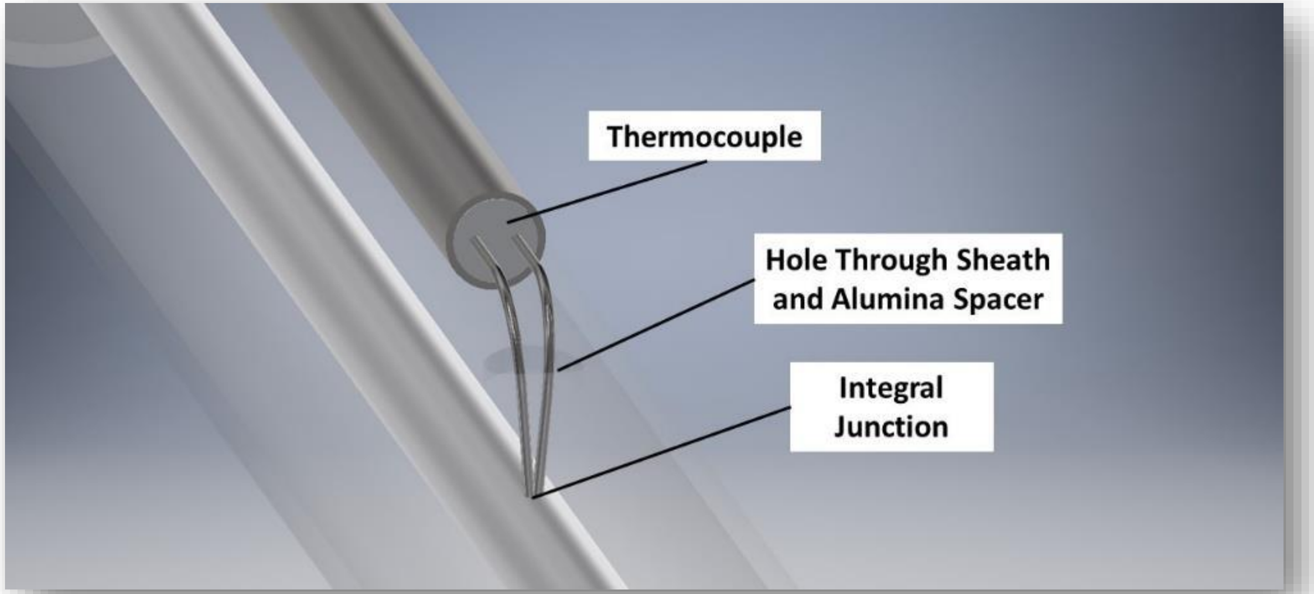
Principle Investigator: Richard Skifton, PhD

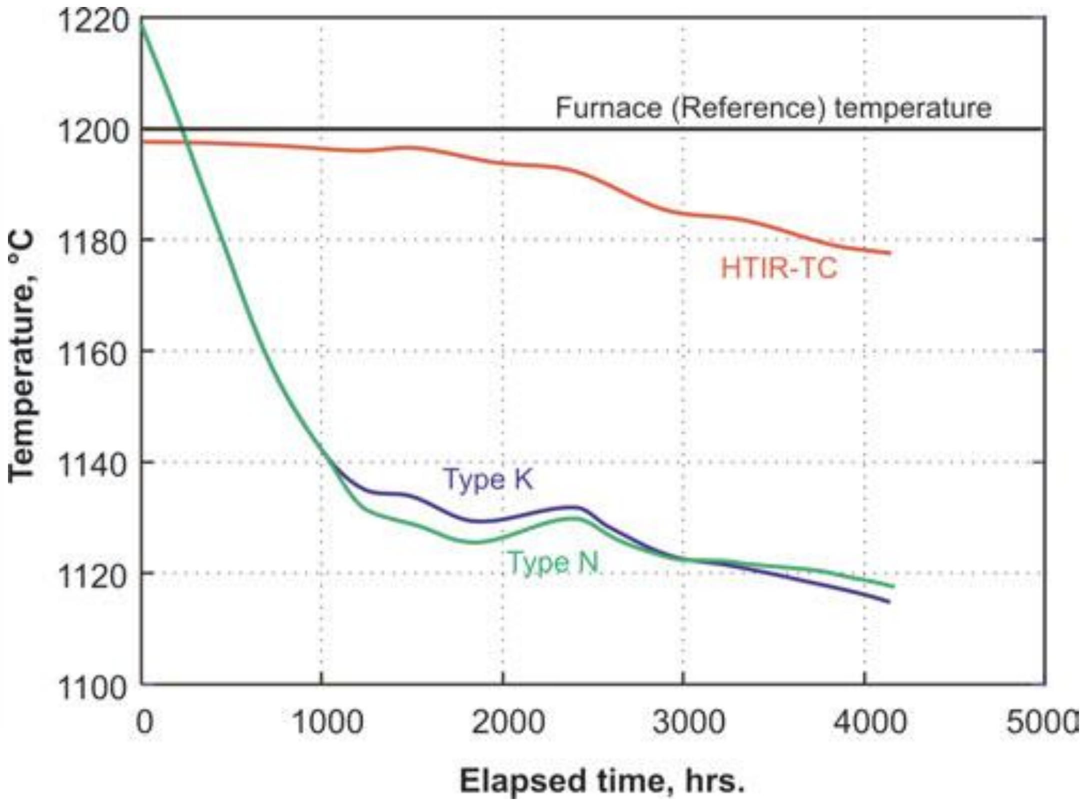
Collaborator: Brian Jaques, Scott Riley (Boise State University)

Idaho National Laboratory, Measurement Science Laboratory

Project Overview

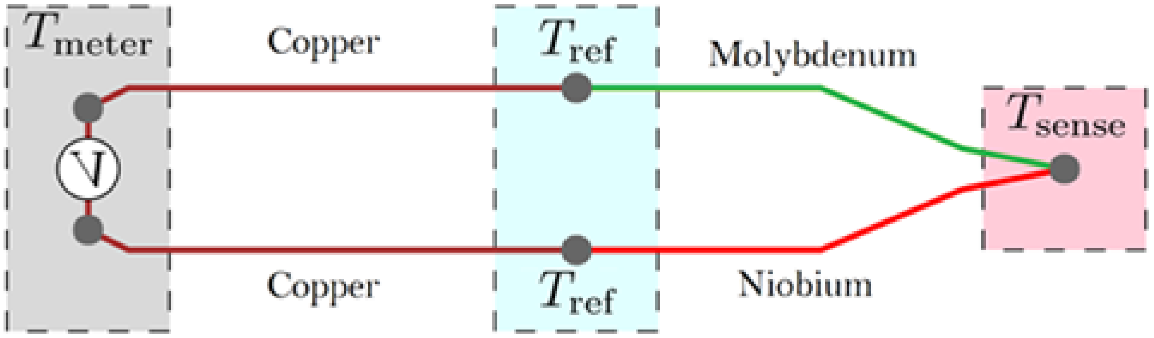
Scope: The thermocouple work package implements R&D activities to develop **nuclear temperature instrumentation that addresses critical technology gaps for monitoring and controlling** existing and advanced **reactors and supporting fuel cycle development**.

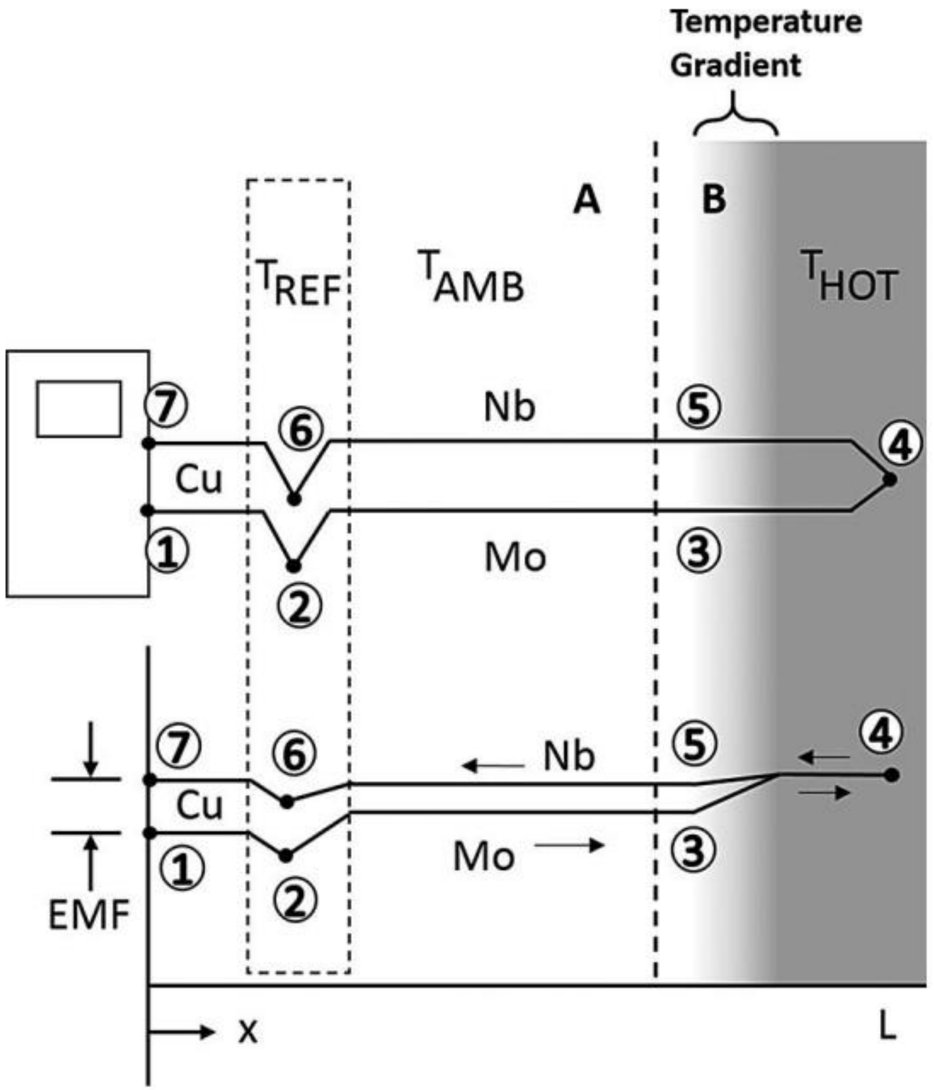




Project Overview

For temperature measurements, **thermocouple instrumentation is typically composed of one or more sensing element**, interrogation systems, data acquisition system as well as processes and procedures to collect, analyze and calibrate data. Instrumentation is used to measure process parameters, such as temperature, independently of the experiment, component or process in which it is deployed.



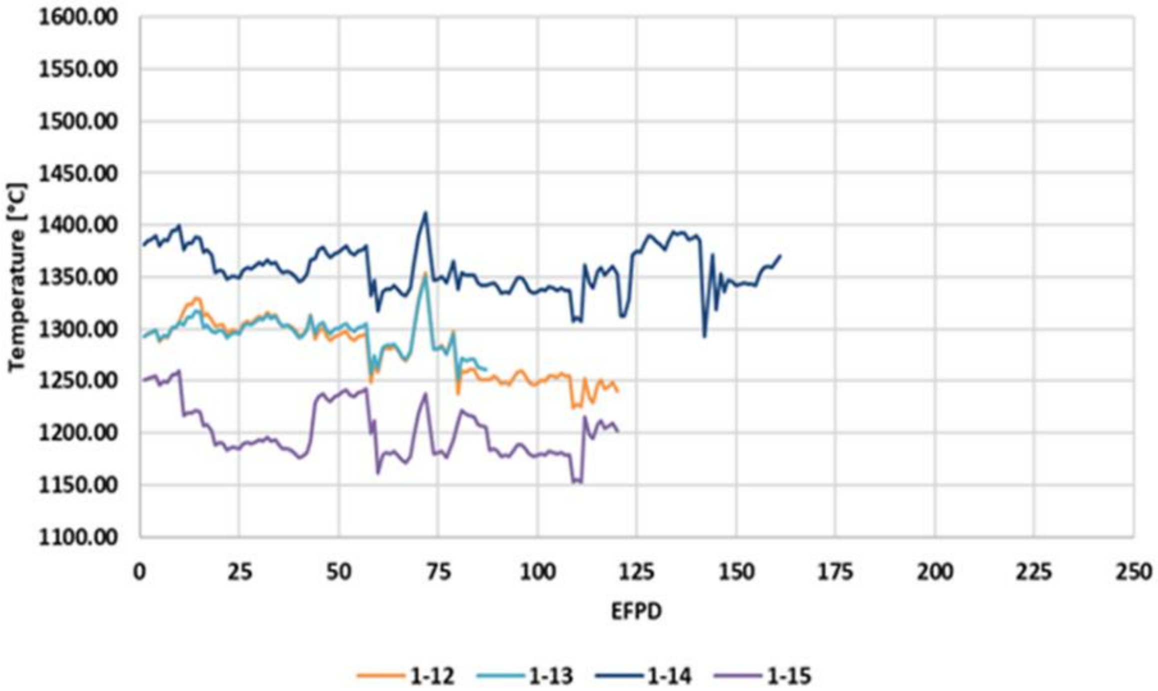


Project Overview

The **two (2)** technical areas under investigation:

1) Intrinsic junction thermocouples for surface temperature measurement.

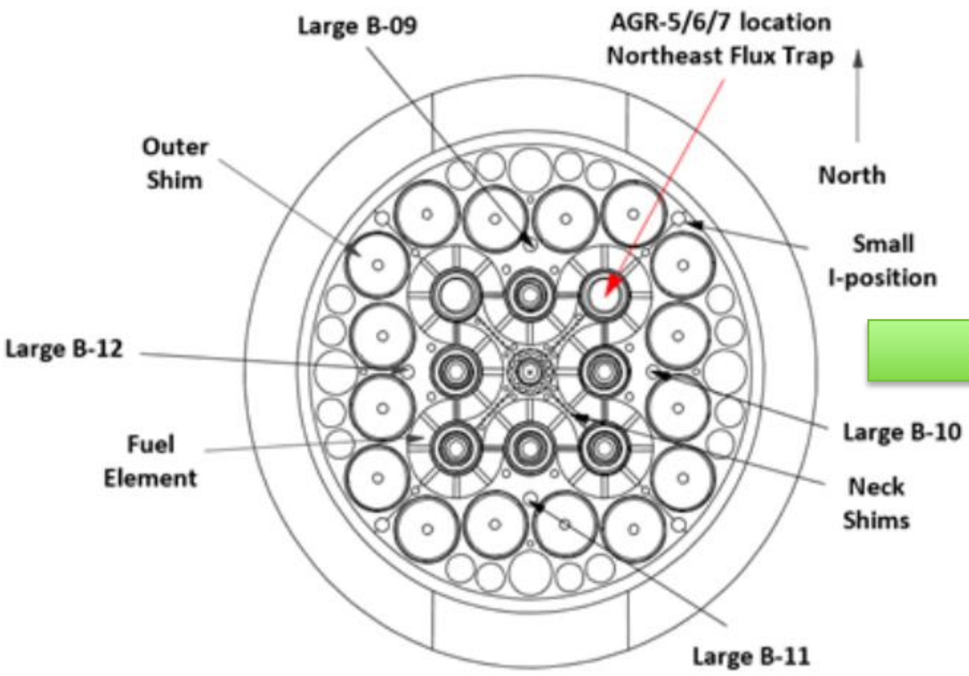
2) Performance assessment of commercial TCs for nuclear applications.

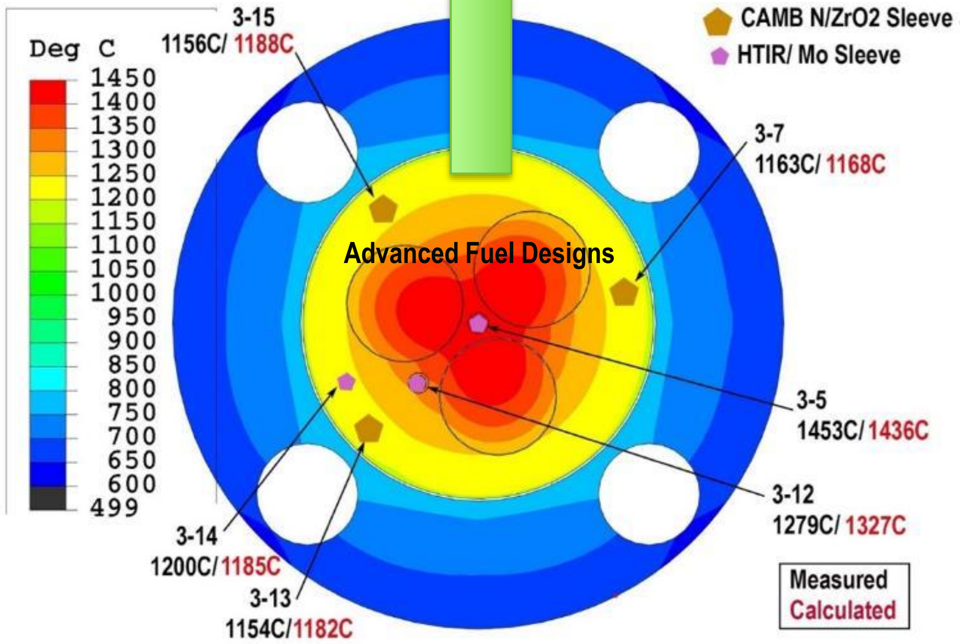


Technology Impact

- Interested parties/stakeholders:
  - Material Test Reactors
  - Advanced Fuel Validation
  - Advanced Nuclear Power Plants

Insert advanced reactor here.

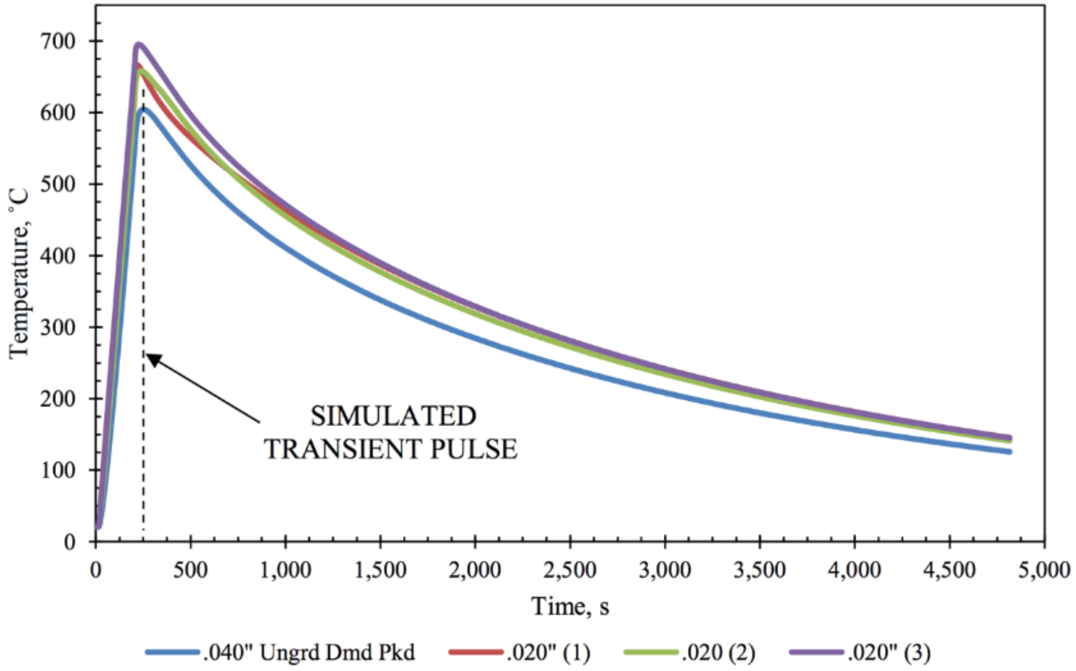




Technology Impact

Nuclear Energy Support:

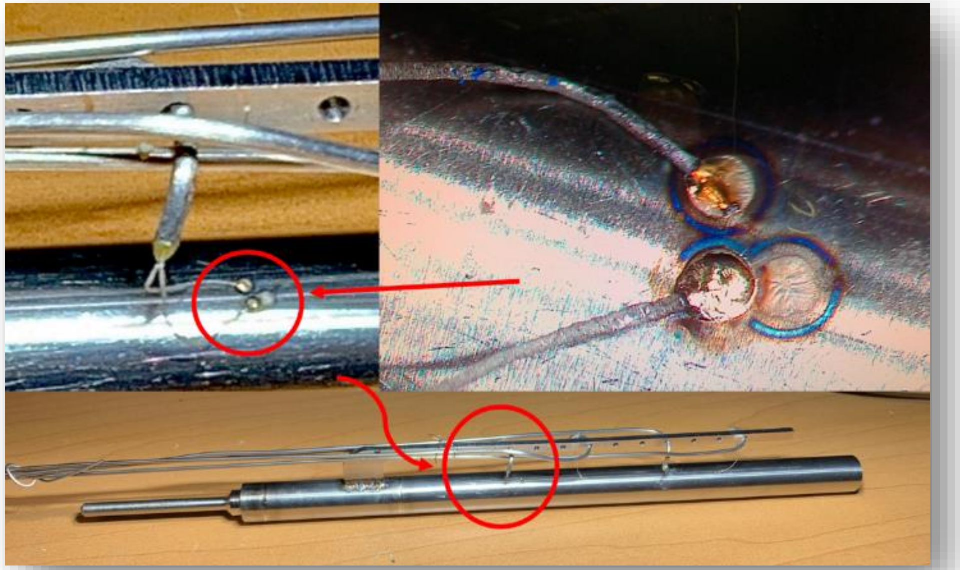
- Temperature measurement apart of the most basic metrics of the reactor.
- Getting closer to the fuel, either surface cladding or inside the fuel, will reduce uncertainties in fuel burnup, fuel/coolant interaction, and modeling (i.e., digital twin).
- Higher temporal resolution during nuclear transients.
- In summary, better “drivability” of the reactor.



Results and accomplishments

Intrinsic junctions for fuel cladding amid critical heat flux:

- Critical heat flux has rapid temperature rise and strong gradients.
- Eutectics may be present in TC attachment, yet EMF generated in the length.
- TC orientation is very important—with paraxial preferred over perpendicular.



Results and accomplishments

The Thermocouple Drift Model

1 → $$EMF = \int_0^L S_{eff}(T,x) * \frac{dT}{dx} * dx$$

2 → $$Reduction\ Factor = e^{-(C_1\varphi_{Thermal} + C_2\varphi_{Fast})t}$$

3 → $$S^*(T,x) = S(T,x) \times Reduction\ Factor.$$

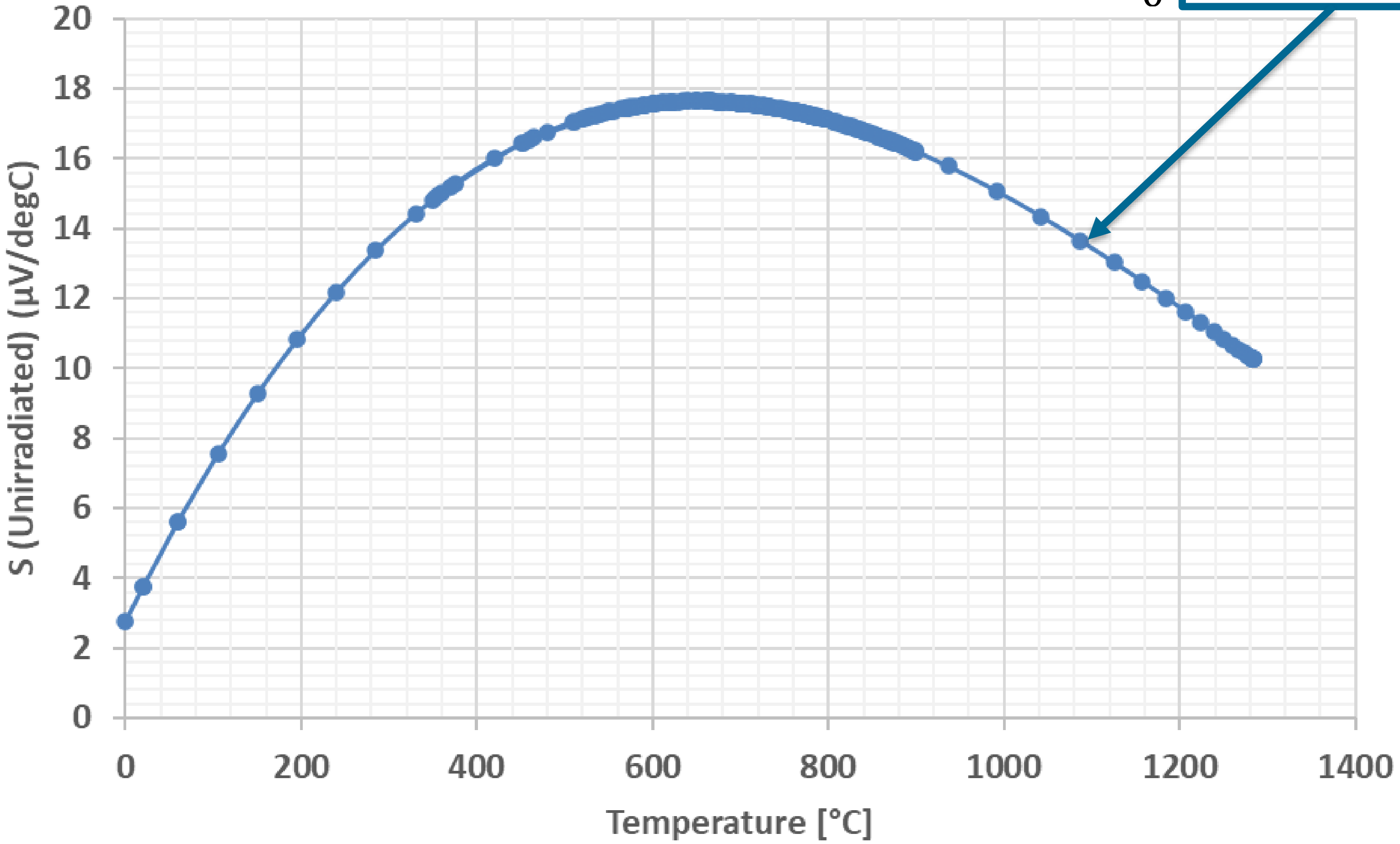
4 → $$EMF^*(T) = \sum_0^L S^*(T,x)\frac{dT}{dx}dx$$

5 → $$Drift(neutron\ fluence)(\%) = \frac{EMF^*(T) - EMF(T)}{EMF(T)} 100\%$$

S_{eff} of Capsule 1 TC

1

$$EMF = \int_0^L S_{eff}(T,x) * \frac{dT}{dx} * dx$$

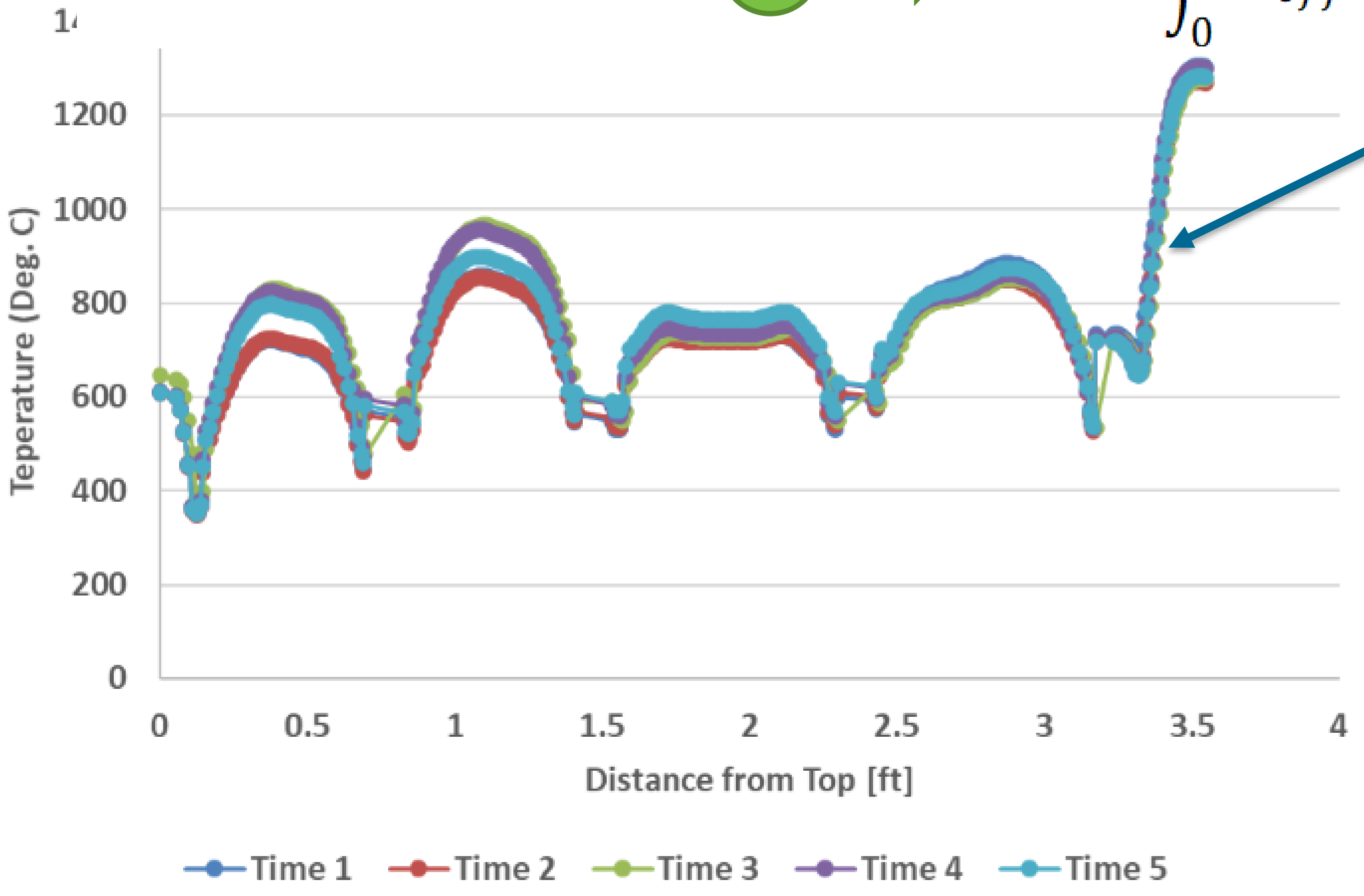


Results and accomplishments

Local Temperature on Capsule 1 TC Cable

1

$$EMF = \int_0^L S_{eff}(T,x) * \frac{dT}{dx} * dx$$

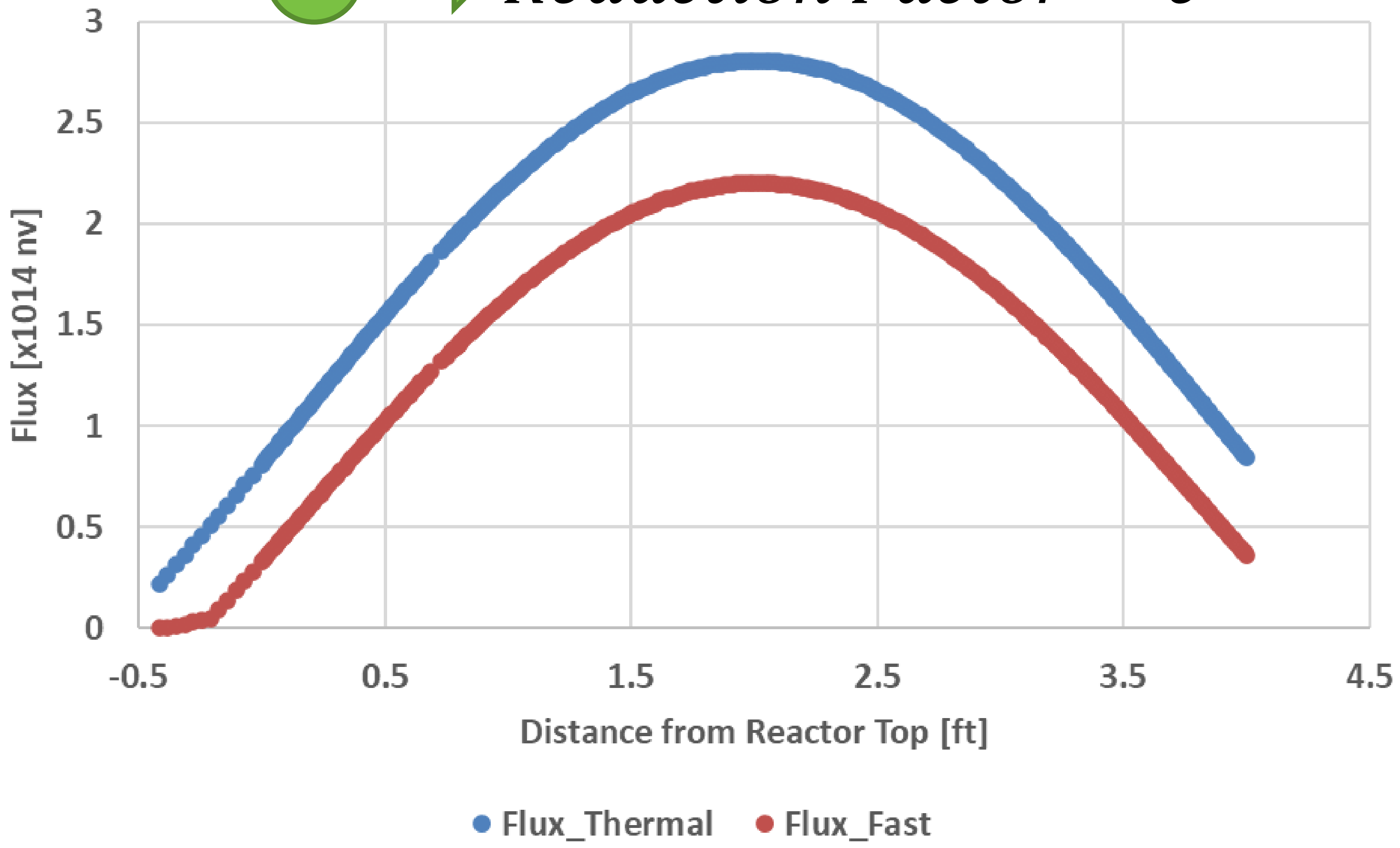


Results and accomplishments

Thermal and Fast Neutron profile of AGR 5/6/7 With Moderation

2

$$Reduction\ Factor = e^{-(C_1\varphi_{Thermal} + C_2\varphi_{Fast})t}$$



$C_1(ATR) = 3.02$ barns

$C_1(BWR) = 2.33$ barns

$C_1(PWR) = 2.27$ barns

$C_2(ATR) = 0.5$ barns

$C_2(BWR) =$ negligible

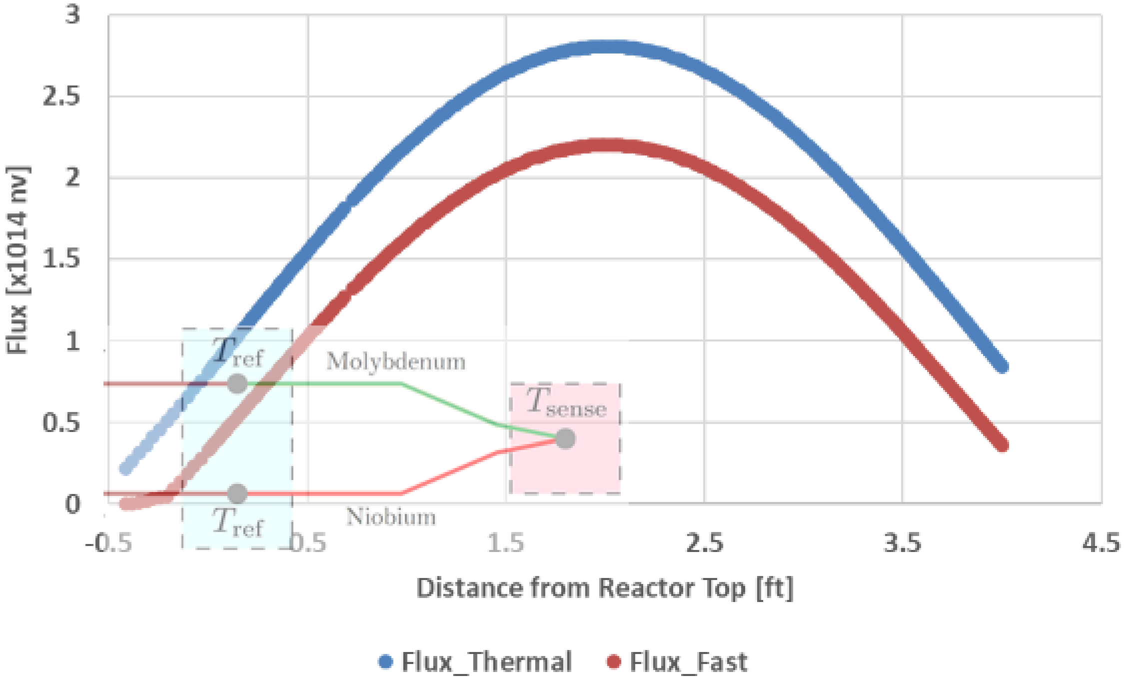
$C_2(PWR) =$ negligible

Results and accomplishments

Drift Due to Neutron Fluence

Table 9. Drift due to neutron fluence, as calculated by the HTIR-TC Drift Model

HTIR-TC #	Calculated EMF (unirradiated) [μV]	Irradiation Time (EFPD)	Calculated EMF (irradiated) [μV]	Calculated Drift [%]
1-14	17812	125	17735	-0.43



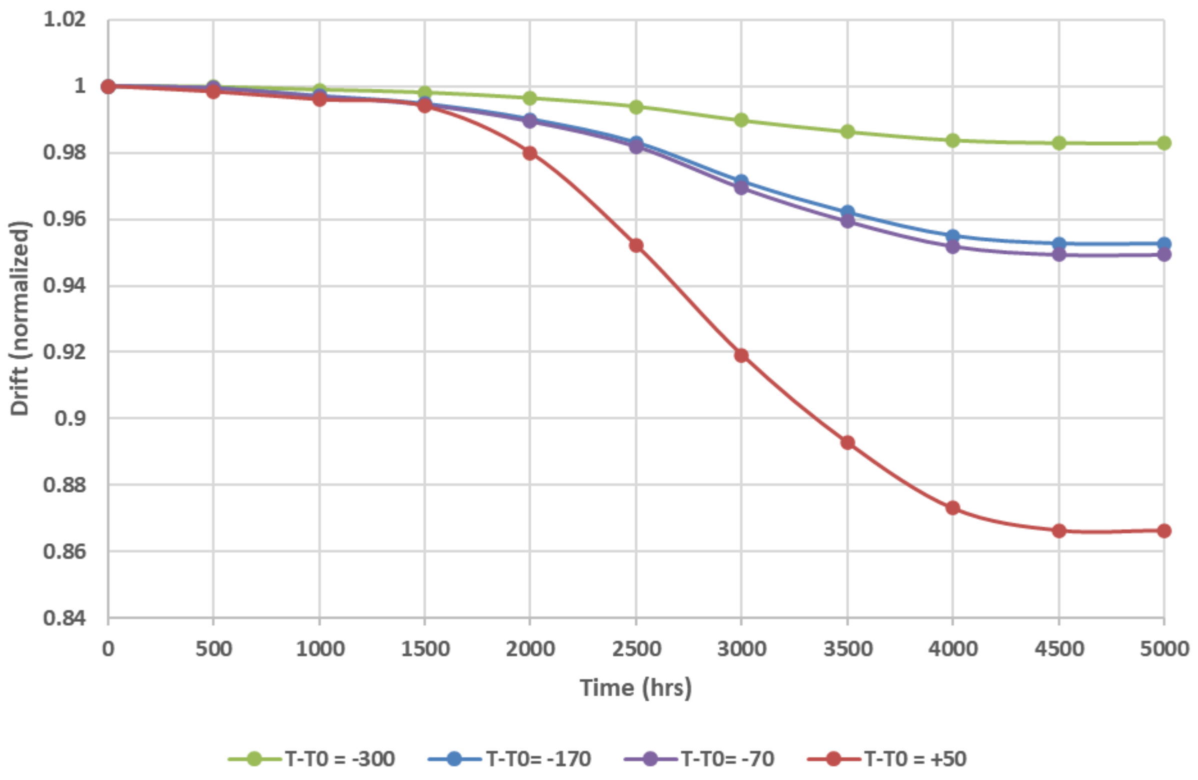
3 → $$S^*(T,x) = S(T,x) \times Reduction\ Factor.$$

4 → $$EMF^*(T) = \sum_0^L S^*(T,x)\frac{dT}{dx}dx$$

5 → $$Drift(neutron\ fluence)(\%) = \frac{EMF^*(T) - EMF(T)}{EMF(T)}100\%$$

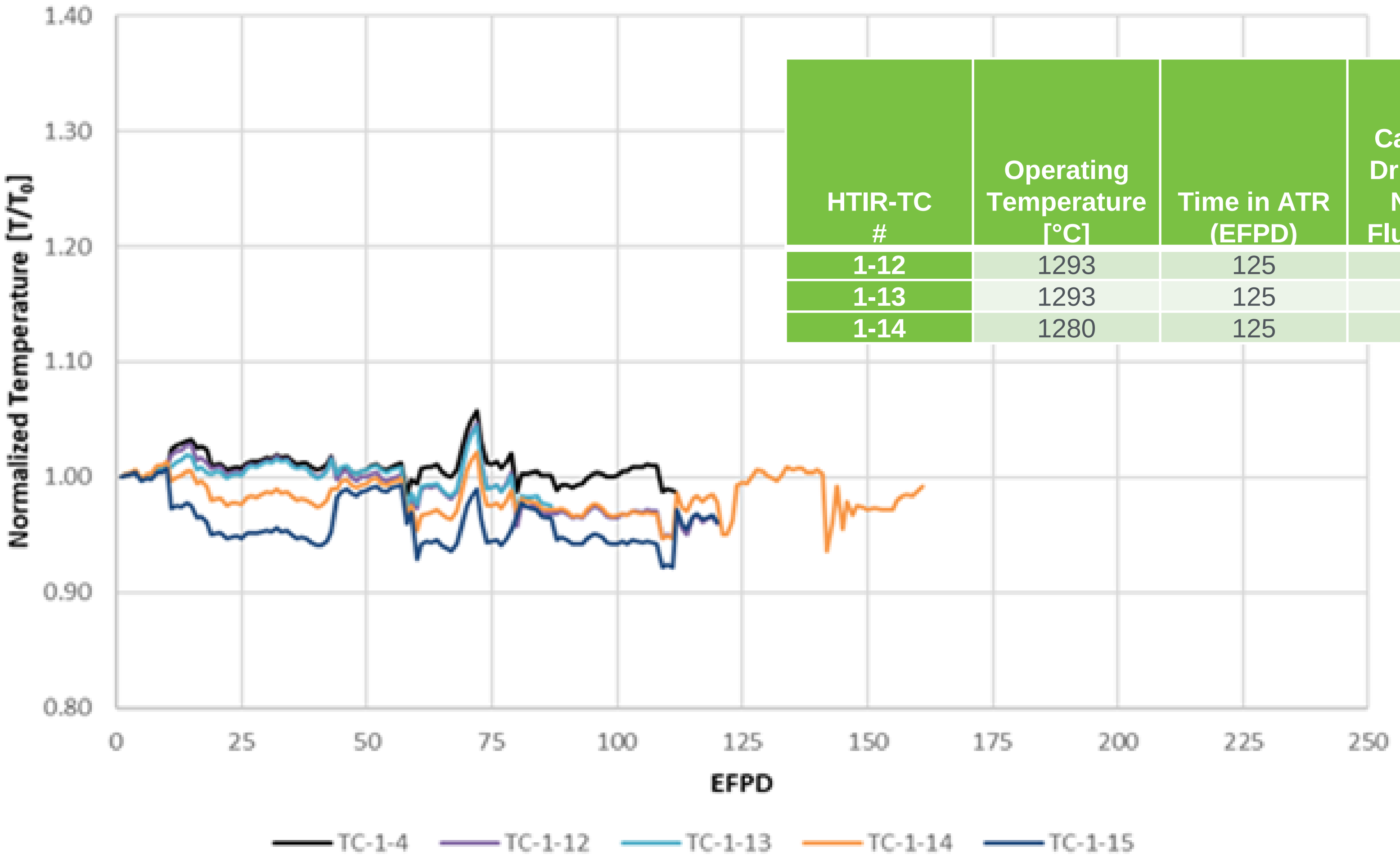
Drift Due to High Temperature

Heat treatment at 1500C



Results and accomplishments

- **Performance assessment of commercial TCs for nuclear applications:**



HTIR-TC #	Operating Temperature [°C]	Time in ATR (EFPD)	Calculated Drift Due to Neutron Fluence [%]	Calculated Drift Due to High-Temperature Operation [%]	Total Calculated Drift [%]
1-12	1293	125	-0.43	-2.86	-3.29
1-13	1293	125	-0.43	-2.86	-3.29
1-14	1280	125	-0.43	-3.07	-3.50

Conclusion

Richard Skifton
Instrumentation Engineer | Measurement Sciences
richard.skifton@inl.gov | 208.526.2696 | 702.306.1258
Idaho National Laboratory | 1955 Fremont Ave. | Idaho Falls, ID | 83415

Summary:

- Apply TC drift model to commercial TCs during reactor use.
- Analyze surface mounted TCs with intrinsic junctions for material interaction, fin effects, and temporal resolution during transients.

Pertinent Work:

- Drift Model: Skifton, R., "High Temperature Irradiation Resistant Thermocouple Qualification Test Results Report," External Report, INL/EXT-21-63346, 2021.
- Hone, L., Jensen, C., "Cladding Temperature Measurement via Thermocouples for Transient Irradiation Experiments," Annual Report, INL, 2019. (Available upon request).

Questions?

ASI | Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Demonstration and benchmarking of SPNDs for advanced reactor application

CT-21IN070201

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

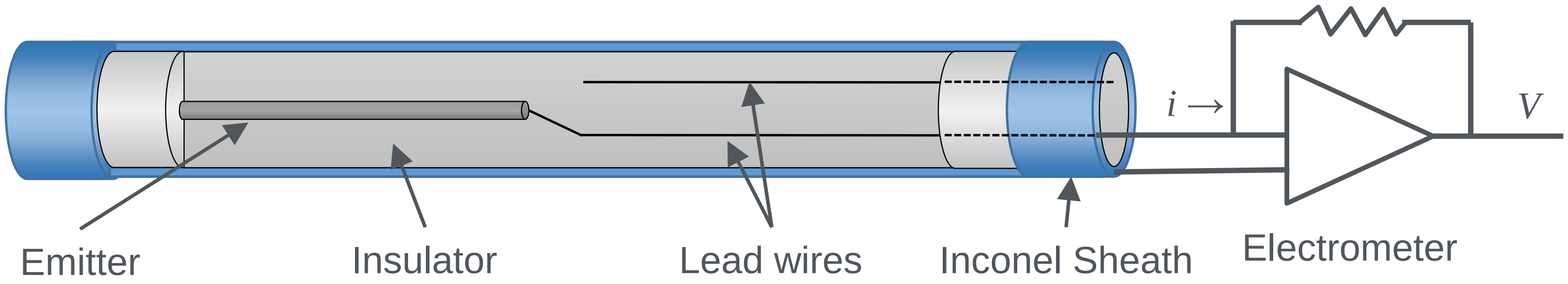
November 15 – 18, 2021

PI: Kevin Tsai

Idaho National Laboratory

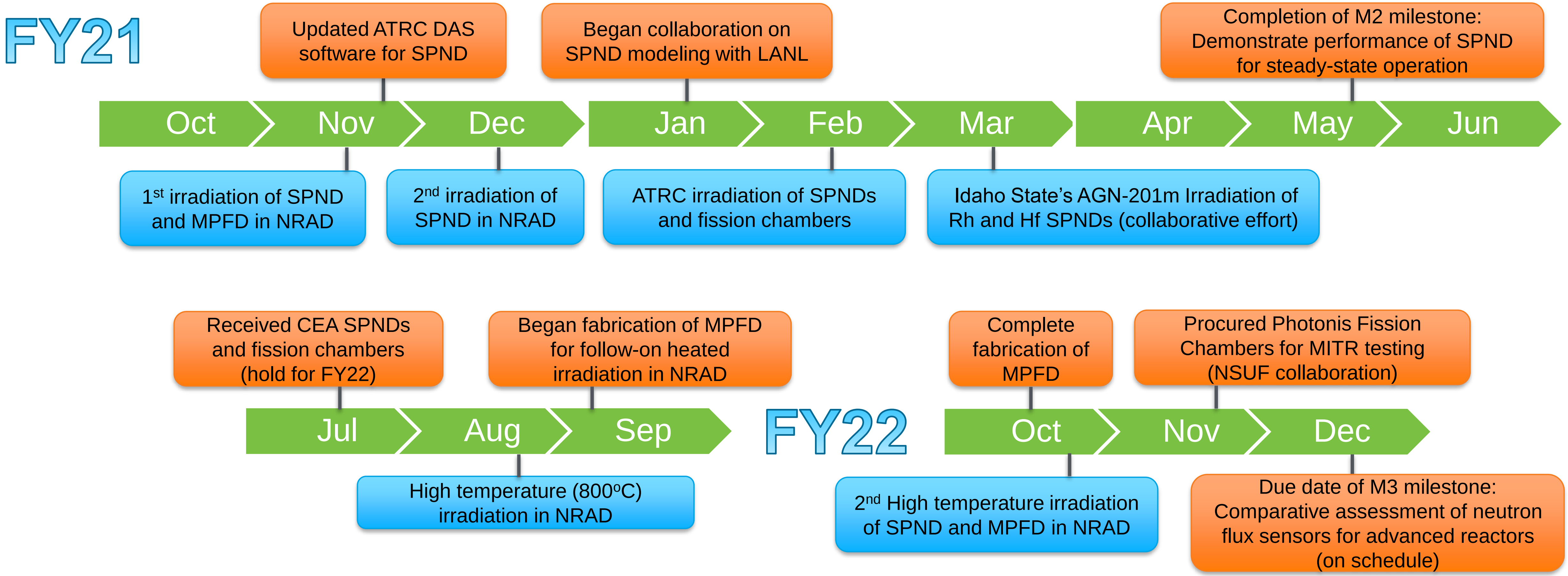
Project Overview

- Goal and Objective
  - To develop and demonstrate self-powered neutron detectors (SPNDs) for advanced reactor research. First iteration begins with classically built rhodium-based SPNDs from a domestic supplier. Testing was performed in INL's Advanced Test Reactor Critical (ATRC) facility, Neutron RADiograpy (NRAD) facility, and Idaho State University's AGN-201m reactor.
- Technology Overview
  - Two primary types of operation—dominant emitter-neutron interaction based
    - Slow-response based on (n, β−) – Rh, V emitters
    - Prompt-response based on (n, γ, e_{ce}) and (n, γ, e_{pe}) – Co, Gd, Hf



Project Overview

- Timeline of activities in FY-21



Project Overview

FY-21 & FY-22 Milestones

Milestone	Due Date	Status
Demonstrate performance of SPND for steady-state operation	5/20/2021	Completed on time
Comparative assessment of neutron flux sensor technologies for advanced reactors	12/31/2021	On schedule

- Participants
  - Kevin Tsai – PI for self-powered neutron detectors (SPNDs)
  - Troy Unruh – PI for CEA fission chamber
  - Dr. Michael Reichenberger – PI for Micro-Pocket Fission Detector (MPFD) and Dosimetry
  - Eric Larsen – Data acquisition software designer
  - Ashley Lambson – Lead technician for MPFD construction
  - Dr. Edward Lum (LANL) – MCNP analyst for SPND modeling

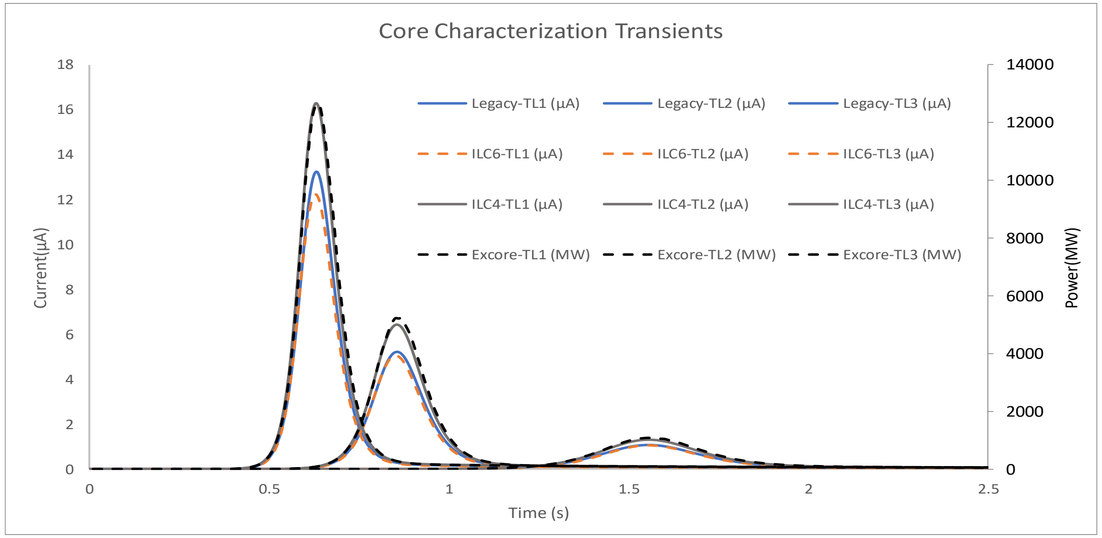
Technology Impact

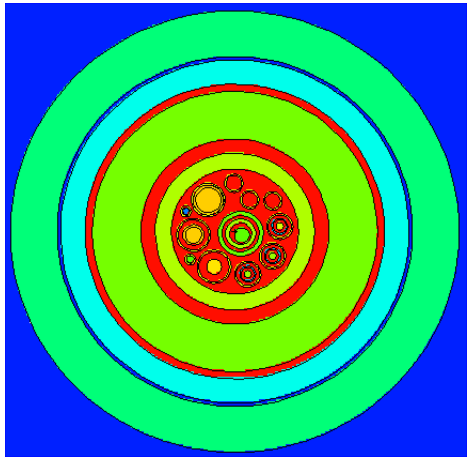
- SPNDs are an established in-core sensor that provides real-time neutron flux measurement for PWR based technology. This research advances the nuclear technology by further developing SPNDs to provide the same measurement in advanced reactor environments.
  - FY 21 activities focus on SPNDs operating in high temperature environments (up to 800C).
- Successful completion of these activities will create a pathway of qualified SPNDs (per ASI qualification process) for use in fuels experiments and advanced reactor demonstrations.
- Developmental fabrication of customized SPNDs are performed in close collaboration with commercial vendors to enable a supply chain accessible for the nuclear energy industry.

Results and accomplishments

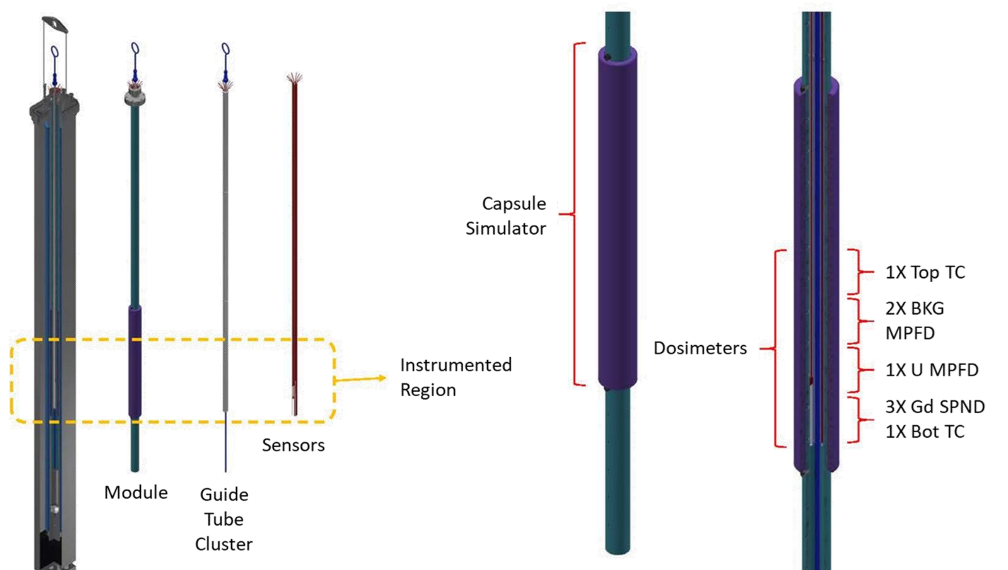
SPND modeling (collaboration with LANL)

- Modeling began with Gd-SPND data from MIMIC-N
  - MCNP more readily available for prompt-response behavior
  - Development of a “dose-response” function model – method based on CEA MATiSSe and Sandia National Laboratory report.
  - Prompt-response results expected to be complete in December
  - Updating model to include delayed-response.





Cross-sectional view of sensors in MIMIC-N via MCNP

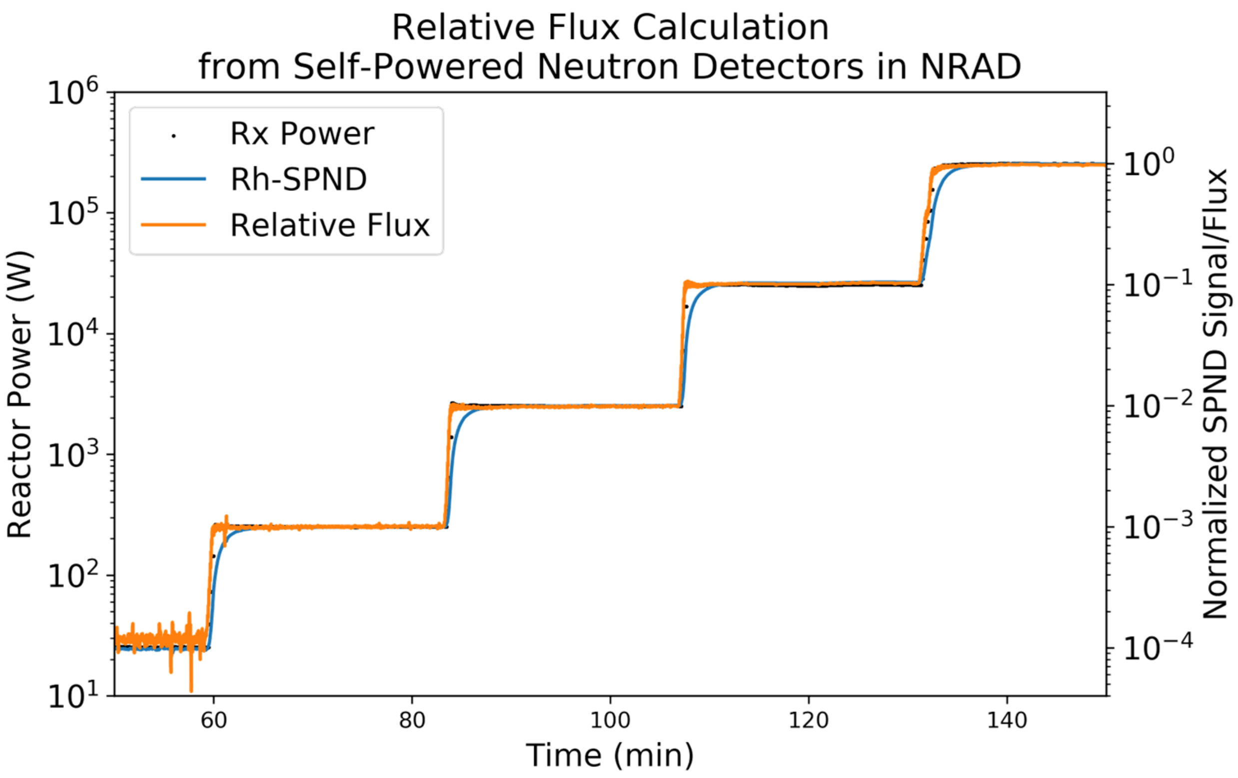


Conceptual Design of MIMIC-N

Results and accomplishments

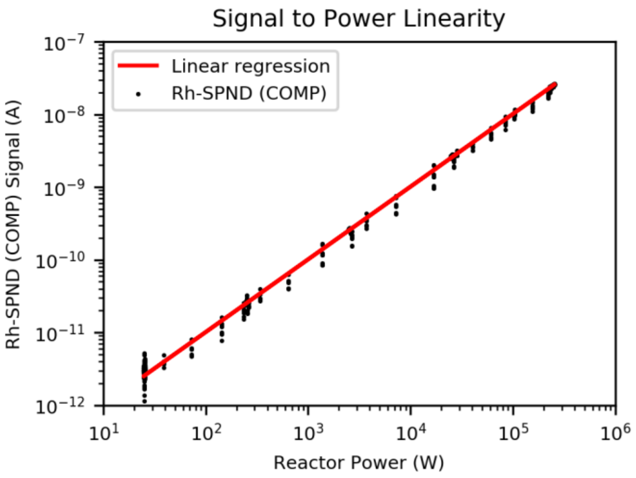
NRAD Irradiation Results (non-heated)

- Test performed over 5 decades of reactor power
  - Lowest power measured at 2.5W (2E7 n/cm·s²)
- Demonstration showed very good linearity



Initial setup for SPND DAS

Insertion of SPND into dry-tube



$$i_{comp}(t) = \left(\frac{1}{\lambda_B}\frac{di(t)}{dt} + i(t)\right)$$

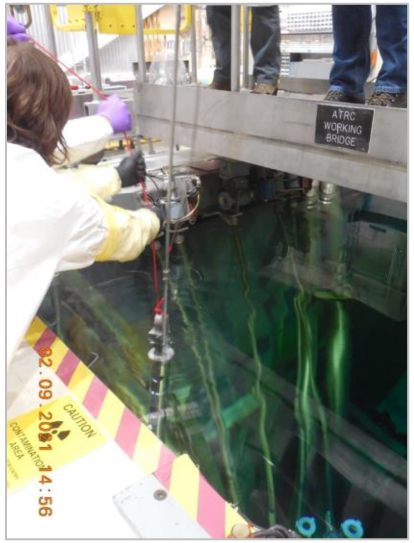
Equation for relative flux

Results and accomplishments

ATRC Irradiation Results

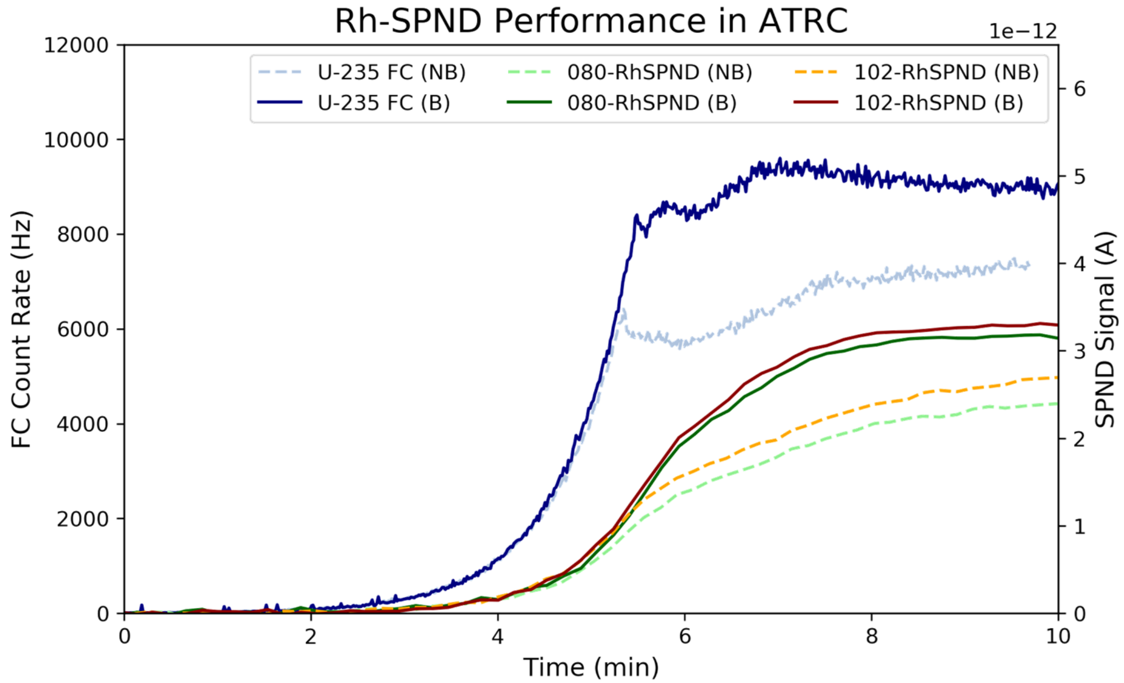
- Measurements fell within flux wire error band
- 102-Rh-SPND indicated a decreased increase in measurement
  - Expected for 0.102” emitter OD via increased self-shielding

Sensor Performance	080-SPND	102-Rh-SPND	U-235 Fission Chamber	Co Axial Flux wire
Without booster fuel and moderator (NB)	2.5018 ± 0.0246 pA	2.7343 ± 0.0173 pA	7358 ± 99 cps	4.377 ± 0.175 E 8 φ_{th}
With booster fuel and moderator (B)	3.1555 ± 0.0222 pA	3.2290 ± 0.0212 pA	9063 ± 107 cps	5.341 ± 0.204 E 8 φ_{th}
Relative measurement increase	1.2613 ± 0.0153	1.1809 ± 0.0108	1.231 ± 0.022	1.218 ± 0.047



Insertion of neutron flux rig into ATRC

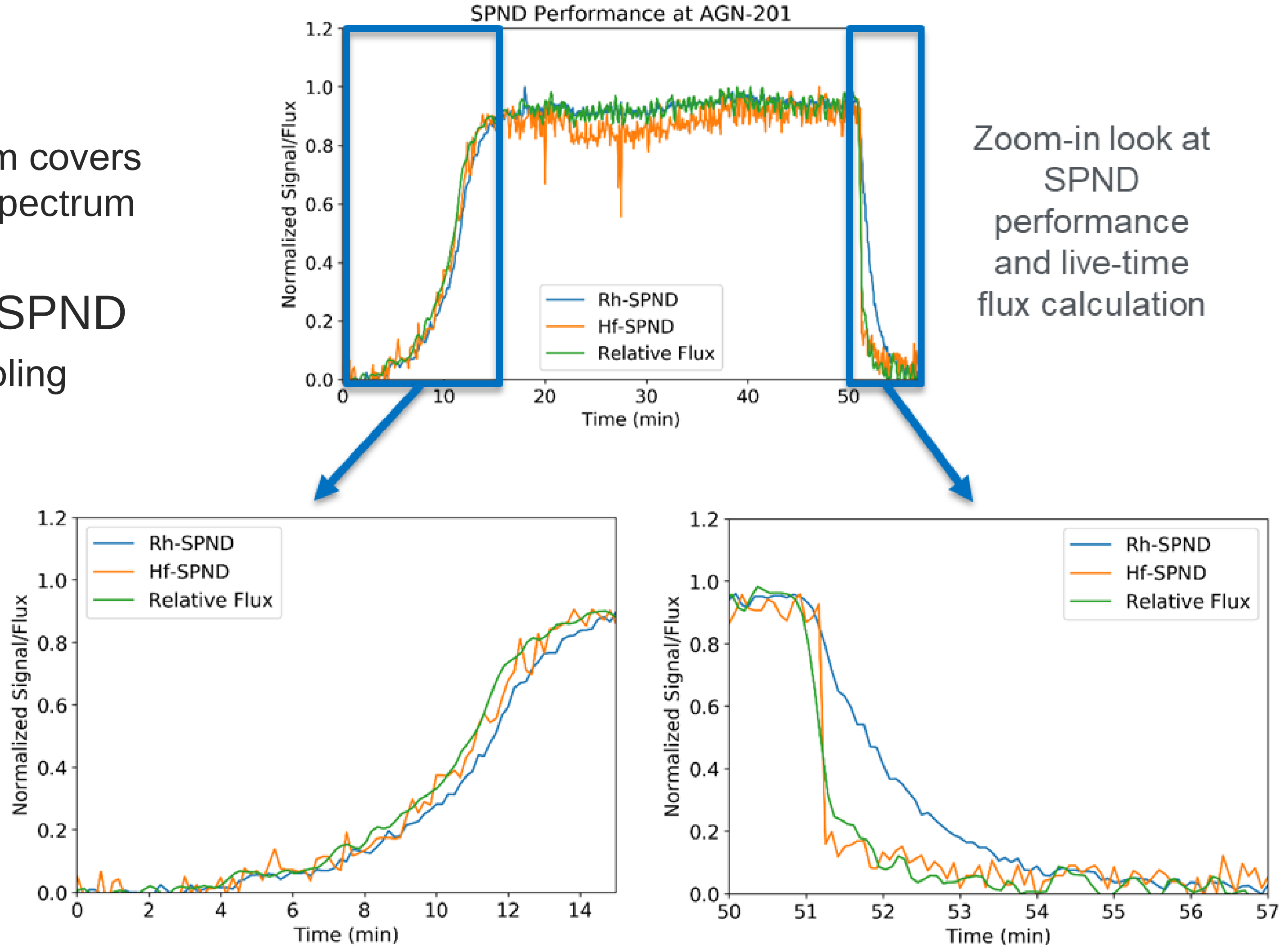
Neutron flux sensors data acquisition station



Results and accomplishments

ISU Irradiation Results

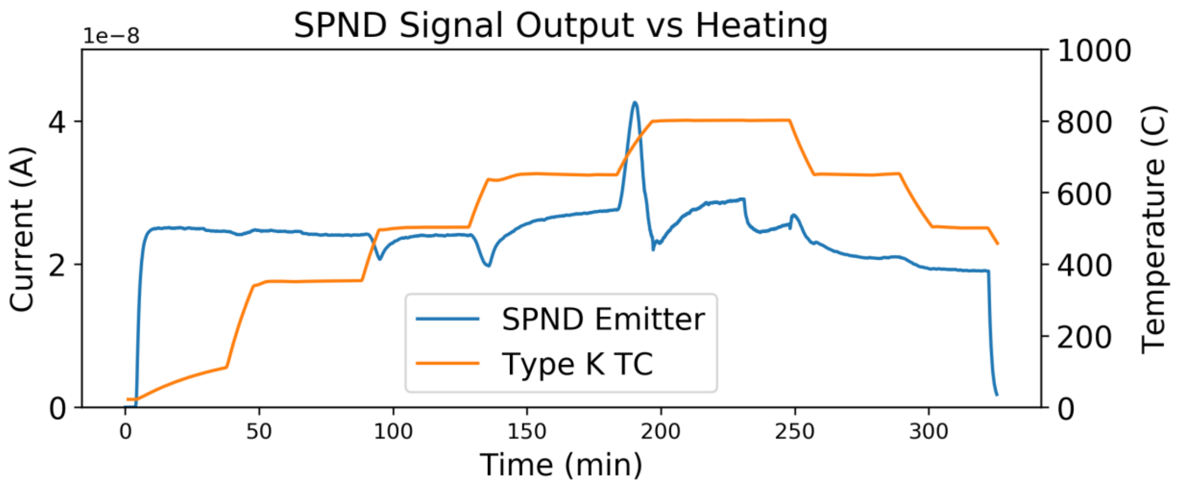
- Performed in collaboration with ISU.
  - Testing reactor’s capability of using cadmium covers to characterize SPND performance in fast-spectrum neutron flux.
- Test performed with Hf-SPND and Rh-SPND
  - Demonstrated electronics’ limitation of sampling rates in low-flux (low-current) environments

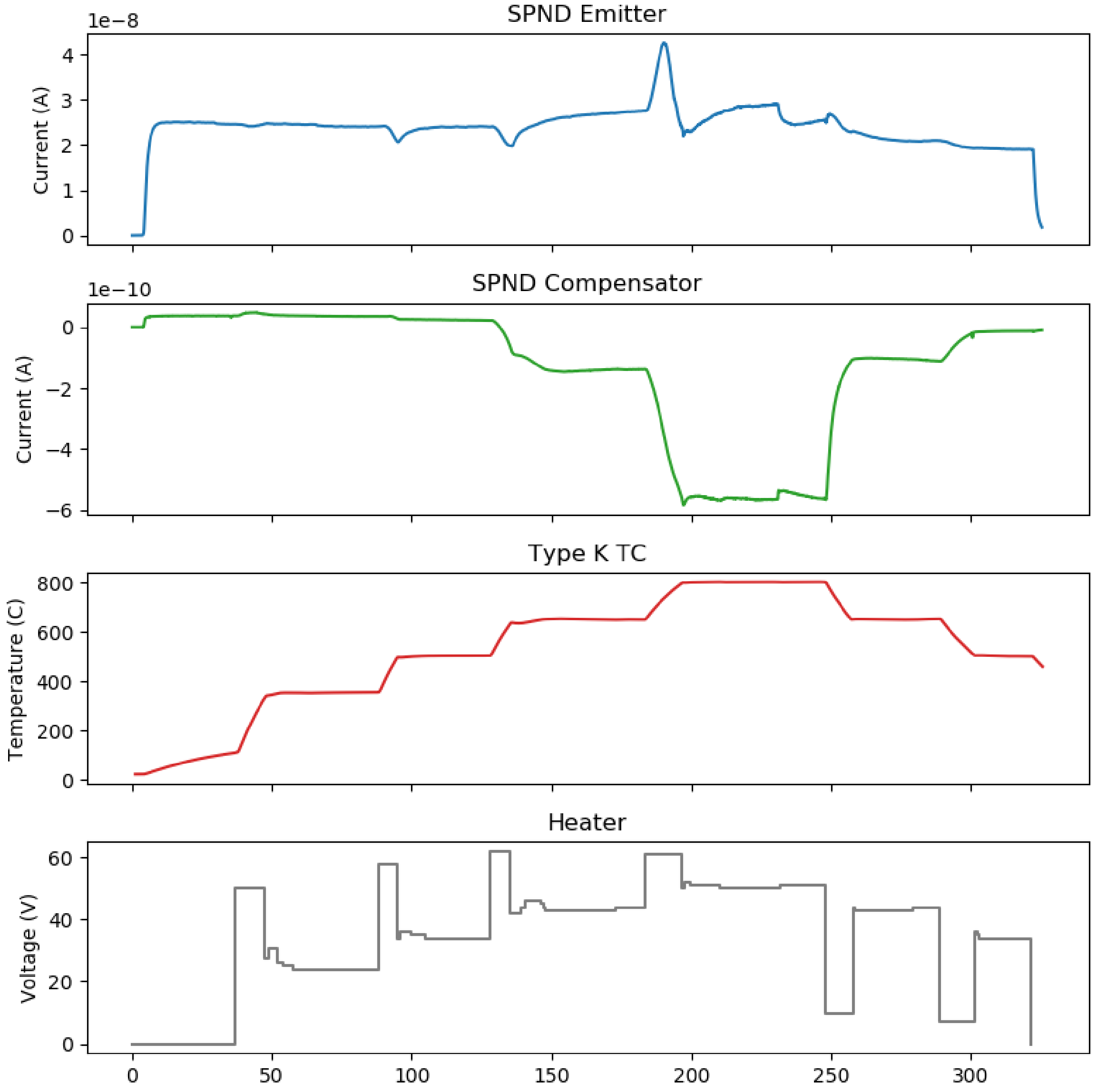


Results and accomplishments

NRAD Heated Irradiation Results

- Temperature includes ambient, 350C, 500C, 650C, and 800C
- Noise related to heater power and temperature identified.
- Power tracking still available in temperatures at 800C, but require stabilization





Conclusion

- Summary
  - Two designs of rhodium has undergone testing in 3 reactors – NRAD, ATRC, and ISU Rx
    - Both a baseline measurement as well as a heated irradiation was conducted in NRAD
  - SPNDs demonstrated a very linear output over 5 decades of reactor power in NRAD
  - SPNDs were also able to measure the flux change within the medium I-positions of ATRC from an inserted booster fuel.
    - Outputs falls within error bars of U-235 fission chamber and cobalt flux wire
  - Limitations of sampling/response time identified both at ATRC and ISU
- Future work (FY22)
  - A second heated irradiation including a MPFD at NRAD was conducted on October 27, 2021 (under analysis).
  - Development of SPND temperature compensation algorithm
    - Supporting eVinci I&C development
  - MITR-NSUF project: Typical PWR condition
    - Benchmarking of ILC-Rh-SPND, MPFD, and Photonis fission chambers.

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Questions?

ASI | Advanced Sensors and Instrumentation

Development of Innovative Sensors for Advanced Reactor Concepts

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Nuclear Instrumentation Engineer: Troy Unruh

Idaho National Laboratory

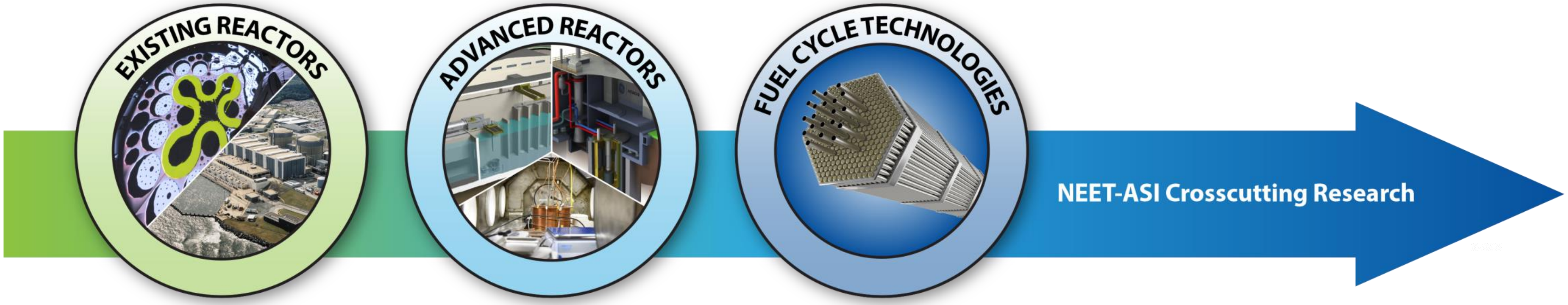
ASI supports **both** existing and advanced reactors

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

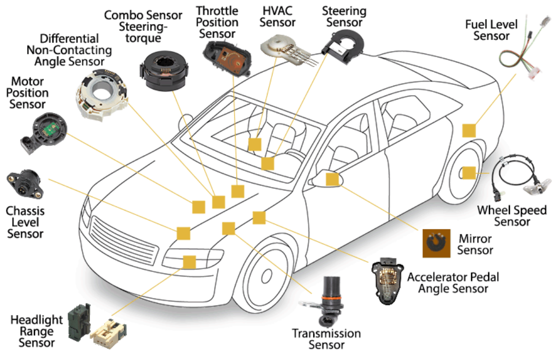
Vision

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

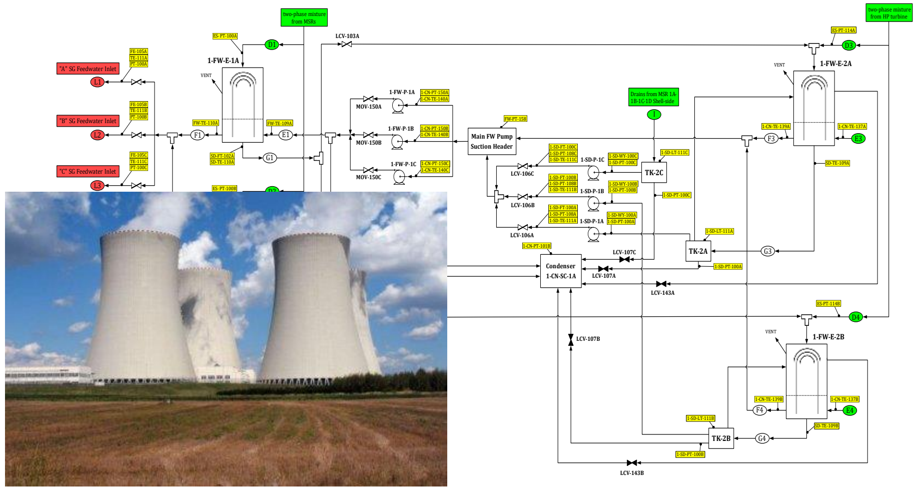


Why are innovative sensors needed? -- Sensing by the numbers

Smartphone (10-20 per phone)[4]

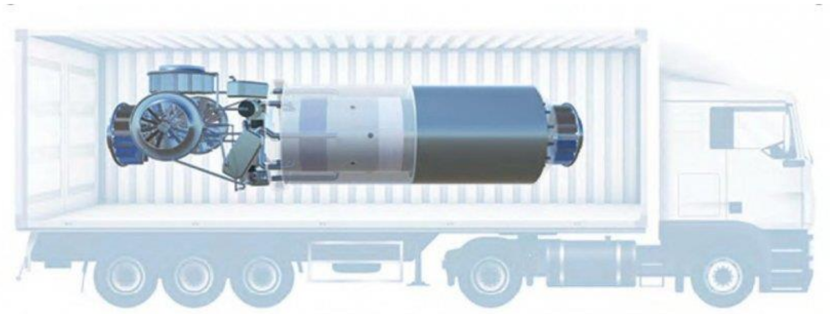


Automotive sensors (200 per vehicle)[1]



Nuclear power plant 10,000 sensors and detectors per plant[3]

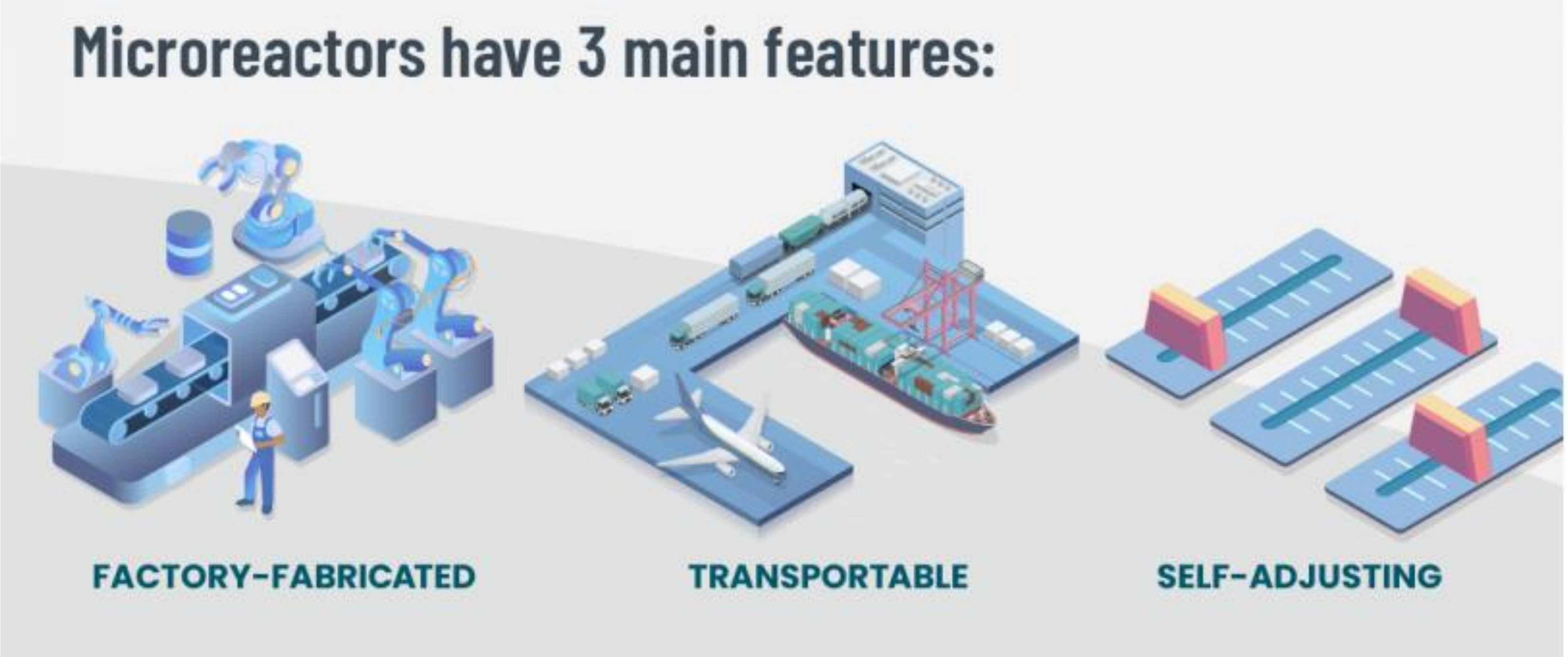
Aerospace 6,000-26,000 sensors per plane[2]



Advanced Nuclear sensors per unit?

[1]https://www.cashcarsbuyer.com/sensors-in-cars/
[2]https://siliconsemiconductor.net/article/102842/Aviation_depends_on_sensors_and_big_data
[3]https://cdn.intechopen.com/pdfs/21051/InTech-Nuclear_power_plant_instrumentation_and_control.pdf
[4]https://www.gotechtor.com/smartphone-sensors/

Why are innovative sensors needed in advanced nuclear?

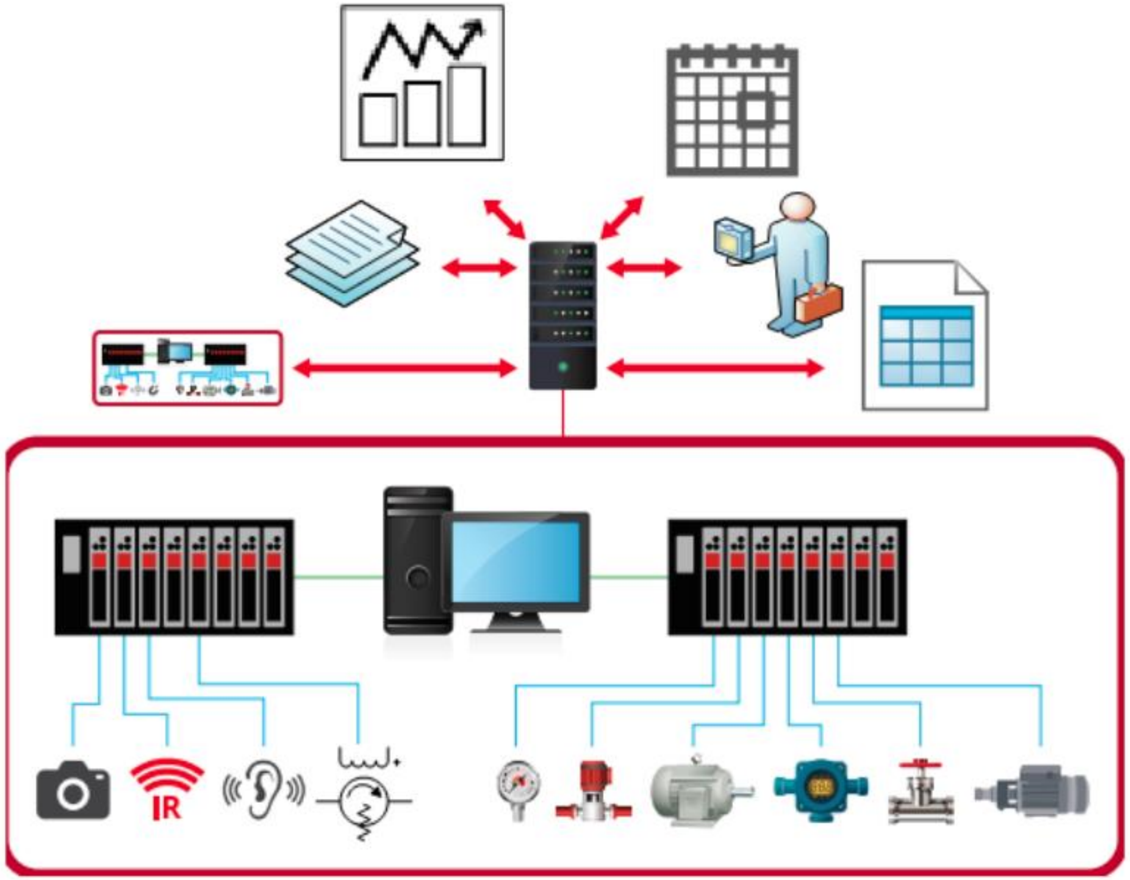


Must have characteristics enabling minimum downtime for periodic instrumentation and sensor replacement or refurbishing, without requiring direct exposure to the nuclear fuel system.

Getting the number of sensors right for advanced nuclear concepts

Sensor considerations:

- Sensors need to continuously measure and monitor variables
- Ensuring the right placement
- Power requirements
- Radiation Hardness
- The number of sensors can not increase indefinitely for cost and integration reasons
- Data generation and integration vs. computing power
- One sensor can not cover all applications, nor should it
- **Optimization is key**



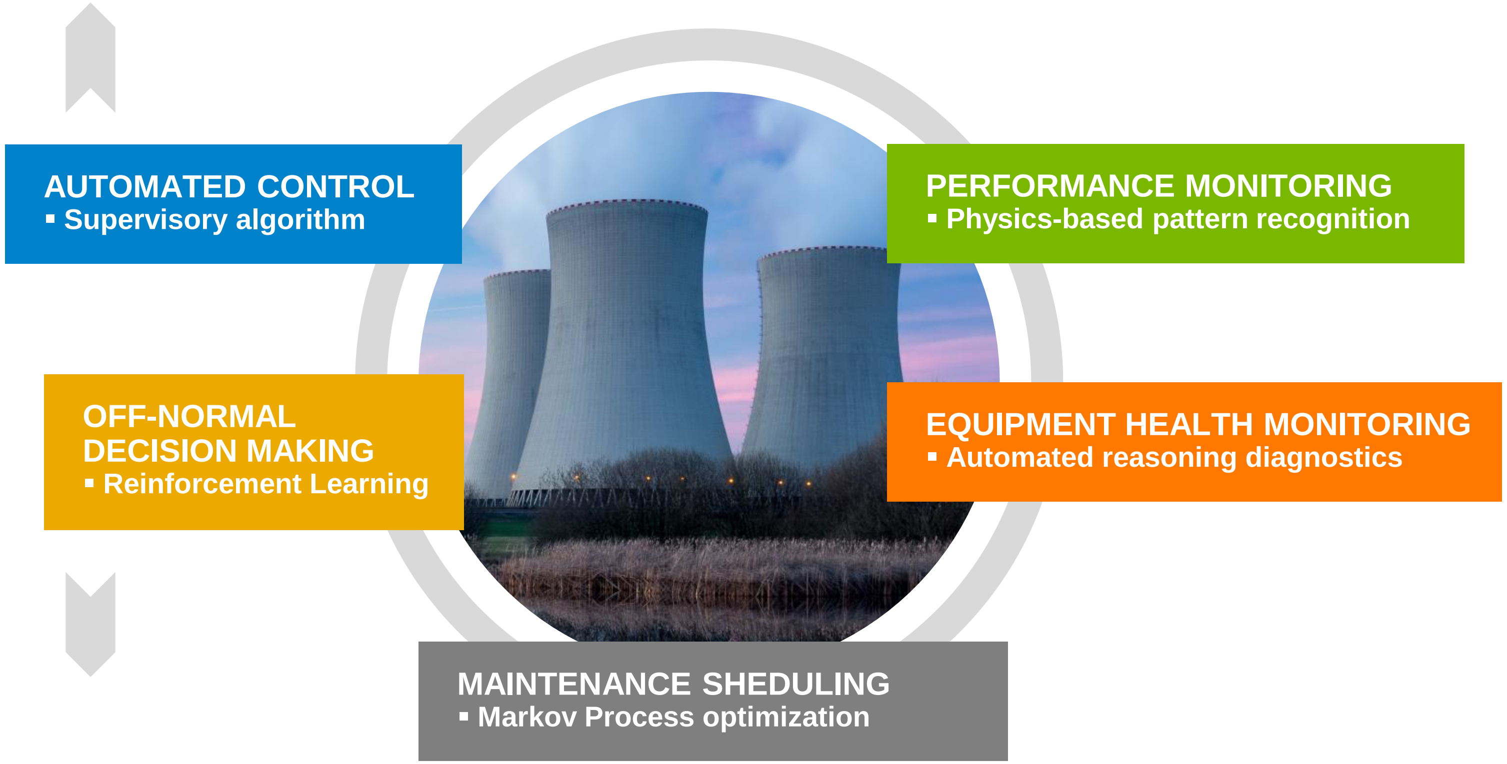
https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_16115.pdf

Digital technology for advanced reactors

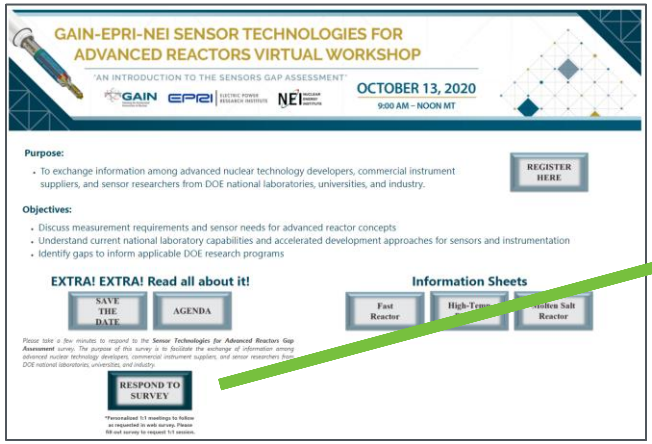
- **Digital technology for advanced reactors**
  - Integrate advanced sensors and instrumentation in Nuclear Digital Twins (NDT) with Hardware in the Loop simulation for the phased demonstration of performance-based control algorithms to enable autonomous operation
  - Develop condition monitoring technologies for anomaly detection, diagnostics, prognostics, and decision making that can operate on streaming data
  - Develop modeling and simulation tools for communication technologies to support integration with control systems

https://dice.inl.gov/

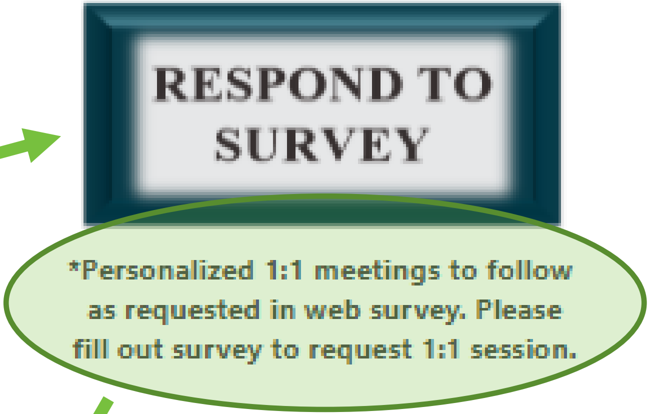
A logical progression towards sensor-based autonomous operation of advanced reactors

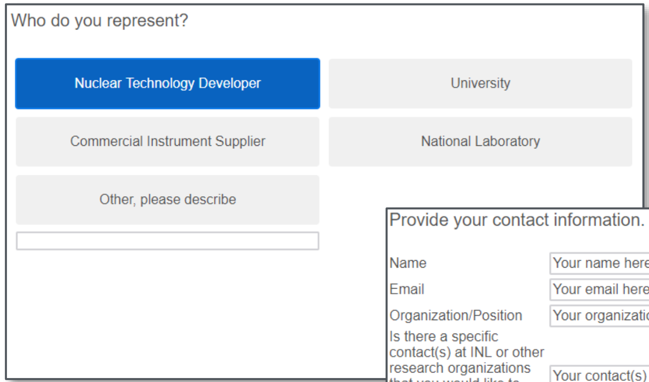


What innovative sensors should we develop? GAIN gap assessment process

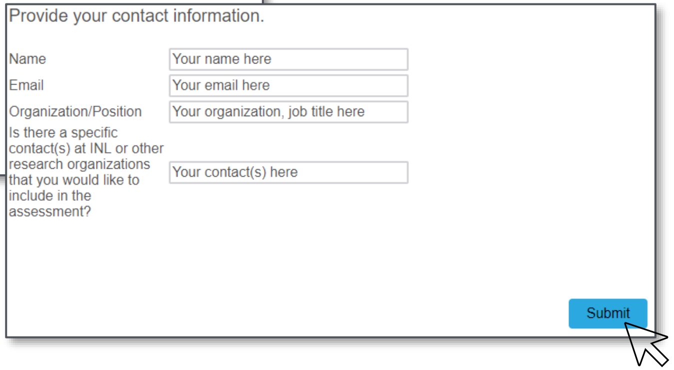


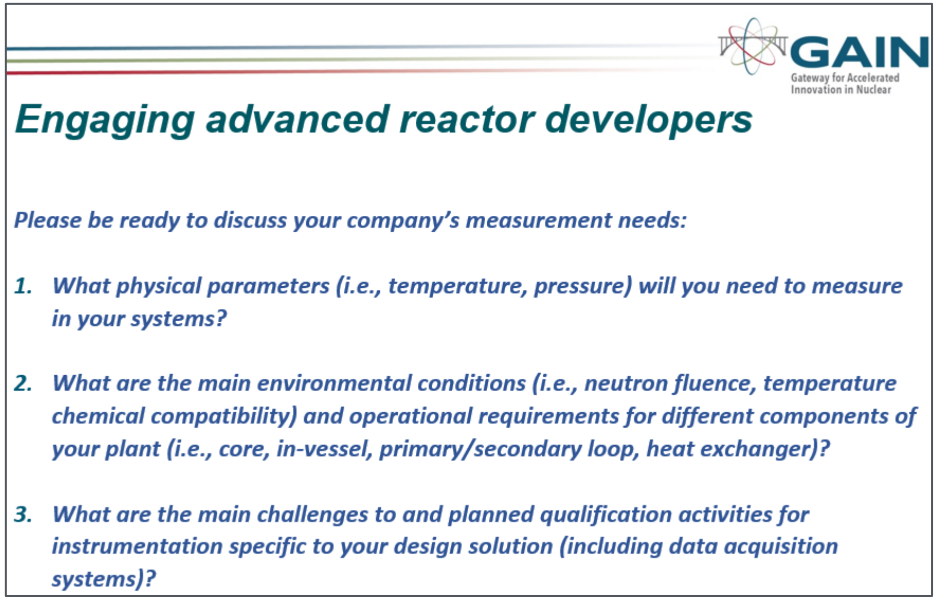
GAIN website





Survey





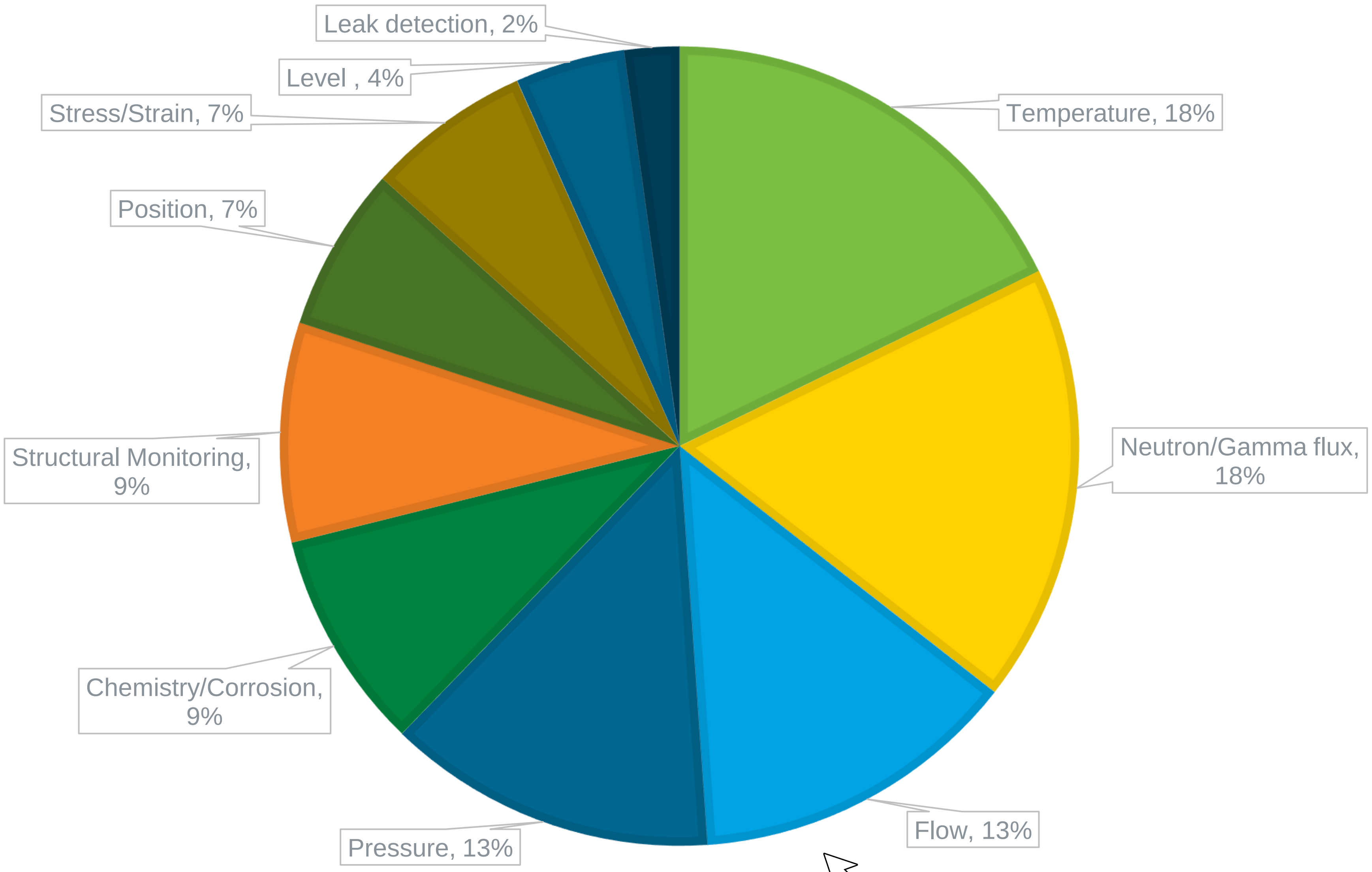
Engaging advanced reactor developers

Please be ready to discuss your company's measurement needs:

1. *What physical parameters (i.e., temperature, pressure) will you need to measure in your systems?*
2. *What are the main environmental conditions (i.e., neutron fluence, temperature chemical compatibility) and operational requirements for different components of your plant (i.e., core, in-vessel, primary/secondary loop, heat exchanger)?*
3. *What are the main challenges to and planned qualification activities for instrumentation specific to your design solution (including data acquisition systems)?*

1:1 interview questions

What innovative sensors should we develop? GAIN gap assessment results



Top 4

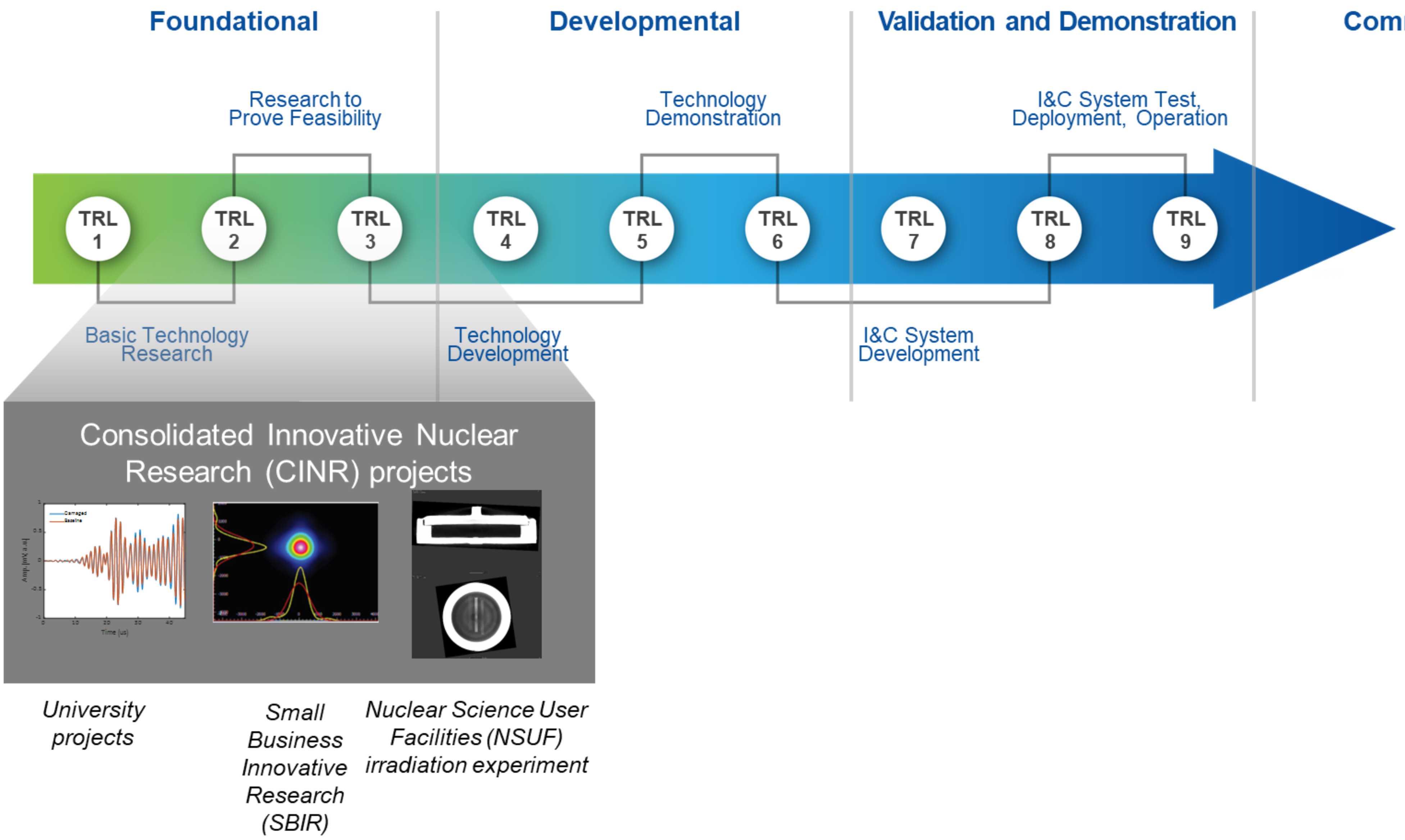
Temperature

Neutron Flux

Flow

Pressure

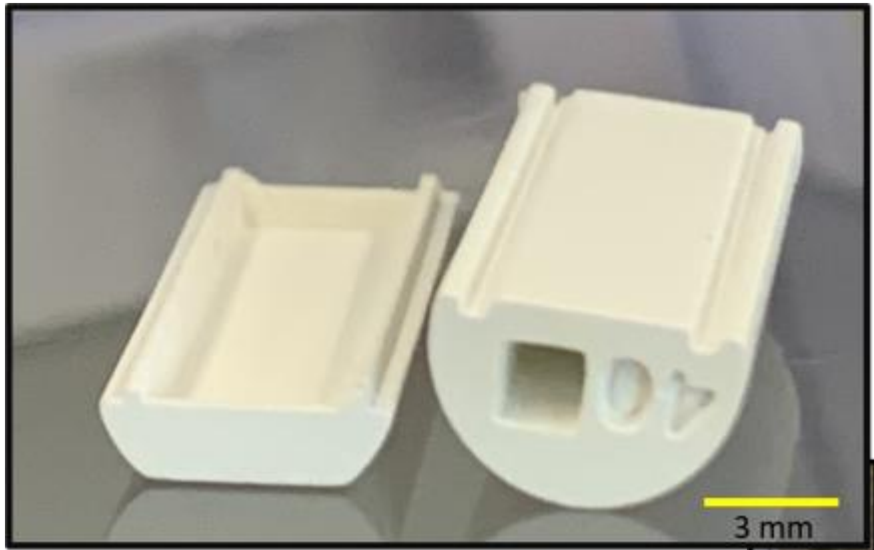
Foundational research to prove feasibility

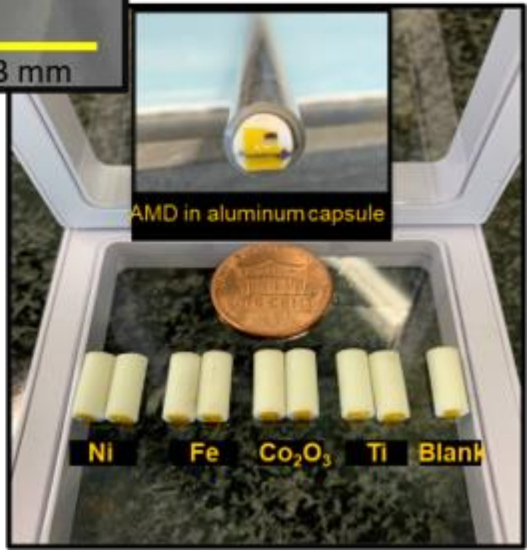


Foundational research to prove feasibility -- example

Advanced Manufactured Dosimeters (AMDs)

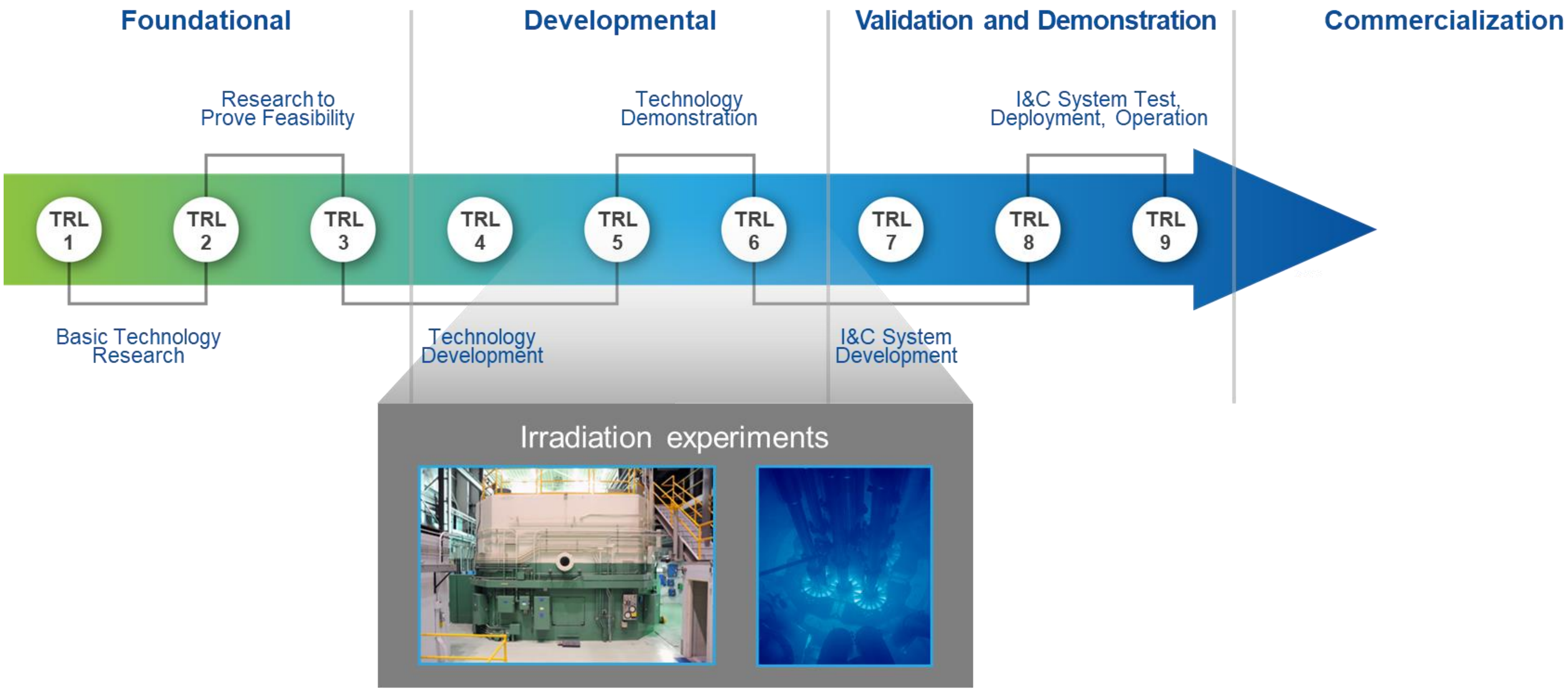
- Offer a cost effective, miniaturized and performance enhanced alternative to standard dosimetry
- Specially developed for the characterization of neutron fluence in irradiation experiments and demonstration facilities





AMD holder (left) fabricated with AMD pastes and ready for installation in TREAT (right)

Irradiation experiments for sensors technology demonstration



Transient Reactor Test Facility (TREAT) *Advanced Test Reactor (ATR)*

Irradiation experiments for sensors technology demonstration -- Example

Instrumentation for irradiation experiments

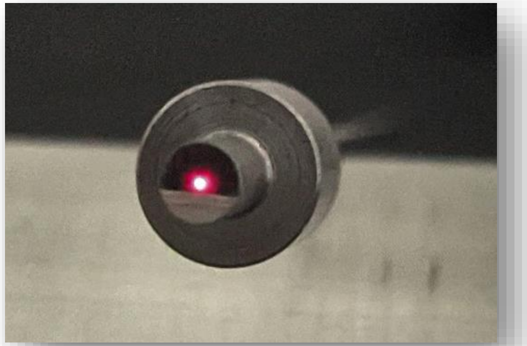
- Provide real time instrumentation and passive monitors to measure local operational parameters (neutron flux, temperature, pressure, mechanical solicitations) in TREAT, ATR, HFIR and MITR experiments
- Develop methods to characterize nuclear fuel and material properties (thermal conductivity, microstructure, mechanical behavior) during irradiation

Instrumented capsule for LWR fuel safety test in TREAT

Irradiation experiments of innovative sensors for advanced reactors

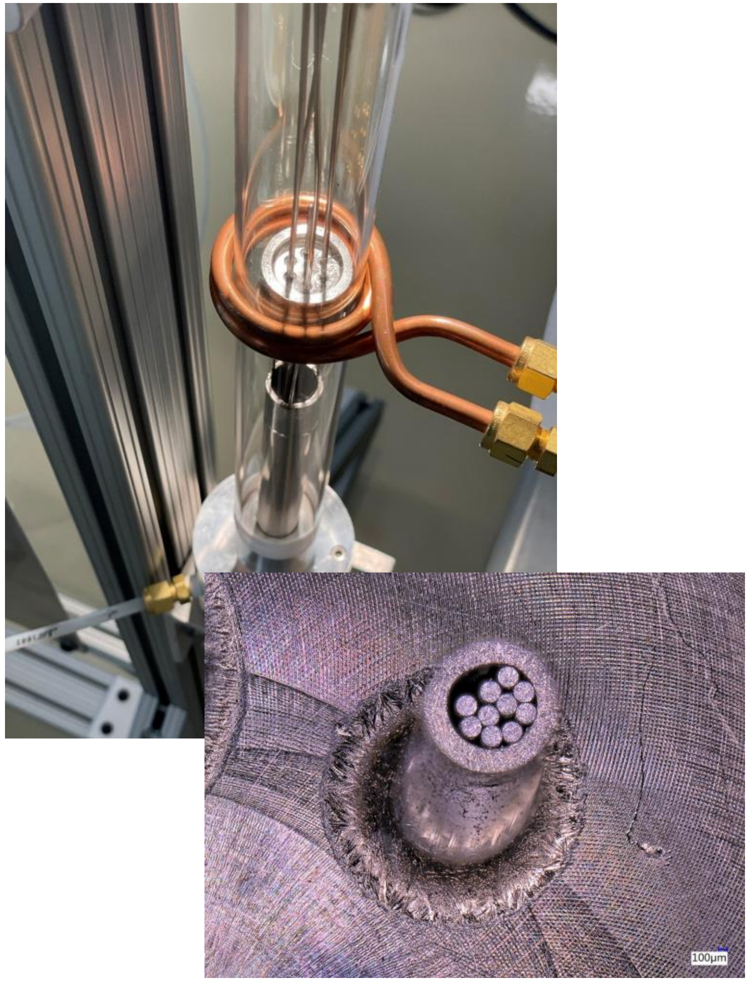
Sensors for advanced reactors

- Develop advanced sensors (multi-mode; multi-point/distributed; miniature size and limited or no penetrations) and supporting technology (rad-hard electronics, wireless communication, power harvesting) for nuclear instrumentation
- Demonstrate nuclear instrumentation performance in conditions relevant to advanced reactors (including irradiation)
- Establish a supply chain for advanced reactor instrumentation (fabrication and services)



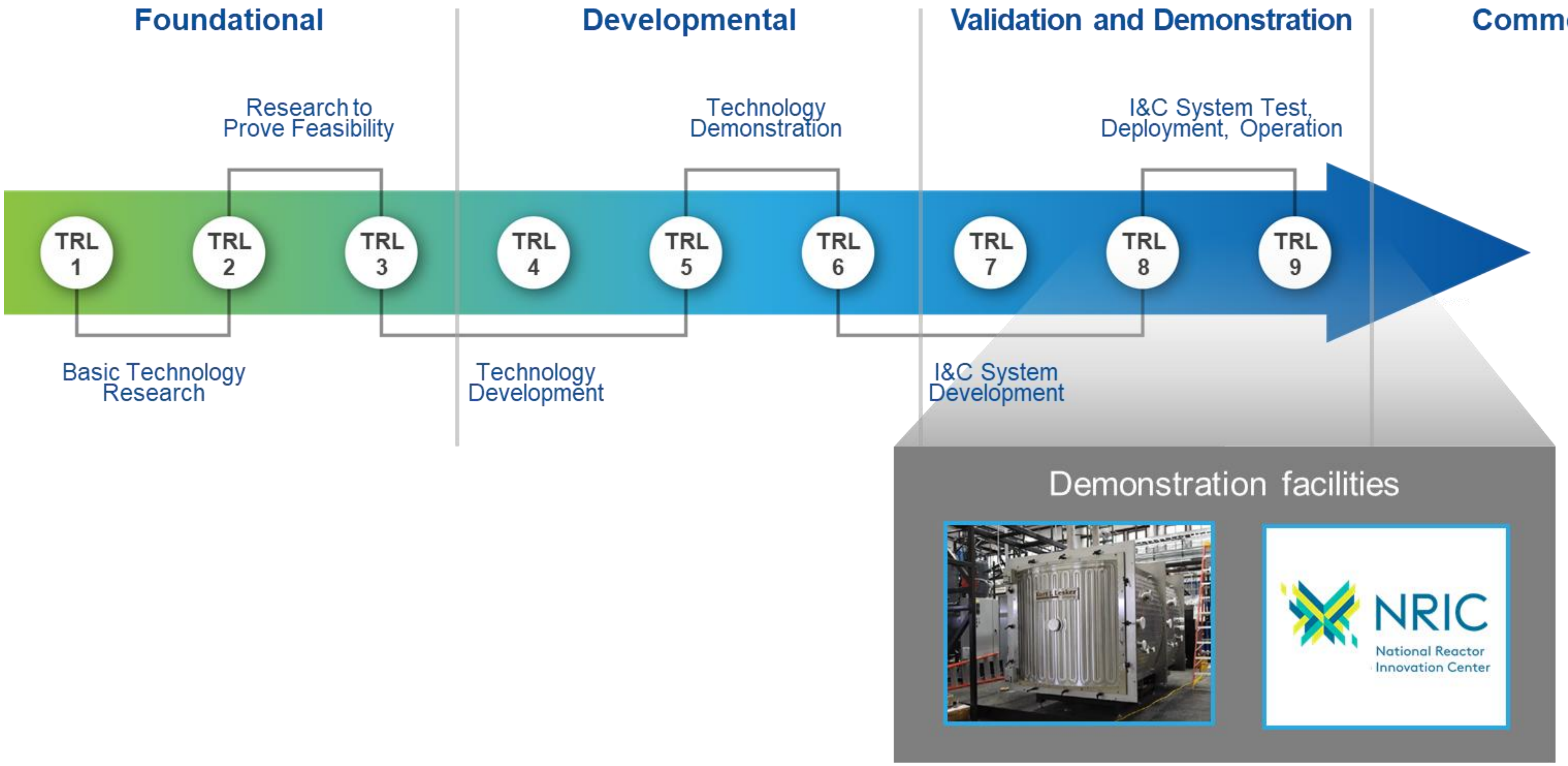
Optical fiber-based pressure sensor under fabrication

Sensor laser weld



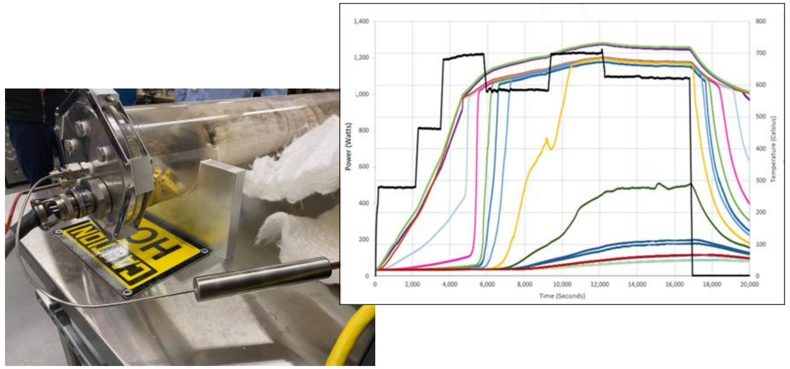
Ultrasonic thermometer induction brazing

Validation and demonstration facilities

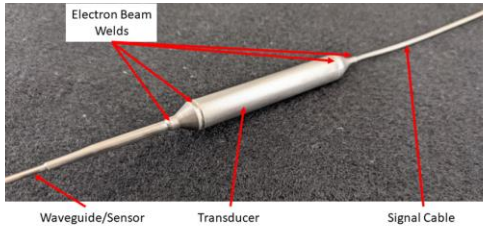


Microreactor Agile Non-Nuclear Testbed (MAGNET)

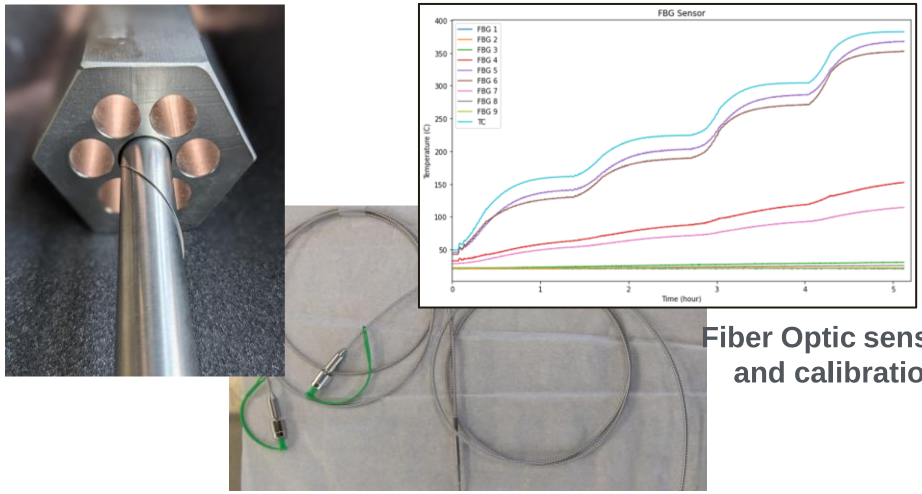
Demonstration facilities example – Microreactor Agile Non-Nuclear Testbed (MAGNET)



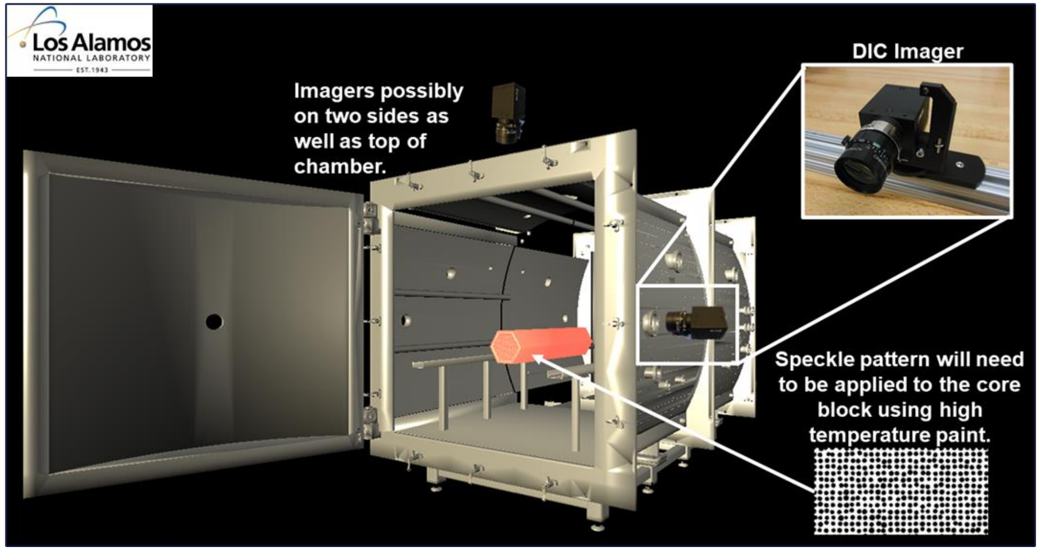
10-point TC installed and tested



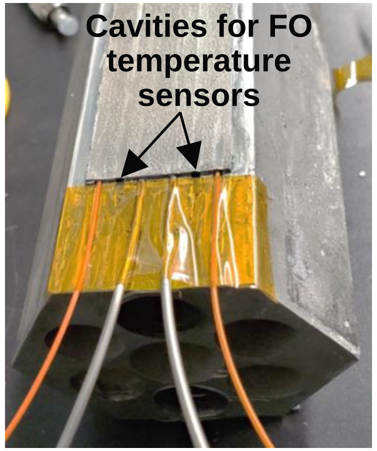
UT transducer



Fiber Optic sensors and calibration

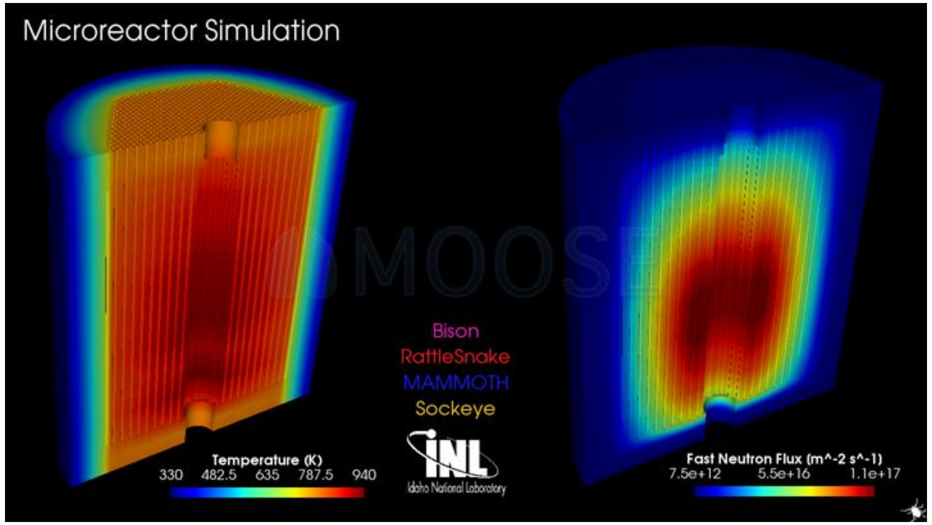


Digital Image Correlation Simulation



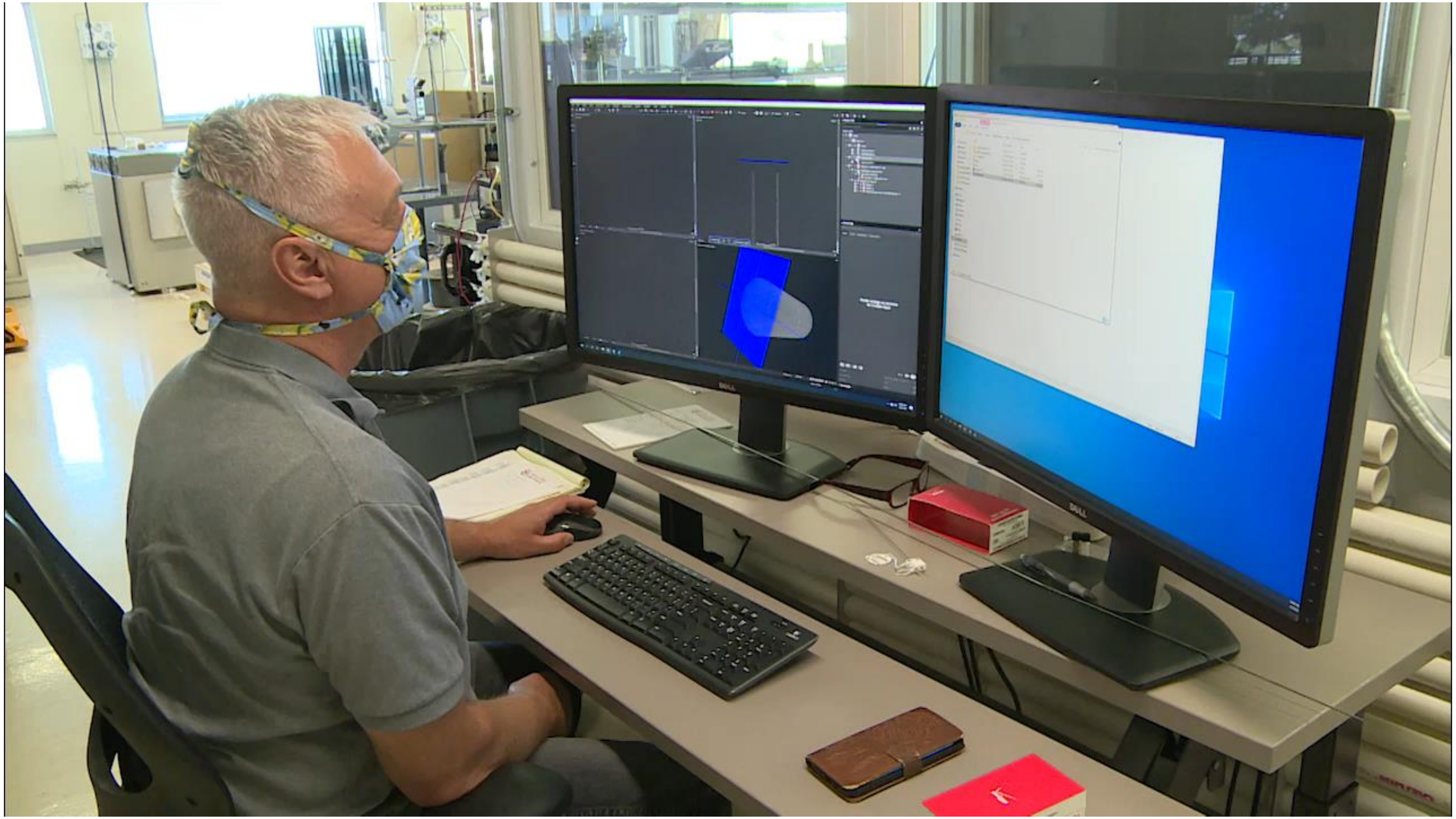
Core block with embedded sensors

Oak Ridge National Laboratory



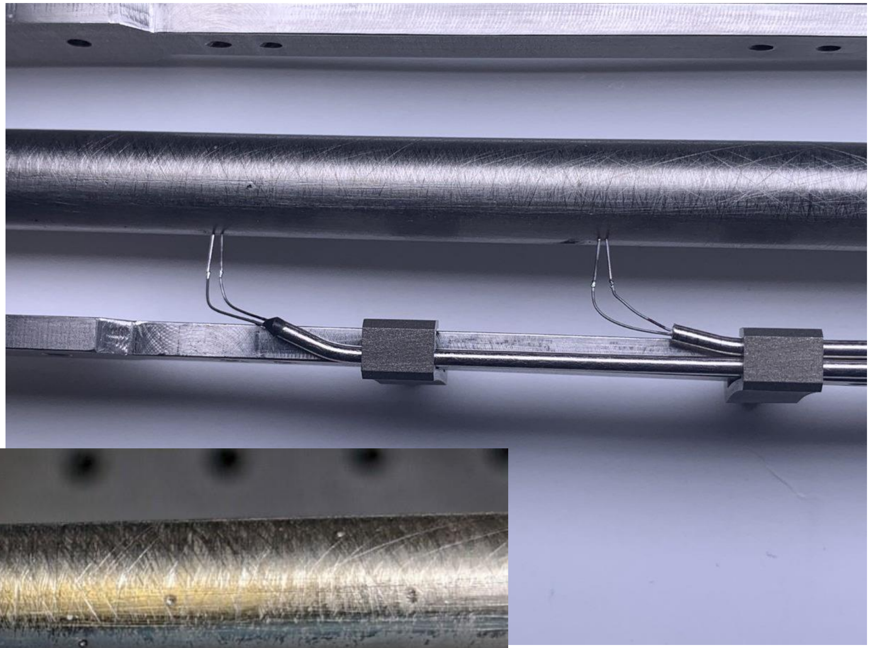
MOOSE Temperature and Fast Neutron Flux Simulation

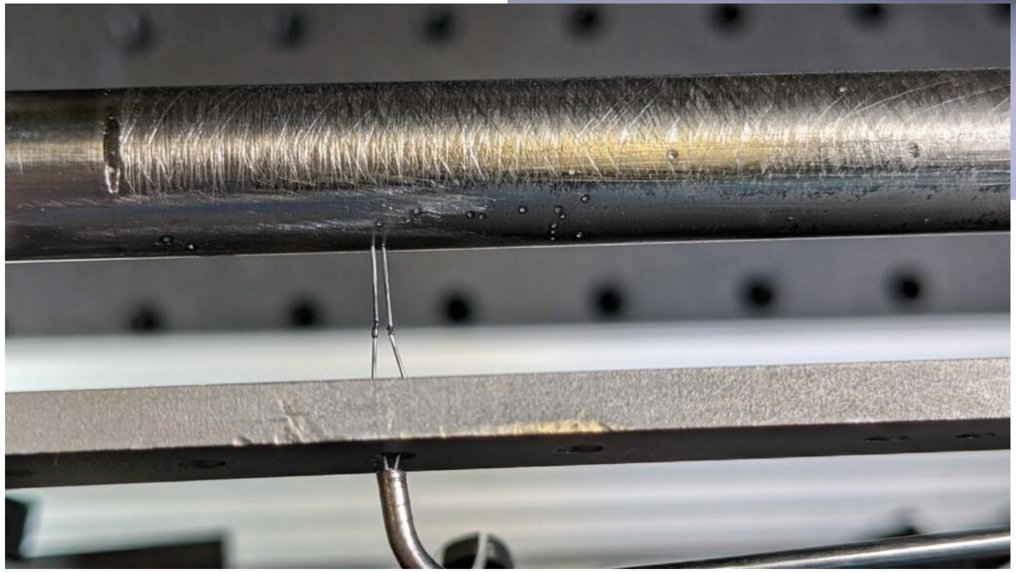
Demonstration example – Thermocouple attachment CT



Demonstration example – Thermocouple attachments

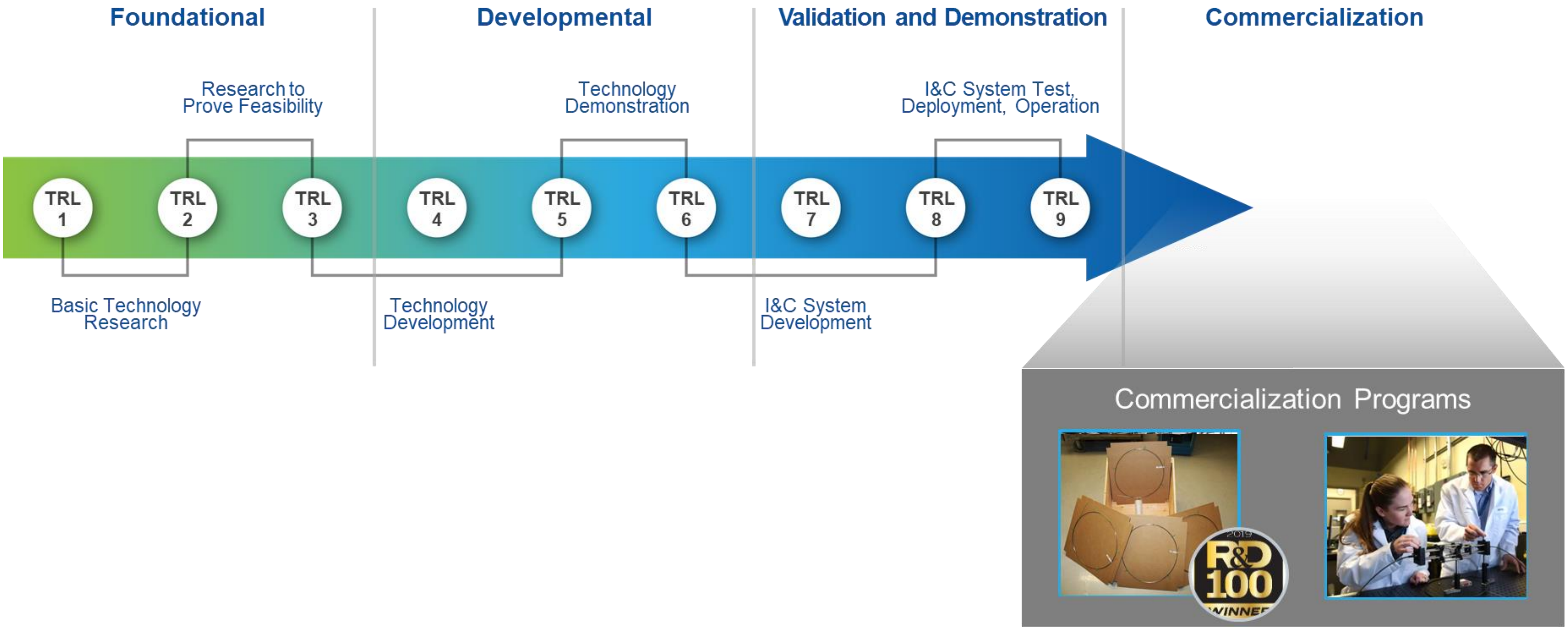
Thermocouple spot weld CT





Integral junction thermocouple attachments

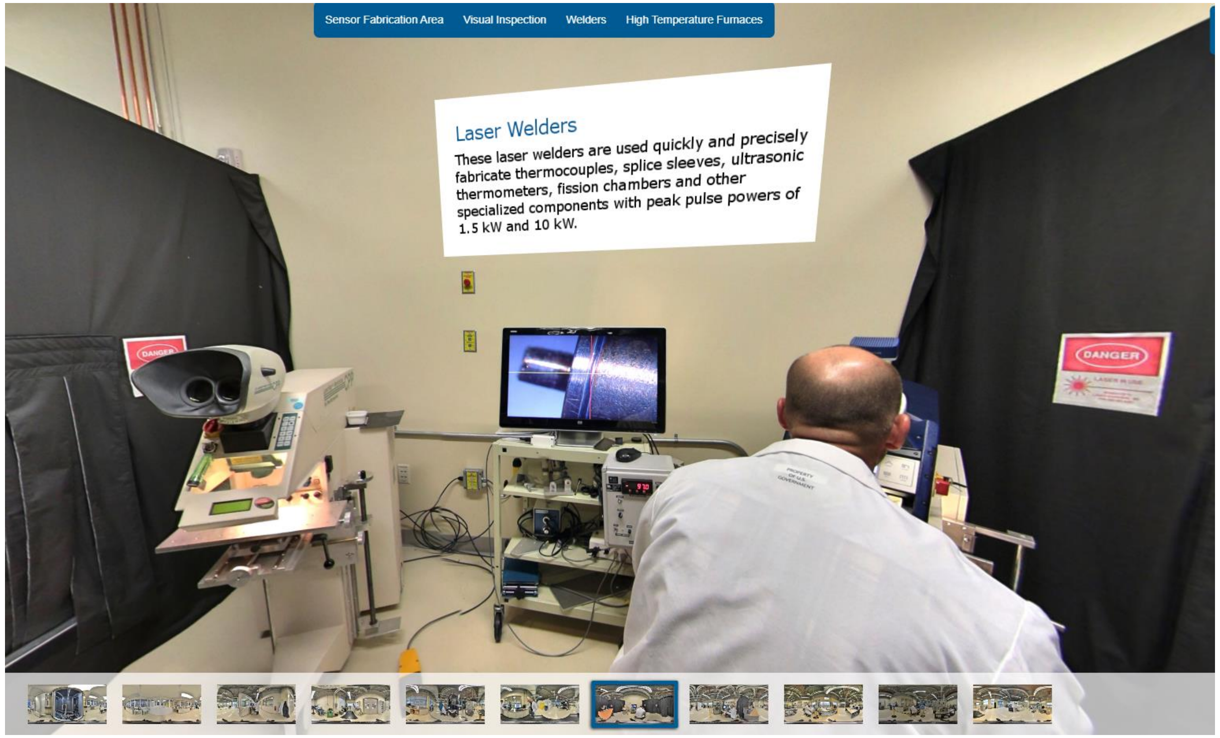
Commercialization of sensors and instrumentation



DOE Technology Commercialization Fund

DOE SBIR Phase II

Measurement Science Laboratories – Virtual tour & fact sheet



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Measurement Science Laboratories

Nuclear instrumentation for irradiation experiments and advanced reactors

A critical part of nuclear energy research is the ability to precisely measure the extreme conditions inside a nuclear reactor. This is a significant technical challenge, but Idaho National Laboratory's Measurement Science Department addresses it with the Measurement Science Laboratories (MSL). MSL are a collection of laboratory spaces, equipment and capabilities supporting the activities of INL's Measurement Science Department. MSL provide broad support to many programs within the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) and allow access to researchers and engineers from organizations inside and outside INL.

Most MSL facilities are located at INL's Energy Innovation Laboratory (EIL), including the High Temperature Test Laboratory (HTTL). Other labs are in the Idaho National Laboratory Research Center (IRC) and Idaho Engineering Demonstration Facility (IEDF).

MEASUREMENT SCIENCE LABORATORY CAPABILITIES

MSL contain an array of specialized equipment for nuclear instruments development, fabrication and testing.

- The autoclave testing area includes various flowing and static containment vessels that simulate pressurized water reactor temperature, pressure, flow and chemistry. This allows instrument testing of advanced instrument concepts, test assemblies, reactor components, materials, and coatings in prototypic, but non-nuclear conditions.

Using a microscope to characterize a strain gauge fabricated by advanced manufacturing methods.

Assembling an experimental capsule for the TREAT reactor.

Idaho National Laboratory

The HTTL houses specialized instrument fabrication equipment and can perform high-temperature evaluations as well as non-destructive analysis of instruments through a micro focus X-ray computed tomography scanner. The HTTL can also handle radioactive materials relevant for instrument research.

MSL researchers use computed tomography analysis to better understand the conditions inside a pebble bed reactor.

- The fiber optics and acoustic sensors fabrication and testing area includes specialized spectrometers, spectrum analyzers, laser interrogators, pulse power system, power meters, and fiber fabrication equipment.

MSL provide research and development, testing and characterization, and engineering services including:

- **Developing and fabricating nuclear instrumentation** for irradiation experiments to provide real-time characterization of local test parameters, such as neutron flux, temperature, pressure and materials mechanical responses. MSL instruments are deployed in INL irradiation facilities, primarily the Advanced Test Reactor (ATR) and the Transient Reactor Test Facility (TREAT), as well as facilities in collaborating institutions, such as the Massachusetts Institute of Technology Research Reactor.
- **Engineering services for instrumented irradiation rigs.** Those include design integration, instrument calibration and out-of-pile testing, assembly processes as well as post-irradiation examination for passive monitors. The assembly of instrumented TREAT experiments, design and calibration of linear variable differential transformers and services related to passive monitors for ATR experiments without sensor leads (melt wires, SiC monitors) are an important component of MSL activities.
- **Development of innovative sensing technologies** for advanced reactors instrumentation and control systems. Through use in irradiation experiments, sensing technologies are matured for commercialization or integration in advanced reactor designs. Innovative technologies such as optical fibers and acoustic measurements are key to enable advanced maintenance (such as early fault detection) and operation modes (toward autonomous operation).

A self-powered neutron detector being inserted into INL's Neutron Radiography Reactor.

FOR MORE INFORMATION

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www.inl.gov

A U.S. Department of Energy National Laboratory

https://factsheets.inl.gov/FactSheets/Measurement%20Science%20Laboratories.pdf

Questions?

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LinkedIn

Schedule for November 15, 2021

<u>All times EST</u>

12:00 pm High temperature embedded/integrated sensors (HiTEIS) for remote monitoring of reactor and fuel cycle systems (Xiaoning Jiang, North Carolina State University)

12:30 pm Development of Optical Fiber Based Gamma Thermometer and its Demonstration in a University Research Reactor Using Statistical Data Analytic Methods to Infer Power Distribution from Gamma Thermometer Response (Thomas Blue, Ohio State University)

1:00 pm Break

1:15 pm Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control (Michael Larche, PNNL)

1:45 pm Development of Microwave Resonant Cavity Transducer for Flow Sensing in Advanced Reactor High Temperature Fluids (PI – Alexander Heifetz, Argonne)

2:15 pm Demonstration and benchmarking of SPNDs for advanced reactor application (Kevin Tsai, INL)

2:45 pm Break

3:00 pm Optical fiber sensors (Austin Fleming, INL)

3:30 pm Acoustic sensors (Josh Daw, INL)

4:00 pm Nuclear Thermocouples (Richard Skifton, INL)

4:30 pm Moderated discussion on Session 1 (Moderator: Troy Unruh, INL)

University of Pittsburgh

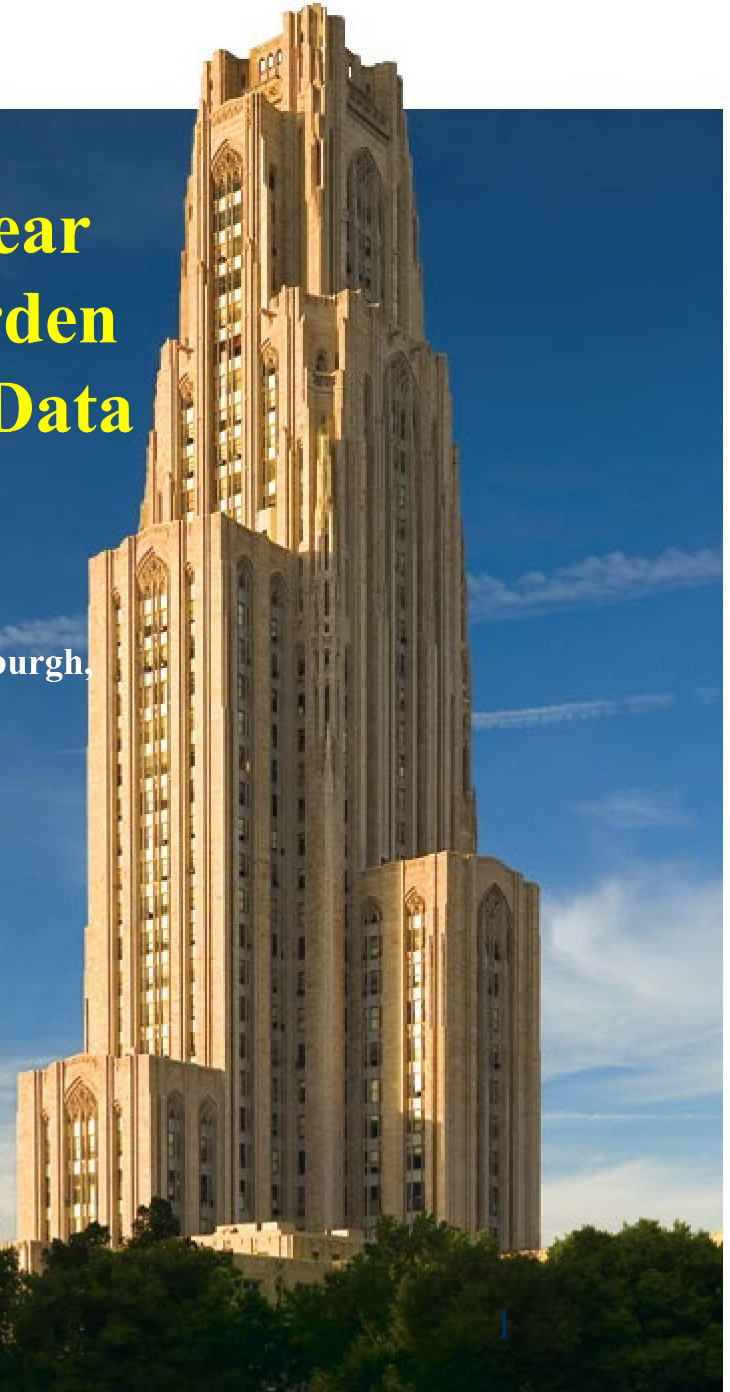
Fiber Sensor Technology for Nuclear Power Applications: Radiation-harden Sensor Devices, Packaging, Sensor Data Fusion, and Instrumentation

Kevin P. Chen (PI)

Department of Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh, PA

Collaborators: **MIT Reactor Lab**
Westinghouse Electric Company
Idaho National Lab
Corning Inc.

Oak Ridge National Lab
Argonne National Lab
Industries

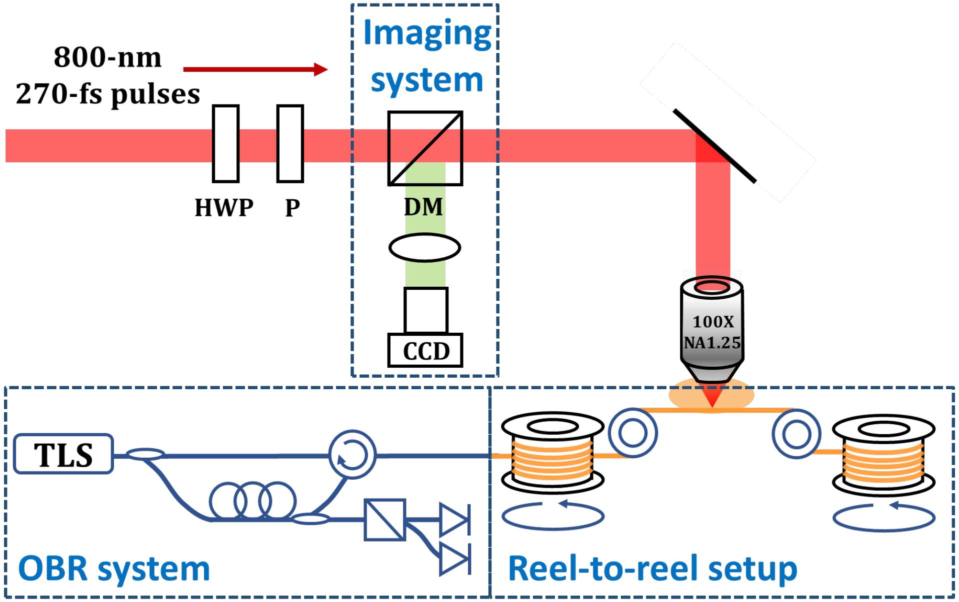


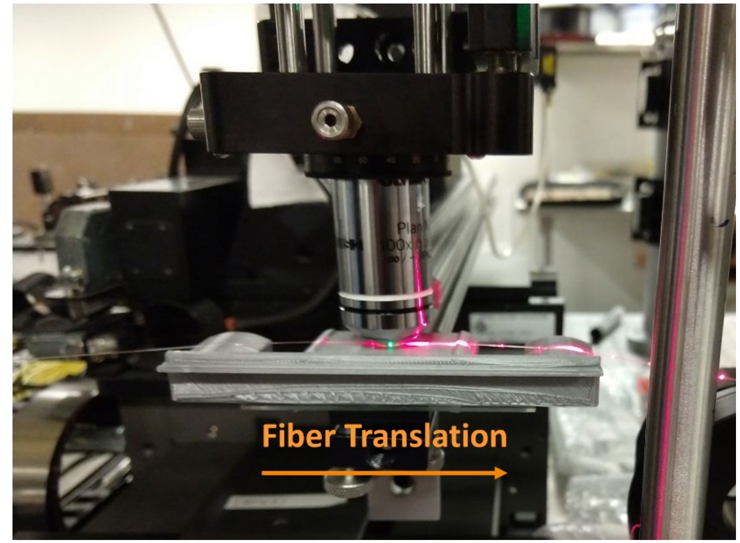
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

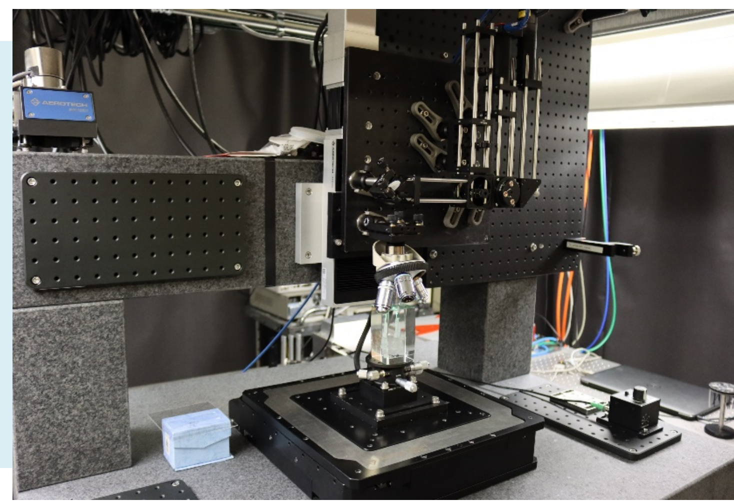
Outlines

- **Fiber Sensors as Key Components of Nuclear I&C Systems – Moving beyond Basic Research**
    - Multiplexable Sensors – Low cost
    - Distributed Sensors – High spatial resolution measurements
    - High Temperature Performance
    - In-Pile test results: Goods and Bads
    - Addressing the bads: Sensor-Fused Enabled Artificial Intelligence Data Analytics
- **Hermetic Sensor Packaging Techniques**
- **Low-cost interrogation techniques: hardware and algorithms**
- **Other Opportunities to use fiber sensors up to 800C**
    - High-T vibration measurements
    - High-T flow sensors
    - High-T hydrogen sensors
- **Summary**

Sensor Fabrications





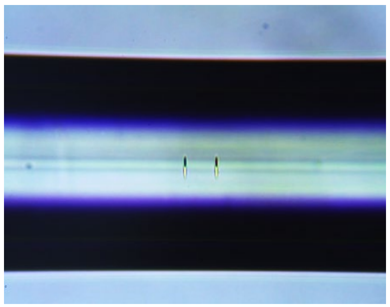


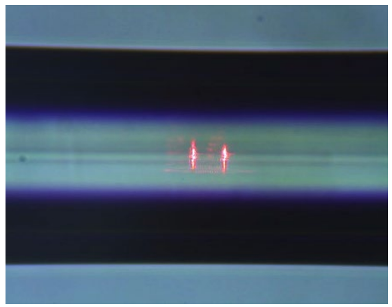
Reel-to-reel oil-immersion fiber writing setup

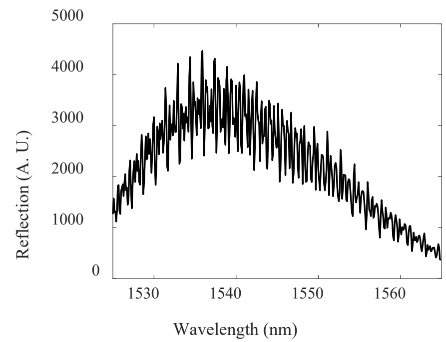
- Fast and continuous fabrication over >tens meters
- -fs (190fs – 5 ps), 800-nm, 532-nm, 355 nm outputs
- Sensors fabrication over 20 m continuously
- Applied to wide array of rad-hard fibers
- Real-time monitoring
- Available for both industry and academic collaborations

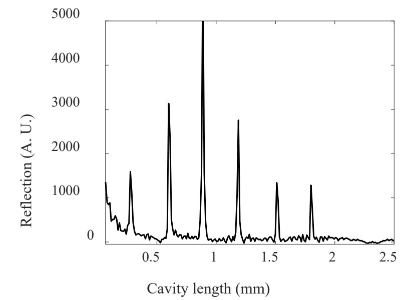
Sensor Fabrications

Fs-laser inscription of IFPI Sensor Array

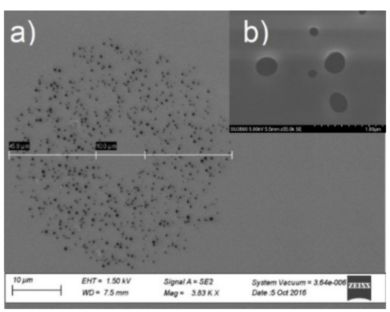


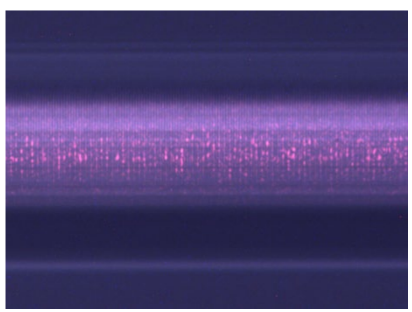


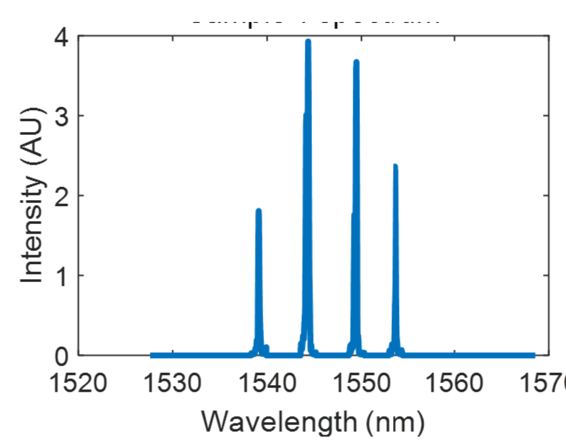




Fs-laser inscription of FBG Sensor Array







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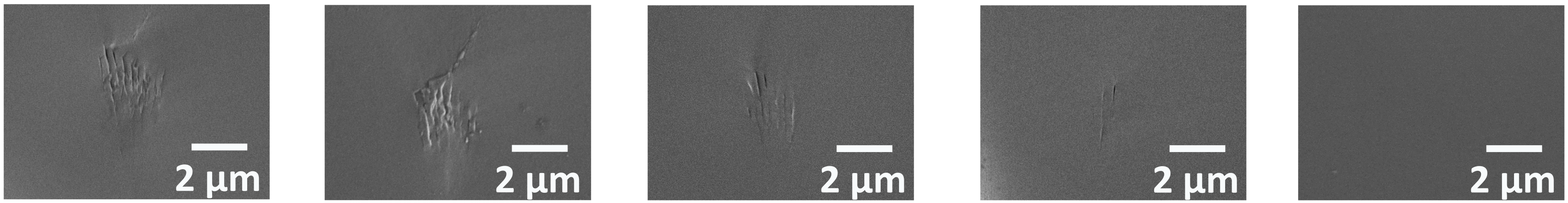
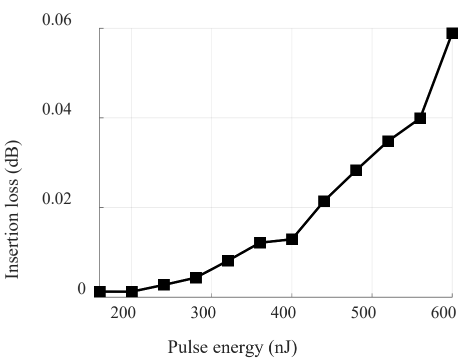
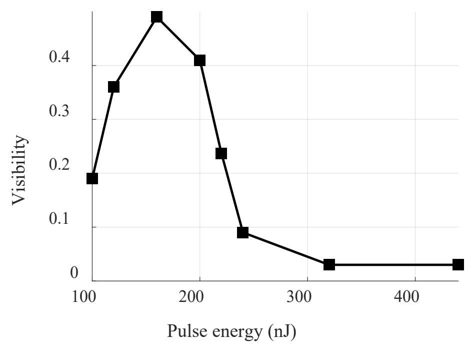
Fabrication Optimization of IFPIs



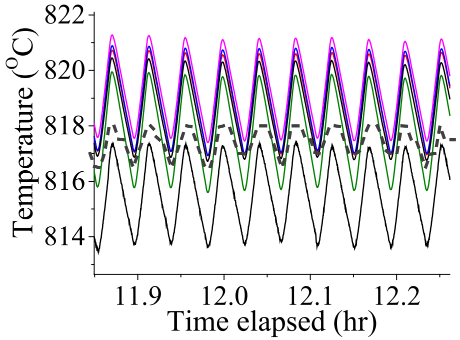
160-nJ | 140-nJ | 120-nJ | 100-nJ | 80-nJ

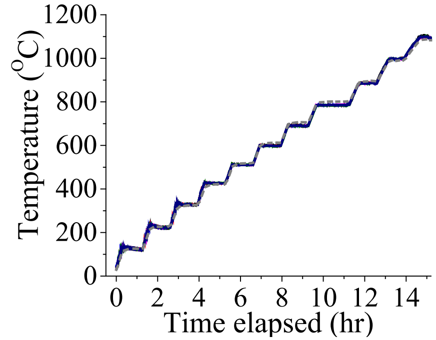


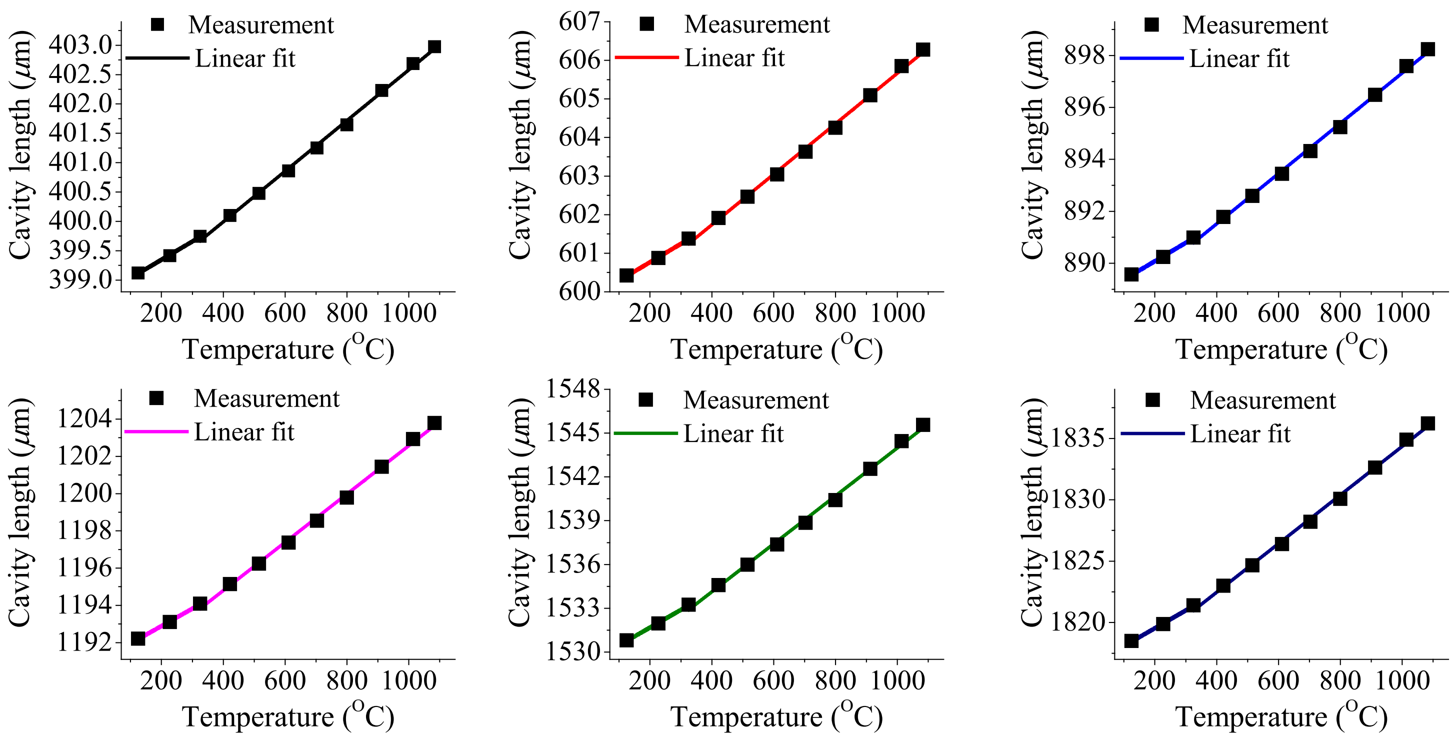


- **Nanograting formation threshold at 100 nJ pulse energy**
- **With the increase of pulse energy, size of nanograting increases**
- **High visibility of 0.49 at optimized pulse energy of 160 nJ**
- **Low insertion loss of 0.0024 dB per sensor**

Quasi-Distributed Sensing Performance

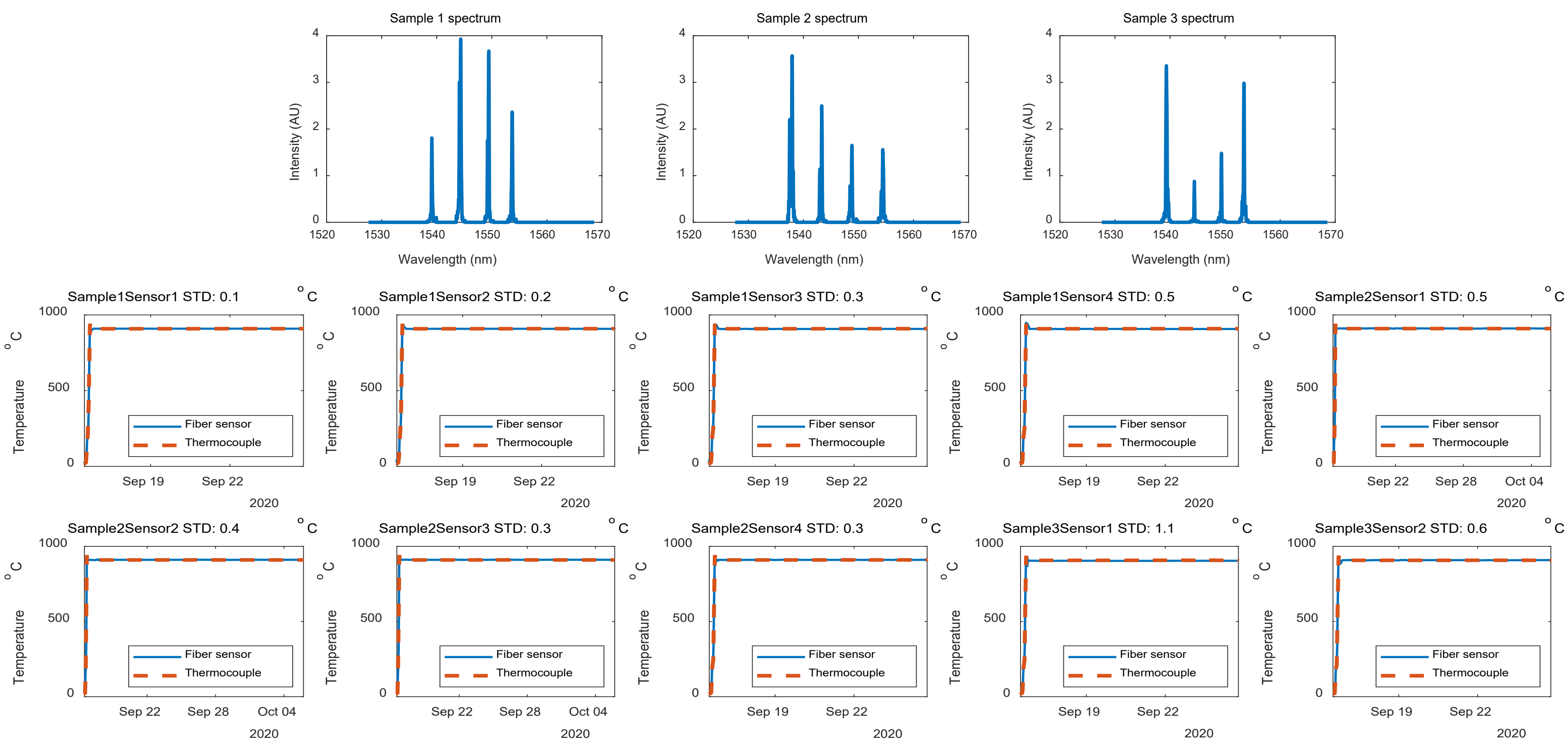






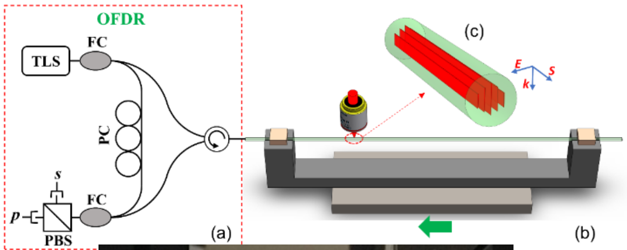
High-T Tests: FBG Sensors

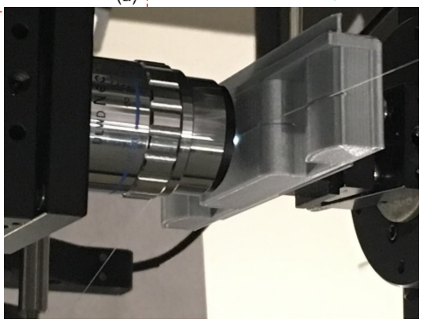
- Comprehensive sensor array high-T testing (900°C-1000°C)
- Interrogation electronics and algorithm used for demodulation
- Average STD <0.6°C over 10 days spans at 900°C (comparing with TC)

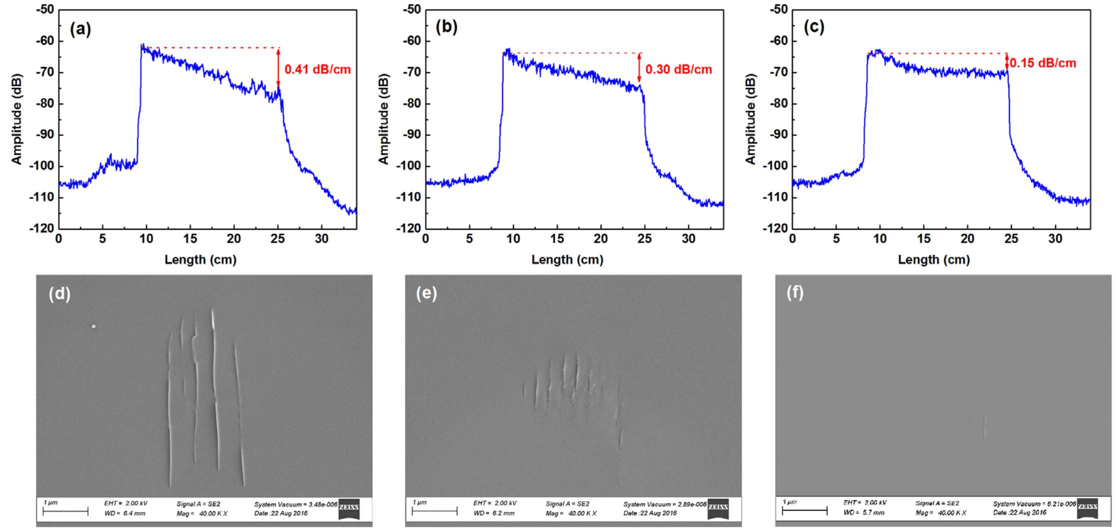


Sensor Fabrication: Distributed

Ultrafast laser irradiation to enhance T resilience and measurement accuracy

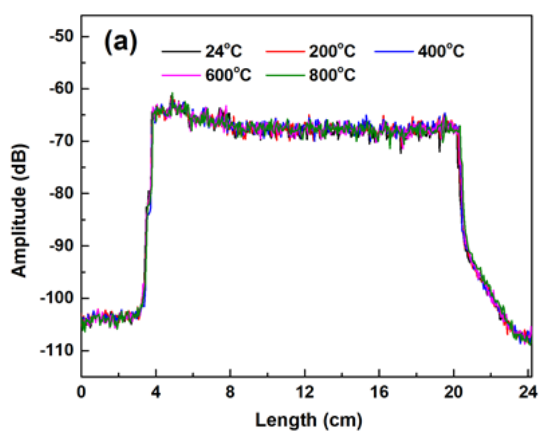




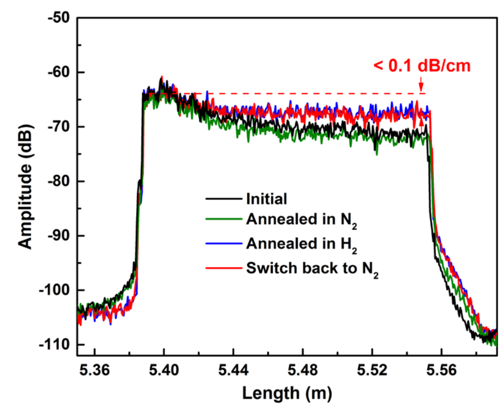


- Temperature can now be measured at 800C with H_2 atmosphere
- Stability verified for ~72 hours at 800C
- 4C accuracy with heat/reheat cycles (10 cycles tested).

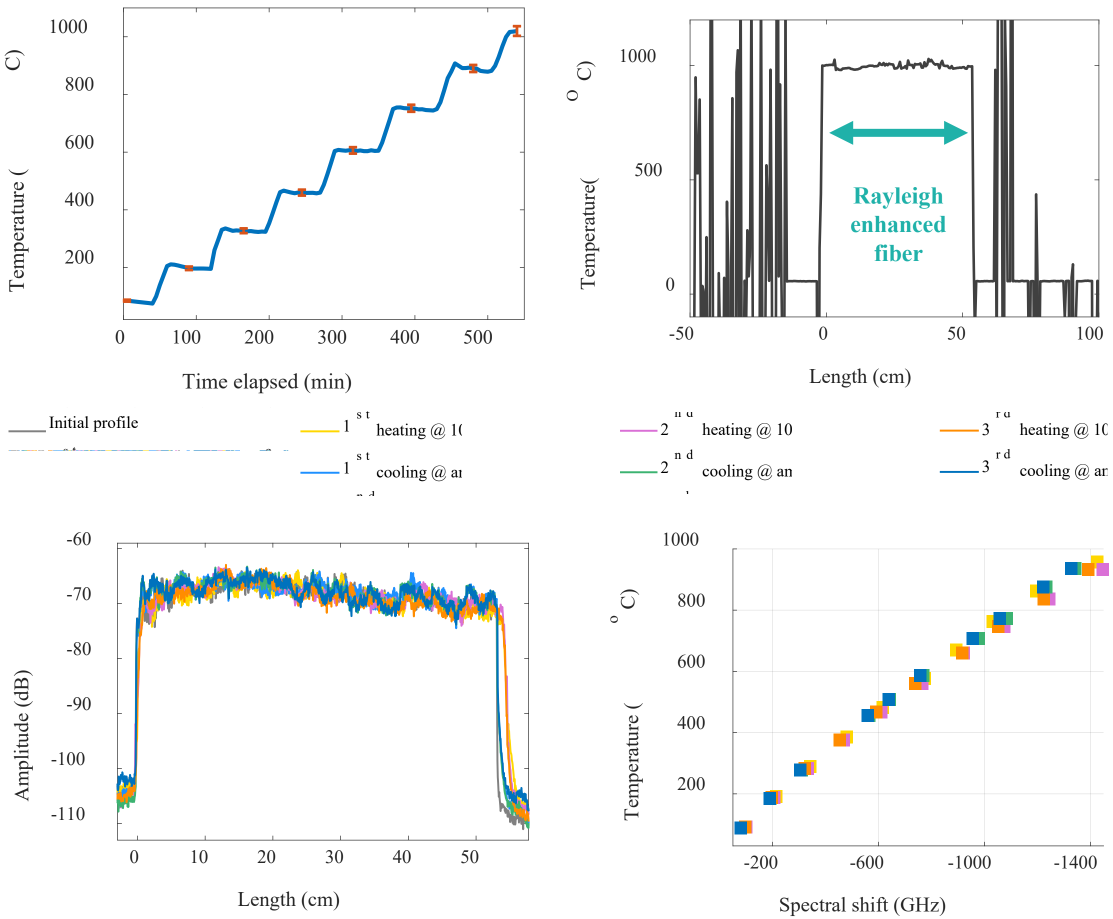
High-T Tests



High-T + Hydrogen



High-T Tests: Distributed Fiber Sensors



- After 16 hours under 1000°C, the processed fiber section still functional compared to the unmodified fiber
- Robust and consistent operation after repeated heating and cooling cycles
- Laser Enhancement is ABSOLUTELY ESSENTIAL!

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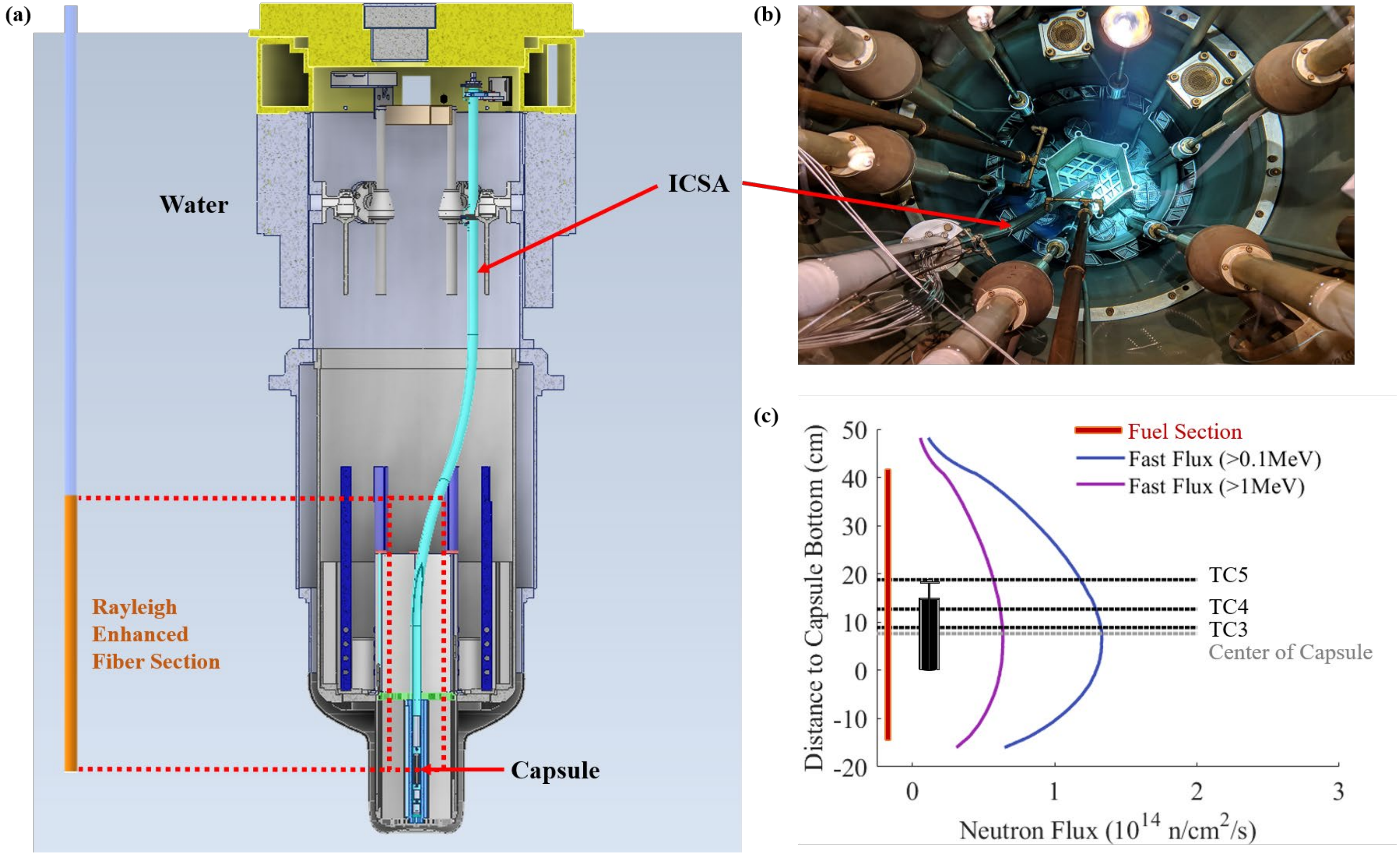
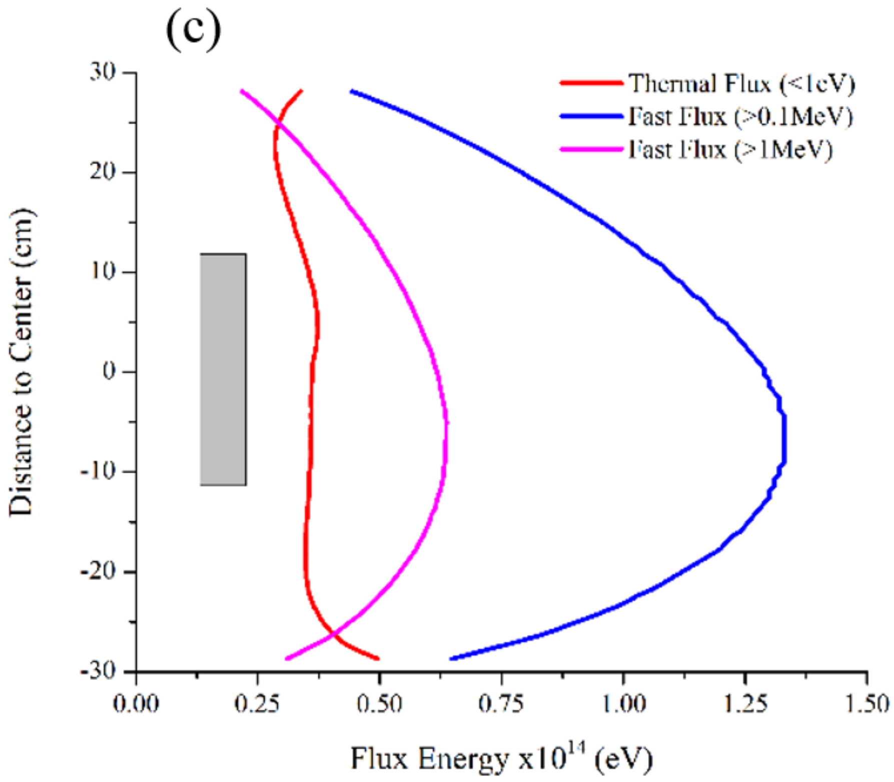
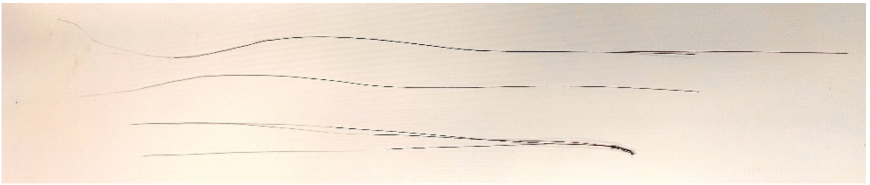
Distributed Fiber Sensors for In-Piles Applications
Backscattering of all fiber enhanced by fs laser

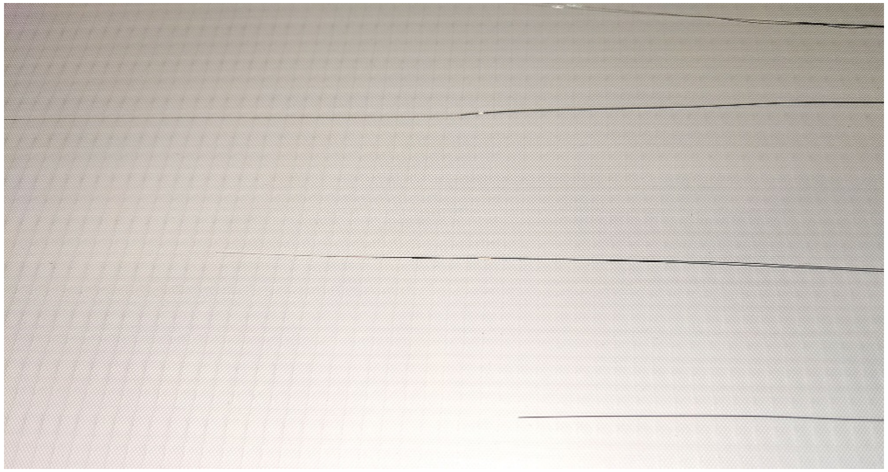


Fiber Sensors in Reactor Cores



GM tube measurements: 2-4 mR/hr β+γ





- **Target temperature 650C**
- **Fast neutron flux >1.5×10^{14} n/s*cm^2**
- **Real-time monitoring (remote access) – every 20 seconds**
- **Minimal contamination of fiber sensors**
- **Hot swap possible!**

Distributed Fiber Sensors for In-Piles Applications
Backscattering of all fiber enhanced by fs laser

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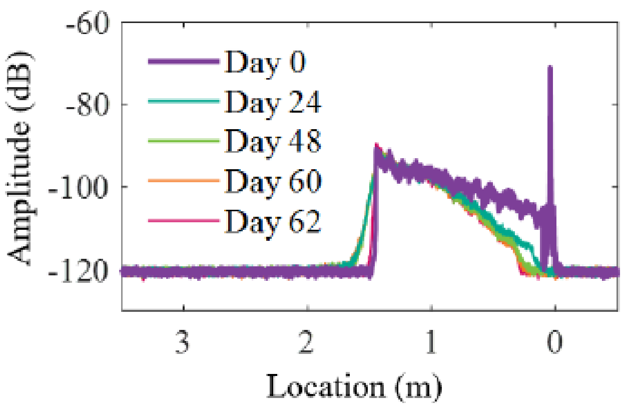
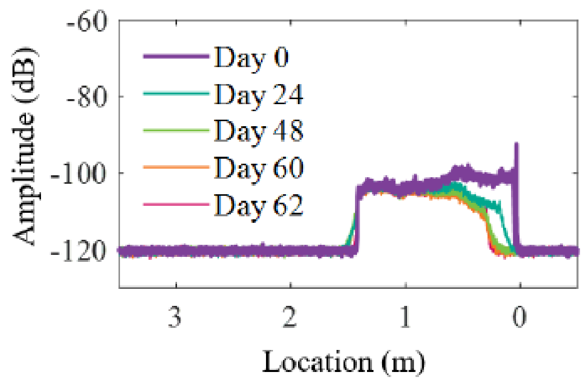
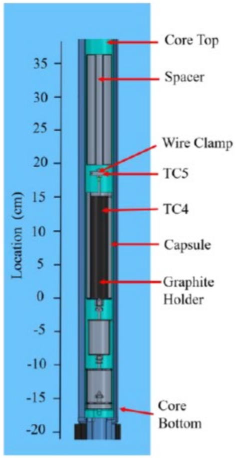
Standard Fibers

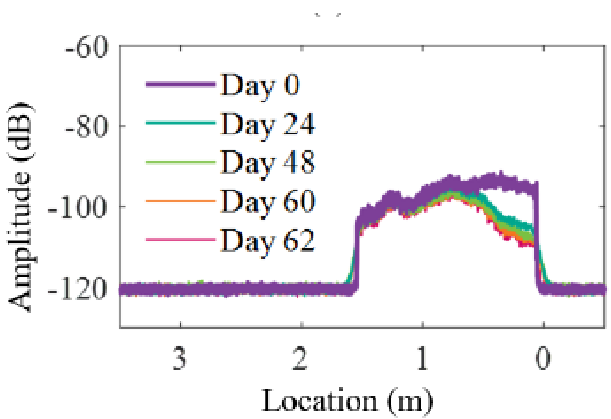


Standard Fibers

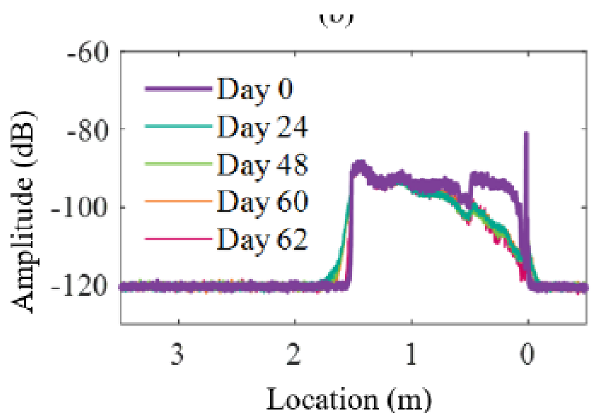




Draka Super RadHard



Fujikura RRSMFB



- **RIA issue can be effectively mitigated!**
- **Standard fiber can be radiation-hardened by –fs process**
- **Standard fiber with laser enhanced can function in strong radiation environments (but not in-pile)**
- **Radiation-harden fiber performed better.**

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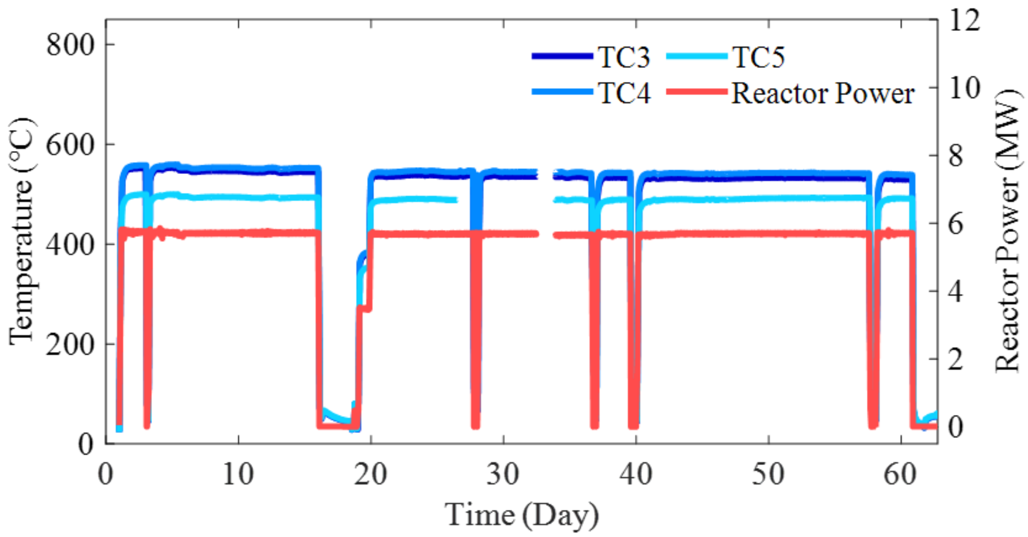
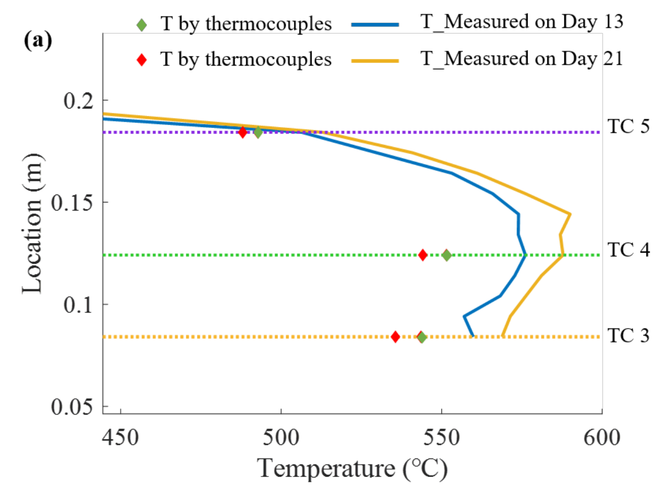
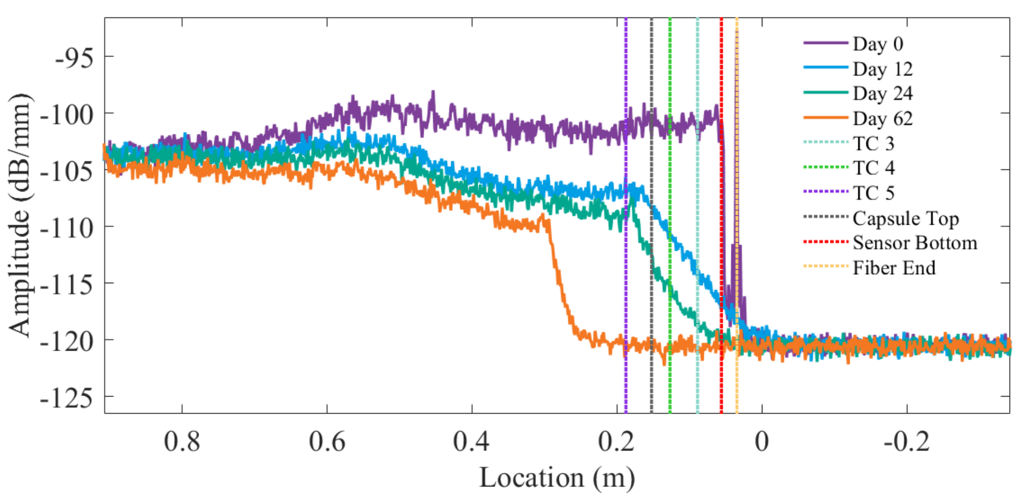
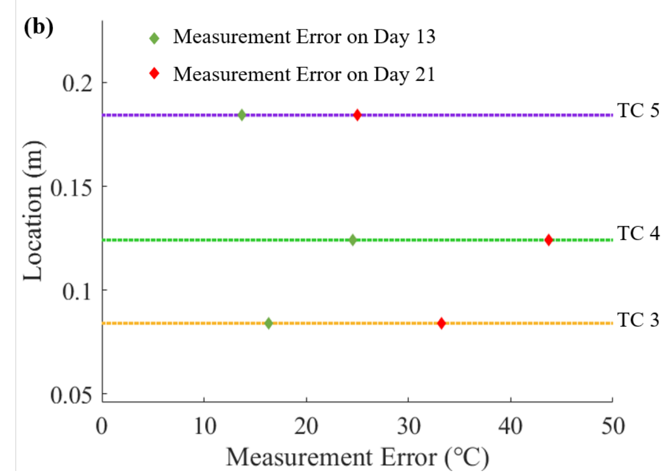
Sensor-Fused AI-Based Data Analytics: Correcting Complex Radiation-induced Drift

UNIVERSITY OF PITTSBURGH









Sensor-Fused AI-Based Data Analytics: Correcting Complex Radiation-induced Drift

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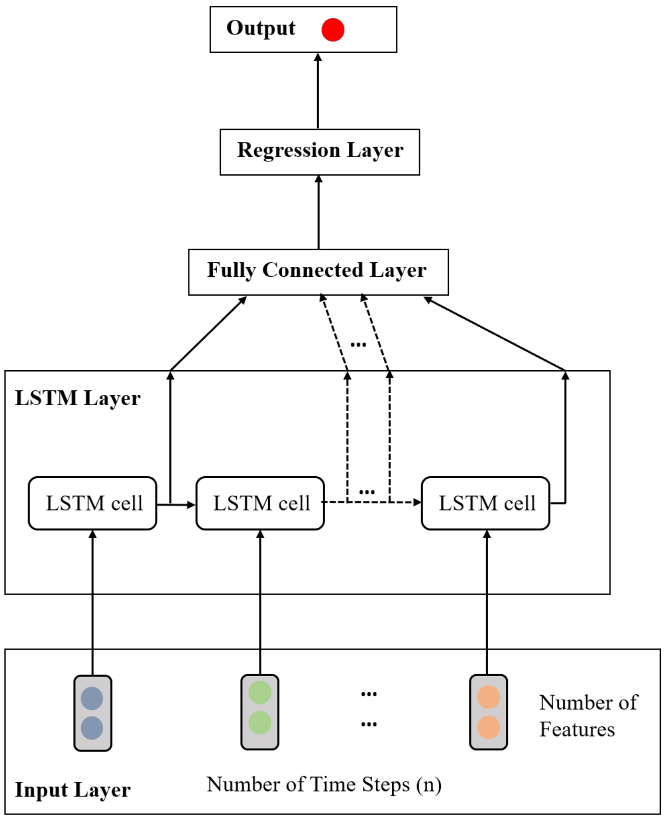
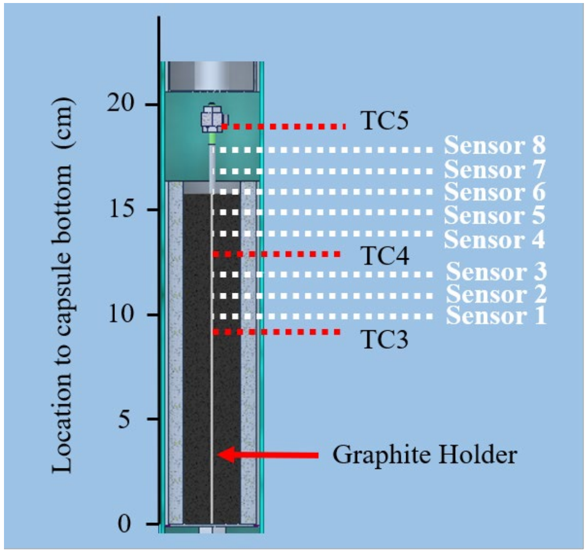
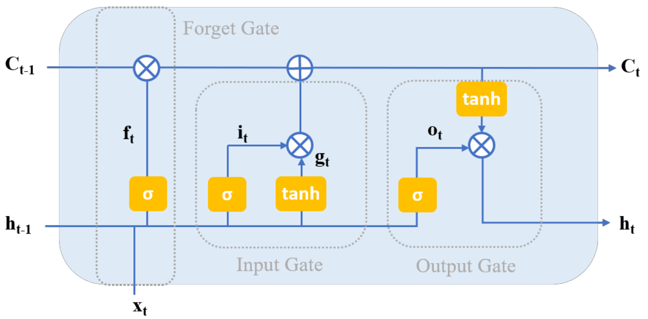
- Sensor Fusion Approach: thermocouple (TC) point sensors as references
- Neural Networks learning for fiber sensor at TC locations
- Long- and Short Term memory deep neural network to acquire knowledges at TC locations
- Fiber Sensors at other locations use look-up tables generated at TC locations to correct drifts
- ACCURATE TEMPERATUER PROFILE can be obtained with 1-cm spatial resolutions



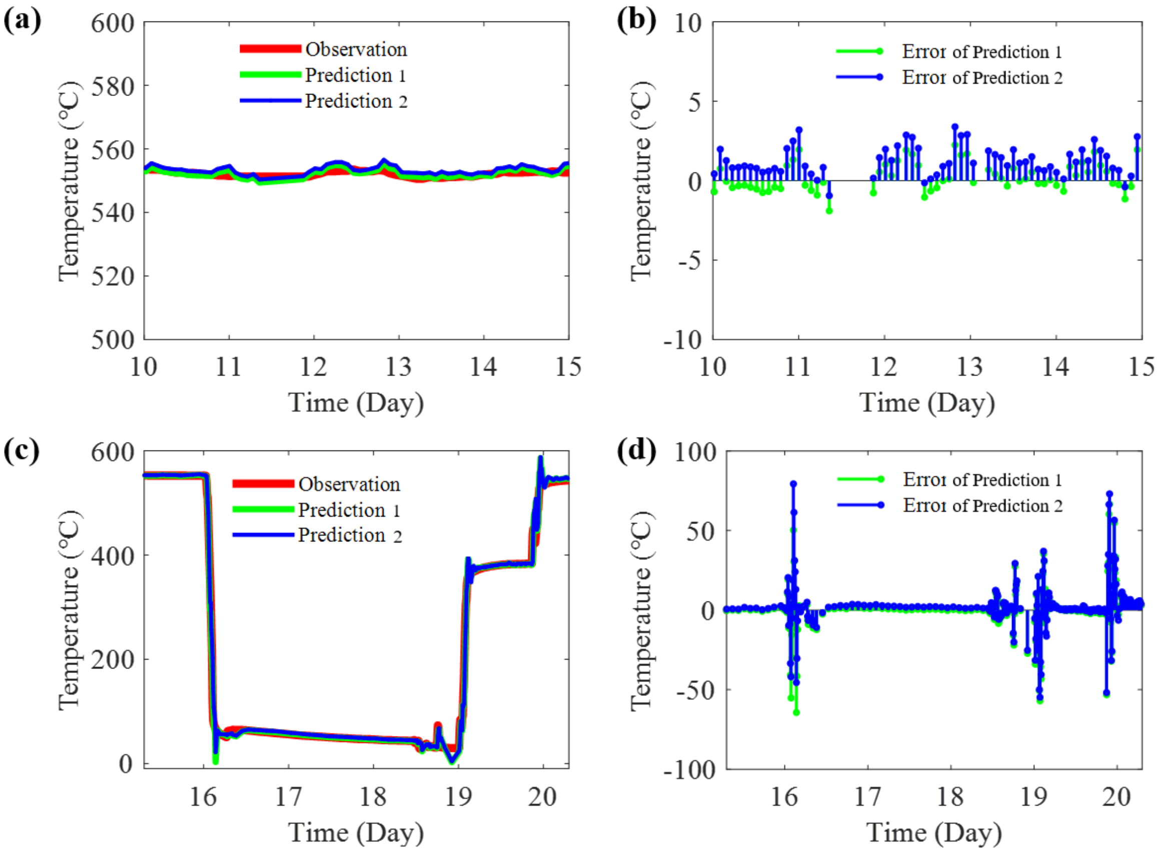


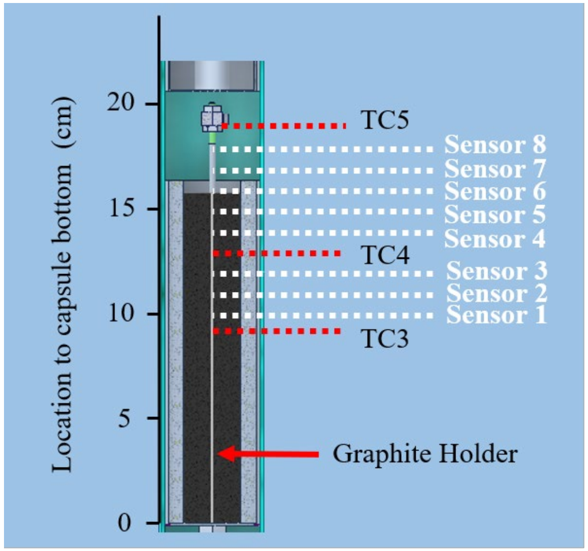


Sensor-Fused AI-Based Data Analytics: Correcting Complex Radiation-induced Drift

Table 1. Temporal temperature predictions and corresponding RMSE for the sensor at TC4 location.

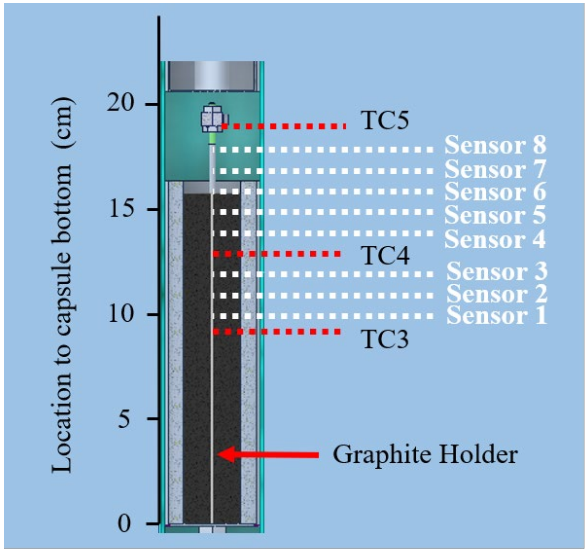
Prediction location Prediction #	**TC4 Location** Prediction 1 by fiber sensor	**TC4 Location** Prediction 2 by fiber sensor
Training Dataset	TC3 data & fiber sensor spectral shifts	TC4 data & fiber sensor spectral shifts
Verification Dataset	Measurements by TC4	Measurements by TC4
Training & prediction location Separation	3.8 cm	6.1 cm
RMSE1 (Normal State, Day 10-15)	0.9479	1.5840
RMSE2 (Abnormal Situation, Day 15-20)	15.5224	16.2152

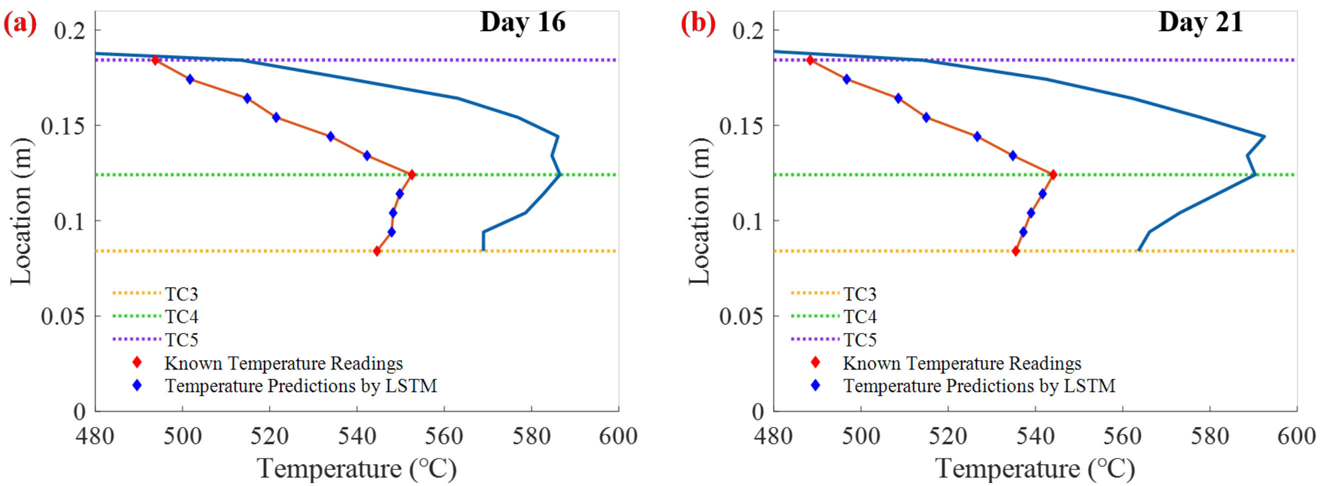




Sensor-Fused AI-Based Data Analytics: Correcting Complex Radiation-induced Drift

Sensors	Sensor 1 to TC3 Location (cm)	Sensor 2 to TC3 Location (cm)	Sensor 3 to TC3 Location (cm)	Sensor 4 to TC5 Location (cm)	Sensor 5 to TC5 Location (cm)	Sensor 6 to TC5 Location (cm)	Sensor 7 to TC5 Location (cm)	Sensor 8 to TC5 Location (cm)
Training Dataset	TC3	TC3	TC3	TC5	TC5	TC5	TC5	TC5
Distance Between Sensors	0.81	1.81	2.81	5.10	4.10	3.10	2.10	1.10
RMSE1 (Normal State, Day 10-15)	0.83322	1.2346	1.1995	1.2986	1.1112	2.0895	1.5636	1.6277
RMSE2 (Abnormal Situation, Day 15-20)	15.3200	15.8914	16.0634	16.1015	16.2379	16.2587	16.1828	16.3199





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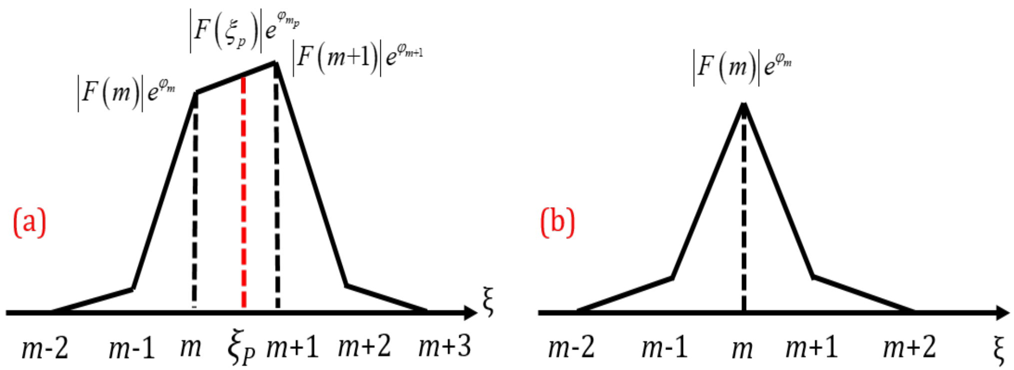
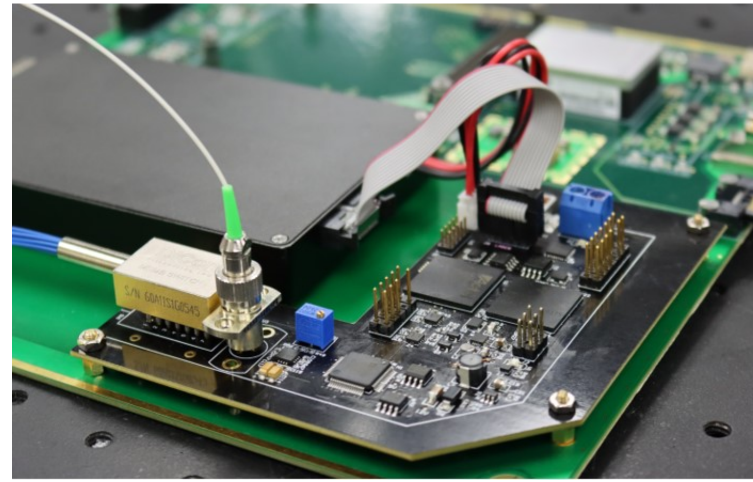
Rapid Demodulation Algorithm and Interrogation Systems for NE I&C

Bunman Frequency Estimation





$$F(\xi) = \sum_{n=0}^{N-1} \gamma e^{i(\frac{l\Delta kn}{N} + lk_0 + \varphi_0)} e^{-2\pi i n\xi/N}$$

$$= \gamma e^{i[lk_0 + \varphi_0 + \pi(\frac{l\Delta k}{2\pi} - \xi)(\frac{N-1}{N})]} \frac{\sin[\pi(\frac{l\Delta k}{2\pi} - \xi)]}{\sin[\pi(\frac{l\Delta k}{2\pi} - \xi)/N]}$$

$$\varphi\left(\frac{l\Delta k}{2\pi}\right) = \varphi_{\xi p} + 2\pi a = \varphi_m + 2\pi a$$

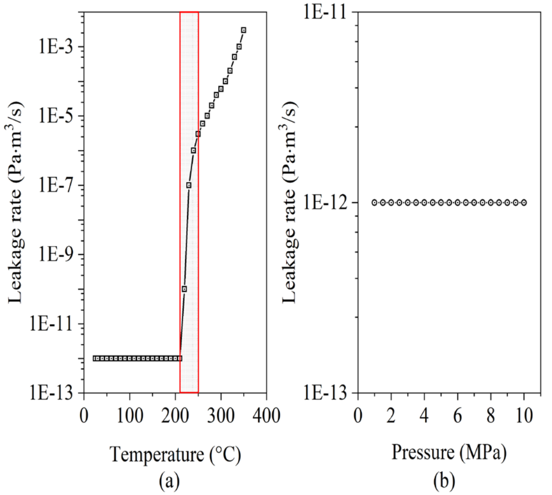
$$\xi_p = \frac{k_1 - k_0}{k_0}\left(\varphi_m - \varphi_0 + 2\pi[a]\right)$$

- Phase based demodulation
- Robust algorithm avoid “phase jump”
- Computationally efficient
- Easy implementation into DSP chips
- Dedicate sensor demodulation electronics developed
- Support 2 kHz sampling rates
- 40-nε or 0.01C temperature accuracy.
- VCSEL based interrogation system ×5 times cost reductions

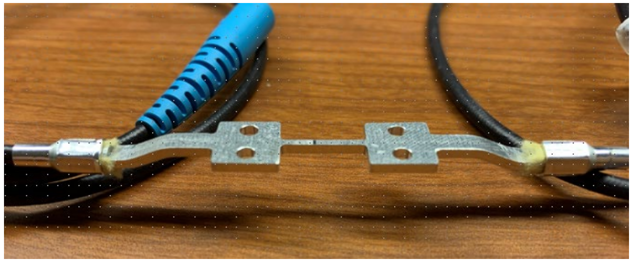
Hermetic Fiber Sensor Embedding

- Embedding scheme to match large discrepancy in Coefficient of Thermal Expansion (CTE) between silica and metal.
- Hermeticity packaging rated for nuclear applications up to 250C.
- Strain measurement confirmed up to 250C.
- Viable path forward to push temperature up to 800C.

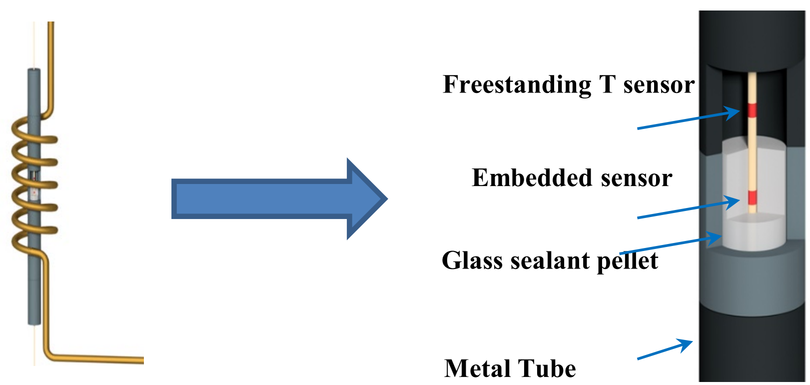
Leak Test: stable for T up to 250C. Pressure up to 10 Mpa.

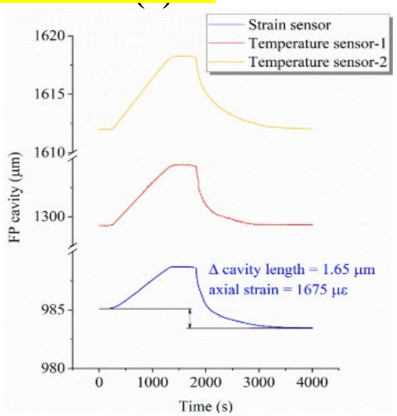


Sensor Embedded Using Ultrasonic AM

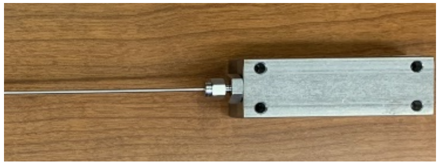


Sensor Embedded Using High-T Glass Sealant

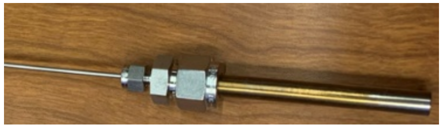




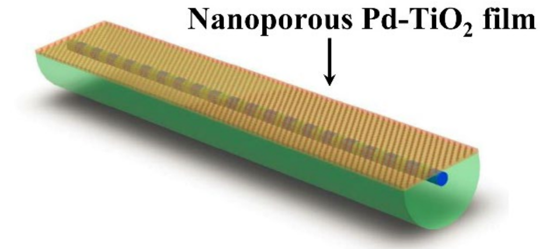
(c)



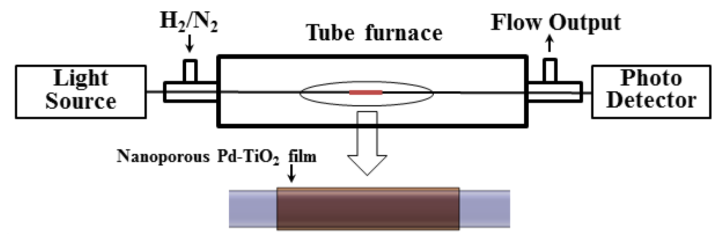
(d)

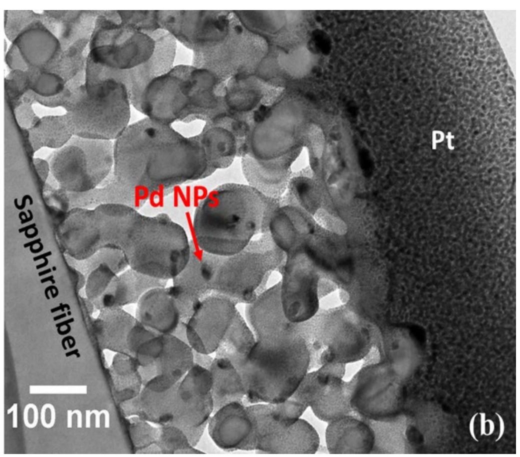


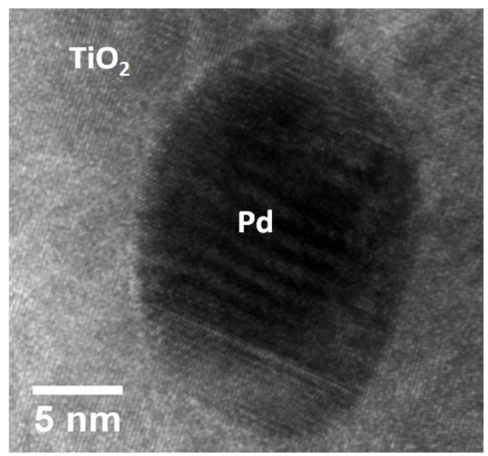
Fiber Optic Hydrogen Sensor at 800^{o}C or Higher

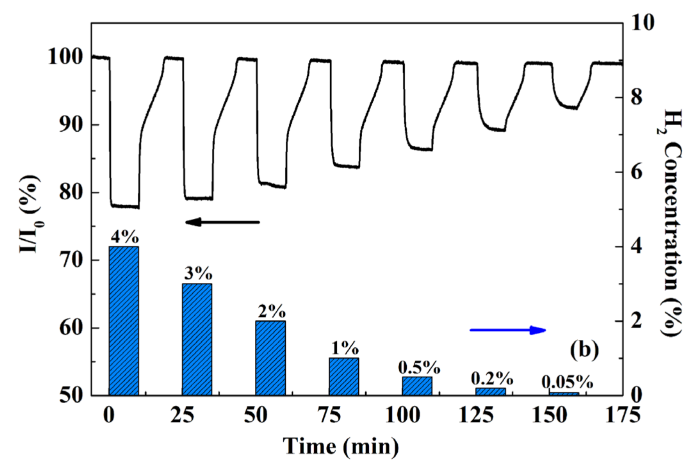


- Applicable for both silica and sapphire fibers
  - Extremely high melting point >2000^{o}C
  - High hardness
  - Resistance to corrosion
- Fiber diameter: 100 µm

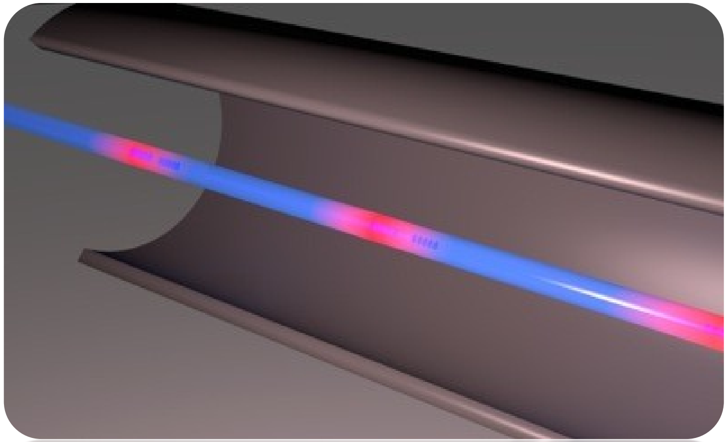


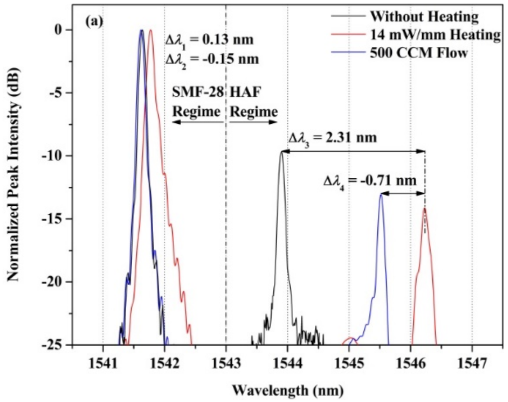


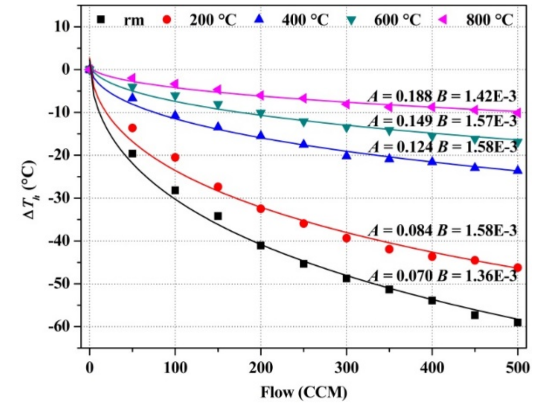


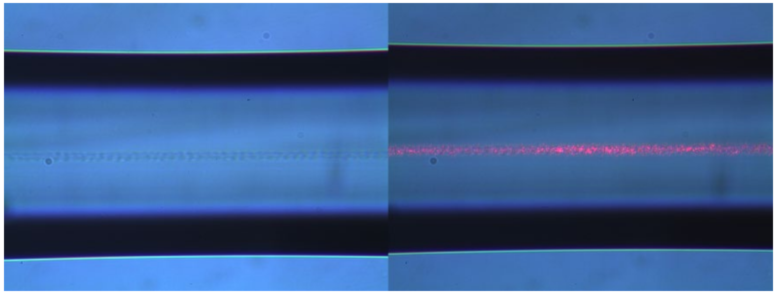


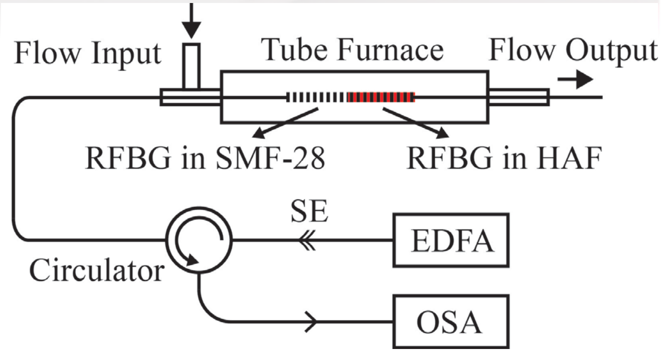
High-T Fiber-Optic Flow Sensor: 800C





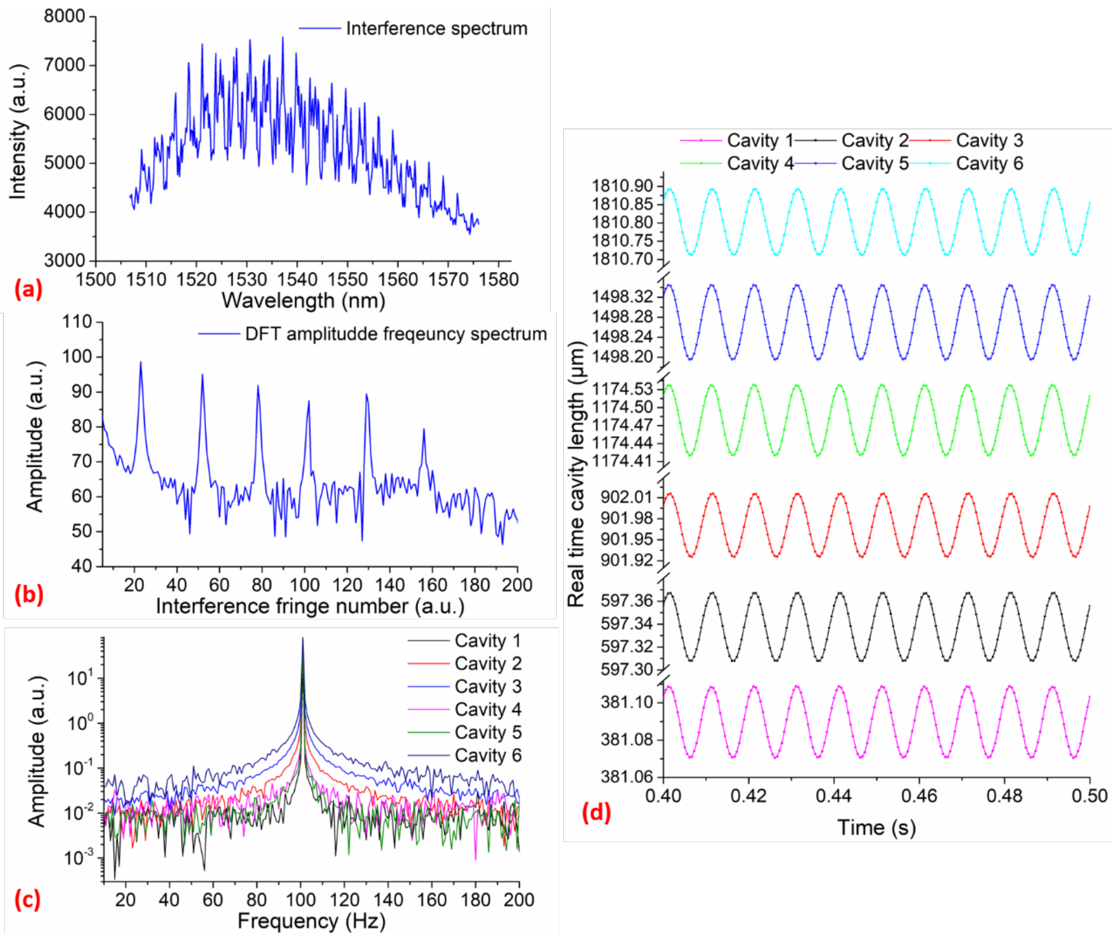


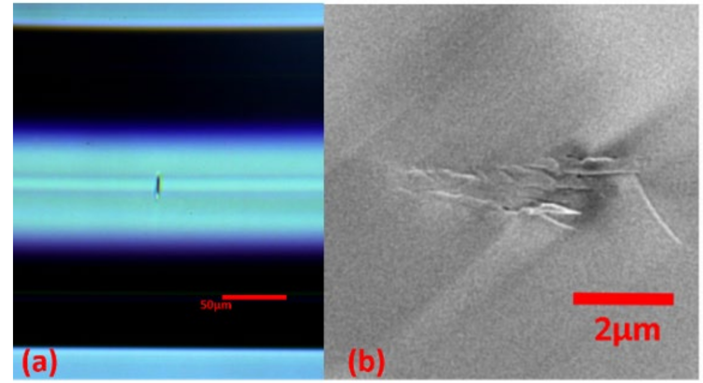




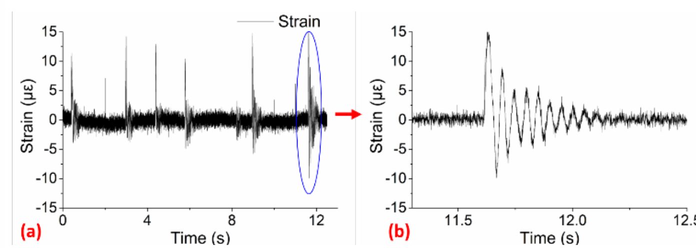
- When power light is turned off: passive sensors
- When power light is turned on: active sensors – flow
- Fiber sensor stable at high temperatures
- Operational temperature tested: 77K to 800C

High-T Fiber-Optic Vibration Sensors: 800C





800C Vibration Test



- Radiation-harden fibers
- Minimal dynamic strain: 10-nε
- Multiplexability: up to 20
- Maximum interrogation rate: 5 kHz
- Maximum testing temperature: 800C

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Summary

- -fs laser fabrication can produce robust fiber sensors
- Sensor high-T performance (900C) can meet I&C requirement for NE
- Even standard fibers (enhanced by fs-laser) can be used for weak to modest radiation environments. (High TRLs)
- Laser enhanced fibers can survive in-pile conditions
  - Radiation-harden fibers fare better
  - Sensor drift issues can be resolved by AI
  - Sensor fusion improves applicability of distributed fiber sensors
- Fiber sensors should be part of Nuclear Energy Future – DATA!!!
  - Expanding applicability of fiber sensors: vibration, acoustic, flow, H2
  - Support sensor packaging efforts
  - Support T2M efforts
  - Encourage industry adaptions

Thank You!

Contact:

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Tel. +1-724-6128935 Email: pec9@pitt.edu

High Temperature Materials for Nuclear Sensors and Instrumentation:

- *High Temperature Irradiation Resistant Thermocouples*
- *Strain Gauges for In-Pile Applications*
- *Line Heat Source Probe for In-Pile Thermal Conductivity*

Predictive Modeling of Nuclear Sensors and Instrumentation:

- *High Temperature Irradiation Resistant Thermocouples*
- *Ultrasonic Waveguide Thermometer & Linear Variable Differential Transformers*

CT-21IN070201, CT-21IN070203, CT-21IN070204, CT-21IN070205

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

PI: Brian J. Jaques, BSU
PI: Pattrick Calderoni, Troy Unruh, INL

Boise State University-Materials Science and Engineering
Idaho National Laboratory

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ASI Advanced Sensors and Instrumentation

High Temperature Irradiation Resistant Thermocouples

Advanced Sensors and Instrumentation (ASI)
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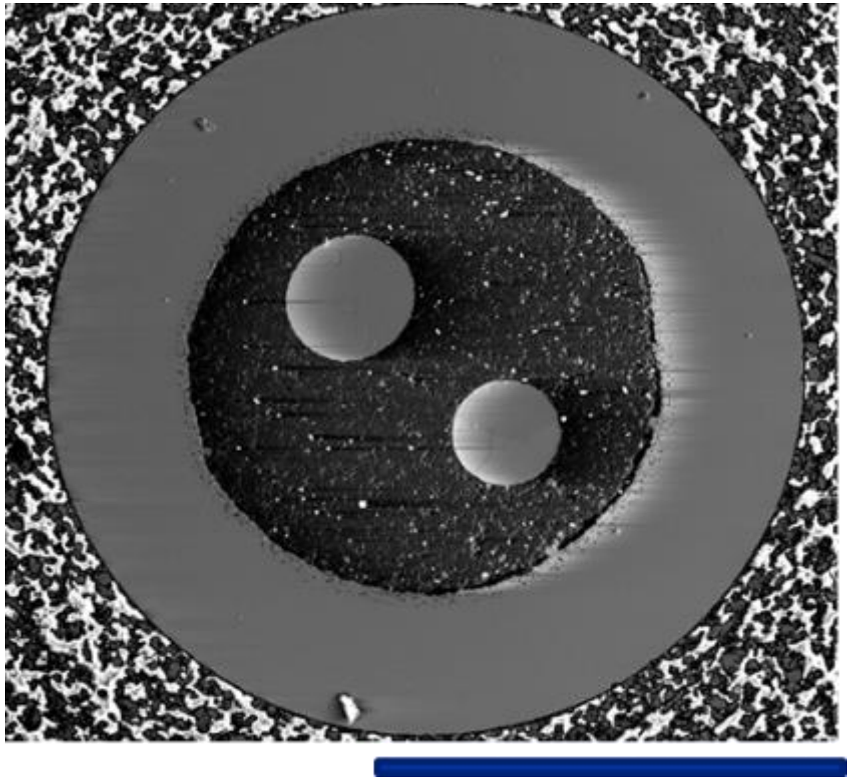
November 15 – 18, 2021

PI: Dr. Brian J. Jaques, BSU
GRA: Scott Riley, BSU
PI: Dr. Richard Skifton, INL

Boise State University-Materials Science and Engineering
Idaho National Laboratory

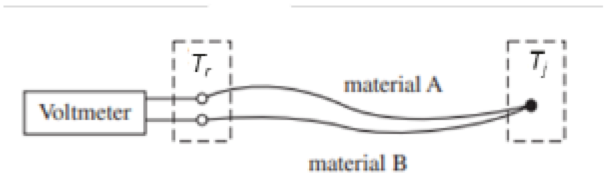
Project Overview

- In order to decrease nuclear innovation time, robust, in-pile measurement techniques and sensors must be developed.

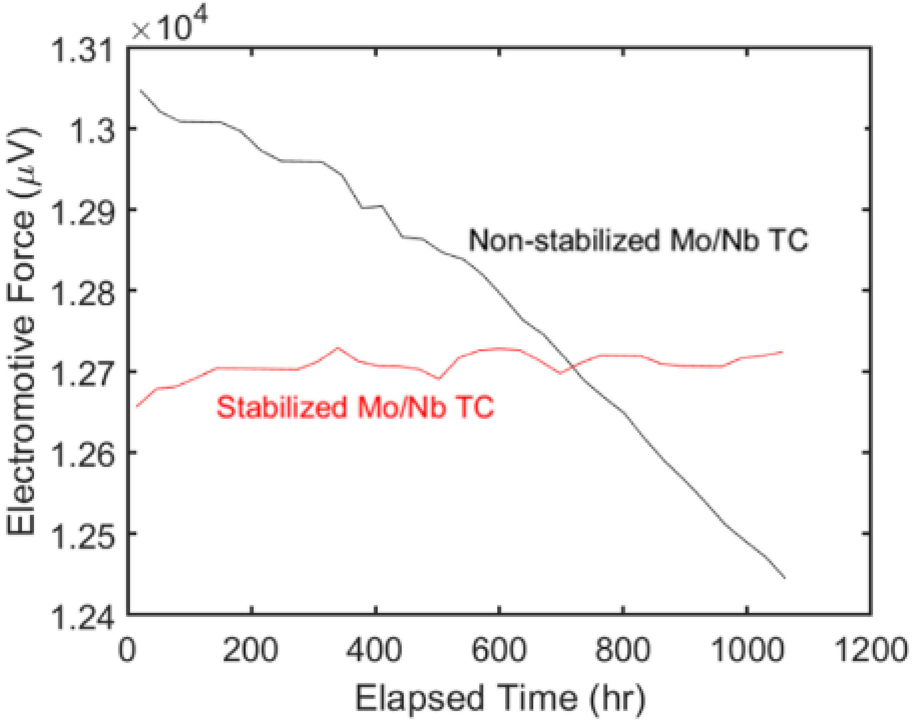


1 mm

SEM micrograph of Nb-1Zr sheathed HTIR-TC heat treated at 1600°C for 24 hours under UHV.



$$EMF_{AB} = \int_{T_r}^{T_j} (\sigma_A - \sigma_B)\, dT$$

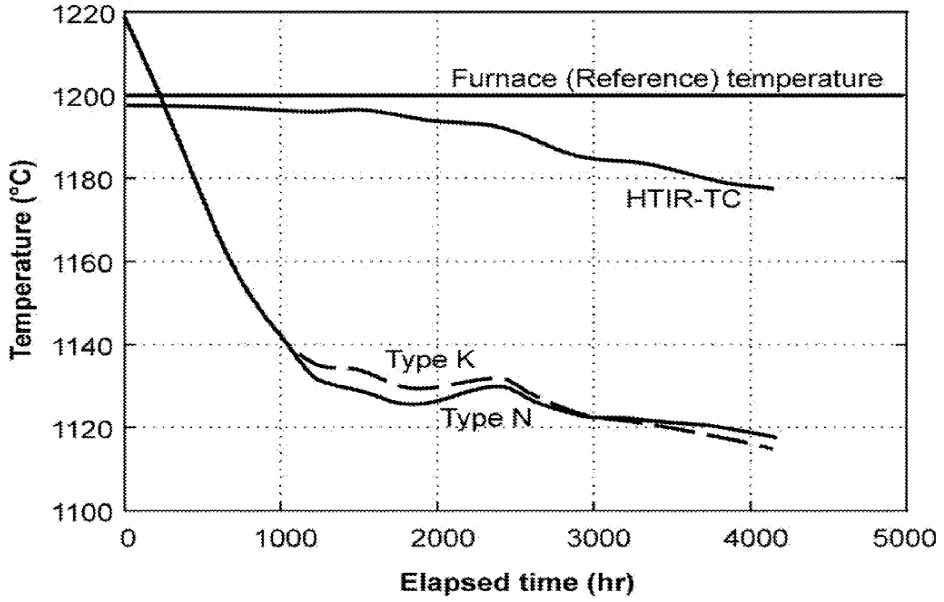


Signal measured by Mo/Nb thermocouples during 1100°C 1000-h test [1].

[1] Bong Goo Kim, Joy L. Rempe, Jean-François Villard & Steinar Solstad (2011) Review Paper: Review of Instrumentation for Irradiation Testing of Nuclear Fuels and Materials, Nuclear Technology, 176:2, 155-187, DOI: 10.13182/NT11-A13294

Technological Impact

Thermocouple[2]	HTIR-TC	Type K	Type N	Type B
Materials	Mo vs. Nb	Chromel vs. Alumel	Nicrosil vs. Nisil	Pt – 30%Rh vs. Pt – 6%Rh
Temp Range	0 – 1700 °C	-270 – 1260 °C	-270 – 1260 °C	0 – 1700 °C
Cost	~$250/ft	~$30/ft	~$50/ft	~$250/ft
Radiation Tolerance as compared to HTIR-TC		1/10th	1/4th	1/100th



- Gen IV: Very high temperature reactor
  Core Outlet Temperature[4]: >900°C

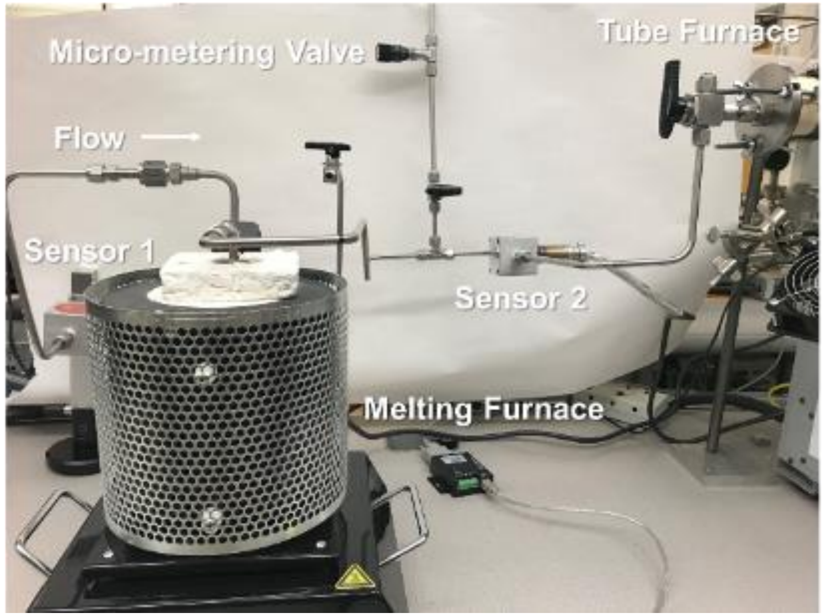
- HTIR-TC combines the high temperature of the Type B thermocouple with the radiation tolerance of Type N & K.

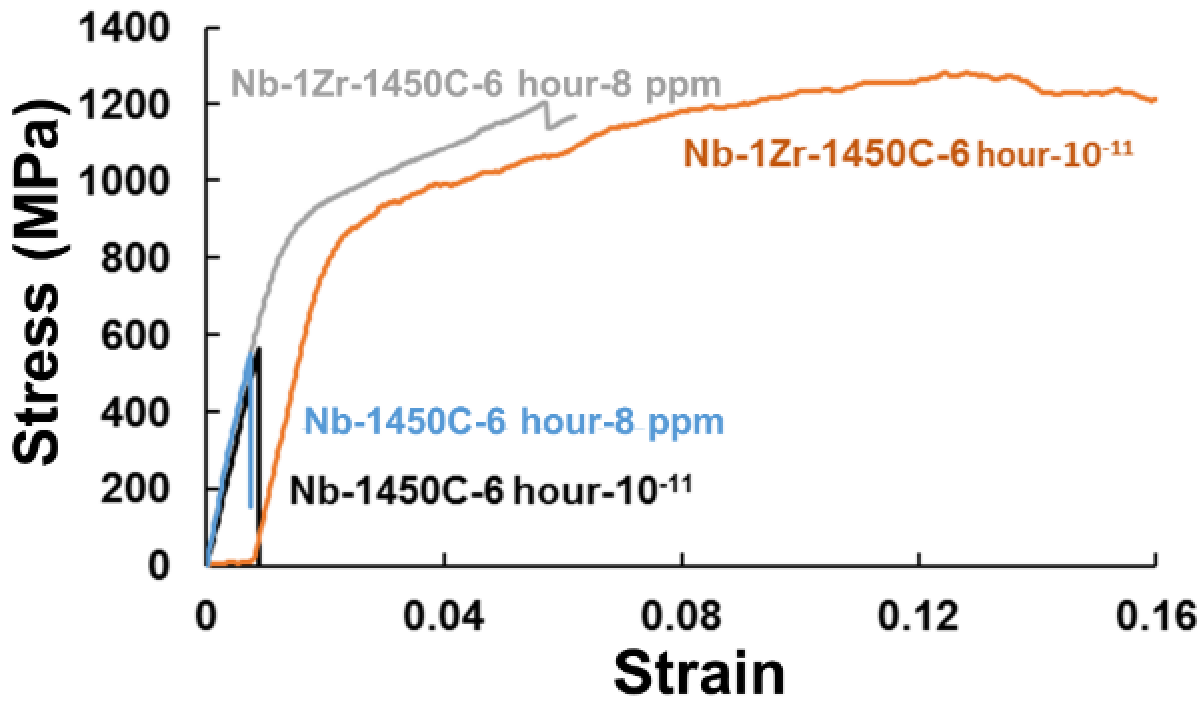
[2] Data courtesy of Dr. Skifton, INL

[3] Rempe, J.L., Knudson, D.L., Condie, K.G., Wilkins, S.C., "Evaluation of Specialized Thermocouples for High-Temperature In-Pile Testing," (INL/CON--05-00944), ICAPP Reno, NV, 2006.

[4] Murty K., Charit I., An Introduction to Nuclear Materials. Vol 1, Wiley-VCH, 2013, Weinheim, Germany.

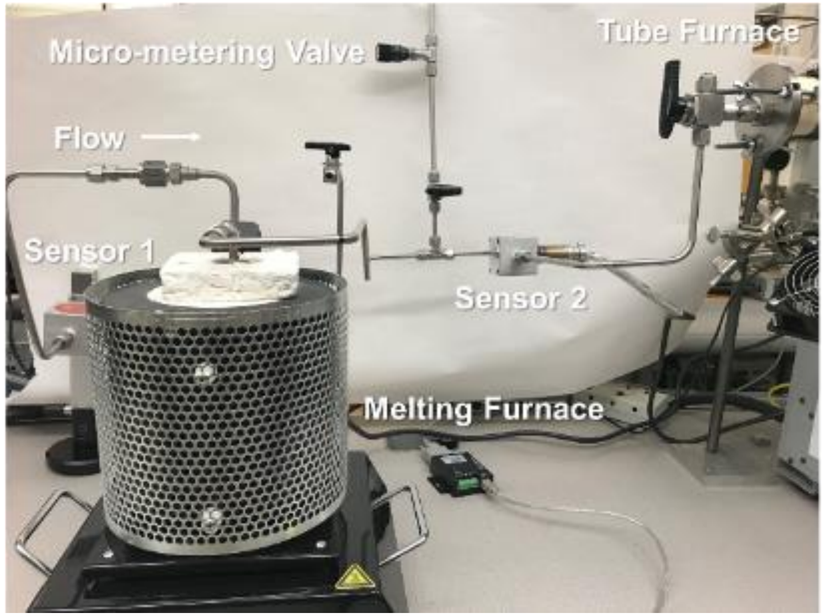
Oxidation Study pO_2 Stability of Alumina Furnace Tubes

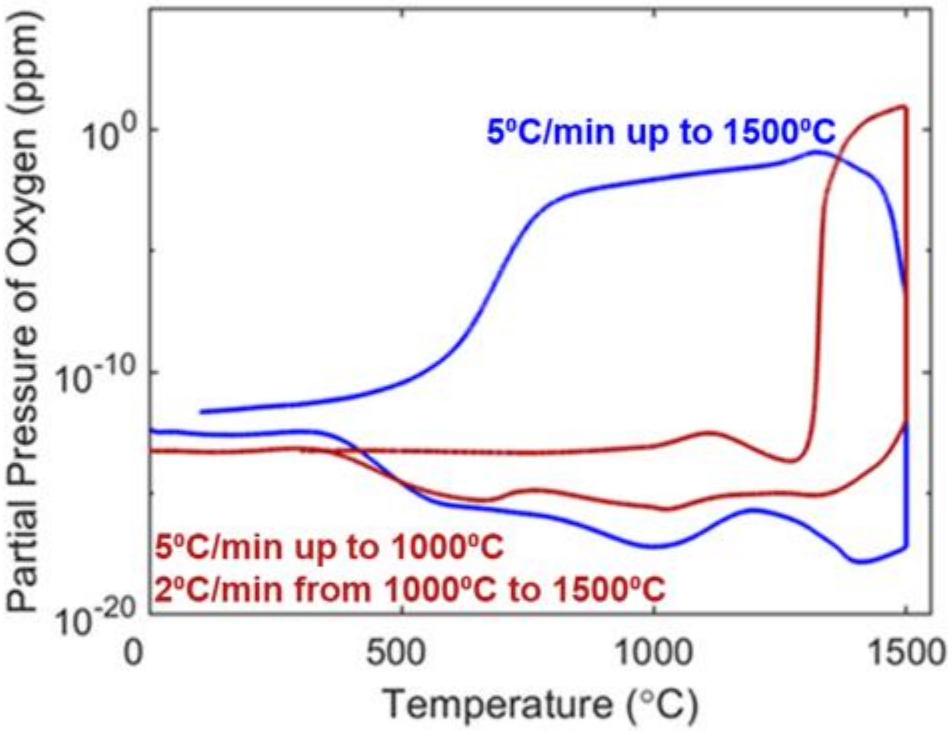




The embrittlement of the Nb HTIR-TC sheaths was attributed to oxygen ingress during the heat treatment

Oxidation Study pO_2 Stability of Alumina Furnace Tubes

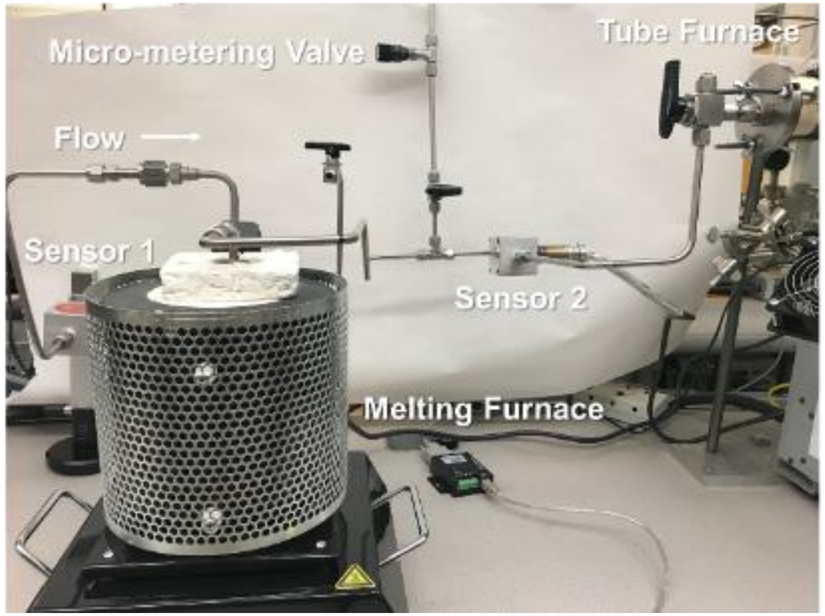


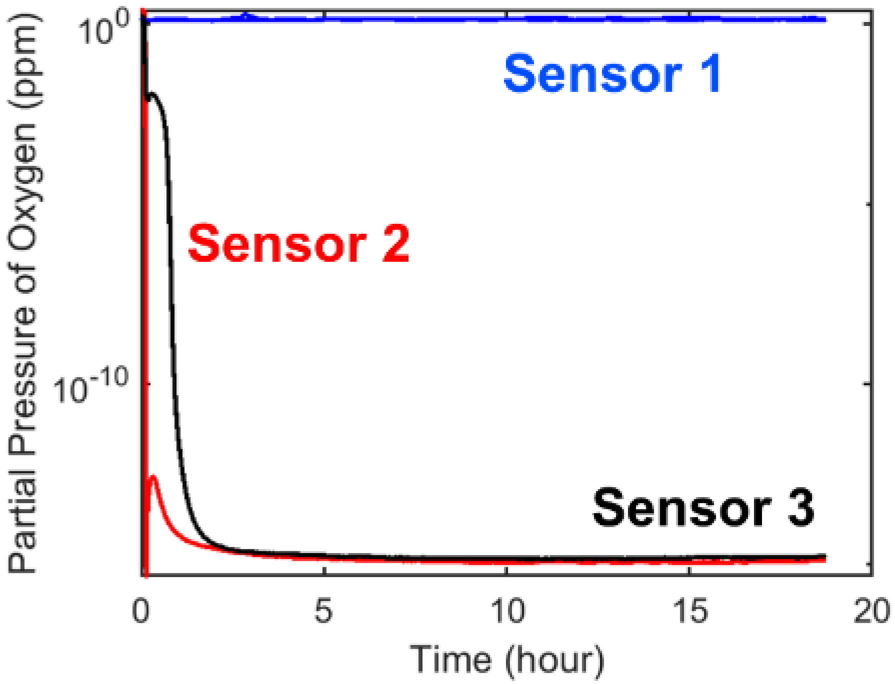


The embrittlement of the Nb HTIR-TC sheaths was attributed to oxygen ingress during the heat treatment

Extensive efforts were completed to control and understand the effects of time, temperature, and oxygen partial pressure on the ductility and performance of HTIR-TCs

Oxidation Study pO_2 Stability of Alumina Furnace Tubes

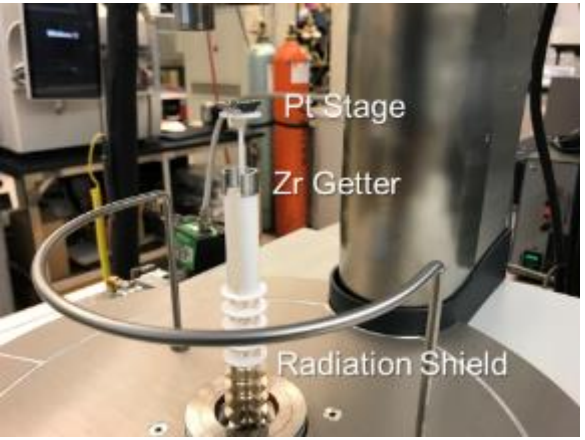


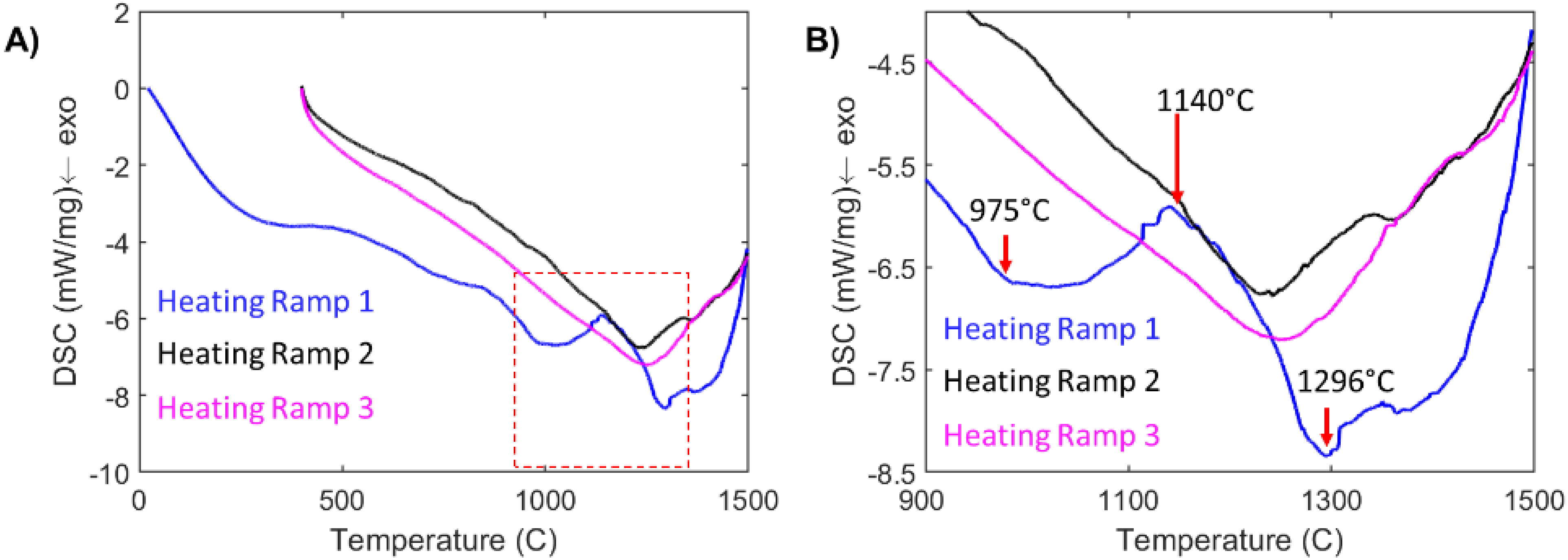


The embrittlement of the Nb HTIR-TC sheaths was attributed to oxygen ingress during the heat treatment

Extensive efforts were completed to control and understand the effects of time, temperature, and oxygen partial pressure on the ductility and performance of HTIR-TCs

DSC Characterization of Swaged Mo-LaO

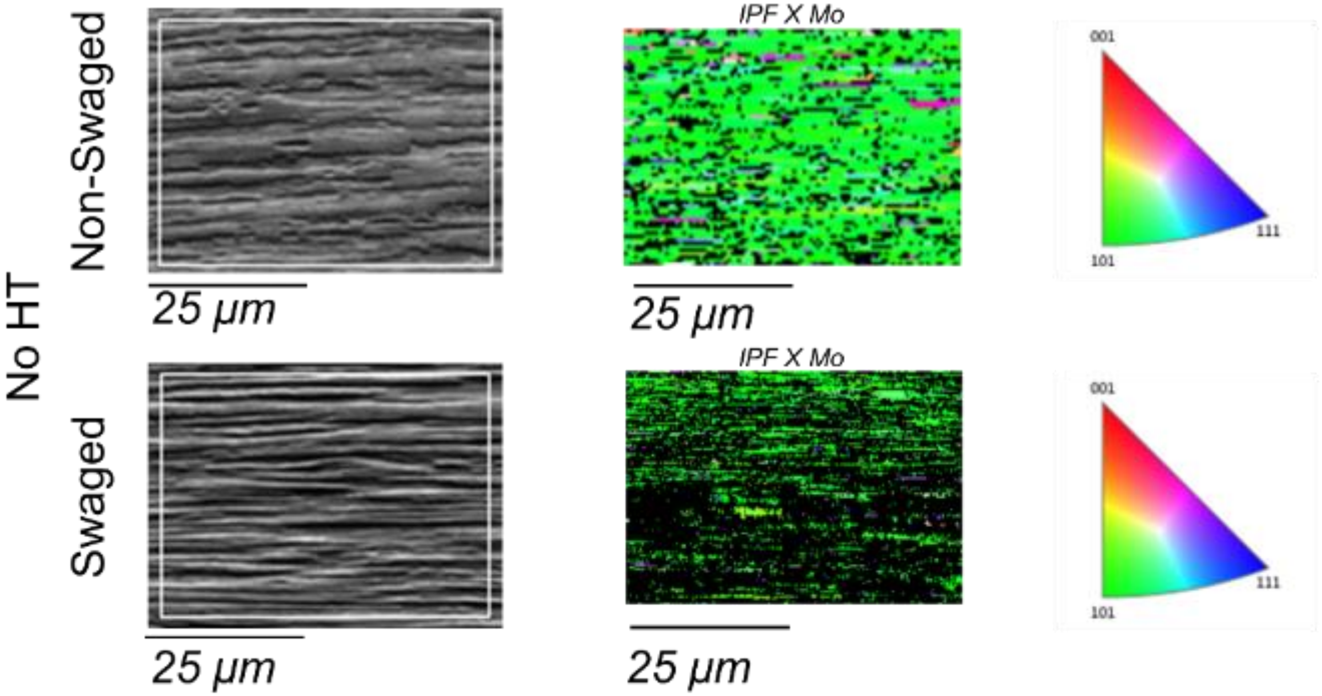


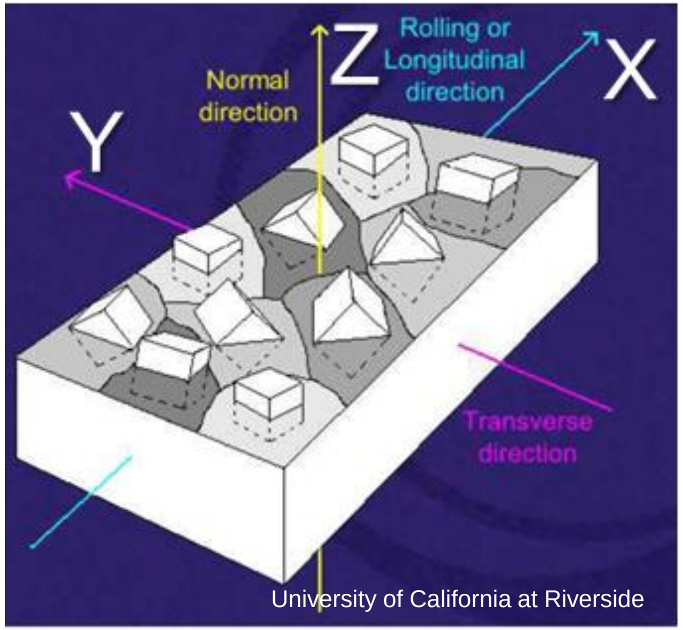


Endothermic peak with an onset at approximately 975 °C and an end point at 1296 °C

This is indicative of the stabilization event predicted/observed at INL at approximately 1300°C in the HTIR-TC thermoelements

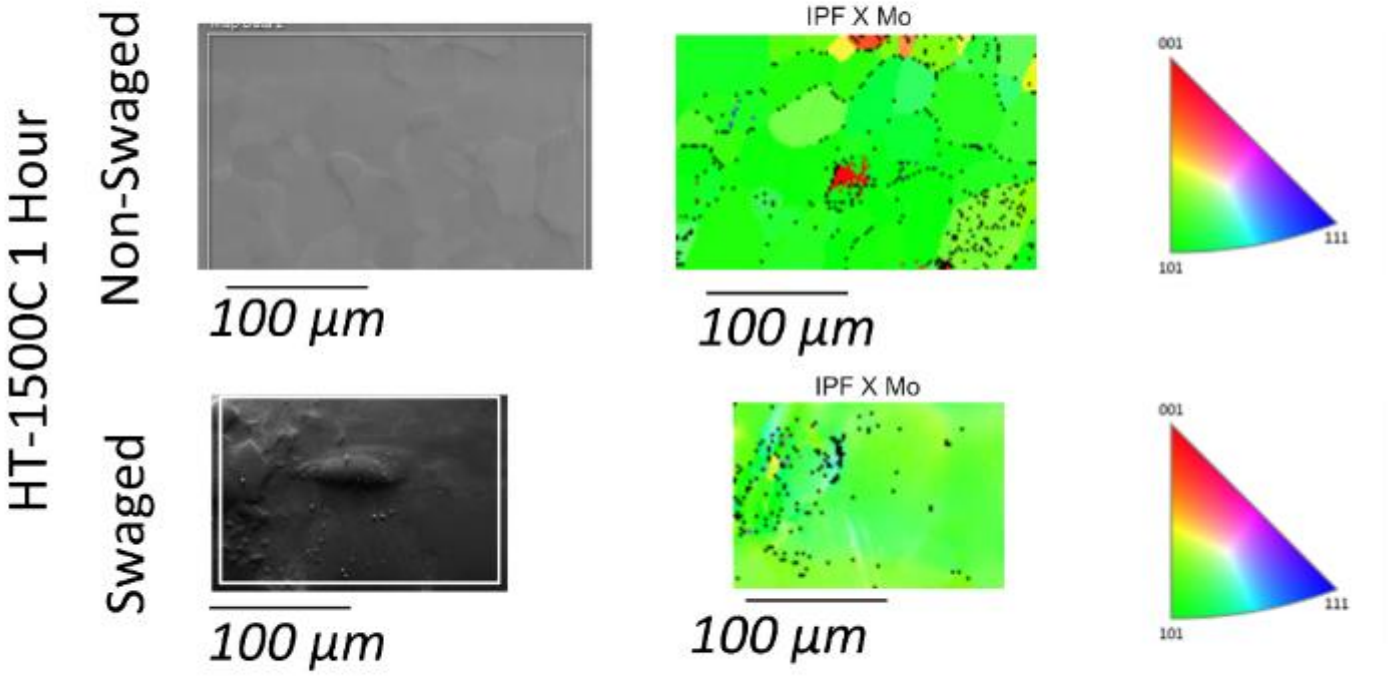
Electron Back Scatter Diffraction Mo-LaO

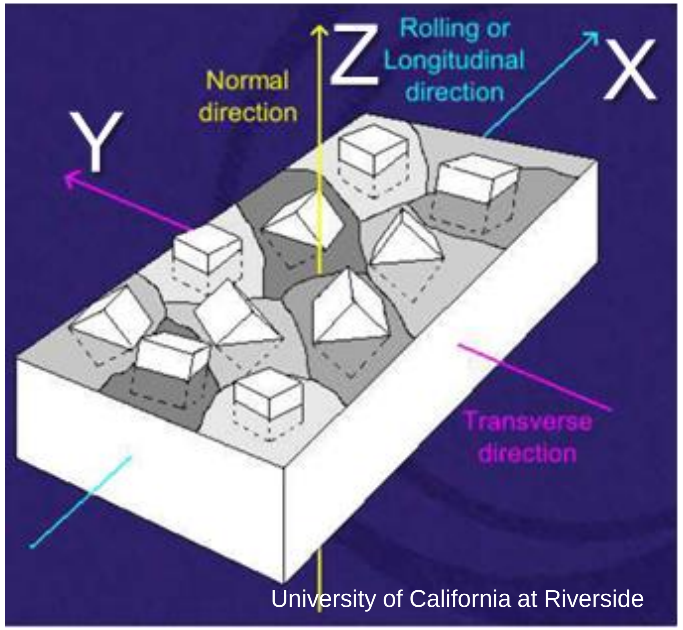




University of California at Riverside

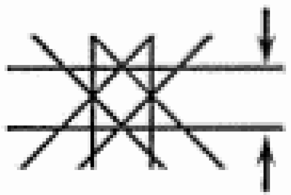
Electron Back Scatter Diffraction Mo-LaO





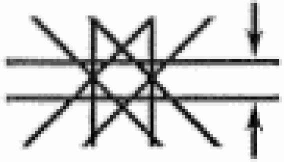
Electron Back Scatter Diffraction Mo-LaO

Before Swaging

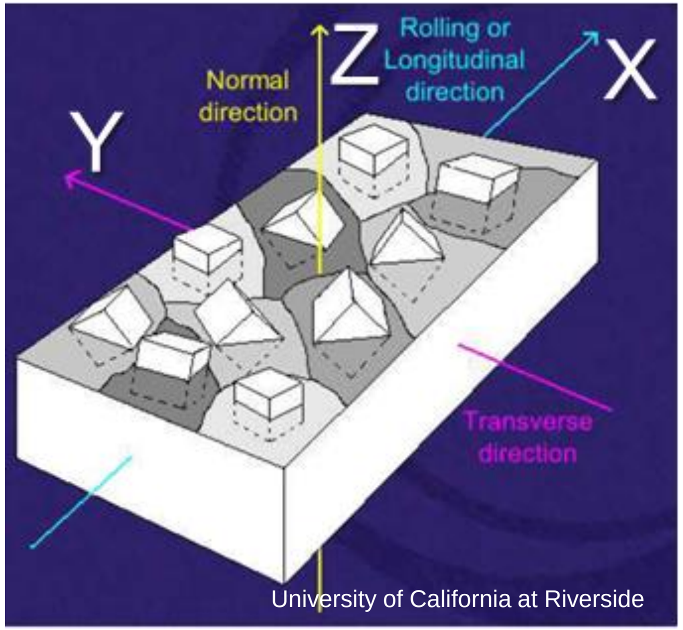


$$W(\varepsilon = 0) = 2\theta_{hkl(0)}$$

After Swaging



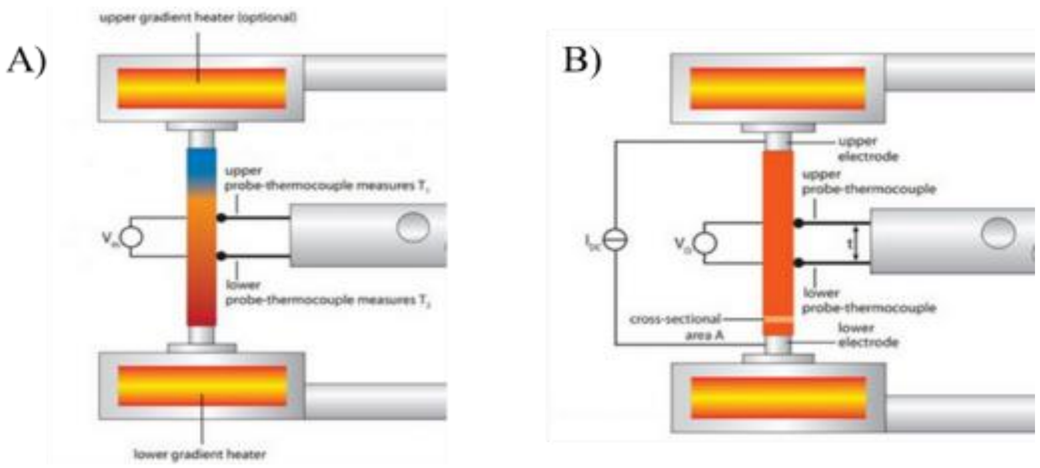
$$W(\varepsilon > 0) = 2\theta_{hkl(swaged)} < 2\theta_{hkl(0)}$$

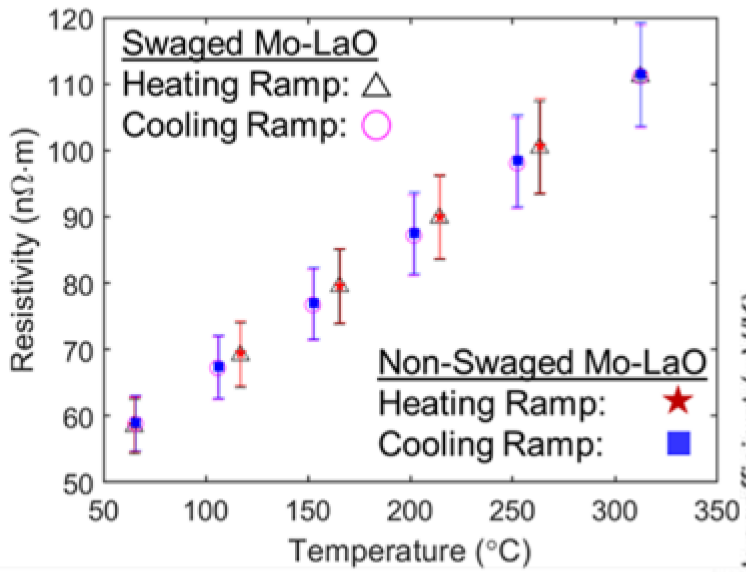


- The Mo-LaO thermoelement is not undergoing recrystallization during heat treatment
- Annealing of residual stresses brought about during the swaging process during the heat treatment

[5] R.R. Keller, EBSD measurement of strains in GaAs due to oxidation of buried AlGaAs layers, Microelectronic Engineering 75 (2004) 96-102.

Electrical Properties of Mo-LaO Thermoelement





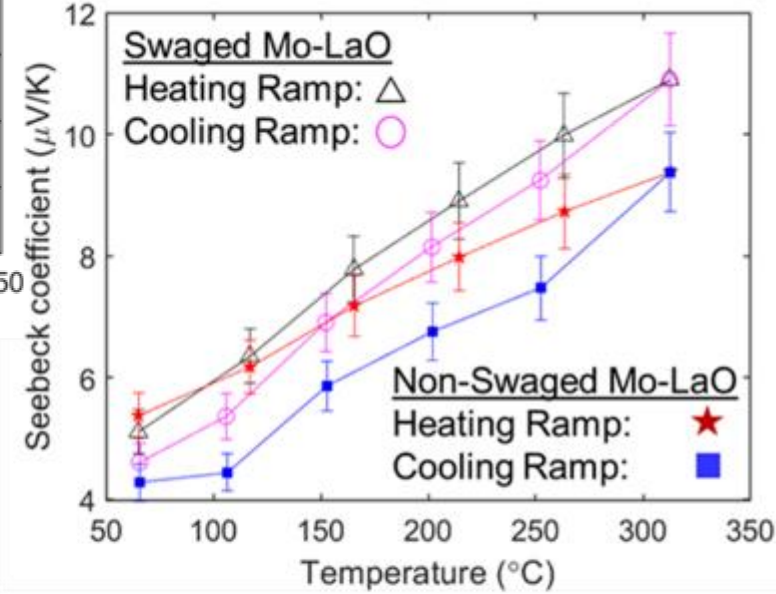


Table 1: Room temperature Seebeck coefficient and Resistivity for swaged HTIR-TC thermoelements as a function of heat treatment.

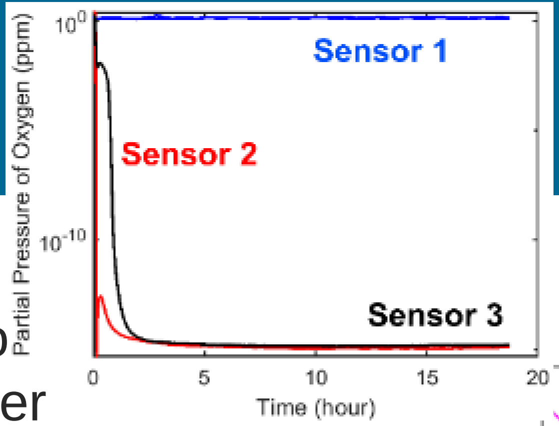
Material		Seebeck Coefficient (µV/K)		Resistivity (nOhm-m)	
		No Heat Treatment	1500°C, 1 Hour	No Heat Treatment	1500°C, 1 Hour
Mo-LaO	Non-Swaged	2.2 ± 0.1	2.1 ± 0.1	52.6 ± 3.7	50.0 ± 3.5
	Swaged	2.3 ± 0.7	1.1 ± 0.6	49.4 ± 3.5	54.2 ± 3.8

*Pure Mo has a Seebeck coefficient of 3.9 µV/K and a resistivity of 52.0 nOhm-m at room temperature [5,6].

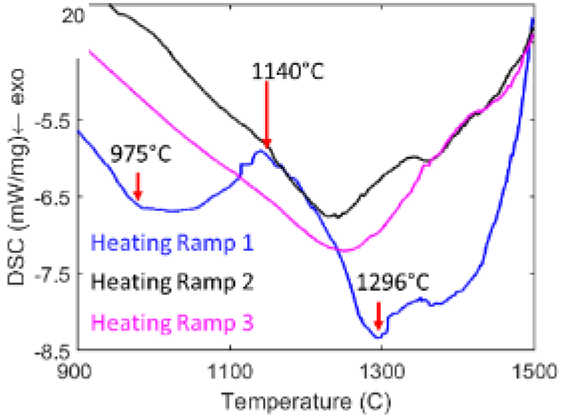
- The Seebeck coefficient in the swaged Mo-LaO decreased by 1.2 ± 0.9 µV/K with heat treatment
- Testing at elevated temperatures is necessary in order to increase the signal resolution.

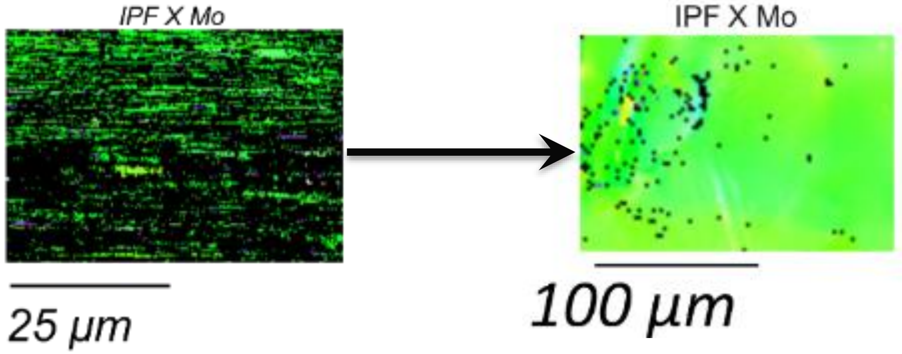
[6] P. Fiflis, Seebeck coefficient measurements on Li, Sn, Ta, Mo, and W, Journal of Nuclear Materials 438 (2013) 224-227.
[7] ASM Handbook, Properties and selection:nonferrous alloys and special-purpose materials, 10 ed., ASM International, Materials Park, OH, 1990.

Conclusion



- Summary:
  - Equipment was repaired and modified (DSC and LSR) to facilitate operation at 1500 and 600 ºC, respectively, under atmospheres of 10^{-15} ppm O_2.
  - EBSD showed the evolution of thermo element microstructure during the stabilization heat treatment
    - Recrystallization was not observed, but residual stresses were annealed out, resulting in a decrease in Seebeck Coefficient
- Future Work:
  - Characterize chemical stability, grain morphology, and the Seebeck coefficient as a function of heat treatment temperature and swaging to study the stabilization phenomena of HTIR-TC thermoelements.





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Strain Gauges for In-Pile Applications

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

PI: Dr. Brian J. Jaques, BSU
GRA: Timothy Phero and Kaelee Novich
PI: Pattrick Calderoni, Troy Unruh, INL

Boise State University-Materials Science and Engineering
Idaho National Laboratory

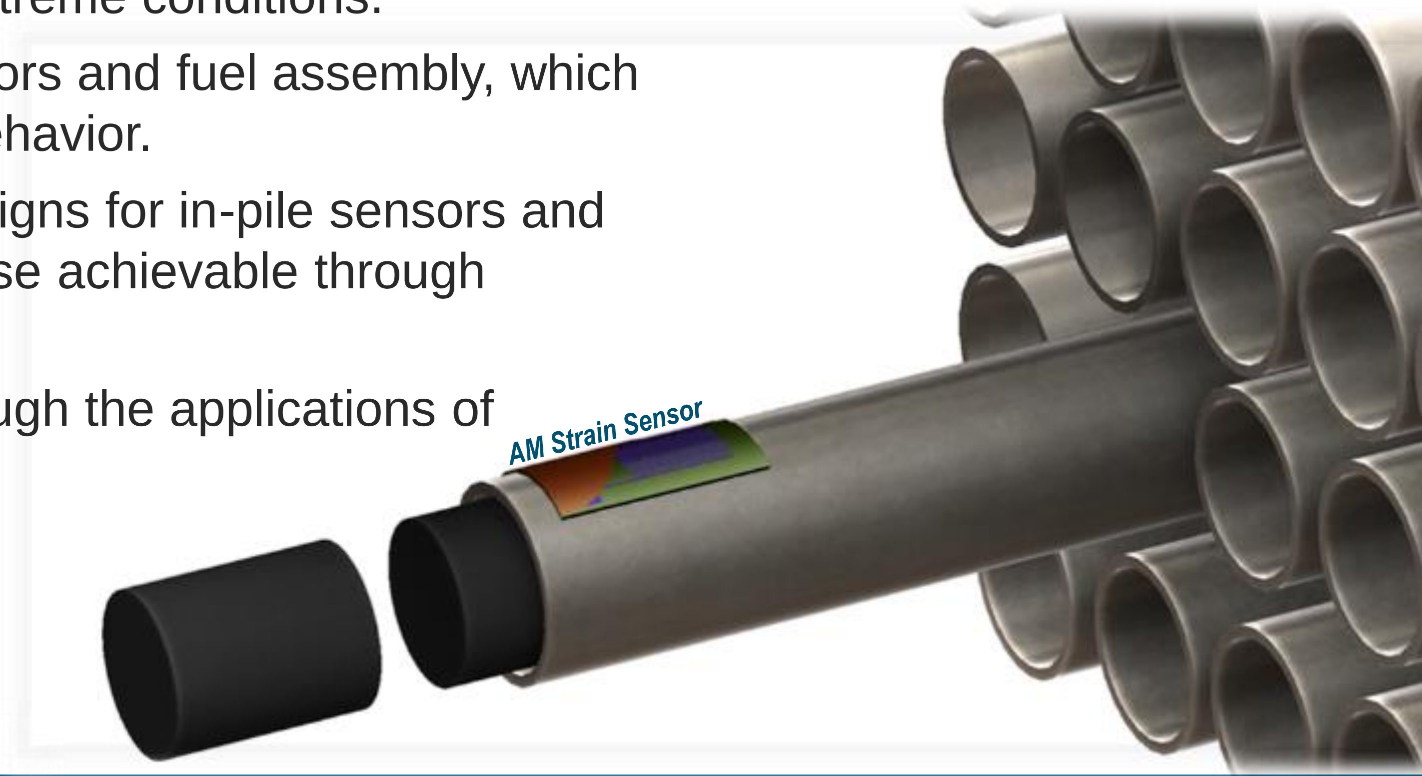
Project Overview

- Goals and Objective
  - To investigate, optimize, and develop manufacturing methods and new capabilities that enable transformative sensor technology for in-pile monitoring and in-situ analysis of fuels and materials.
- Participants
  - **Boise State University**: GRAs: Timothy Phero and Kaelee Novich. UGRAs: Bette Gougar and Sarah Cole PIs: Brian Jaques, & Dave Estrada
  - **Idaho National Laboratory**: PI: Mike McMurtrey
- Schedule
  - Platform development for testing/benchmarking classically and advanced manufactured strain gauges through conducting a thorough literature review and implementing the discoveries. Using the platform, we will use resistive strain gauges and digital image correlation techniques to establish testing and validation protocols of various modalities including optical fiber strain gauges, capacitive strain gauges, etc. Validate protocols using 3D finite element models as appropriate. (08/31/2021)
  - Examination of heterogeneous integration techniques to develop interconnection strategies to connect to AM sensors. (07/09/2021)

Technology Impact

The advanced manufacturing (AM) activities:

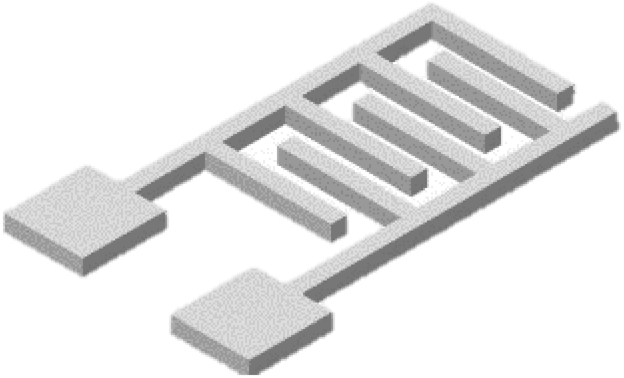
1. Have cross-cutting research objectives to fulfill the listed research and development activities.
2. Seeks to deploy and advance state-of-the-art sensor manufacturing methods and leverage lessons learned from other industries, especially those related to sensor manufacturing for extreme conditions.
3. Provides non-destructive integration of sensors and fuel assembly, which is crucial to accurately monitor in-pile fuel behavior.
4. Facilitate the production of novel sensor designs for in-pile sensors and instrumentation designs that are not otherwise achievable through classical fabrication techniques.
5. Supports the DOE-NE research mission though the applications of additive manufacturing.



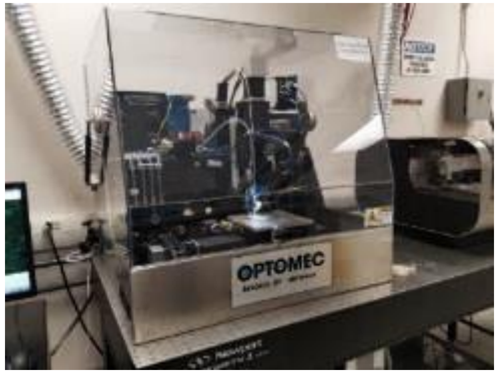
Overview of Accomplishment

- Investigate the design, printing (using aerosol jet printing (AJP)), consolidation, and interfacial behaviors of printed strain gauges on nuclear relevant substrates up to 300 ºC
- Complimentary deformation measurement techniques (i.e., digital image correlation, finite element modeling, commercial strain gauges) were demonstrated and used for comparison
- Methods for heterogeneous integration (interconnects) to AM strain gauge was investigated and performance were characterized
- Resilience and adhesion of AM printed material to the substrate was investigated

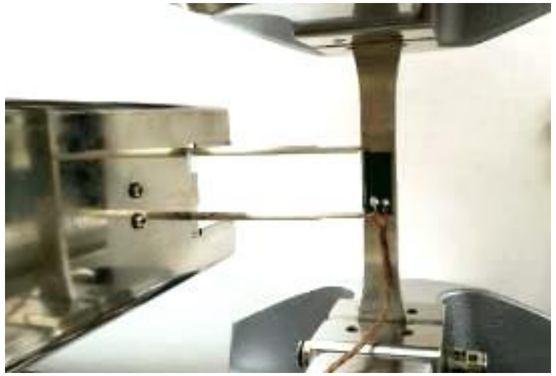
Design → **Fabrication** → **Testing & Characterization**



- Interdigitated Electrode Capacitive Sensor



- Aerosol Jet Printing
  - Voltera Printer

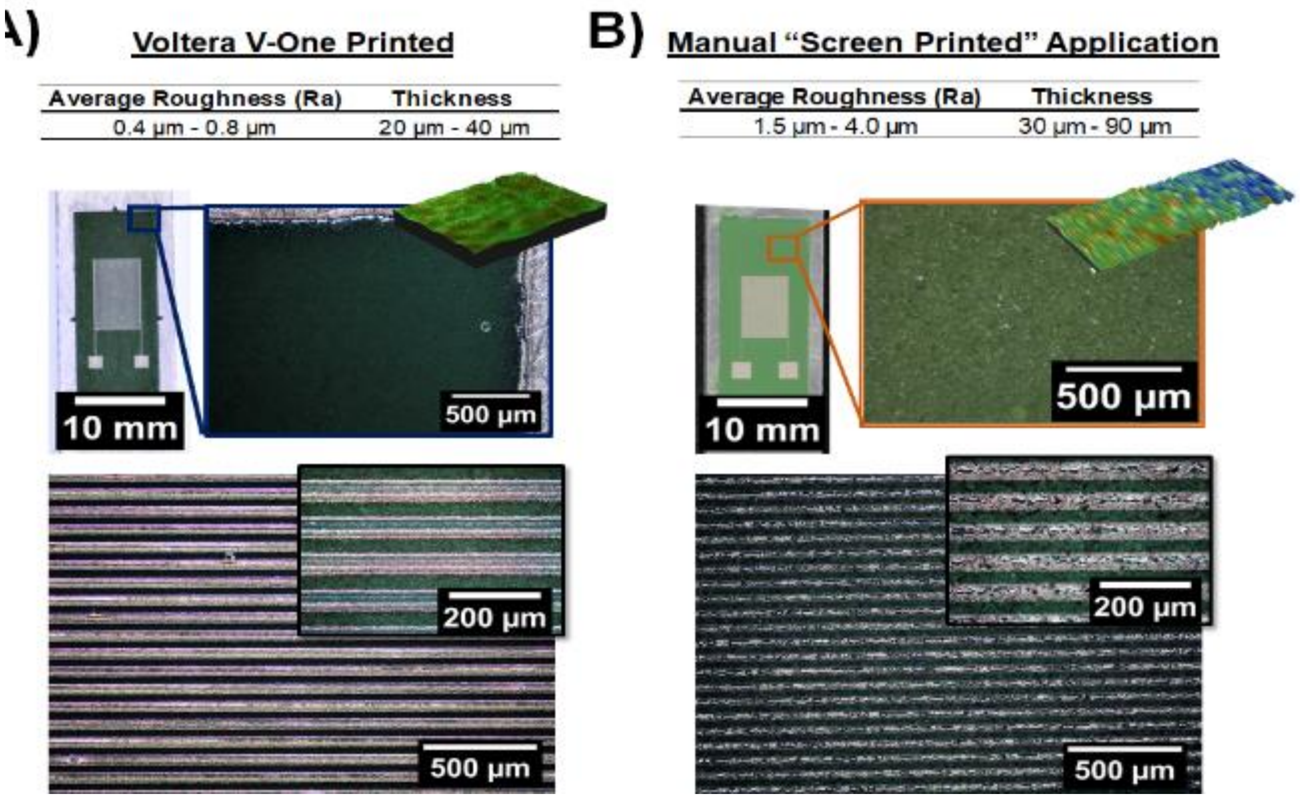


- Separate Effects Testing
- Resilience and Reliability

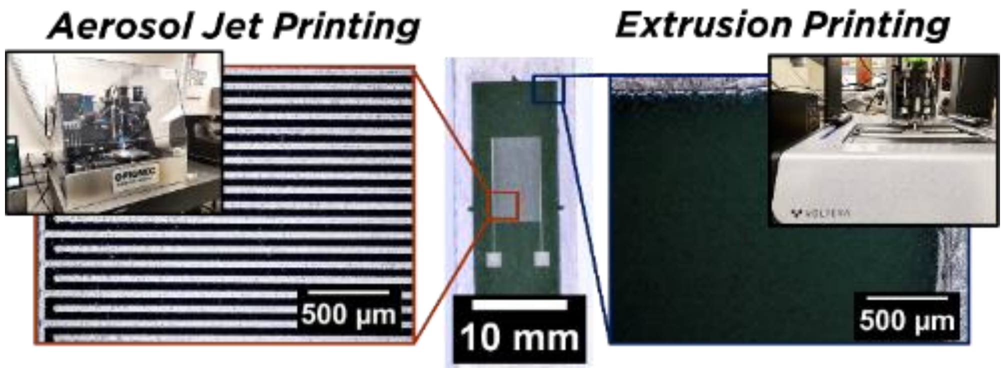
Accomplishment (1/4): Design and AM Fabrication

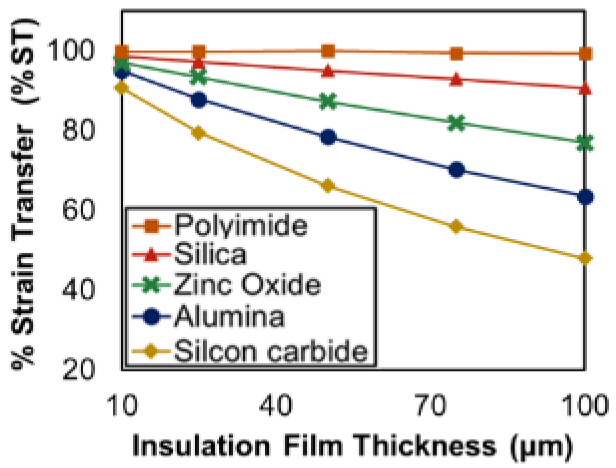
Challenge: Strain gauge required an electrically insulative barrier that is resilient to extreme environments, has surface characteristics that are conductive to AM fabrication, and compliant to allow strain measurements

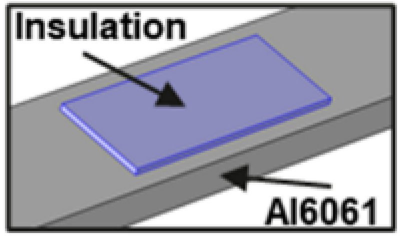
AM Printing Electrical Insulation



Compliance of Insulation barrier







$$\varepsilon = strain$$

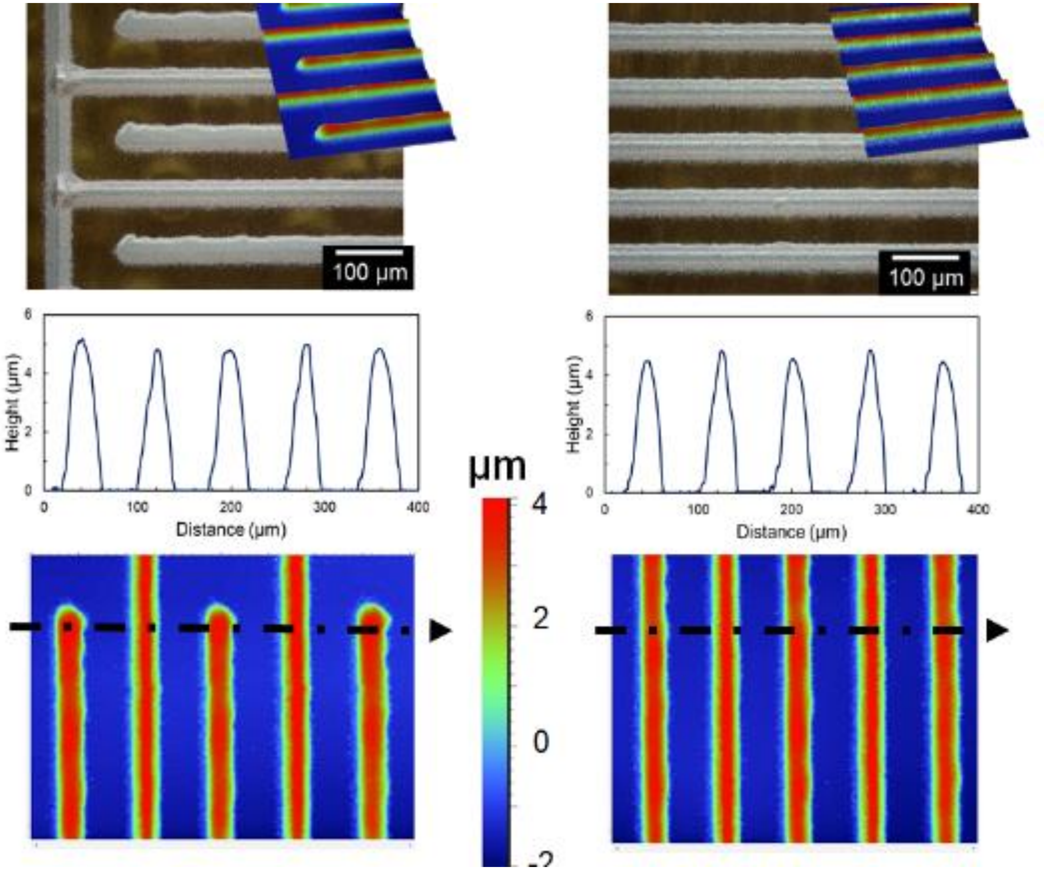
$$\%ST = \frac{\varepsilon_{insulation}}{\varepsilon_{Al6061}} \times 100$$

Accomplishment (1/4): Design and AM Fabrication

Challenge: AM strain gauges need to be reliably fabricated with consistent and uniform morphology.

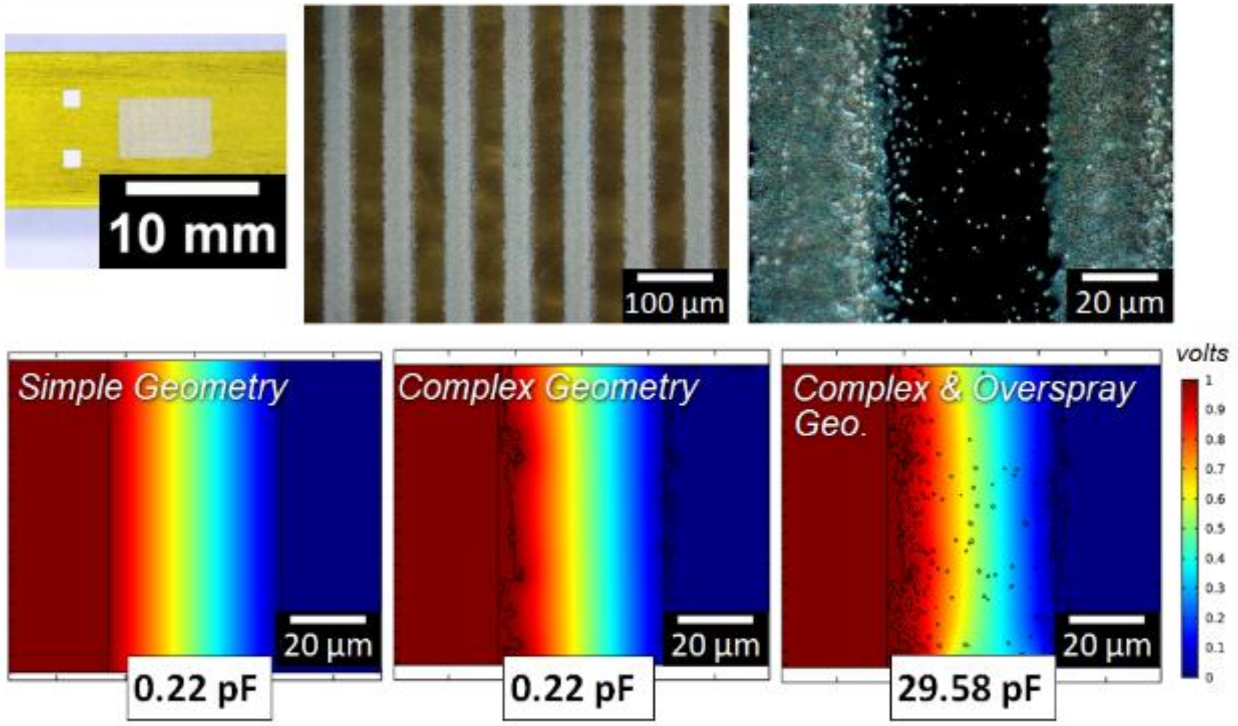
Uniformity of Electrode Morphology

- AM printing process was optimized to allow uniform deposition of conductive electrodes



Enhanced Capacitance from AM Process

- Finite element modeling was used to show that the residual particles from the AM process (i.e., overspray) enhances the inherent capacitance of the capacitive sensor

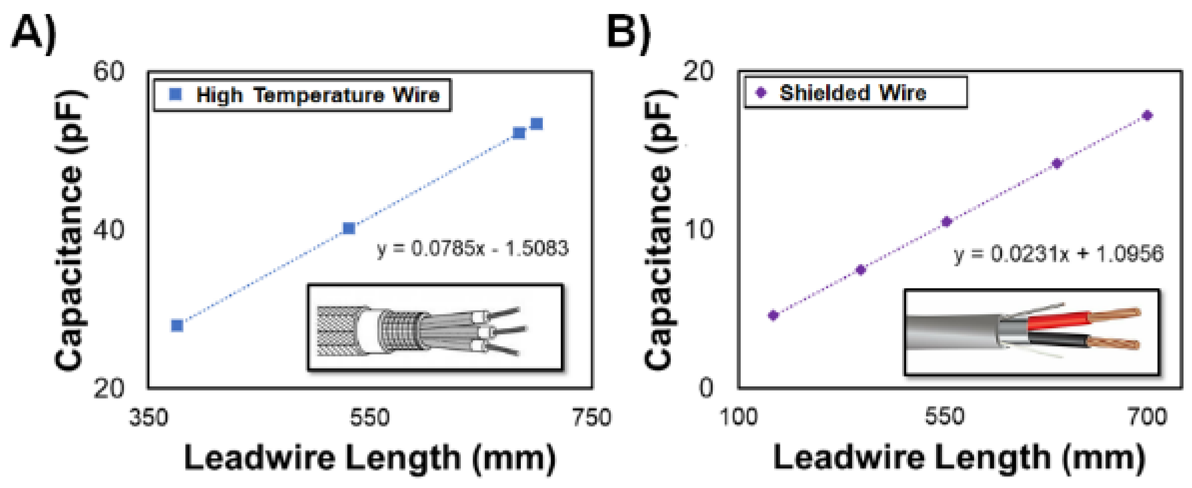


Accomplishment (2/4): Heterogenous Integration

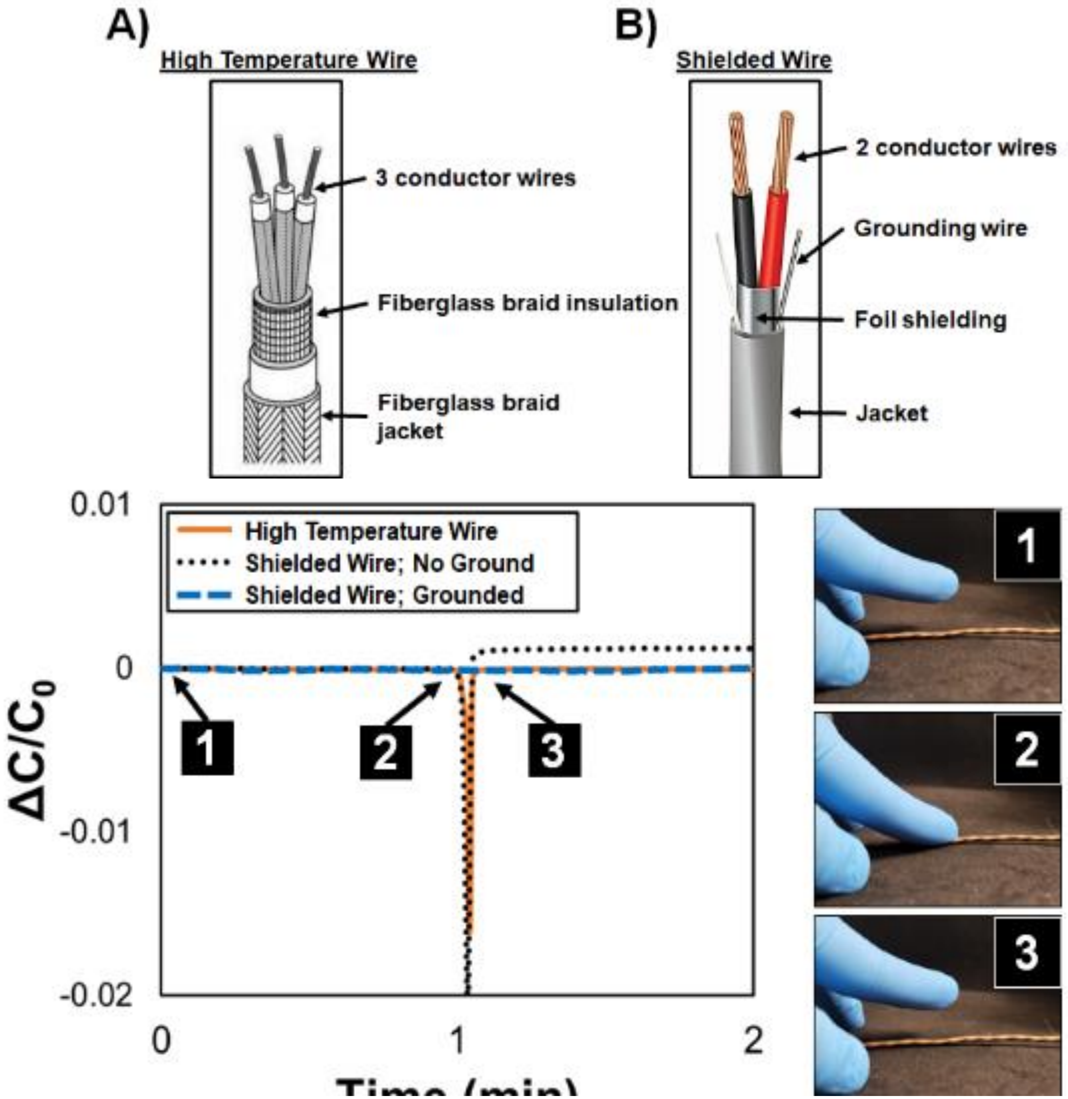
Challenge: An appropriate interconnection and packaging technologies is needed to maintain reliable electrical and mechanical performance in harsh environments.

- Efficacy of wire types and integration methods (i.e., traditional soldering, conductive paste) was investigated to mitigate environmental noise and parasitic capacitance affecting the capacitive sensor signal

Inherent Capacitance in Multi-conductor Wire



Environmental Noise from Lead wires



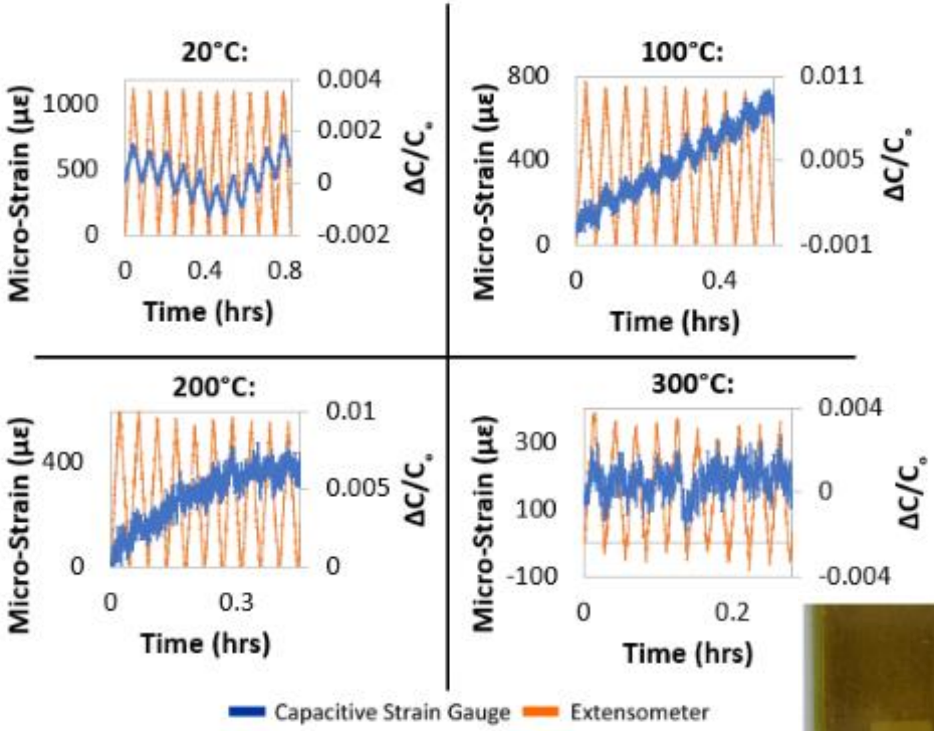
energy.gov/ne

Accomplishment (3/4): Strain Gauge Performance Characterization

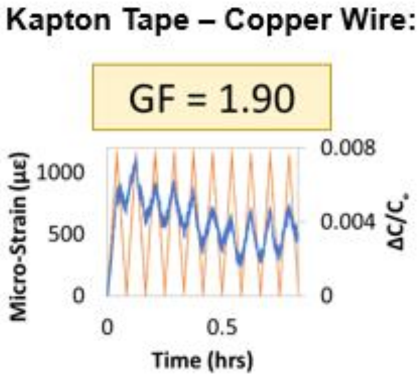
Challenge: Demonstrate the efficacy of the interdigitated structure to sense strain on metallic substrates at high temperatures

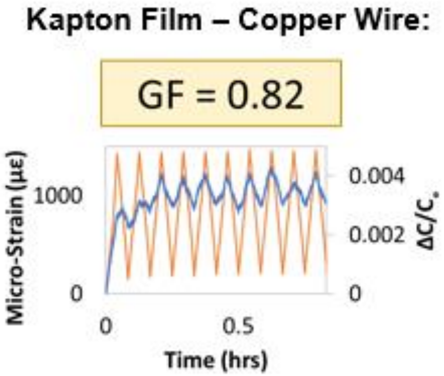
- AM printed capacitive strain gauges were tested up to 300 ºC and sensitivities (i.e., gauge factor) were calculated
- The AM printed sensors were validated against and compared to an external extensometer and commercially available resistive strain gauge

High Temperature Testing of CSG



CSG Insulation Performance Comparison



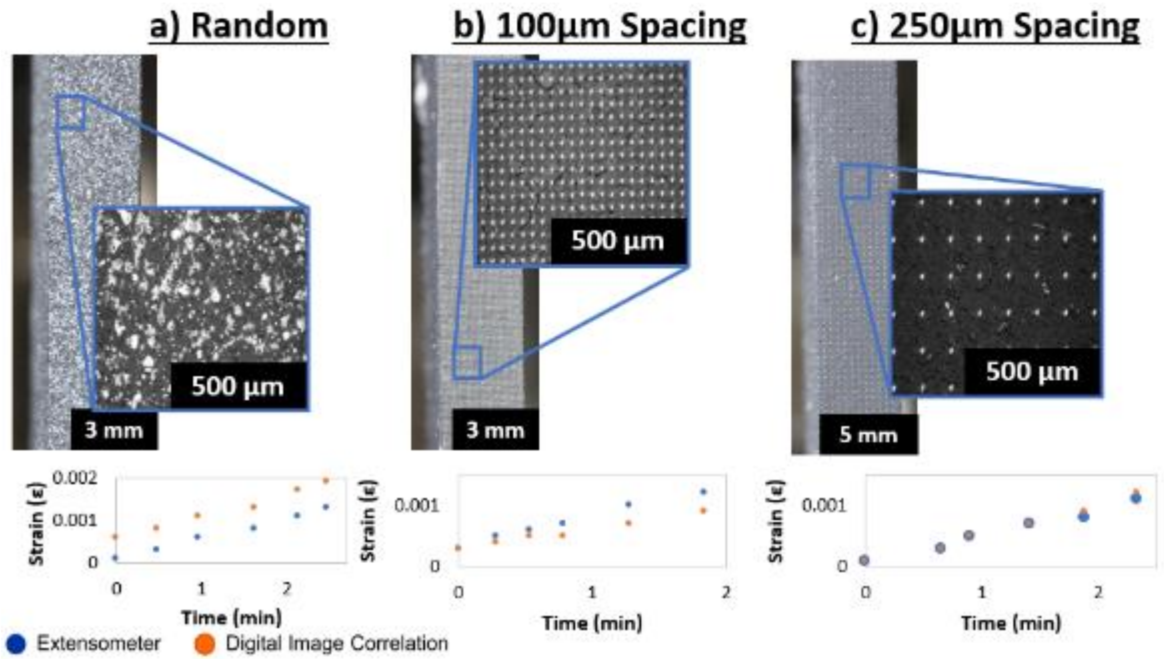


Accomplishment (3/4): Strain Gauge Performance Characterization

Additional mechanical strain validation methods were explored:

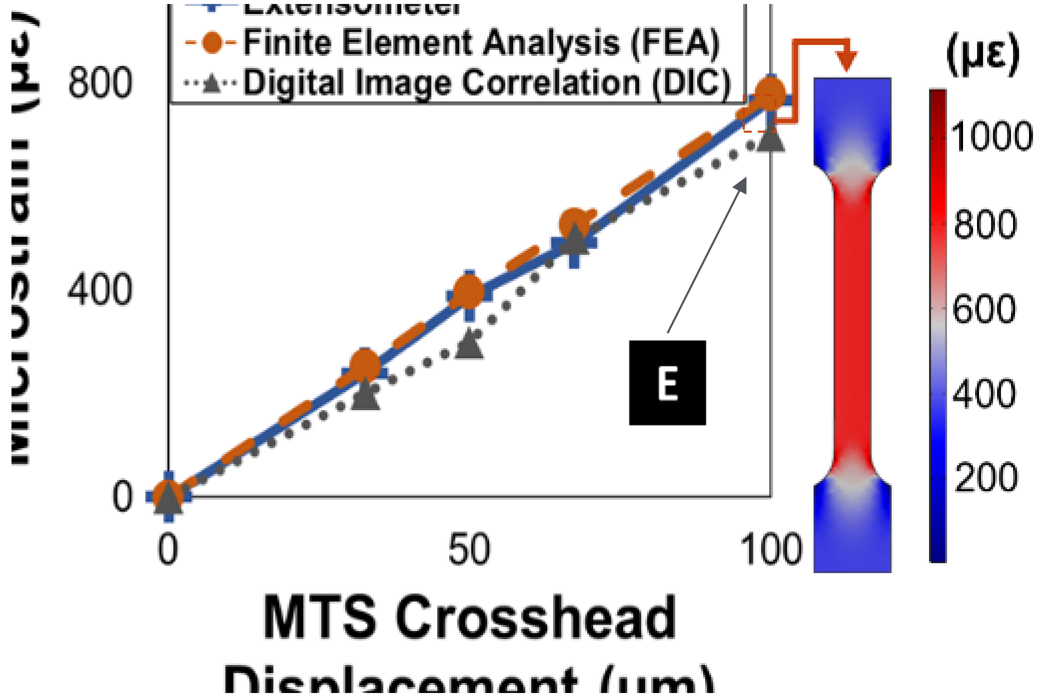
Digital Image Correlation (DIC)

- Non-contact process to measuring deformation, utilizing a speckle pattern and camera
- BSU is investigating printed grid patterns and comparing them to traditional random, spray painted patterns



Finite Element Analysis (FEA)

- BSU is using COMSOL, FEA software, to computationally validate mechanical testing

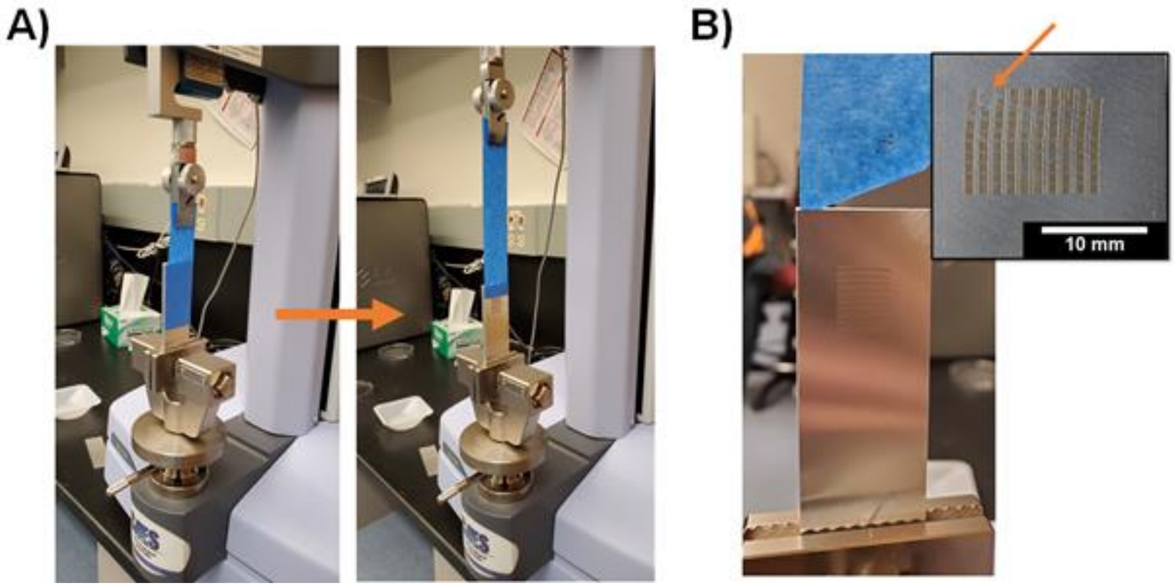


Accomplishment (4/4): Interfacial Behavior and Investigation

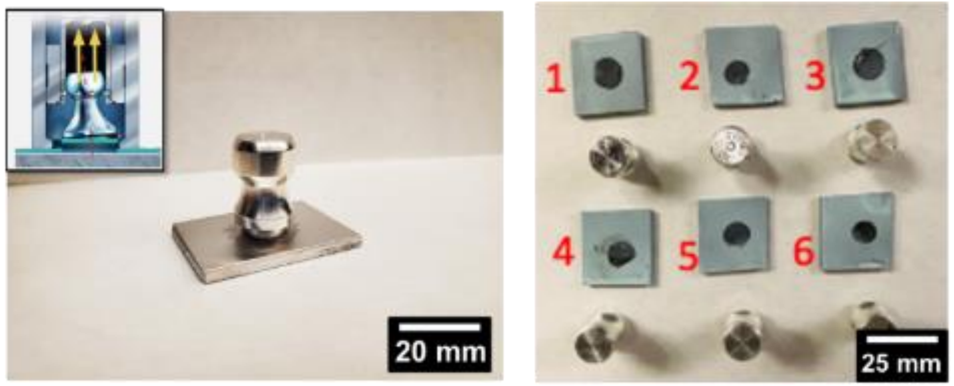
Challenge: Quantify the effects of fabrication parameters (i.e., surface preparation, printing parameters) on the adhesion strength of AM printed sensor materials

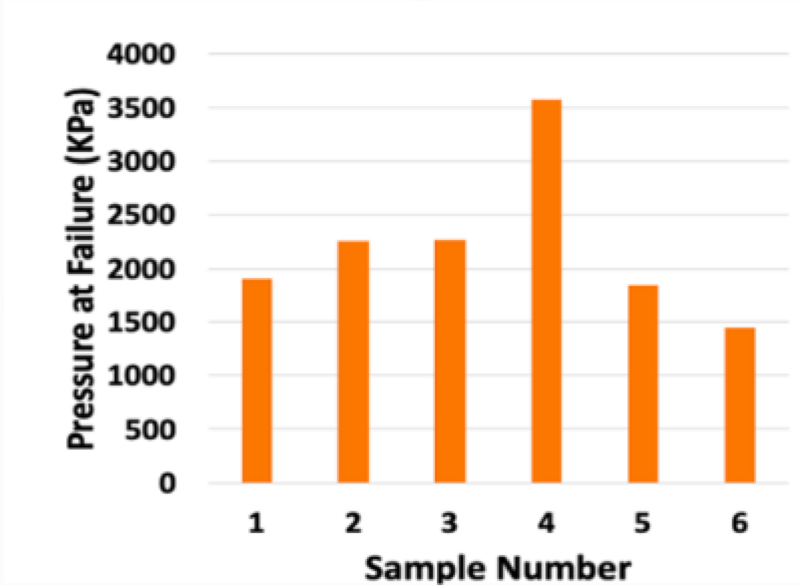
- Development of a standard pull-off adhesion testing enables the quantification of adhesion strength between printed ink and substrate surface

Cross-hatch Tape Adhesion Test



Pull-off Adhesion Test

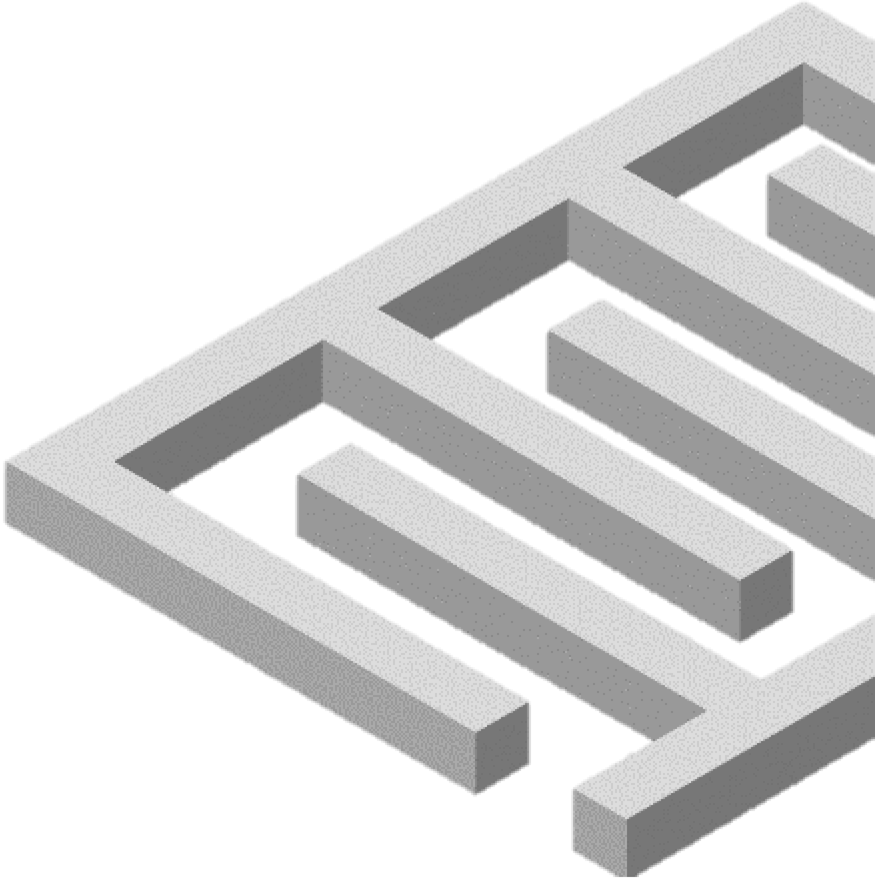




Conclusion

In the FY21:

- Improved and consistent AM fabrication of electrodes was demonstrated
- Investigation of harsh environment interconnection and packaging was started
- AM capacitive strain gauge was tested up to 300 ºC and validated with complimentary strain measurement techniques
- Techniques to allow for the quantification of adhesion resiliency and reliability of AM sensors was demonstrated



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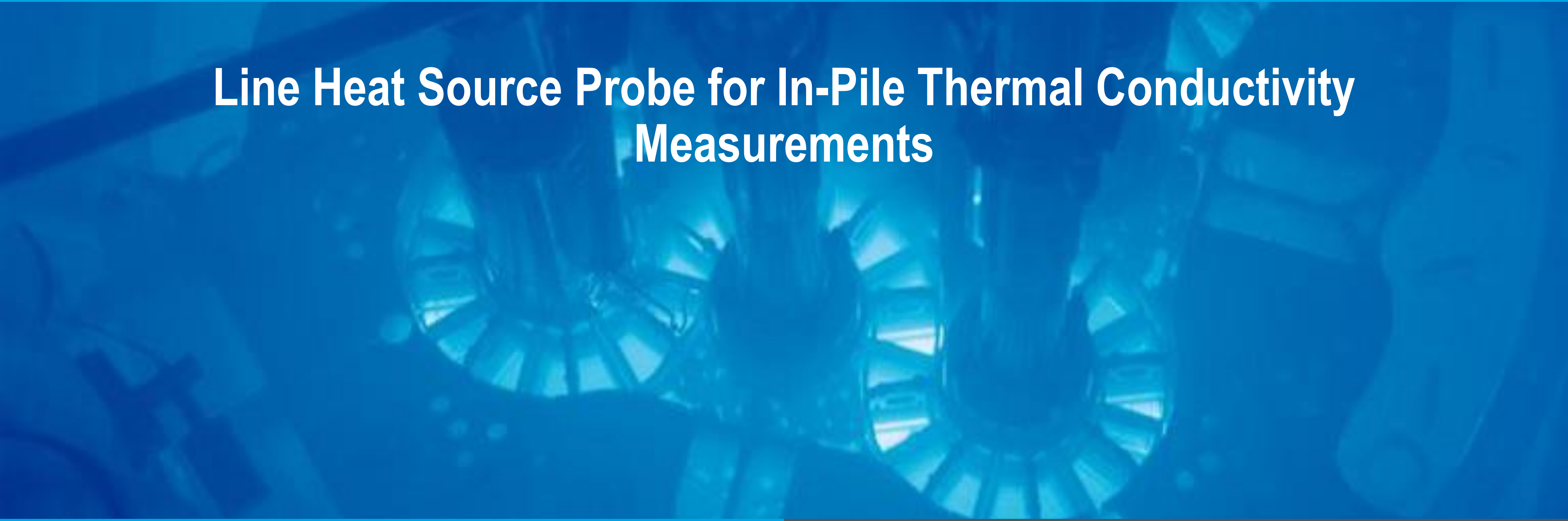
ASI Advanced Sensors and Instrumentation

Line Heat Source Probe for In-Pile Thermal Conductivity Measurements



Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

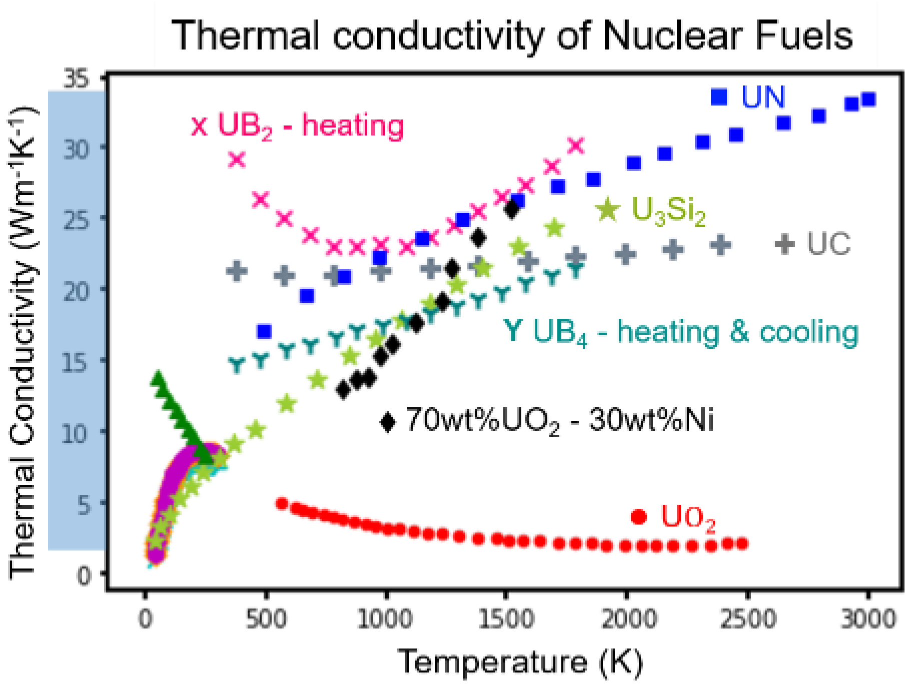
PI: Dr. David Estrada, BSU
GRA: Kati Wada, BSU
PI: Dr. Austin Fleming, INL

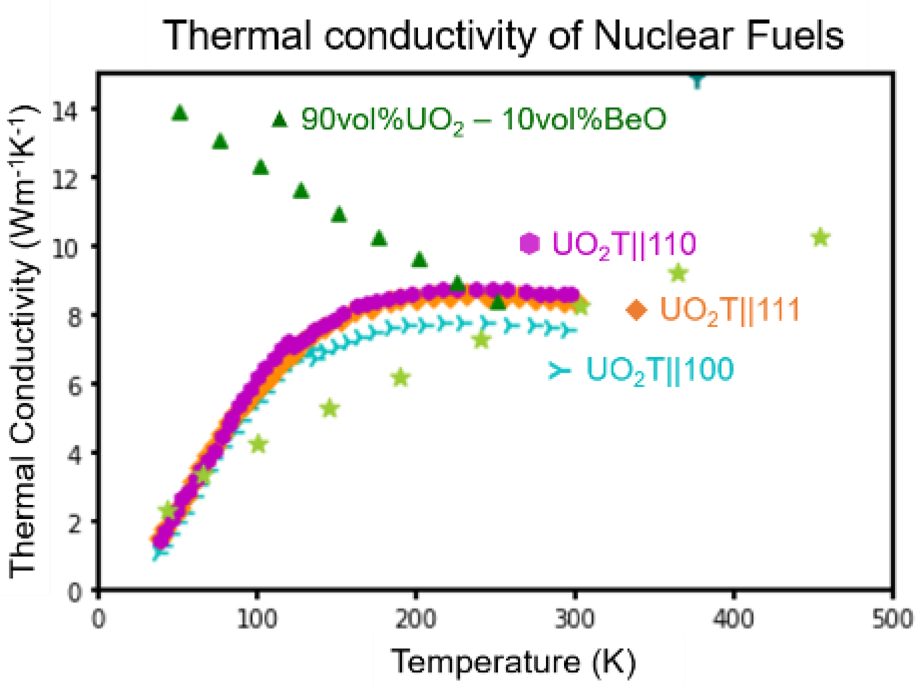
Boise State University-Materials Science and Engineering
Idaho National Laboratory

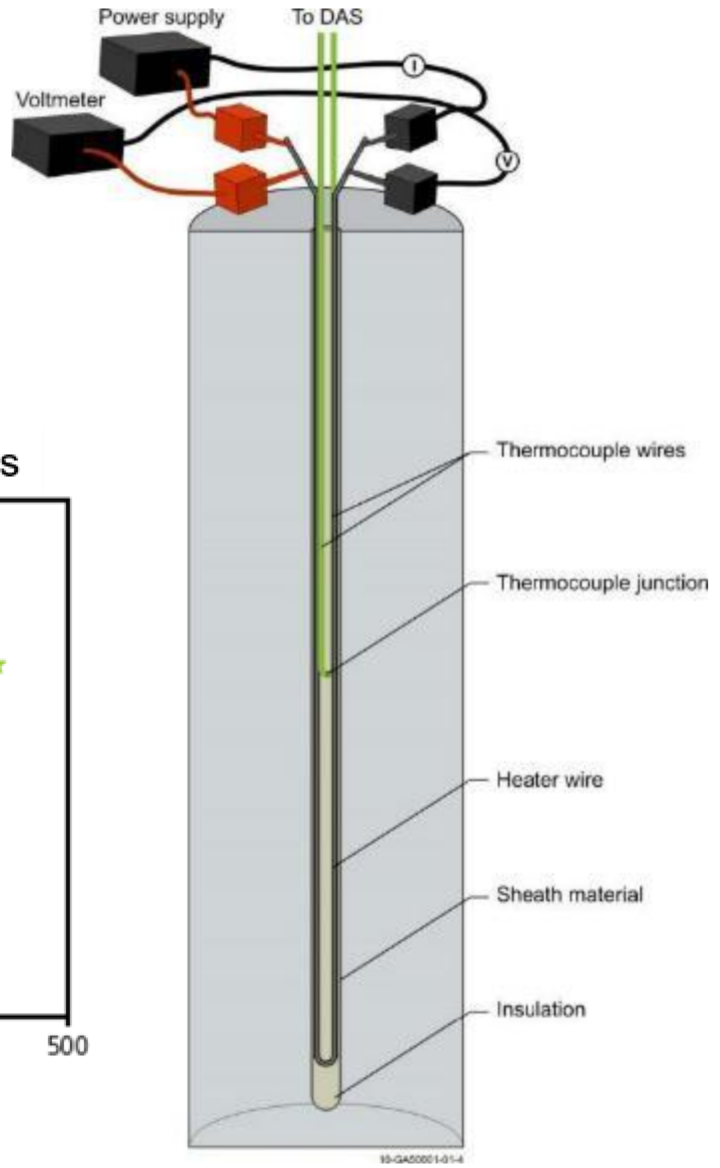
Project Overview

Thermal conductivity degradation limits fuel performance and lifetime.

- Need to develop an accurate thermal conductivity measurement for real-time in-pile characterization of fuel thermal properties.
- Advanced fuel of interest typically have smaller diameters and higher thermal conductivities compared to standard UO_2







Project Overview

Previous work at INL:

- Heater and thermocouple
- Measures temperature as a function of time
- Limited by boundary effects and other assumptions

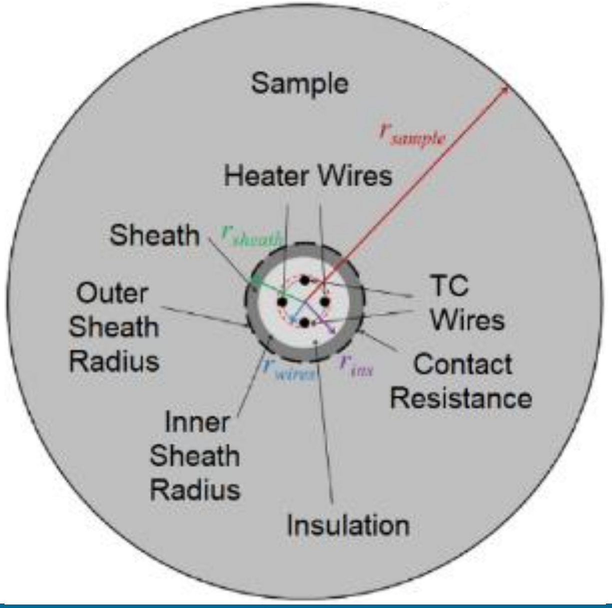
Current work:

- Single heater wire with no thermocouple
- Uses Ohms law and the temperature dependent resistance of the wire
- Small signal for SNR

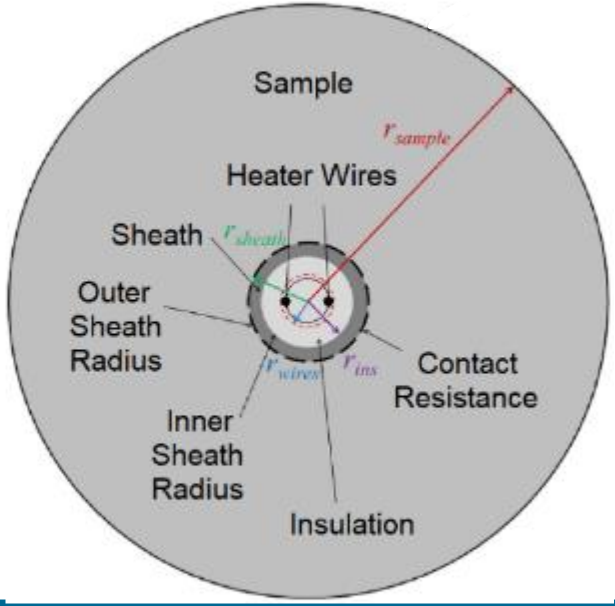
Analytical model:

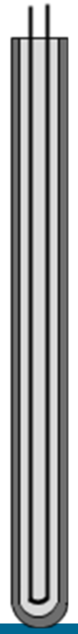
- Using the thermal quadrupoles approach
- Models a simplified effective geometry
- Enables hybrid measurement technique

4 Wire Probe Geometry

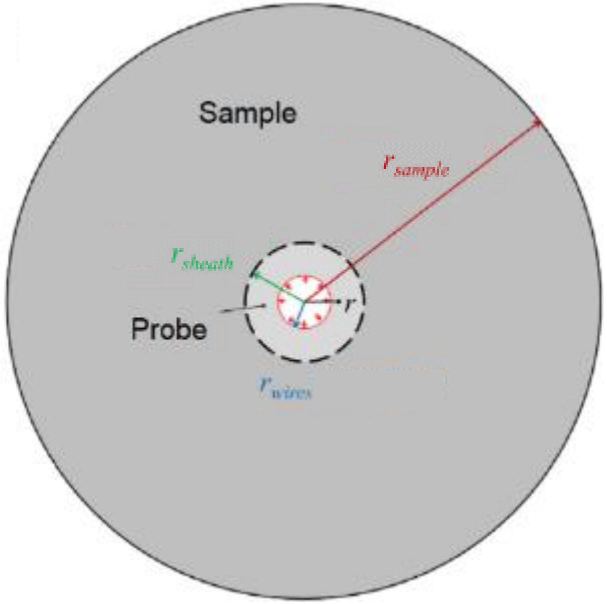


2 Wire Probe Geometry





Effective Geometry



Project Overview

Project Schedule

A. Complete transient multilayer analytical model

B. Analytical and finite element model validation using room temperature out-of-pile experimental measurements

C. High-temperature out-of-pile experimental measurements

D. Irradiation and in-pile deployment plan

Project Stage	US Fiscal year					
	21	21	22	22	23	23
Developmental	A					
Experimental			B			
Demonstration				C		
Deployment						D

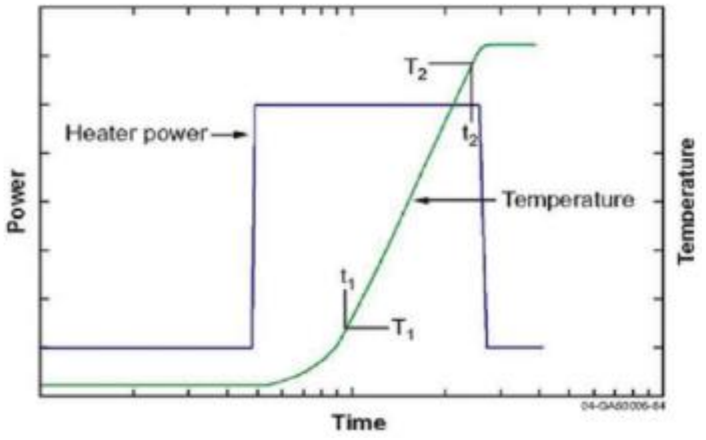
Participants

- PI: Dr. David Estrada
- GRA: Kati Wada
- INL Mentor: Dr. Austin Fleming

Technology Impact

Standard out-of-pile thermal conductivity measurements

- Loss of information

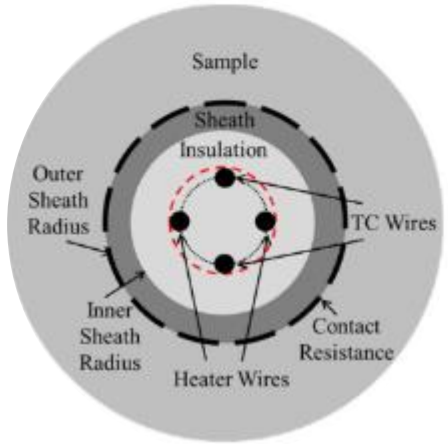


Traditional transient needle probe method

- Heater and thermocouple

Previous work at INL: Solution for when a linear response was not established

- Heater and thermocouple
- Larger package
- Crosstalk issue

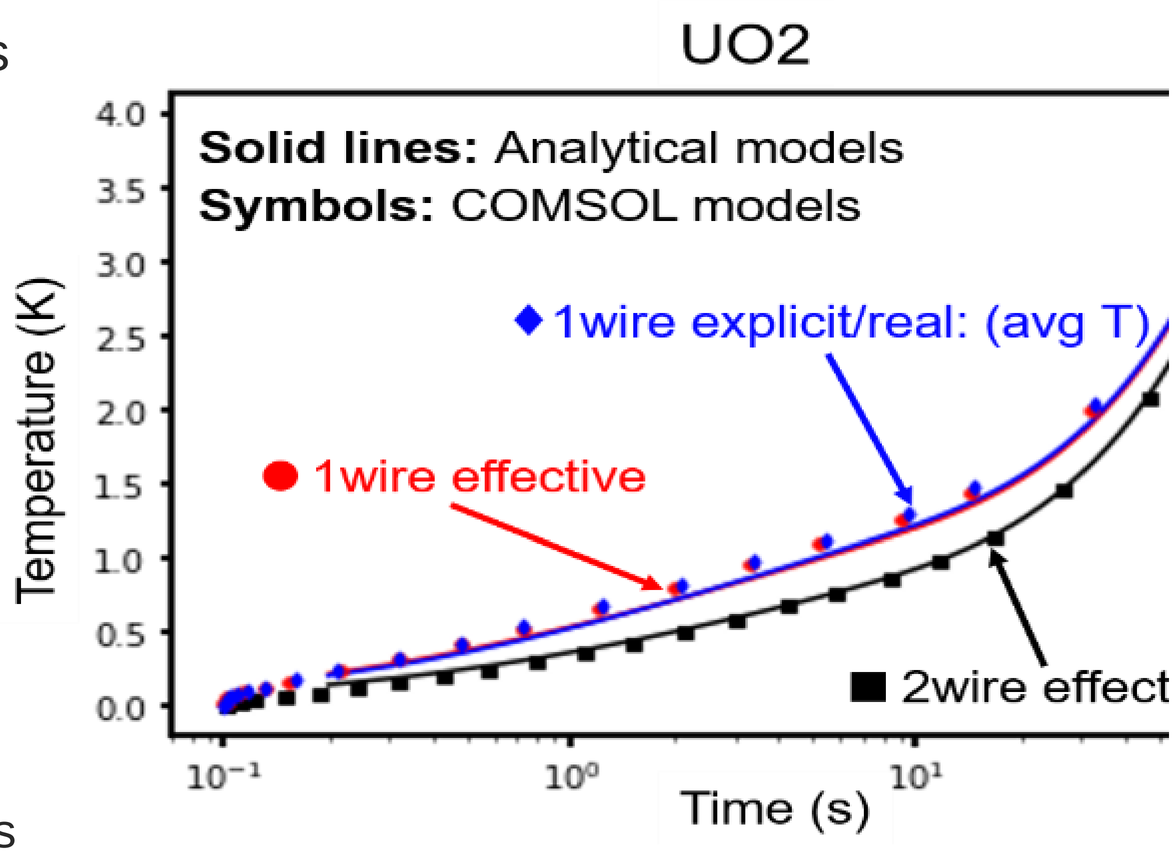


Results and accomplishments

- 2 analytical models for 2 different probe geometries
  - Effective and explicit/real models for 1-wire
  - Effective and combination models for 2-wire

- COMSOL Multiphysics FEM validation

- Type-K thermocouple chosen for measurements
  - – Modeled as a 2-wire geometry
  - – Thermocouple doesn't effect measurement
  - – Ease of use
  - – Inexpensive
  - – In the process of deriving thermal transport equations

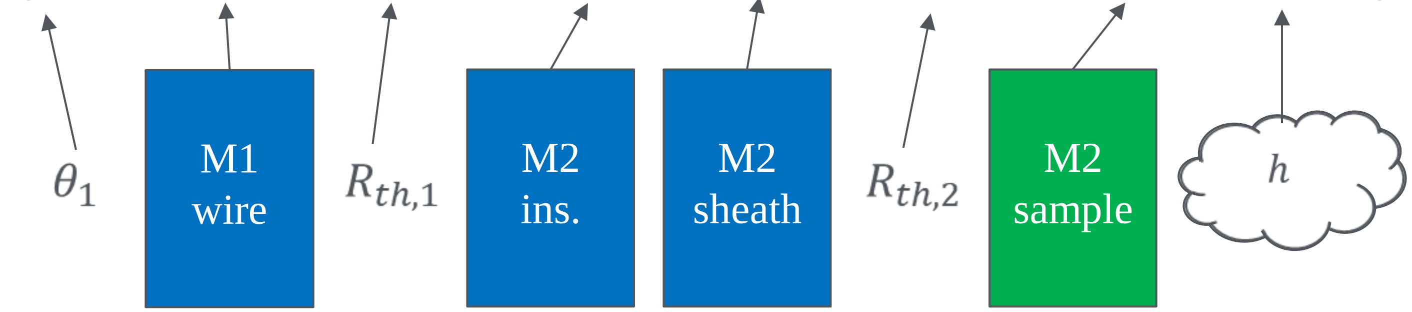


Results and accomplishments

2-Wire Combination Analytical Model

*Traditional needle probe neglects

$$\begin{bmatrix}\theta_1\\ \varphi_1\end{bmatrix} = \begin{bmatrix}A_1 & B_1\\ C_1 & D_1\end{bmatrix}\begin{bmatrix}1 & R_{th,1}\\ 0 & 1\end{bmatrix}\begin{bmatrix}A_2 & B_2\\ C_2 & D_2\end{bmatrix}\begin{bmatrix}A_3 & B_3\\ C_3 & D_3\end{bmatrix}\begin{bmatrix}1 & R_{th,2}\\ 0 & 1\end{bmatrix}\begin{bmatrix}A_4 & B_4\\ C_4 & D_4\end{bmatrix}\begin{bmatrix}1 & 0\\ h & 1\end{bmatrix}\begin{bmatrix}\theta_3\\ \varphi_3\end{bmatrix}$$



Insulation, sheath, and sample layers:

$$q_{1,i} = r_i\sqrt{p/\alpha_i}\,, q_{2,i+1} = r_{i+1}\sqrt{p/\alpha_i}$$
$$A_i = q_{2,i}\left[I_0(q_{1,i})K_1(q_{2,i}) + I_1(q_{2,i})K_0(q_{1,i})\right]$$
$$B_i = \frac{1}{2\pi kL}\left[I_0(q_{2,i})K_0(q_{1,i}) - I_0(q_{1,i})K_0(q_{2,i})\right]$$
$$C_i = 2\pi kLq_{1,i}q_{2,i}\left[I_1(q_{2,i})K_1(q_{1,i}) - I_1(q_{1,i})K_1(q_{2,i})\right]$$
$$D_i = q_{1,i}\left[I_0(q_{2,i})K_1(q_{1,i}) + I_1(q_{1,i})K_0(q_{2,i})\right]$$

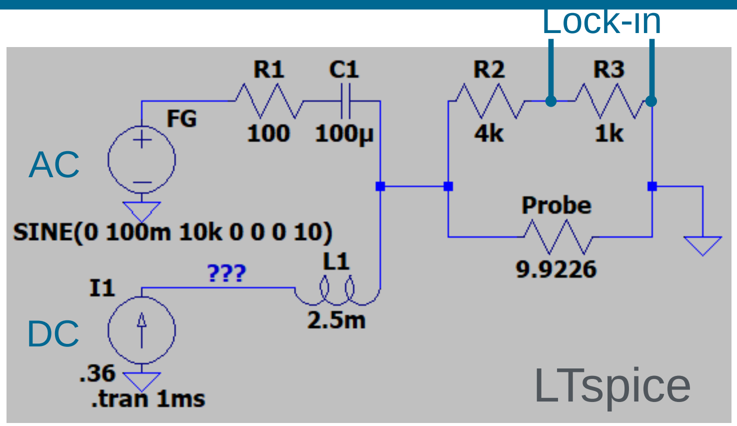
Wire layer (M1):
average temperature solution:

$$q_i = r_i\sqrt{p/\alpha_i}$$
$$A_i = 1$$
$$B_i = \frac{1}{2\pi kL}\frac{I_0(q_i)}{q_iI_1(q_i)} - \frac{1}{\rho c\pi r_i^2 Lp}$$
$$C_i = \rho c\pi r_i^2 Lp$$
$$D_i = \frac{q_i}{2}\frac{I_0(q_i)}{I_1(q_i)}$$

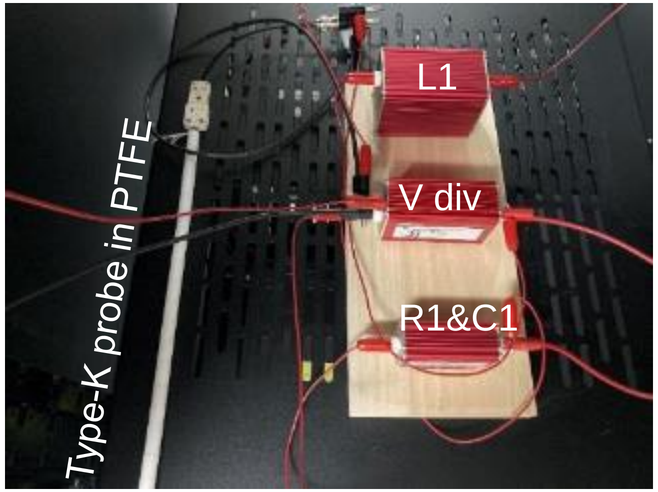
θ = Laplace temperature, φ = Laplace heat flux, R_{th} = thermal contact resistance, h = convection coefficient, index 1 = probe layer, index 2 = sample layer, α = thermal diffusivity, p = Laplace parameter, r = radius, k = thermal conductivity, L = length, I and K = modified Bessel functions, ρ = density, c = specific heat capacity

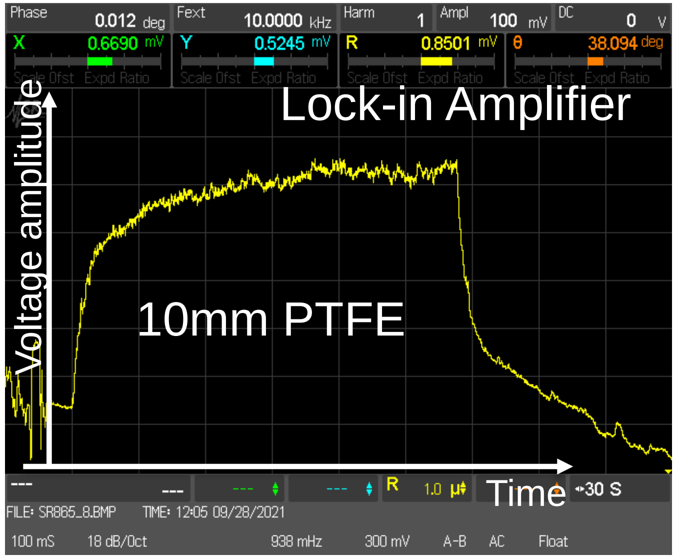
Results and accomplishments

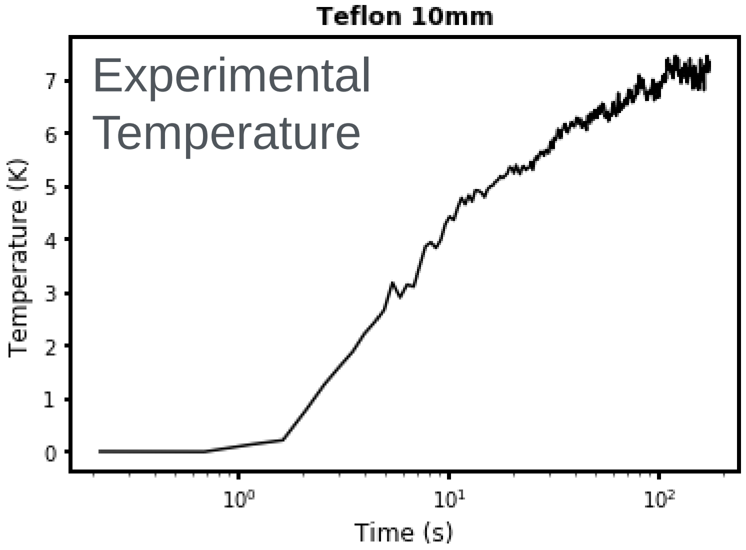
- Electronics setup (at BSU and INL)
  - Complex circuit to increase signal to noise ratio
  - Hybrid AC/DC measurement technique developed
  - Lock-in amplifier used to measure small AC signal superimposed on DC signal to induce heating



- PTFE and Al samples of varying diameters acquired and measurements started

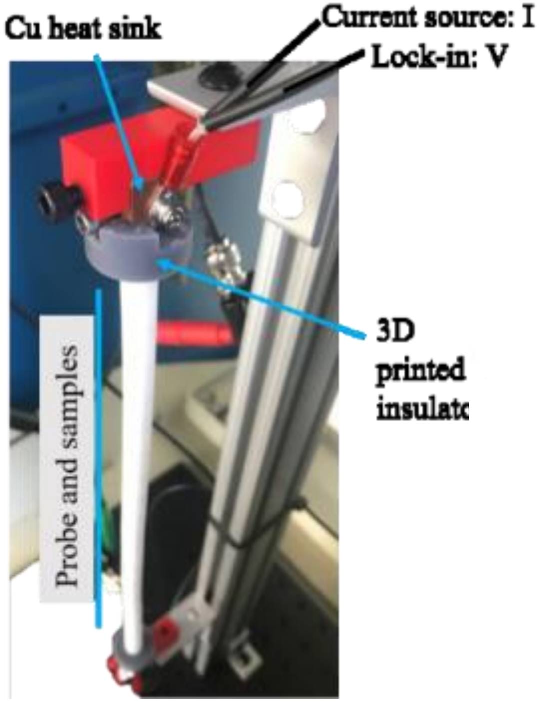


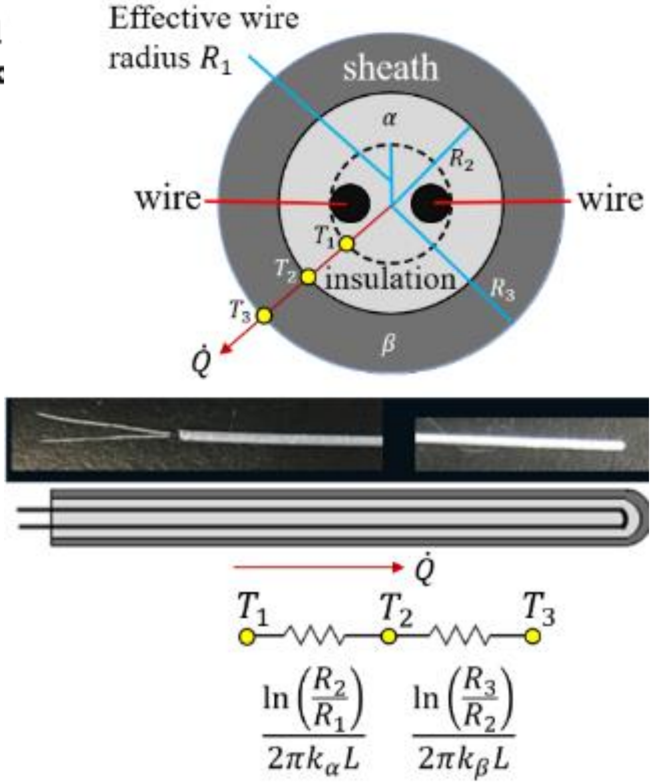




Conclusion

- Solutions identified for: cross talk and probe size
- Analytical models and FEM developed
- Experimental set-ups established
- New measurement technique
  - Hybrid technique
- Samples with a range of properties identified and procured
- New probe procured and used for measurements

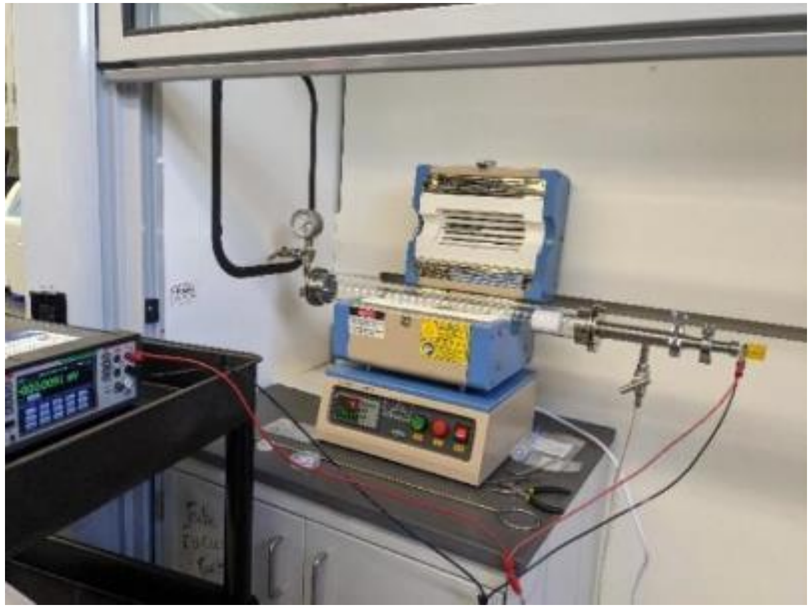




Conclusion

Next Steps

- Complete derivations of thermal transport equations
- Continue experimentation
  - Validation of analytical model with experimental results
- Publish manuscripts
  - Hybrid technique
  - High temperature results
- Further testing
  - Tube furnace



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Questions?

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High Temperature Materials for Nuclear Sensors and Instrumentation:

- High Temperature Irradiation Resistant Thermocouples

- Strain Gauges for In-Pile Applications

- Line Heat Source Probe for In-Pile Thermal Conductivity

Predictive Modeling of Nuclear Sensors and Instrumentation:

- High Temperature Irradiation Resistant Thermocouples

- Ultrasonic Waveguide Thermometer & Linear Variable Differential Transformers

CT-21IN070201, CT-21IN070203, CT-21IN070204, CT-21IN070205

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

PI: Brian J. Jaques, BSU
PI: Pattrick Calderoni, Troy Unruh, INL

Boise State University-Materials Science and Engineering
Idaho National Laboratory

High Temperature Irradiation Resistant Thermocouple(HTIR-TC) Modeling

Contract DE-AC07-05ID14517

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Associate Professor & CAES Fellow: Lan Li, PhD

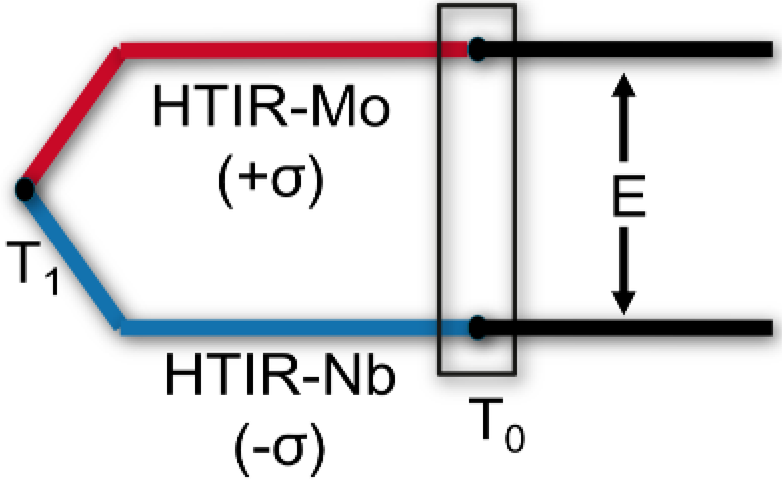
Micron School of Materials Science and Engineering, Boise State University, Boise, ID

Center for Advanced Energy Studies (CAES), Idaho Falls, ID

Project Overview

Intro to HTIR-TCs

High Temperature Irradiation Resistant Thermocouples (HTIR-TCs)[1]



- The Seebeck Effect: Two metals with different Seebeck coefficients (σ) will produce a voltage, *E*, proportional to the temperature difference (T_1-T_0).
- Seebeck coefficients (σ): A measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across a material[2]

$$\boxed{E} = \int_{T_0}^{T_1} (\sigma_+ - \sigma_-) dT$$

Voltage = performance

[1] https://www.inl.gov/article/computational-physics-student-gets-hands-on-experience-during-inl-internship/
[2] Seebeck coefficient - Wikipedia

Project Overview

Research Scope: Improve the reliability of HTIR-TCs across a wider range of target operational parameters through a combination of computational modeling and experiments

FY21 Deliverables:

- Simulate HTIR-TC performance under relevant nuclear environments
- Simulate water diffusion in Mo and Nb sheaths at different temperatures

Participants:

Comp: Dr. Lan Li
MSE, BSU

Comp: Dr. Ember Sikorski
Former PhD Student, MSE, BSU
(Now) Postdoc, Sandia National Laboratory

Exp: Dr. Richard Skifton
High Temperature Test Laboratory, INL

Exp: Dr. Brian Jaques
MSE, BSU

Technology Impact

Where does it operate?

Computing Facilities Support:

- This research made use of the resources of the High-Performance Computing Center at INL, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No.DE-AC07-05ID14517
- Further computational resources were provided by the R2 cluster (DOI: 10.18122/B2S41H) provided by Boise State University's Research Computing Department

Who should be interested in this technology?

People in various fields, including sensors and instrumentation (specifically temperature sensors), computational materials and engineering.

How does the technology support the nuclear energy industry?

- Advance an understanding of HTIR-TCs performance under different nuclear environments
- Improve the reliability of HTIR-TCs across a wider range of target operational parameters

Results and accomplishments

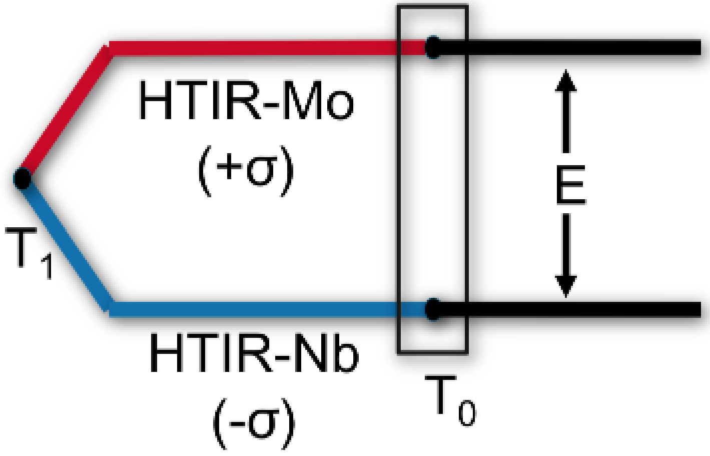
FY21 Accomplishments

- Completed FY21 deliverables
- Paper, entitled “Combined Experiment and First-Principles Study of In-Pile Temperature Sensor Materials,” received reviews. Will revise and resubmit the paper
- Ember Sikorski was awarded Ph.D. in Materials Science and Engineering. Her dissertation was entitled “Computational Modeling towards Accelerating Accident Tolerant Fuel Concepts and Determining In-Pile Fuel Behavior”
- Awarded CAES collaboration fund for Thermal Analysis of Nuclear Materials with Dr. Lu Cai and Dr. Tsvetoslav Pavlov at INL
- Awarded CAES Working Group Fund for organizing 2021 CAES Summer Boot Camp
- Ember Sikorski was awarded Graduate Student of the Year through the MSME at BSU, 1st Place, and Statewide 3-Minute Thesis Competition in 2021 (CAES Student of the Year in FY20, INL Summer Internships in 2018, 2019 & 2020)
- Successfully hosted 2021 CAES Virtual Summer Boot Camp in Data Science in collaboration with faculty at BSU and ISU on July 12-15, 2021

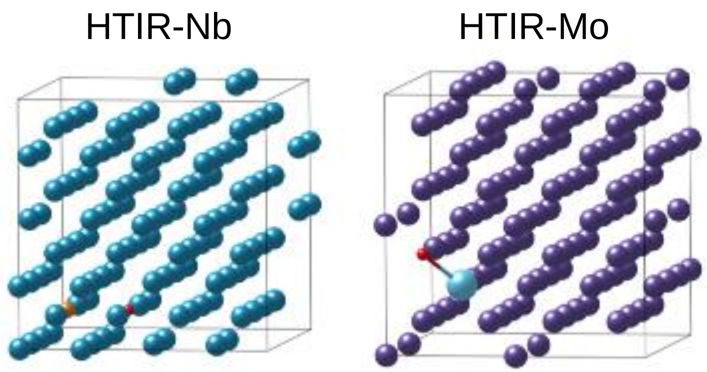
Results and accomplishments

Experiment-Computational Modeling

High Temperature Irradiation Resistant Thermocouples (HTIR-TCs)



The Seebeck Effect: Two metals with different Seebeck coefficients (σ) will produce a voltage, *E*, proportional to the temperature difference (T_1-T_0).



Boltzmann Transport Equations

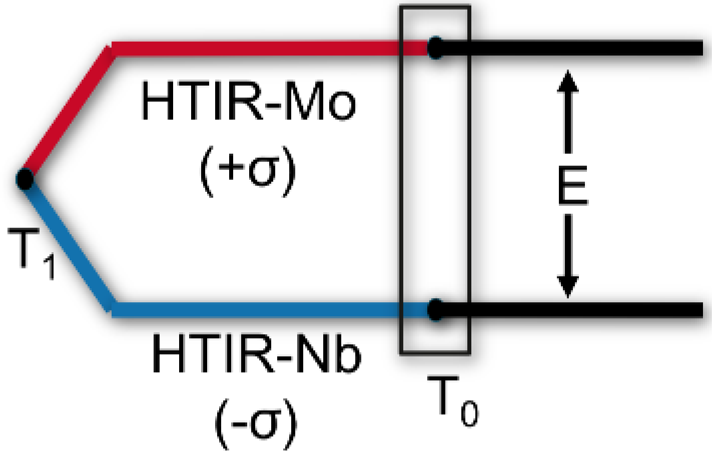
$$\boxed{E} = \int_{T_0}^{T_1} (\sigma_+ - \sigma_-)\,dT$$

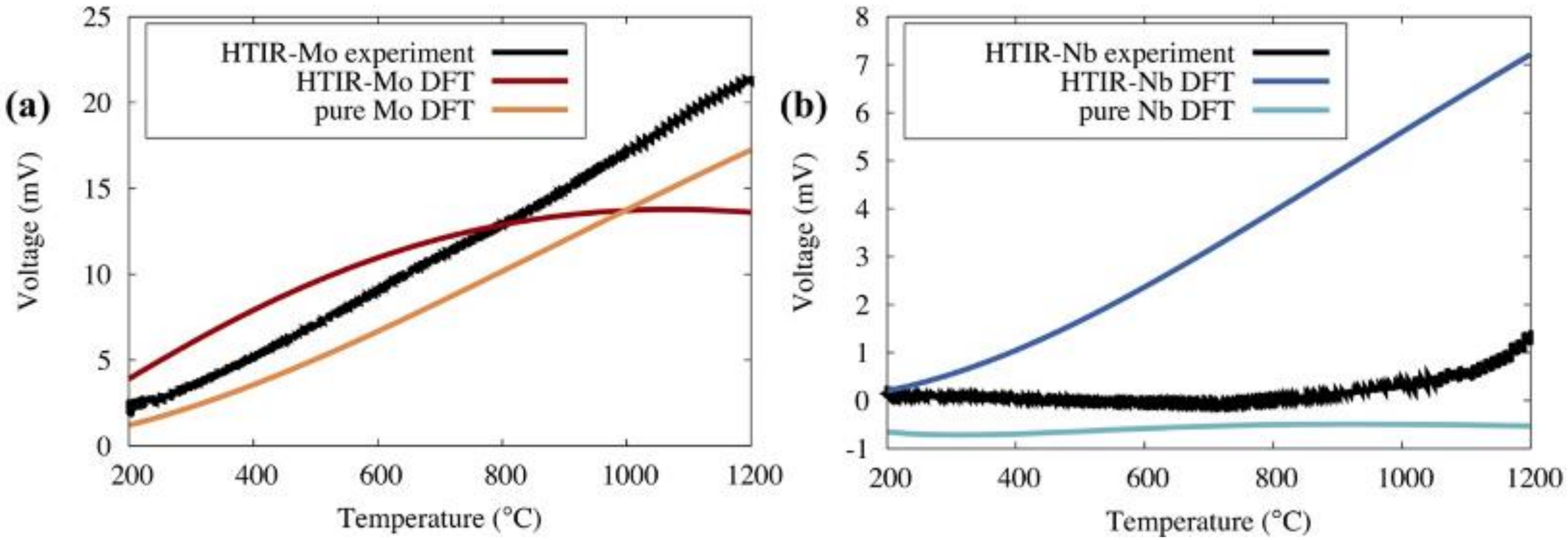
Voltage = performance

Materials / systems we have simulated: Pure Mo, Pure Nb, Mo with 0.8%La, Mo with 0.8%LaO, Mo-1%Nb, Nb with 0.8%P, Nb with 0.8%PO, Nb-1%Mo, Nb-1%Zr

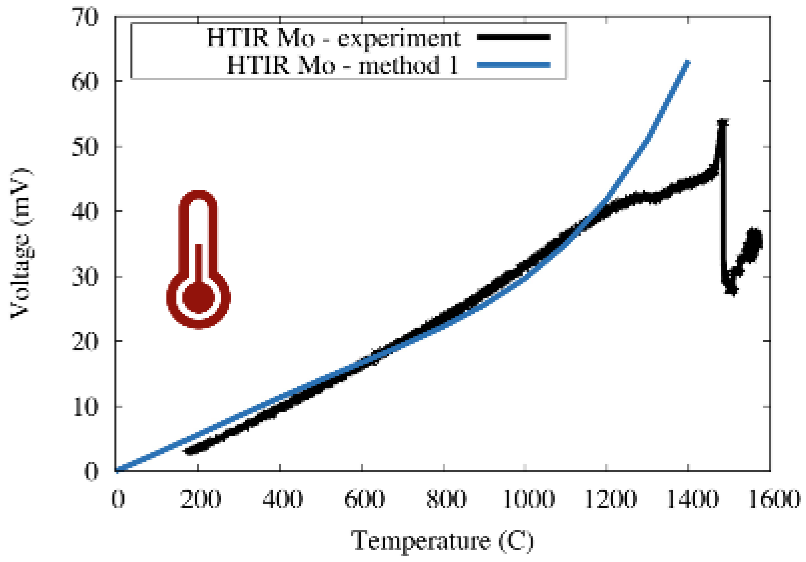
Results and accomplishments

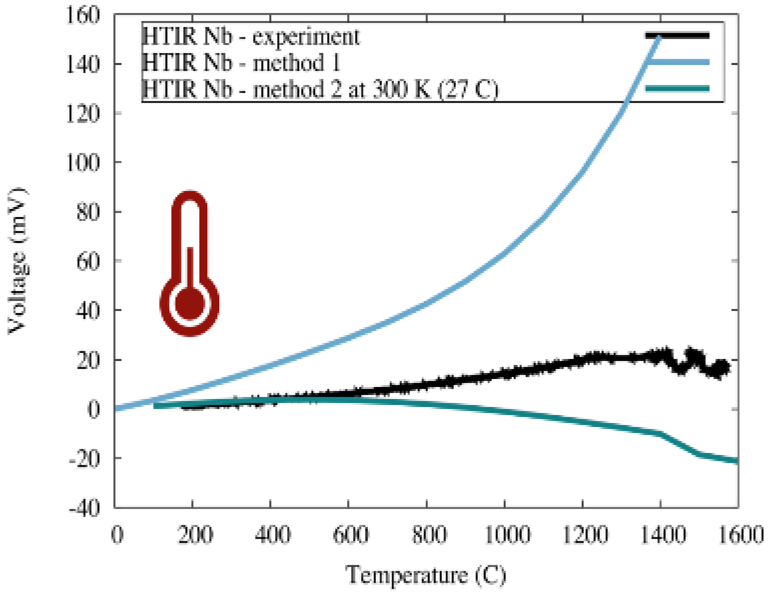
<u>Methods:</u> Density Functional Theory (DFT) + Ab-initio Molecular Dynamics (AIMD) + Boltzmann Transport Equations

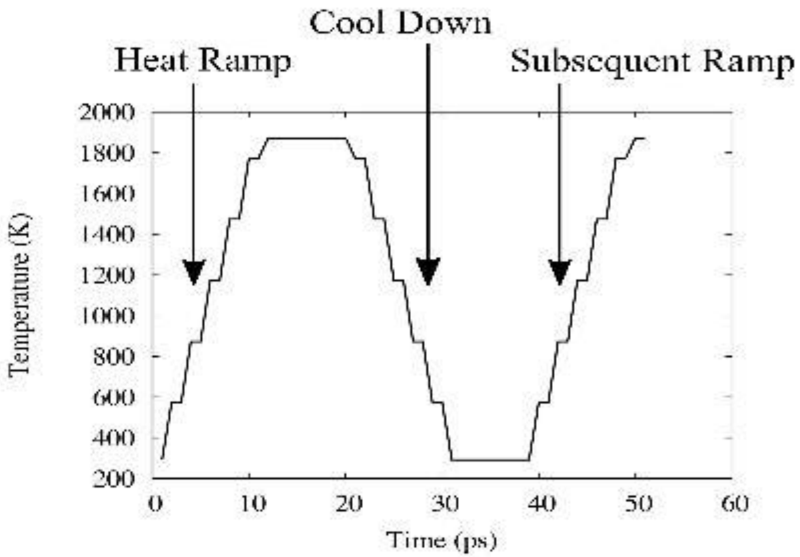




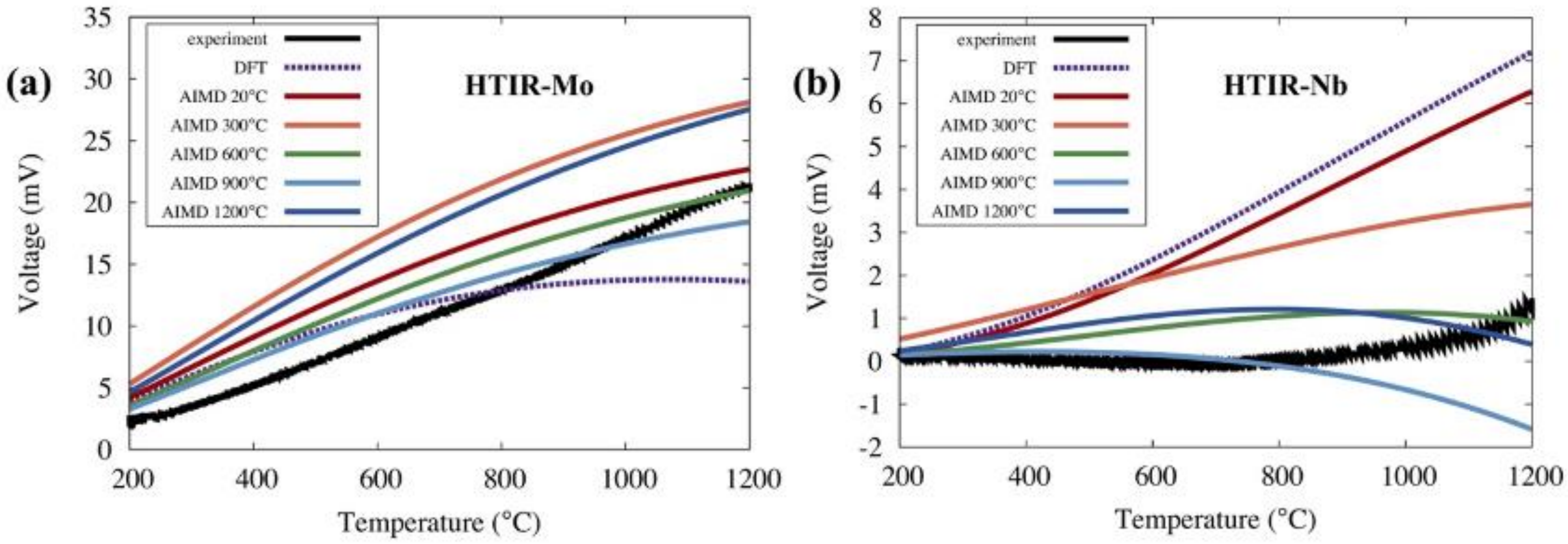
Matching Experimental Heat Treatment







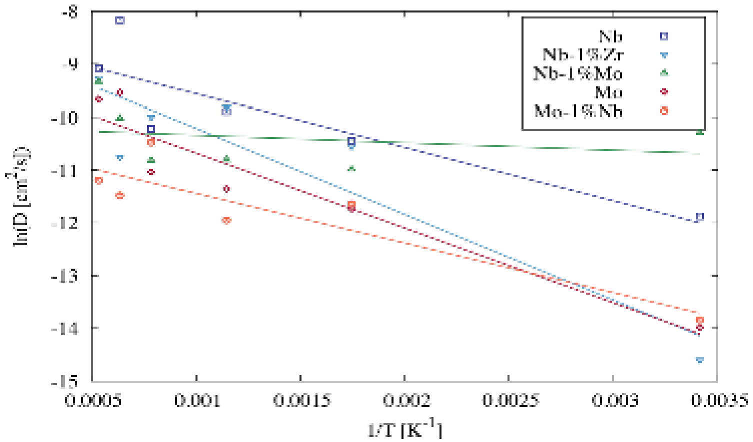
Results and accomplishments



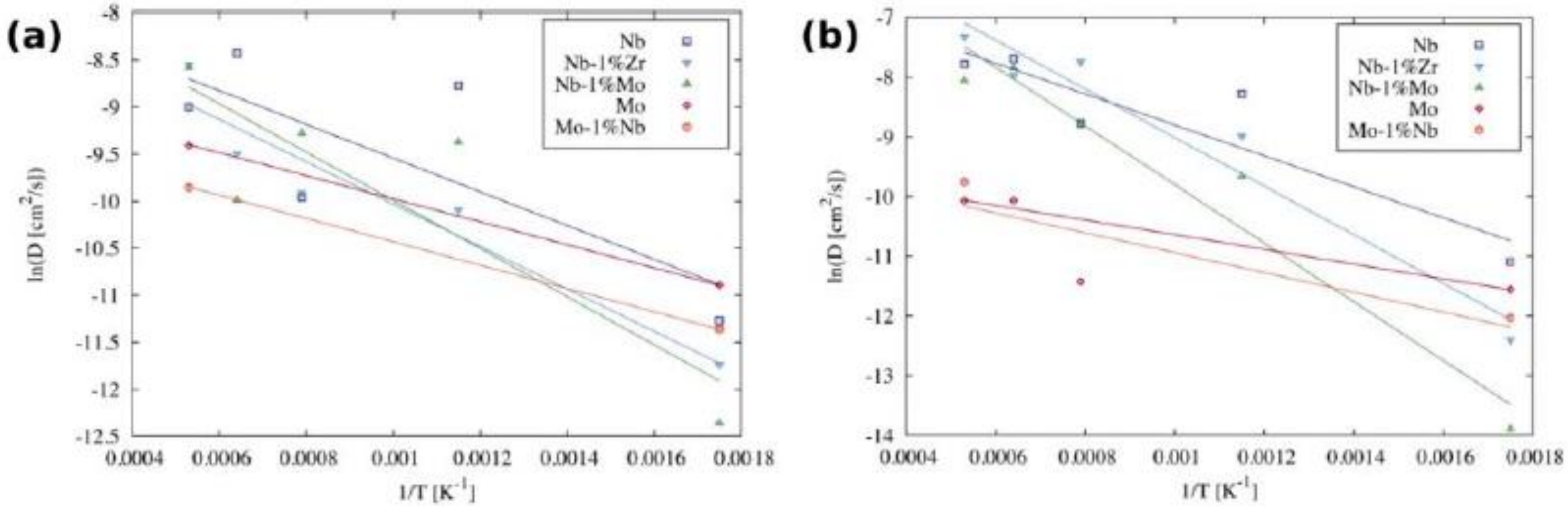
- Computational prediction suggested that the atomic structures obtained at 600 ^{0}C for HTIR-Mo and for HTIR-Nb represent the closest to the average structures of the experimental samples over the full temperature range
- Heat treatment induced structural changes that lead to a reduction in voltage occur not only at the mesoscale as previously understood but also at the atomic scale

Results and accomplishments

Corrosion/Oxidation of HTIR-Thermoelement at Desired Temperature Range (20-1600 ^{0}C)



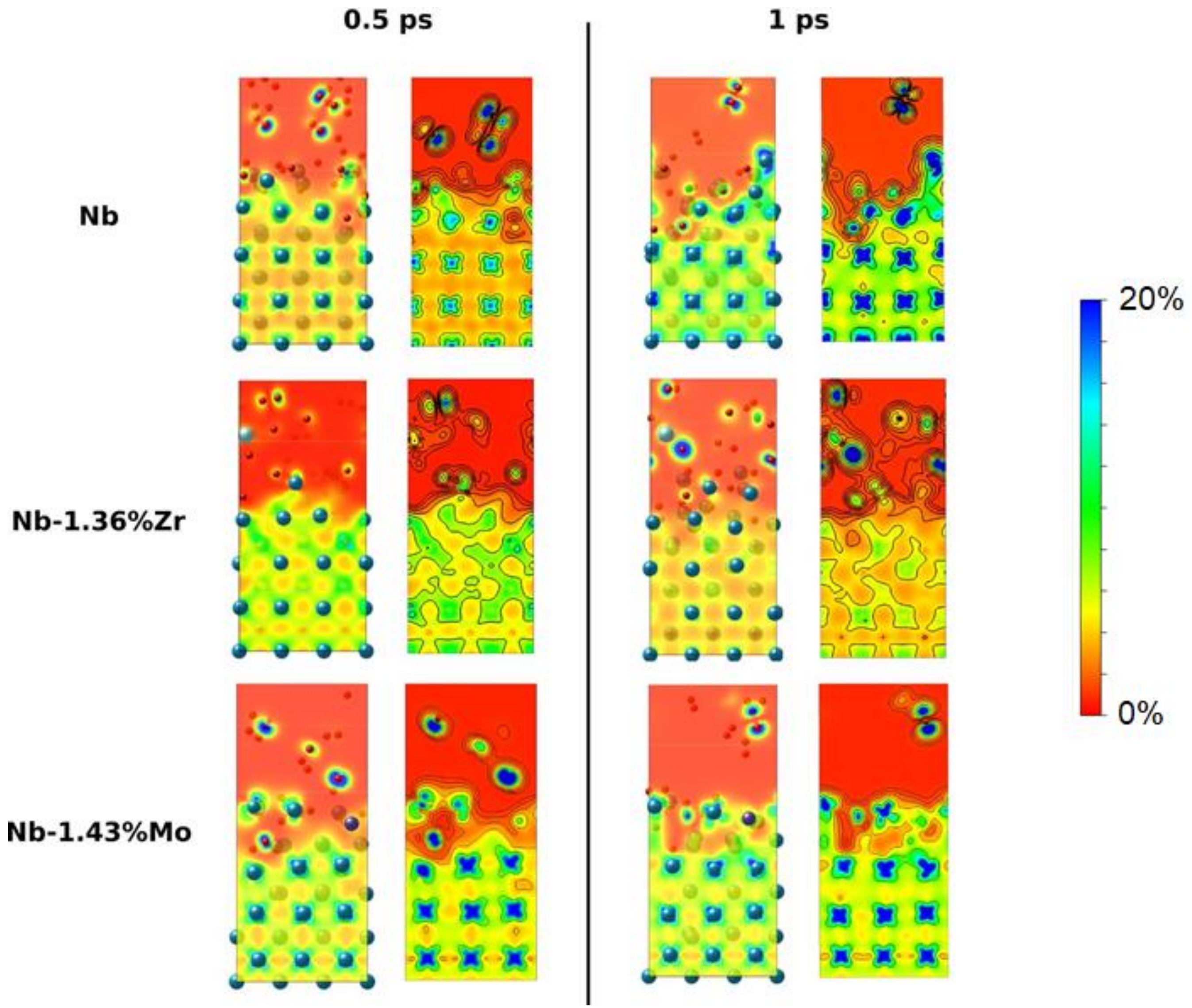
Diffusion coefficients of each surface exposed to O_2



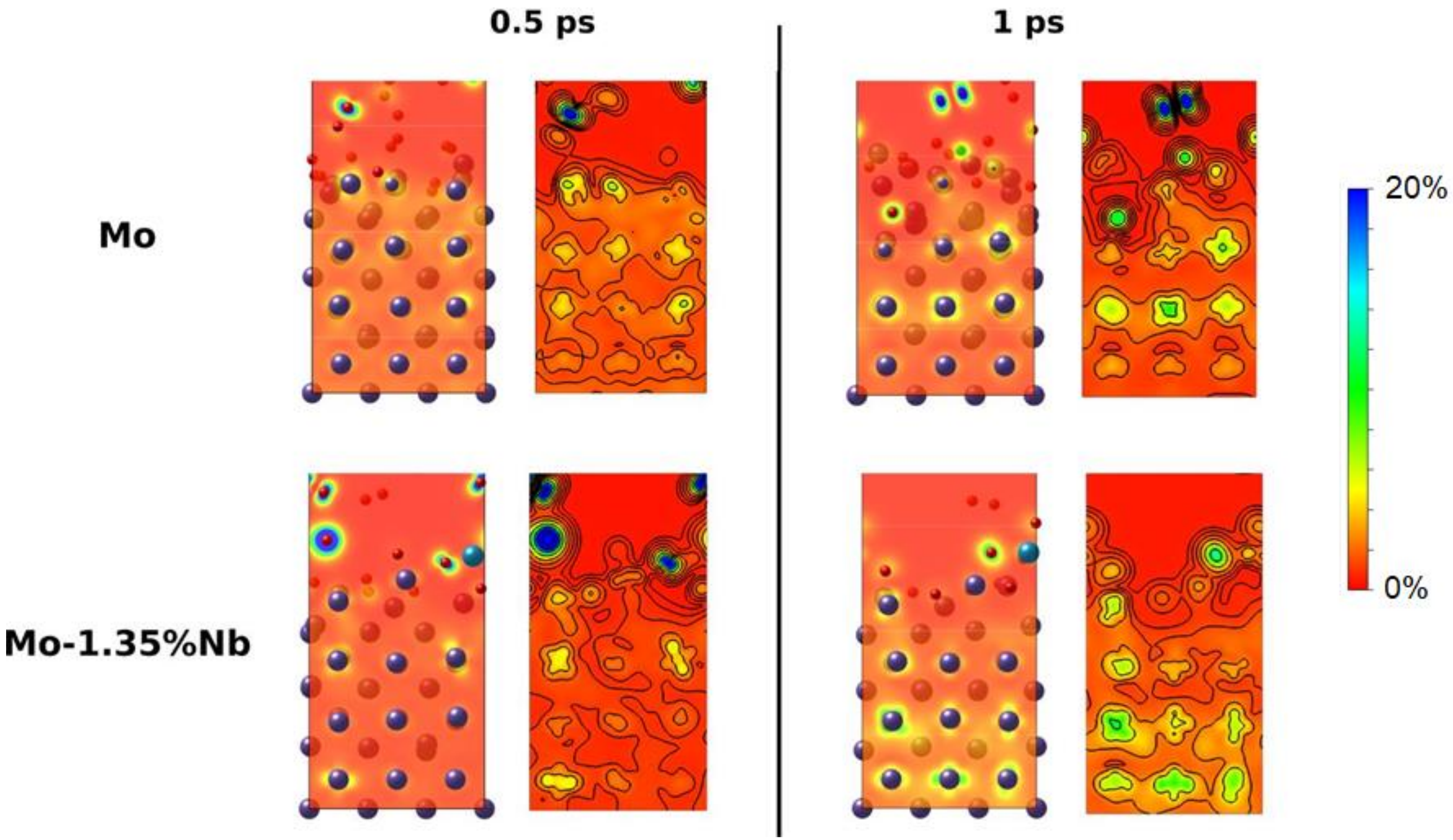
Diffusion coefficients for (a) O and (b) H after each surface is exposed to H_2O.

Results and accomplishments

- **Partial Charge Densities (PCDs)** of metal surfaces under O_2 after 0.5 and 1 ps at 1600 ° C
- The scale has been narrowed to 20% of the total electronic states to improve the visibility of bonds
- Contour lines indicate areas with the same energy and are consistent across structures
- Blue and red indicate many and no electronic states, respectively



Results and accomplishments



Conclusion

- Developed and validated an DFT-AIMD-BTE method to predict HTIR-thermoelement voltage based on composition and temperature
- Recommended Mo-1%Nb and Nb-1%Mo for best overall corrosion/oxidation resistance

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Questions?

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Ultrasonic Waveguide Thermometer & Linear Variable Differential Transformers, Modeling

Contract DE-AC07-05ID14517

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

Assistant Professor: Zhangxian (Dan) Deng

Boise State University, Mechanical and Biomedical Engineering

Technology Impact

Motivation: A total of 11 core melt accidents have occurred worldwide since 1952, including the famous Chernobyl and Fukushima disasters

Needs:

a) Develop advanced sensors for in-pile monitoring

b) Develop digital twins of advanced reactors enabling predictive maintenance

Objective: Multiphysics modeling of in-pile sensors

Ultrasonic Thermometer

Surface Acoustic Wave Thermometer

Linear Variable Differential Transformer

Project #1 Overview

Project #1: Magnetostrictive Ultrasonic Waveguide Thermometer (UT) – measure in-pile temperature through speed of sound

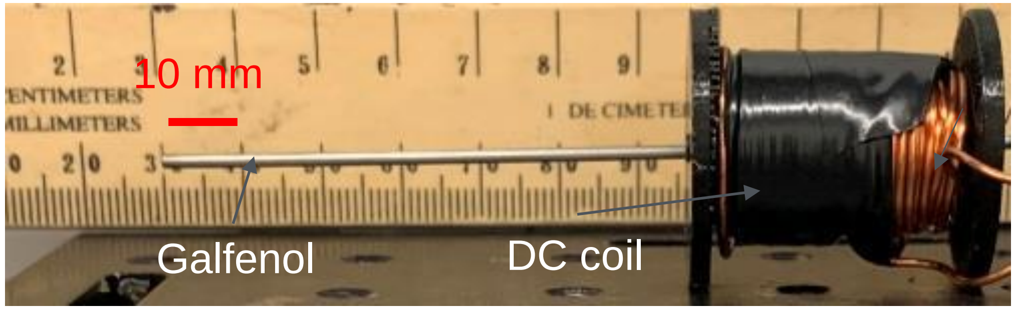
POCs: Josh Daw (INL); Zhangxian Deng (BSU)

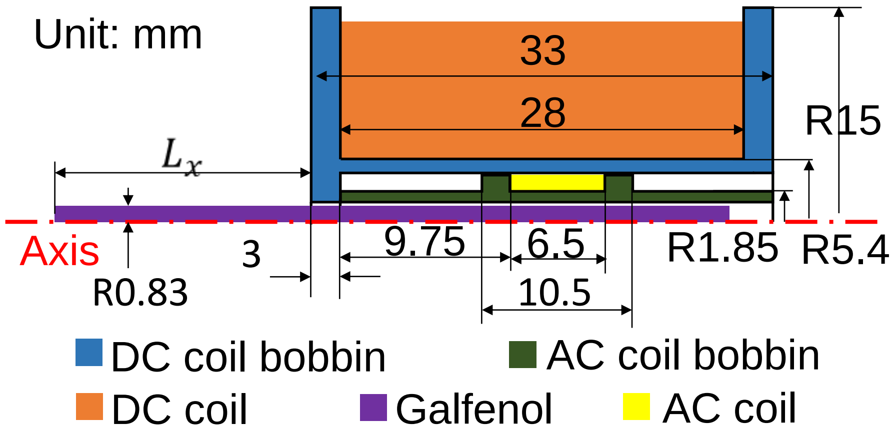
Students: Drew Keller (undergraduate); Ashton Enrriques (undergraduate)

Research Scope:

a) Enhance signal-to-noise ratio

b) Improve signal post-processing



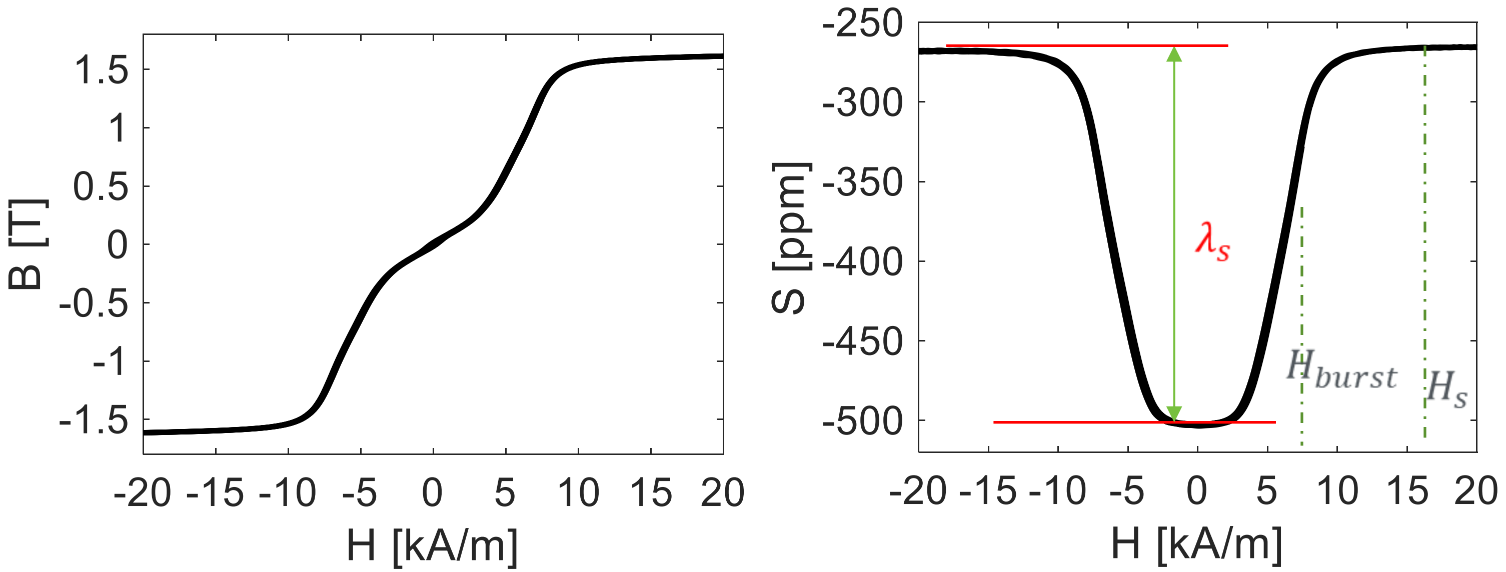


Project #1 UT: Magnetic Field

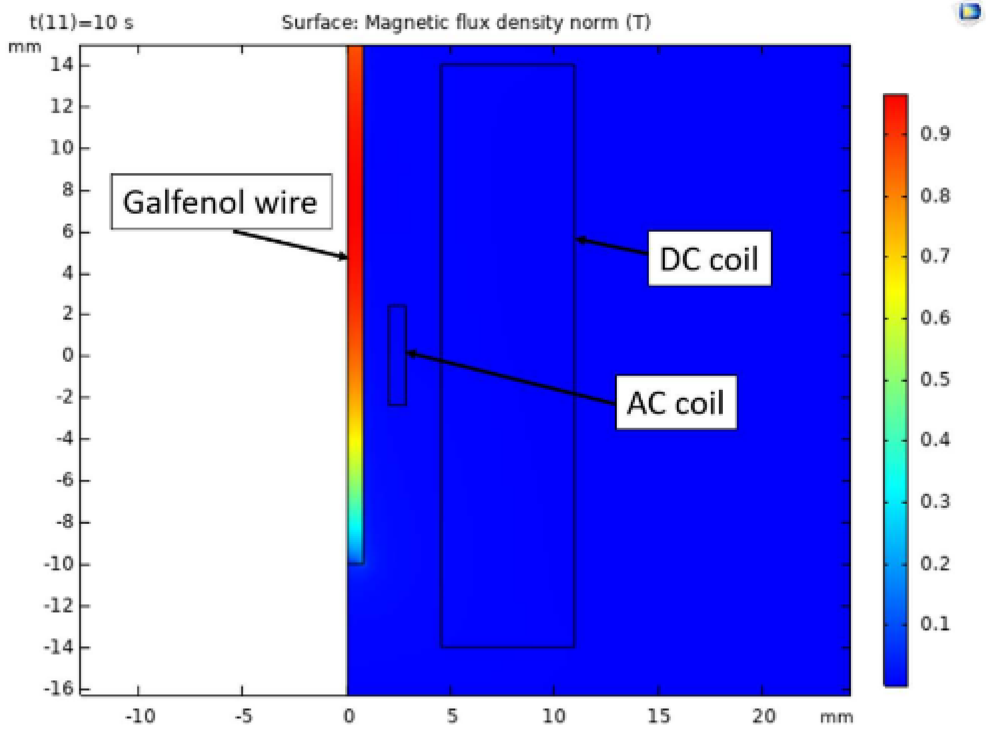
Objective: Optimize the magnetic field across the magnetostrictive waveguide to improve signal-to-noise ratio

Findings: Best configuration is to apply 1.0 A DC current through a 120-turn and 28 mm long DC coil

Characterization curves of iron-gallium alloys



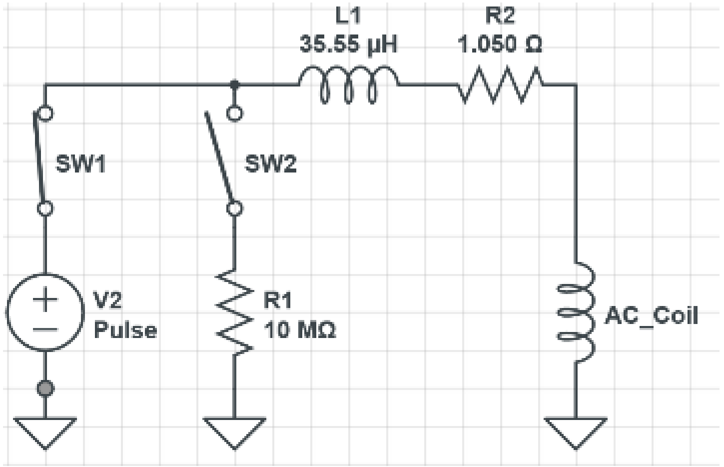
Flux density distribution at 1.0 A current



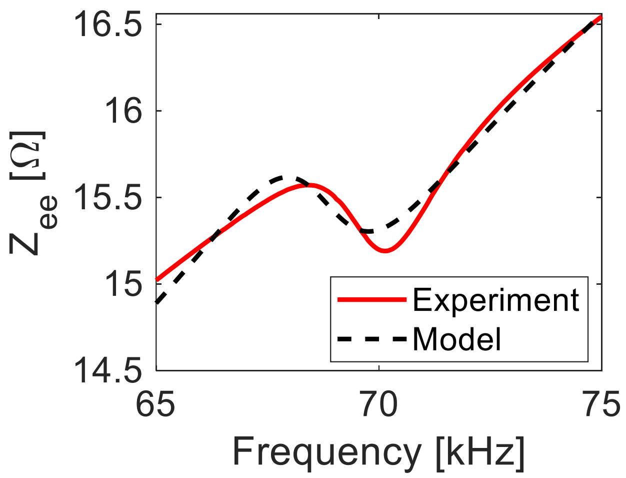
Project #1 UT: Electrical Excitation

Objective: Optimize the electrical excitation (driving frequency) to enhance signal-to-noise ratio
Method: Simulate the electrical dynamics using an equivalent electrical circuit

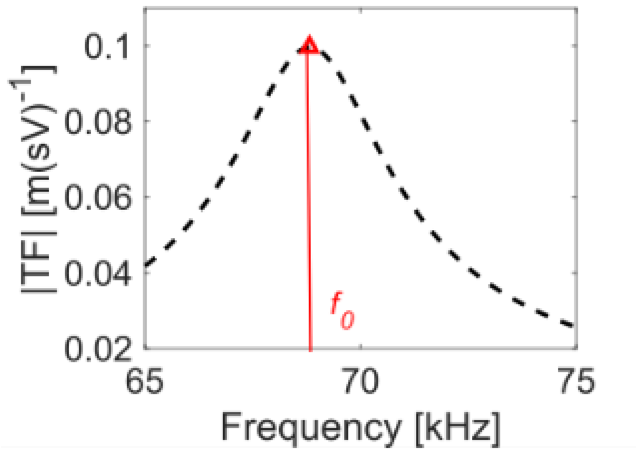
Equivalent Circuit



Electrical Impedance



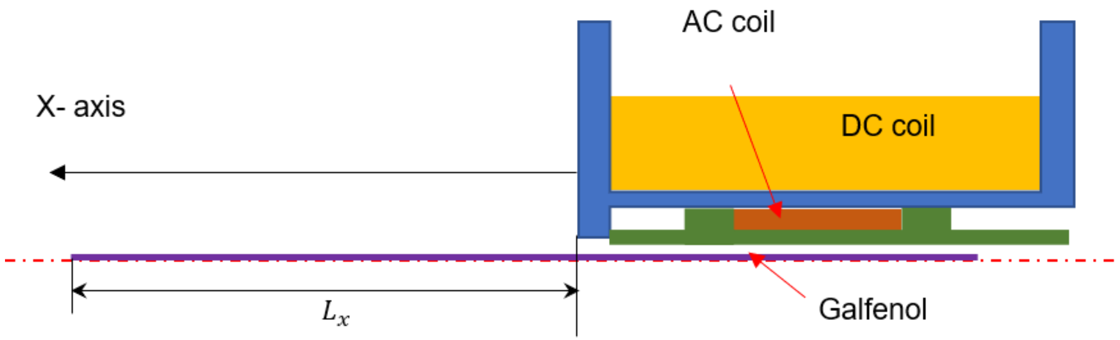
Mechanical Resonance

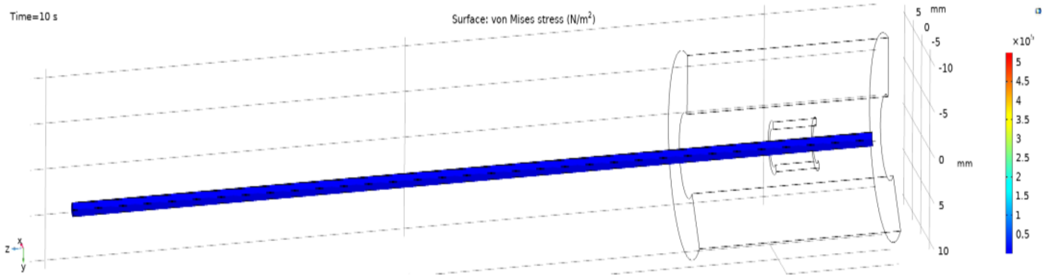


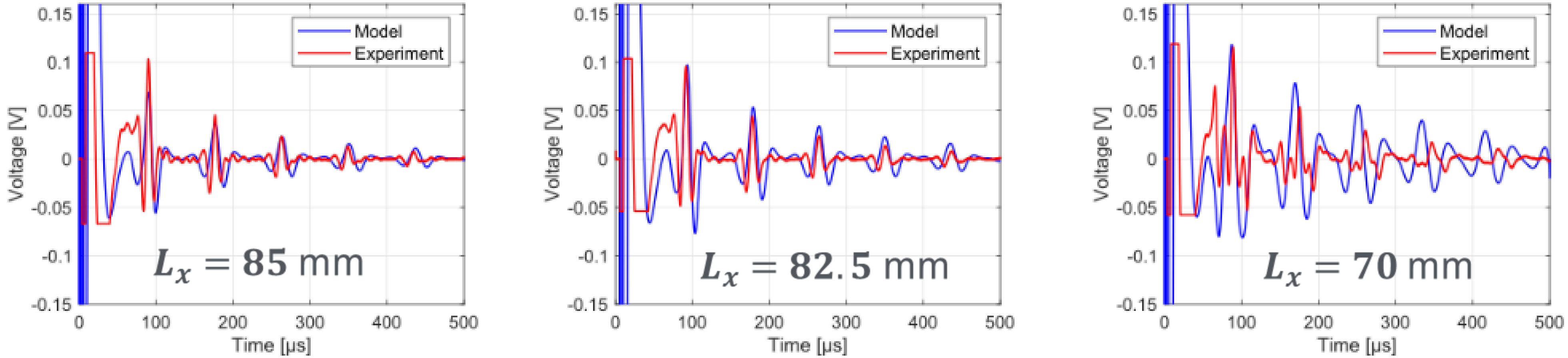
Finding: One of the optimal driving frequency is 69 kHz; this model can also predict other resonances of the system

Project #1 UT: Waveguide Location

Objective: Optimize waveguide location (L_x) to enhance measurement accuracy
Method: Simulate the UT at room temperature for different L_x values



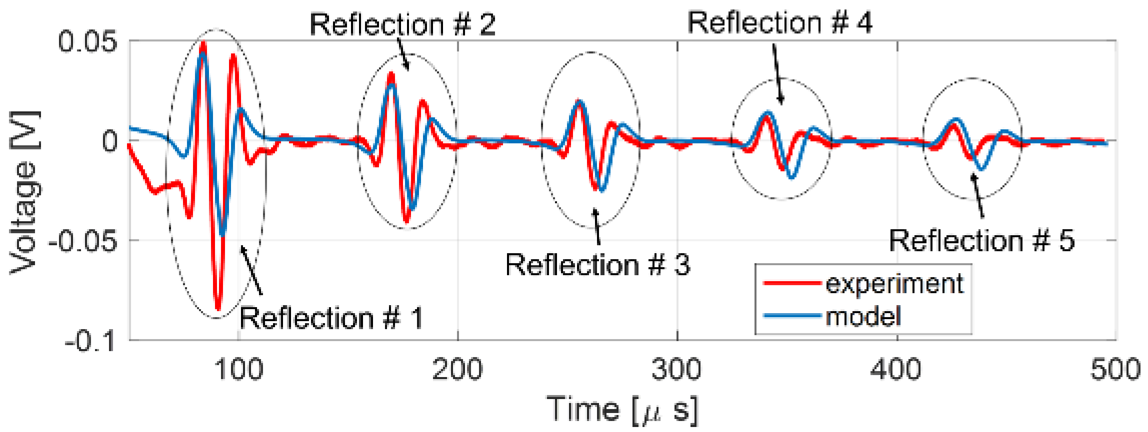


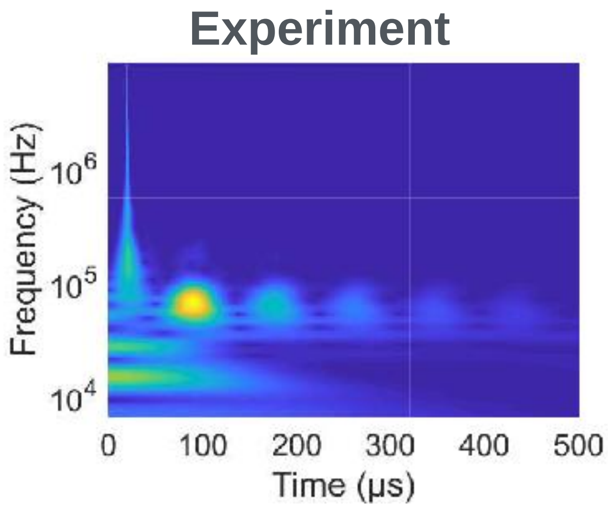


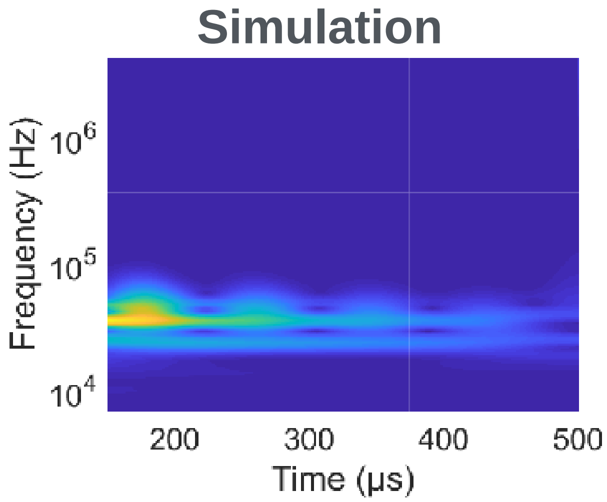
Findings: $L_x \approx 82.5$ mm returns a good balance between signal-to-noise ratio and reflection separation

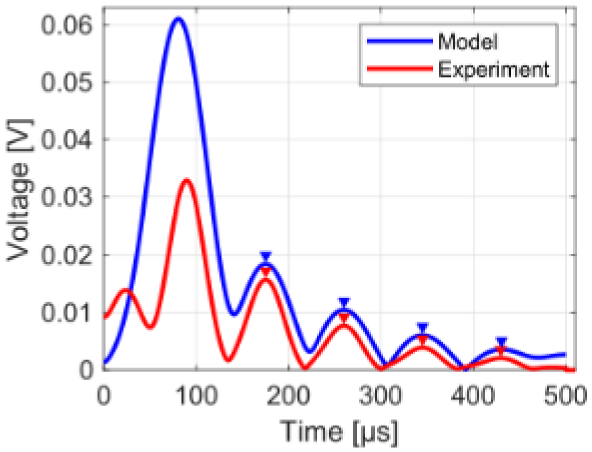
Project #1 UT: Signal Processing

Objective: Use multiphysics modeling to evaluate the signal post-processing method
Method: Use wavelet analysis to find reflection location









Findings: achieved less than 0.33% error in time-of-flight simulation

Project #2 Overview

Project #2: Surface Acoustic Wave (SAW) Thermometer – measure in-pile temperature through scattering parameters

POCs: Josh Daw (INL); Zhangxian Deng (BSU); David Estrada (BSU)

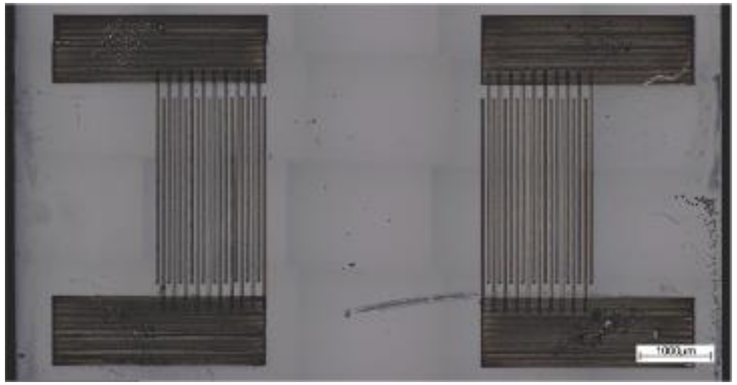
Students: Alex Draper (undergraduate); Blake Ryel (undergraduate); Nick McKibben (graduate)

Research Scope:

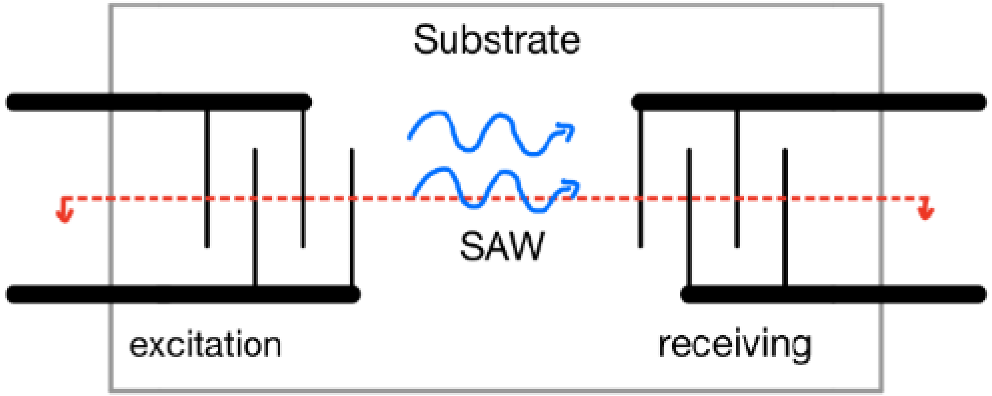
a) Enhance signal-to-noise ratio
b) Improve signal post-processing
c) Investigate temperature varying performance of SAW devices

Project #2 SAW: Model Configuration

Actual SAW Sensor



2D SAW Sensor Model

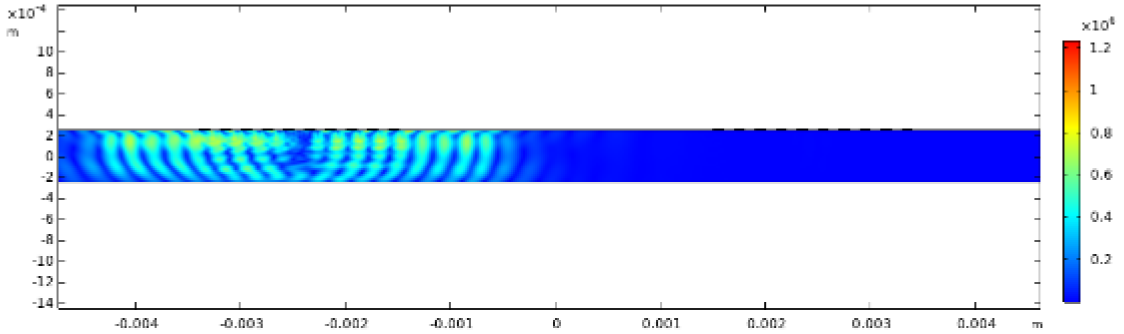


- 10 pairs of electrodes on each side
- 38-micron line width
- 38-micron line spacing
- 3 mm distance

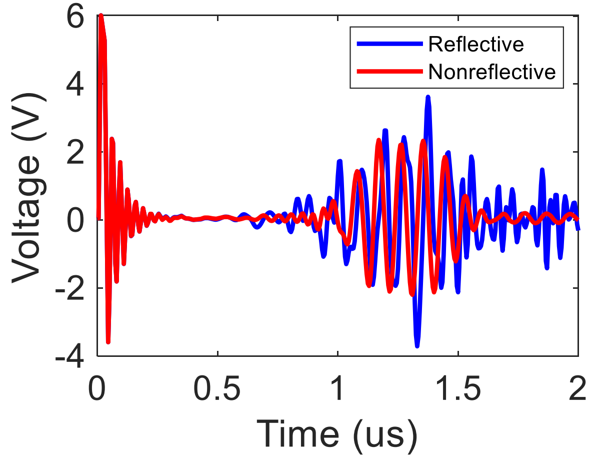
Project #2 SAW: Time-domain Simulation

Objective: Identify the noise sources in scattering parameter measurement
Findings: SAW reaches the other electrode pair between 0.75 us to 2 us; reflections from boundaries cause noise in the time-domain signal

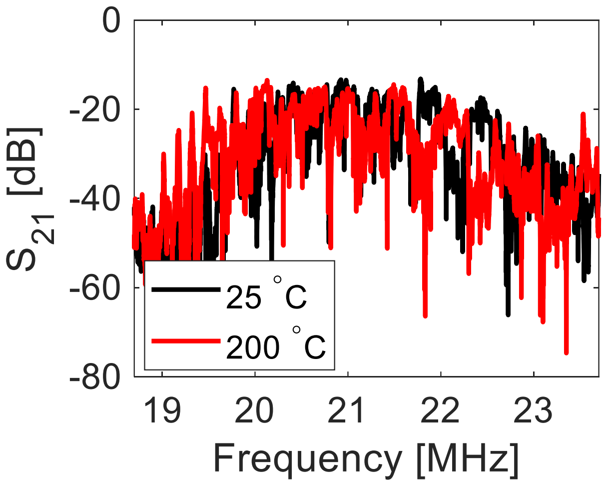
Simulated Wave Propagation



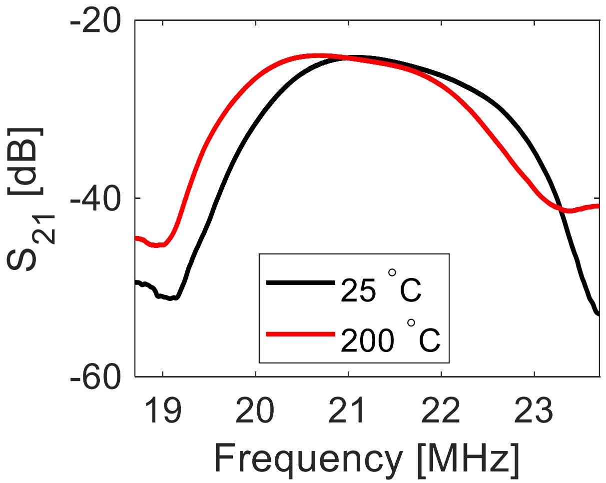
Simulated Voltage



Original Data



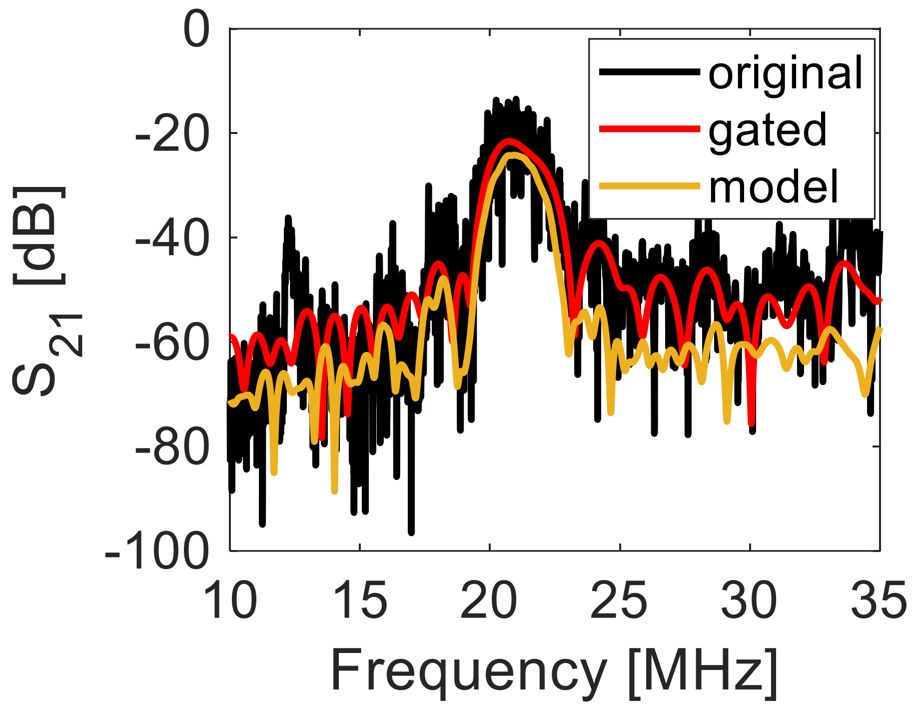
Time-gated Data



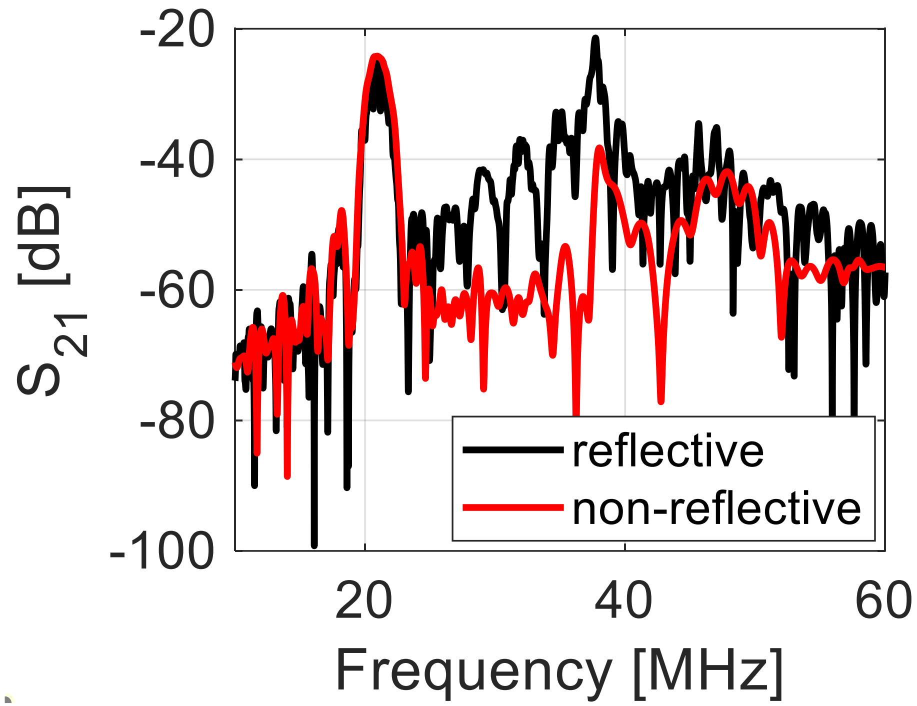
Project #2 SAW: Frequency-domain Simulation

Objective: Reproduce scattering parameters and guide SAW device development
Findings: The model accurately replicate the scattering parameter; signal processing can be improved by using time gating or reduce device boundary conditions

Experiment vs. Model



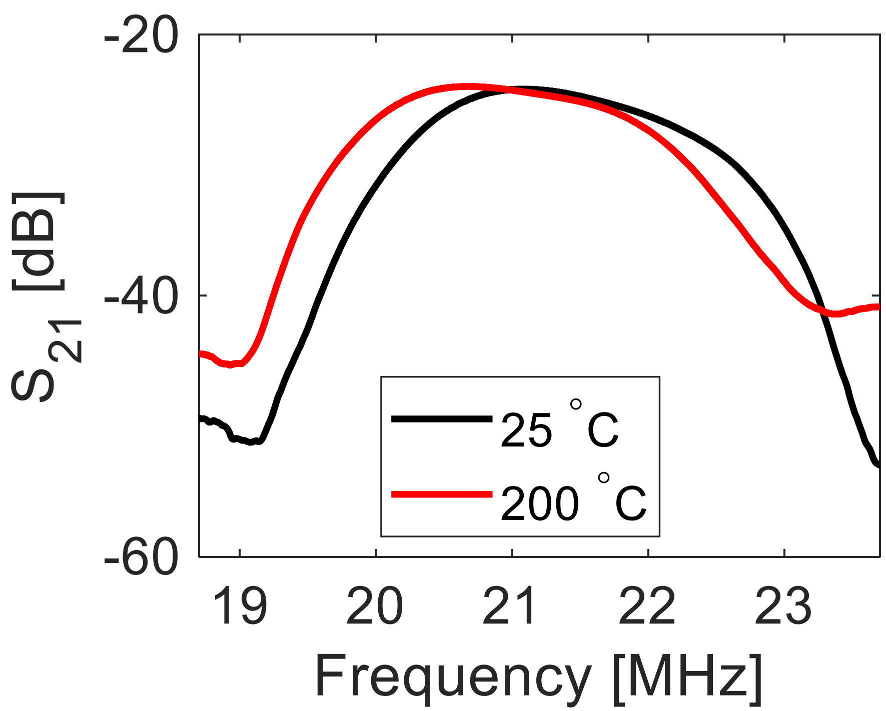
With/without Reflections



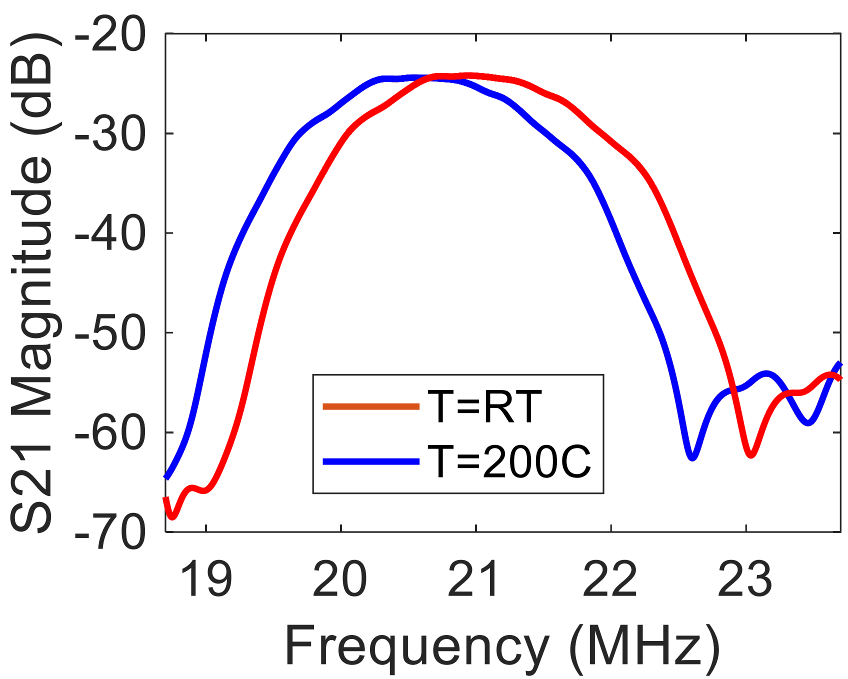
Project #2 SAW: Temperature Dependence

Objective: Predict temperature varying performance of SAW devices
Findings: The sensitivity obtained from modeling is -106 ppm/C, which is 11% higher than the nominal value (-95 ppm/C).

Experiment



Model



Project #3 Overview

Project #3: Linear Variable Differential Transformer (LVDT) – investigate the thermal drift in LVDT pressure sensors

POCs: Austin Fleming (INL); Malwina Wilding (INL); Kurt Davis (INL); Zhangxian Deng (BSU)

Students: Alex Draper (undergraduate)

Research Scope:

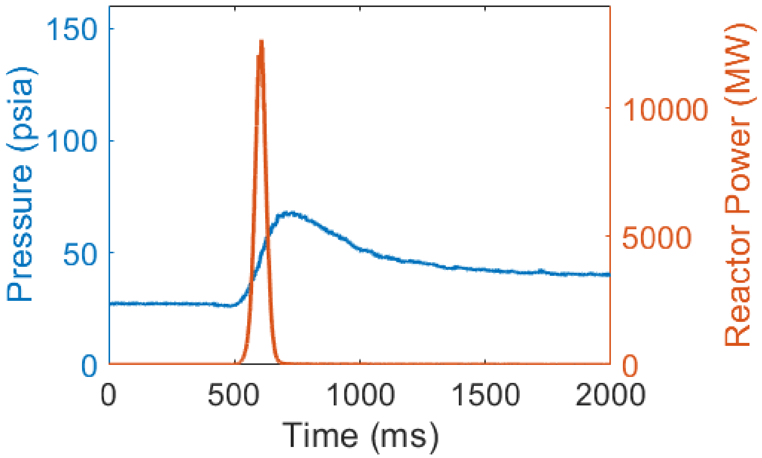
a) Reproduce the LVDT pressure sensor performance at room temperature

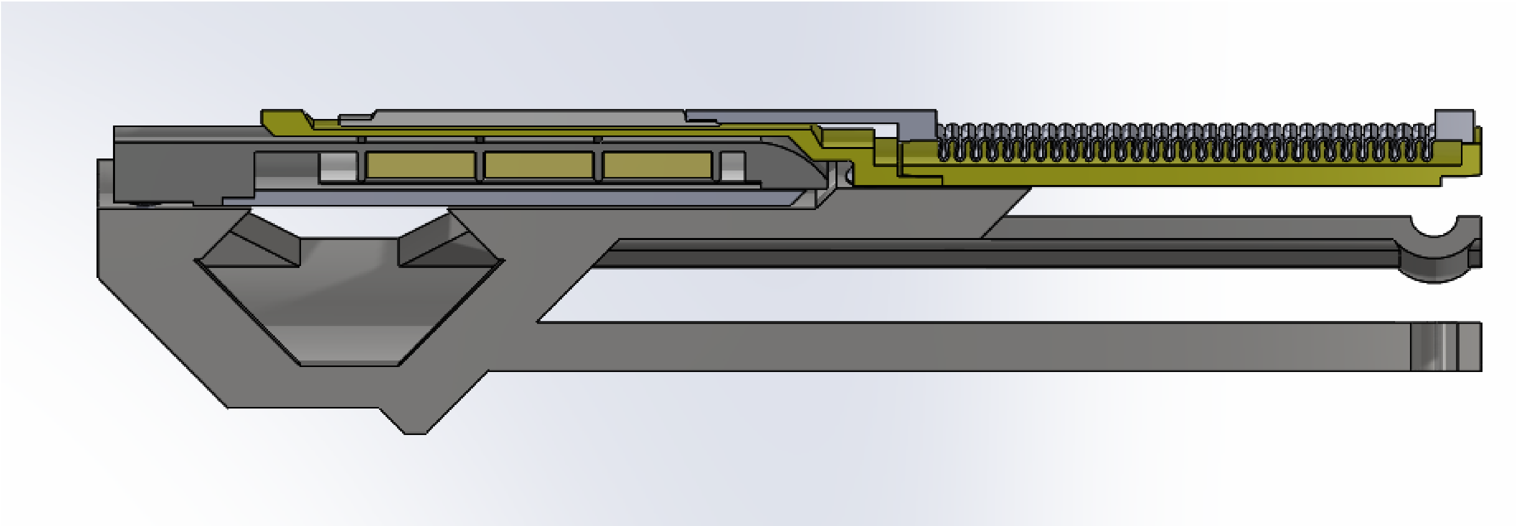
b) Investigate the thermal drift of the LVDT pressure sensor in TREAT tests

c) Explore potential improvements of current LVDTs.

Project #3 LVDT: Model Configuration

Objective: Configure a model replicating a LVDT pressure sensor tested previously in TREAT; Investigate the thermal drift observed in TREAT tests

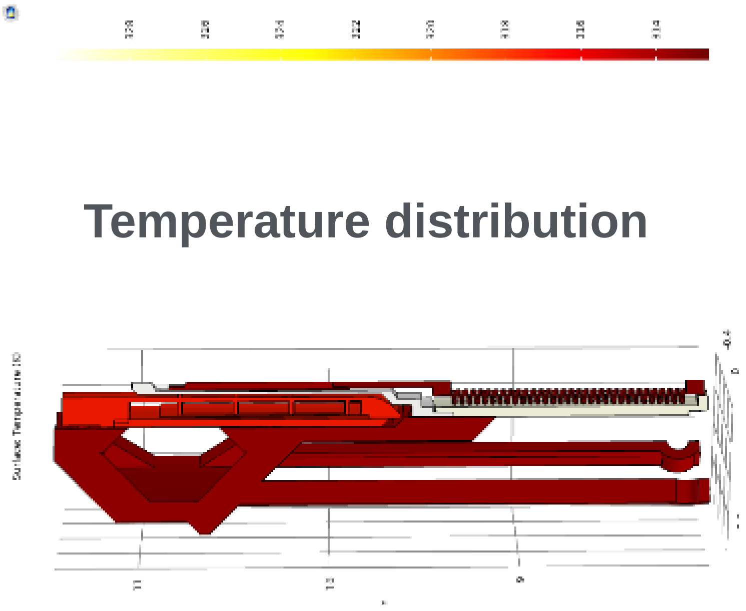




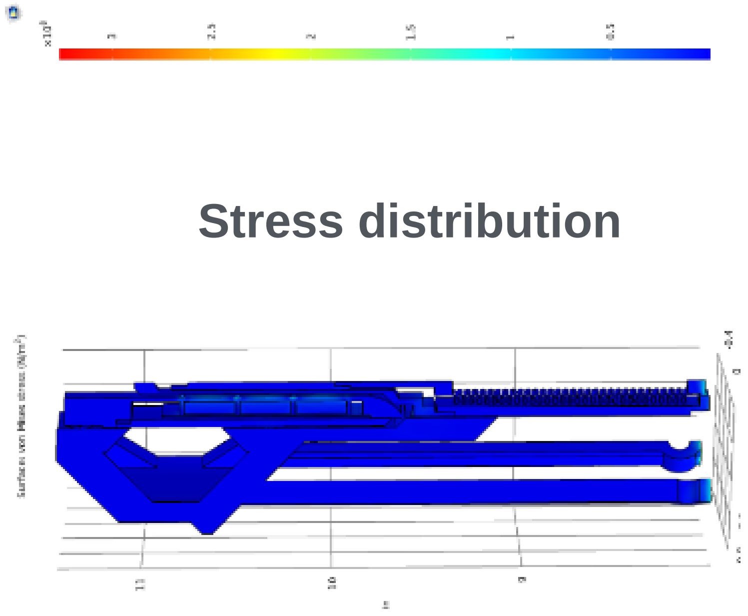
Project #3 LVDT: Thermal Drift

Objective: Predict the drift in pressure readings when the LVDT sensor is subjected to a reactor pulse

Findings: The model predicted a sensor drift of 16 psia, which is 26% higher than the drift observed in experiments (12.7 psia); a parametric study on LVDT is completed (excitation frequency and core resistivity are the key design parameters)



Temperature distribution



Stress distribution

Conclusion

Summary of Accomplishment

- Developed multiphysics models accounting for mechanical, magnetic, electrical, and/or thermal dynamics in advanced sensors and instrumentation for nuclear applications
- Used the developed model to optimize sensor performance and guide signal processing
- Enhanced the fundamental understanding of acoustic sensors and magnetic sensors

Future Work

- Incorporate temperature dependence into UT model
- Incorporate temperature dependence into LVDT model
- Use the LVDT model to design an experiment that investigates its thermal drift

Zhangxian Deng
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ORCiD: 0000-0003-1084-1738

Questions?

ASI Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

Irradiation of Optical Components of In-situ Laser Spectroscopic Sensors for Advanced Nuclear Reactor Systems

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Igor Jovanovic
University of Michigan

Project Overview

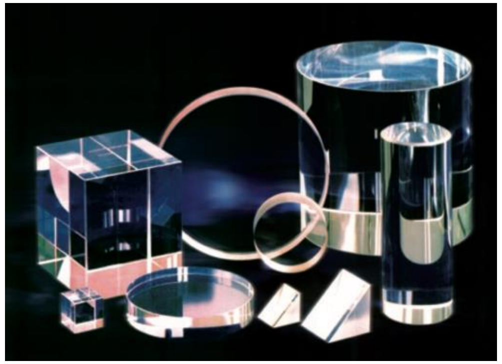
- Goal and Objective: understand the effect of radiation damage on the performance of optical spectroscopic sensors:
  (1) nonlinear refractive index; (2) transient radiation-induced absorption;
  (3) concurrent radiation damage and thermal annealing

- Participants: Igor Jovanovic, Bryan Morgan, Milos Burger (UM)
  Piyush Sabharwall (INL), Paul Marotta (MicroNuclear), Lei Cao (OSU-NRL: NSUF), Sungyeol Choi (Seoul National University – INERI)

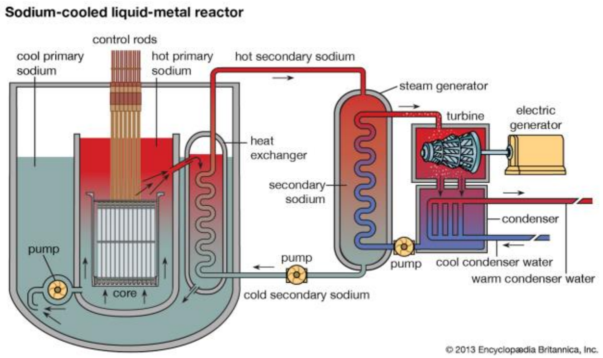
- Schedule:
  - Year 1: Procure samples; develop mobile PIE system
  - Year 2: Evaluate neutron activation; construct and test heating setup; conduct gamma irradiation with post-heating
  - Year 3: Conduct neutron irradiation with post-heating
  - Year 4: Conduct gamma and neutron irradiation with concurrent heating

Technology Impact

- Real-time, *in-situ* measurements of important operational parameters in advanced nuclear systems
- Optical instrumentation can be subjected to challenging environments: radiation, temperature, pressure, limited access
- Develop an improved understanding of radiation damage in optical materials <u>in conditions relevant for their operation in real-time optical sensors</u>
- First-ever attempt to quantify the effect of irradiation on <u>nonlinear</u> optical properties of materials
- **Cross-cutting impact: design and concept of operation for a wide range of optical instrumentation in nuclear applications**
- Integration with nuclear technology corporate partner to develop preliminary concept for deployment

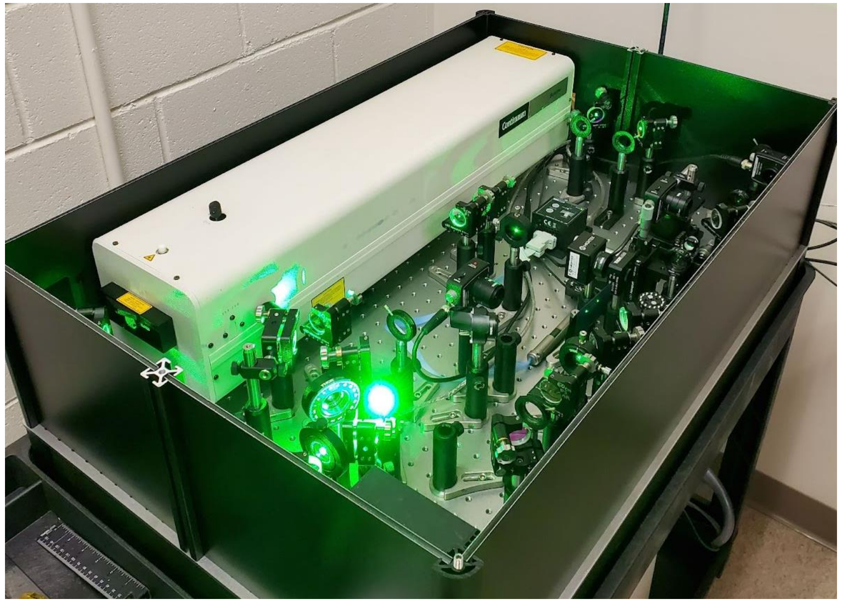


Heraeus



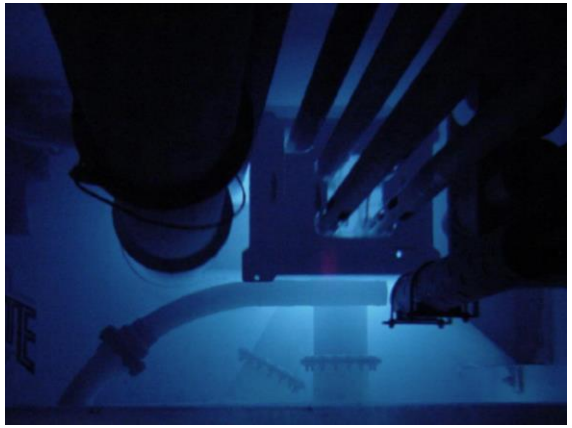
Encyclopedia Britannica

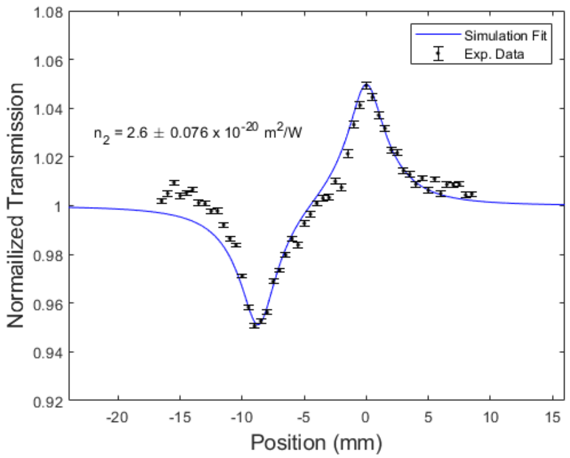
Summary of Accomplishments



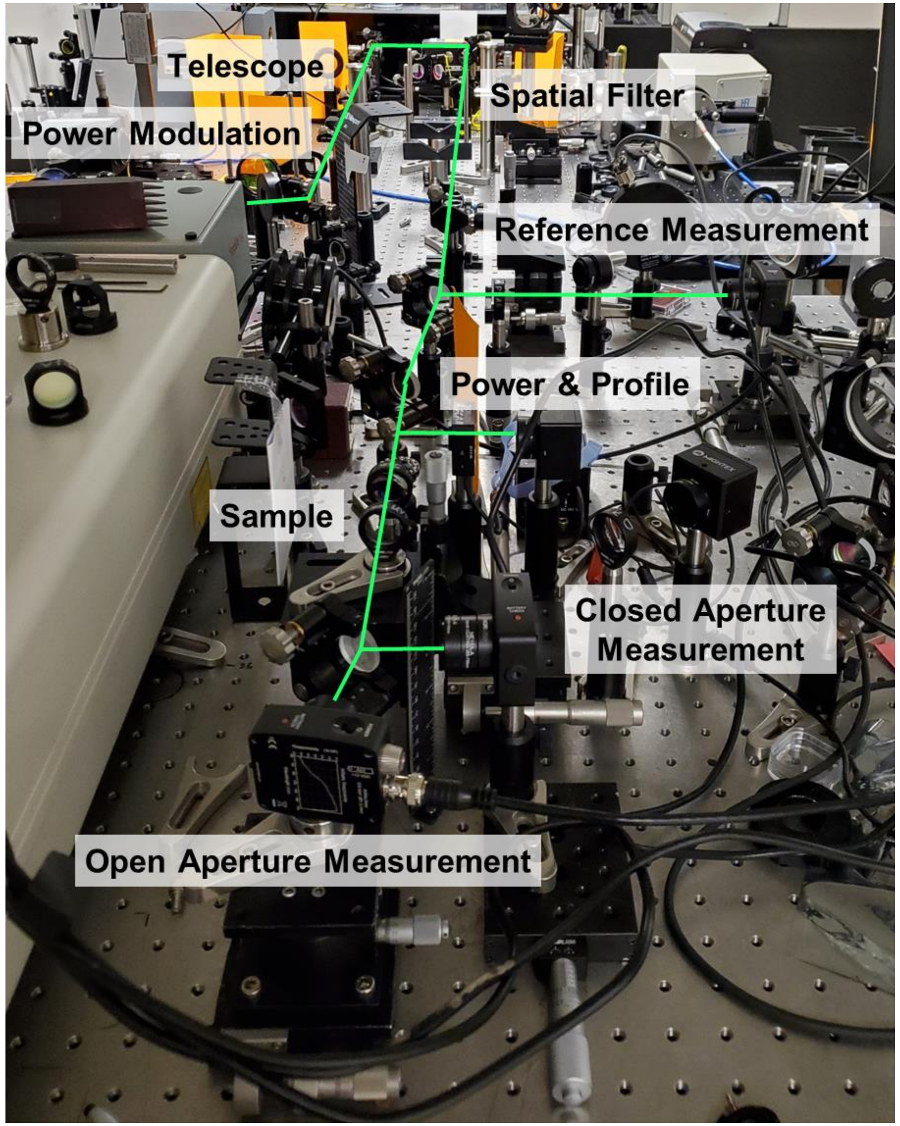
FY 2021 Accomplishments:

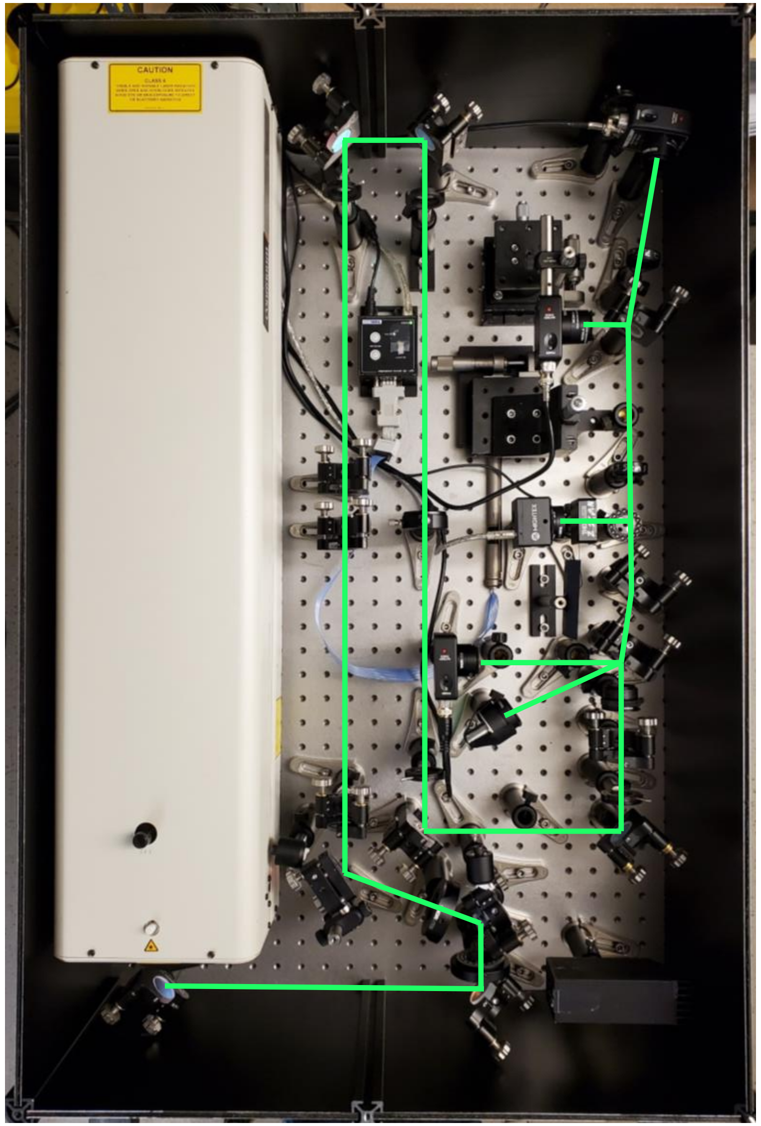
- Mobile PIE system constructed and validated
  - Z-scan
  - Linear absorption
- PIE system established and validated at OSU NRL
  - Dedicated laboratory
  - Integrated with radiation safety protocol
- Completed gamma irradiation series
  - Post-irradiation thermal annealing
  - Concurrent thermal annealing
  - Opportunity measurement (PSU) 10 Mrad irradiation
- Initiated mixed neutron/gamma irradiations
- One paper published; one more submitted





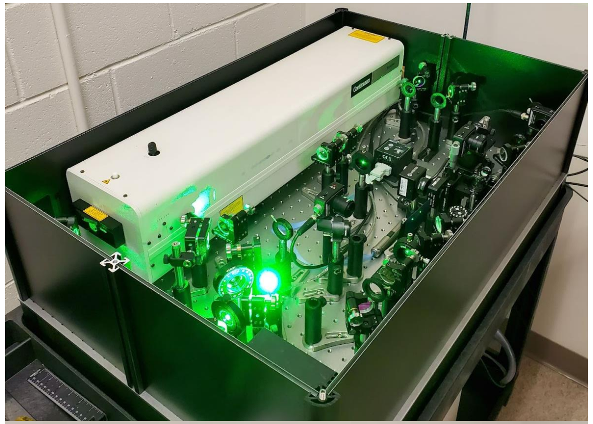
Mobile PIE System Constructed and Validated at UM

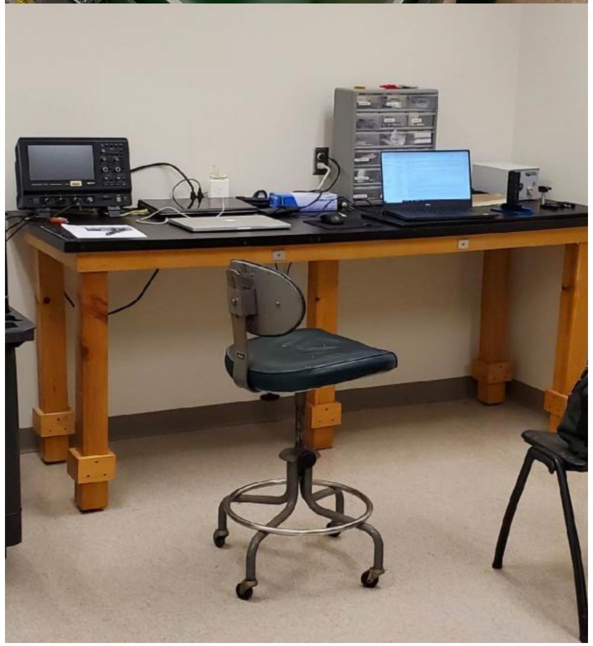




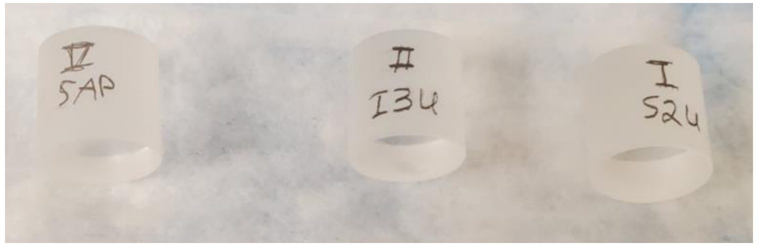
- Z-scan concept developed in laboratory
- Transitioned to PIE cart and validated
- Integrated with DAQ

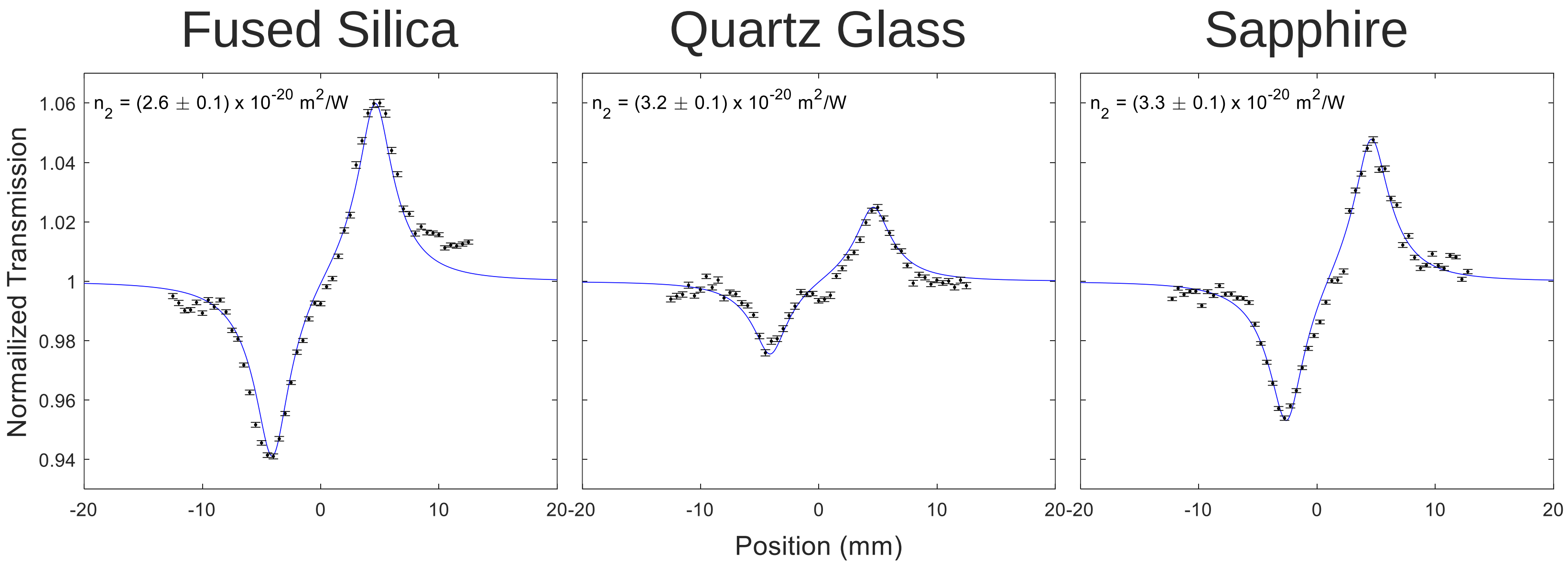
PIE System Established and Validated at OSU NRL



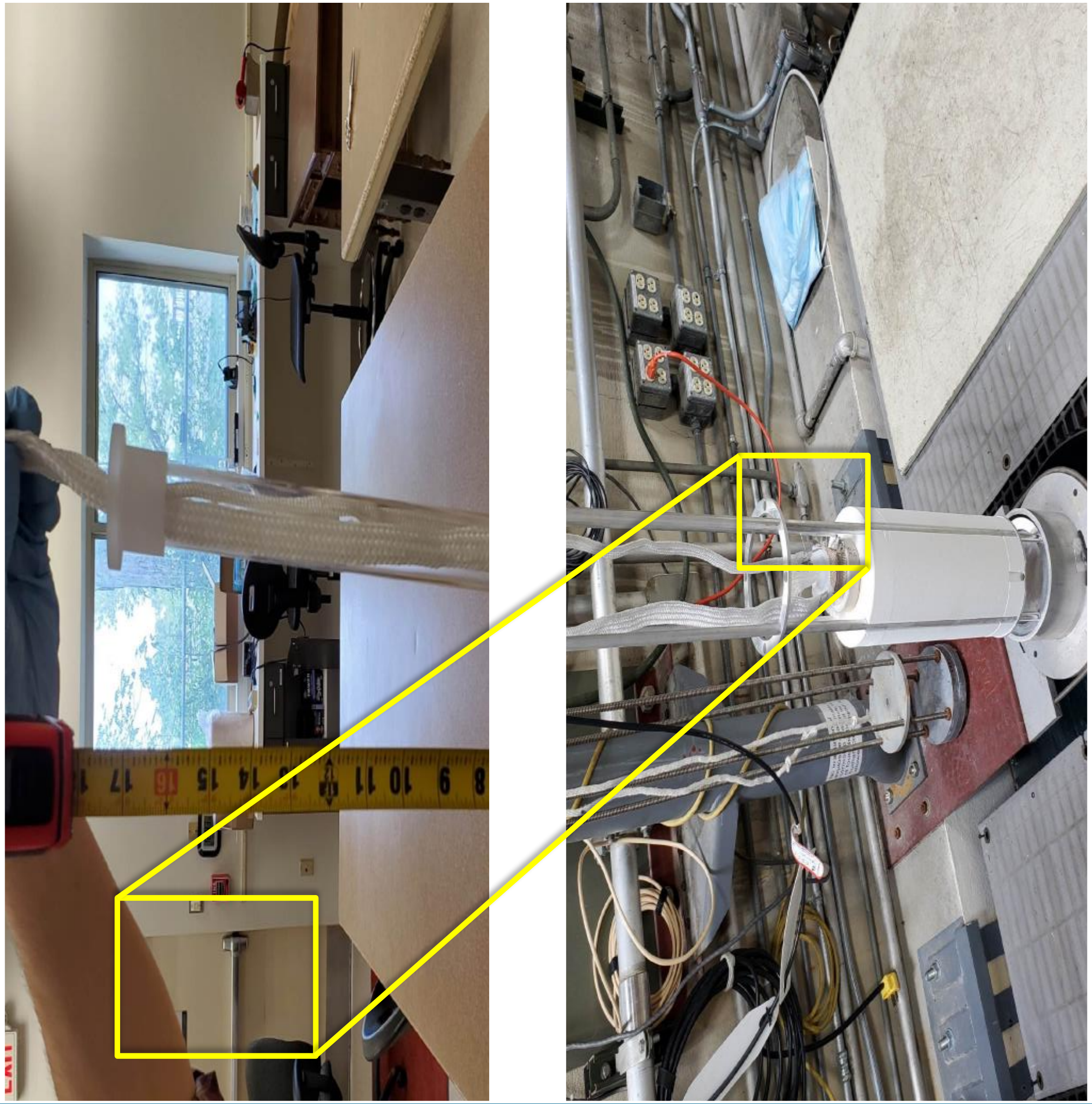


- Dedicated space for certified laser laboratory
- Aligned and validated PIE Z-scan and linear absorption
- Radiation safety certified for irradiated sample storage
- All required spare optical parts and equipment on hand





Thermal Annealing Furnaces Completed



- Thermal annealing furnaces constructed for insertion into ^{60}Co irradiator and nuclear reactor
- Capable of heating samples to 800 ºC for duration of irradiations (12 days)
- Samples suspended is silica sleeve inside fused silica tube, inside heating element
- Materials selected for minimum neutron cross-section and activation
- Silicon carbide heating element
- Silica-alumina insulation
- Aluminum frame

Gamma Irradiation Series

Test	Dose	Thermal Annealing
Initial Gamma Irradiation	500 krad	No
Gamma Irradiation with Post Heating	600 krad 1.2 Mrad 3.6 Mrad	150 ºC Fiber 800 ºC Window
Gamma Irradiation with Concurrent Heating	600 krad 1.2 Mrad 3.6 Mrad	150 ºC Fiber 800 ºC Window
Neutron Irradiation with Post Heating	2×10^{16} n/cm^2 1×10^{17} n/cm^2 2.1×10^{17} n/cm^2	150 ºC Fiber 800 ºC Window
Neutron Irradiation with Concurrent Heating	2×10^{16} n/cm^2 1×10^{17} n/cm^2 2.1×10^{17} n/cm^2	150 ºC Fiber 800 ºC Window

Optical windows

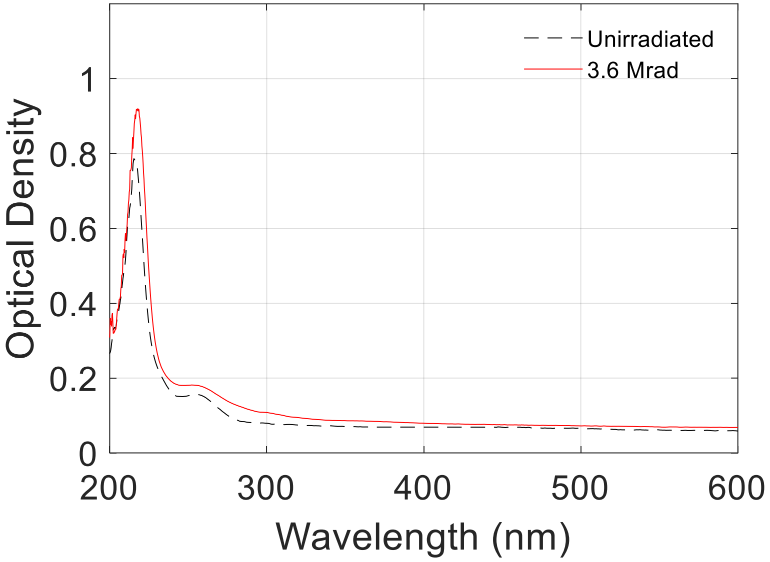
- Heraeus Spectrosil 2000
- Heraeus Spectrosil 2000 AR
- Heraeus Infrasil 302
- Heraeus Infrasil 302 AR
- Sapphire
- Schott BK7G18
- Schott NBK7

Optical fibers

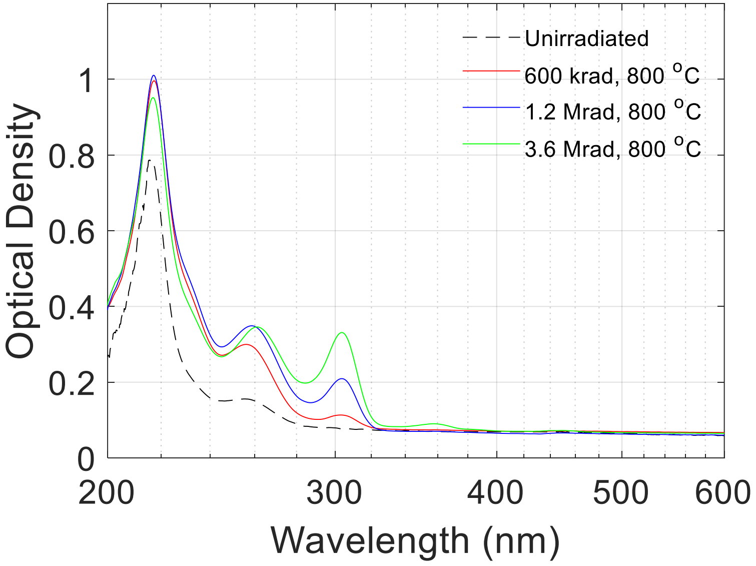
- FG2000UEA High OH
- FP1000ERT Low OH
- Sapphire
- ZBLAN ZMF-100

Linear Absorption and Thermal Annealing

Sapphire, post-annealing

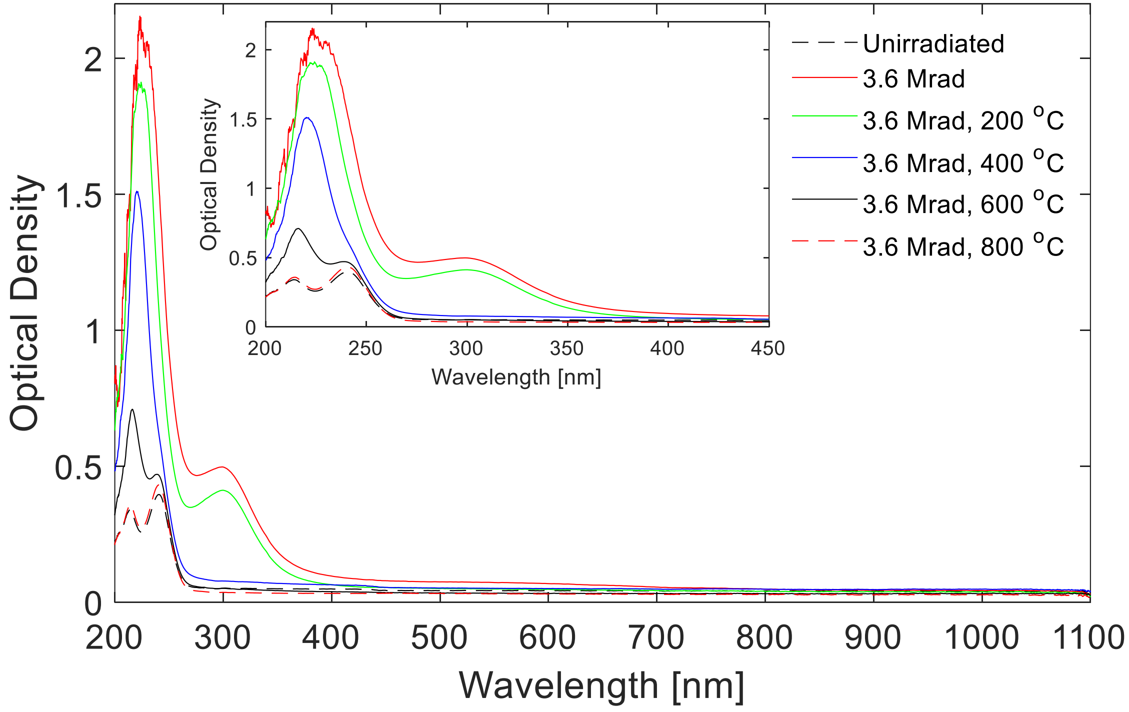


Sapphire, concurrent annealing

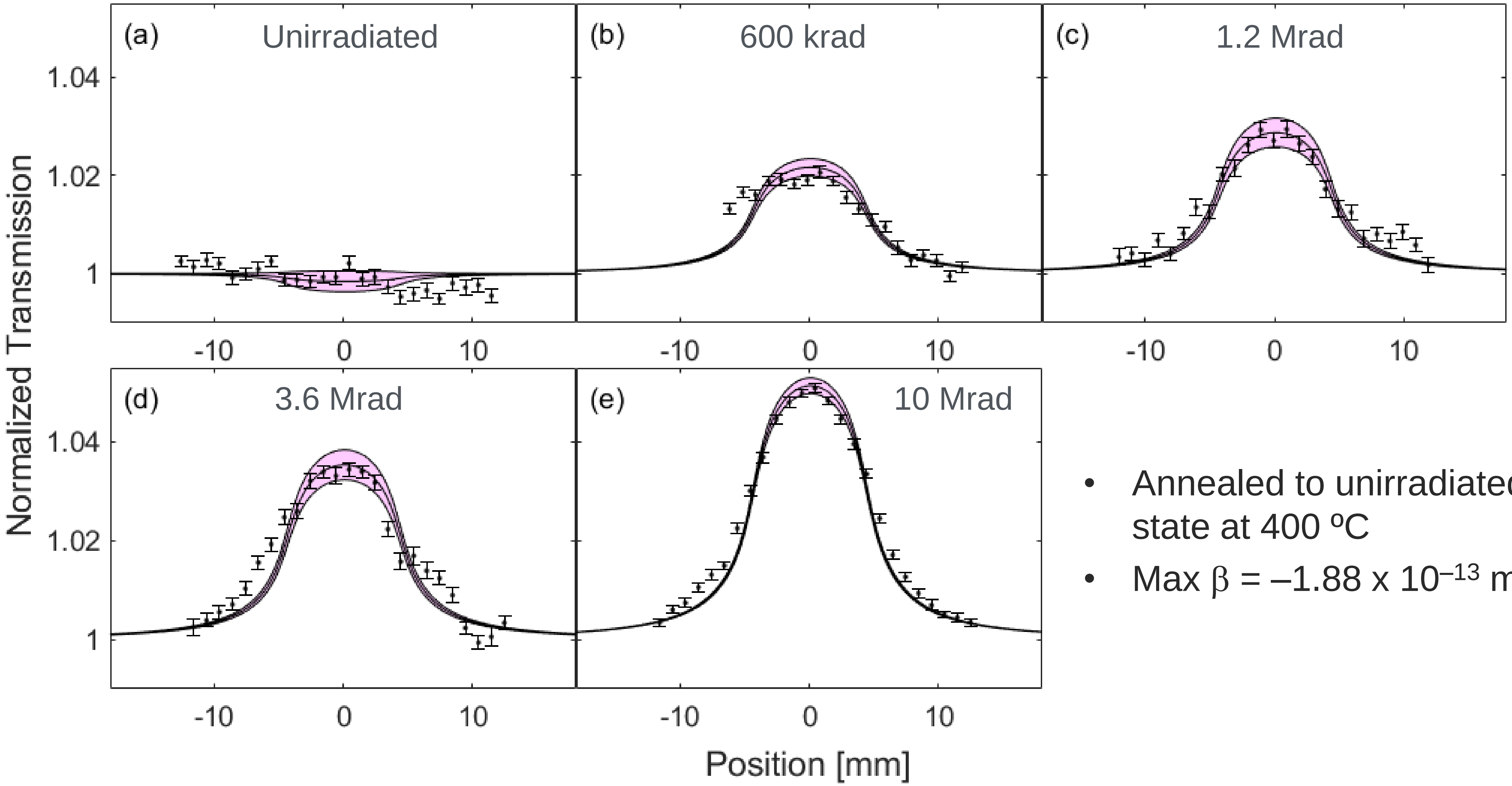


- Thermal annealing effective at restoring quartz glass to pre-irradiated linear absorption.
- Concurrent thermal annealing *enhances* the linear absorption in sapphire.

Quartz Glass



Gamma-Induced Negative Nonlinearity in Quartz Glass

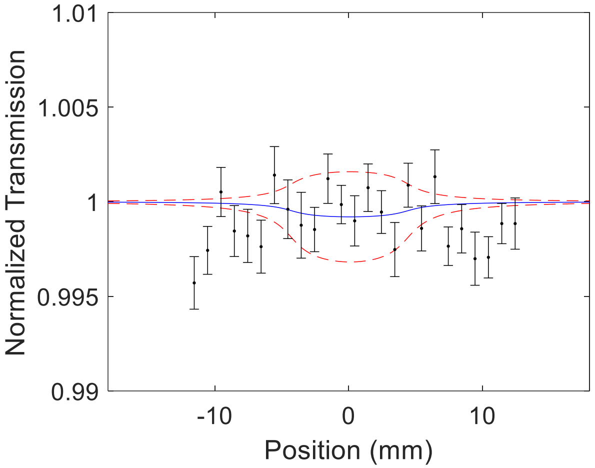


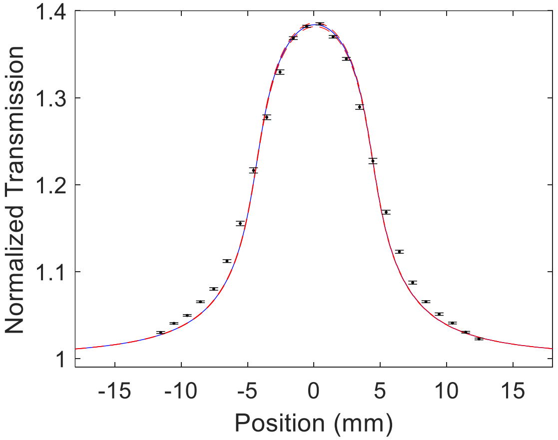
- Annealed to unirradiated state at 400 ºC
- Max $\beta = -1.88 \times 10^{-13}$ m/W

Initial Neutron/Gamma Results

Neutron Fluence 2 x 10^{16} n/cm^2

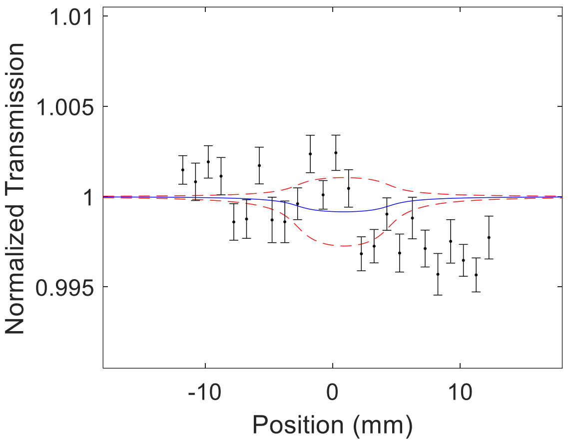
Quartz Glass

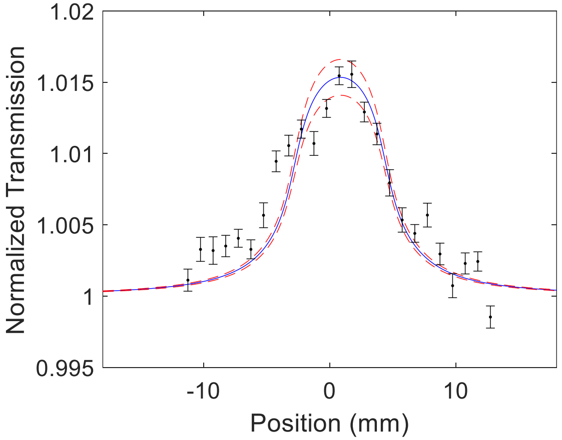




$\beta = -1.26 \times 10^{-12}$ m/W

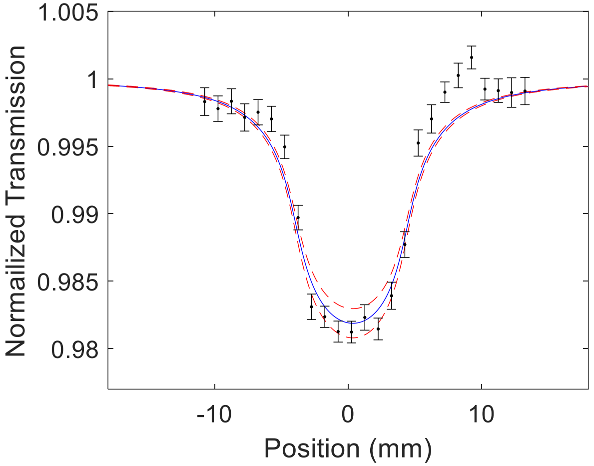
Sapphire

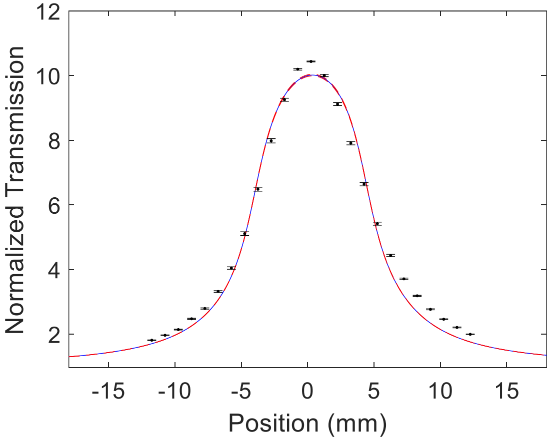




$\beta = -3.54 \times 10^{-14}$ m/W

NBK7





$\beta = -1.17 \times 10^{-11}$ m/W

Pre-irradiation

Post-irradiation

Ongoing and Future Work and Conclusions

- We have observed interesting nonlinear behavior of irradiated bulk optical materials including **negative nonlinear absorption** in quartz glass, sapphire, and NBK7.
- We have observed **increased absorption in sapphire when subjected to concurrent heating** in high gamma radiation field
- Quartz glass has annealed well to the unirradiated state throughout the experiments.
- Neutron/gamma mixed irradiations continue with concurrent and post-irradiation thermal annealing.

- B. W. Morgan, M. Van Zile, P. Sabharwall, M. Burger, and I. Jovanovic, "Gamma-radiation-induced negative nonlinear absorption in quartz glass," under review.
- B. W. Morgan, M. Van Zile, P. Sabharwall, M. Burger, and I. Jovanovic, "Post-Irradiation Examination of Optical Components for Advanced Fission Reactor Instrumentation," Review of Scientific Instruments 92, 105107 (2021).
- B. Morgan, M. Van Zile, P. Skrodzki, X. Xiao, P. Sabharwall, P. Marotta, M. Burger, and I. Jovanovic, "Post-Irradiation Examination of Irradiated Optical Components of In-Situ Spectroscopic Sensors for Advanced Fission Reactors," ANS Winter Meeting, November 30–December 3, 2021.
- B. Morgan, P. Skrodzki, M. Burger, P. Sabharwall, P. Marotta, and I. Jovanovic, "Post-Irradiation Examination System Development for Irradiated Optical Components of In-Situ Spectroscopic Sensors," ANS Winter Conference [online], November 15-19, 2020.

Questions?

This work has been supported by the Department of Energy, Nuclear Science User Facilities Program under award DE-NE0008906.

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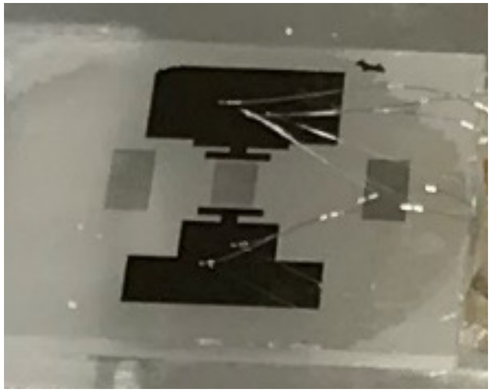
Irradiation behavior of piezoelectric materials for nuclear sensor applications

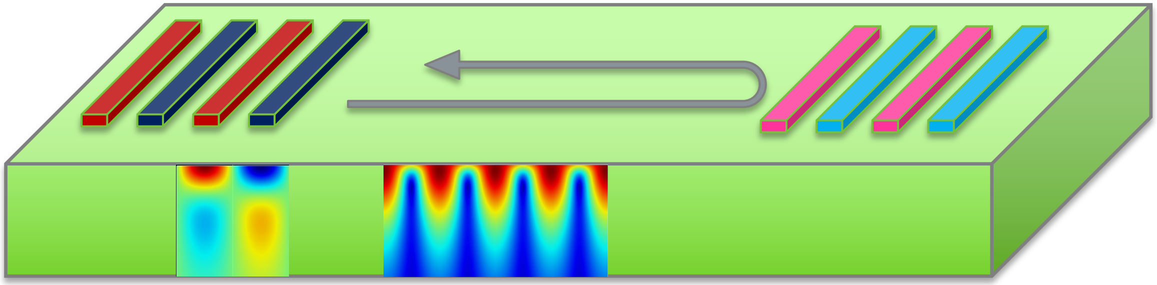
Advanced Sensors and Instrumentation Annual Webinar

November 16, 2021

Marat Khafizov
The Ohio State University

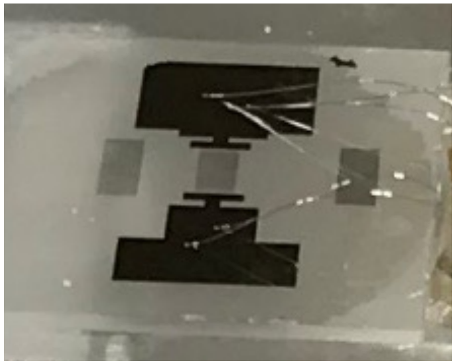
Project Overview

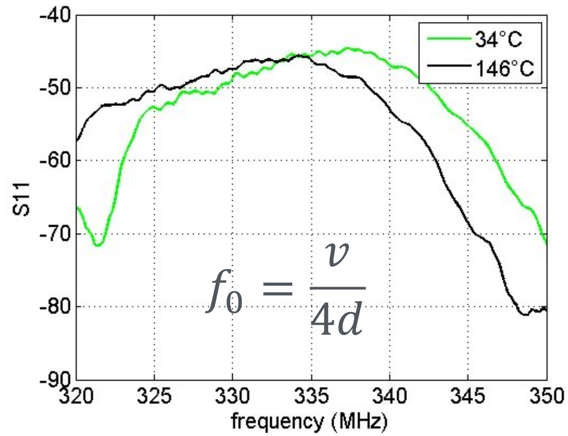


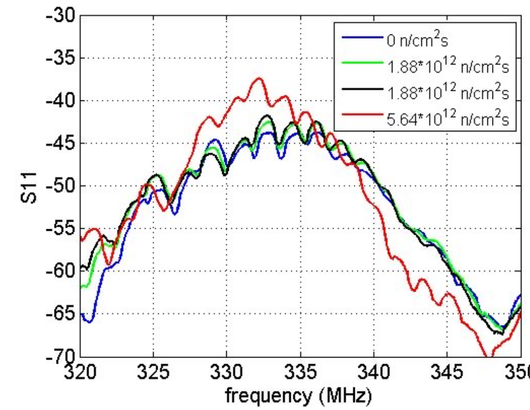


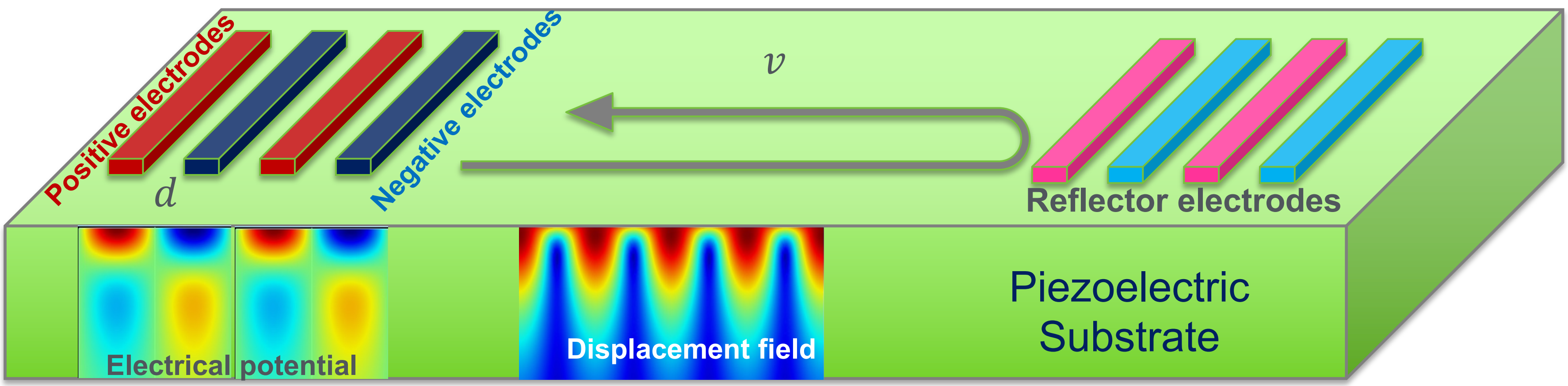
- NSUF Project Goal and Objective:
  - Understand the impact of radiation environment on behavior of piezoelectric materials
- Participants (2020):
  - Marat Khafizov (Ohio SU), Alex Chernatynskiy (Missouri S&T), Joshua Daw (Idaho NL)
  - NSUF facilities: Ohio SU Reactor, U Wisconsin Ion Beam
- Performance period: October 2018-September 2022, no cost extension

Interdigitated transducer (IDT) SAW





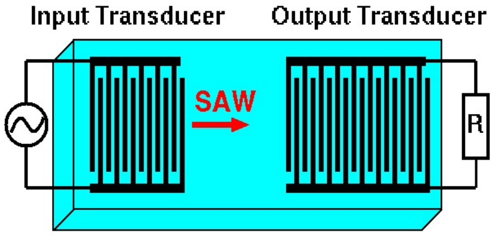




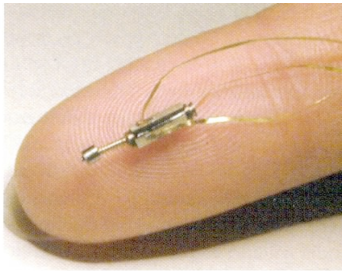
- Surface acoustic wave (SAW) are generated and detected through piezoelectric effect that couples electric field between adjacent electrodes and elastic strain
- SAW devices are sensitive to environmental conditions and used as sensors

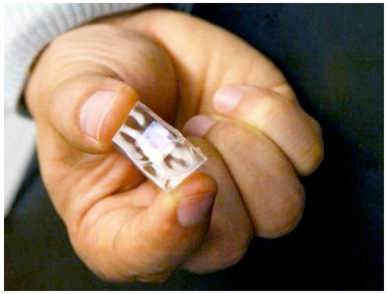
Piezoelectric devices


Google Image: Piezoelectric transducer



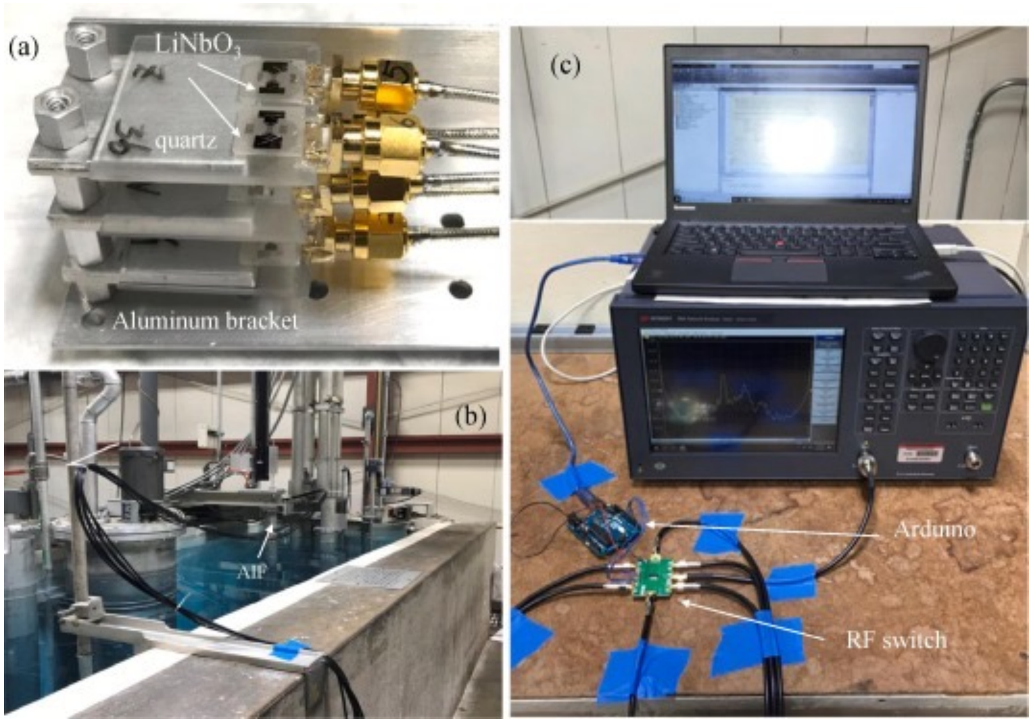
Google image for IDTs SAW


Google Image: micromotor


Google Image: Energy Harvester

- Piezoelectric materials are considered for communication and sensor application in nuclear energy applications
- Engineering performance parameters of piezo-electric devices:
  - electromechanical coupling coefficient $K^2 = \frac{C_{33} d_{33}^2}{e_{33}}$
  - Resonant frequency $f_0 = \frac{v}{d}$,
    - *d* is device thickness and sound velocity is $\rho v^2 = C_{33}$
- Goal: measure impact of radiation environment on these parameters

Neutron irradiations at OSU Research Reactor



Irradiation conditions:

- Ohio State University Research Reactor
- AIF dry tube facility
- Max total flux 4.5×10^{12} $n/cm^2\cdot s$ at full power (500 kW)
- Total fluence upto
  - 5.0×10^{17} n/cm^2

Device characterization:

- S_{11} parameter are measured using RF network analyzer

Materials irradiated:

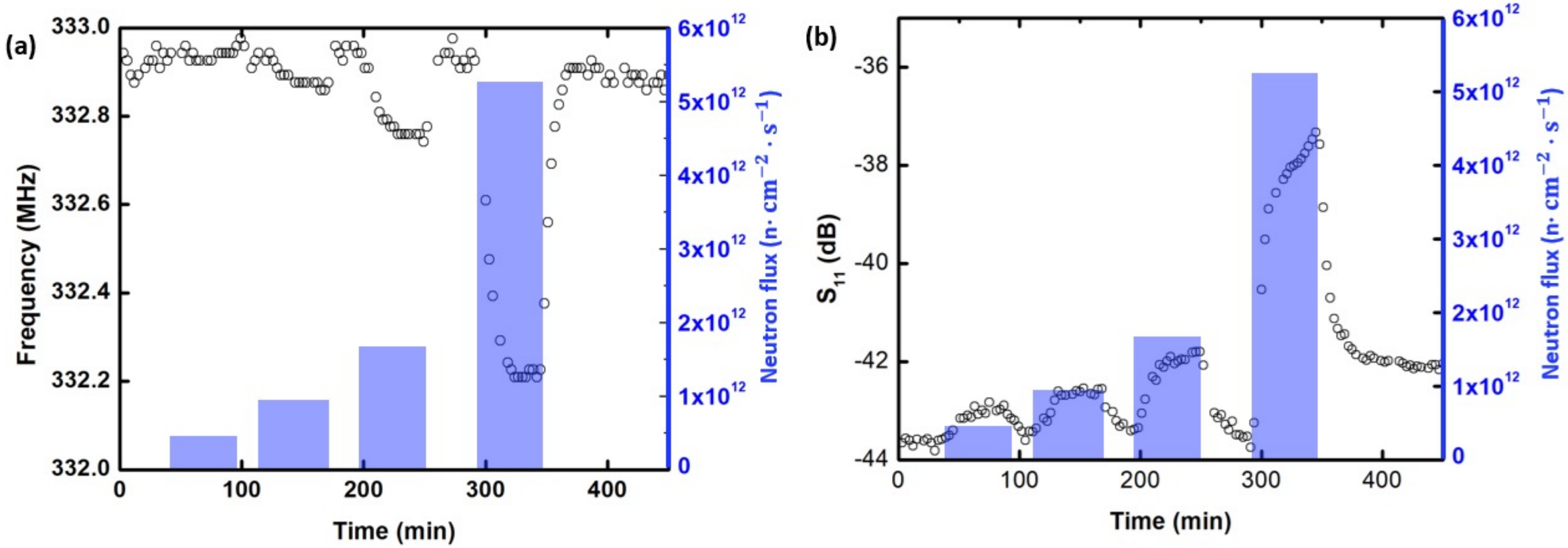
- AlN, $LiNbO_3$

Irradiations funded by Nuclear Science User Facility

- Additional in-situ measurement under ion-beam irradiation were proposed

Sha et al., Nucl. Instrum. Meth. B **472**, 46 (2020)
Wang et al., Nucl. Instrum. Meth. B **481**, 35 (2020)

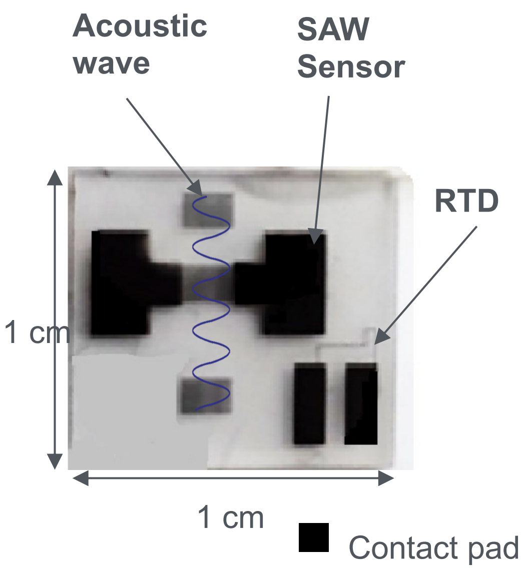
Reactor power dependent response of AlN



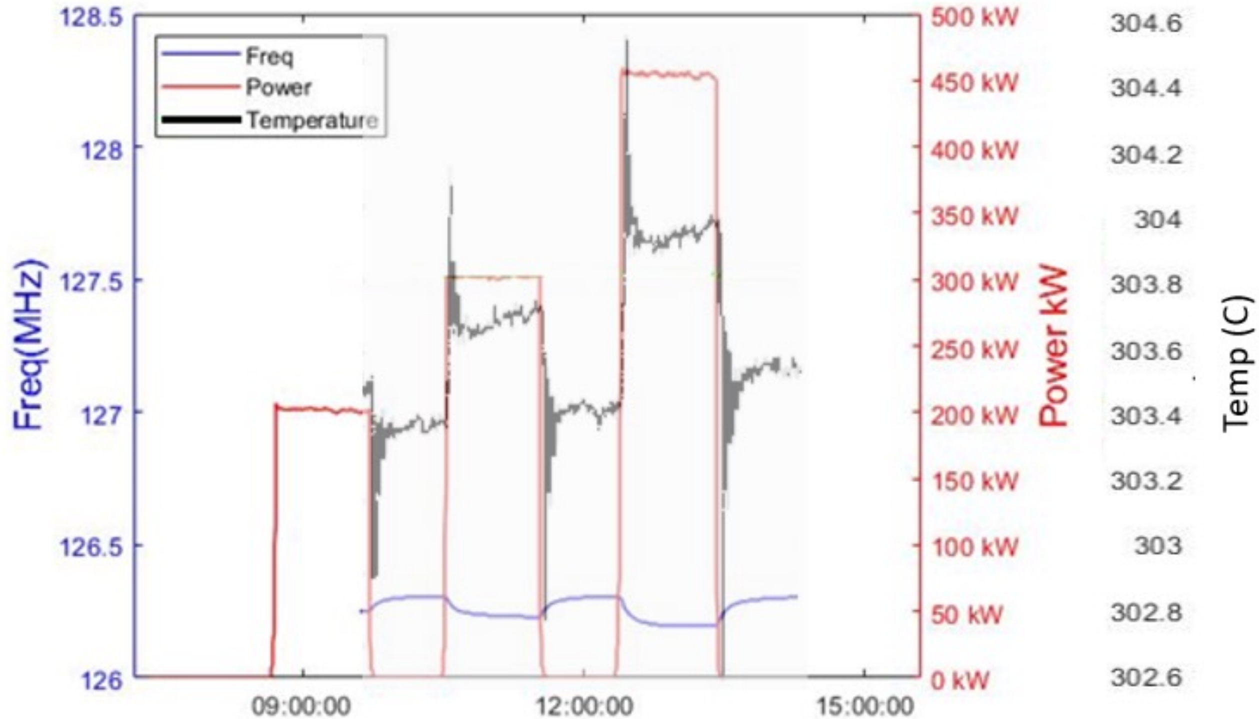
- Device: epitaxial AlN on c-cut Al2O$_3$, wave propagation $[11\bar{2}0]$
- Under neutron irradiation both resonant frequency and amplitude undergo gradually increasing change that saturates with time
- Changes are reversible
- Hypothesis that observed change are either a result of damage from neutrons and gamma rays or gamma heating

Wang et al., Nucl. Intrum. Meth. B **481**, 35 (2020)

SAW device response at high temperatures

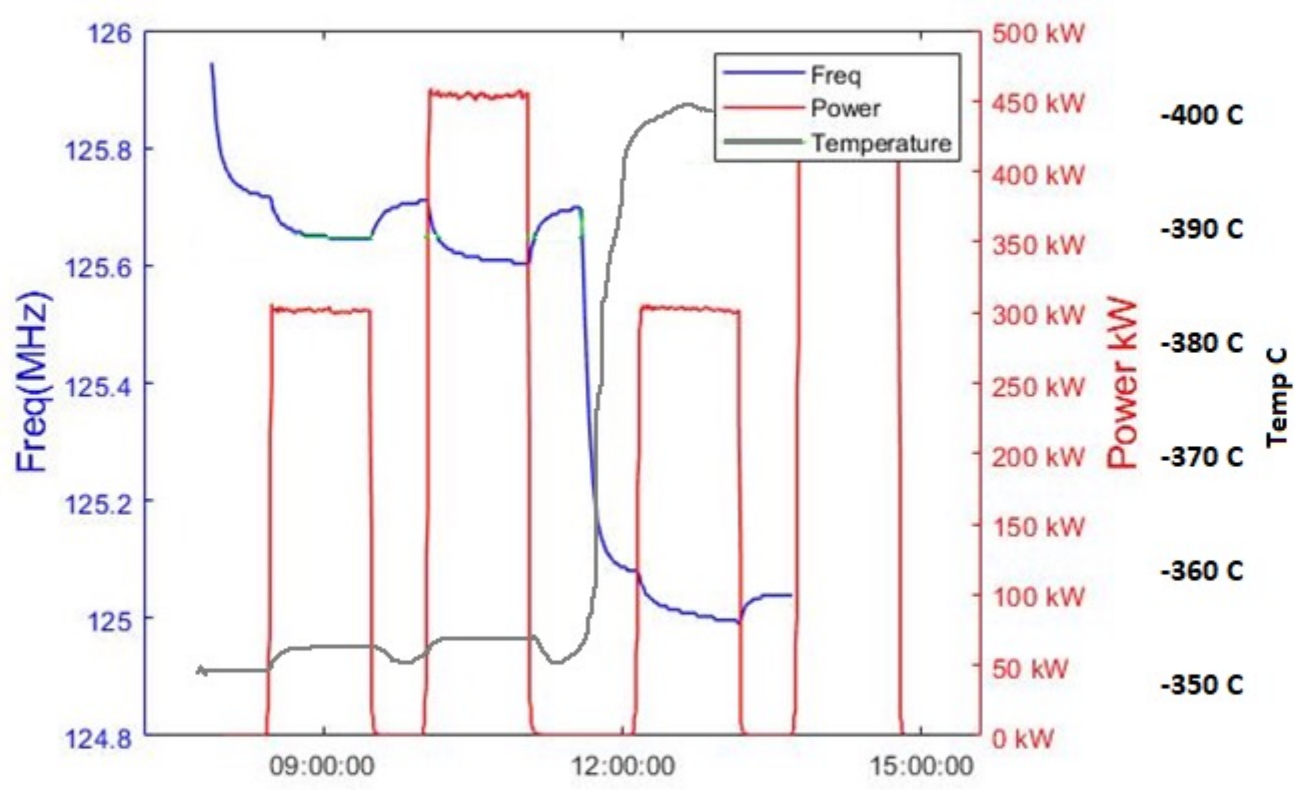


Thickness = 120 nm
Length = 3 mm, width = 8 μm



- To isolate gamma heating from neutron effects an RTD-temperature sensor has been embedded
- Constant temperature variable power characterization show that both RTD and SAW device respond to reactor power fluctuations

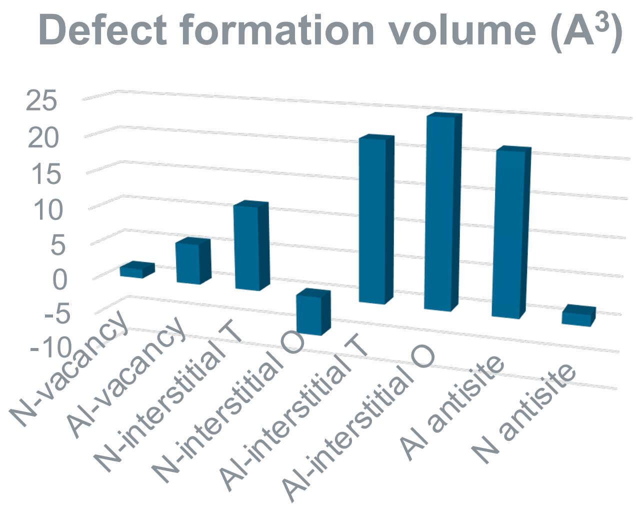
SAW device response at high temperatures

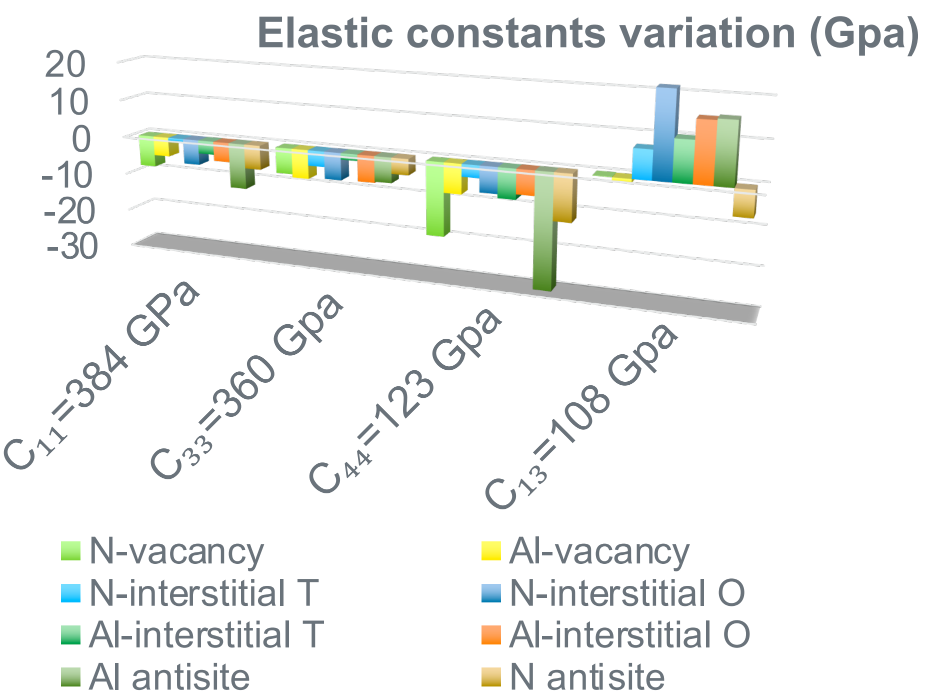


- variable temperature and variable power response suggest that SAW sensor would require temperature and gamma ray heating compensations

Point defects properties from DFT- Chernatynskiy

Experiment: C_{11}=411, C_{33}=389, C_{44}=125, C_{13}=99.





Presence of any defects softens all diagonal elastic constants, the elastic constant to which the experiment is most sensitive.

Deliverable and Accomplishments

- Two journal publications
  - "*Impact of nuclear reactor radiation on the performance of AlN/sapphire surface acoustic wave devices*", Y. Wang, G. Sha, C. Harlow, M. Yazbeck, M. Khafizov, Nucl. Instrum. Meth. B **481**, 35 (2020)
  - "*In-situ measurement of irradiation behavior in $LiNbO_3$*", G. Sha, C. Harlow, A. Chernatynskiy, J. Daw, M. Khafizov, Nucl. Instrum. Meth. B **472**, 46 (2020)
- 5 conference presentations
  - TMS 2021, TMS 2020, MS&T 2020, REI 2019, OSU IMR 2019
- Enable development of piezoelectric based sensing for radiation environments
  - Pressure, temperature and vibration sensors
- *Marat Khafizov, Khafizov.1@osu.edu.*

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

ASI Advanced Sensors and Instrumentation

Health Monitoring of Digital I&C Systems using Online Electromagnetic Measurements

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

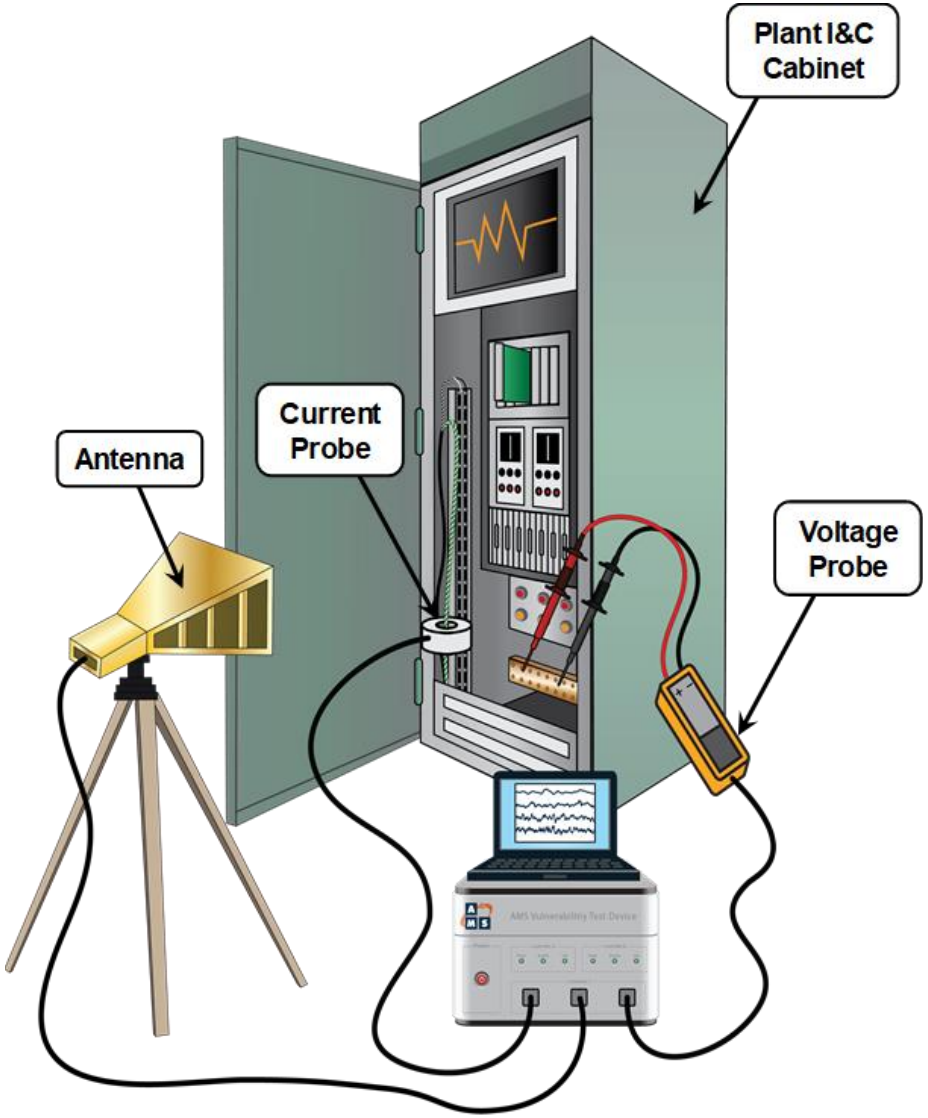
November 15 – 18, 2021

Project Manager: Morgan F. Berg

Analysis and Measurement Services

Project Overview - Summary

- Design and build a condition monitoring system
  - Capable of collecting and analyzing emissions measurements
  - Designed for both predictive maintenance and RF environment characterization
- Measure emissions from I&C equipment and components as they are artificially degraded



Project Overview - Participants

Chad Kiger, PI

Morgan Berg, PM

Ryan Kettle

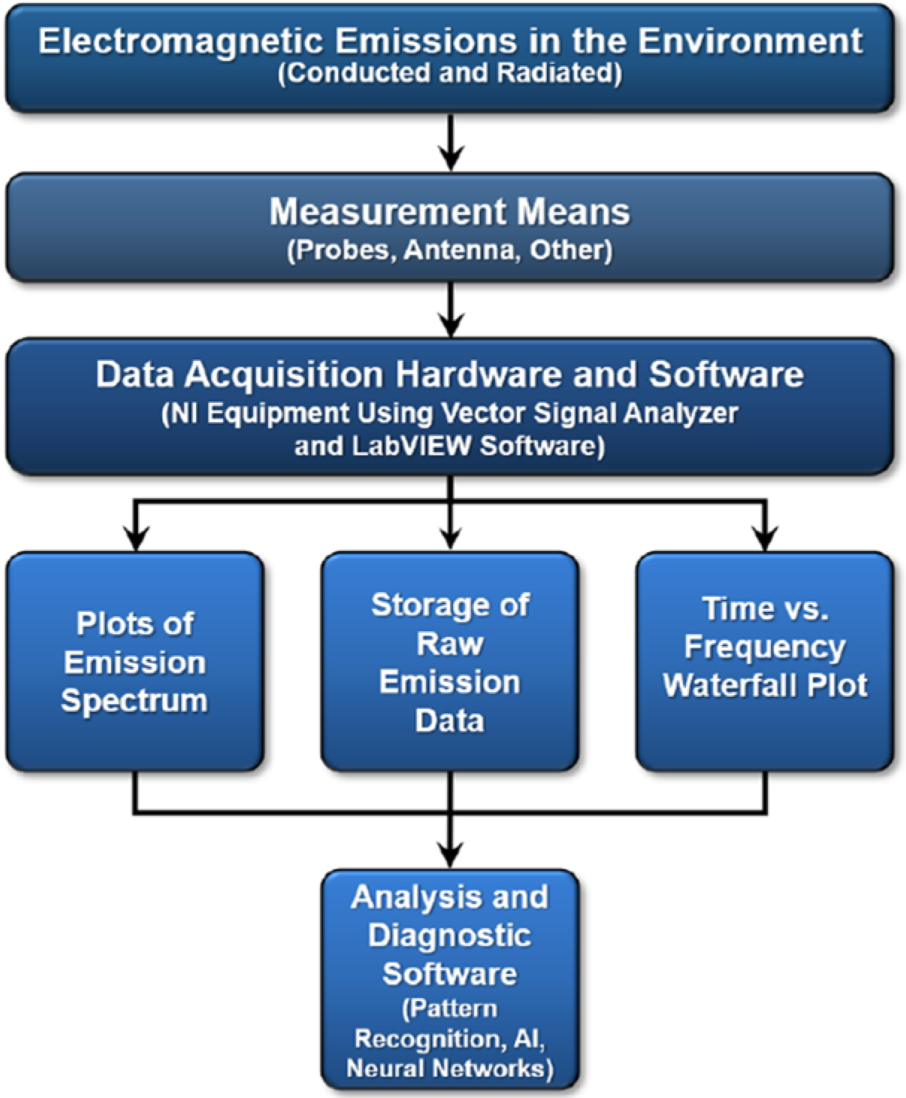
Kaleb Frizzell

Emily Weeden

Kevin Brandel

Current Efforts

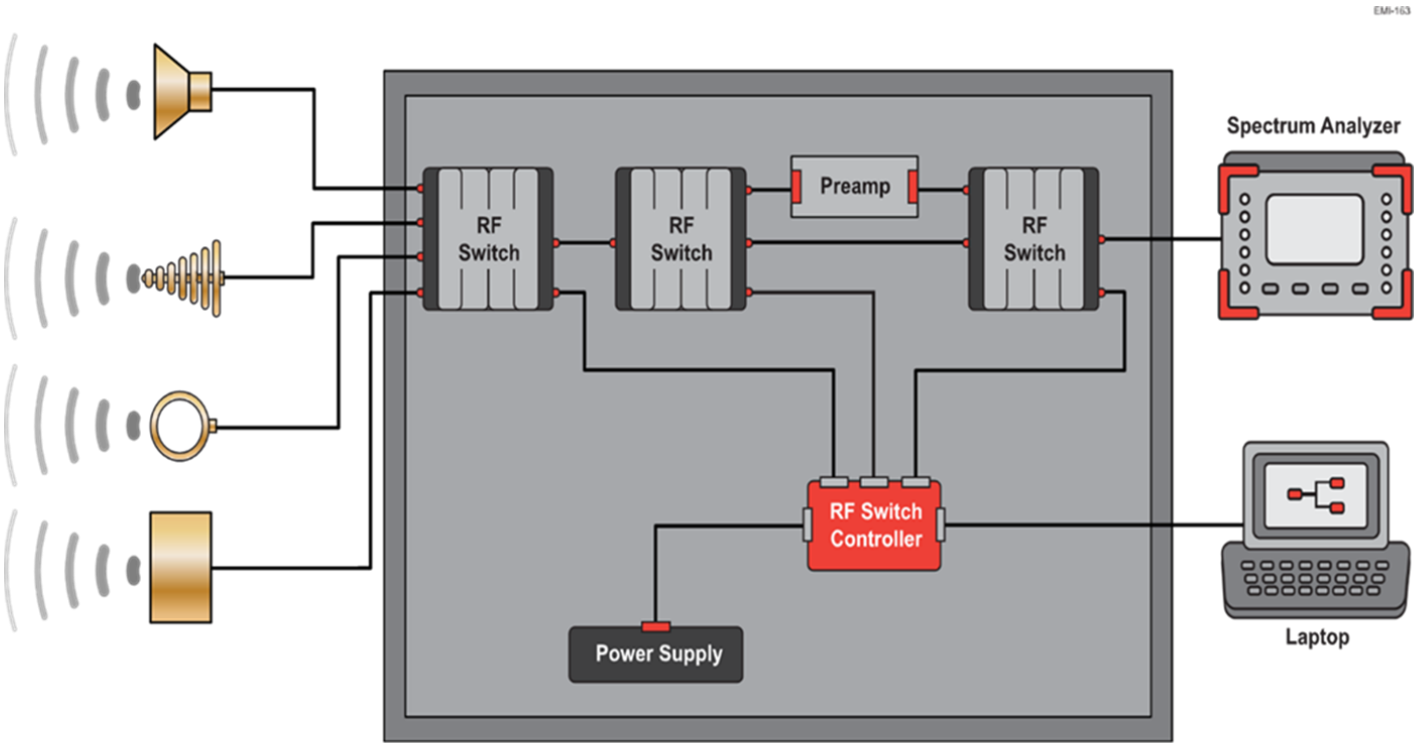
- Establishing correlations between I&C equipment degradation and emissions spectrums
- SERF Software Development
  - Data Acquisition
  - Field Analysis
  - Monitoring System control
- Monitoring System Construction and Verification



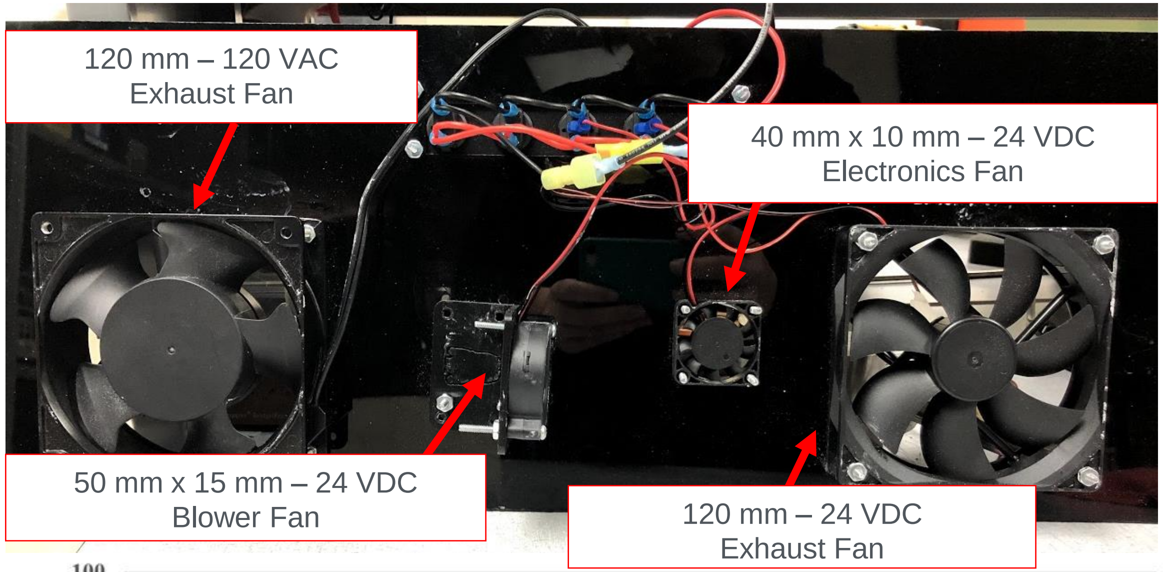
Technology Impact

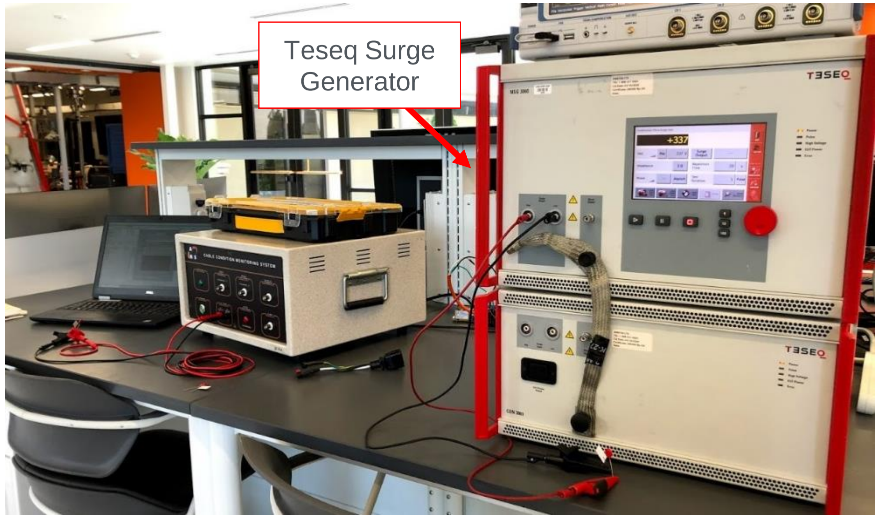
Passive Monitoring System

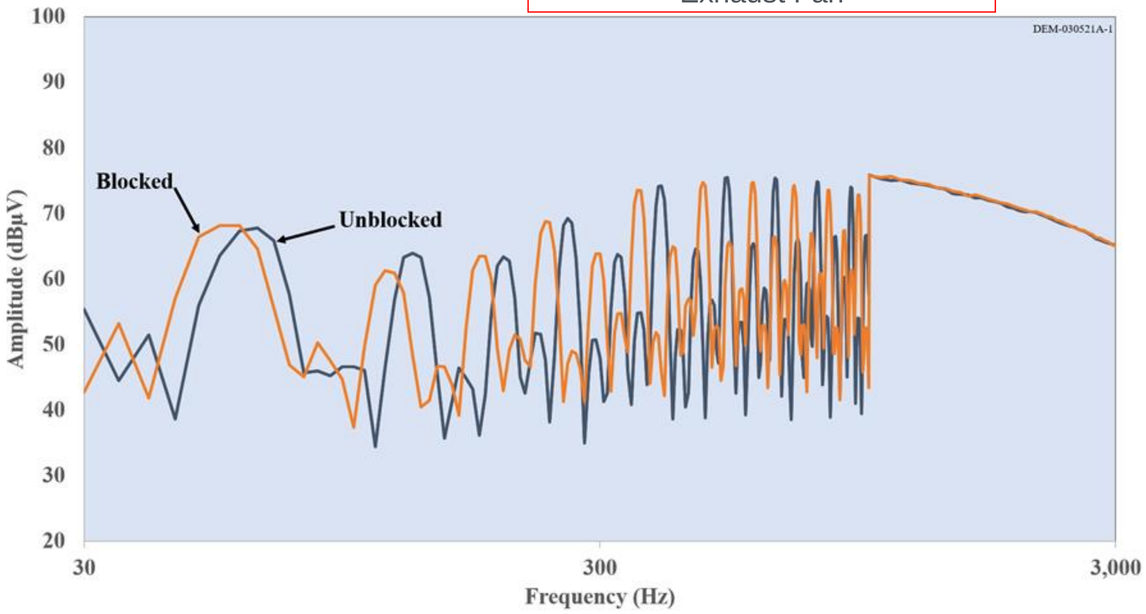
- Collects and analyzes electromagnetic signatures
- Allow for long duration emissions measurements
- Capture emissions data in the time and frequency domains
- Potentially identify impending equipment failures
  - Allow for less forced shutdowns and reactor trips due to equipment failures
  - Assist the preventative maintenance programs

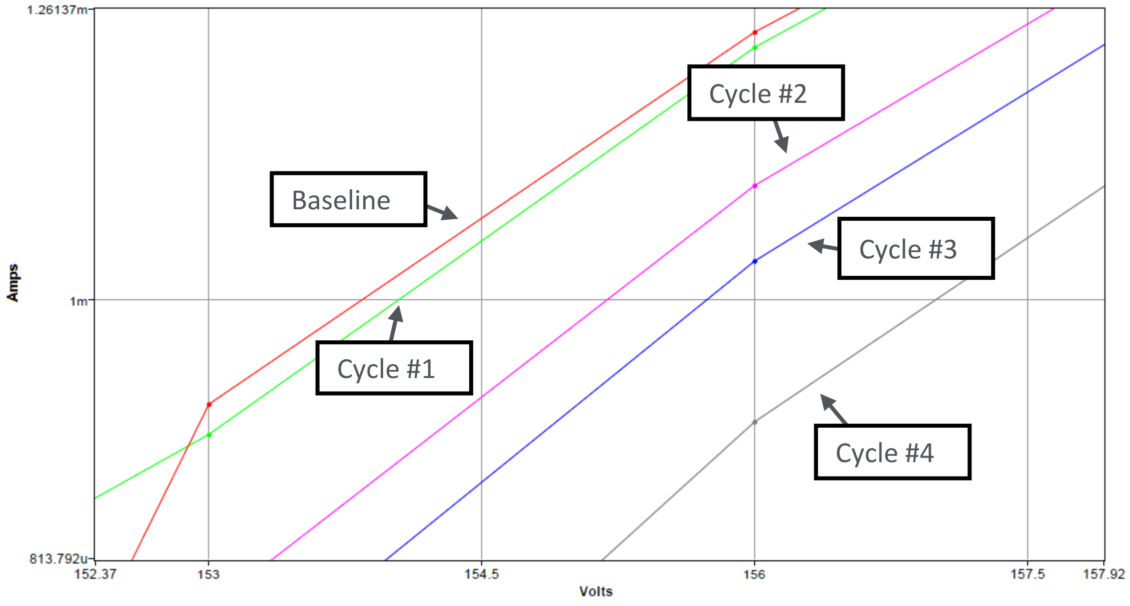


Results and Accomplishments

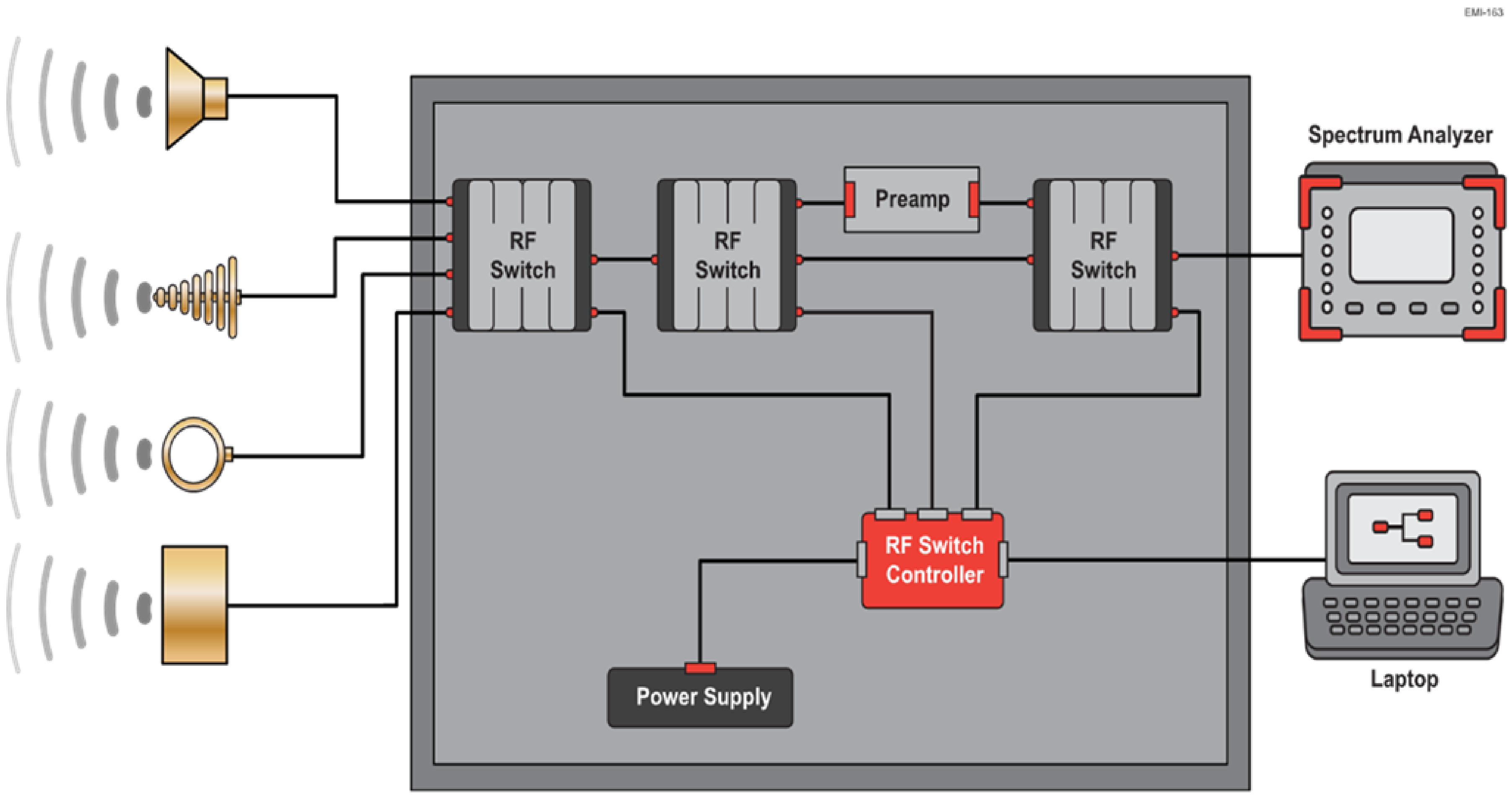








Results and Accomplishments



Results and Accomplishments

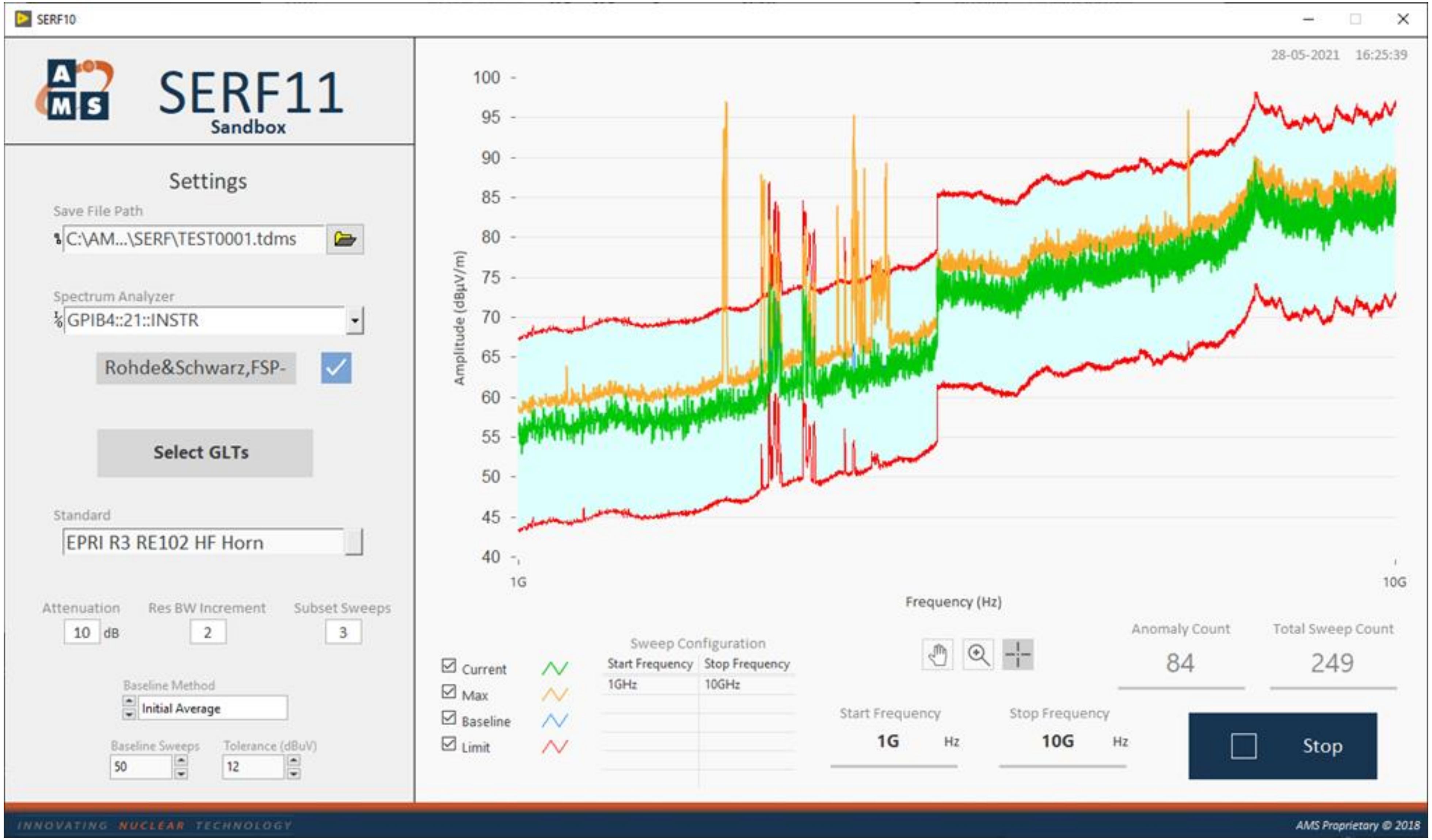
4 to 1 RF Switch

2 to 1 RF Switch

Preamplifier

NI Controller

Results and Accomplishments

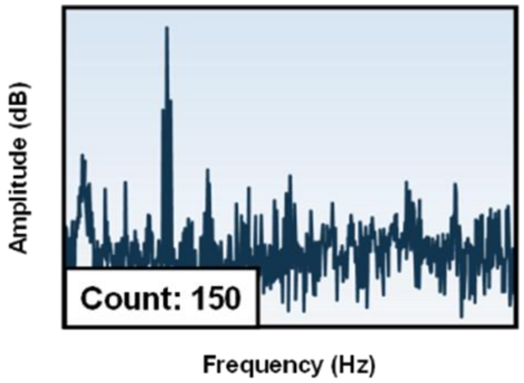


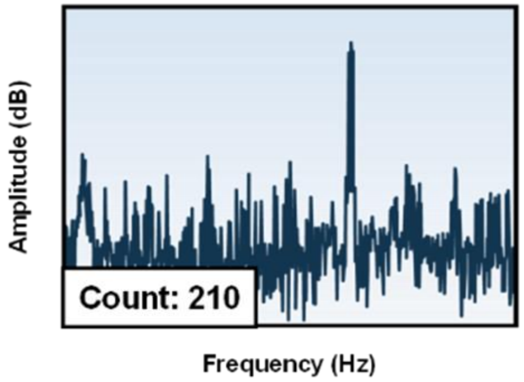
Results and Accomplishments

Identify
- Automatically ID Anomaly

Categorize
- Existing or New Anomaly?

Save
- Increment Anomaly Count or
- Save New Anomaly Signature





Conclusions

Summary

- Completed degradation of cooling fans
- Solidified design plan for the monitoring system
- Started work on the SERF software

Future Work

- Complete degradation of remaining I&C equipment
- Construct, test, and verify the condition monitoring system
- Complete development, QA, and implement the SERF software

Publications

Automated System to Characterize Electromagnetic Environments in Nuclear Power Plants
M.F. Berg, C.J. Kiger
American Nuclear Society Winter Meeting and Technology Expo, November 30 – December 3, 2021

Health Monitoring of Digital I&C Systems using Online Electronic Measurements
B.D. Shumaker, C.J. Kiger, D.E. McCarter
12th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies Conference, June 14-17, 2021

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LinkedIn

Questions?

ASI | Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

Sensor Advanced Manufacturing – Feedstock Development and Process Control

CT-21IN070203

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

INL Graduate Fellow: Kiyo T. Fujimoto

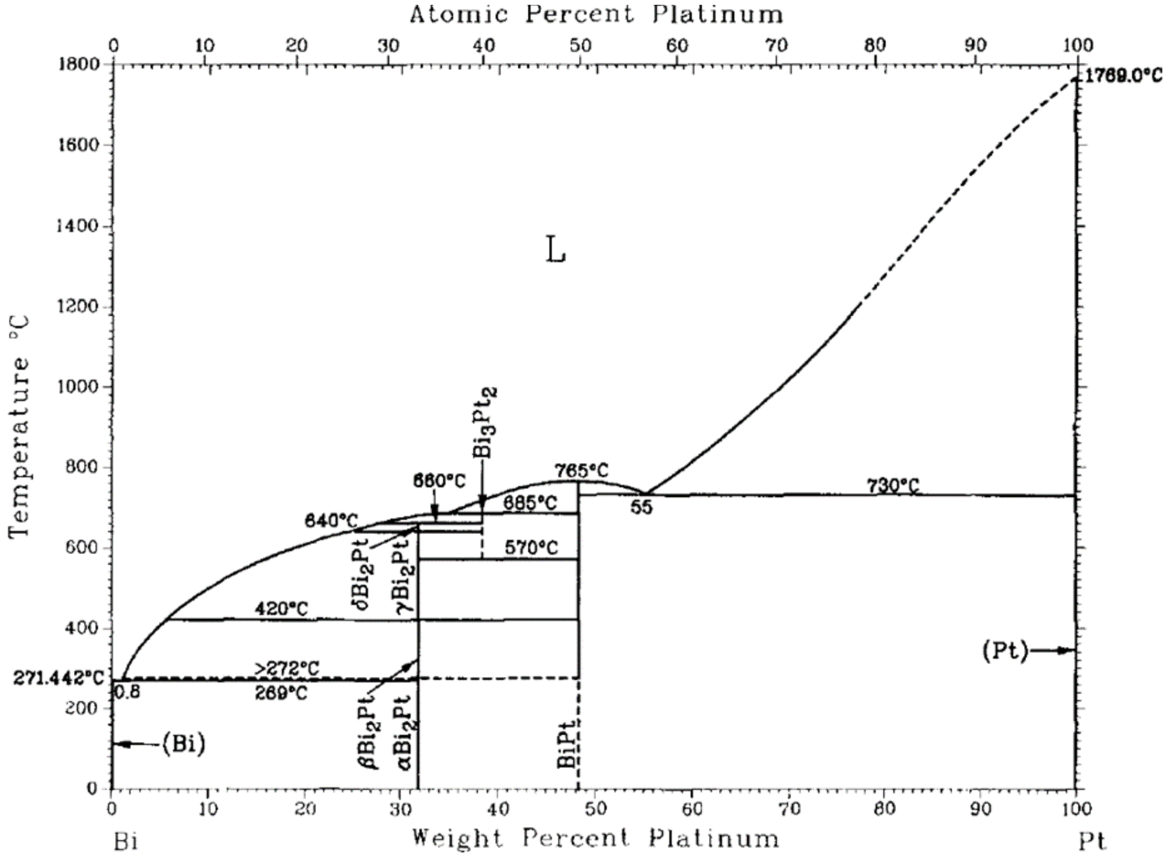
INL Research Scientist: Amey Khanolkar

Idaho National Laboratory and Boise State University

Project Overview: Feedstock Development

- ***Feedstock Development*** *for FY21 looked to d*etermine a manufacturing pathway for specialized ink for use in melt wires development, such as bi-metallic ink, to extend the temperature monitoring range and to provide finer temperature resolution than classical melt wires.
- **Targeted system** for FY21 - Bismuth/Platinum
  - Indium Melting Point: 271.4 ˚C
  - Platinum Melting Point: 1769.0 ˚C
- **Participants** - Kiyo Fujimoto, Kory D. Manning and Michael McMurtrey
- **Schedule** –Submitted milestone report in July 2021 and FY22 includes a milestone report for December 2022

Bismuth/Platinum Phase Diagram



Enabling novel sensor design through advanced manufacturing by expanding feedstock synthesis capabilities to include the synthesis of multi-element nanoparticles.

Technology Impact

Technology Application:

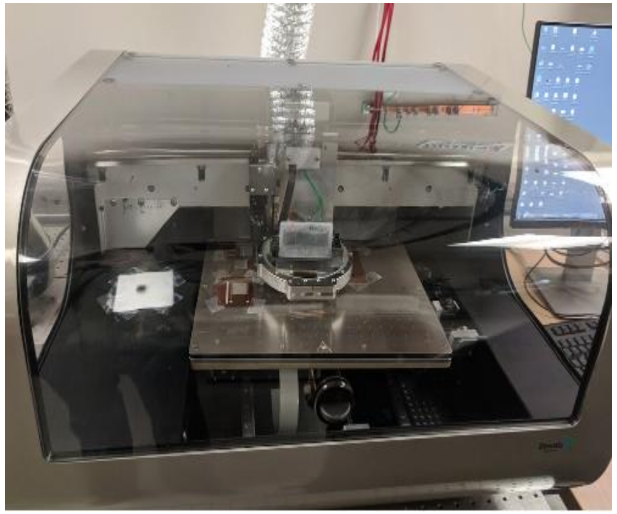
- To expand the current library of commercially available feedstock materials to encompass nuclear-relevant materials that can be utilized for manufacturing in-pile sensors and advanced nuclear instrumentation

Support to NE Industry

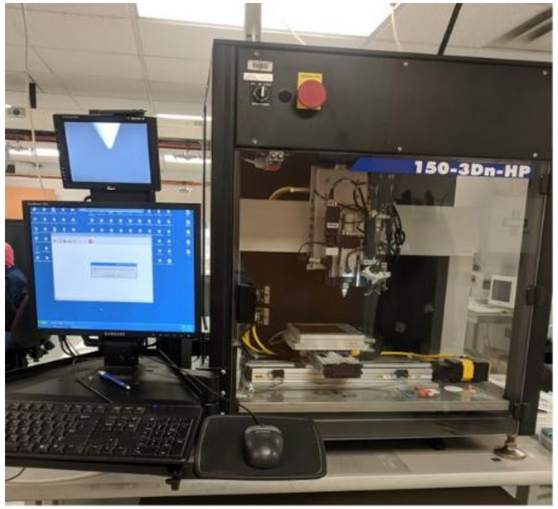
- Customer base - Anyone conducting irradiation experiments in MTRs
  - DOE, NSUF, National Laboratories, Universities, Commercial Nuclear entities, etc.
- Potential to expand outside of NE industry to include passive temperature monitoring of high energy systems.

Technology Impact: *Provides the necessary pathway towards incorporating advanced manufacturing methods for in-pile sensor development and fabrication.*

Additive Manufacturing



Dimatix Inkjet
- ❑ 20 µm linewidths
- ❑ 16 nozzles
- ❑ ± 25 µm repeatability
- ❑ Drop-on-demand



Nscrypt Micro Dispenser
- ❑ 20 µm linewidths, dual ink
- ❑ 1 – 10^6 cP ink viscosity
- ❑ Conformal 3D laser mapping
- ❑ 20 pL volumetric control

Optomec Aerosol Jet 200
- ❑ 10 µm – 5 cm linewidths
- ❑ 0.7 – 5000 cP ink viscosity
- ❑ 1 – 5 mm working distance

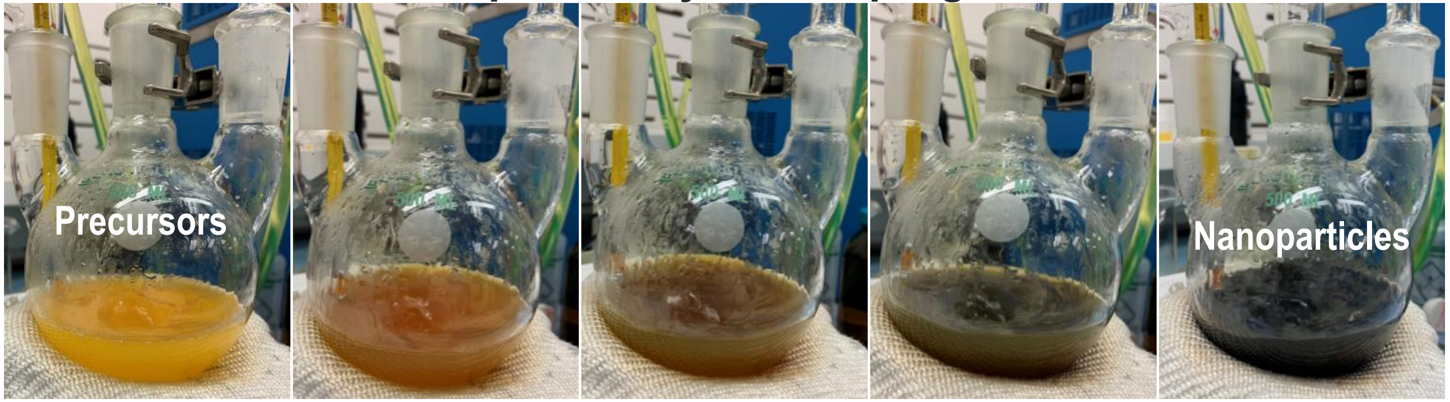
Plasma Jet Printer
- ❑ 100 µm linewidths
- ❑ Ink viscosities similar to AJP
- ❑ Multi material compatible:
  Low temp & high temp substrates, 2D & 3D Objects

Bi/Pt Nanoparticle Synthesis

Synthesis of bismuth and bismuth/platinum nanoparticles using a simple reduction method.

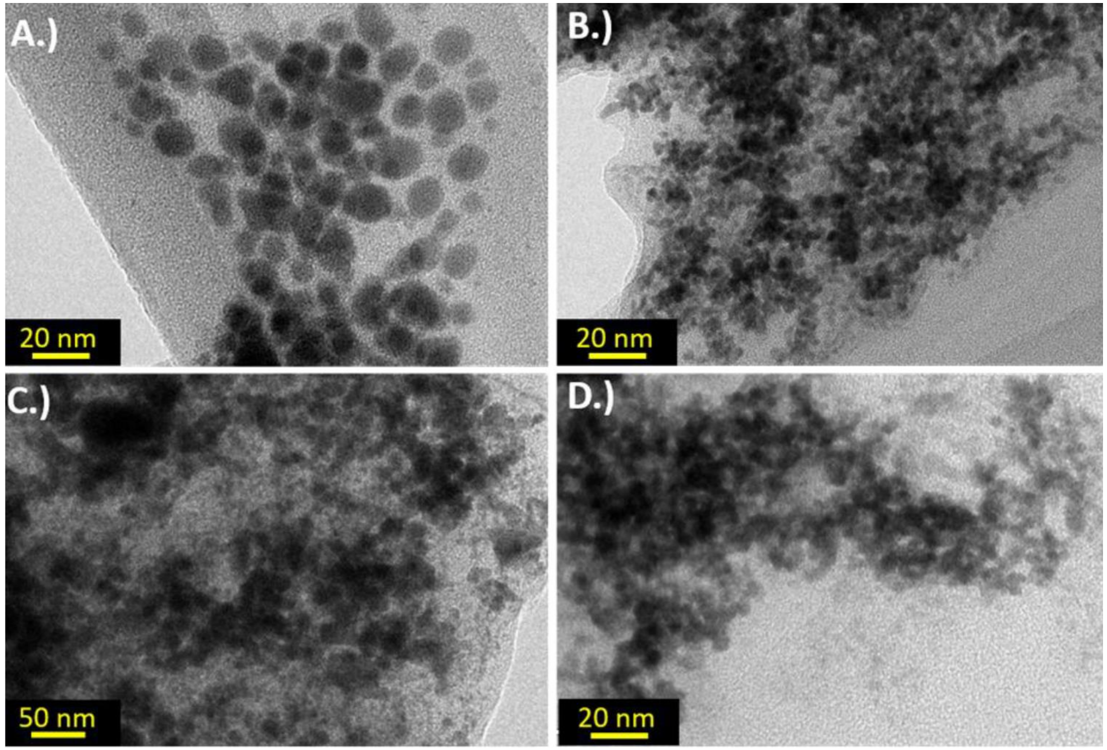
- 4 different compositions of the Bi/Pt system were synthesized
- Composition control achieved by varying metal precursor ratios
- Bulk composition analysis of each Bi/Pt system performed with TXRF
- TEM confirmed the formation of spherical nanoparticles

Bi/Pt nanoparticle synthesis progression



Bi/Pt Nanoparticles synthesized via reduction method – TEM and TXRF

TXRF Results		
Sample	Bismuth (%)	Platinum (%)
A	100	0
B	76.5	23.5
C	49.1	50.9
D	39.4	60.6



Results and accomplishments

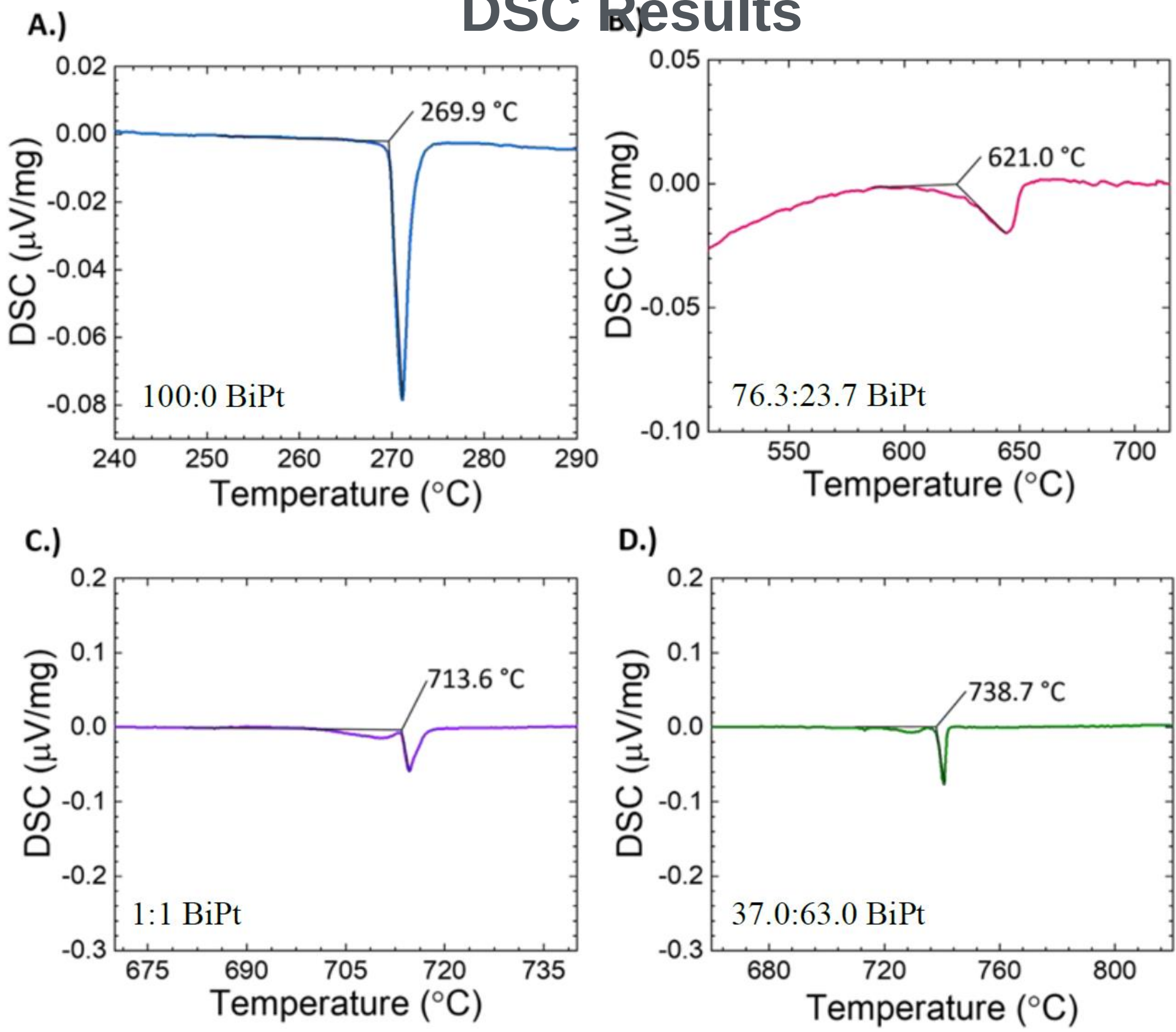
DSC evaluation of melting point for each Bi:Pt composition

- The melting point indicated by the onset of the phase change.
- Different melting point observed with each Bi/Pt composition

Sample	Expected Melting Point	Actual Melting Point
A	274.1 °C	269.9 °C
B	~640 °C	621 °C
C	~760 °C	713.6 °C
D	~870 °C	738.7 °C

Initial bi-metallic efforts demonstrate significant potential to tailor melting point of melt wires with bi-metallic nanoparticles as AM feedstock used in melt wire fabrication

DSC Results

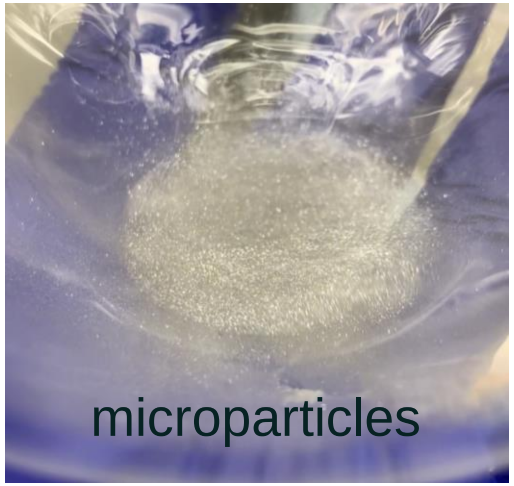


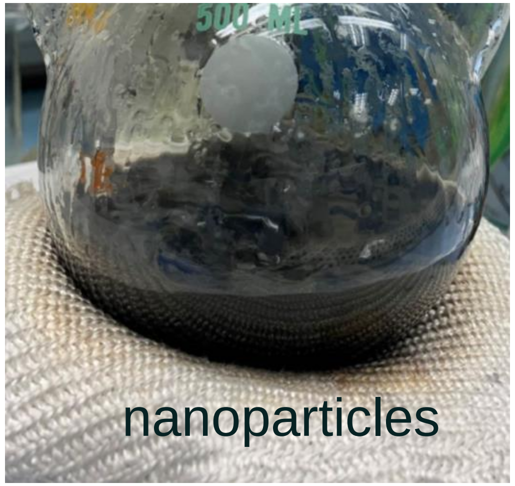
Results and accomplishments

Challenges:

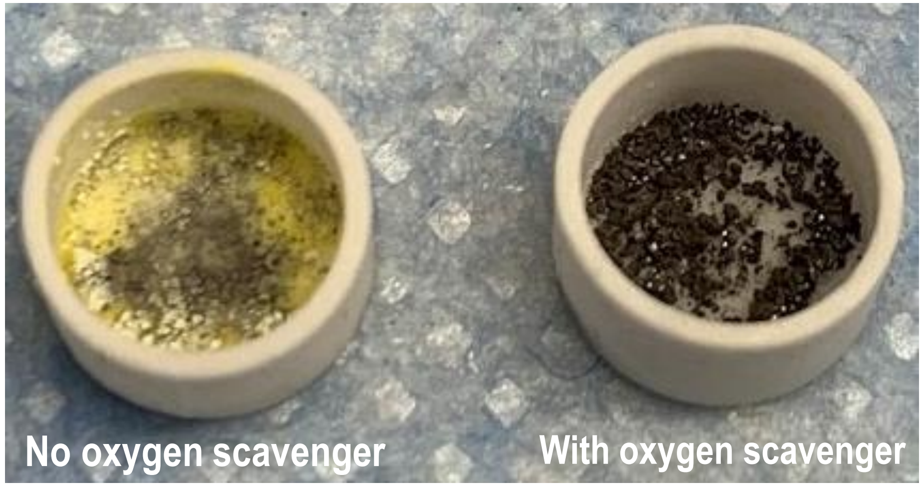
- DSC evaluation – oxidation issues resulted in significant delays
- Synthesis optimization:
  - Synthesis methods were developed in-house guided by literature search
  - Variables to consider: Reducing agent, amount of reducing agent, rate at which reducing agent is added, capping agent, synthesis temperature, purification, etc.
  - Purification of nanoparticles (reaction by-products and excess polymer capping agent)

Microparticle formation vs. nanoparticle formation





Oxidation of bismuth nanoparticles



Conclusion

- **Summary:**
  - Demonstrated a pathway for multi-element nanoparticle synthesis via reduction method
  - Using reduction method four different compositions of Bi/Pt bi-metallic nanoparticles were created.
  - DSC evaluation resulted in different melting points for each Bi/Pt nanoparticle composition
- **Future work:**
  - TEM/EDS particle mapping to evaluate the composition of the individual particles formed (i.e. uniform composition? Or discrete areas of bismuth and platinum within particle?)
  - In/Pt and Ag/Pt bi-metallic systems
  - Demonstrate compatibility with AM techniques: Aerosol Jet Printing (AJP), Plasma Jet Printing (PJP) and Micro Dispense Printing (MDP)

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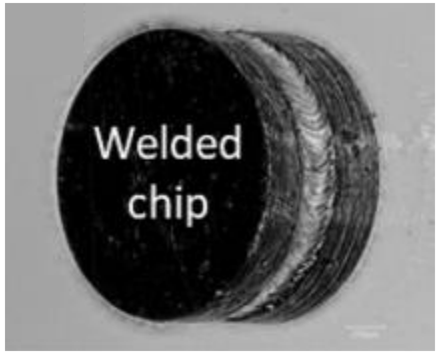
LinkedIn

Durability & Robustness of In-pile Sensors

- ***Advanced manufacturing*** (AM) based on *direct-write techniques* has shown potential in overcoming technical & economic barriers for fabricating sensors & microelectromechanical devices on a large scale
- Sensor robustness and reliability is an important characteristic for nuclear sensors, as in-reactor sensor failure can be both time- and cost-prohibitive.
- ***Typical failure modes***: peeling due to poor adhesion
- Current methods of adhesion measurement based on 'tape peel test'
  - Often unreliable, dependent on type of tape used, applied pressure
  - Destructive – removal of centimeter-sized printed regions

Developing rapid & reliable, *non-destructive* (or *locally destructive*) sensor adhesion/ quality measurement techniques is critical for continued developed of AM in-pile sensors



AM printed melt wire

Aerosol Jet Printed Sensor lines

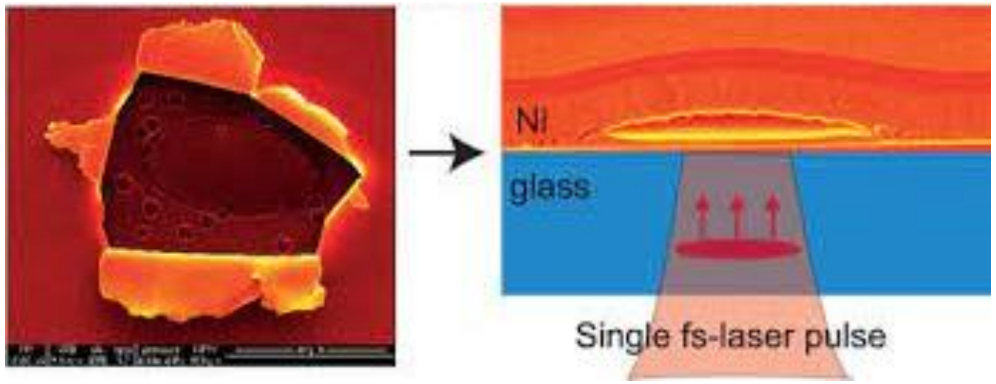
ASTM D3359: Tape Peel Test


Current standard for printed thin film/substrate adhesion measurement

Laser-based techniques for Advanced Manufacturing *Process Control*

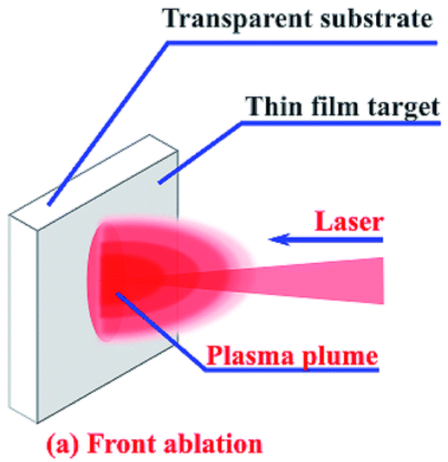
- Laser-based techniques such as *laser spallation*, *laser ablation* & *laser ultrasonics* have been used to measure thin film/ substrate adhesion

Laser-generated shock-induced thin film spallation



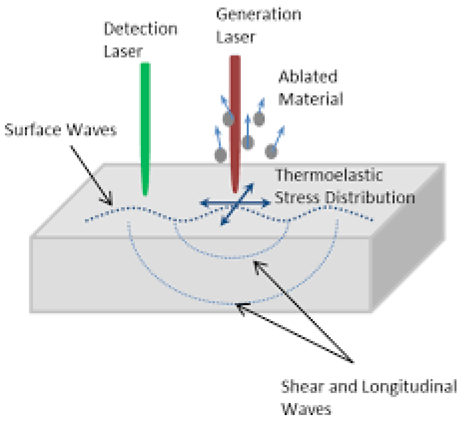
V.V. Temnov, Nano Letters, 20(11), 7912-7918 (2020).

Laser-induced ablation



A. Mondal, J. Analytical Atomic Spectrometry, 34(9), 1822-1828 (2019).

Laser ultrasonics



L. Lindamood, EWI

- Laser-based techniques have potential to serve as process control tool to monitor sensor integrity and determine the combination of factors that affect sensor durability & sensor/substrate adhesion:
  - Substrate surface energy
  - Substrate surface roughness
  - Post-deposition ink sintering temperature & duration
  - Ink deposition rate, ink composition

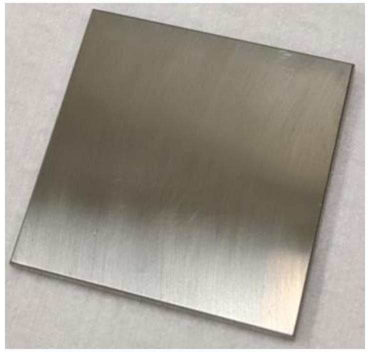
Technology Impact: Accelerate the development of robust sensors for performance in extreme in-pile environments for ***extended durations***.

Effect of Print Parameters on Sensor Morphology & Adhesion

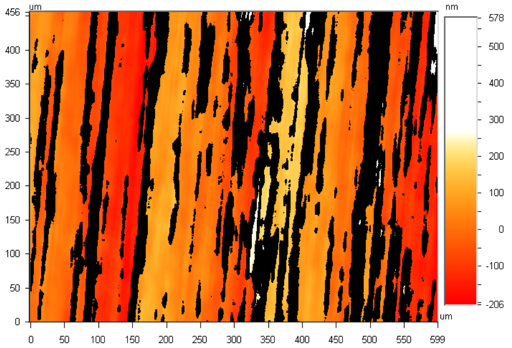
Substrate surface treatment & Ink treatment parameters varied as follows (36 samples total):

- Substrate Surface Roughness:
  - Smooth (R_a ~ 3 nm), Intermediate (R_a ~ 8 nm), Rough (R_a ~ 75 nm)
- Substrate surface energy – Plasma treatment duration:
  - No plasma treatment, short duration (2.5 minutes), long duration (5 minutes)
- Post-printing ink sintering temperature:
  - 250° C or 400° C
- Post-printing ink sintering duration:
  - Short duration (30 minutes), or long duration (60 minutes)

(a) High Surface Roughness

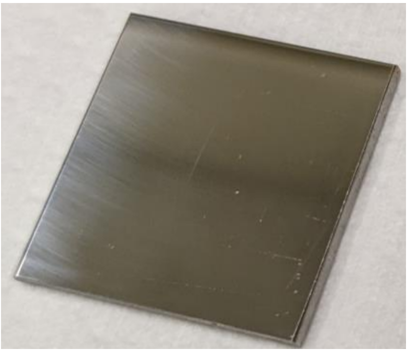


Polished with 600 grit

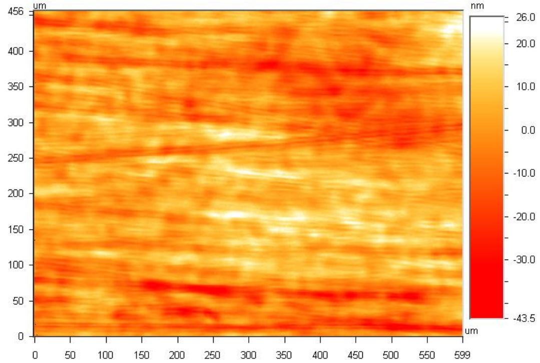


Average Surface Roughness: 73.74 nm

(b) Intermediate Surface Roughness

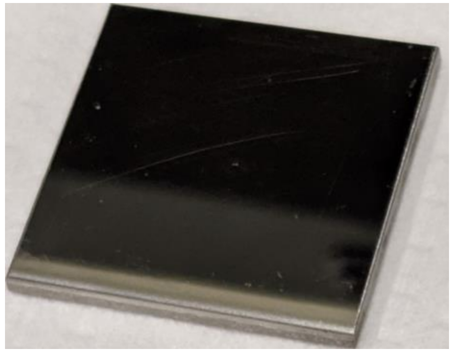


Polished with 800 grit

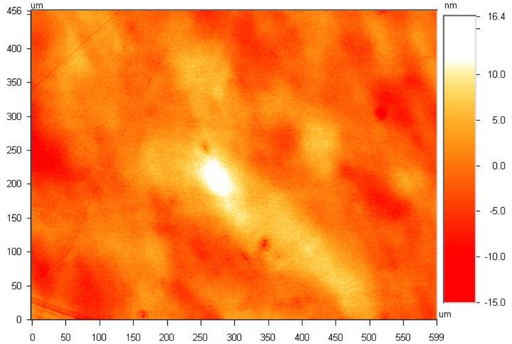


Average Surface Roughness: 7.62 nm

(c) Low Surface Roughness



Polished with 1 μm diamond paste



Average Surface Roughness: 2.72 nm

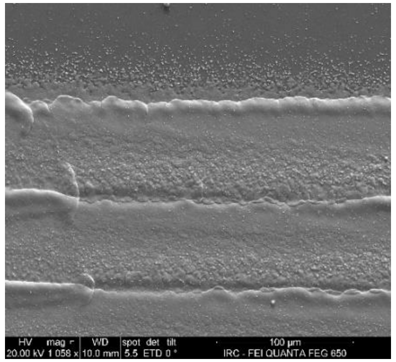
Effect of Print Parameters on Sensor Morphology & Adhesion

Substrate surface treatment & Ink treatment parameters varied as follows (36 samples total):

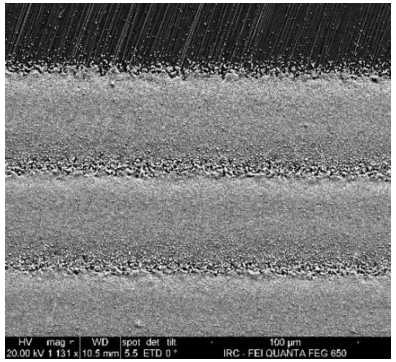
- Substrate Surface Roughness:
  - Smooth (R_a ~ 3 nm), Intermediate (R_a ~ 8 nm), Rough (R_a ~ 75 nm)
- Substrate surface energy – Plasma treatment duration:
  - No plasma treatment, short duration (2.5 minutes), long duration (5 minutes)
- Post-printing ink sintering temperature:
  - 250° C or 400° C
- Post-printing ink sintering duration:
  - Short duration (30 minutes), or long duration (60 minutes)

Sensors printed with silver nanoparticle inks on stainless steel 316L using Aerosol Jet Printing

Sintered at 250° C for 30 minutes



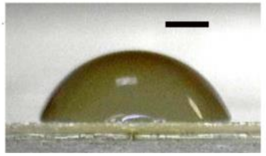
Sintered at 400° C for 60 minutes

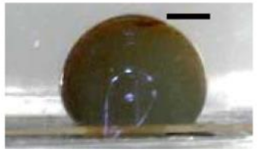


SEM images show silver nanoparticles are “fused” into a continuous film with low porosity for both cases

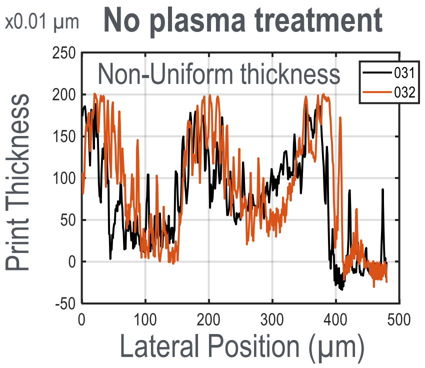
Sensor morphology characterization using optical profilometry

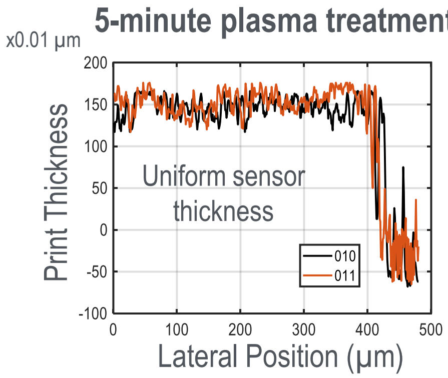
- Plasma treatment yielded uniform sensor thickness in the direction transverse to the print direction
- Non-uniform thickness profiles in substrates that were not plasma treated possibly due to the higher contact angle of the ink droplet on the substrate in these samples



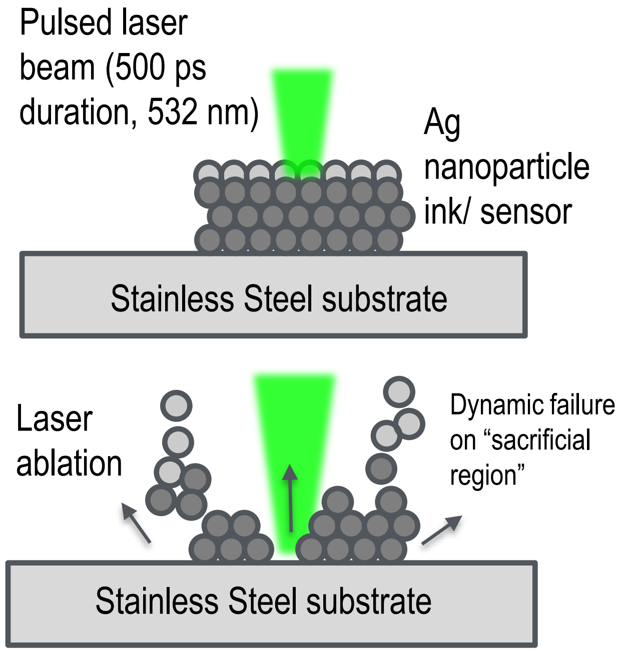


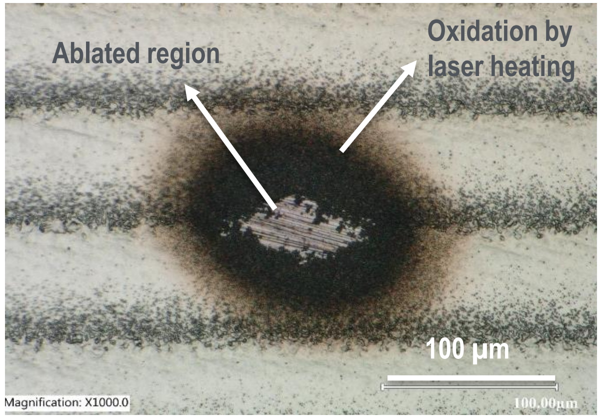
Liu & Watt, Sci. Rep. (2019)



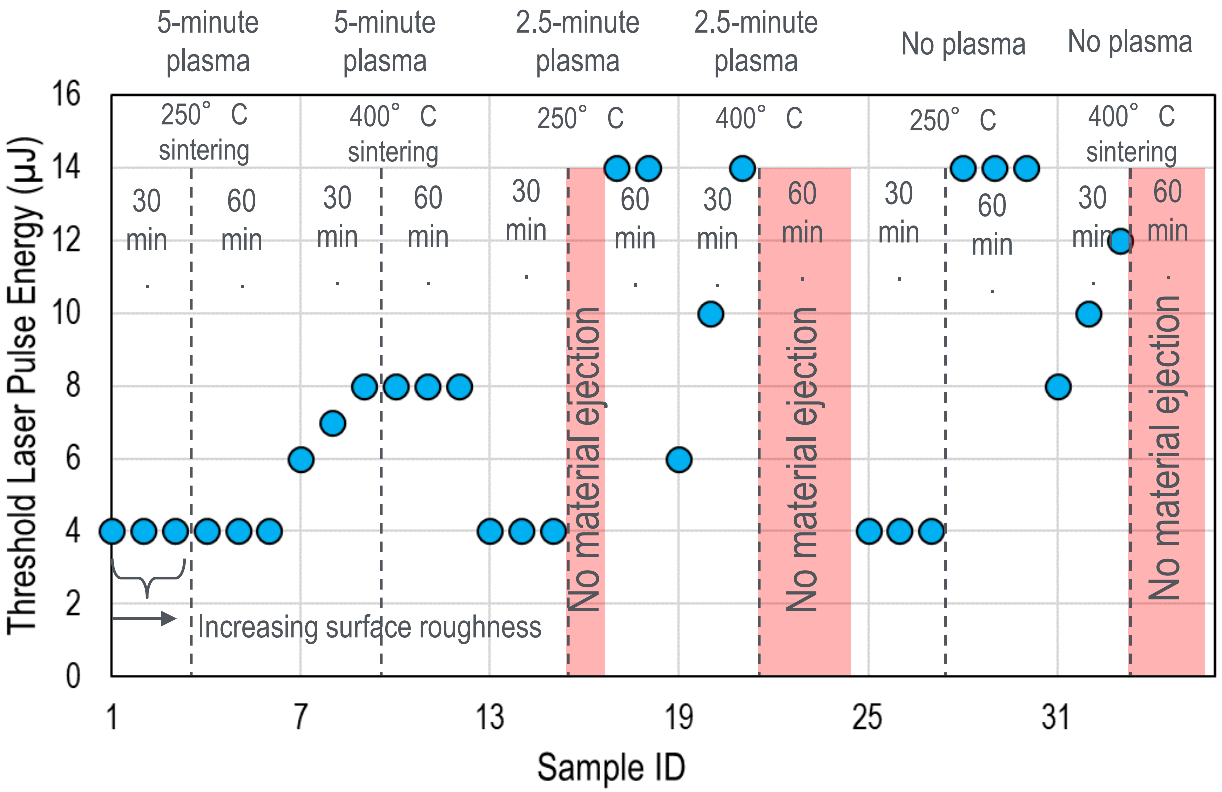


Locally-destructive Measurements of Sensor/Substrate Adhesion using *Laser Ablation*





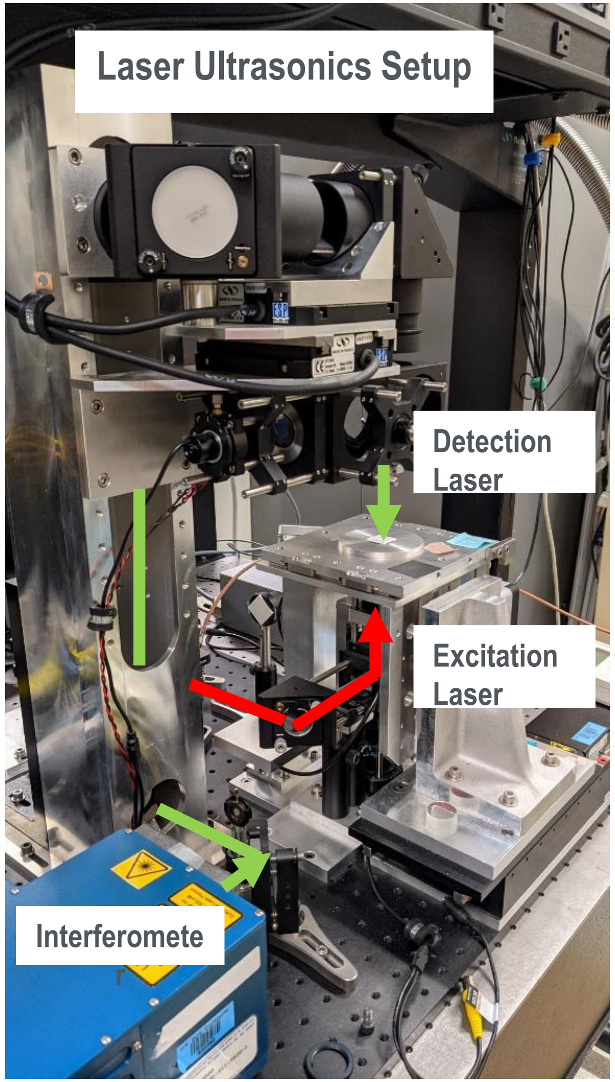
- Printed sensors were irradiated with a *nanosecond-duration pulsed laser beam*
- Senor/substrate interfacial adhesion measured by threshold laser pulse energy required to *ablate* the sensor from the substrate



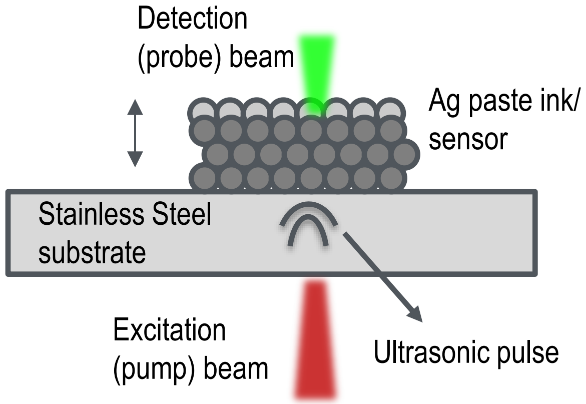
Minimal ablation damage in sensor whose ink was sintered for 60 minutes at 250° C

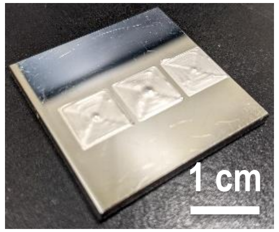
- Highest sensor/substrate adhesion found in sensors that were sintered at **400° C** following ink deposition for **60 minutes**
- For 30-minute sintered samples, **higher surface roughness yielded better adhesion**

Non-destructive Measurements of Sensor Vibration using *Laser Ultrasonics*

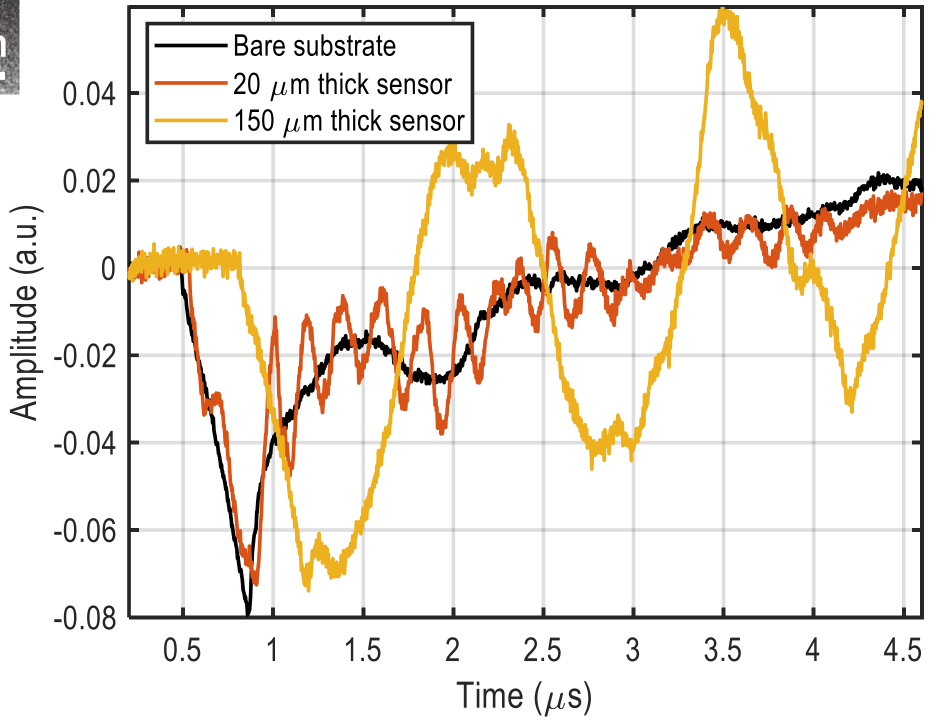


- Pulsed laser beam used to excite ultrasonic pulse in substrate that excites fixed-free vibration of the printed sensor. These vibrations are detected with an interferometer
- Measurements performed on 20 – 150 µm-thick sensors printed with silver ink using Voltera V-One PCB printer

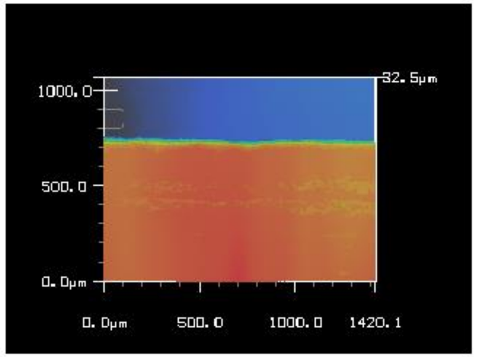




Sensor vibration frequency is a function of sensor thickness



Sensor thickness map



Summary & Future Work

- Laser ablation method for adhesion characterization:
  - Locally destructive (< ~100 µm region of sensor removed from substrate)
- Effect of substrate surface condition & ink treatment conditions on adhesion:
  - Ink sintering duration & temperature are dominant factors that affect adhesion
  - Substrate roughness is a secondary factor – higher roughness → stronger adhesion
  - Substrate surface energy did not alter adhesion, although it influenced sensor morphology

- Future work
  - Develop non-destructive laser ultrasonic technique for adhesion measurement
  - AM techniques: Aerosol Jet Printing (AJP), Plasma Jet Printing (PJP), Extrusion
  - Connection between sensor durability & sensor performance:

Sensor Durability
(Morphology, Adhesion)

↔

Sensor Performance
(Electrical Conductivity)

Questions?

ASI Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Harsh Environment-Tolerant
Flow Sensors For Nuclear Reactor Applications

Dept of Energy #: DE-SC0013858

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

PI: Jon Lubbers, Lead Mechanical Engineer

Sporian Microsystems, Inc.

SPORIAN® MICROSYSTEMS, INC

Project Overview

Objective: Develop a sensor for monitoring SMR coolant flow

- High-temperature + pressure operation (300°C+, 1500psi+)
- Compatible with conductive & corrosive fluids
- Single penetration, compatible with non-circular x-section

Approach: Thermal anemometry (i.e., hot wire/film)

General Functional Requirements:

	Long-term Target Application: SMRs	Near-term Target Application: Industrial Processes
Fluid	Borated water	Molten salts
Operating Temp	300°C	500-700°C
Operating Pressure	>1600 psi	<150 psi
Radiation	~~5E+20 n/cm²~~ 1E+18 n/cm²	N/A, or uncertain
Operating Life	2 years	6 months - 5 years
Commercialization Path	Licensing, partnership, or acquisition	Direct sales

SPORIAN® MICROSYSTEMS, INC

Project Overview

Participants

- Sporian Microsystems, Inc. – product design and development
- Texas A&M University Thermal Hydraulics Lab – superheated water flow testing
- United Controls International – QA consulting

Schedule:

Task #	Task Description	Year 1 (Months)												Year 2 (months)											
		Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20	Feb-20	Mar-20	Apr-20	May-20	Jun-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Mar-21	Apr-21	May-21	Jun-21	Jul-21
Task 1	Work with OEMs & stakeholders to guide transition activities						M1																		
Task 2	Design and implement QA program						M2																		
Task 3	Construct prototypes and perform lab-scale V&V testing													M3											
Task 4	Revise design based on test results, and construct systems for final testing/demonstration															M4									
Task 5	Final V&V testing and demonstration in representative system tests																								M5

SPORIAN® MICROSYSTEMS, INC

Technology Impact

Applicable Industries

- SMR
- MSR
- Concentrating solar power & thermal energy storage
- Glass processing (salt ion exchange)
- Metal making / refining

Benefits

- Visibility over flow conditions
- Characterize fluid (coolant) mixing and cooling

Features

- No pipe necessary
- Single penetration

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Results and accomplishments

System Design

- Standard footprint
- Custom process interfaces
- Developing plug-and-play functionality

Challenges

- Stability of internal components
- Calibration across wide operating range
- COVID and supply chain delays

QA program updates

- Approaching NQA-1 / 10-CFR-50 Appendix B compliance
- Goal is to facilitate commercialization, not certification

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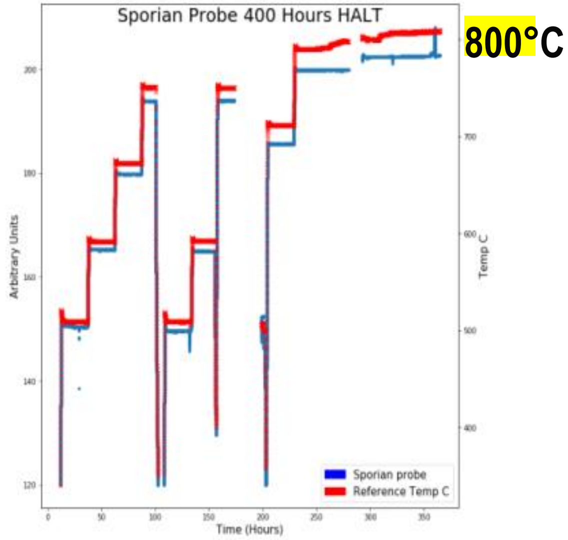
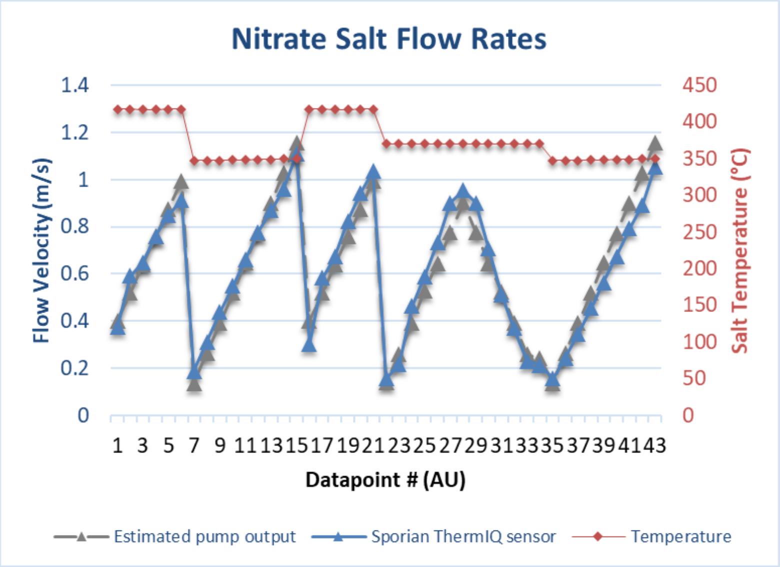
Results and accomplishments

Testing

- High pressure: 100-hour soak at 1700 psig in borated water
  - After “burn-in” period, no effect on flow sensing performance in water
- High temperature survival and aging
  - Stable over 100+ hours at 800 ° C, drift in flow response but appears repeatable





- Superheated water system testing
  - Extensive testing at Texas A&M to start in early 2022
  - Evaluation in AMS (results not yet available)
- Molten salt system testing
  - Nitrate salts – demonstrated roughly ±5% FS accuracy
- Still to come: neutron irradiation stability testing
  - 1E18 n/cm^2

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Coming Soon…

Upcoming Flowmeter Product Release

- Limited initial sales in January 2022
- Currently seeking early adopters
- More information at **http://www.sporian.com/ASI.html**

Related devices on the way…

- High-temperature pressure sensor
- In situ chemistry analyzer for molten salts

Contact Information

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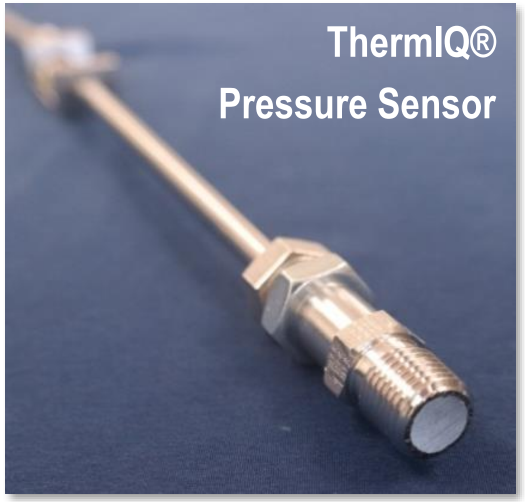
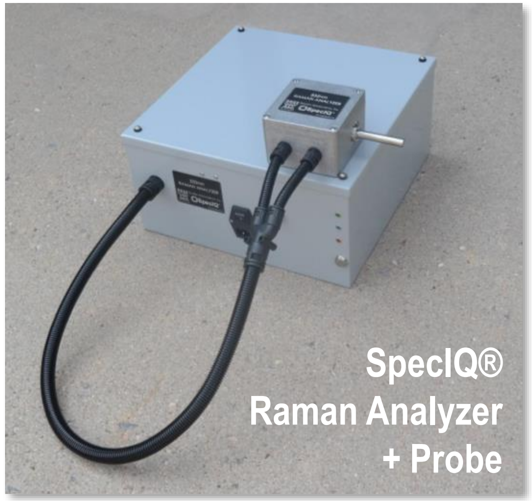
jlubbers@sporian.com
(303)-516-9075 ext.16





SPORIAN® MICROSYSTEMS, INC

Questions?

Advanced Sensors and Instrumentation

Unprecedented capabilities in the world's harshest environments

Contact Information

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https://www.sporian.com/ASI.html

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ASI Advanced Sensors and Instrumentation

High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Graduate Fellow: Kelly McCary, Ph.D. Candidate

Idaho National Laboratory/Measurement Science

Project Overview

- Goals and Objectives

Investigate the in-pile performance of sapphire optical fiber temperature sensors and to develop clad sapphire optical fibers for in-pile instrumentation. Evaluate the distributed sensing performance of the sensors through optical backscatter reflectometry under combined radiation and temperature effects, and high fluence.

- Objective 1: Fabricate sapphire optical fiber sensors.
- Objective 2: Evaluate the clad sapphire fiber to verify few-mode behavior and determine and characterize light modes supported by optical fibers.
- Objective 3: Characterize in-pile temperature sensing of sapphire optical fiber and combined temperature and irradiation effects.
- Objective 4: Evaluate the lifetime and sensing performance of the sensor under irradiation to high neutron fluence.

- Participants (2021)
  - Idaho National Laboratory: Lead organization
    - Dr. Joshua Daw, Kelly McCary
  - The Ohio State University
    - Dr. Thomas Blue, Josh Jones, NRL
  - The Massachusetts Institute of Technology
    - NRL
  - National Energy Technology Laboratory
    - Dr. Michael Buric
  - Oak Ridge National Laboratory
    - Dr. Christian Petrie

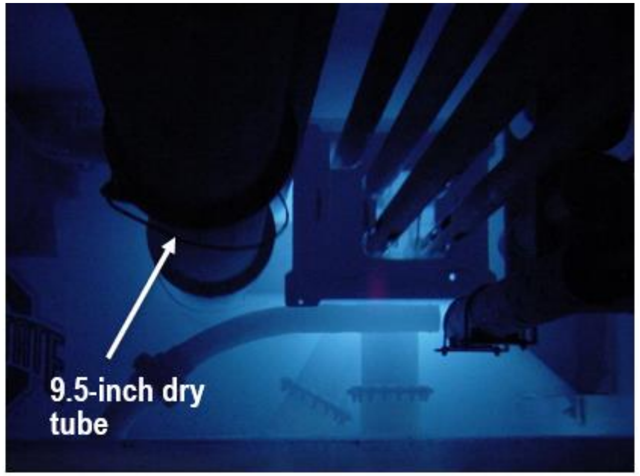
FY2020		Status	Scheduled	Actual	Notes
Task 1	Clad Sapphire Optical fiber	Complete	January 2020	March 2021	Delayed due to procurement of sapphire fibers
Task 2	Characterize Sapphire Fiber	*Complete	June 2020	April 2021	Delayed -covid travel restrictions
Task 3	OSURR Irradiation	Complete	October 2020	April 2021	Delayed -covid travel restrictions
	Deliverable 1: Sapphire Fibers	Complete	September 2020	March 2020	
	Deliverable 2: FY20 Annual Report	Complete	September 2020	September 2020	
FY2021					
Task 2	Characterize Sapphire Fiber	*Complete	June 2020	April 2021	Delayed -covid travel restrictions
Task 3	OSURR Irradiation	Complete	October 2020	April 2021	Delayed -covid travel restrictions
Task 4	Data Analysis: OSURR Data	On-going	May 2022		
Task 5	MITR Irradiation	Delayed	January 2022	TBD	Scheduling delay
	Deliverable 1: Experimental Data	Complete	September 2021	April 2021	
	Deliverable 2: FY21 Annual Report	Complete	September 2021	September 2021	
FY2022					
Task 4	Data Analysis: MITR	Planned	September 2022		
Task 5	MITR Irradiation	Delayed	January 2022	TBD	Scheduling delay
	Deliverable 1: Journal Paper	Planned	September 2022		
	Deliverable 2: Final Report	Planned	September 2022		

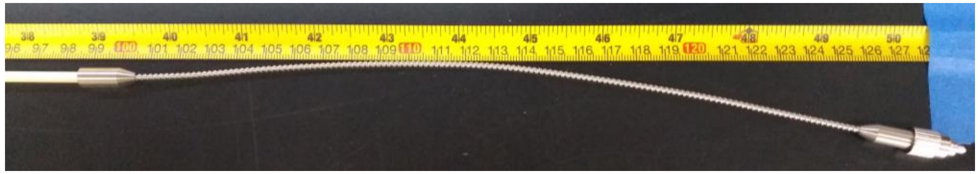
Technology Impact

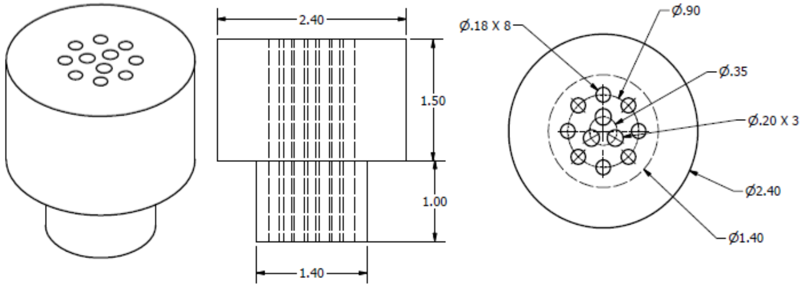
- This work is advancing nuclear technology by characterizing and demonstrating a new sensor technology with the potential to make measurements with high spatial and temperature resolution at higher temperatures than prior optical sensors. This technology can also be applied to measurements other than temperature.
- This research will deliver modern optical fiber sensing techniques usable in multiple extreme environment applications. In the area of nuclear fuel/material testing, these fibers will enable access to operational data with excellent time and space resolution during irradiation testing.
- Commercialization is underway by Luna Innovations. This research represents the opportunity to close technology gaps and demonstrate the potential of sapphire optical fibers.

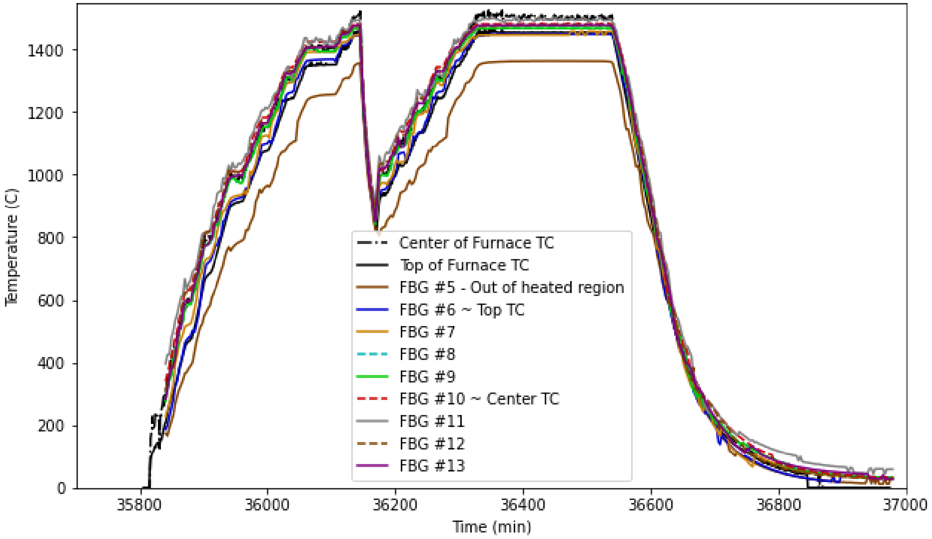
Accomplishments

- Sapphire fiber preparation:
  - Fiber procurement
  - FBG inscription
  - Fiber cladding irradiations
  - Annealing
  - Mode-stripping treatment
- Out of pile furnace testing
- Heated irradiation at OSURR









Accomplishments: Sapphire Preparation

Sapphire fiber cladding:

- Four one-day irradiations were completed with the purpose of cladding sapphire fiber
  - Cladding Irradiation #1: Completed January 24, 2019
    - 2 fibers, 100 um OD, with 2 FBGs inscribed by UPitt
    - 1 fiber, 100 um OD, without FBGs
    - 1 fiber, 75 um OD, with 13 FBGs inscribed by FemtoFiberTec
  - Cladding Irradiation #2: Completed March 13, 2020
    - 4 fibers, 100 um OD, each with 1 FBG inscribed by UPitt
  - Cladding Irradiation #3: Completed March 12, 2021
    - 2 fibers, 125 um OD, each with 4 FBGs inscribed by FemtoFiberTec
  - Clad Irradiation #4: Completed March 19, 2021
    - 4 fibers, 125 um OD, each with 4 FBGs inscribed by FemtoFiberTec

Post-Processing:

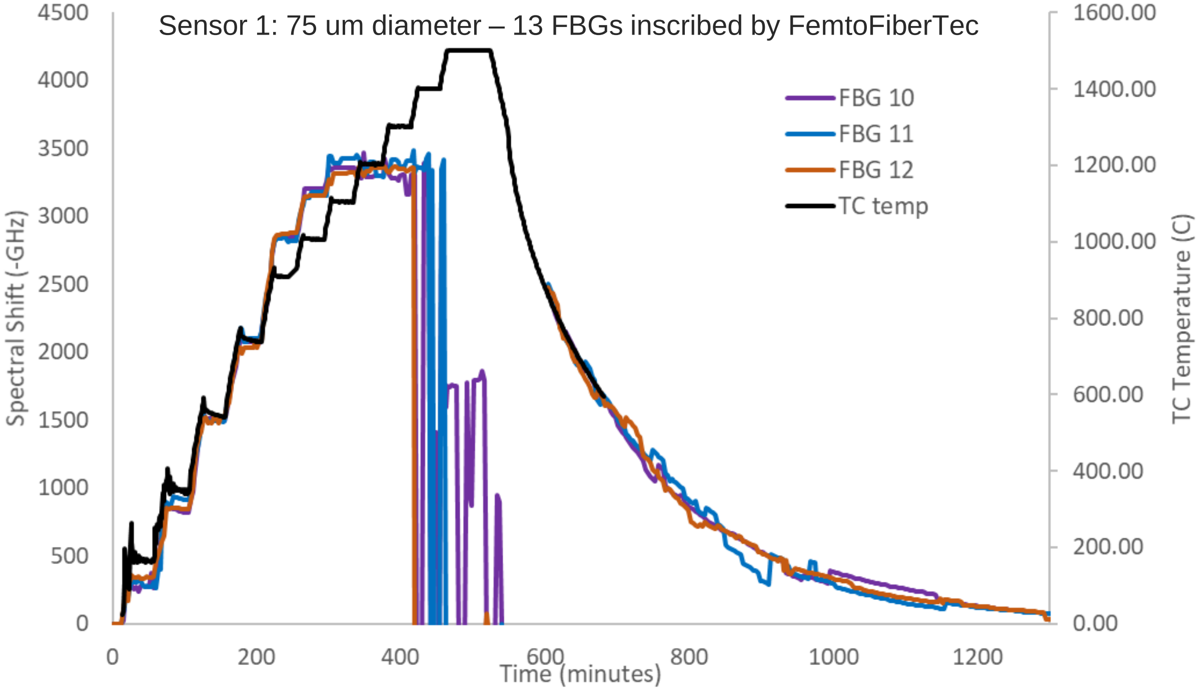
- Thermal annealing, polishing and splicing

Challenges: Annealing, Splicing

Results: Out of Pile Testing

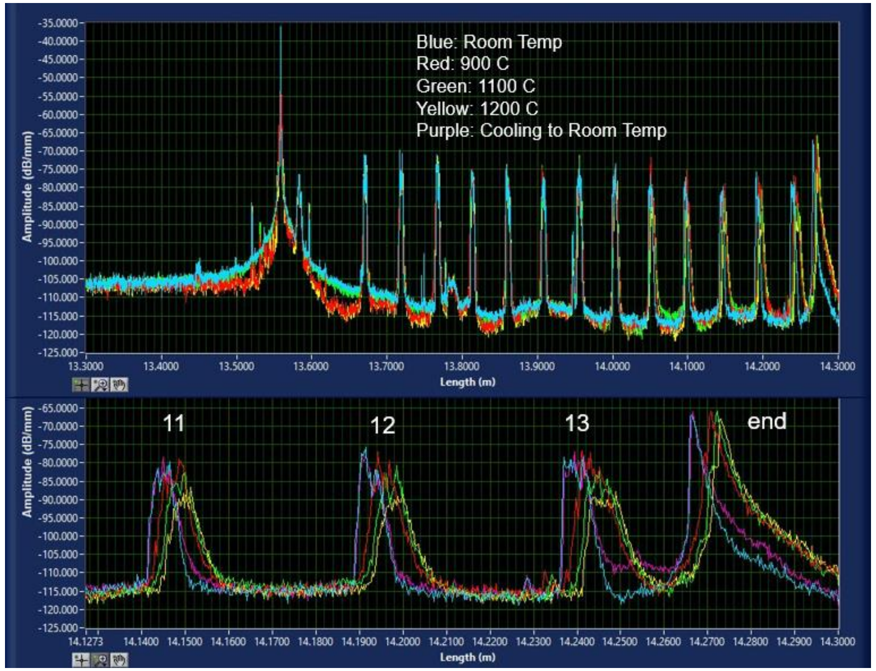
Sapphire optical fiber sensors were tested in a box furnace at up to 1500ºC prior to deployment in OSURR

- 8 in. heated region
- Interrogated with a Luna Innovations OBR 4600
- All the fibers were placed in alumina tubes that were closed on the heated end, then spliced to silica lead-out fibers
- When the furnace was heated past 1100ºC, the sensing mechanism failed



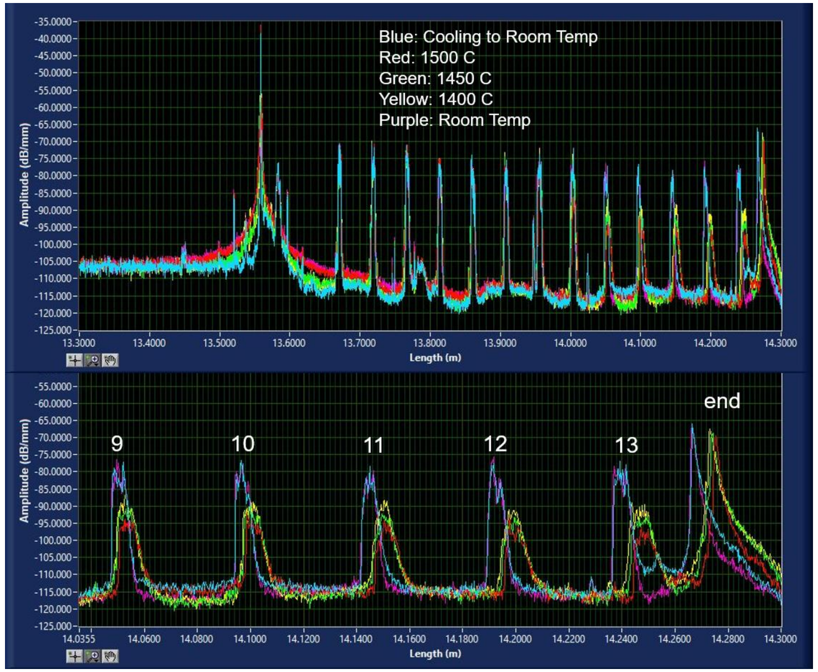
Results: Out of Pile Testing

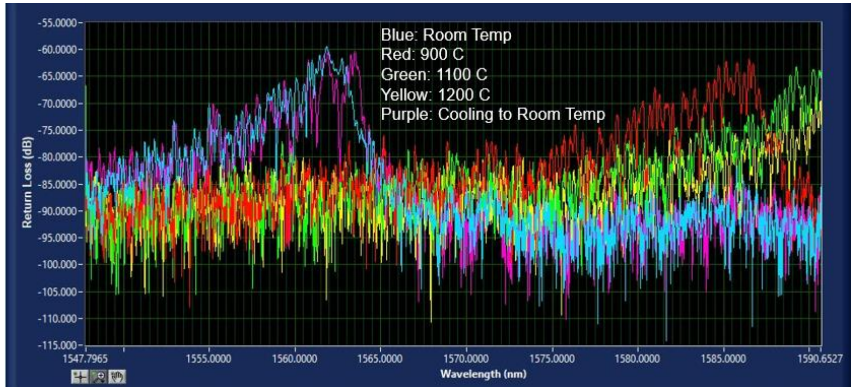
We believe this sensing failure was partially due to the wavelength range of the interrogator



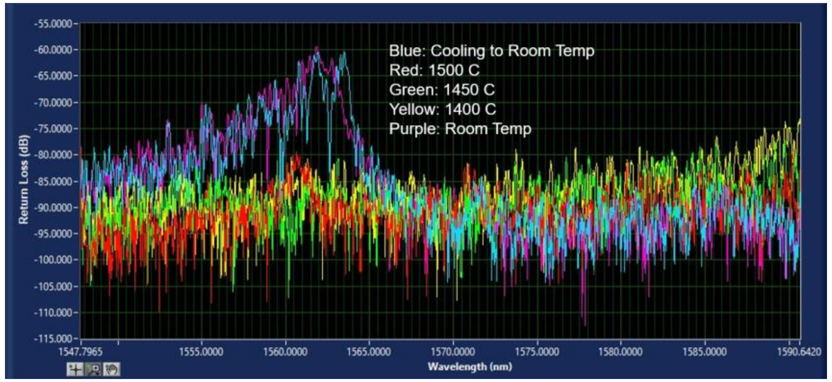
Top: Backscatter profile of sensor #1 before, during, and after the out-of-pile heating from room temperature to 1200°C. Bottom: Top image zoomed in on the last three FBGs in the fiber.

Top: Backscatter profile of sensor #1 before, during, and after the out-of-pile heating from room temperature to 1500°C. Bottom: Top image zoomed in on the last three FBGs in the fiber.





Top: Frequency response of FBG #12 before, during, and after the out-of-pile heating from room temperature to 1200°C. Bottom: Frequency response of FBG #12 before, during, and after the out-of-pile heating from room temperature to 1500°C.



Results: Heated Irradiation

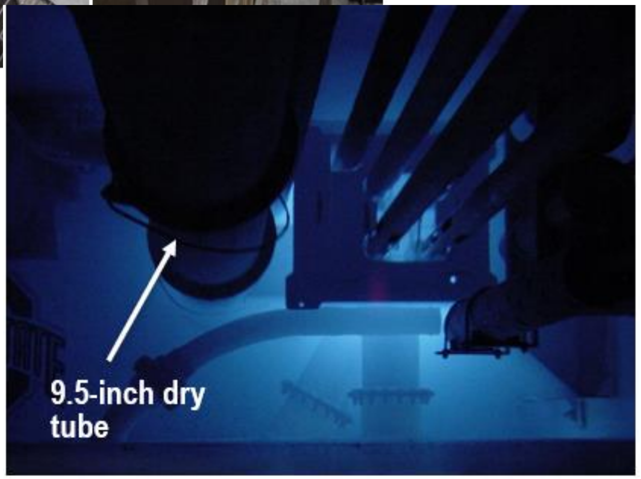
Sensor 1: 75 um diameter – 13 FBGs inscribed by FemtoFiberTec
- Annealed to 1500˚C in air, 23.5 in. long

Sensor 2: 100 um diameter – 2 FBGs inscribed by UPitt
- Annealed to 1500˚C in air, 13 in. long

Sensor 3: 100 um diameter – 1 FBG inscribed by Upitt
- Annealed to 1200˚C in air, 15.25 in. long

Sensor 4: 100 um diameter – No FBGs
- Annealed to 1500˚C in air, 9.25 in. long

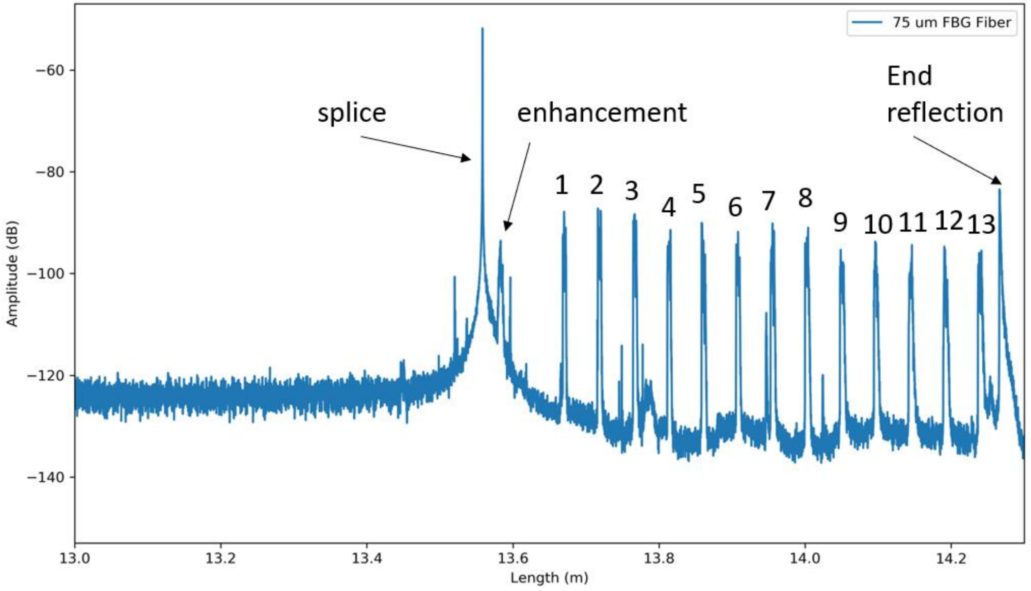
Sensor 5: 100 um diameter – 1 FBG inscribed by Upitt
- Annealed to 1500˚C in air, 16.25 in. long



Results: Heated Irradiation

The heated irradiation was designed to test the fibers at various temperatures from ambient to 1600ºC

- Total fluence: 3.2×10^{17} n/cm^2
  - Thermal: 2.3×10^{17} n/cm^2

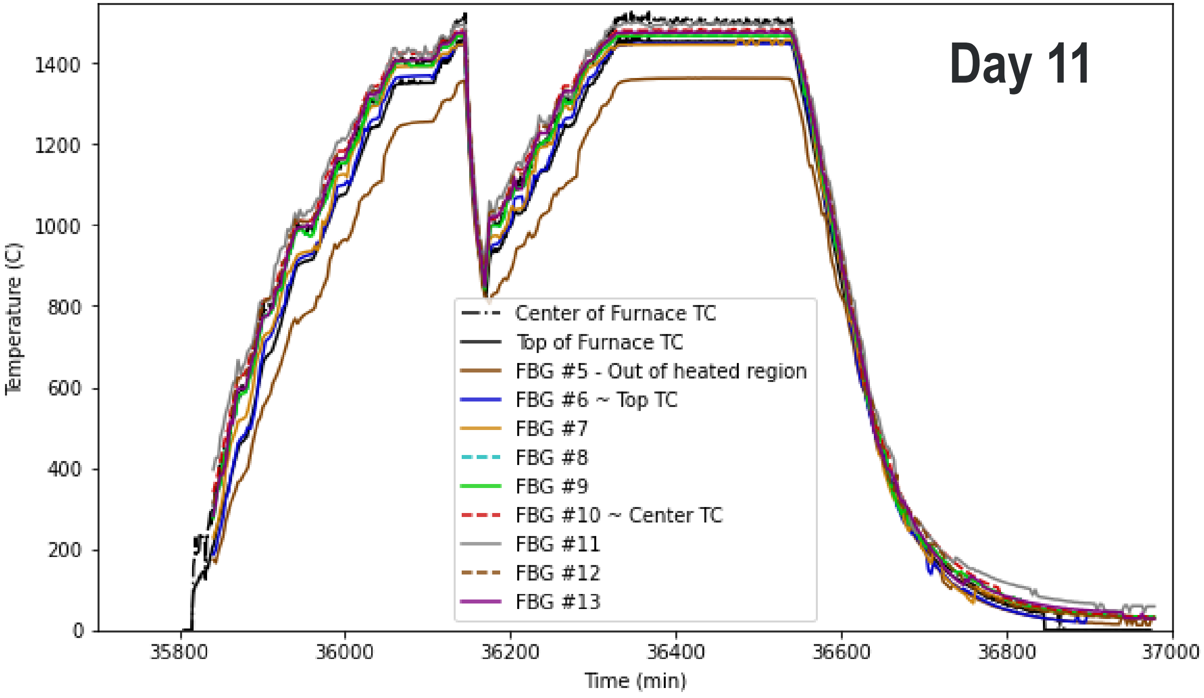


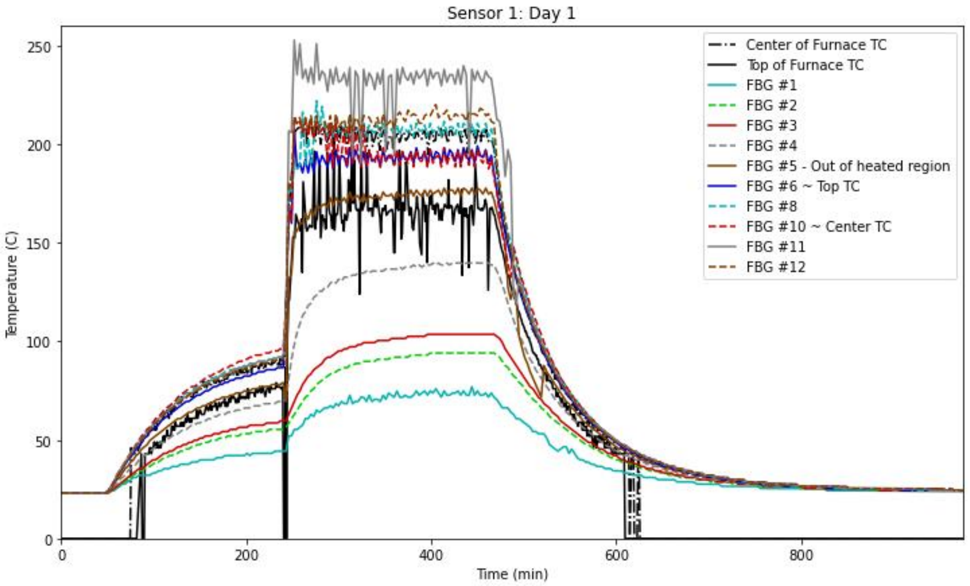
Backscatter profile of sensor #1, 75 um OD sapphire fiber featuring FBGs inscribed by FemtoFiberTec.

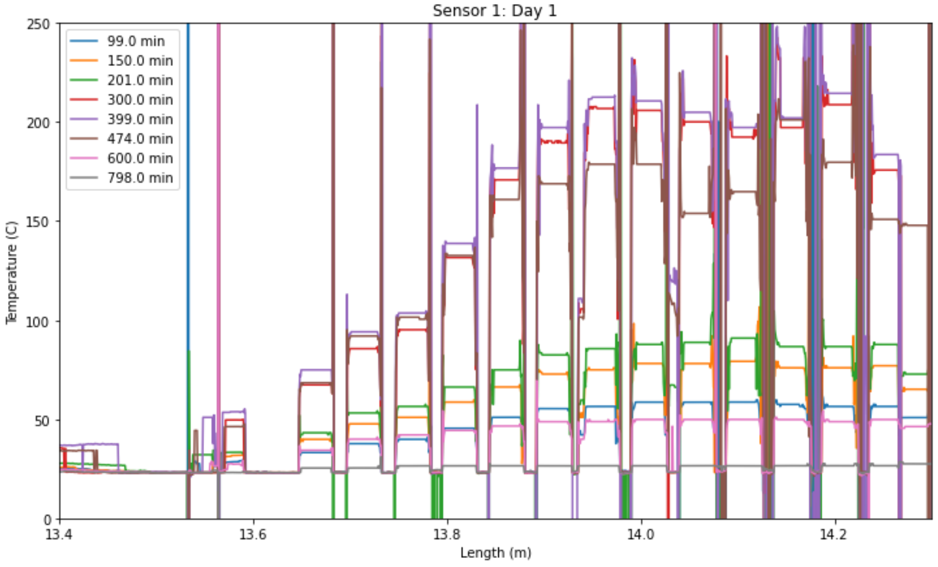
Day	Hours	Power (kW)	Furnace Temp. (Celsius)	Notes
1	7	450	off/200	
2	7	450	400/600	
3	7	450	800	
4	4	450	900	4 hours, some hours for another customer at 5 kw
5-1	0		1000	Fuse blow
5-2	7	450	1000	
6	7	450	1100	
7	7	450	1200	
8	7	450	1300	
9	7	450	1400	
10	7	450	1.5 hrs at 800, 2 hrs at 1000, 2 hrs at 1200	
11	7	450	1400 1 hr at 1500	Fuse blow during heating
12	6	450	1500 1 hr at 1600	

Results: Heated Irradiation

- The measurement was resolved at the locations of the FBGS
- Sensor 1 – 75 um OD – performed the best
- Sensor gets less noisy with higher temperatures

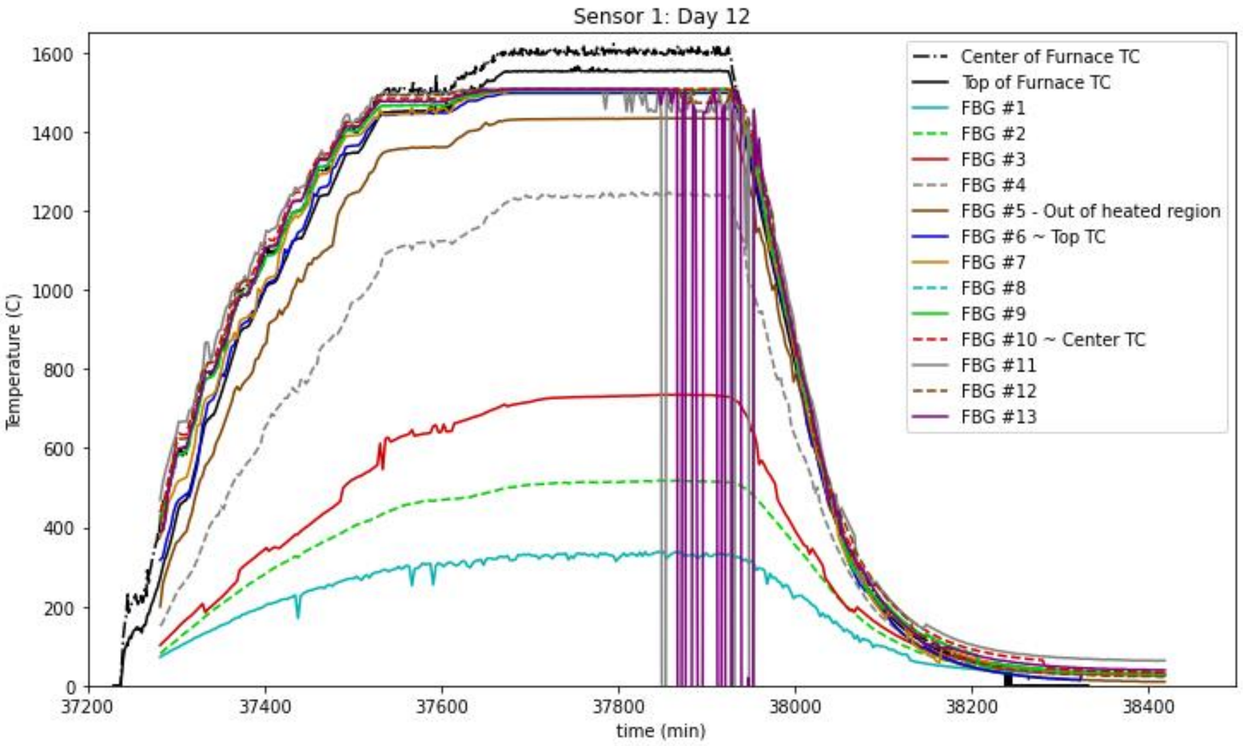


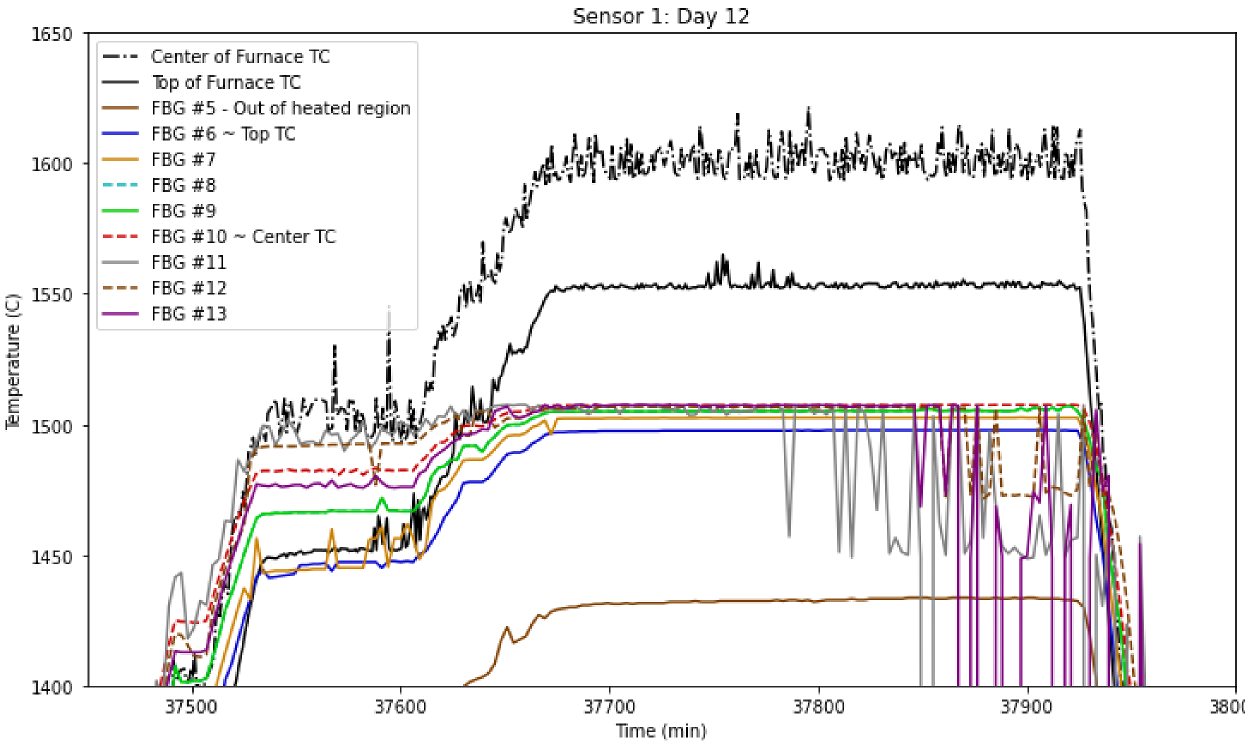




Results: Heated Irradiation

- Similar failure mechanism was observed at 1600ºC in-pile as was observed in out of pile testing.



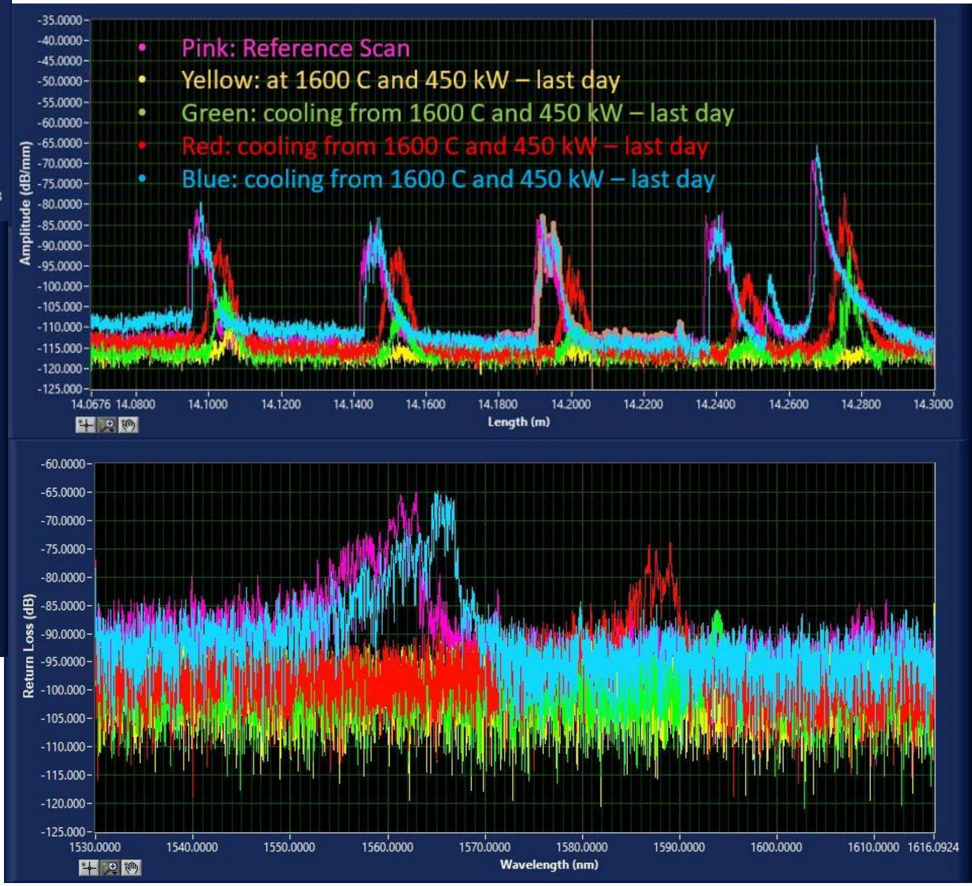


Results: Heated Irradiation

- After signal loss and amplitude reduction the FBGs recover as the fiber cools to room temperature
- Similar amplitude reduction up to 1500ºC that was seen in furnace testing

Backscatter profile and wavelength response of FBG #12 for sensor #1 for the last day of irradiation heating.

Backscatter profile and wavelength response of FBG #12 for sensor #1 for the last day of irradiation cooling.



Conclusion

Challenges:

- Procurement, inscription, and processing of sapphire
  - Non-commercial supplier of sapphire fibers experienced unforeseen issues
  - Inscription of sapphire fibers is not a trivial task
  - Splicing fibers can produce variable results
- Handling tritium-implanted fibers at INL
- Navigating through travel restrictions and shutdowns

Conclusions:

- Objectives 1-3 have been completed
- Heated irradiation indicates potential for sapphire fiber-based sensors to be used in extreme environments beyond silica fiber limits

Future Work:

- Further evaluation of un-clad sapphire fibers to determine source of attenuation in fiber
- High-fluence irradiation at MITR

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We would like to acknowledge the support of The Ohio State University Nuclear Reactor Laboratory and the assistance of the reactor staff members, Andrew Kauffman, Dr. Susan White, Kevin Herminghuysen, Matthew Van Zile, and Maria McGraw for the irradiation services provided.

Special thanks to Dr. Blue, Josh Jones, and Dr. Birri for their assistance at Ohio State.

This work was supported by the U.S. Department of Energy, Office of Nuclear Energy as part of a Nuclear Science User Facilities experiment

NSUF Nuclear Science User Facilities

Questions?

ASI

Advanced Sensors and Instrumentation

Advanced Materials and Manufacturing Methods for Sensors Applications

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

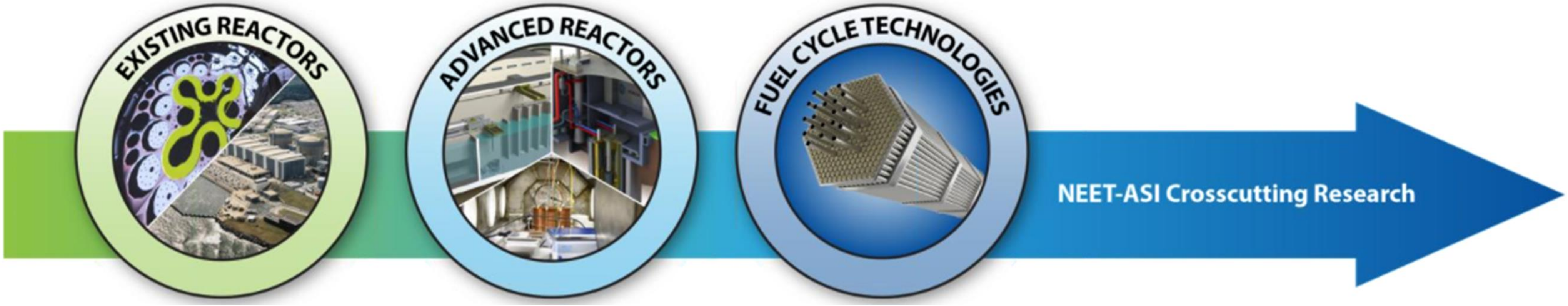
November 15 – 18, 2021

Michael McMurtrey, PhD

Idaho National Laboratory

Advanced manufacturing for ASI

- ASI supports both existing (including test reactors) and advanced reactors
- Mission: Develop advanced sensors and I&C that address critical technology gaps for monitoring and controlling existing and advanced reactors and for supporting fuel cycle development
- AM within ASI: Integrate advanced manufacturing technology in sensor fabrication process for performance improvement and cost reduction



Sensors produced by AM

- NASA looking to 3D printing to allow technicians to print a suite of sensors on one platform to simplify the integration and packaging process, including sensors for planetary rovers to detect trace amounts of chemicals
- The US Department of Defense has been exploring printed sensors for a number of application, including the printing of flexible sensors worn by soldiers to provide real-time monitoring of toxins and other physiological events
  - AM allows more functionality into less volume
  - Integrates electronic circuitry with physical packaging
- Biomedical, robotic, aerospace and other industries are examining AM produced sensors for similar reasons

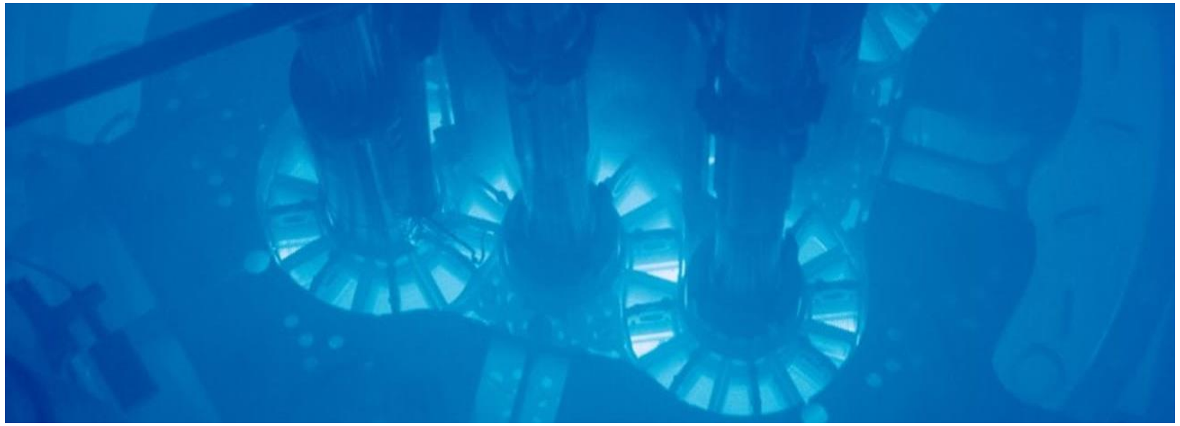
https://www.nasa.gov/feature/goddard/2019/nasa-to-advance-unique-3d-printed-sensor-technology
D.T. Bird, et. al., Polymers, 2021, 13, 1455
R.S. Mahale et. al., Biointerface Research in Applied Chemistry, 2021, Vol. 12, 3, 3513

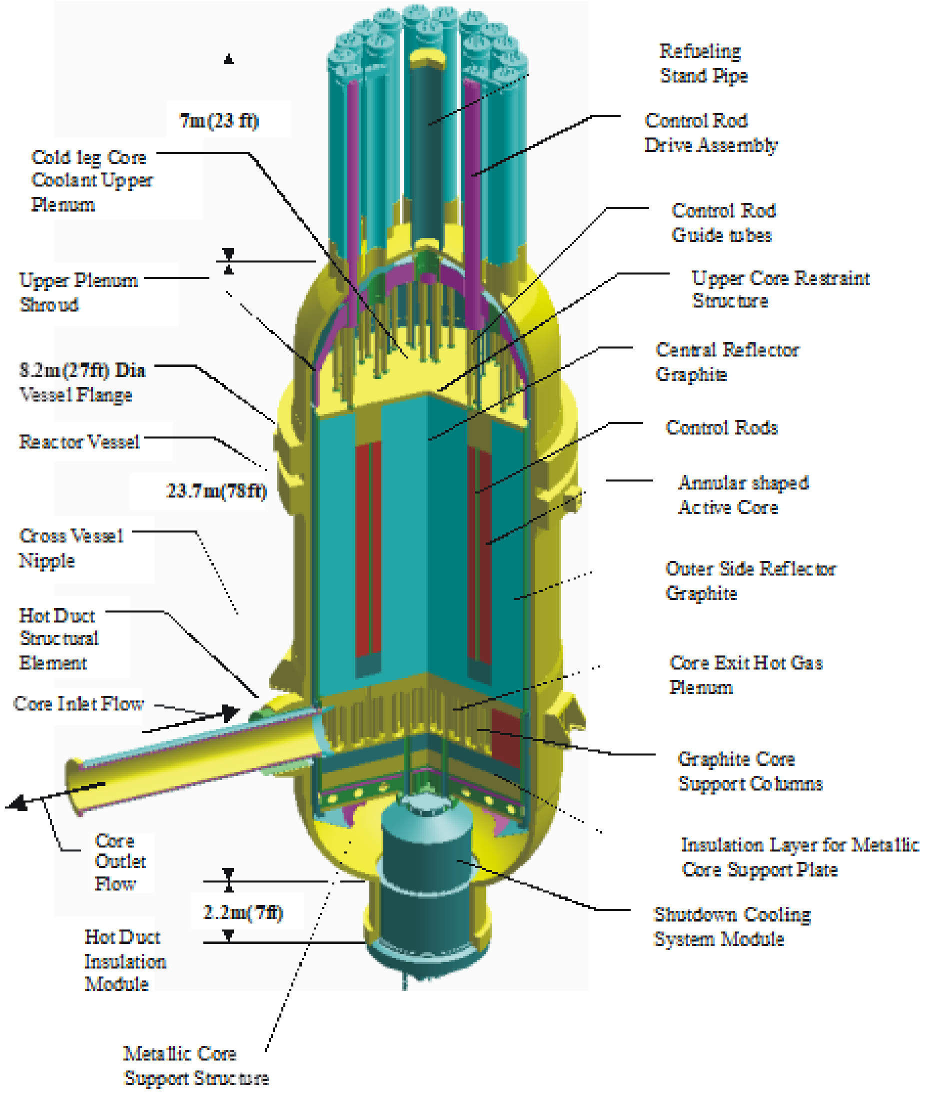
Nuclear Sensors by AM Overview

- Harsh environments inside nuclear reactors are challenging for materials, whether fuels or structural
- There has always been a need to understand material behavior in these environments
  - Test reactors and surveillance/monitoring in commercial reactors have helped fill in the gaps in understanding
  - Severe limitations in data collected solely in post-irradiation examination
- High difficulty in collecting information during irradiations due to the very harsh environment
- Clever sensor designs, novel material choices have historically made some instrumented experiments possible
- Integration of advanced manufacturing techniques paired with advanced materials will further expand possible measurements – more measurements, smaller sensors, fewer feedthroughs

Sensors by AM Overview

- Measurements of interest
  - Temperature
  - Flux
  - Pressure
  - Fluid flow
  - Composition
  - Structural integrity
  - Cracking
  - Deformation (strain/creep, swelling, etc.)
  - Stress
  - Microstructural changes





AM overview

- Advanced manufacturing covers a broad spectrum
  - On a general level, use of innovative technology to improve processes to create products
- One such technique is additive manufacturing, the process of joining material together layer by layer
  - Has seen significant interest for nuclear structural materials, fuels/cladding, as well as sensors and instrumentation

Additive Manufacturing

- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
- Sheet Lamination
- Vat Photopolymerization

Additive Manufacturing

- Binder Jetting
  - An additive manufacturing process (AM) in which a liquid bonding agent is selectively deposited to join powder materials
  - Can print almost any material
  - Typically used for structures, which could house electronics
- Powder Bed Fusion
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
- Sheet Lamination
- Vat Photopolymerization

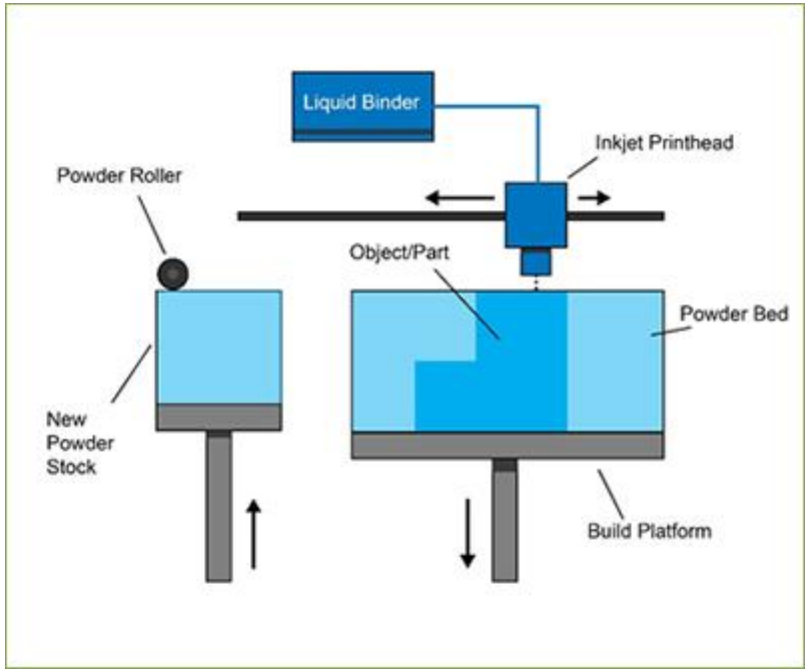


Image courtesy of Loughborough University

Additive Manufacturing

- Binder Jetting
- Powder Bed Fusion
  - An AM process in which thermal energy selectively fuses regions of a powder bed
  - One of the leading metal AM technologies
  - Already used in industrial application (aerospace, medical, etc.), but almost exclusively for structural components
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
- Sheet Lamination
- Vat Photopolymerization

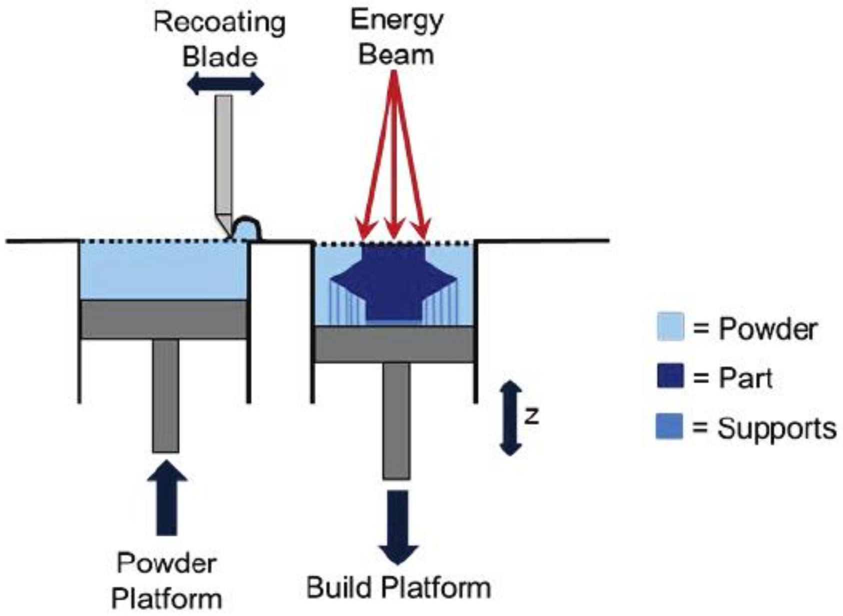


Image courtesy of NIST

Additive Manufacturing

- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
  - – An AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited
  - – Similar in application to Powder Bed
- Material Extrusion
- Material Jetting
- Sheet Lamination
- Vat Photopolymerization

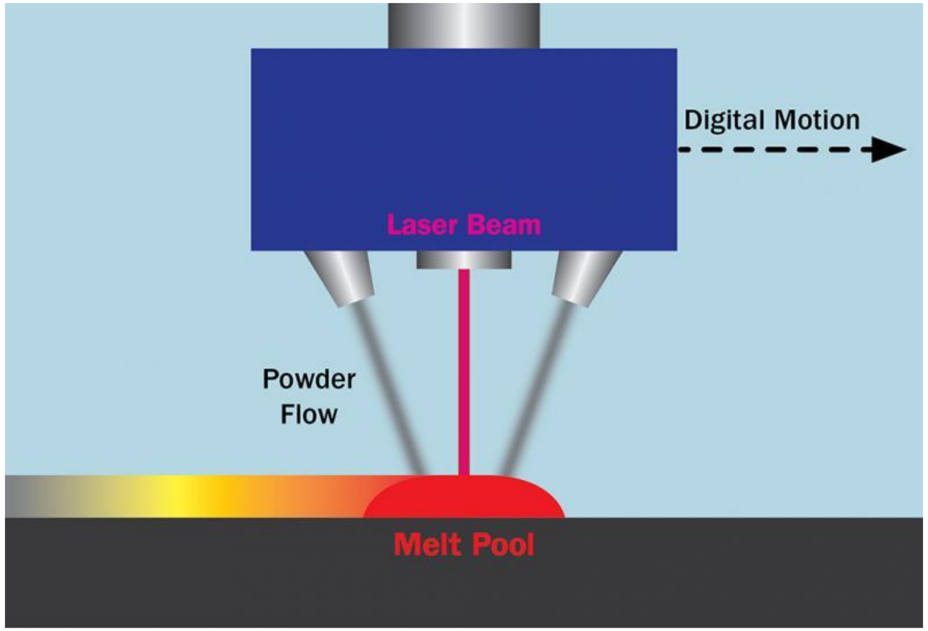


Image courtesy of Optomec

Additive Manufacturing

- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
- Material Extrusion
  - An AM process in which material is selectively dispensed through a nozzle or orifice
  - Typical plastic 3D printer, commercially available for home or industrial use, but has been used for other materials, including slurries
  - Relatively cheap
- Material Jetting
- Sheet Lamination
- Vat Photopolymerization

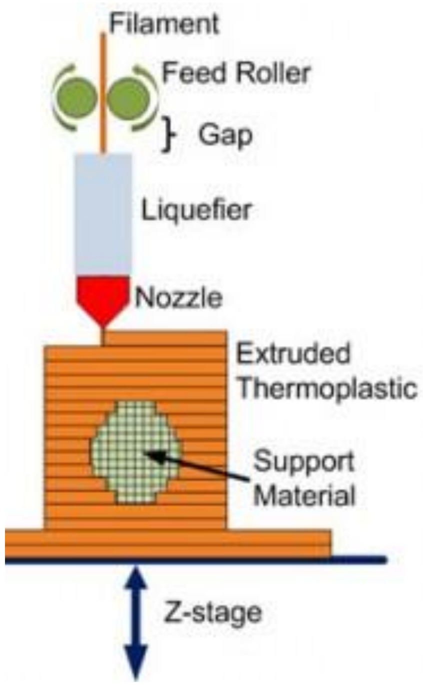
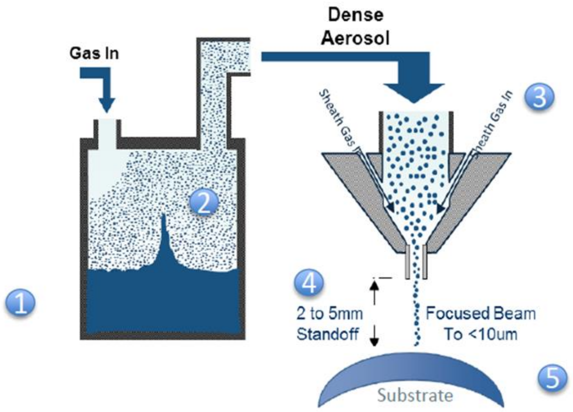
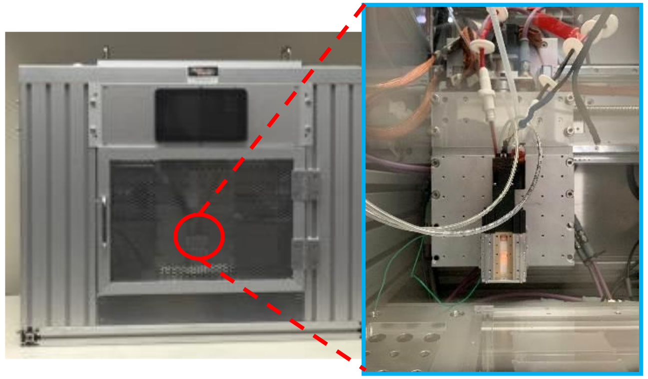


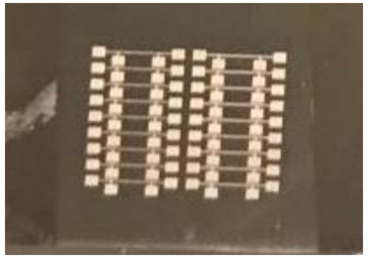
Image courtesy of Virginia Tech

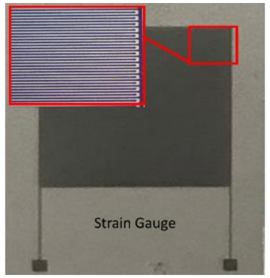
Additive Manufacturing

- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
  - An AM process in which droplets of build material are selectively deposited
  - Droplets originate from an "ink", which may be a polymer or a liquid carrying nanoparticles
  - Typically high resolution, but slower, so large builds are not practical
  - Great for fine features and low profile associated with many types of instrumentation
- Sheet Lamination
- Vat Photopolymerization









Additive Manufacturing

- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
- Sheet Lamination
  - An AM process in which sheets of material are bonded to form an object
  - Works for a variety of materials:
    - Paper, bond using glue
    - Plastic, bond using heat or glue
    - Metal, bond using welding
- Vat Photopolymerization

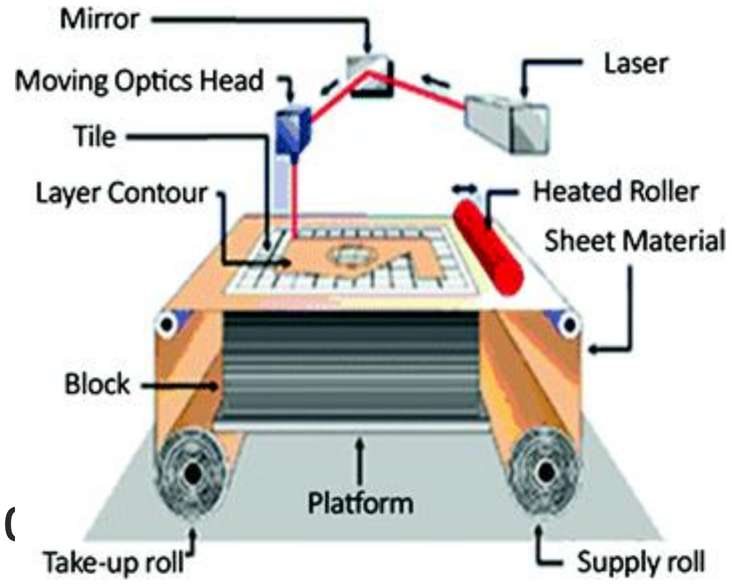
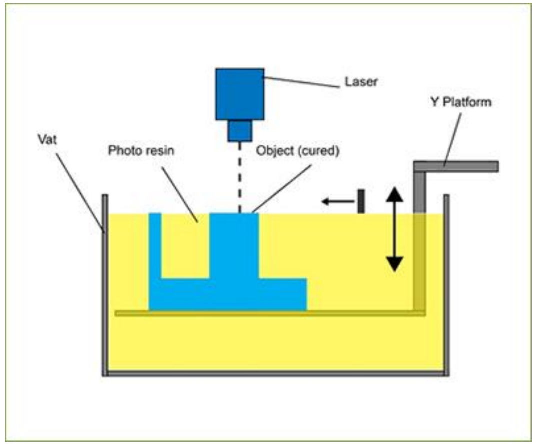


Image courtesy Li Yang: Introduction to Additive Manufacturing

Additive Manufacturing

- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
- Sheet Lamination
- Vat Photopolymerization
  - An AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
  - Materials are limited plastics
  - Can have fine resolution or be scaled up for larger volumes
  - Typically used for structural materials, similar to binder jetting. Could house instrumentation



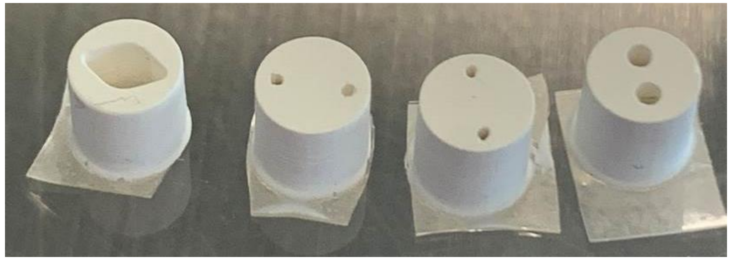


Image courtesy of Loughborough University

Advanced Materials

- Radiation and temperature resistant sensor material
  - Stable structure
  - Resist irradiation damage in the microstructure
  - Continues to function as expected (need not be consistent if it can be predicted)
- Includes
  - Thermocouples
  - Optical fibers
  - Thermoelectric materials
  - Piezoelectric materials
  - All materials used in sensor/instrumentation contruction

Technology Impact

- More data from irradiation experiments
  - Robust in harsh environments
  - Better resolution
  - Novel measurements not previously feasible

- Sensors applied in novels ways not possible with traditional methods
  - Compact size/geometry
  - Reduced feedthroughs

Session 2: Advanced materials and manufacturing methods for sensors applications

FY22 ASI activities

- Printed Sensors Technology for Harsh Environments
  - Bi-metallic melt wires for improved peak temperature resolution measurement
  - Sensor robustness and quality control to ensure reliable operation in test reactors
- High Temperature Materials and Sensors Predictive Modeling
  - Development of high temperature materials for nuclear sensors and instrumentation
  - Development of predictive models for sensors performance

NSUF irradiation projects

- Irradiation Behavior of Piezoelectric Materials for Nuclear Reactor Sensors (Marat Kafizov, OSU)
- High-performance nanostructured thermoelectric materials and generators for in-pile power harvesting (Yangliang Zhang, University of Notre Dame)
- Irradiation of optical components of in-situ laser spectroscopic sensors (Igor Jovanovic, U of Michigan)
- High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors (Kelly McCary, INL)
- Irradiation of Sensors and Adhesive Couplants for Application in LWR Primary Loop Piping and Components (James Wall, EPRI)
- Fiber Sensor Technology for Nuclear Power Applications: Radiation-harden Sensor Devices, Packaging, Sensor Data Fusion, and Instrumentation (Kevin Chen, U of Pitt)

SBIRs

- High Temperature Operable, Harsh Environment Tolerant Flow Sensors For Nuclear Reactor Applications (Jon Lubbers, Sporian Microsystems, Inc.)
- Metamaterial Void Sensor for Fast Transient Testing (Mark Roberson, Goldfinch Sensor Technologies and Analytics LLC)
- Health Monitoring of Digital I&C Systems using Online Electromagnetic Measurements (Chad Kiger, Analysis & Measurement Services Corp.)

Session 2: Advanced materials and manufacturing methods for sensors applications

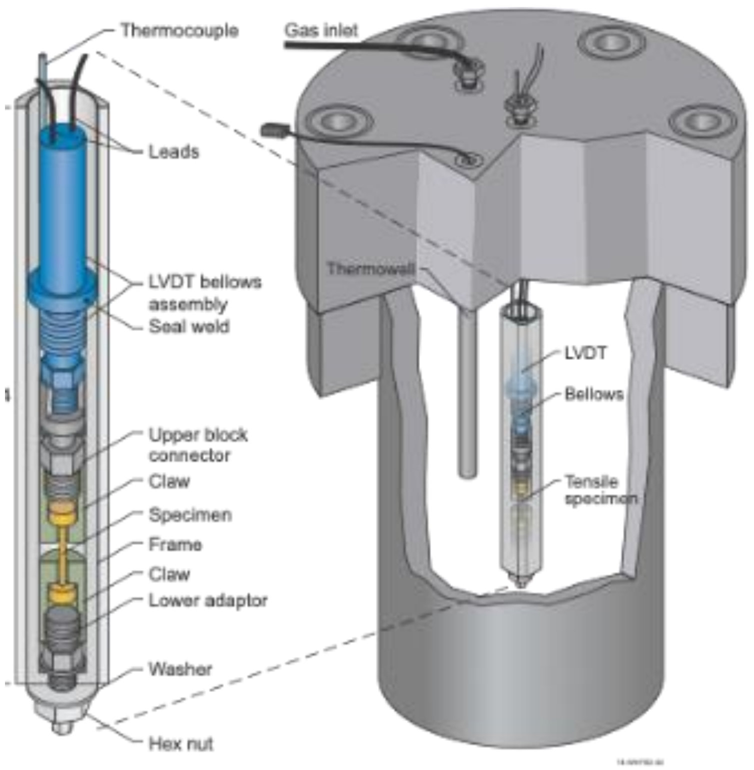
- Enabling sensor designs through advanced manufacturing
  - Sensor material feedstock development
  - Design of printed sensors specific for nuclear applications
  - Determination of printing parameters
  - Quality control and reliability
- Examination of high temperature nuclear sensor materials
  - Including thermocouples, LVDTs, and ultrasonic waveguide thermometers
- Modeling and simulation as a means to predict sensor behavior

Aerosol Jet printed sensor pad

Localized dynamic failure of sensor using laser ablation

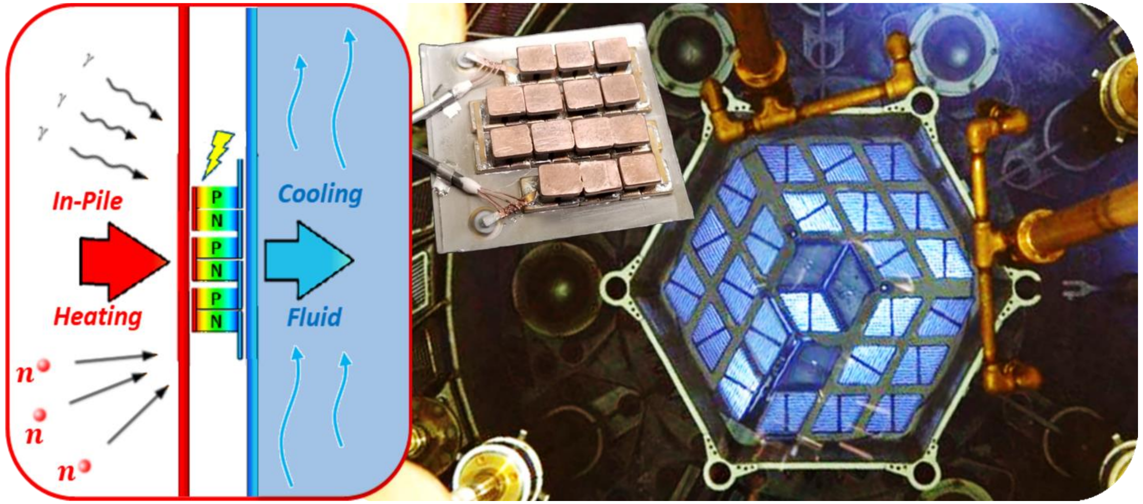
Session 2: Advanced materials and manufacturing methods for sensors applications

- Methods for testing structural materials and in-situ creep testing development
  - Offer more control over experimental variables
  - Provides more details regarding creep behavior
  - Improved accuracy compared to non-instrumented tests.
- These innovated sensors and sensor technologies will be employed in irradiation tests and demonstration facilities to progress their Technical Readiness Level and enable stakeholders to adopt them with minimal risk.



Session 2: Advanced materials and manufacturing methods for sensors applications

- Examinations of the behavior of piezoelectric materials under irradiation for nuclear sensor applications
- Neutron irradiation effects on piezoelectric ultrasonic sensors and adhesive couplants
  - Goal to facilitate the development of online monitoring tools for monitoring of, e.g., stress corrosion cracking in light water reactor primary loop piping and components.
- High-power-density, high-temperature and robust thermoelectric generator (TEG) for in-core power harvesting
  - Need stable power density output even under irradiation
  - Opportunities for solid-state power harvesting in the harsh environment of a nuclear reactor for a range of important nuclear applications



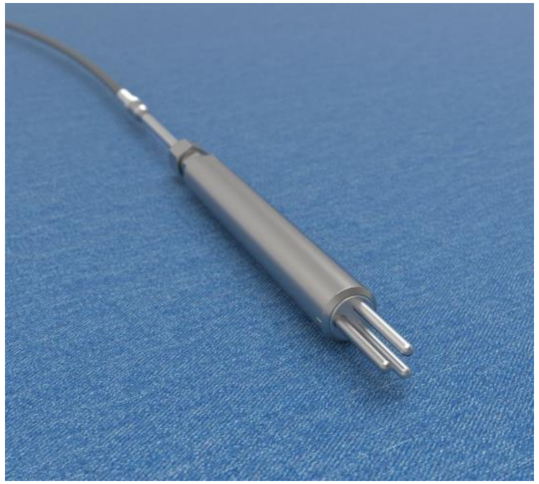
Session 2: Advanced materials and manufacturing methods for sensors applications

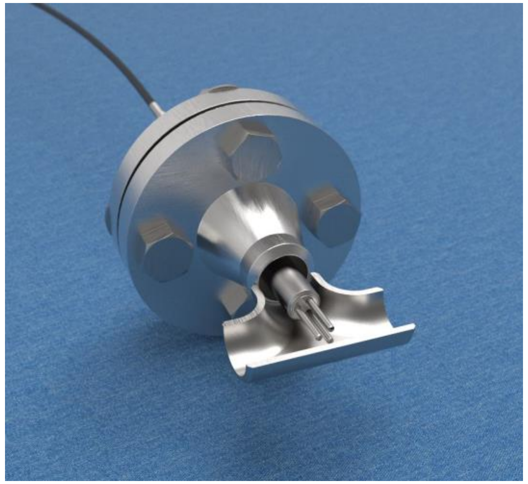
- Optical fibers for nuclear applications
  - Examination of effects of radiation damage and thermal annealing of optical components for in-situ laser spectroscopic sensors on operation and performance
  - Test of suitability for continuous, in-line spectroscopic instrumentation of next-generation reactor coolant systems to allow in-situ evaluation of reactor coolant-fuel composition and to prevent reactor system degradation through corrosion and for early detection of fuel failure by sensing small releases of fission gases
  - Study on the performance of sapphire optical fiber temperature sensors under combined radiation/temperature effects and high fluence and to determine an operational limit for the sensors
  - Develop clad sapphire optical fibers for in-pile instrumentation

Heated irradiation furnace rig.

Session 2: Advanced materials and manufacturing methods for sensors applications

- Transition a newly developed, high-temperature flowmeter technology into a commercially available product
- Using RF sensors to measure void formation on rodlets
  - Greatly reduces the number of electrical feedthroughs required enabling much higher fidelity in void formation analysis
  - Works at high pressure and high temperature
  - Necessary for producing safer fuel rods
- Health Monitoring of Digital Instrument and Controls Systems using Online Electromagnetic Measurements





Summary of session

- Ink development for sensors additive manufacturing (Kiyo Fujimoto, INL)
- Direct Digital Printing of Sensors for Nuclear Energy Applications (Pooran Joshi, ORNL)
- High temperature materials for nuclear sensors and instrumentation (Brian Jaques, Dan Deng, Davis Estrada, BSU)
- Predictive modeling of nuclear sensors and instrumentation (Lan Li, Dan Deng, Brian Jaques, BSU)
- Structural materials characterization (Malwina Wilding, INL)
- Irradiation Behavior of Piezoelectric Materials for Nuclear Reactor Sensors (Marat Kafizov, OSU)
- High-performance nanostructured thermoelectric materials and generators for in-pile power harvesting (Yangliang Zhang, University of Notre Dame)
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- Metamaterial Void Sensor for Fast Transient Testing (Mark Roberson, Goldfinch Sensor Technologies and Analytics LLC)
- Health Monitoring of Digital I&C Systems using Online Electromagnetic Measurements (Chad Kiger, Analysis & Measurement Services Corp.)
- Moderated discussion on Session 2 (Moderator: Mike McMurtrey, INL)

Questions?

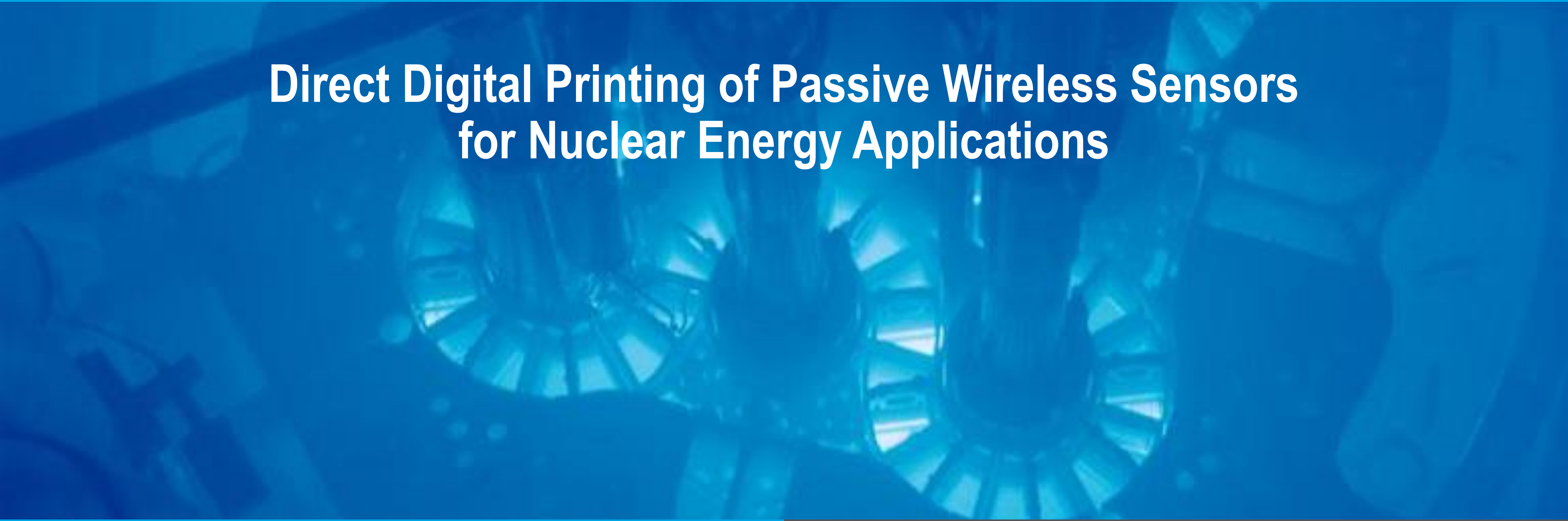
ASI

Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Direct Digital Printing of Passive Wireless Sensors for Nuclear Energy Applications



Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Pooran Joshi

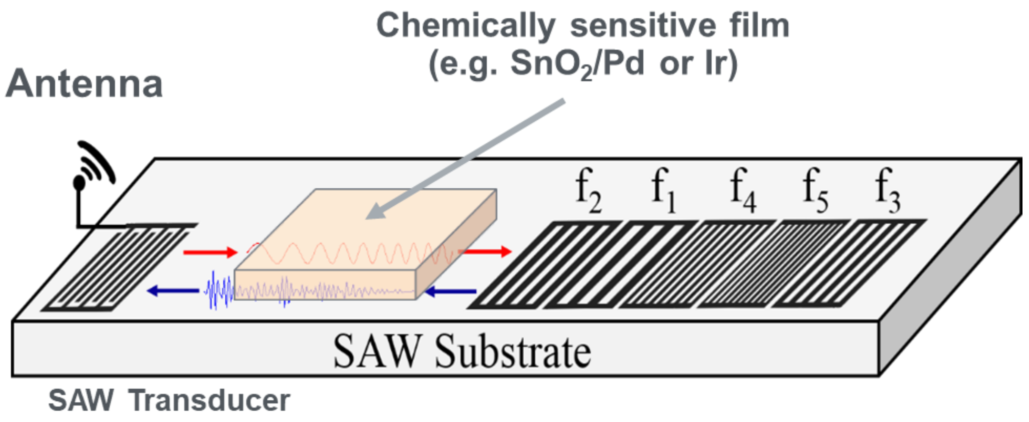
Oak Ridge National Laboratory

Project Overview

- **Goal and Objective**
  - Develop a prototype passive wireless sensor network including surface acoustic wave (SAW) sensors, or other printed electronic devices as needed for measurement of temperature, hydrogen, voltage, and current. The sensors will be made by advanced additive manufacturing (AM) technologies for functional materials (FM) developed by ORNL

- **Participants**
  - Tim McIntyre, Ben LaRiviere, Kyle Reed, Nance Ericson, Jim White, Stephen Killough, DaHan Liao, Timothy McKnight, Tolga Aytug, Bruce Warmack, Pooran Joshi (all ORNL) and Don Malocha (U. of Central FL)

Project Overview: SMART Sensors for Nuclear Applications



Design and Development of $LiNbO_3$ Integrated Sensor System:

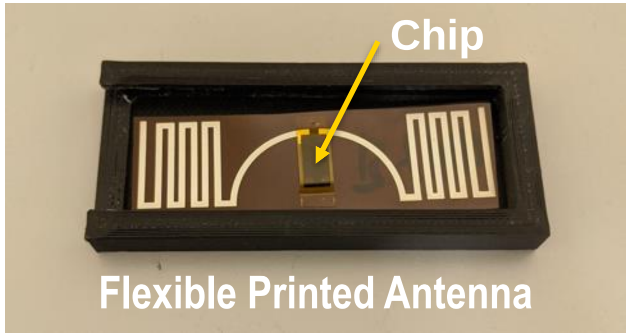
→**Passive** (No batteries required)

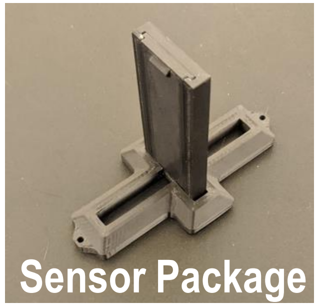
→**Wireless** (Long range communication)

→**Low-cost** (Widespread deployment)

Project Technology Development Areas

- Surface Acoustic Wave (SAW) sensor fabrication
- Orthogonal frequency coding (OFC); unique ID
- Antenna design & integration
- Interrogator hardware & software
- Signal processing
- Functionalizing coatings
- Sensor & interrogator packaging
- The deployed sensor network





Project Overview: Direct Digital Printing Enabling Hybrid Integration

Flexible Hybrid Technology will achieve unprecedented Low-cost and Functionality

Some fundamental challenges to be overcome along the way, include:

- **Printing the SAW sensor – spatial feature size**
  - Then: 20µm feature size
  - Now: 1.0 to 5.0µm – need to go smaller
- **Printing the antenna**
  - Then: Only Redux of conventional antennas (10-20cm x 2cm)
  - Now: Dipole (10cm x 1cm); folded micro-patch (2.5cm x 0.5cm) @ 915MHz
- **Printing the functional coatings**
  - Then: None available
  - Now: Wide selection of solution, nano-particle and 2D material-based inks with unique chemical and physical parameters
- **Printing the sensor package**
  - Then: None available
  - Now: Concepts emerging – Sensors packaged in traditional AM printed structures, sensors embedded in components during manufacturing, or sensors printed on items (smart label), etc.

Technology Impact

Passive Wireless Sensor Concept → Concept to Manufacturing → Wireless Interrogation of Distributed Sensors

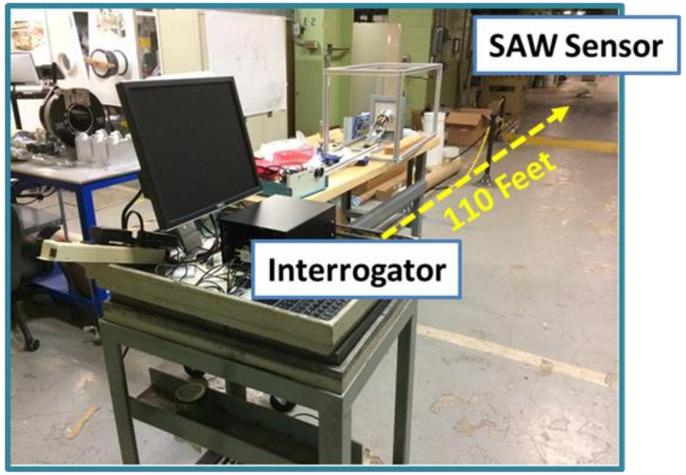
This technology:

- Enables a new paradigm for low cost, passive, wireless, highly reconfigurable, multiparameter sensor networks critical for nuclear power plant measurement needs
- Impacts the nuclear industry by making autonomous, ubiquitous sensing feasible economically and logistically: low cost; radiation tolerant; no wires or batteries; miniature
- Advanced sensor technology that impacts the DOE mission of resilient, reliable and cost-effective energy supply for the nation.
- Collaboration with Southern Company, EPRI and commercial sensing companies is being pursued to refine technology performance criteria and perform field demonstration
- Supports the DOE-NE research mission by pushing the state-of-the-art for applications of additive manufacturing to NE

Results and accomplishments

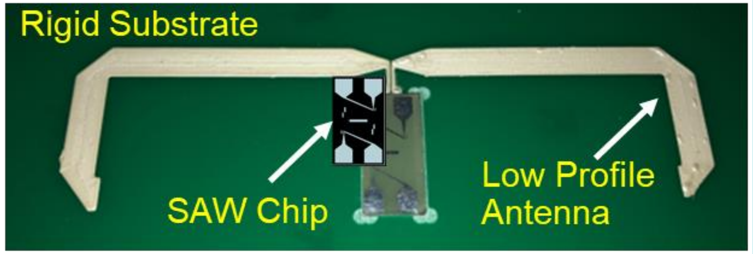
High Gain, Big Size Antennas

Test Setup:
- 250 milliwatt interrogator transmitter
- Large Yagi antenna (interrogator)
- Moderate sized (3 element) Yagi for the sensor



Range: 100 ft

Microelectronic Processing and Integration on FR4

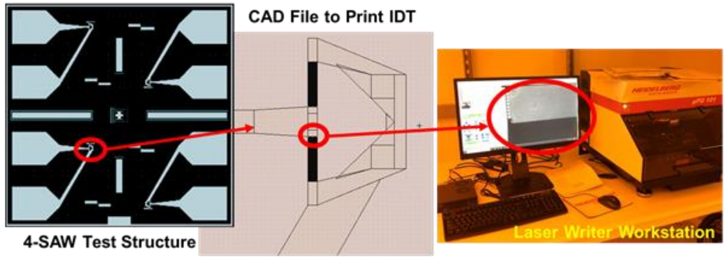


- Direct-write Printed Dipole Antenna Integrated with SAW Sensor

- Photolithography

Direct-write Techniques for Flexible Integration

- Chip and Antenna on Flexible Polyimide Substrates



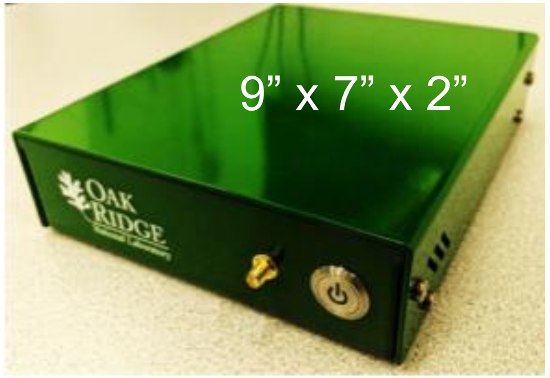
- Maskless Laser Writer: 0.6µm Line-width Control

Initial Demonstration: 30 ft (at 250mW TX Power)

Printed Dipole Antenna on: Rigid FR4 → Flexible Polyimide

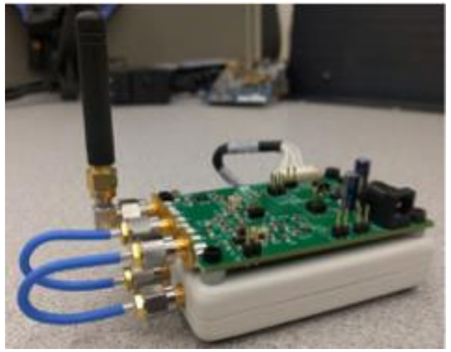
Results and accomplishments

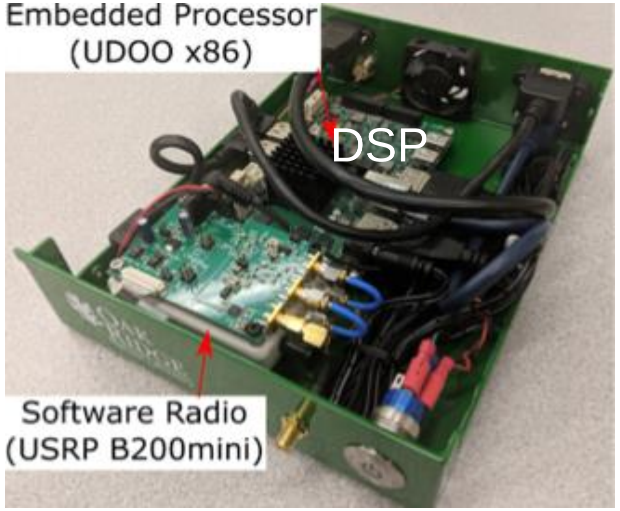
➢ **Interrogator Hardware & Software**



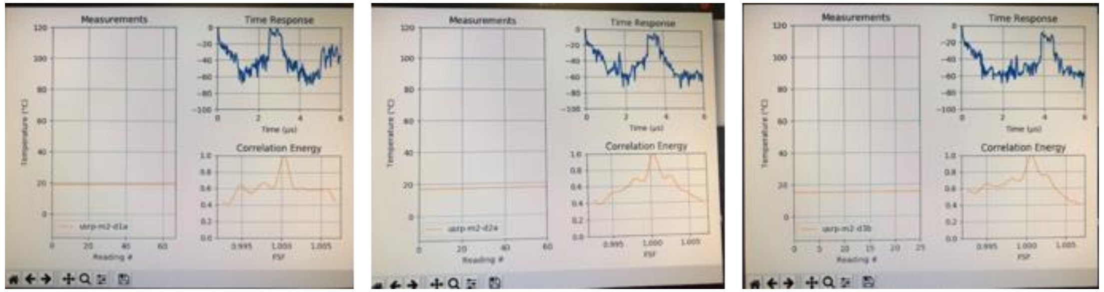
ORNL Custom Interrogator
- Cost < $1k
- Portable/mobile
- Reconfigurable

Software defined radio (SDR) interrogator



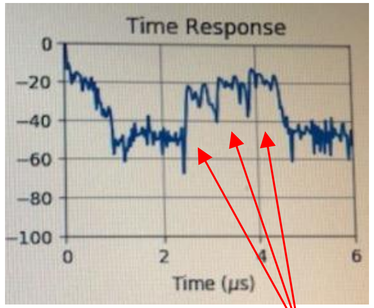


All commercial components + ORNL DSP (data-2-info) & communication to the enterprise network



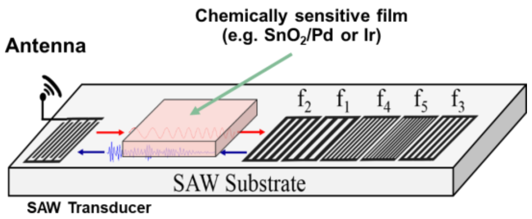
RF echo returning from (3) SAW sensors with time diversity

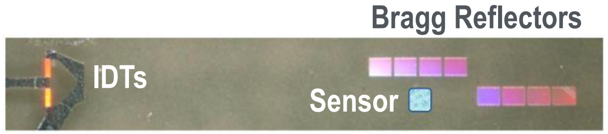
Currently operating at 5mW transmit power; can be increased >1W as needed for extended range and improved SNR.



Simultaneous echoes from (3) sensors

Results and accomplishments





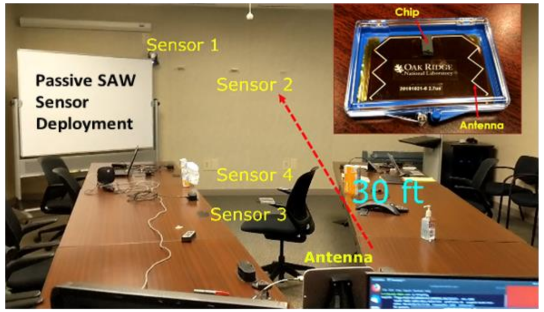
Design and Development of $LiNbO_3$ Integrated Sensor System:

→ **Passive** (No batteries required)

→ **Wireless** (Long range communication)

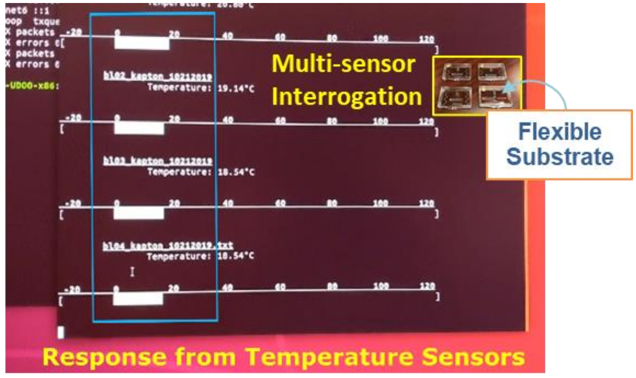
→ **Low-cost** (Widespread deployment)

Distributed Temperature Sensors: Wireless Interrogation



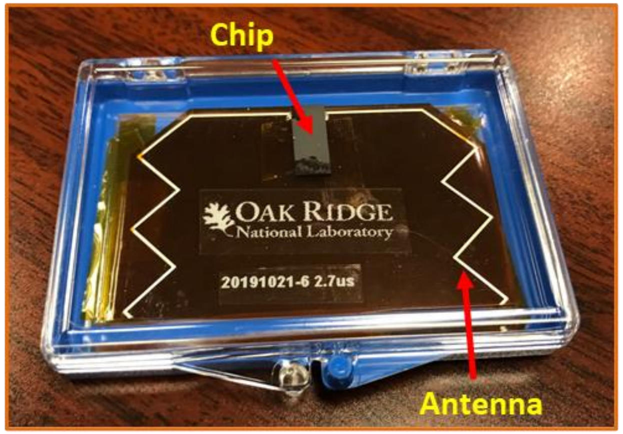
→ Conference room with 4 sensors (above) installed

Distributed Temperature Sensors



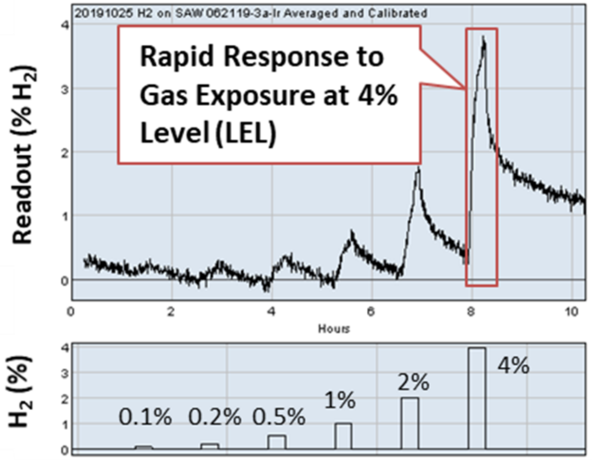
→ Readout showing 4 sensors operating simultaneously

915 MHz Antenna on Flex



Latest printed RF/SAW sensor with integrated antenna. Total package about 4" x 4" and is printed on Kapton.

Passive Hydrogen Sensors



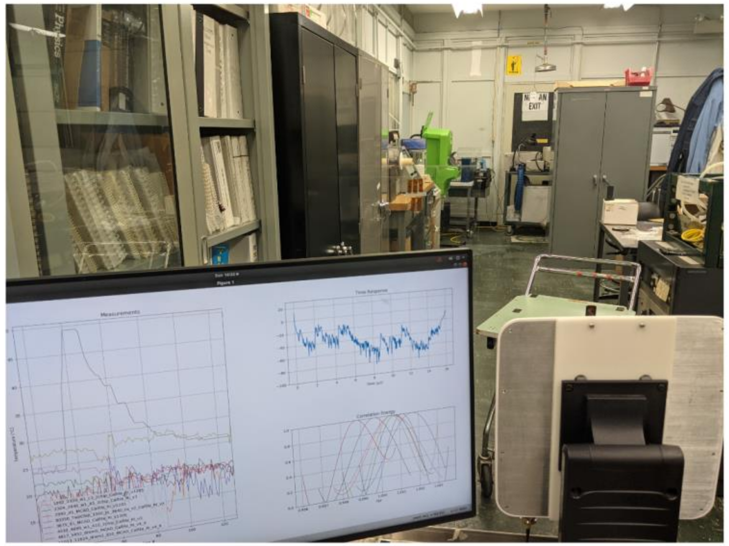
Preliminary measurements down to 0.1% H_2 sensitivity

Room temperature hydrogen sensor operation on SAW Platform

Results and accomplishments

- ➢ **Multi-sensor Deployments at the Lab**
- ➢ **Field-like Demonstration at Commercial Partner Site**

@ ORNL

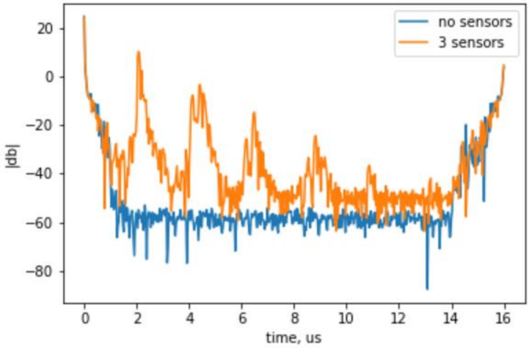


10-node Temperature Sensor Network

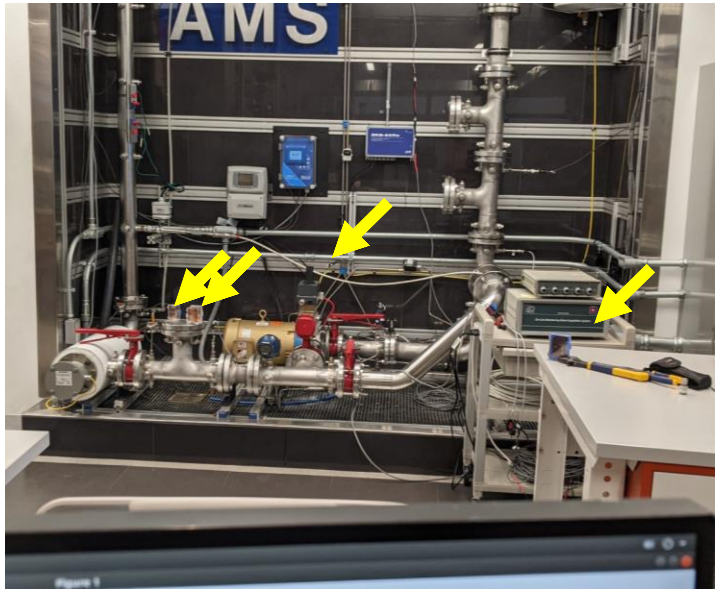
- An array of 10 sensors was tested in a lab setting containing RF reflecting objects, with sensors arranged from 6 ft to 26 ft interrogator-PSAW distance
- While the interrogator was able to lock onto each sensor in the deployment, successful simultaneous reading was sensitive to the arrangement
- Additional testing indicated a need for increased number of chip frequencies on each sensor

Sensor Performance Outside the Lab

- Sensors placed adjacent to flow loop for the purpose of evaluating feasibility of multi-sensor deployments
- Location: Analysis and Measurement Services Corp. (AMS) in Knoxville TN
- Confirmed: RF environment does not inhibit system function (and vice-versa)
- Improved thermal coupling of SAW body to equipment (e.g. pipe) needed for improved response time and accuracy



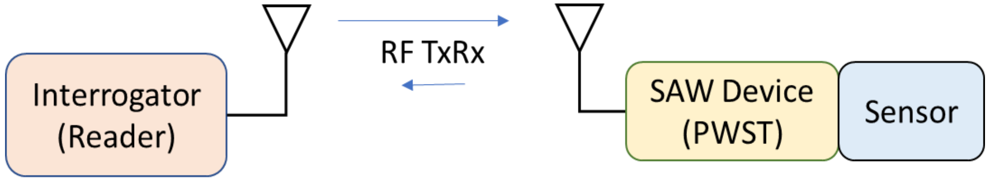
@ AMS

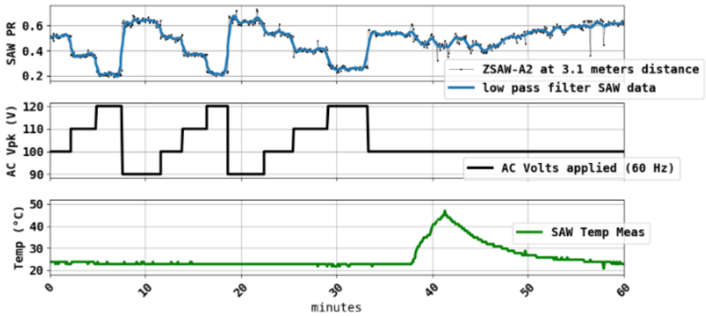


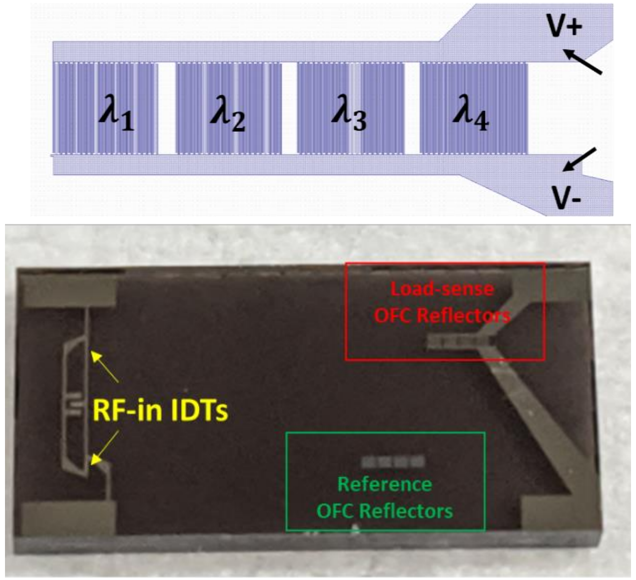
Results and accomplishments

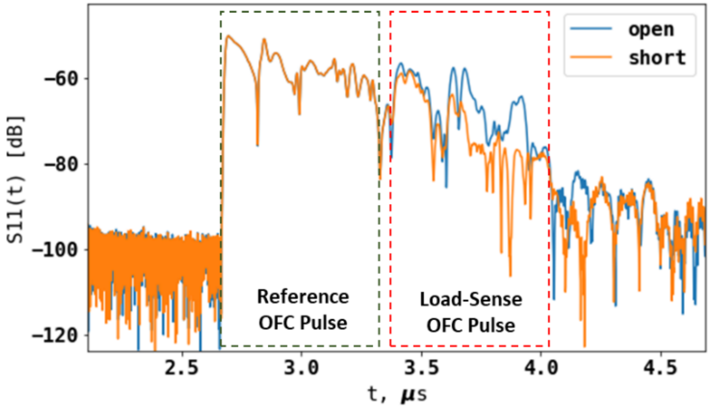
➢ **Impedance-loading Approach for Sensing Beyond Temperature**

- PSAW sensors for voltage, current, and H_2 monitoring can be realized with the PSAW acting as a sensor-transponder, rather than a directly affecting the piezoelectric
- Avoids need for functional coatings or high-voltage connection to the piezoelectric
- Previous FY work demonstrated the concept for both fully printed and printed hybrid PSAWs
- Recent work demonstrated frequency coding of the measurand sensing SAW port, which will enable higher SNR signal extraction and better temperature compensation



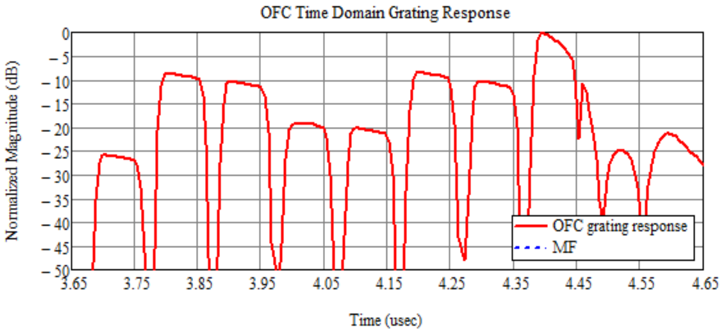




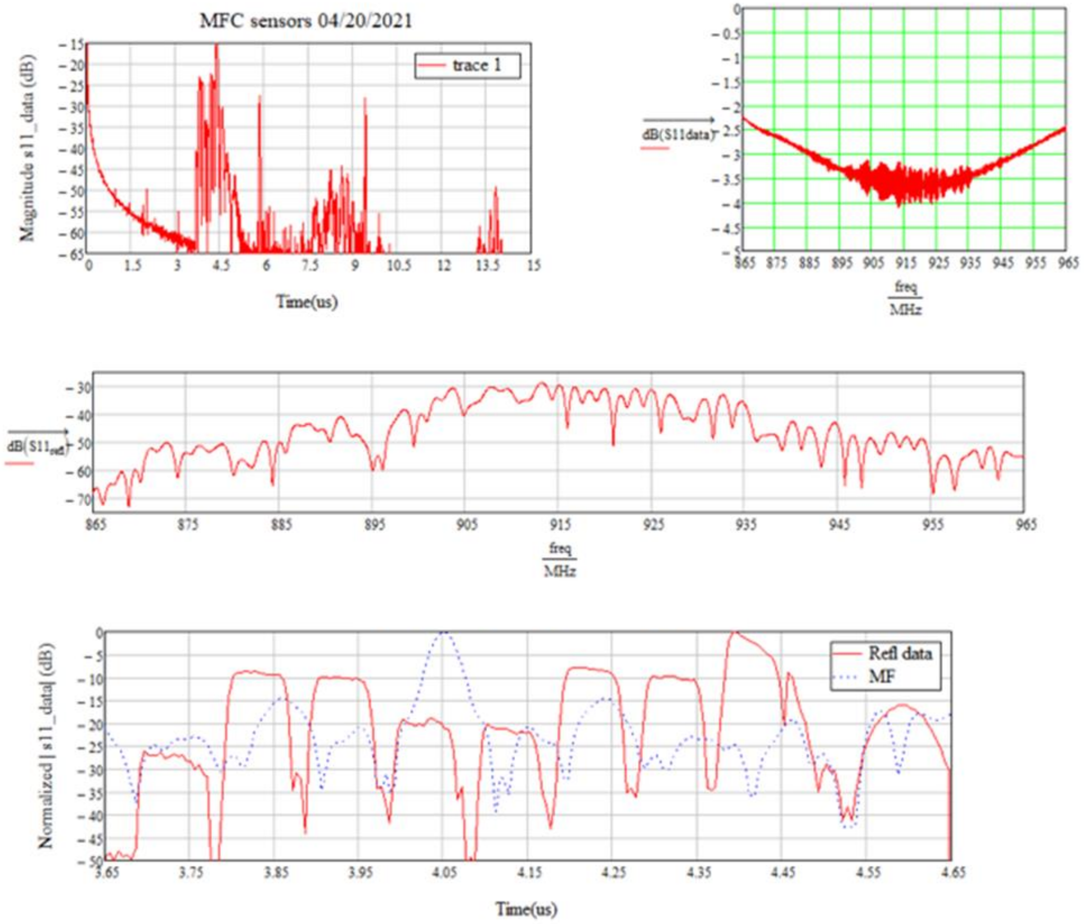


Results and accomplishments

- **Need for improved sensor differentiation in multi-sensor deployments**
- 8-chip SAWs were designed, simulated, fabricated, and tested to improve robustness to sensor-sensor interference
- A modulated withdrawal-weighting of the reflector chips was pursued to balance signal from “front” and “back” chips in 8-chip line
  - Withdrawal weighting from 5 (every 5th grating period present) to 1 (all grating periods present)
  - FY22: evaluating the improvement of signal extraction in multi-sensor deployments for temperature extraction



Simulated (Pegasense Inc.)



Measured

Chip #	Extracted chip frequencies (MHz)	Time gate (us)
1	912.31	3.68-3.76
2	921.44	3.79-3.88
3	924.88	3.89-4.0
4	902.5	4.0-4.07
5	917.44	4.09-4.17
6	908.69	4.18-4.27
7	929.75	4.28-4.37
8	911.56	4.37-4.46

Conclusion

- We have developed passive (no batteries) wireless sensors based upon radio frequency (RF) surface acoustic wave (SAW) technology.
- We have demonstrated the ability to monitor multiple miniature passive sensors simultaneously.
- Relying on additive manufacturing, complete sensors can be printed.
- These sensors can be functionalized to monitor multiple parameters simultaneously such as temperature, hydrogen, voltage and current.

Publication

Lariviere, B. A., Joshi, P. C., & McIntyre, T. J. (2020). Surface Acoustic Wave Devices Printed at the Aerosol-Jet Resolution Limit. *IEEE Access*, *8*, 211085-211090.

Invention Disclosure

Invention ID: 4741“Passive saw transponder with multi-code, electrical impedance loaded sensor reflectors” B. LaRiviere, P. Joshi, S. Killough, T. Aytug, T. McIntyre.

Questions?

Email contact information for any additional questions: Pooran Joshi: **joshipc@ornl.gov**

Questions?

ASI | Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Metamaterial Void Sensor for Fast Transient Testing

Phase II SBIR DE-SC0018808

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

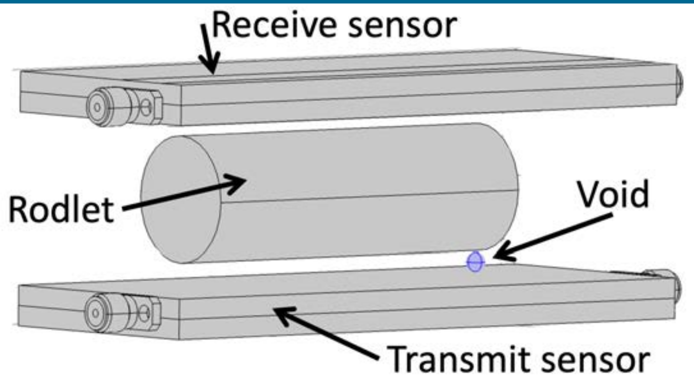
November 15 – 18, 2021

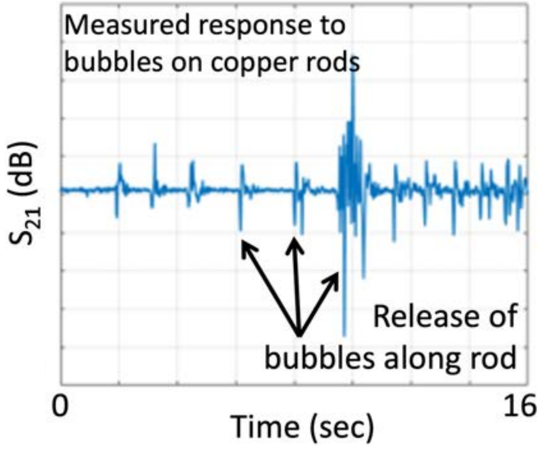
President: Mark W Roberson, Ph.D.

Goldfinch Sensor Technologies and Analytics LLC (GSTA)

Project Overview

- Research scope – Develop and demonstrate "Direct, time-resolved and multi- position detection and characterization of boiling in high-pressure, high-temperature environments with minimal electrical feedthrough requirements." GSTA's technology uses RF sensing of the void-induced impedance changes to localize and time-resolve void formation.
- The project received a No-Cost-Extension and is scheduled to end in May 2022. Thanks to the NCE, GSTA will be able to conduct **in-core testing** of key RF elements at INL TREAT during reactor operation in early 2022.
- GSTA's end-goal is to integrate the sensor technologies in INL test cells during transient tests and with fast time resolution measure accurately when, where, and how the voids form.
- GSTA is working with INL to complete the test plan paperwork and deliver the test package and and electronics. GSTA will use the TREAT operational time to conduct irradiation experiments on key RF elements to understand the RF element performance and reactor-induced noise.





Project Overview – Participants and acknowledgments

- GSTA
  - PI: Mark Roberson
  - Staff: Charles Bartee, Kate Frohman, Eric Wagner, Joseph White
  - Students: Brian Alonso[2], William Arana[2], Isaac King[2], Grant Robertson[2], Russell Robertson[2], Davis Roper[1]
- Virginia Tech
  - Sub-awardee lead: Juliana Pacheco Duarte
  - Students: Bruno Pinheiro Serrao[2], Evelyn Washburn[1]

Names in each sub-bullet are listed alphabetically

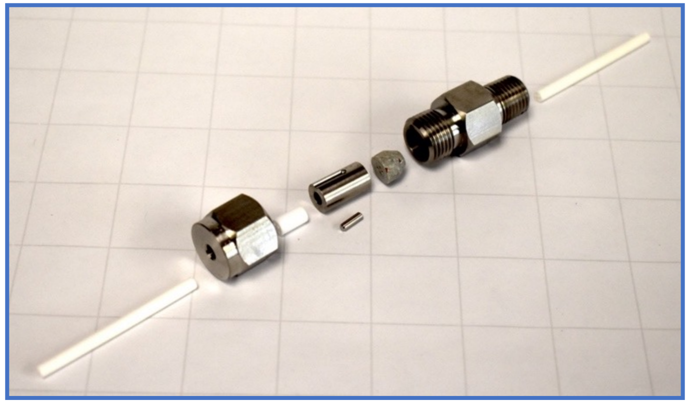
[1]Graduate student
[2]Undergraduate student

The project has supported 8 students at the undergraduate and graduate levels, including design of equipment, construction of devices, and testing of performance.

- Acknowledgments - the SBIR effort has benefitted greatly with support from DOE/NE and INL
  - ASI program manager
    - Melissa Bates (current)
    - Suibel Schuppner (prior)
  - INL
    - Pattrick Calderoni, Kara Cromwell, Austin Fleming, Colby Jensen, Kevin Tsai, Nicolas Woolstenhulme
  - CAP services from LARTA
    - Gunjan Siroya

Technology Impact – minimize device size and decrease penetrations
Reduce the connector count required by 10x

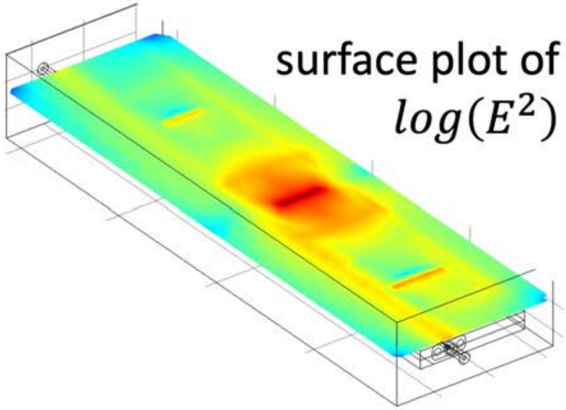
- Researchers use near-DC capacitive plates to sense the presence of voids due to a change in the dielectric constant. Sensing at multiple locations requires multiple feedthroughs, limiting the number of locations that can be sensed.
- GSTA’s method of sensing requires only two ports in order to sense ten or more locations with high time-resolution. The approach **reduces the connectors needed by 10x**. The sensor shows promise for “bubble spectroscopy,” for differentiating between different bubble size distributions.
- GSTA’s technology works at both high pressure and high-temperature, making the technology applicable for in-core instrumentation and supporting the nuclear energy industry.
- The stakeholders for the technology are test groups requiring time-resolved sensing of voids along rods.

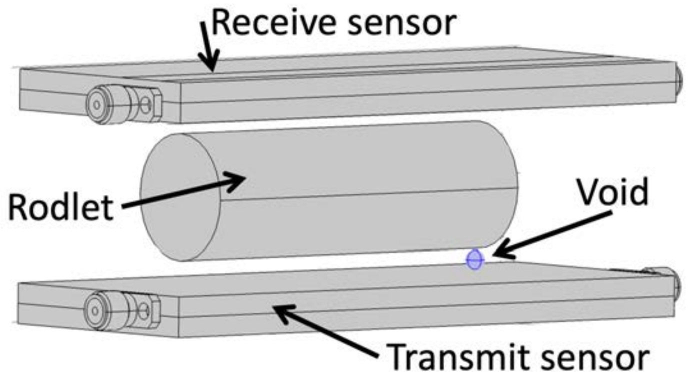


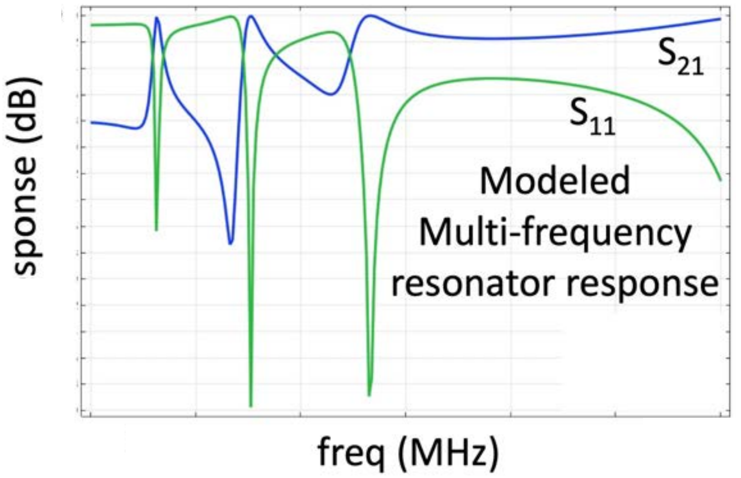
Commercial high-pressure feed through

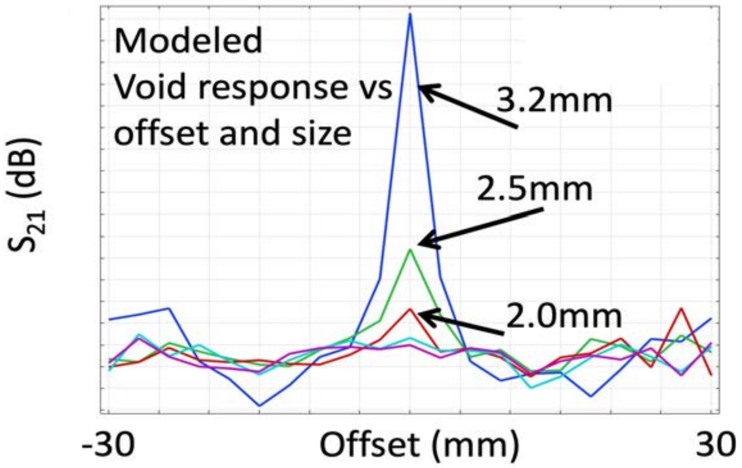
Minimizing the required sensor electrical feedthroughs is critical for experimental design

Results and accomplishments – RF simulation, modeling, and experimentation









Clockwise from top left: electric field calculations at the sensor surface; model including rodlet, sensor, and void; frequency response of the sensor set; predicted spatial response of the sensor to a single void

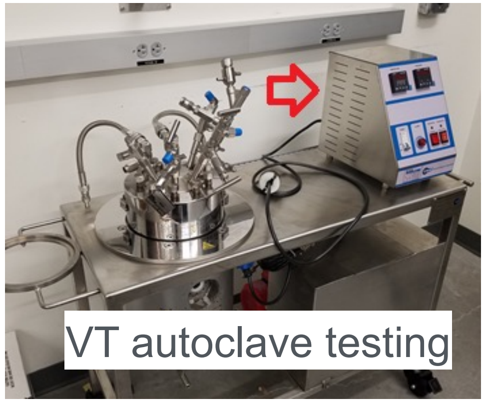
- GSTA conducted extensive RF modeling and simulation of details of void sensing using both COMSOL and MATLAB
- GSTA's modeling work was consistent with previous experimental measurements; the experiments were more sensitive than the FEM uncertainties
- GSTA conducted extensive modeling of the RF feeds from the sensor electronics to the sensor element in the core

Results and accomplishments – system validation: pressure, temperature

- Part of the SBIR Phase II project was to test the operation of sensor elements parts in operational conditions.
- GSTA and VT have tested parts at high temperatures and at high pressures.
- The original effort did not include neutron irradiation testing nor operation while under neutron irradiation at high temperatures...

Source	Pressure			Temperature Temperature			Bubbles			Neutron Flux
(conditions)	15PSI, .1MPa	3 kPSI, 21Mpa	kPSI, 34Mpa	300F, 150 C	575F, 300C)	932F, 500C	.5mm	3mm	10mm	> 10^{10} n/cm³/s
GSTA lab	✓			✓	✓	✓	✓	✓	✓	
VT lab	✓	✓		✓	✓		✓	✓		
TREAT cooling channel	✓			✓	✓	✓				✓
TREAT / test cell	✓	✓	✓	✓	✓	✓	✓	✓		✓

GSTA kiln testing

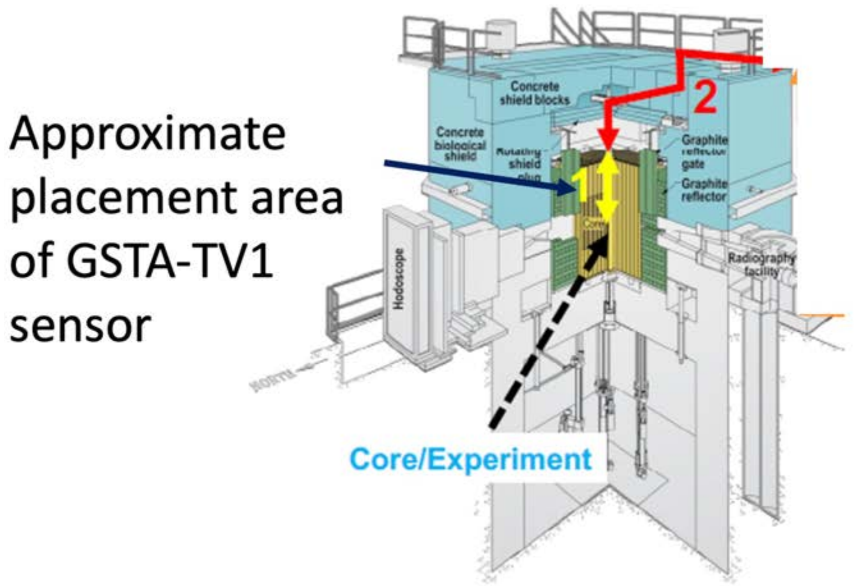

VT autoclave testing

Results and accomplishments – CY2022 INL TREAT irradiation

- GSTA discussed with INL testing of the SBIR Phase II parts at TREAT but testing the full-sized void sensor was not feasible.
- INL offered to include a GSTA sensor on a non-interference basis in a TREAT reactor core interstitial during irradiation experiments.
- Making this happened required agreement at multiple levels and across INL groups. "THANK YOU, INL!!!"

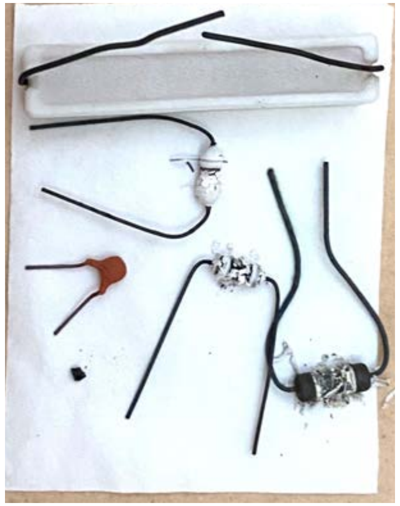
- GSTA will be validating key elements of the sensor design in an interstitial channel in early 2022. This unique opportunity has been a highlight of GSTA's Phase II effort

TREAT Cutaway view



Results and accomplishments – new challenges in RF measurements during TREAT irradiation

- Challenges that arise in designing for an interstitial reactor location
  - Size (much narrower than a SERTTA cell)
  - Temperature (can reach 500℃ / 900℉)
  - Materials (cannot interfere with reactor core operation)
  - Remote operation of sensors in radioactive bay (20+m away), remotely controlled by instrumentation operator
  - Test plan documentation !!
- To meet these challenges GSTA redesigned the RF elements and modified GSTA's software to permit operation during reactor operation.
- The metal in the system was changed whenever possible from SS316 to Ti-Grade 2 to reduce the residual radioactivity post-testing

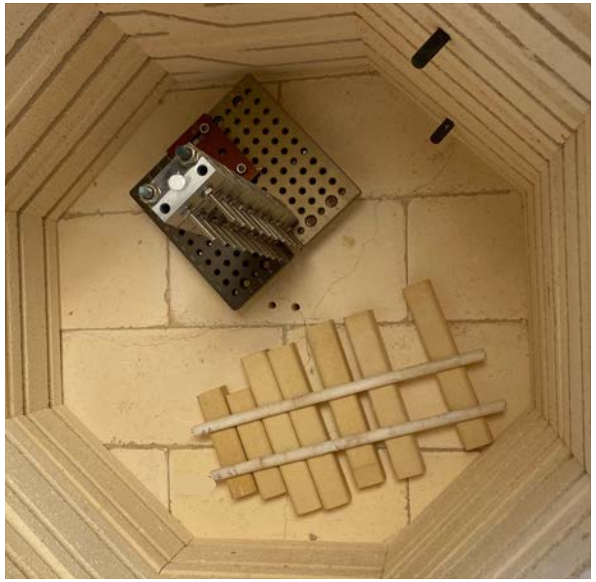


Commercial passive components before and after backing at 500℃

Results and accomplishments – fabrication using high-temperature encapsulant

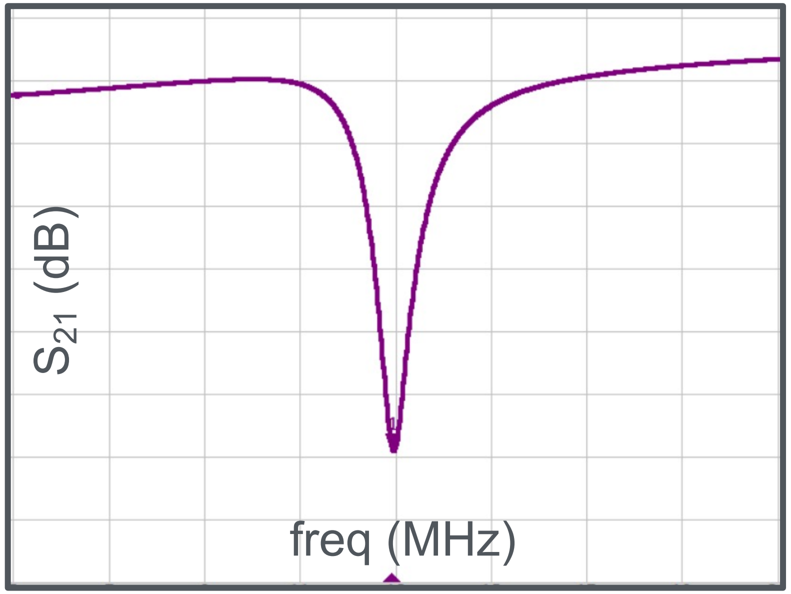
- GSTA redesigned the sensor elements to accommodate a 0.43” OD sensor (to fit inside a 0.5” OD Ti tube) that can withstand 900°F.
- GSTA used an encapsulant rated for 3,000°F and 11,800 PSI to create sensor modules.
- The TREAT sensor is completed, and GSTA is working with VT to complete pressure testing on schedule by end of CY2021.

Dispensing encapsulant into form



Mold form in kiln prior to curing

Completed sensor rods



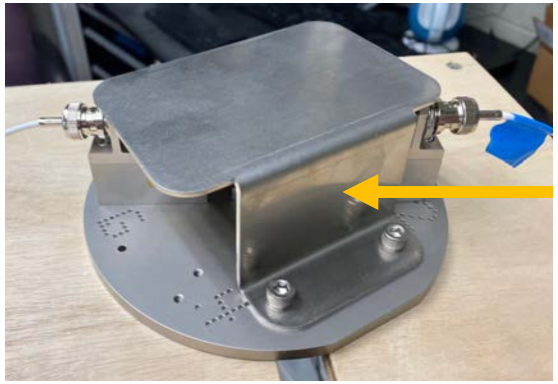
RF measurements of resonance using return loss

Results and accomplishments – sensor assembly

TIG Micro-welding SS316 sensor joints

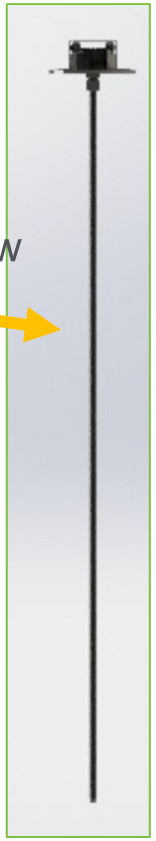
Interstitial sensor GSTA TV-1 elements in the reactor region

Ti tube
Resonator
Device carrier
Ti end-plug

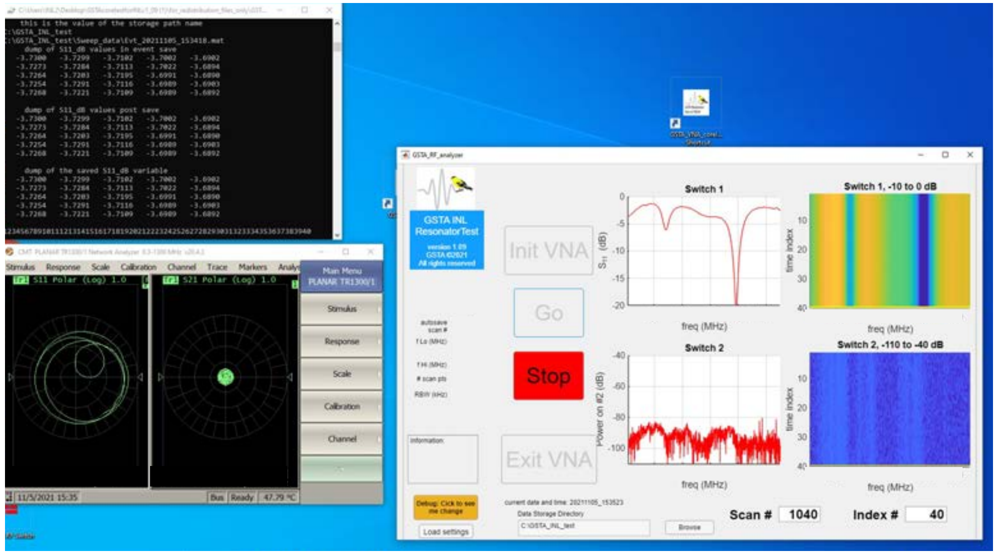


GSTA TV-1 top

GSTA TV-1 side view



- GSTA is nearing shipment of GSTA TV-1 to permit TREAT core insertion before the 20222 reactor experiments
- The system includes a reactor core sensor, cabling, electronics, and control software, and documentation of the system



Screen shot of GSTA TV-1 software during development

Results and accomplishments –
Science value to GSTA of TREAT exposure experiments

- GSTA designed four experiments which will run in GSTA-TV-1

1. RF resonator performance at varying temperatures and neutron fluxes
2. "RF-off" pick-up sensor noise level measurements
3. Coupling between resonator and pick-up sensor
4. Irradiation exposure of a high bandgap device

Conclusion – Summary of presentation and accomplishments

- GSTA and its partner VT are completing a Phase II SBIR for rodlet void measurement.
- The Phase II conducts validation and verification of key sensor elements.
- Key technologies: **void sensing, sensor size minimization and reduction of feedthroughs by 10x**.
- The total void sensing package will exit at Technology Readiness Level 5 (TRL5) with GSTA laboratory testing in relevant environment and interfaces.
- GSTA’s RF sensor elements **will exit at TRL 6** in 2022 with TREAT testing.
- GSTA acknowledges that achieving TRL 6 is a ***direct result of the support of INL*** and thanks them again for their support.

Conclusion – Commercialization

- Harvesting: potential applications
  - Reactor core instrumentation for distributed, multi-point sensing of neutron flux
  - Non-nuclear:
    - Downhole well measurements for oil extraction and carbon storage
    - On-orbit and re-entry vehicle sensors
    - Pharmaceutical manufacturing for human cell therapy
- Intellectual property (IP) portfolio generated
  - RF circuit designs
  - Sensing algorithms
  - Fabrication process flow
  - Software design
  - Held as trade secrets presently

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LinkedIn

Questions?

ASI | Advanced Sensors and Instrumentation

Irradiation of Sensors and Adhesive Couplants for Application in LWR Primary Loop Piping and Components

WP NA-20EPRI010701

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

Joe Wall, PhD, Principal Technical Leader

Electric Power Research Institute

Project Overview

- EPRI launched a project in 2020 to assess the feasibility of using semi-permanently mounted piezoelectric sensors to monitor existing cracks in primary loop piping and components.
  - Of particular interest is the stability of the piezoelectric crystals and the ability of adhesive couplants to transmit sound reliably under operational environment conditions.
    - Elevated temperature
    - Irradiation – Specifically at the hot and cold leg nozzle dissimilar metal welds.
  - The EPRI funded portion of the research focuses on elevated temperature effects.
  - The NSUF funded portion of the research focuses on irradiation effects.

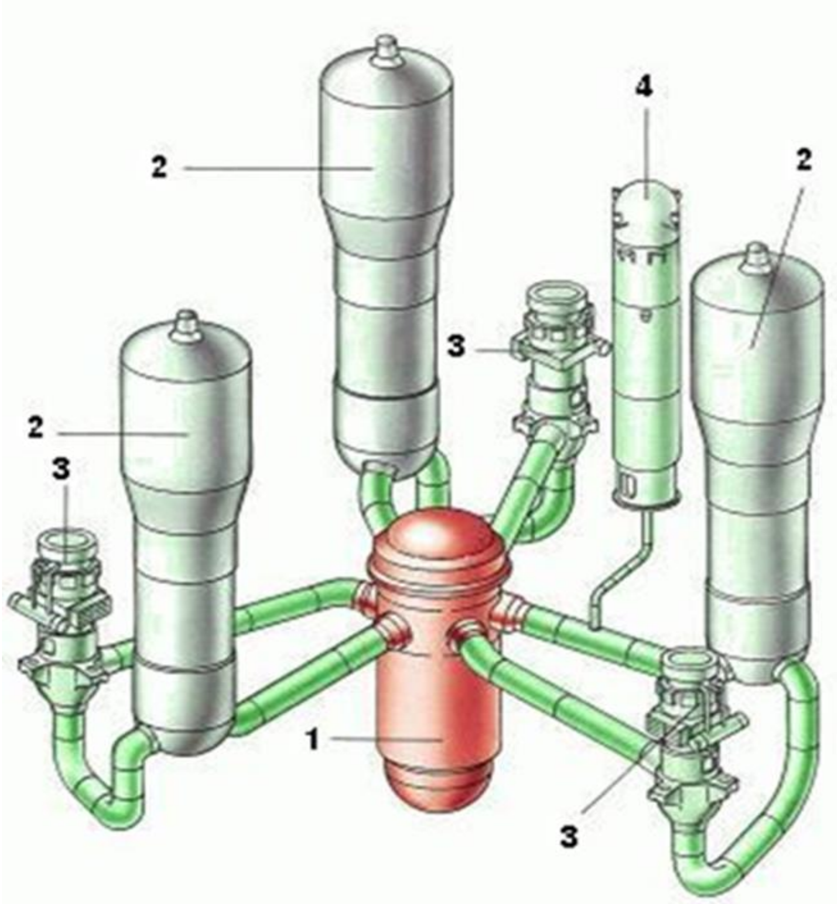


Illustration of the primary loop piping and components in a commercial PWR (primary loop piping is in green). 1 – Reactor Pressure Vessel; 2 – Steam Generator; 3 – Reactor Coolant Pump; 4 – Pressurizer.

Project Overview

Project Team

- Principal Investigator: Dr. Joe Wall, Principal Technical Leader, Nuclear Sector, EPRI
  - Overall responsibility for project
- Collaborator: Dr. Luke Breon, Senior Technical Leader, Nuclear Sector, EPRI
  - Subject matter expert – acoustic sensors, PI for the EPRI elevated temperature companion study
- Collaborator: Dr. Maria Guimaraes, Program Manager, Nuclear Sector, EPRI
  - EPRI program manager
- Collaborator: Dr. Josh Daw, Principal Researcher, INL
  - Consultant for irradiation experiment and capsule design
- Collaborator: Dr. Pradeep Ramuhalli, Distinguished R & D Staff Member, ORNL
  - Consultant for irradiation experiment and capsule design as well as post irradiation examination

Project Overview

- The goal of the project is to characterize microstructural and acoustic property changes in piezoelectric sensors bonded to aluminum substrates (1” diameter x 3/8” thickness discs) using adhesive ultrasonic couplants.
- 3 types of transducers and 4 types of adhesive couplants will be irradiated and acoustic data (signal to noise ratio) will be collected in-situ.
  - If in-situ data collection is not possible, data will be collected before insertion into and after extraction from the reactor.
- The target fluence is 5×10^{16} n/cm^2 (E > 1MeV) – estimated hot leg weld 80 year fluence (estimated using radiation transport simulations)

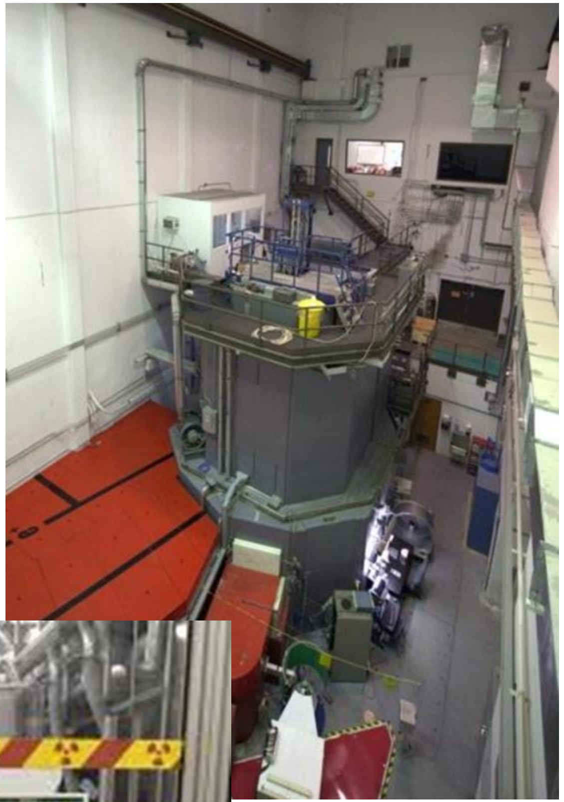
Substrate	Transducer	Adhesive Couplant
Aluminum Disc 1	Lithium Niobate	Zirconia Ceramic
Aluminum Cube 2	Lithium Niobate	Alumina Ceramic/Silica
Aluminum Cube 3	Lithium Niobate	Alumina Ceramic/Silica/Potassium Oxide
Aluminum Cube 4	Lithium Niobate	Epoxy
Aluminum Cube 5	Bismuth Titanate	Zirconia Ceramic
Aluminum Cube 6	Bismuth Titanate	Alumina Ceramic/Silica
Aluminum Cube 7	Bismuth Titanate	Alumina Ceramic/Silica/Potassium Oxide
Aluminum Cube 8	Bismuth Titanate	Epoxy
Aluminum Cube 9	Sol-Gel	N/A

Project Overview

NSUF Facilities

PULSTAR Reactor

- The NC State University PULSTAR reactor was chosen for this study because it uses 4% enriched, pin-type fuel consisting of uranium dioxide pellets in zircaloy cladding which gives it characteristics that are similar to commercial light water power reactors.
- The PULSTAR reactor has been used for sensor irradiation studies in the past and we will leverage that experience in this research.
- Principal Contact: Dr. Ayman Hawari



LAMDA Laboratory

- The ORNL LAMDA facility is a multipurpose laboratory for evaluation of radioactive materials with low radiological threat without the need for remote manipulation. The LAMDA laboratories are equipped for analysis of samples at less than 100 mR/hr at 30 cm.
- Unirradiated sensor assemblies were sent to LAMDA in 2021 to develop sample preparation procedures for the irradiated assemblies.
- Principal Contact: Dr. Kory Linton

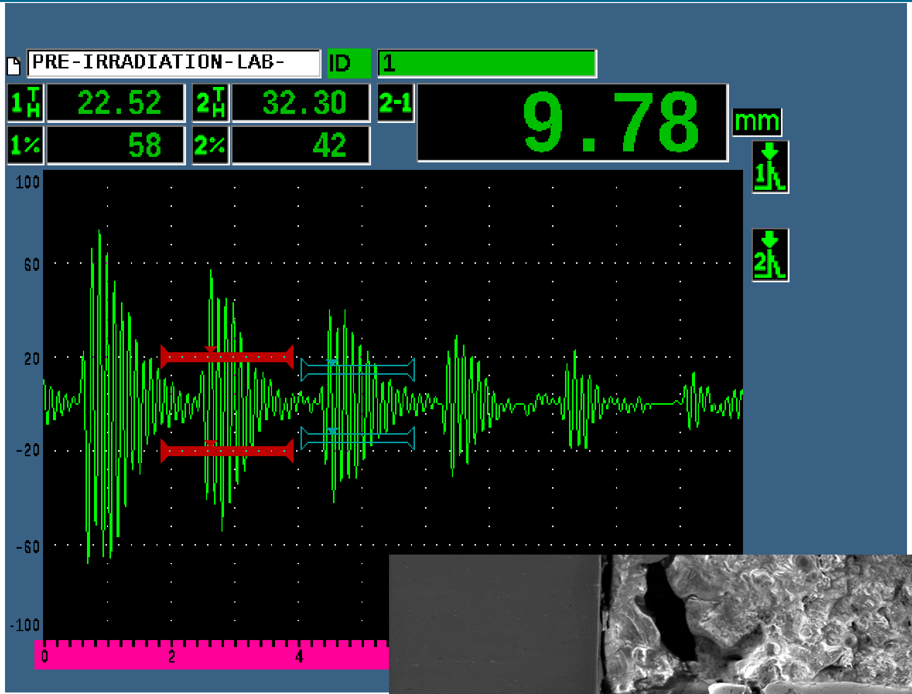
Technology Impact

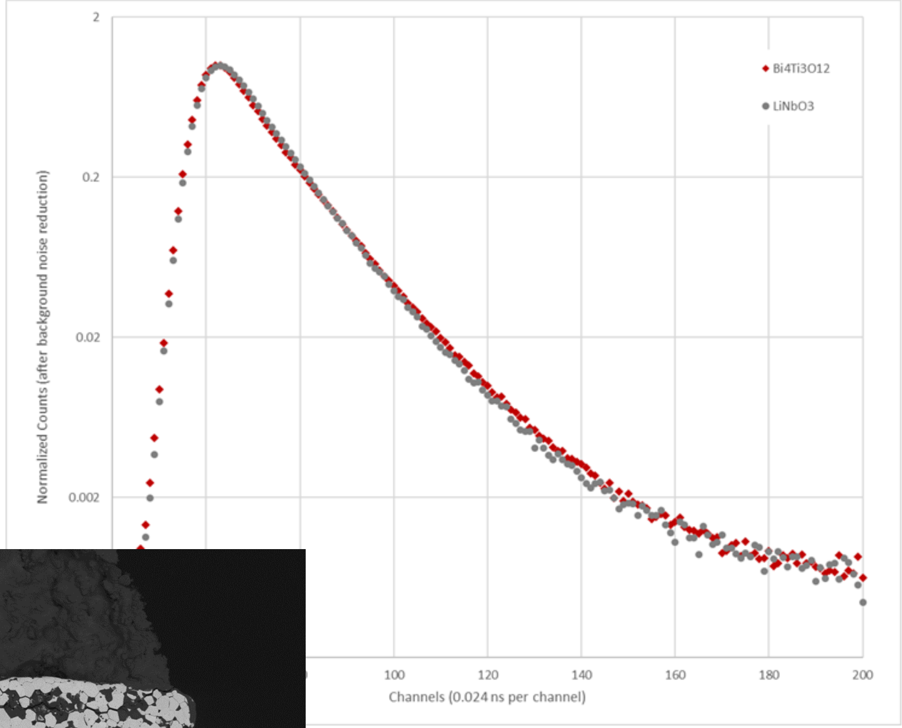
- Currently the majority of required nondestructive evaluations of LWR primary loop piping and components are performed manually.
- Going forward, it is in the interest of utilities to minimize manual inspections by development of online monitoring capabilities.
  - Minimization of human error
  - Reduction of dose to personnel
  - Real time inspection data
- To achieve this, semi-permanently installed sensors will have to operate at elevated temperatures and in radiation fields.
- This NSUF project will fill a gap in knowledge gaps associated with how piezoelectric ultrasonic transducers and, more specifically, adhesive couplants perform in a chronic radiation environment.
- This research will benefit both existing LWRs and advanced reactors
- EPRI is ideally positioned to utilize the NSUF research to facilitate sensor development and, subsequently, technology transfer to the industry.

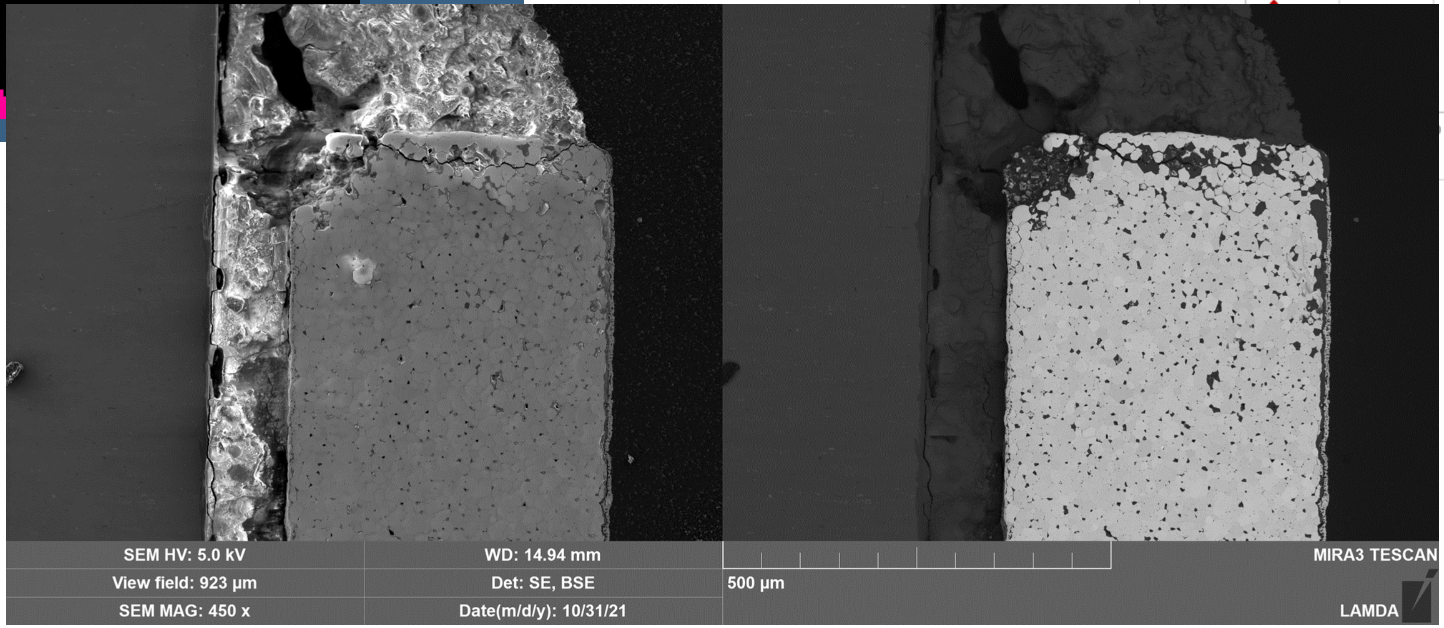
Results and accomplishments

- EPRI hosted a kick off meeting in Q1, 2021
- Acquisition of materials and equipment and construction of transducer/couplant/substrate irradiation assemblies were done in Q1 2021 – Q3 2021.
- Design and construction of the sample capsule was done in Q2 – Q4 2021.
- Baseline ultrasonic data for the unirradiated assemblies was acquired and analyzed.
- Irradiation of the sensor/couplant/substrate assemblies will proceed in Q1 2022.
- Characterization of unirradiated assemblies is currently under way (PALS, STEM, XRD, light microscopy).
- PIE of the assemblies and piezoelectric crystal wafers will be done subsequent to irradiation.

Results and accomplishments







Conclusion

- DOE NSUF funding was awarded to characterize radiation effects in piezoelectric sensors and adhesive couplants.
- 3 types of sensors and 4 types of adhesive couplants will be tested.
- The samples will be irradiated at the NC State University PULSTAR reactor.
- Ultrasonic data will be collected in-situ to determine signal stability and ability of the couplants to transmit ultrasonic energy in an irradiation environment.
- After irradiation the microstructure of the sensors themselves, as well as sensor-couplant-substrate interfaces will be characterized using light and electron microscopy, XRD and positron annihilation spectroscopy at the ORNL LAMDA laboratory and PULSTAR Intense Positron Beam facility.
- The results will be utilized immediately for an industry initiative

Principal Investigator:
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Nuclear Sector
Electric Power Research Institute (EPRI)
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Questions?

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ASI Advanced Sensors and Instrumentation

Status of the Creep Testing Capability for Characterizing the Structural Materials of Nuclear Components

CT-21IN070203

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Malwina Wilding
Nuclear Instrumentation Engineer

Idaho National Laboratory

Background

- Halden Boiling Water Reactor Shutdown in 2018
  - Halden Reactor Project provided unique testing and evaluation capabilities (in-pile creep and stress relaxation testing capability)
  - No facility is currently capable of such capabilities
- Light Water Reactor (LWR) life extension
  - Basis for assessing materials degradation and developing aging management practices for key LWR components during license renewal
  - Basis for economic decisions related to plant asset management and continuing plant feasibility
- Advanced Test Reactors
  - Provide quantitative demonstrations that show the durability and longevity of the materials selected

Project Overview

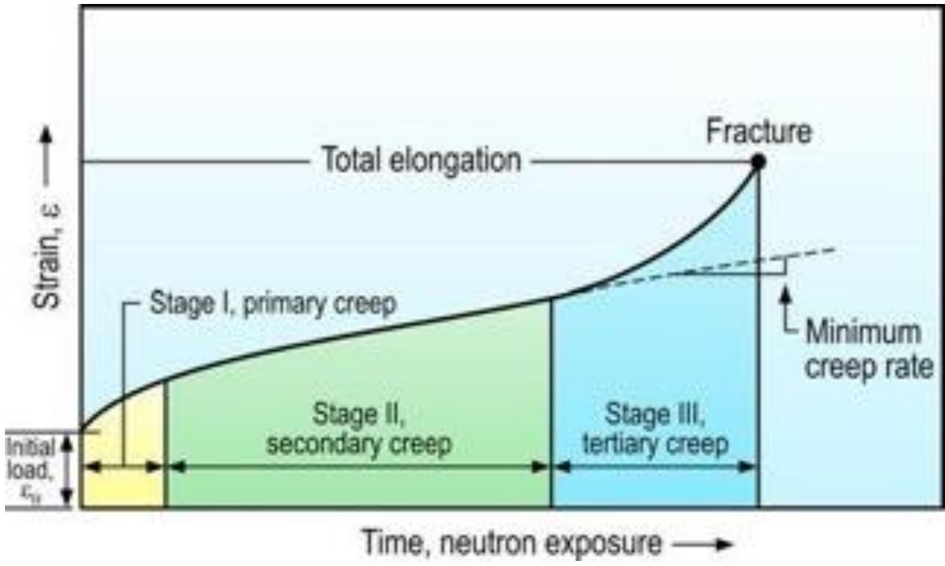
- Project Overview:
  - Creep behavior is critical for safety concerns and longevity of current and future nuclear reactors
  - In-situ creep testing capability offers more control over experimental variables, provides more details regarding creep behavior, and gives you improved accuracy compared to non-instrumented tests
  - These innovated sensors and sensor technologies will be employed in irradiation tests and demonstration facilities to progress their capability and enable stakeholders to adopt them with minimal risk
- Participants (Idaho National Laboratory)
  - Malwina Wilding (PI), Michael McMurtrey (WPM), Anthony Crawford, Wesley Jones, Hollis Kristopher Woodbury, and Kory Manning
- Schedule:
  - Sept. 2021: M2CT-21IN0702036
  - Technical Report titled “Development of real time, in-pile test rigs for the characterization of nuclear components structural materials”

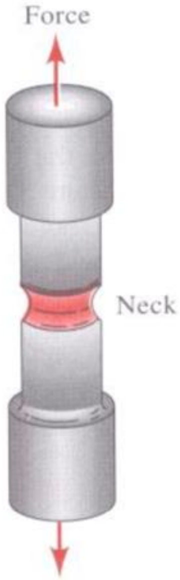
Technology Impacts

- This technology advances the state of the art for nuclear application:
  - With the closure of the Halden Reactor, this work maintains and develops mechanical testing (in-situ creep and stress-relaxation) capabilities that would otherwise be lost
- How it impacts the nuclear energy industry:
  - These technologies enable the Department of Energy (DOE) to establish core capabilities and respond to complex in-pile measurement objectives identified by different stakeholders and DOE-Office of Nuclear Energy R&D programs, while qualifying materials for both current and future nuclear energy systems
- How it supports the nuclear energy industry:
  - In-situ creep testing capability is currently being designed into future Navy tests that will be conducted at ATR; as well as, in-situ stress relaxation capability part of the FIDES JEEP proposals for future work

Creep Test Fundamentals

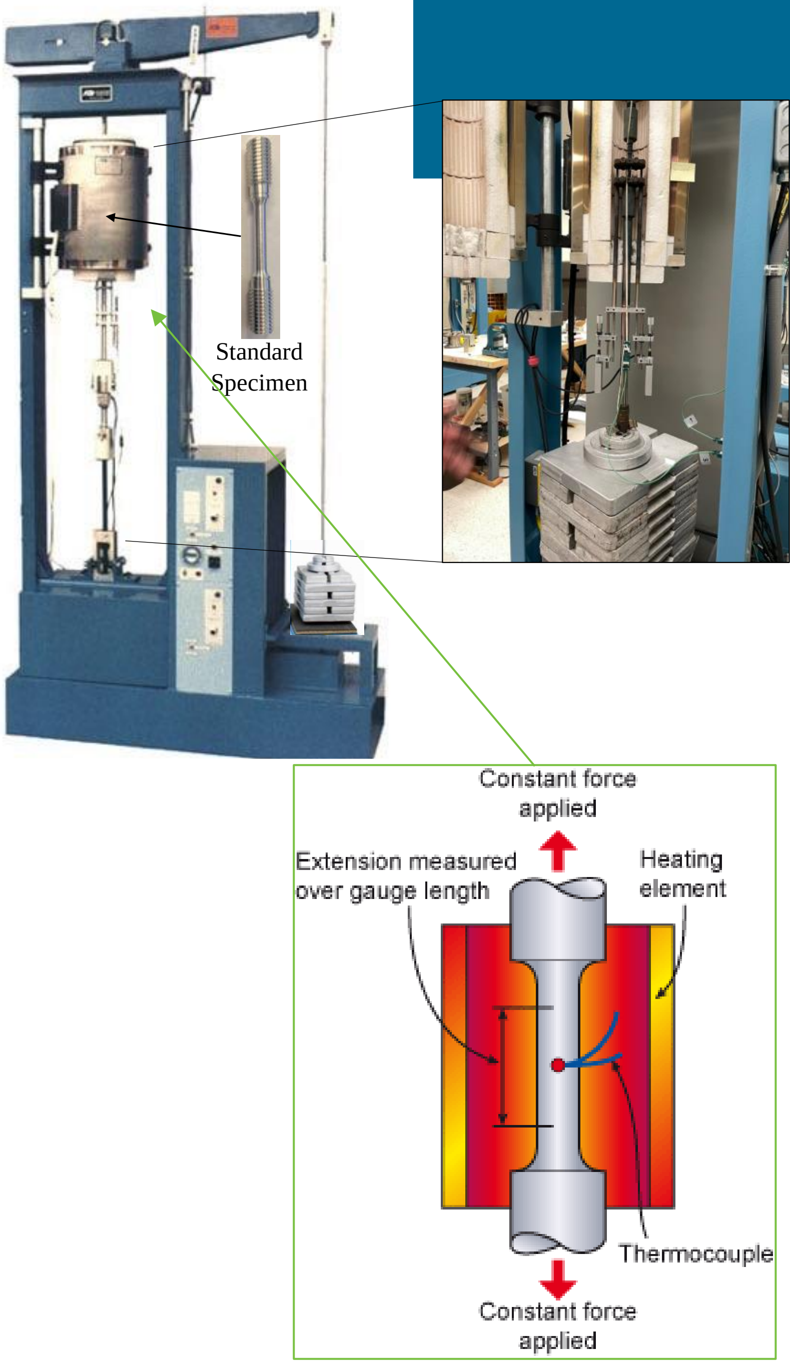
- Creep is a very slow, time-dependent plastic deformation that occurs in materials subjected to a stress (or load) at relatively high temperatures
- Generally, occurs at high temperatures (thermal creep), but can also happen at lower temperatures (irradiation creep)
- As a result, the material undergoes a time-dependent deformation (strain) that could be dangerous while the material is in service
- Creep rupture tests are used to measure the limitations of the material prior to being used in service
- Fairly limited data on the irradiation-enhanced stress relaxation and irradiation creep behavior of austenitic stainless steels
  - Fast neutron spectrums are much different from the spectra generated in LWRs





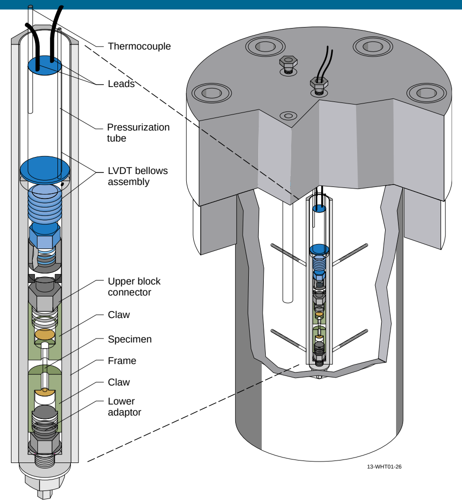
Standard Creep Testing

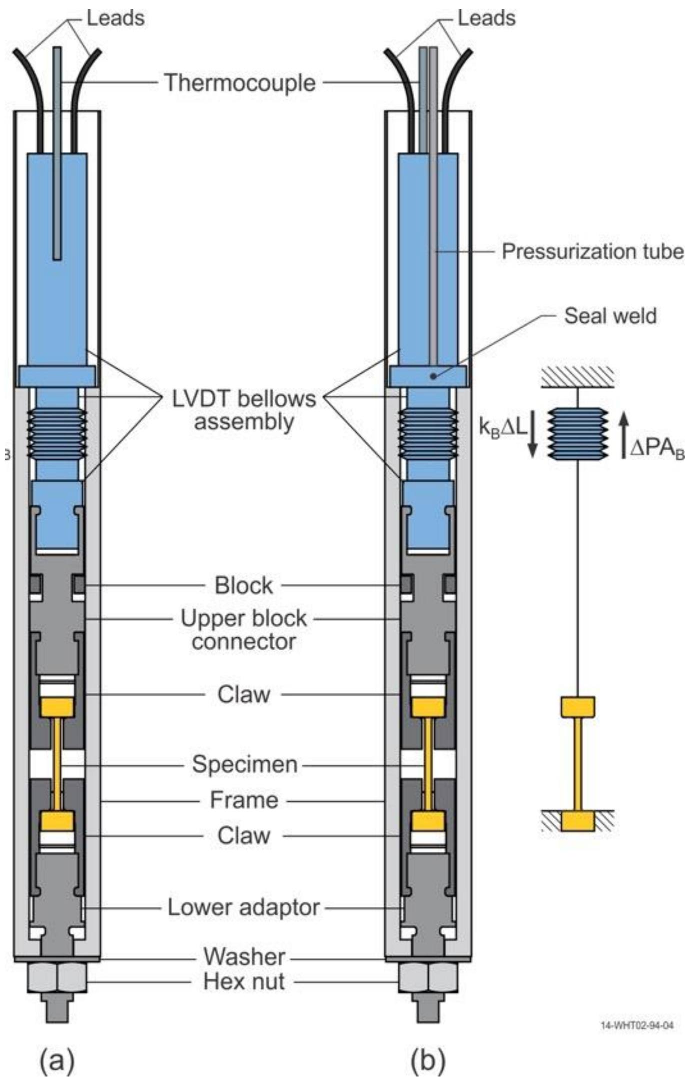
- Creep tests are conducted per the *ASTM E139 standard*
- *A standard creep test uses a creep* specimen that is placed under a constant stress, often by the simple method of suspending weights from it (direct load)
- Containing the specimen in a furnace whose temperature is controlled by a thermocouple (TC) attached to the gauge length of the specimen
- The increase in length of the specimen is measured using a very sensitive extensometer and commercial LVDTs
- The test results are then plotted on a graph of strain versus time to produce a creep curve



INL Creep Test Rig Design

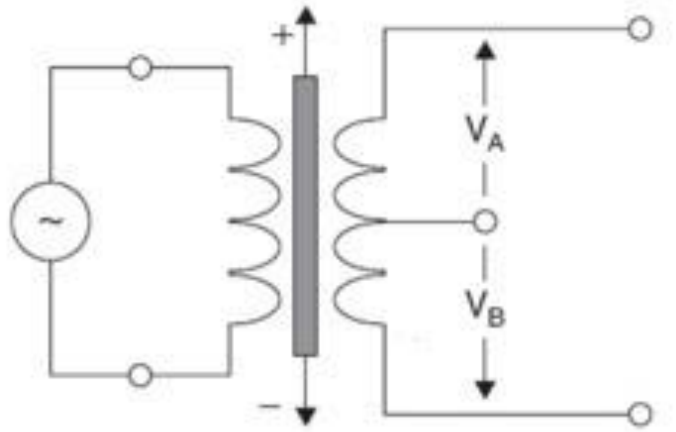
- Based on HRP design
- Originally made for ATR PWR Loop testing
- Composed of several elements:
  - Creep dumbbell specimen
  - linear variable displacement transducer (LVDT) to measure dimensional changes (supplied by IFE/HRP)
  - two types of bellows assemblies to measure creep or stress relaxation (static and variable pressure/load)
  - thermocouple holder
  - support structure to maintain the experiment in an in-pile environment
  - National Instruments data acquisition system for reading both live and recorded sensor signals





Linear Variable Differential Transformer

- LVDTs are simple, reliable sensors that convert a specimen’s mechanical movement into an electrical output.
- Magnetically permeable core is attached to a specimen.
- The core then moves inside a tube in response to changes in the specimen’s length or position.



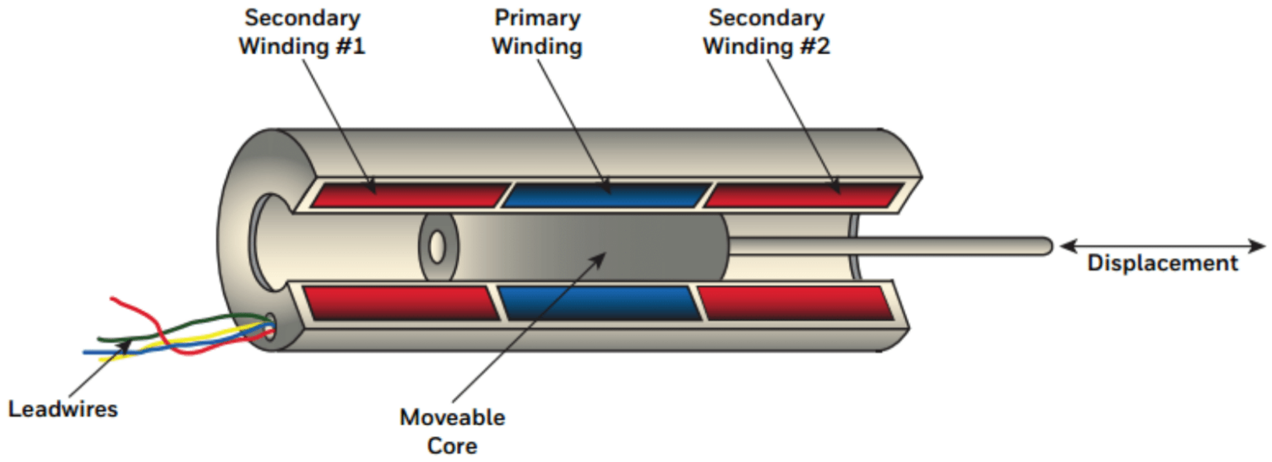
$$\Delta X = S(LVDT_f - LVDT_i)$$

ΔX = change in displacement [mm]

S = sensitivity at a given temperature [mm / (V/V)], interpolated from calibration graph

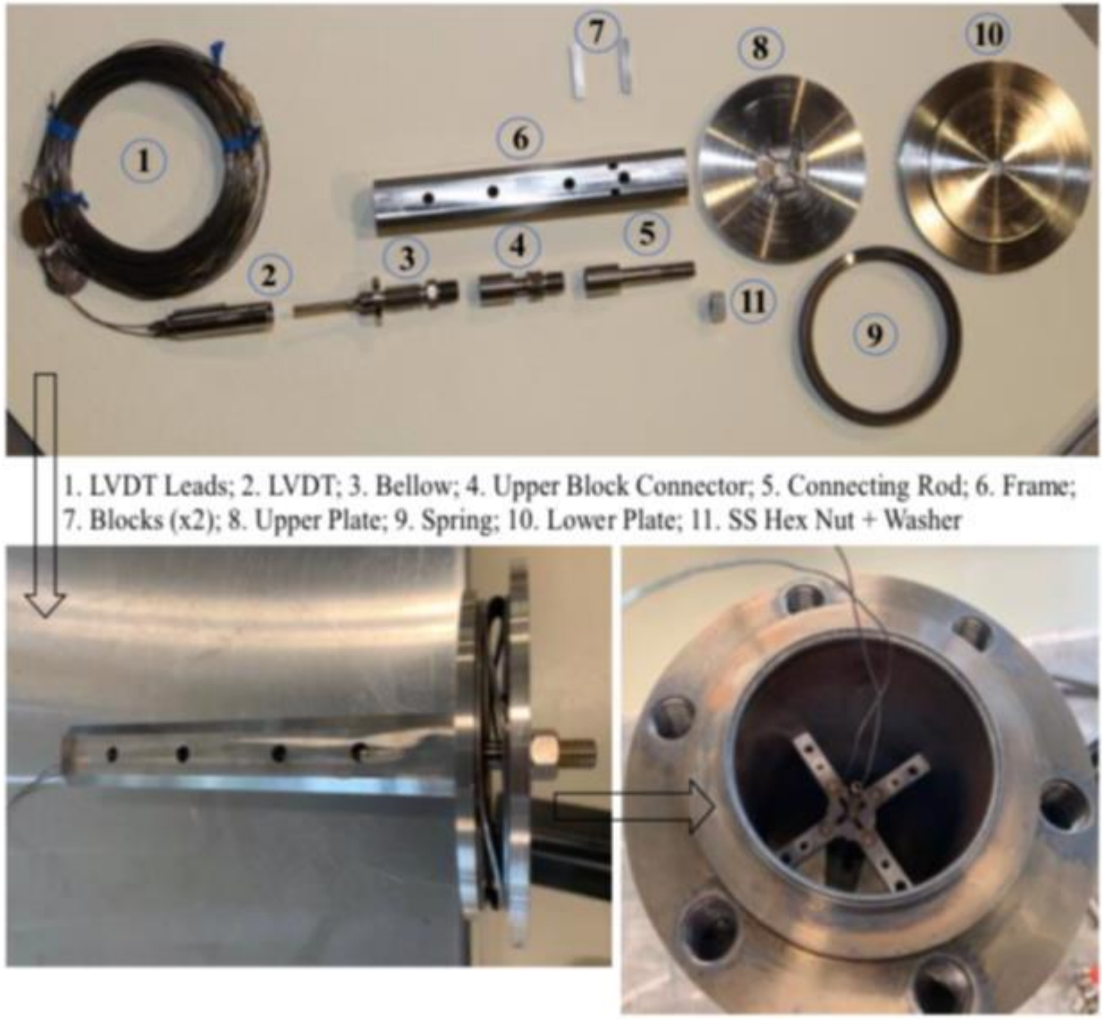
$LVDT_f$ = final demodulation reading [V/V]

$LVDT_i$ = initial demodulation reading [V/V]



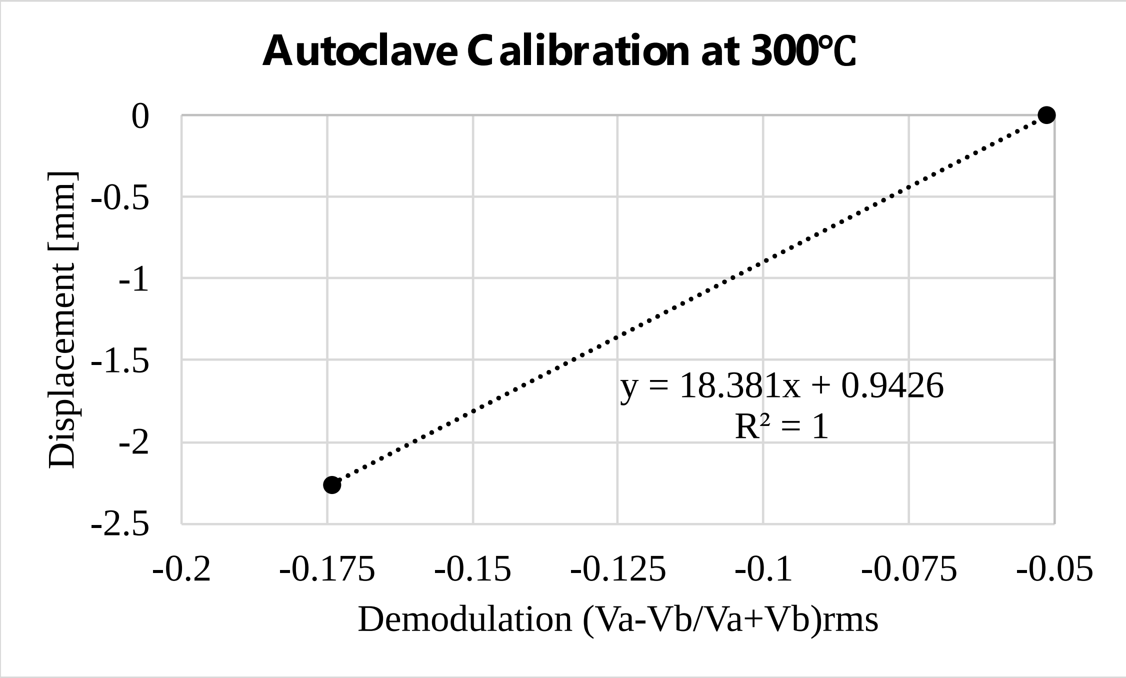
Autoclave Testing

- Autoclave testing is used for calibrating and verifying the full LVDT bellow assembly
- Specifications:
  - PWR prototypic conditions
  - Maximum allowable working pressure of 22.75 MPa with a 19.31 MPa relief valve
  - Maximum temperature of 354°C
  - Maximum flow rate of 15 gal per hour
- Flowing Autoclave:
  - Maximum allowable working pressure of 15.5 MPa
  - Maximum temperature of 315°C
  - Maximum flow rate of 50 gal per minute



Autoclave Calibration

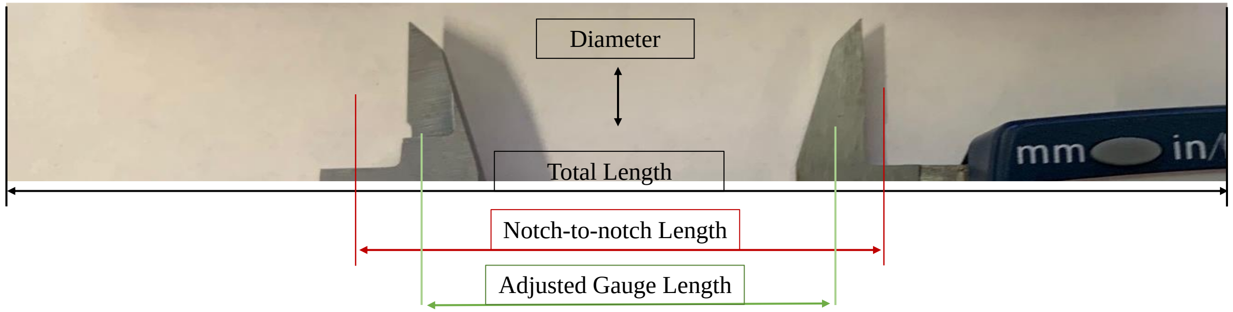
- The LVDT bellow assemblies must be calibrated for the range of temperatures expected during deployment in PWR coolant conditions
- Calibration was completed at room temperature and at 100, 200, and 300° C that represent typical PWR conditions
- For creep testing we used 300° C sensitivity of 18.381 (V/V)/mm for the LVDT

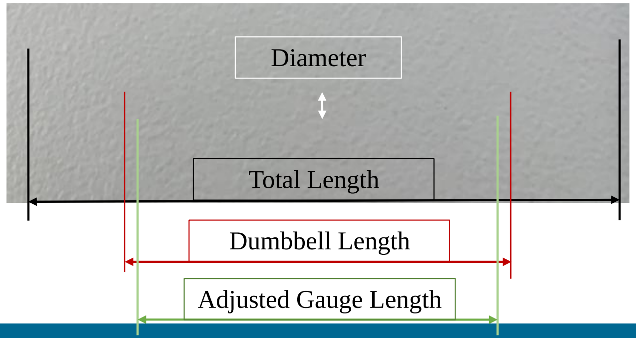


Temperature (°C)	Sensitivity (V/V/mm rms
21	16.539
100	16.531
200	17.615
300	18.381

Creep Specimen Material Selection

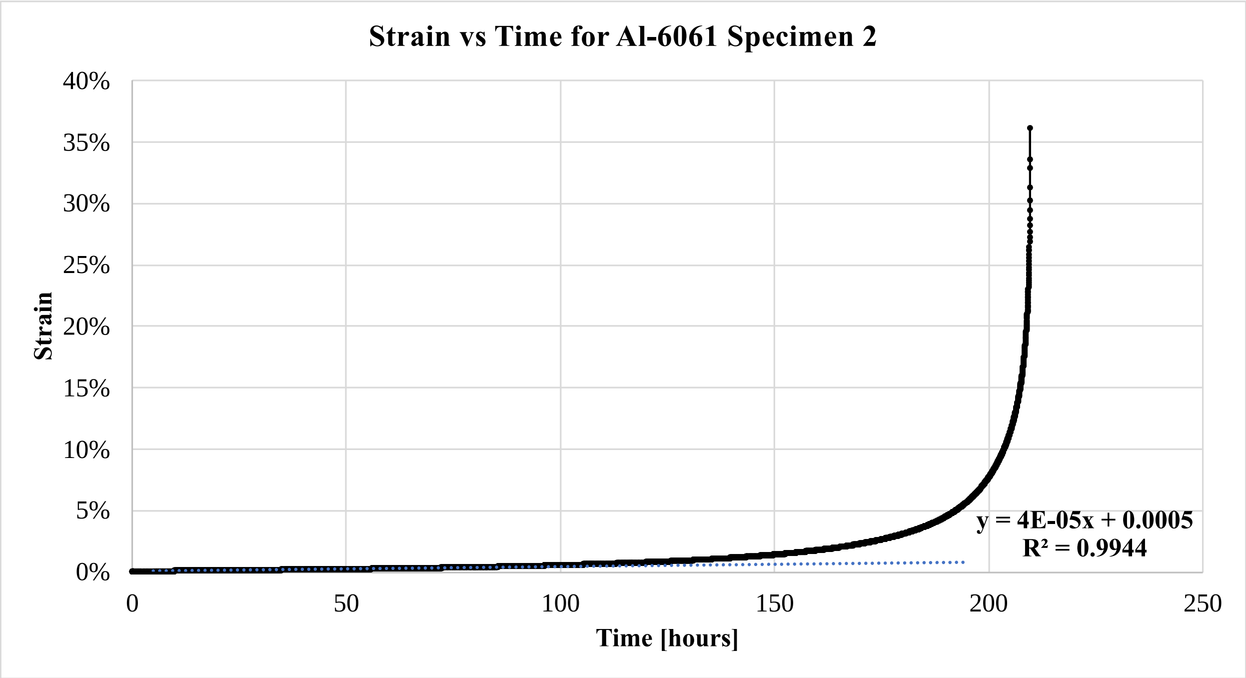
- The primarily motive for selecting aluminum was its low melting temperature (i.e., ~650°C) that fosters accelerated creep testing results:
  - Aluminum 6061 isn't a common nuclear alloy used in reactors
  - Testing at irradiation creep temperatures (~300°C) of most nuclear materials, without irradiation, wouldn't be creeping at those temperatures
  - 420–560°C for common stainless steels, but creep begins at 195–260°C for Al-6061
- Benefits of Al-6061:
  - has good mechanical properties
  - easy to machine
  - remains a very common material for general-purpose use
- Creep tests last anywhere from 2,000–10,000 hours; however, using materials with much lower melting temperatures can significantly decrease the time to material failure (e.g., 200 hours)





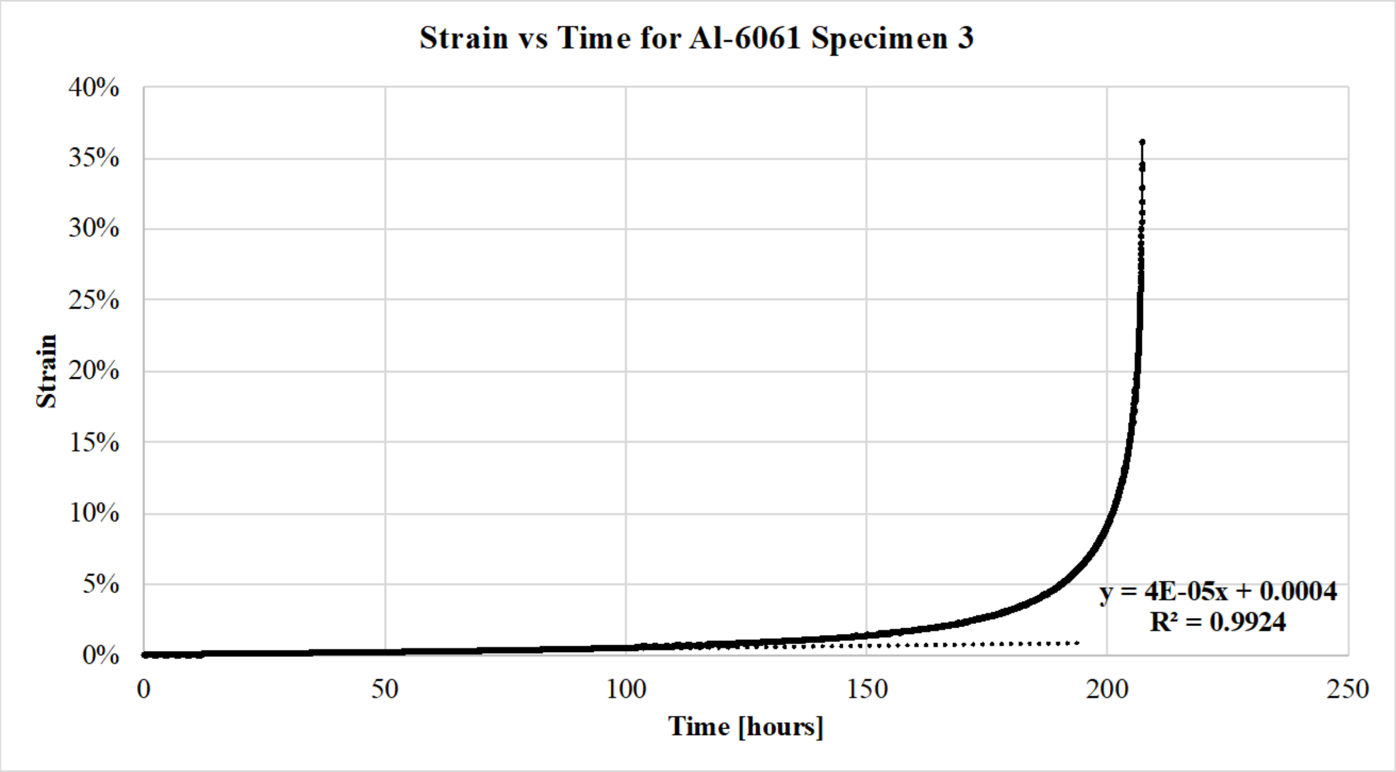
Standard Creep Testing Results

- The first standard creep specimen was used to learn whether the actual rupture time was comparable to the predicted rupture time estimated via the Larson-Miller parameter method
- A temperature of 345°C and a stress of 16.86 MPa that failed at ~54 hours
- A final temperature of 325°C and a stress of 15.896 MPa were chosen for standard creep specimens #2 and #3
- The Figure shows the creep curve for Al-6061 specimen #2:
  - Primary creep is very fast
  - Secondary steady-state creep rate of 0.004% strain per hour
  - Tertiary creep stage is also very rapid
  - Final failure of the sample occurred at ~210 hours



Standard Creep Testing Results Cont.

- Temperature of 325°C and stress of 15.896 MPa
- The Figure shows the creep curve for Al-6061 specimen #3
  - Primary creep is very fast
  - Secondary steady-state creep rate of 0.004% strain per hour
  - Tertiary creep stage is also very rapid
  - Final failure of the sample occurred at ~207 hours



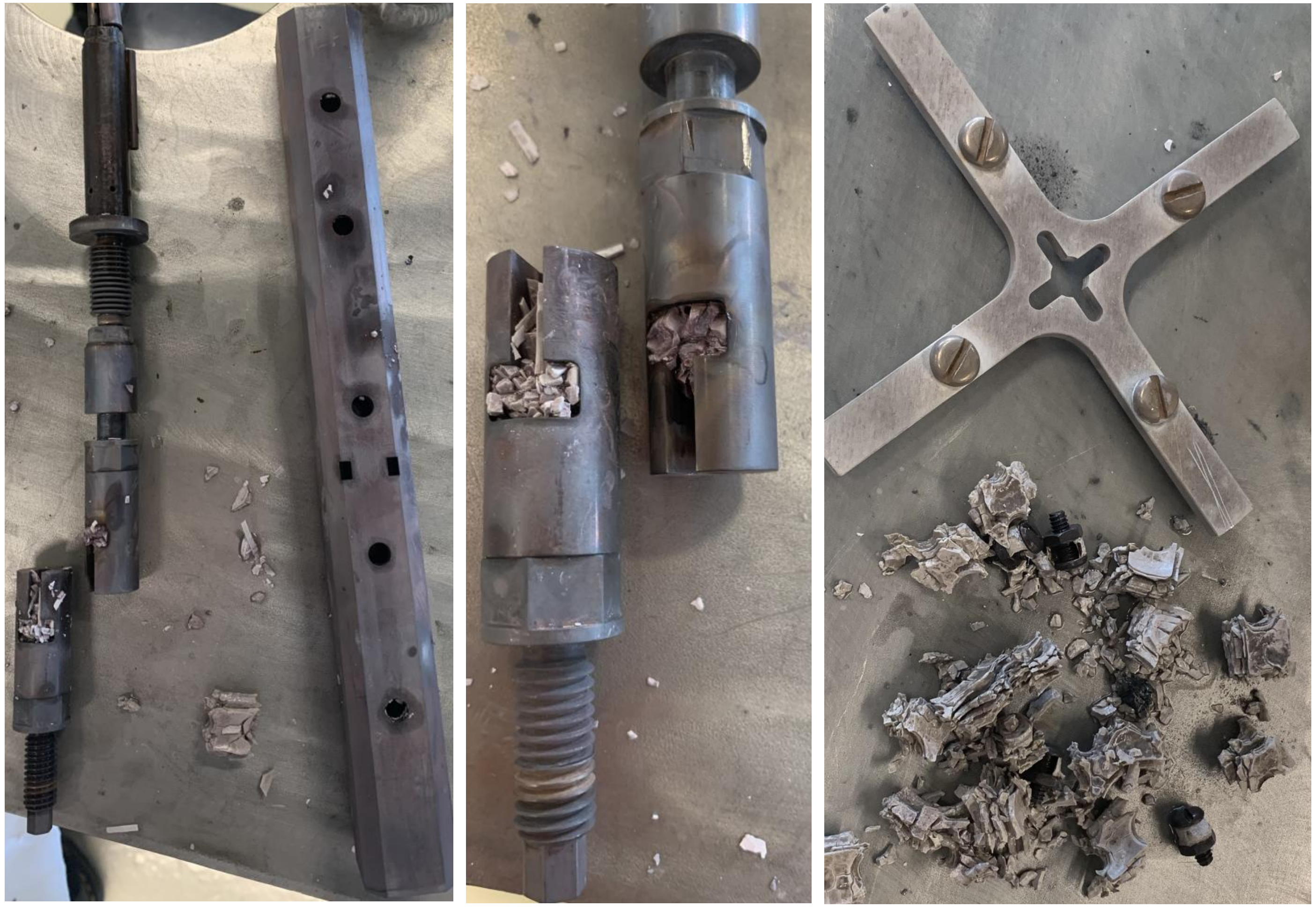
Standard Creep Specimen Results

- As expected, all the Al-6061 standard specimens failed by breaking within the gauge length region
  - Each sample broke at different points within that region
- Since aluminum is a ductile metal, standard specimen #2 had to be cut off at the shoulder grip after getting stuck in the creep testing frame
  - For creep specimen #2 it was impossible to measure the total length post-testing

Sample ID	Total Length (mm)			Notch-to-Notch Length (mm)			Average Delta (mm)
	Before	After	Delta	Before	After	Delta	
Standard 2	99.15	N/A	-	42.923	55.35	12.427	12.427
Standard 3	99.11	115.67	16.56	42.923	59.68	16.757	16.659

Dumbbell Creep Specimen Results

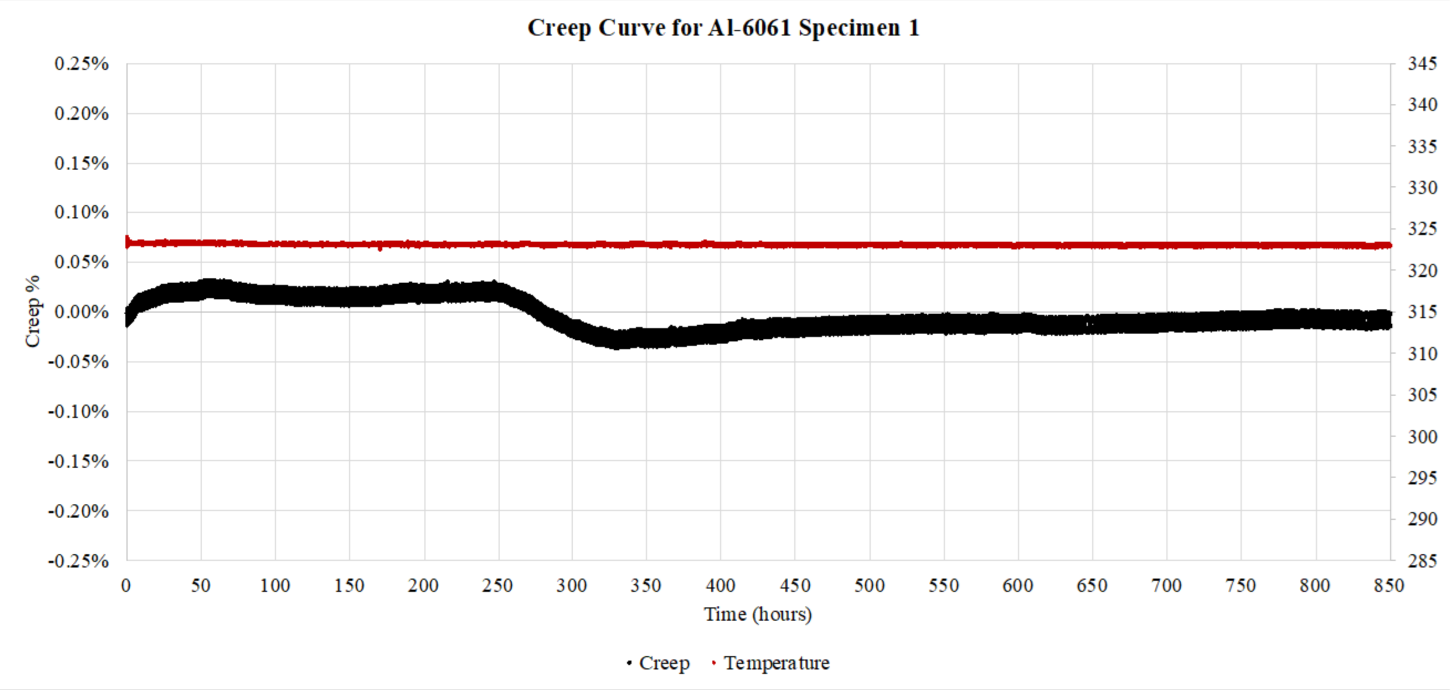
- Unfortunately, when the test ended, Al-6061 dumbbell specimen #1 was fully oxidized
- It was no longer intact in the creep test rig
- It is unknown how fast the Al-6061 specimen began oxidizing in the autoclave
- Furthermore, the deionized water in the autoclave was not chemically controlled to prevent oxidization from occurring

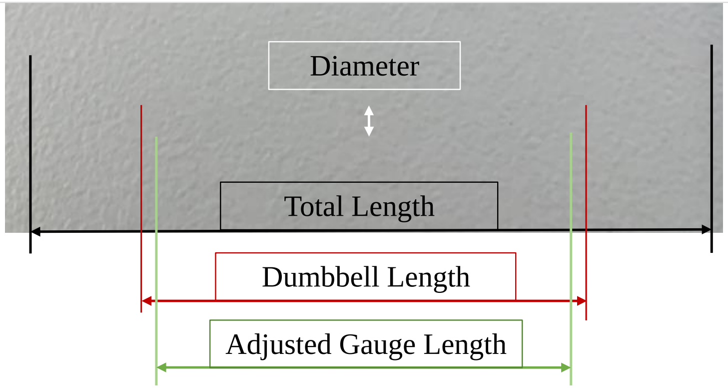


(a) (b) (c)

Autoclave Creep Testing Results

- The creep curve results in Figure are inconclusive
- The following main autoclave creep testing objectives were met:
  - Test creep rig can withstand elevated temperatures, pressures, long working hours (36 days) as a robust system
  - Verification of signal processing equipment using the NI DAQ system, and no data loss over a duration of 36 days
  - Gain insights from lessons learned that can be applied when finalizing the design prior to deployment in the Materials Test Reactor





Conclusion

- As part of the Nuclear Energy Enabling Technology's Advanced Sensor and Instrumentation program, an instrumented creep testing capability was developed by the HTTL team to enable specimens (e.g., Al-6061) to be tested under prototypic PWR conditions (e.g., 325° C and 2300 psi)
- Results from the autoclave evaluations demonstrated even the worst-case scenario of having the specimen completely disintegrate, while still being able to record and maintain the system at steady state conditions indicating that robust system construction of the test rig was a success.
- These lessons learned will be used to finalize recommendations for an enhanced design that will be inserted into the flowing autoclave
- Although the INL-developed creep testing capability will ultimately be applied to a wide range of materials, initial efforts focused on aluminum 6061 verification testing
- Finally, testing of the INL creep test rig confirmed its availability and robustness for deployment
- And its ability to partially replace those testing capabilities lost due to the termination of HBWR operations

Future Work

- The first lesson learned from this work is that autoclave testing requires either a dry environment (inert gas) testing capability or a chemically controlled water flow capability to prevent any oxidization issues from arising in the creep specimens
- Additionally, stress relaxation measurements would broaden the in-pile test rig capability for future work
- LVDTs supplied by the Halden Reactor Project are not sustainable long-term; therefore, looking into the use of strain gauges, printed strain gauges, or other small strain measuring devices would greatly benefit and broaden the capabilities for multi-sensor and multi-specimen in-pile testing

Contact Information

- *Contact Info:*

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- References:

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Questions?

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Clean. Reliable. Nuclear.

High-Performance Nanostructured Thermoelectric Generators (TEGs) for In-Pile Power Harvesting

Advanced Sensors and Instrumentation Annual Webinar

November 16 , 2021

Yanliang Zhang

University of Notre Dame

Project Overview

Objectives:

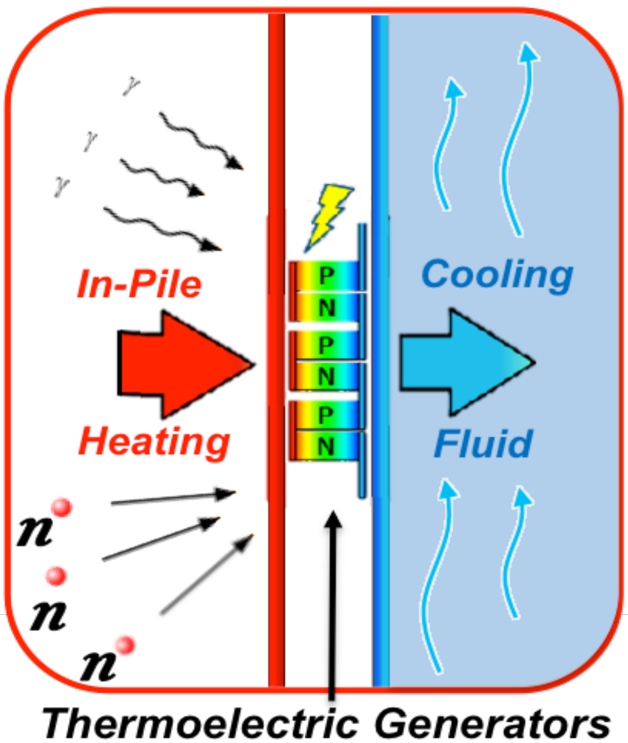
- Investigate the in-pile performance of high-efficiency nanostructured bulk thermoelectric materials and devices
- Develop radiation-resistant thermoelectric generators (TEGs) for in-pile power harvesting

Participants:

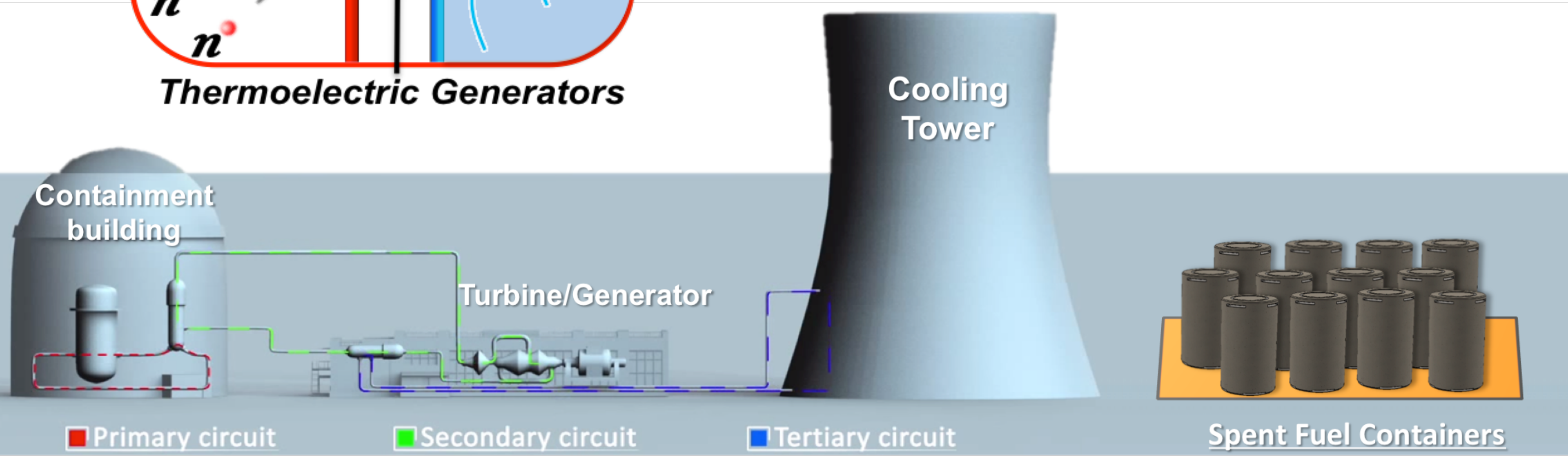
- Yanliang Zhang, University of Notre Dame;
- Josh Daw, Idaho National Laboratory;
- Mercouri Kanatzidis, Northwestern University.

Schedule: 10/2018 - 09/2021

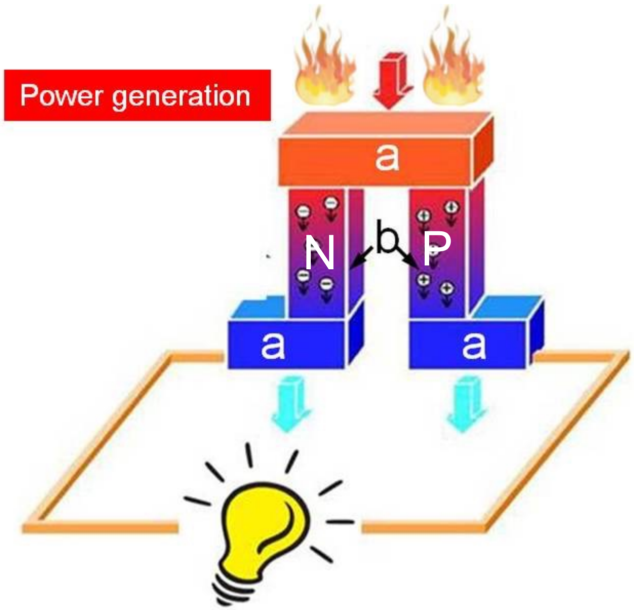
Nanostructured Bulk Thermoelectric Generators (TEGs) for In-pile Power Harvesting



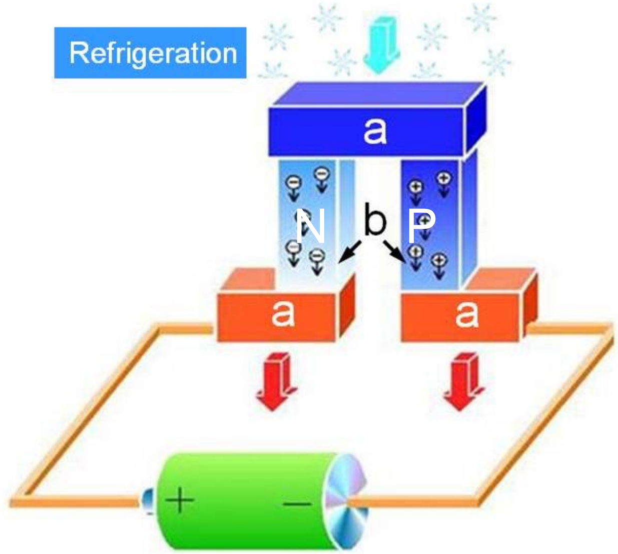
- Thermal energy is very abundant in nuclear power plants;
- The nanostructured bulk thermoelectric materials have significantly higher efficiency and potentially improved radiation resistances over bulk materials.



Principles of Thermoelectric (TE) Energy Conversion

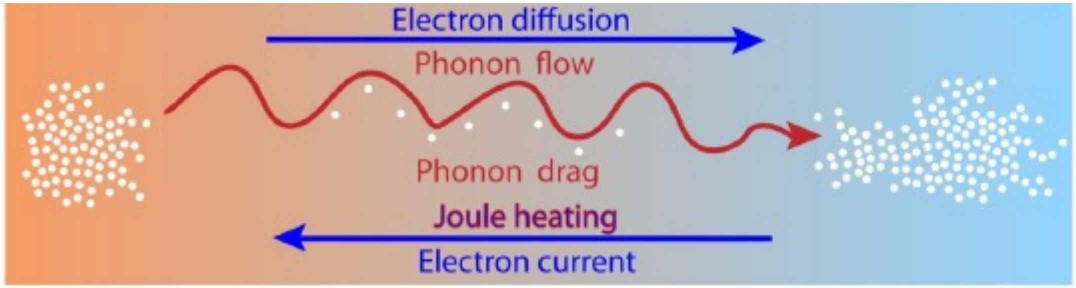


Seebeck effect



Peltier effect

Electrical power generation



Electrons Phonons

Energy carriers

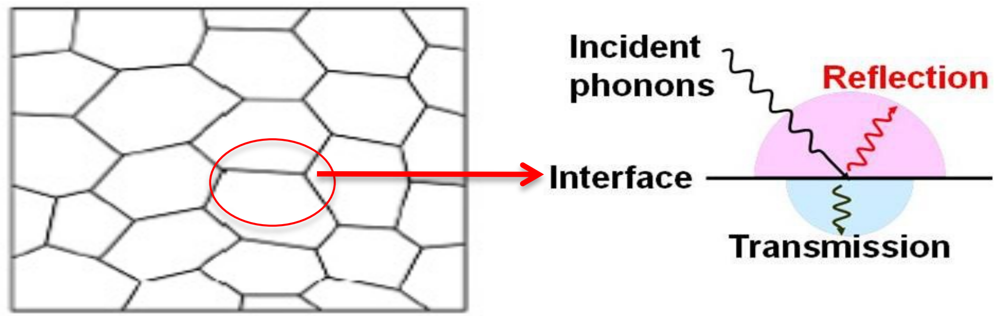
Electron flow is the "working fluid" for cooling and power generation.

Nano-Engineering to Increase Thermoelectric Figure of Merit ZT

Seebeck coefficient — Electrical conductivity

$$ZT\uparrow = \frac{\alpha^2\uparrow\sigma}{\kappa_E + \kappa_L\downarrow}T$$

Electronic — Lattice thermal conductivity



Power factor: $\alpha^2\sigma$

$$\eta_{max} = \frac{T_H - T_C}{T_H}\,\frac{\sqrt{1+Z\bar{T}}-1}{\sqrt{1+Z\bar{T}}+\frac{T_C}{T_H}}$$

Device efficiency increases with ZT and ΔT

Mean free path

Electrons 1-100 nm

Phonons 1-500 nm

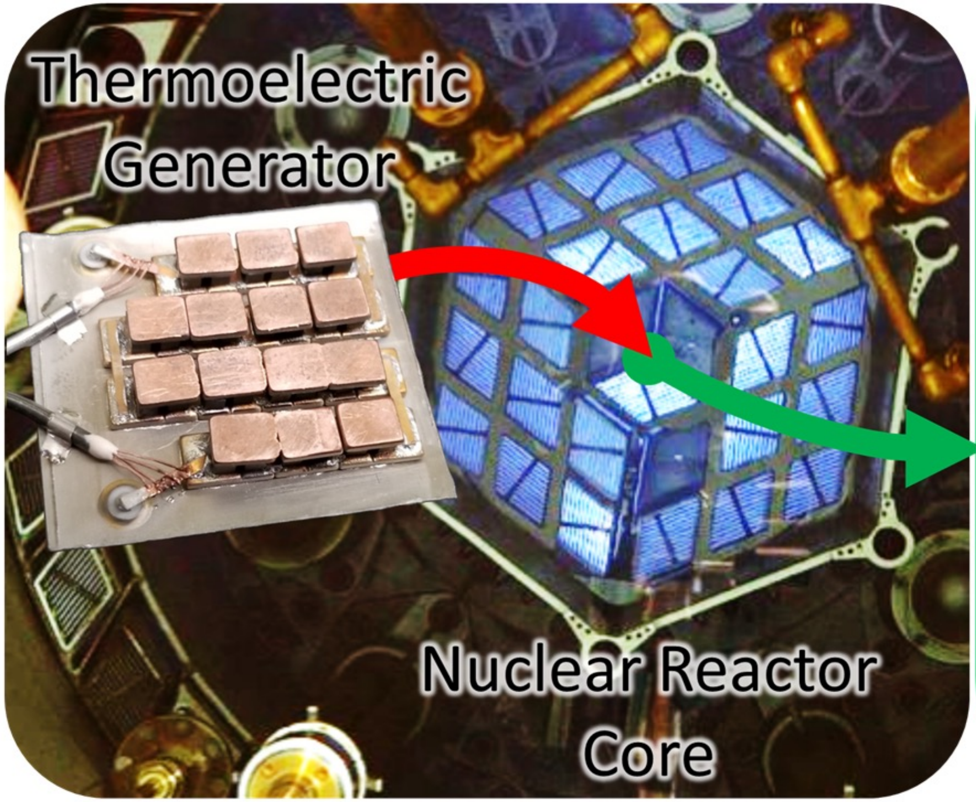
Summary of accomplishments

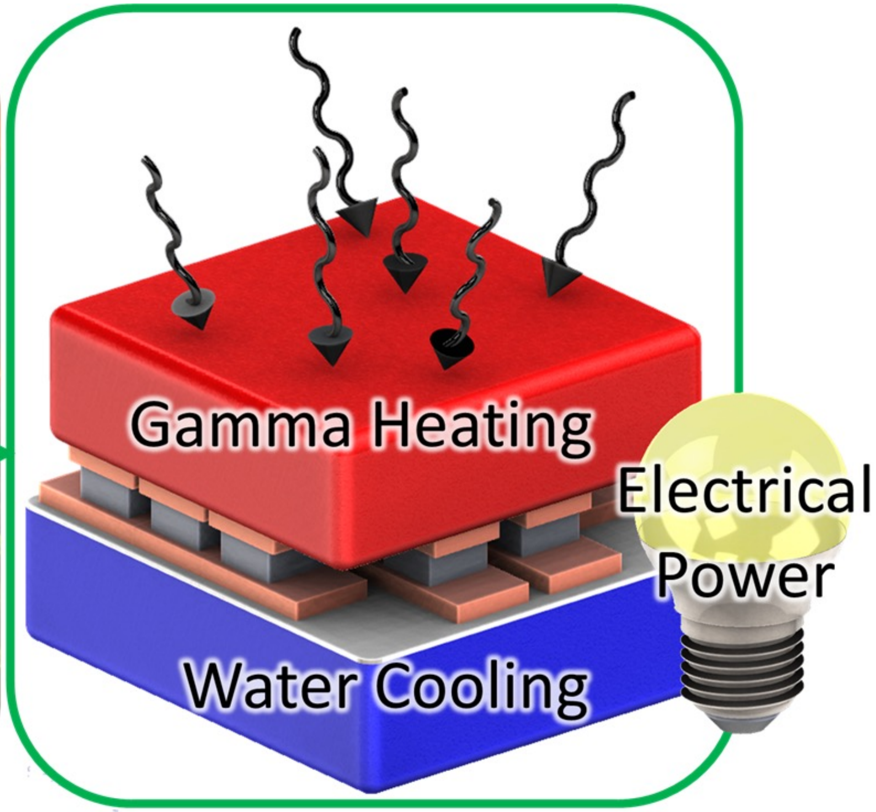
- Developed high-temperature and high-power-density thermoelectric generators (TEGs) and associated instrumentation for in-pile irradiation and in-situ testing
- Performed in-situ test of TEG performances in the core of MIT reactor
- Investigated the effect ion-irradiation on thermoelectric materials

Technology Impact

- Generate power in the nuclear reactor core or other NPP areas
- Enable TEG-powered sensors for in-pile instrumentation
- Enable self-powered wireless sensors for broad NPP applications
- Reduce the cost of sensors installation and maintenance
- Improve the safety of nuclear power plants

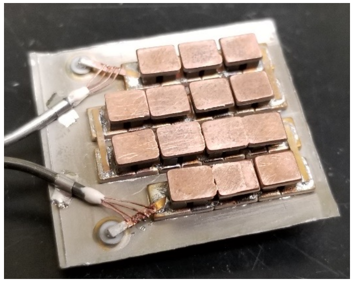
Thermoelectric Generators for In-pile Power Harvesting



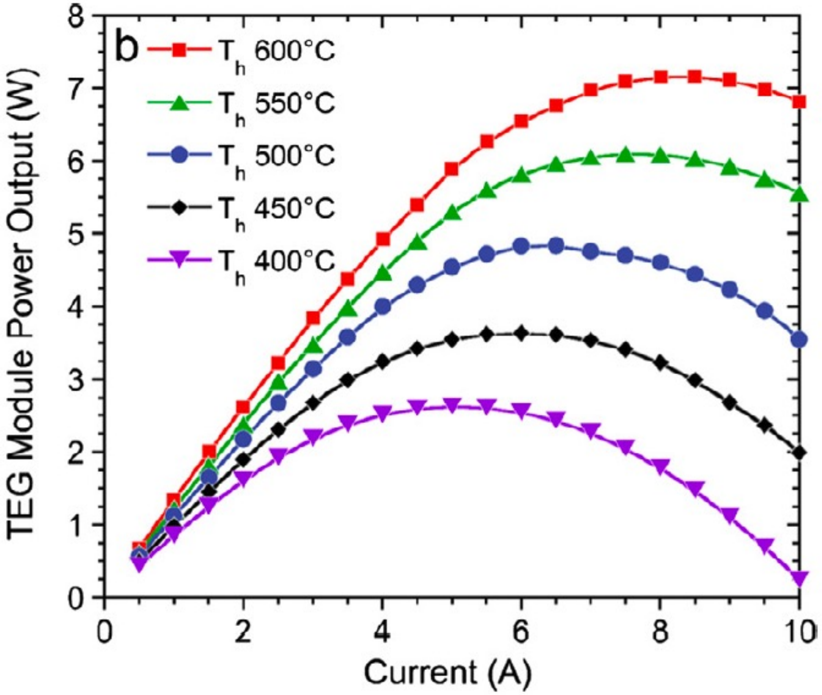


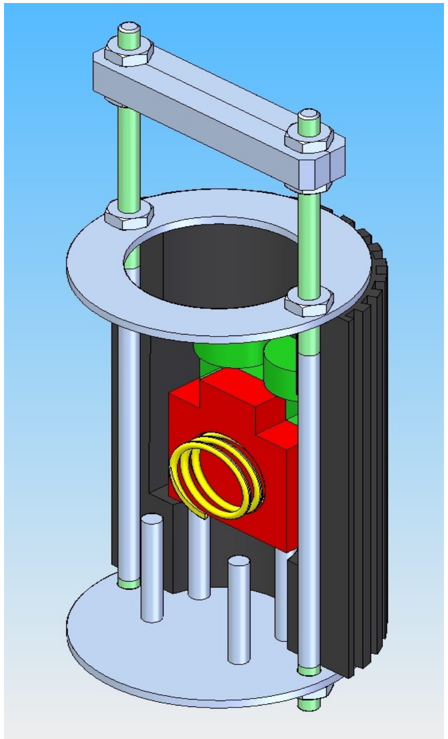
High-temperature & high-power-density thermoelectric generators (TEGs) for in-core power harvesting

Nanostructured bulk Half-Heusler TEG

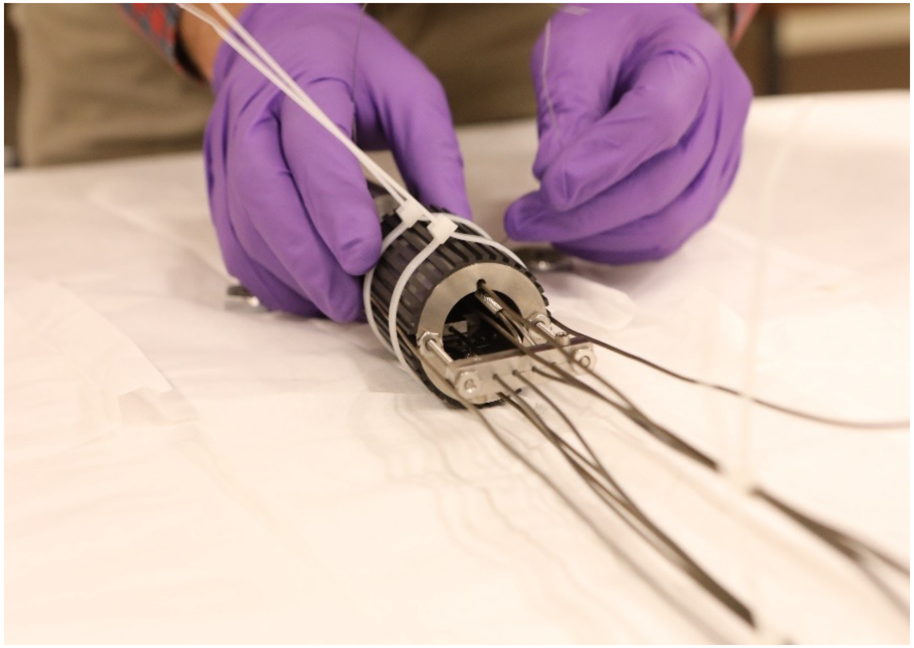


KEY METRICS	Half-Heusler TEG	COMMERCIAL BISMUTH TELLURIDE TEG
Power density (W/cm^2)	2-3	0.2-0.3
Max Operating temp	650 ^oC	250 ^oC

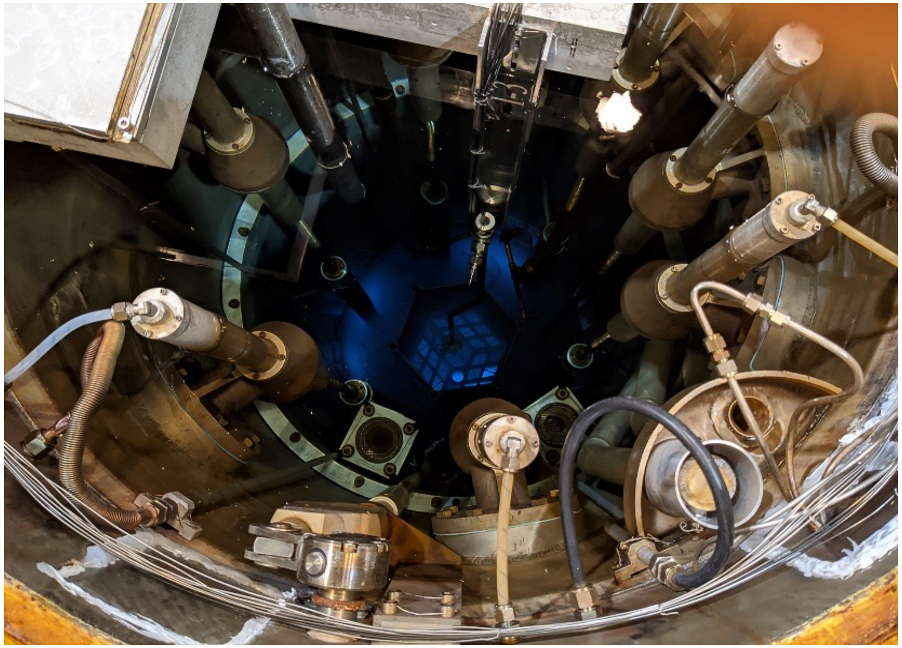




Two TEGs inserted into the core of MIT reactor

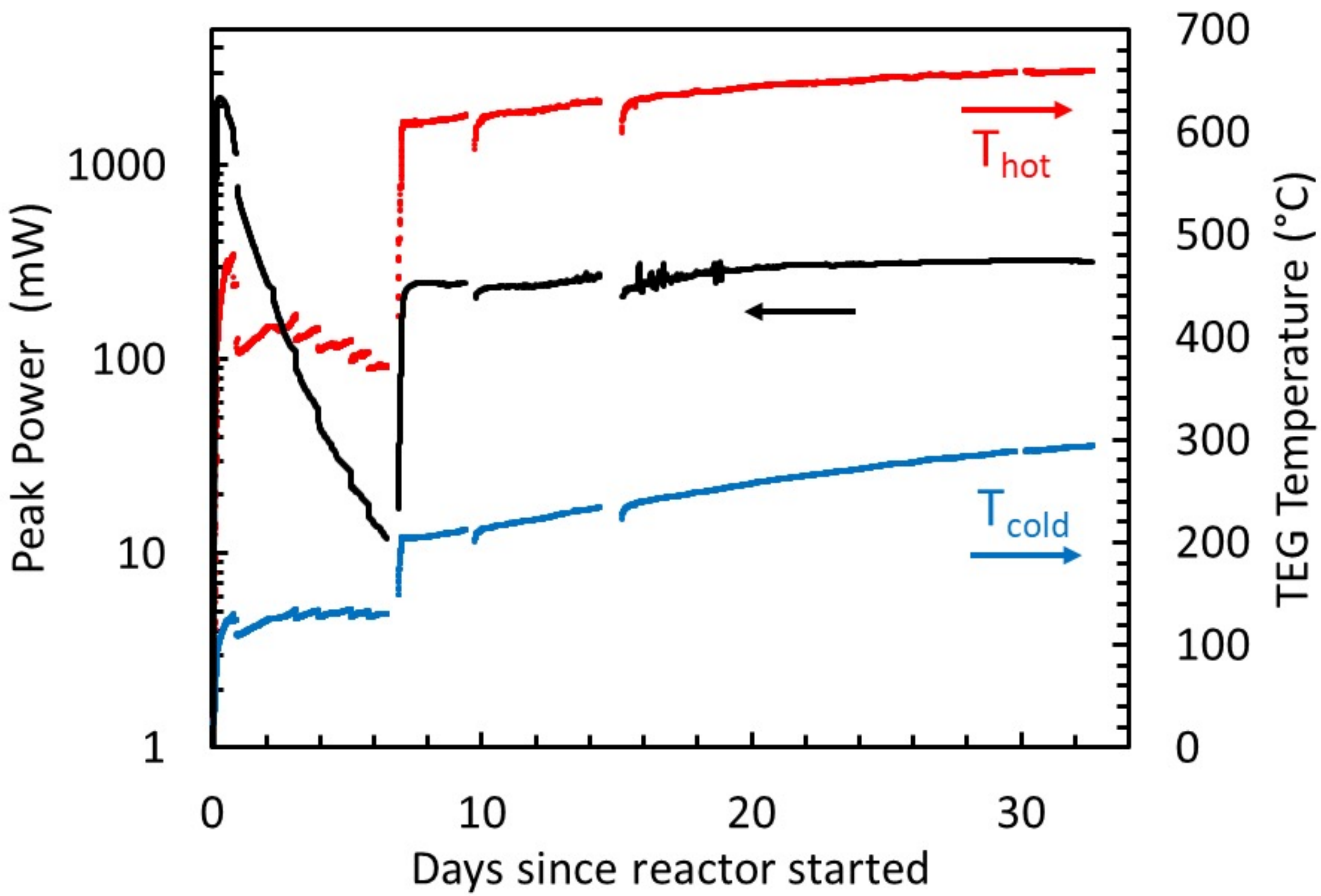


TEGs assembled with the capsule



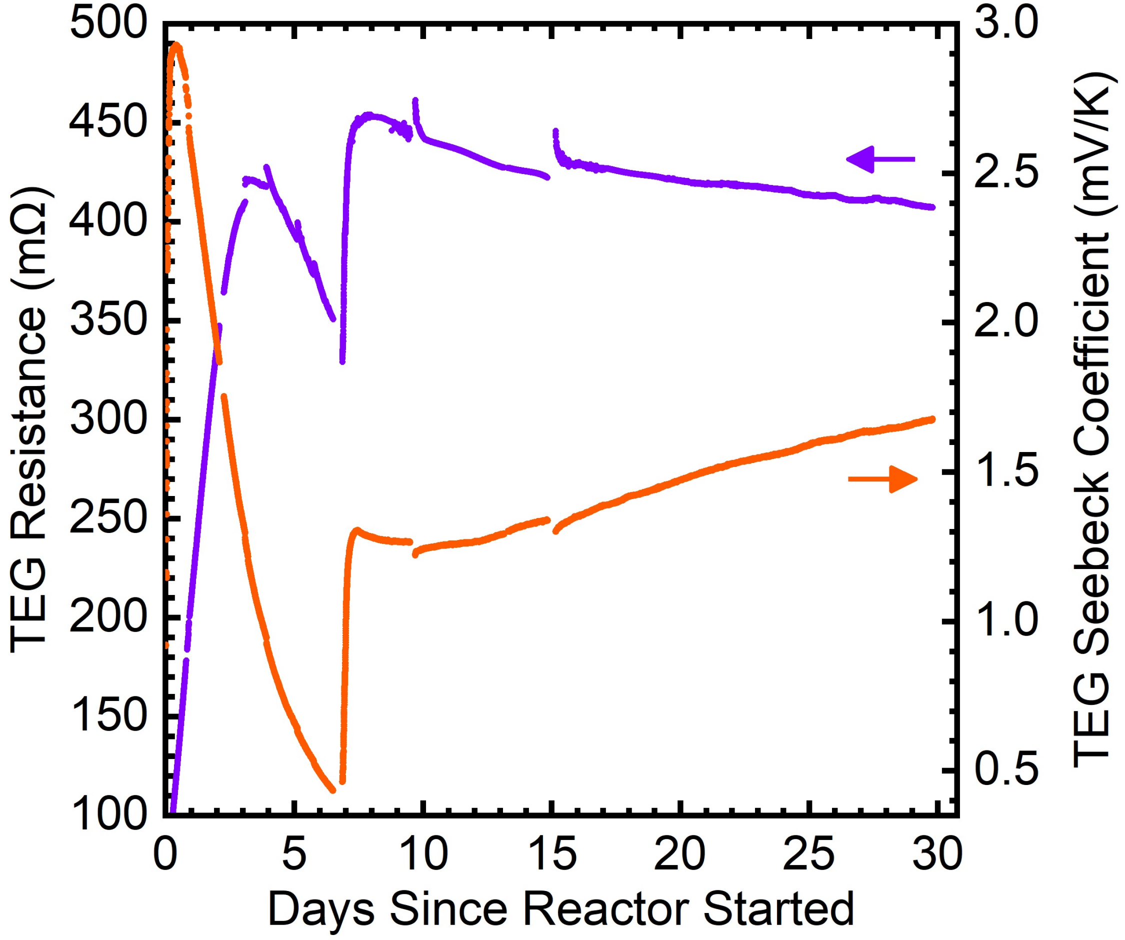
TEG capsule inserted into reactor core

In-situ TEG in-core testing results

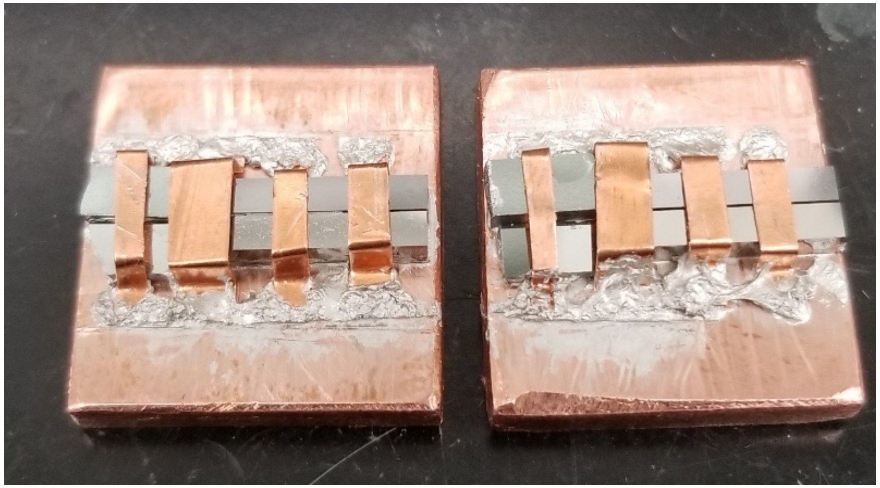


- The TEG in core produces steady **>50 mW/cm²** (**100 kW/m³**) power density

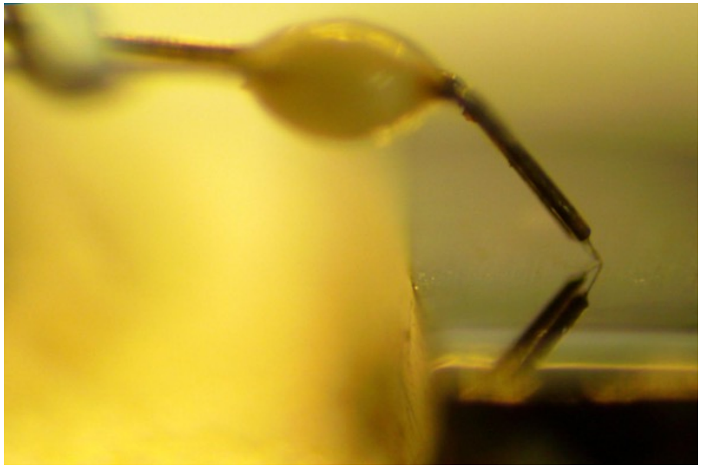
TEG recovery due to in-situ healing/annealing

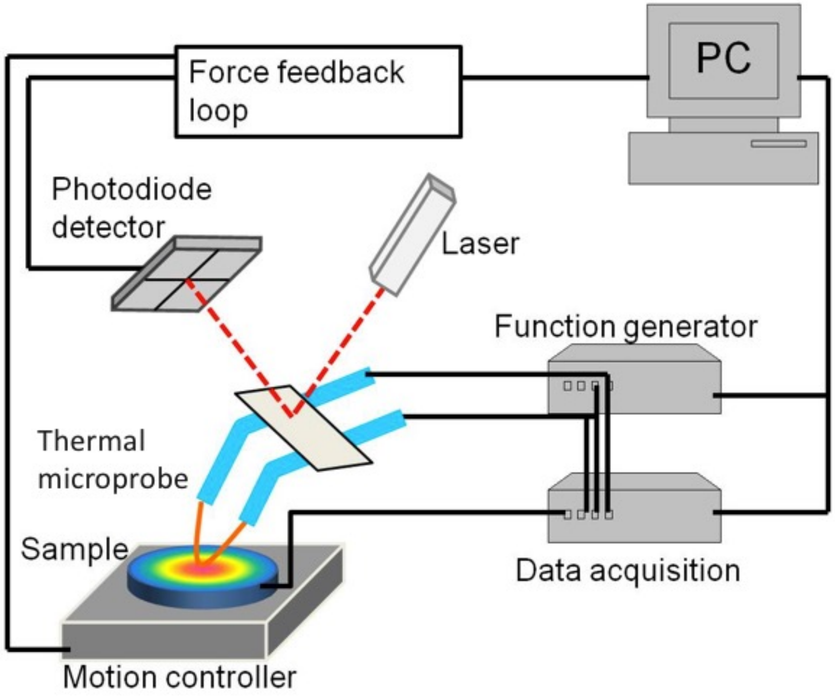


Ion-irradiation effect on thermoelectric properties



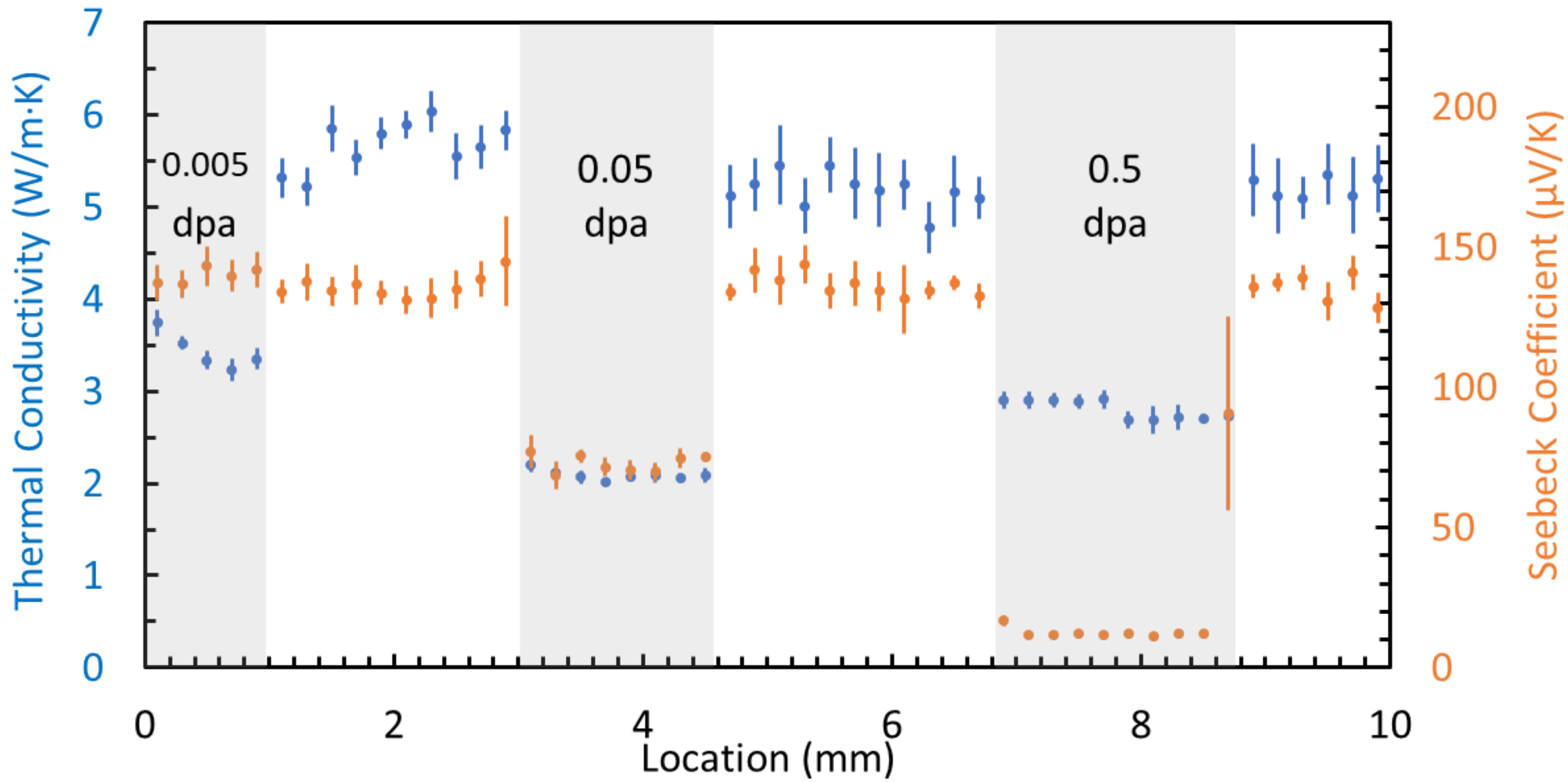
Half-Heusler materials selectively irradiated using helium ion;
The copper covers the non-irradiated regions





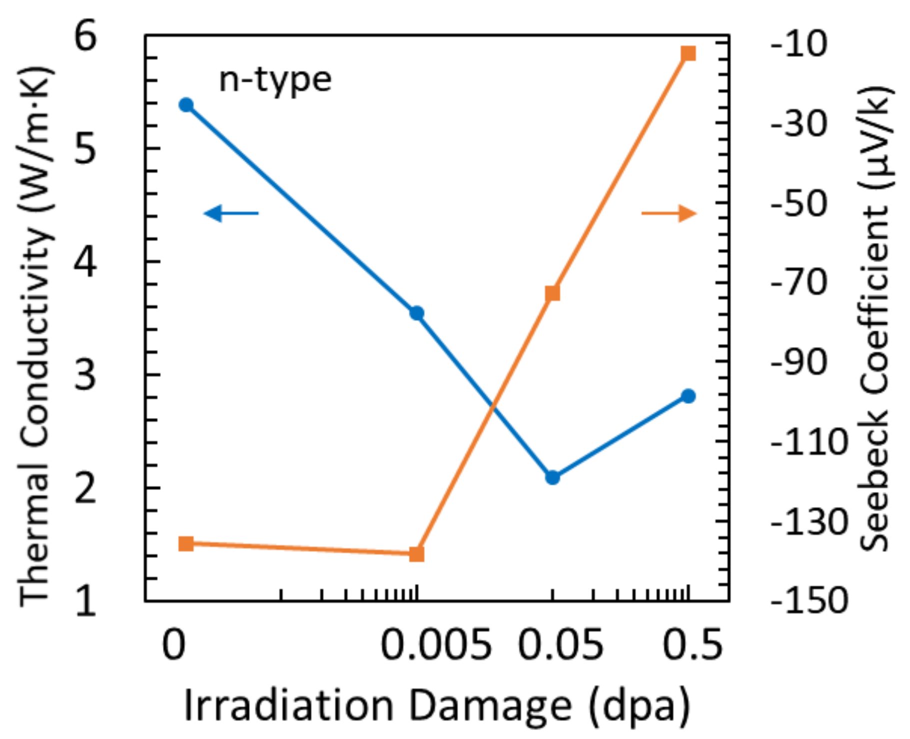
Scanning thermal probe to map thermal conductivity and Seebeck coefficient simultaneously

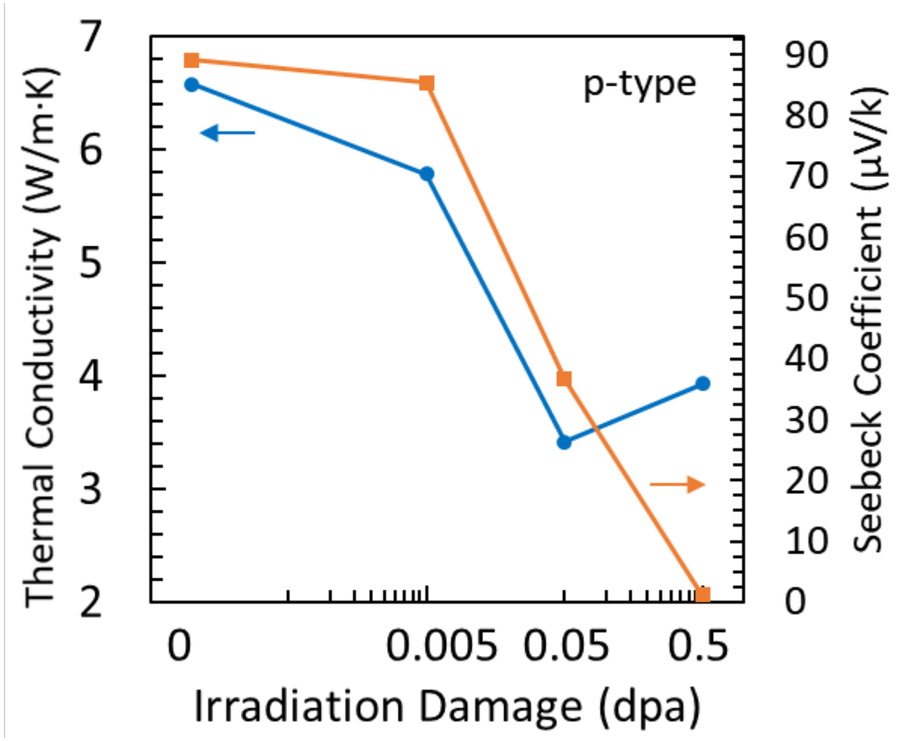
Thermoelectric property of ion irradiated half Heusler



Reduced thermal conductivity and Seebeck coefficient due to ion irradiation

Thermoelectric property of ion irradiated half Heusler

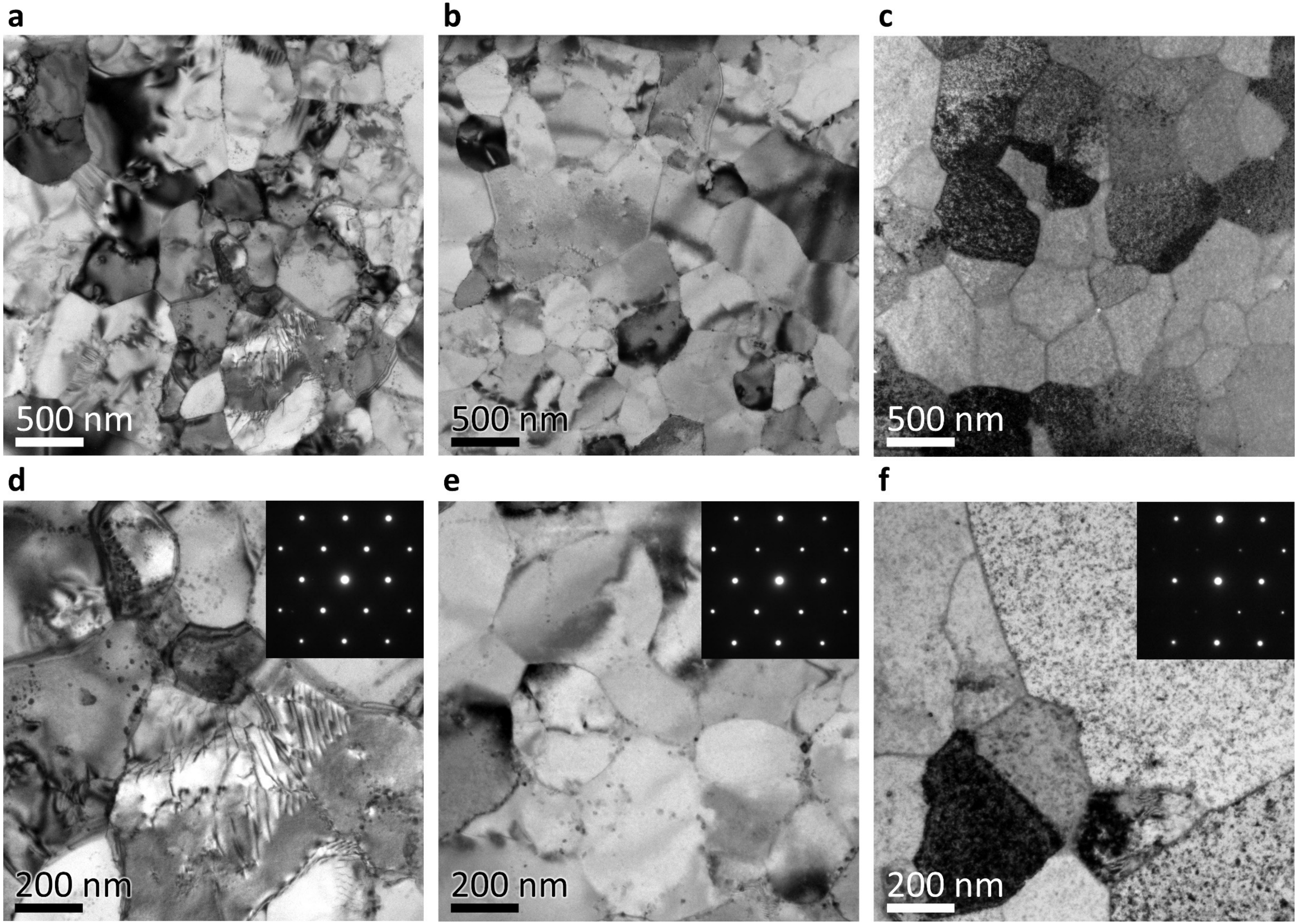




Reduced thermal conductivity and Seebeck coefficient due to ion irradiation

Microstructures of ion-irradiated n-type half Heusler materials

Un-irradiated | 0.05 dpa | 0.5 dpa



Conclusion

- Ion irradiation can result in significant change in materials microstructure and thermoelectric properties
- In-core neutron irradiation results in decreased TEG power output when operating at relatively low temperature
- In-situ annealing of radiation damage occurs when TEG is operating in core at elevated temperature
- The TEG can operate in core and produce steady >50 mW/cm^2 power density, sufficient to power a wide range of sensors
- The TEG can enable self-powered wireless sensors for both in-core and out-of-core nuclear energy applications
- The TEG powered sensors can improve the reliability and reduce the cost of sensors and instrumentation

Acknowledgements

Graduate Student: Nick Kempf

Collaborators:

- Josh Daw, Idaho National Laboratory
- Mercouri Kanatzidis, Northwestern University
- David Carpenter, MIT

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Ultrasonic Sensors for TREAT Fuel Condition Measurement and Monitoring

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Andy Casella

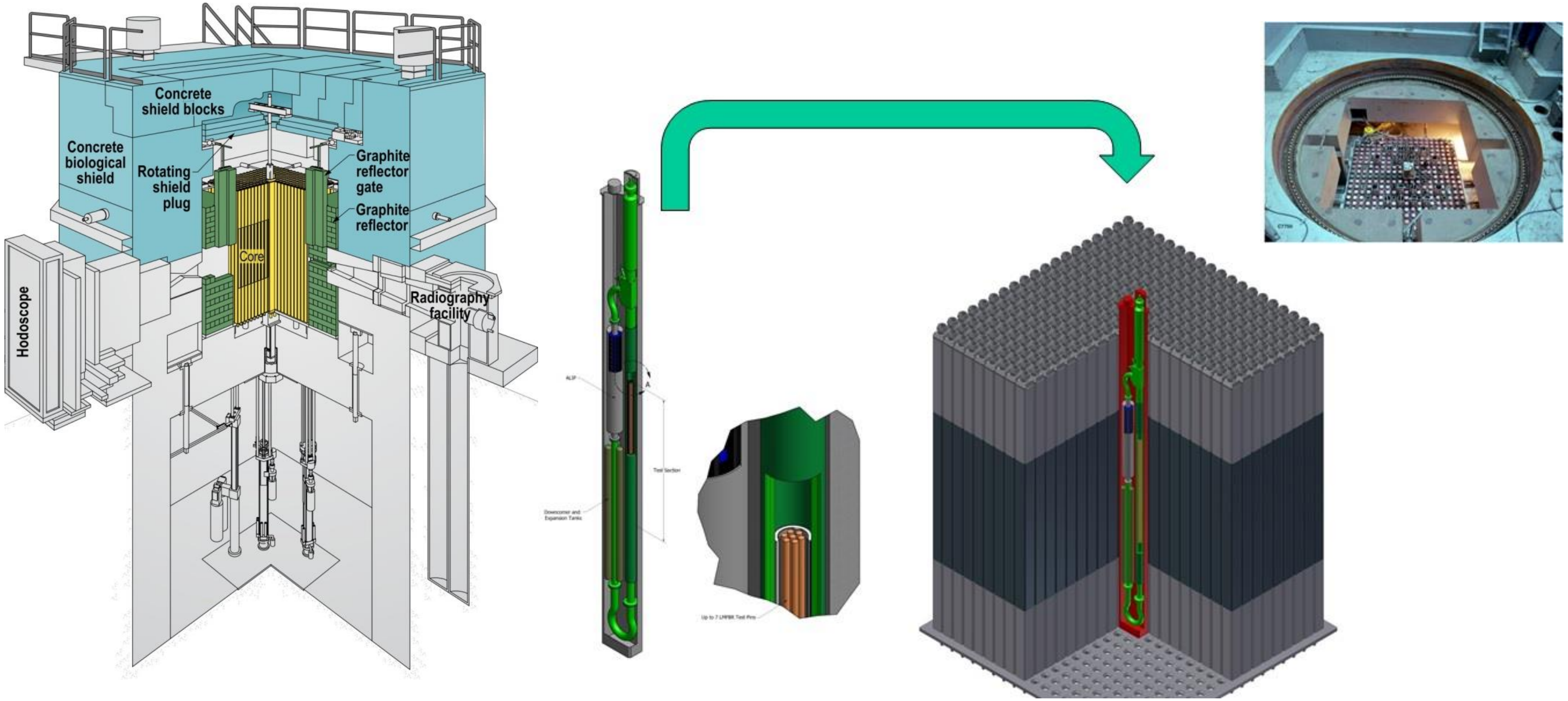
Pacific Northwest National Laboratory

Project Overview

- **Purpose:** The goal of this project is to provide a new measurement capability that enables in-situ characterization of fuel pin deformation during a transient irradiation test in the Transient Reactor Test (TREAT) facility.
- **Objectives:** Design, fabricate, and test an ultrasonic sensor for rapid, non-contact, in-situ measurements of dimensional changes in nuclear fuel that is capable of
- Reliable operation at elevated temperatures (between ~300 C and 600 C)
- Direct measurement of changes in fuel rod diameter
- High-speed measurements to enable rapid characterization of changes during a transient irradiation test.
- Future qualification and deployment at the TREAT Facility
- **Schedule:** This project is complete and was executed from FY18 to FY21
- **Project Participants**
  - PNNL – Andy Casella, Matt Prowant, Chris Hutchinson, Morris Good
  - ORNL – Pradeep Ramuhalli
  - INL – Josh Daw

Technology Impact

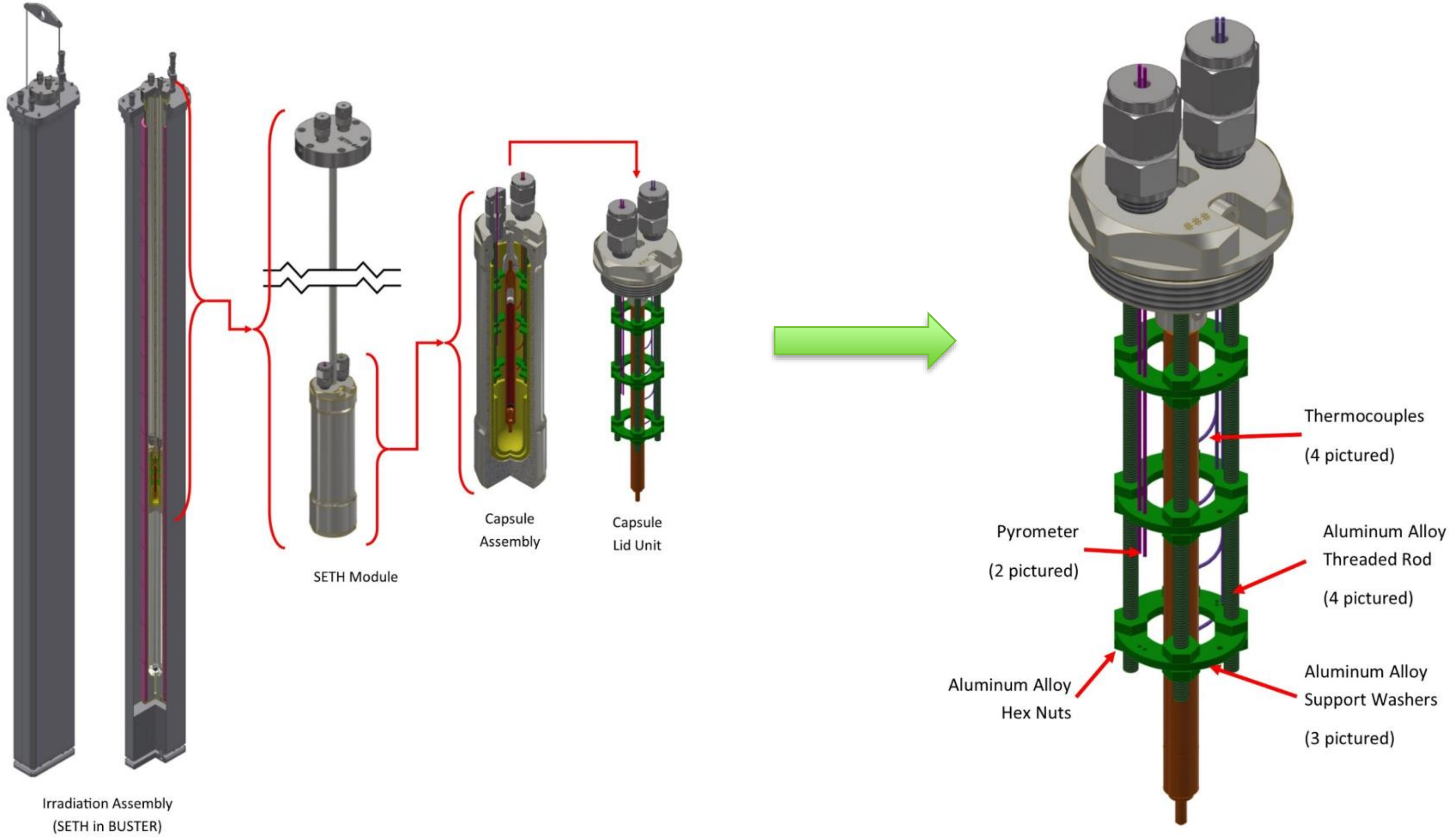
The TREAT facility allows for testing of reactor fuels and materials under a variety of conditions (including accident conditions). This project focused on developing an ultrasonic sensor that would be able to monitor fuel rod radial swelling during power transient tests.



The TREAT facility

Technology Impact - Continued

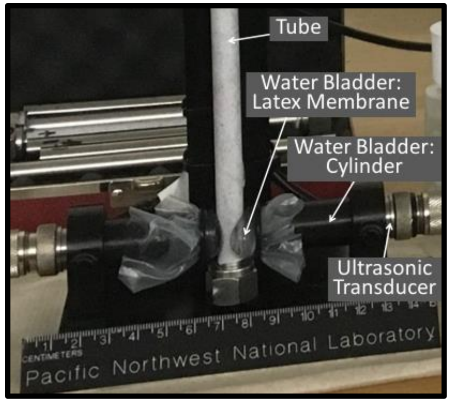
The target sensor must fit within a SETH capsule and should be able to withstand the conditions within the capsule for as long as possible. For planned tests for light water reactor fuels, the capsule would be filled with water and would be subjected to extreme heat and pressure.

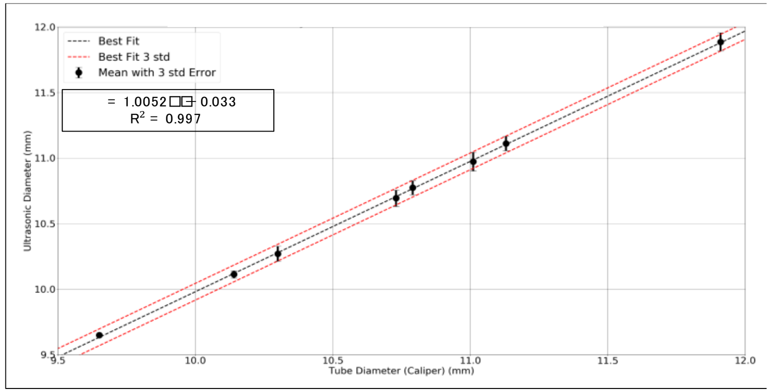


Results and Accomplishments - Initial Sensor Design and Configuration

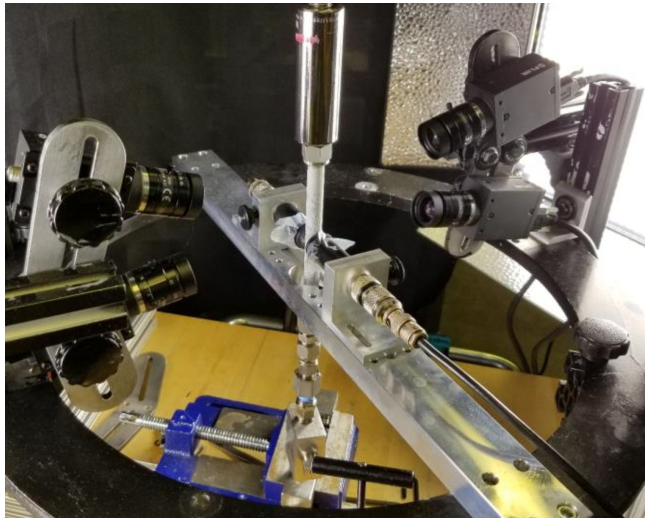
Static Tests

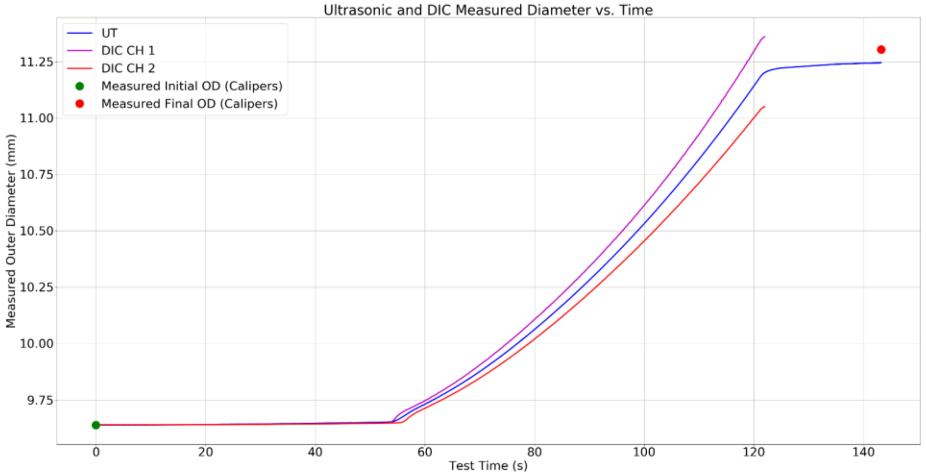
Materials Considered
- Lead Zirconate Titanate
- Aluminum Nitride
- Bismuth Titanate
- Lead Metaniobate
- Langasite



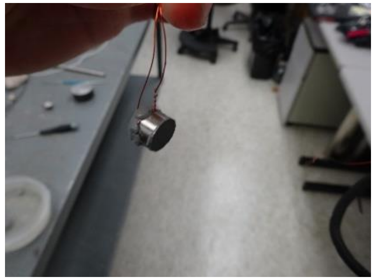


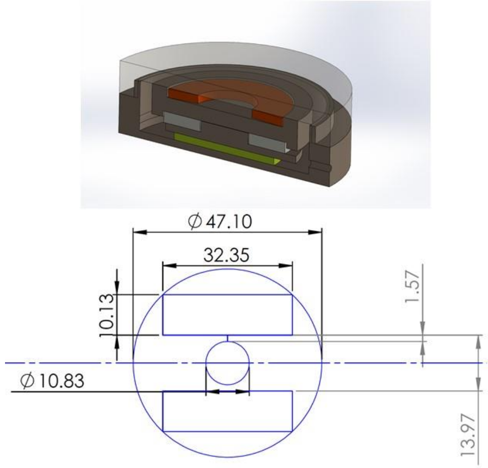
Dynamic Tests with Digital Image Correlation

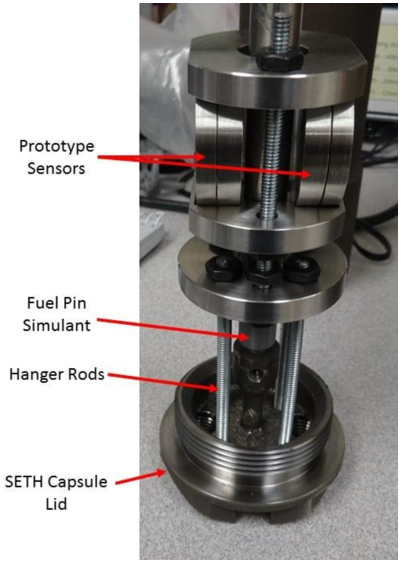




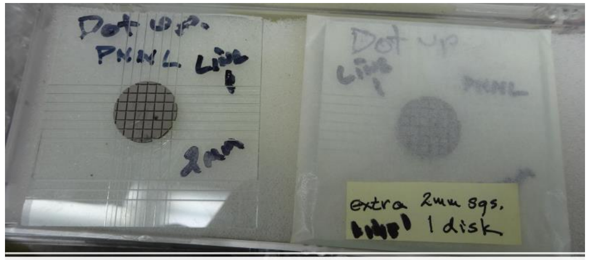
Sensor Configuration within SETH



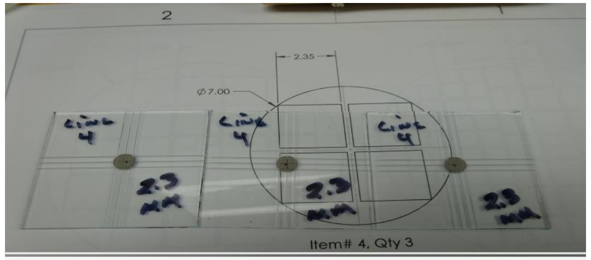




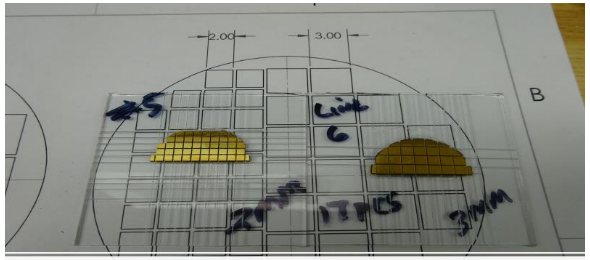
Sensor Miniaturization



2mm 2 Mhz BiT



2.3mm 10 Mhz BiT



2mm and 3mm 2 Mhz AlN

Results and Accomplishments - Design and Fabrication Issues

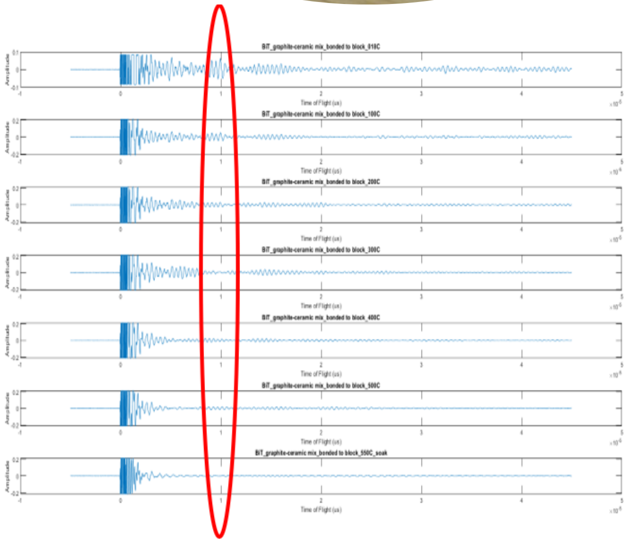
Sensor components and concerns

- Element – will the small piezoelectric elements provide appropriate signals at temperature?
- Face plate – is a faceplate necessary to protect the element? If so, what bonding agent should be used?
- Casing – is a casing necessary to protect the element? If so, what bonding agent should be used?
- Backing – what is the minimum backing that is needed so that a clean signal can be obtained while minimizing sensor size?
- Leads – how are leads attached while maintaining a protective environment of the sensor?
- Overall, how are the sensor components bonded together with appropriate thermal expansion matching as well as optimal electrical conductivity/insulation?

Results and Accomplishments- Sensor Prototypes

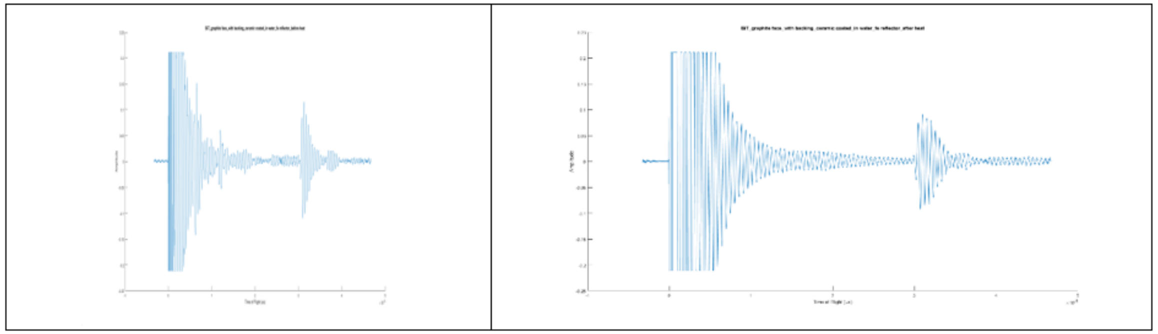
Prototype #1 (failed by heat)

Small BiT sensor bonded to Kovar with graphite and graphite/zirconia adhesives



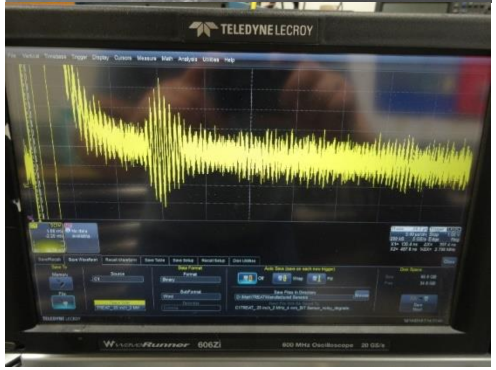
Prototype #2 (failed by water)

Small BiT sensor bonded to Kovar with 60/40 mix of zirconia to graphite adhesives. The whole sensor was coated in zirconia.



Prototype #3 (failed by water)

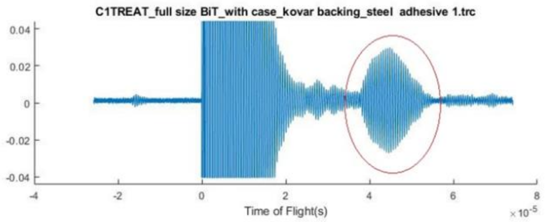
Same as Prototype #2 but with a stainless steel casing. A water resistant adhesive layer over the front of the sensor was not resistant enough.



Prototype #4 (failed by heat)

Full 1 cm BiT element with kovar backing sealed to a stainless steel lip with water resistant adhesive.

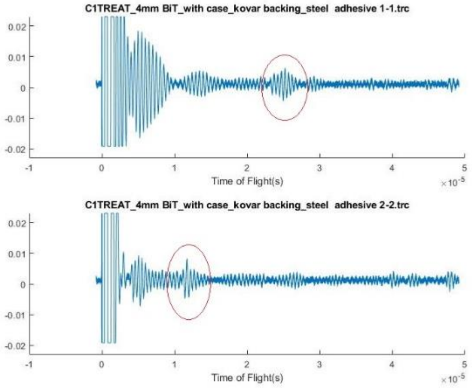
Response Before Heating



Results and Accomplishments - Sensor Prototypes

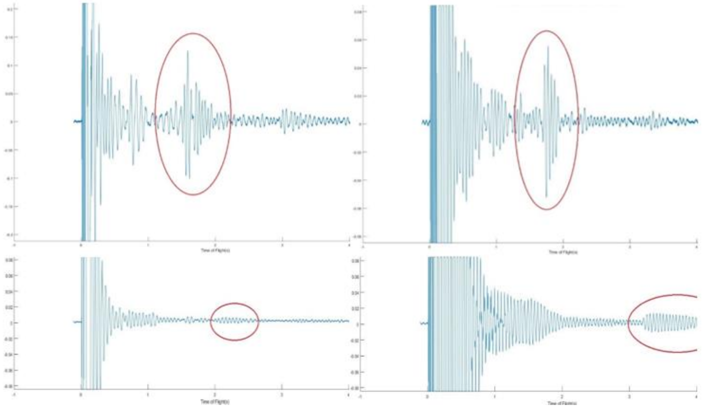
Prototype #5 (failed during thermal cycling and water exposure)

A 4 mm BiT element was bonded to Kovar backing with 60/40 zirconia to graphite. A stainless steel infused adhesive was used as a face plate. Sensor internals were coupled together with nano particle alumina adhesive.

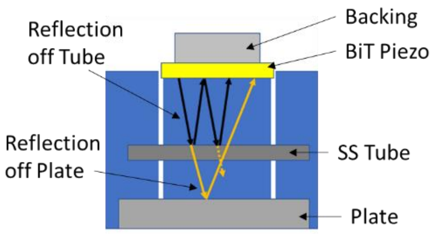


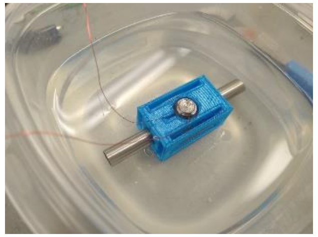
Prototype #6 (Initially survived, but failed after extended water soak)

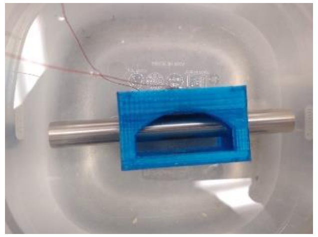
Full 1 cm BiT element with Kovar backing. Electrodes are removed from the element and bonded with 1) silver or 2) zirconia/graphite mixture

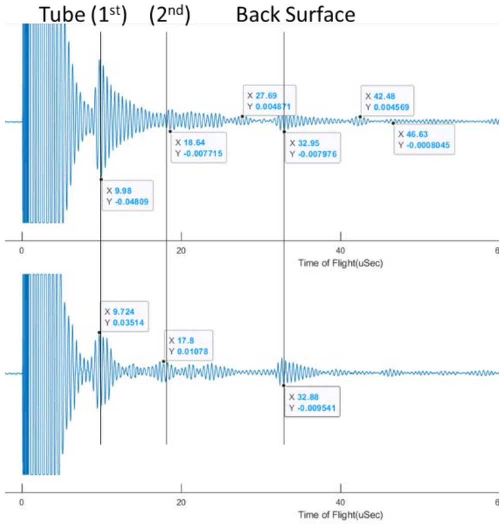


Larger Element Testing









Conclusions

- A sensor design was tested with common acoustic sensor materials.
- The sensor design was modified to use a high temperature piezoelectric element and to fit and function within the size constraints of the SETH capsule.
- Ultimately, the appropriate bonding materials could not be identified and further work is necessary.

Questions?

ASI | Advanced Sensors and Instrumentation

C R I S P

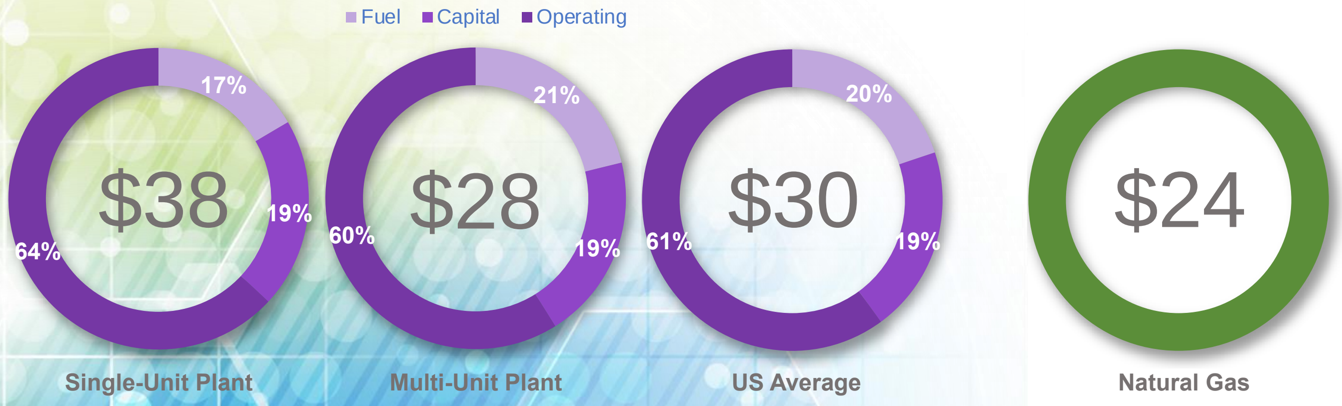
INL/MIT Center for Reactor Instrumentation and Sensor Physics

Sacit Cetiner, Ph.D.
Senior Research Scientist, Measurement Sciences Department, INL
Scientific Director, INL/MIT CRISP

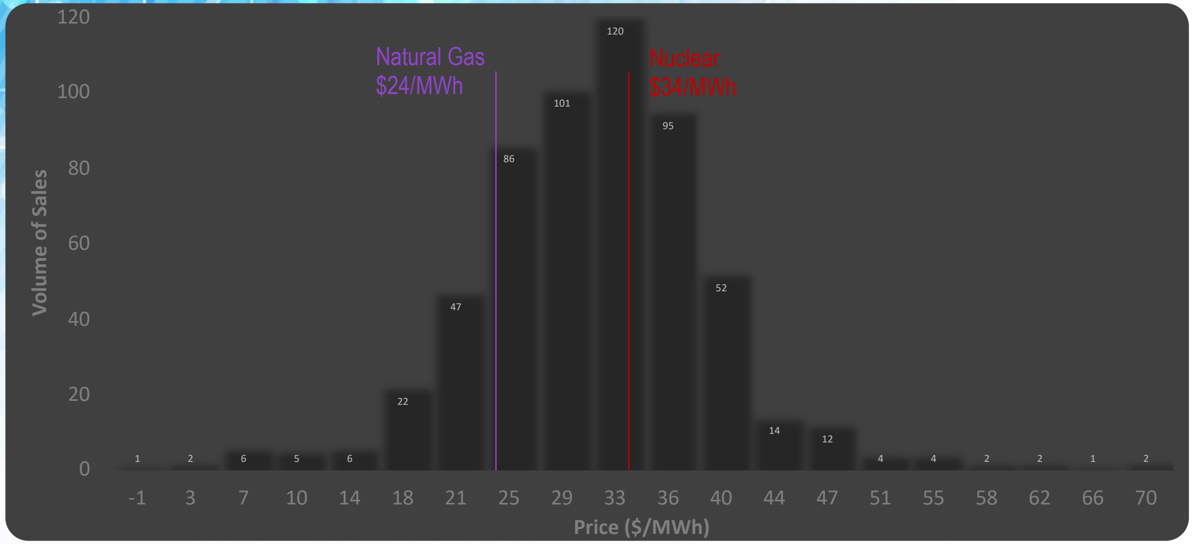
Idaho National Laboratory

Significance of Instrumentation and Controls

- Nuclear industry is facing an existential stress test
- Analysis after analysis show that growing operating costs have risen to unsustainable levels for most US plants
- Included in the “operating” cost
  - Operations staff
  - Maintenance
  - Physical security



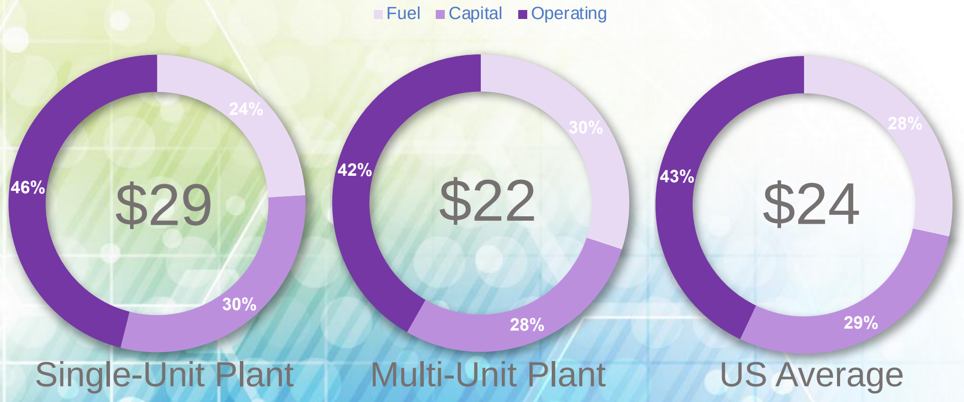
Source: NEI White Paper—Nuclear Costs in Context (October 2020)



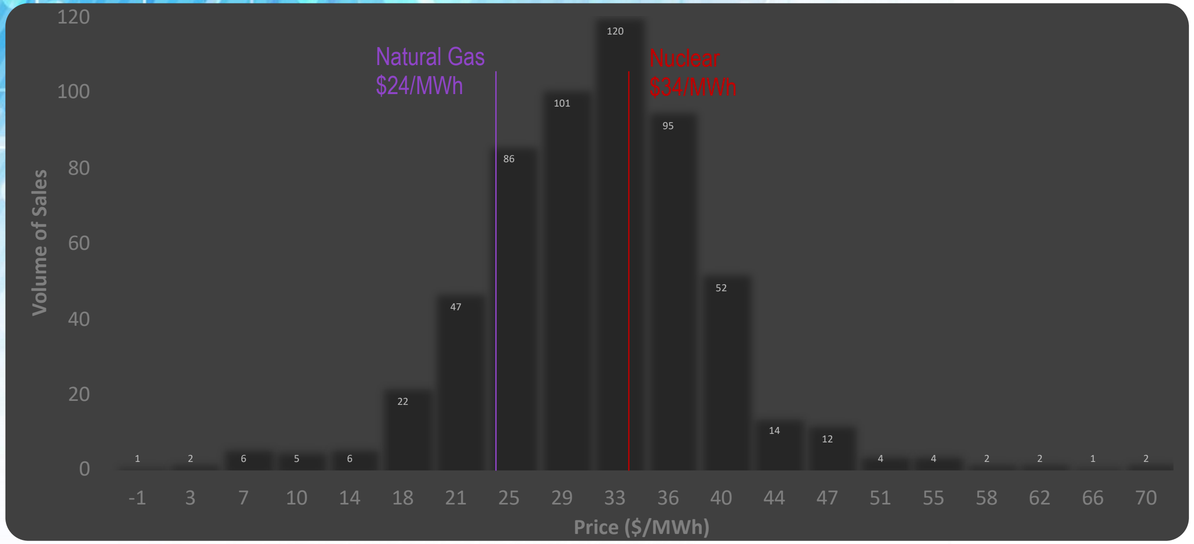
Source: U.S. Energy Information Administration (EIA)

Significance of Instrumentation and Controls

- So, hypothetically:
  what if we reduced operating and maintenance costs by half?
- The path to achieving this vision goes through adopting Industry 4.0 transformation



Assumption: Other costs fixed…

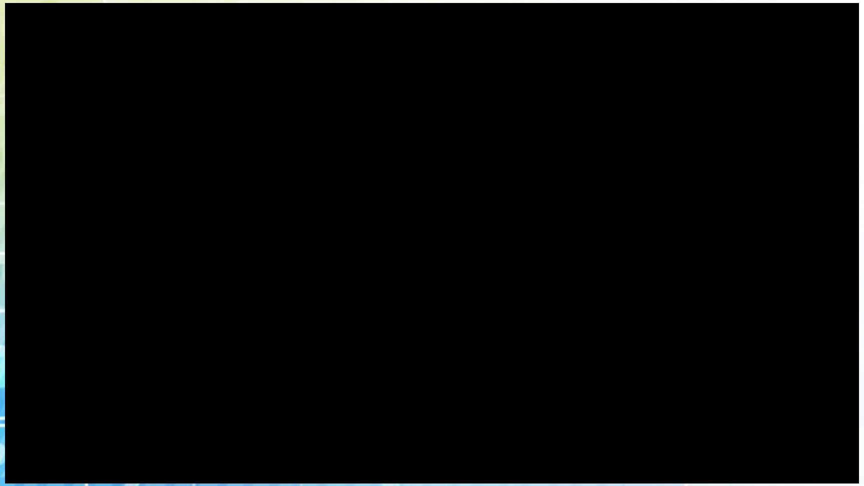


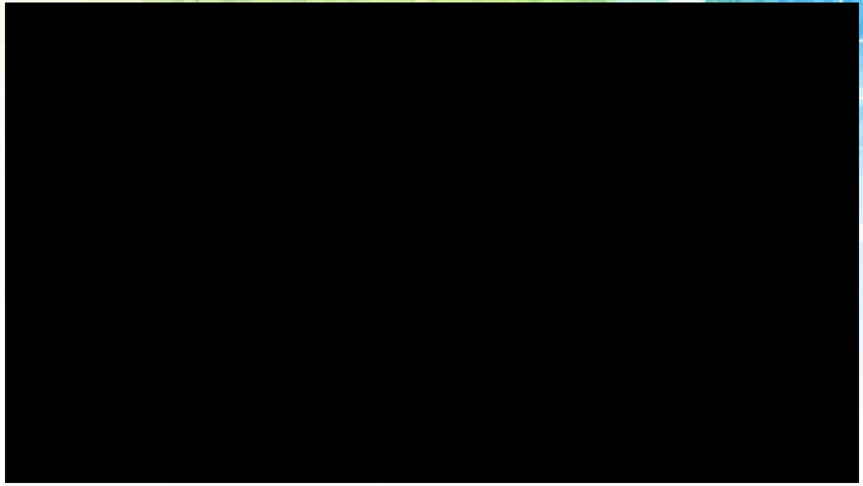
Source: U.S. Energy Information Administration (EIA)

Is this vision achievable?

Source: http://tesla.com

Source: http://blueorigin.com



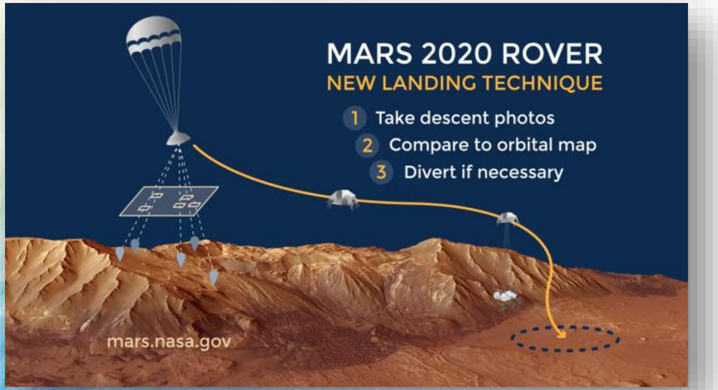


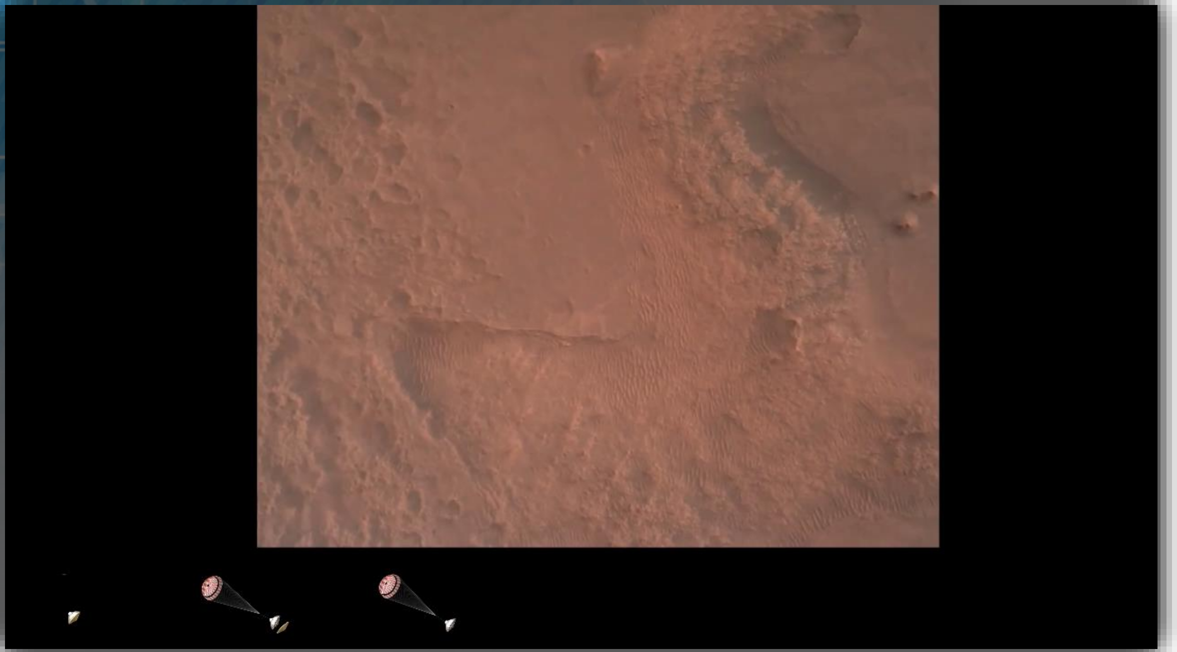
Source: http://waymo.com

Source: http://spacex.com

A more recent example of successful autonomous mission… from Mars…

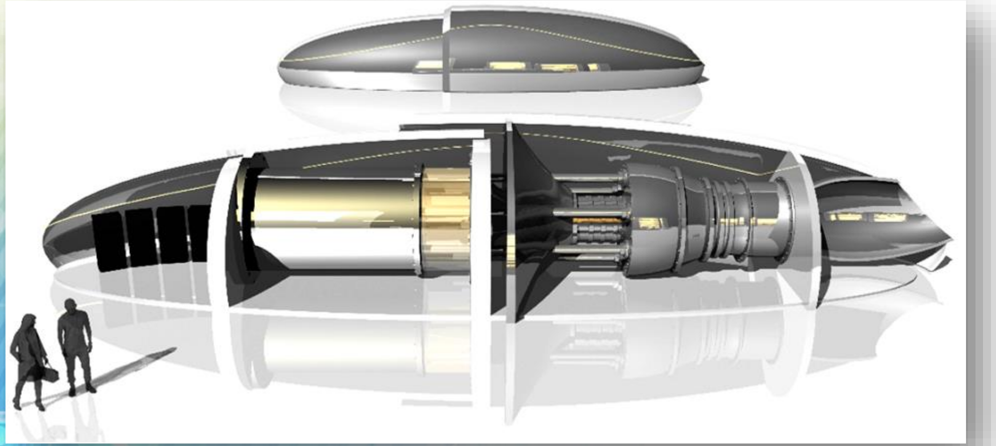
- Round-trip comm time is prohibitive for human intervention
  - Fully autonomous control is a mission requirement!
- from the NASA Perseverance website…
  - For successful descent and landing, **terrain-relative navigation (TRN)** is the mission-critical technology at the heart of the **landing vision system (LVS)** that captures photos of the Mars terrain in real time and compares them with onboard maps of the landing area, <u>autonomously directing the rover to divert around known hazards and obstacles as needed</u>.

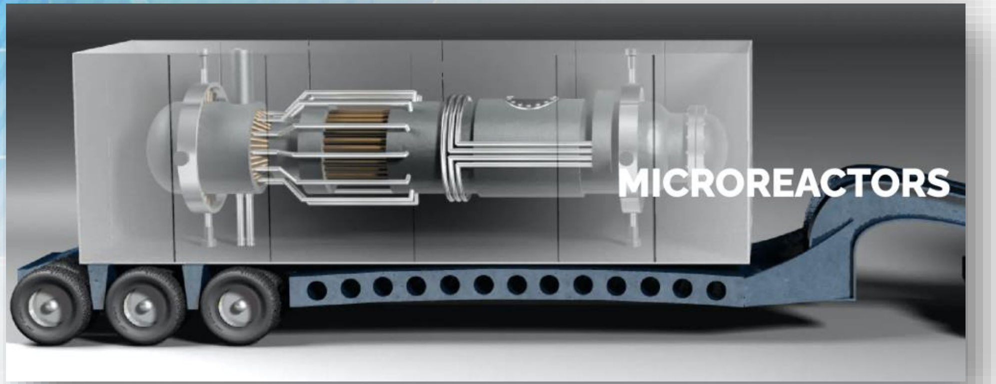




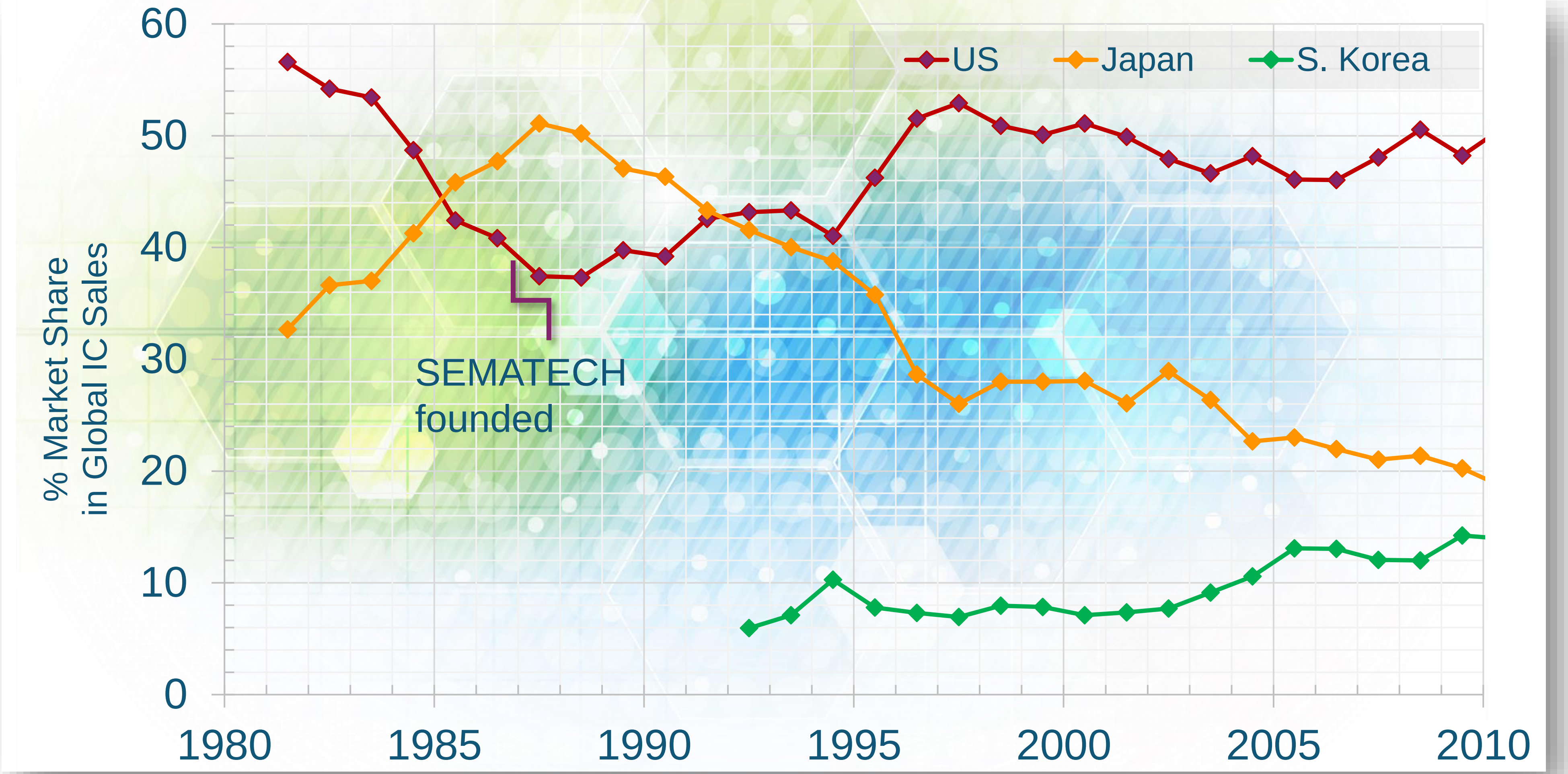
What is the problem statement of autonomy for nuclear systems?

- Current-generation nuclear power plants already use automation
  - Traditional feedback control systems can maintain key variables around desired setpoints—this is a mature technology
- Decision-making capabilities begin to make sense when a plant undergoes major operational swings, e.g.,
  - mode transitions
  - unexpected transient due to equipment degradation or failure
- Frequent maneuvers will lead to faster equipment wear, hence higher frequency of failures, that cannot be handled by feedback control or simple state machines
  - load following
- **It is because of these complex combinatorial effects with large uncertainties do we need *sequential decision-making* functionality to achieve autonomous or semi-autonomous control capabilities**



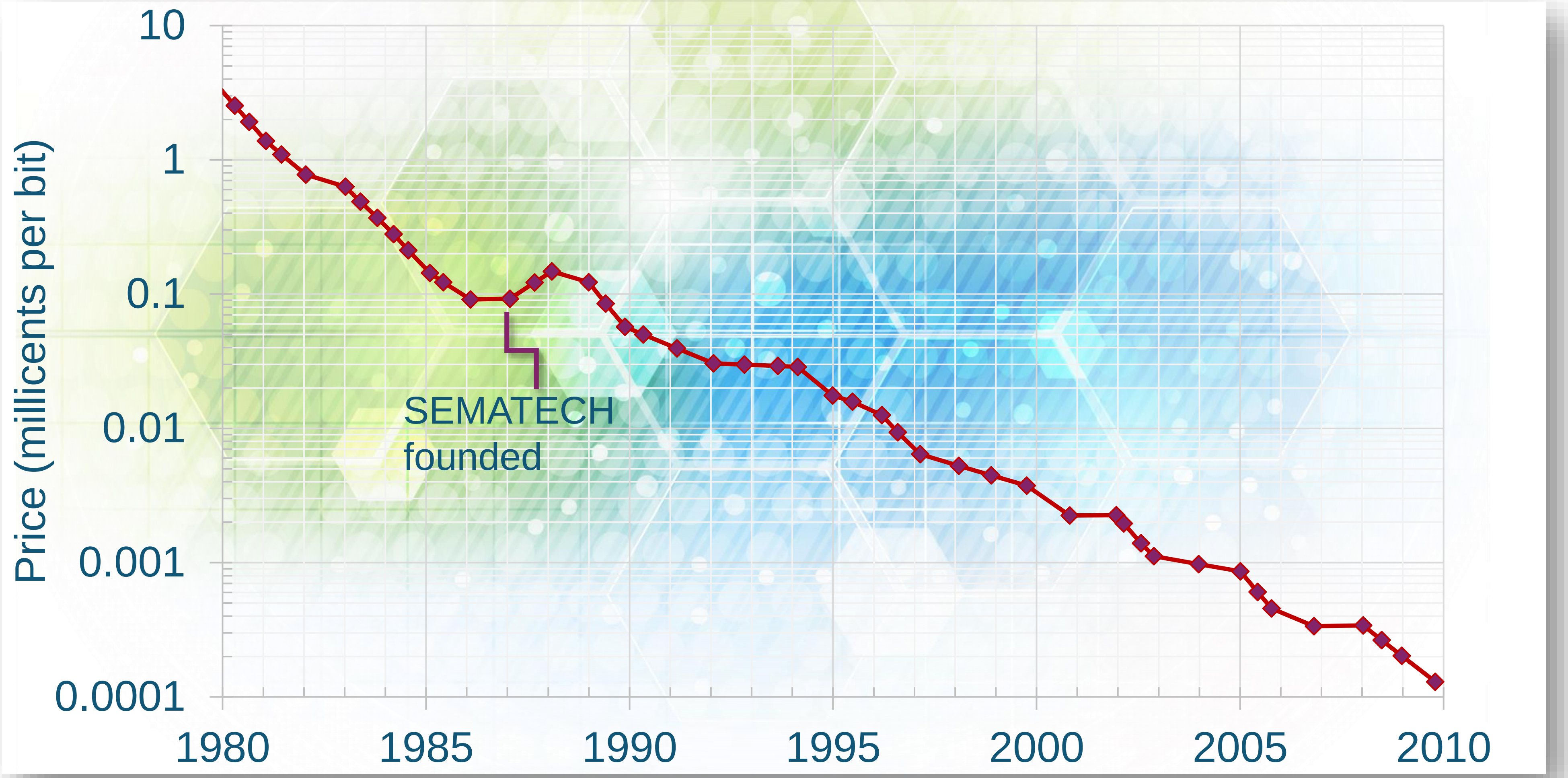


SEMATECH can be a model for technological transformation in our quest to innovate nuclear systems



Source: SIA/World Semiconductor Trade Statistics/iSuppli/PwC/IC Insights

SEMATECH can be a model for technological transformation in our quest to innovate nuclear systems



Source: SIA/World Semiconductor Trade Statistics/iSuppli/PwC/IC Insights

Previous Attempts at Establishing a Center of Excellence for Advanced I&C – 1985

- In 1985, the U.S. Department of Energy (DOE) established a task force to determine the need for, assess the feasibility of, and recommend an approach to the introduction of advanced control into the nuclear power industry
- The task team report recommended that an Advanced Controls program with a centralized, multi-user capability be established
- **"The goal is to provide a national center of excellence in research, development and testing of nuclear control systems employing the latest advances in automation, artificial intelligence, expert systems, hierarchical computer architectures, and optimal control."**
- This led to the Advanced Control Test Operation (ACTO) program

CONF-870472--1

ADVANCED CONTROL TEST OPERATION (ACTO) FACILITY

S. J. Ball
Instrumentation and Controls Division
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37831

CONF-870472--1

DE87 004252

ABSTRACT

The Advanced Control Test Operation (ACTO) project, sponsored by the U. S. Department of Energy (DOE), is being developed to enable the latest modern technology, automation, and advanced control methods to be incorporated into nuclear power plants. The facility is proposed as a national multi-user center for advanced control development and testing to be completed in 1991. The facility will support a wide variety of reactor concepts, and will be used by researchers from Oak Ridge National Laboratory (ORNL), plus scientists and engineers from industry, other national laboratories, universities, and utilities. ACTO will also include telecommunication facilities for remote users.

INTRODUCTION

The major objective of the ACTO project is to maximize the benefits that the nuclear industry derives from advanced control technology, particularly in the areas of plant availability and safety. By using control systems that are more intelligent, reliable, and fault-tolerant, there can be significant reductions in the number and duration of nuclear plant outages, reductions in the likelihood of "incidents" becoming "accidents", and improvements in operating performance. Operator errors presently account for about 3% of the forced outage time in U. S. power reactors, and were responsible for conditions that led to major accidents at Three Mile Island and Chernobyl. It is maintained that by use of advanced equipment and computer software techniques, operational errors (both operator and equipment problems) can be reduced to improve plant availability by at least 3%, and overall safety can be enhanced significantly. Reactors in the U. S. have a relatively poor record of on-line availability, and every 1% improvement in average plant availability would be approximately equivalent to the operation of another (new) large plant; hence the economic incentives for improvement are substantial.

Figure 1 shows a conceptual layout of the ACTO facility. Shown symbolically are the large (number cruncher) computers, which will incorporate the reactor dynamics simulators, the symbolic computers for artificial intelligence (AI) and expert system development, the database computers for storage of archives of data, a test control room for setting up and testing prototype controls and interfaces with operators, a series of advanced design workstations for control system development, and the communications networks for both the local and remote signal transmissions. Figure 2 shows an architect's sketch of the ACTO facility to be located at ORNL.

ACTO FACILITY JUSTIFICATION AND SCOPE

The ACTO concept is based on the premise that advanced control systems featuring innovative hardware and software system designs can provide a high degree of automation and result in considerable benefits to the reactor industry. It is clear, however, that such advanced systems will not be incorporated into any reactor designs without extensive prior demonstration, testing, qualification, and verification. A major driving force behind the ACTO project is the thesis that effective support for promoting and developing these advanced controls could best (and most efficiently) be provided by a centralized general purpose simulation and test facility.

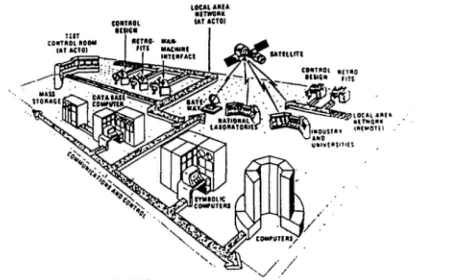


Fig. 1 ACTO CONCEPT

*Operated by Martin Marietta Energy Systems, Inc., for the U. S. Department of Energy, under Contract No. DE-AC05-84OR21400.

MASTER

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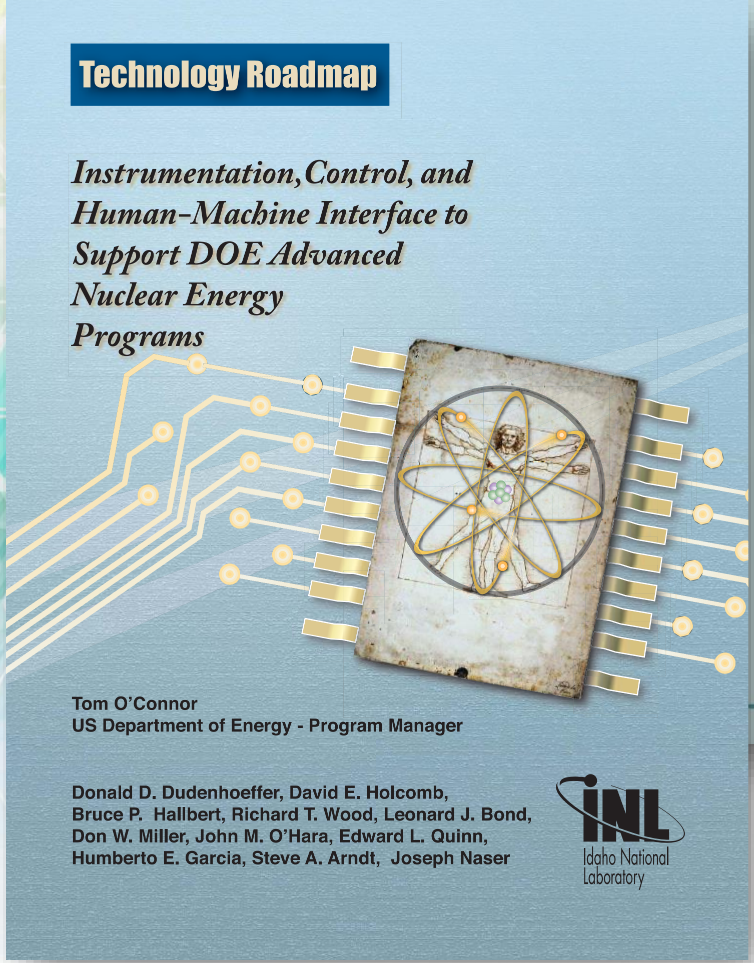
Previous Attempts at Establishing a Center of Excellence for Advanced I&C – 2008

Proposed Focus Areas:

- Cyber Security
- Diversity & Defense-in-Depth
- Risk-Informing Digital I&C
- Digital Systems Communications
- Control Room and Beyond Control Room
- Human Factors
  - Role of Personnel and Automation
  - Staffing and Training
  - Normal Operations Management
  - HFE Methods and Tools
- Fuel Cycle Facilities
- Validation (software, etc.)
- Advanced Monitoring/Diagnostics
- Advanced Sensors
- General Issues

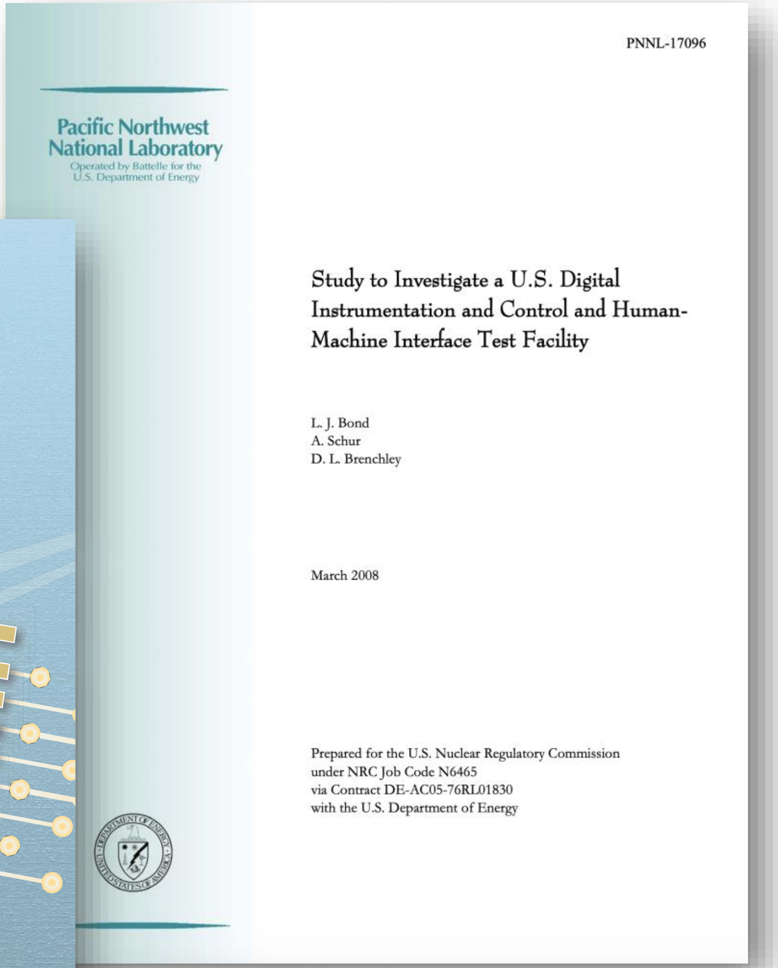

Technology Roadmap

Instrumentation, Control, and Human-Machine Interface to Support DOE Advanced Nuclear Energy Programs

Tom O'Connor
US Department of Energy - Program Manager

Donald D. Dudenhoeffer, David E. Holcomb, Bruce P. Hallbert, Richard T. Wood, Leonard J. Bond, Don W. Miller, John M. O'Hara, Edward L. Quinn, Humberto E. Garcia, Steve A. Arndt, Joseph Naser

INL Idaho National Laboratory


PNNL-17096

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Study to Investigate a U.S. Digital Instrumentation and Control and Human-Machine Interface Test Facility

L. J. Bond
A. Schur
D. L. Brenchley

March 2008

Prepared for the U.S. Nuclear Regulatory Commission
under NRC Job Code N6465
via Contract DE-AC05-76RL01830
with the U.S. Department of Energy

CRISP Vision, Mission, and Thrusts

VISION*

Advance the state-of-the-technology for monitoring and controls of future nuclear systems

MISSION*

Become the center of excellence and a technology development hub to enable advanced operational paradigms in nuclear systems

THRUST* AREAS

- Sensing Physics and Instrumentation
- Signal Processing and AI/ML-based Data Analysis
- Advanced Controls and Decision Sciences

*** Preliminary**

INL – MIT Coordination Paths

PROGRAMS
ASI
LWRS
NRIC
IES
NSUF

DICE

DEPTS
Measurement Sciences
I&C and Data Sciences

Idaho National Laboratory

CRISP

CENTERS
CANES
Quest for Intelligence
MIT.nano
sense.nano

LABS
NRL/MITR
Draper
Lincoln
CSAIL
…

DEPTS
NSE
MechE
EECS
AeroAstro

CRISP Organization

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Sacit Cetiner
Scientific Director/INL

David Carpenter
Director/MIT

Advisory Board

Ongoing…

Members/stakeholders from
- INL
- DOE
- NRC
- EPRI
- Industry
- Academia

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Assoc. Prof. of NSE

Ongoing…

Faculty and Staff from
- EECS
- AeroAstro

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CANES
Center for Advanced Nuclear Energy Systems

ANPEG

External Collaborators

TBD

Postdocs

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NSE, INL Fellow

Zhen Zhang
MSE

Masters Students

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Undergrad Students

TBD

Massachusetts Institute of Technology

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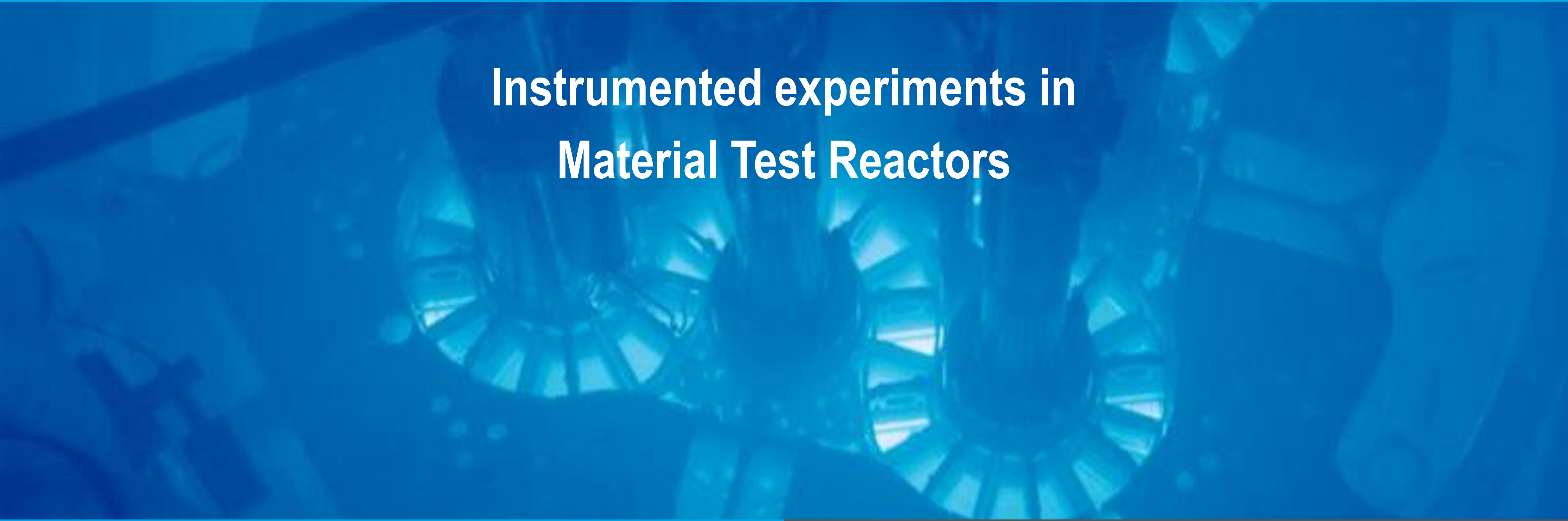
ASI Advanced Sensors and Instrumentation



Instrumented experiments in Material Test Reactors

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

Technical Point of Contact: Austin Fleming PhD

Idaho National Laboratory

Instrumentation Development Goal

- GOAL: To develop, test, and qualify a sensor measurement capability to a maturity level in which a customer adopts the technology to a sustainable level
- This is independent of applications
  - Advanced reactor applications
    - Reactor Control
    - Design Qualification
  - Research objectives
    - Nuclear fuel & materials testing
- The customer needs to successfully adopt the technology to a level at which is sustainable
  - Commercialization (company will maintain supply and support of a sensor)
  - Adopted by other programs or long-term project (Perhaps inside or outside of DOE)

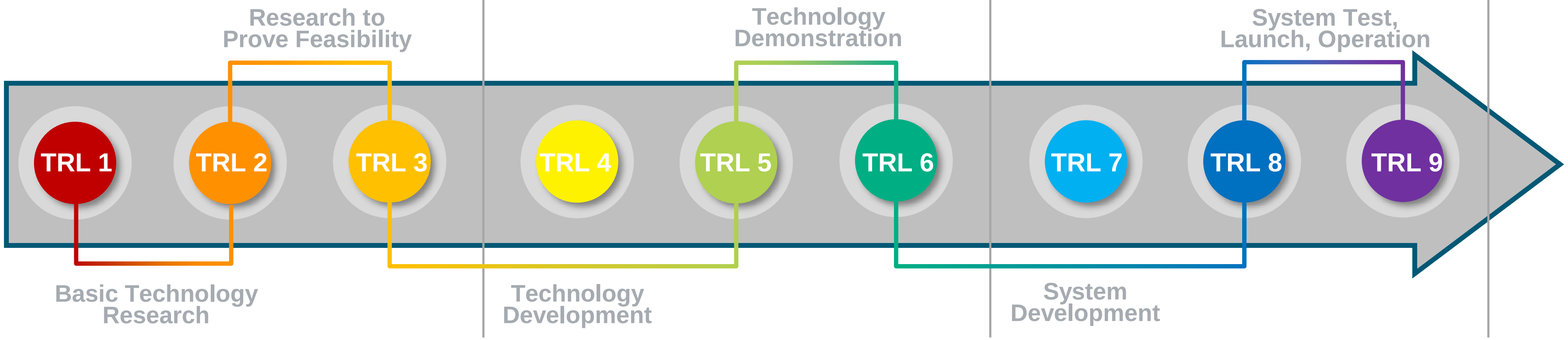
"Valley of Death" for sensor success

ASI can Provide the Bridge

Innovative Sensor Development (Lab Bench)

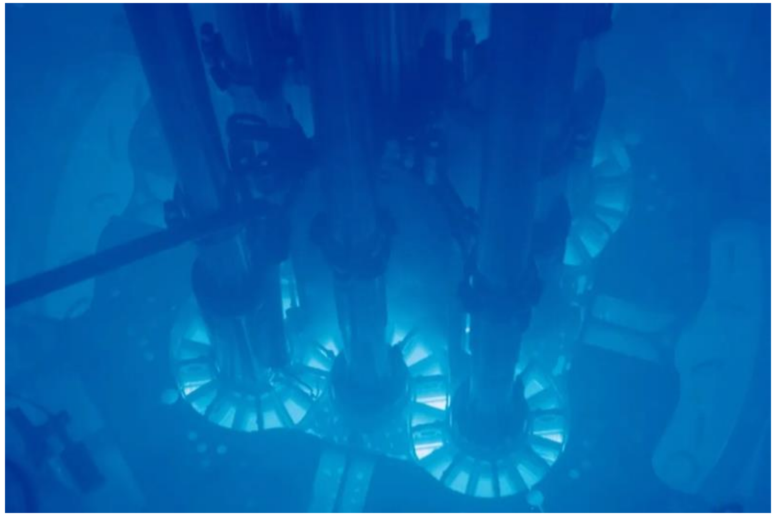
Sensor Integration in Nuclear Systems (In-Reactor)

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



Instrument Material Test Reactors Experiments

- Instrumentation in experiments has some data or control objective for the experiment (not the reactor)
- Variety of customers
  - Science based experiments (NSUF)
  - Nuclear fuel & materials (AFC/NEAMS)
  - Advanced reactor demonstrations
  - Defense applications
  - Other
- Wide range of instruments are desired for experiments depending on measurement needs
- Commonly used Material Test Reactors (generally can provide prototypic conditions of interest)
  - ATR
  - HFIR
  - MITR
  - TREAT
  - NSUF website is a good resource (https://nsuf.inl.gov/Home/PartnerFacilities)



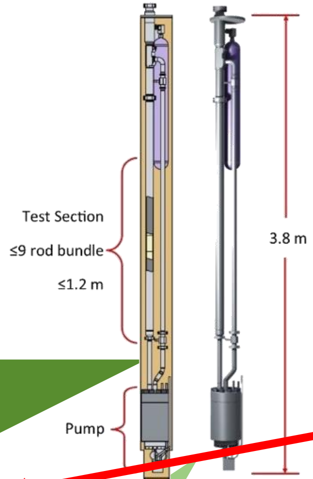
What Role Does ASI Play?

- Why am I talking about "other" experiments?
  - Sensors performance greatly depend on the implementation and integration
    - Thermocouple without good thermal contact…
  - Sensors development under ASI needs to have an eye toward the end use applications
    - Development toward the prototypic application
  - Deploying sensor in irradiation experiments provides opportunities to also "test" sensor
    - Ideally mature enough to provide some value to the experiment
    - Sometimes opportunities arise where "supplemental" instrumentation is a possibility. (Data is not necessary for experimenter, but would be "nice to have" and comes at a low cost)
  - Establishing other stakeholders in the sensor improves the long-term viability of the technology

Instrument Qualification

Qualification: science-based approach to show an instrument will operate in established limits for its intended purpose

Experimental Device Integration (mechanical/ logistical)



- Geometry
- Feedthroughs
- Connectors
- Leads

Adequate definition = GOAL!

In-Pile Characterization & Testing

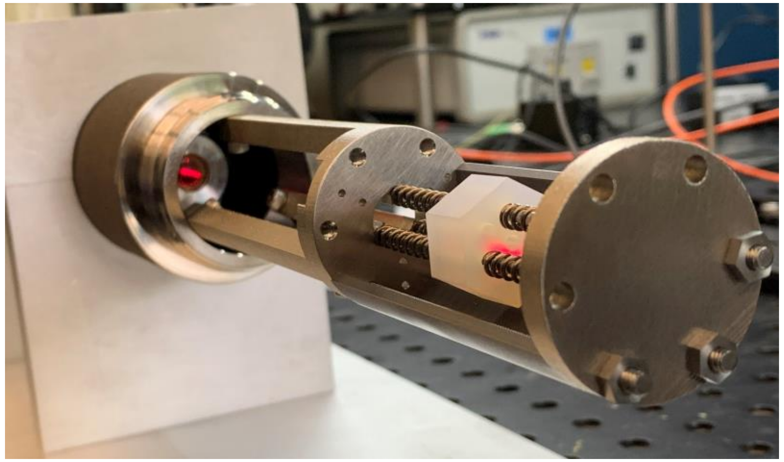
- Flux/fluence
- Electromagnetic environment
- Facility integration

Out-of-Pile Characterization & Testing

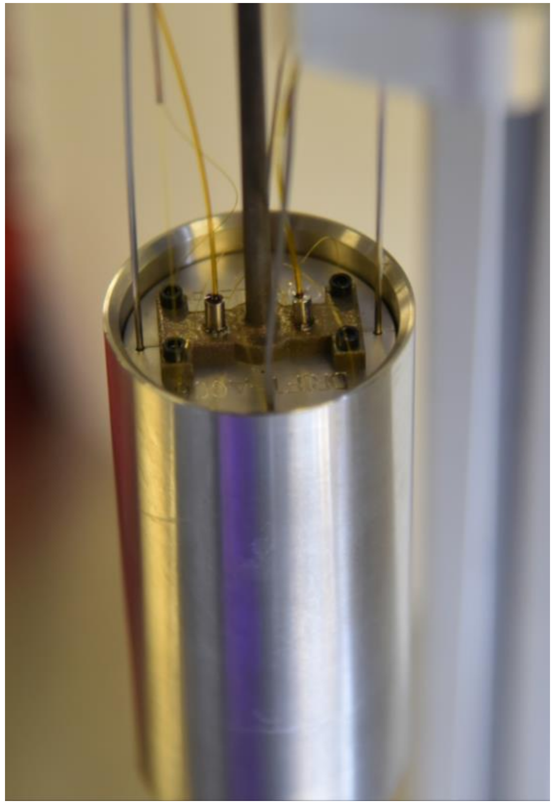
- Temperature/Pressure
- Coolants
  - Chemistry/Flow
- Transient response

Instrumentation for Transient Testing

- Transient experiments often require significant instrumentation
  - 2 detailed examples will be provided
- Images of various irradiation experiments



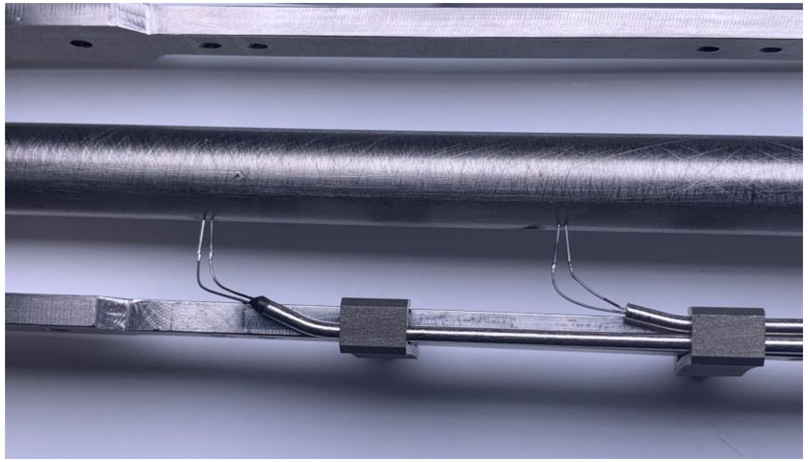
NASA-SIRIUS



DRIFT Experiment

ATF-SETH Experiment

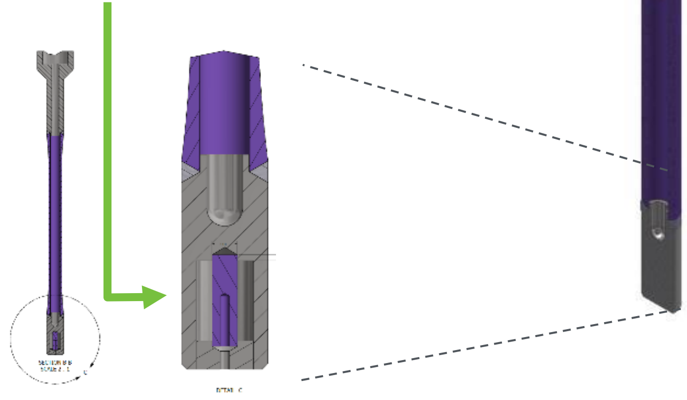
CHF-SERTTA

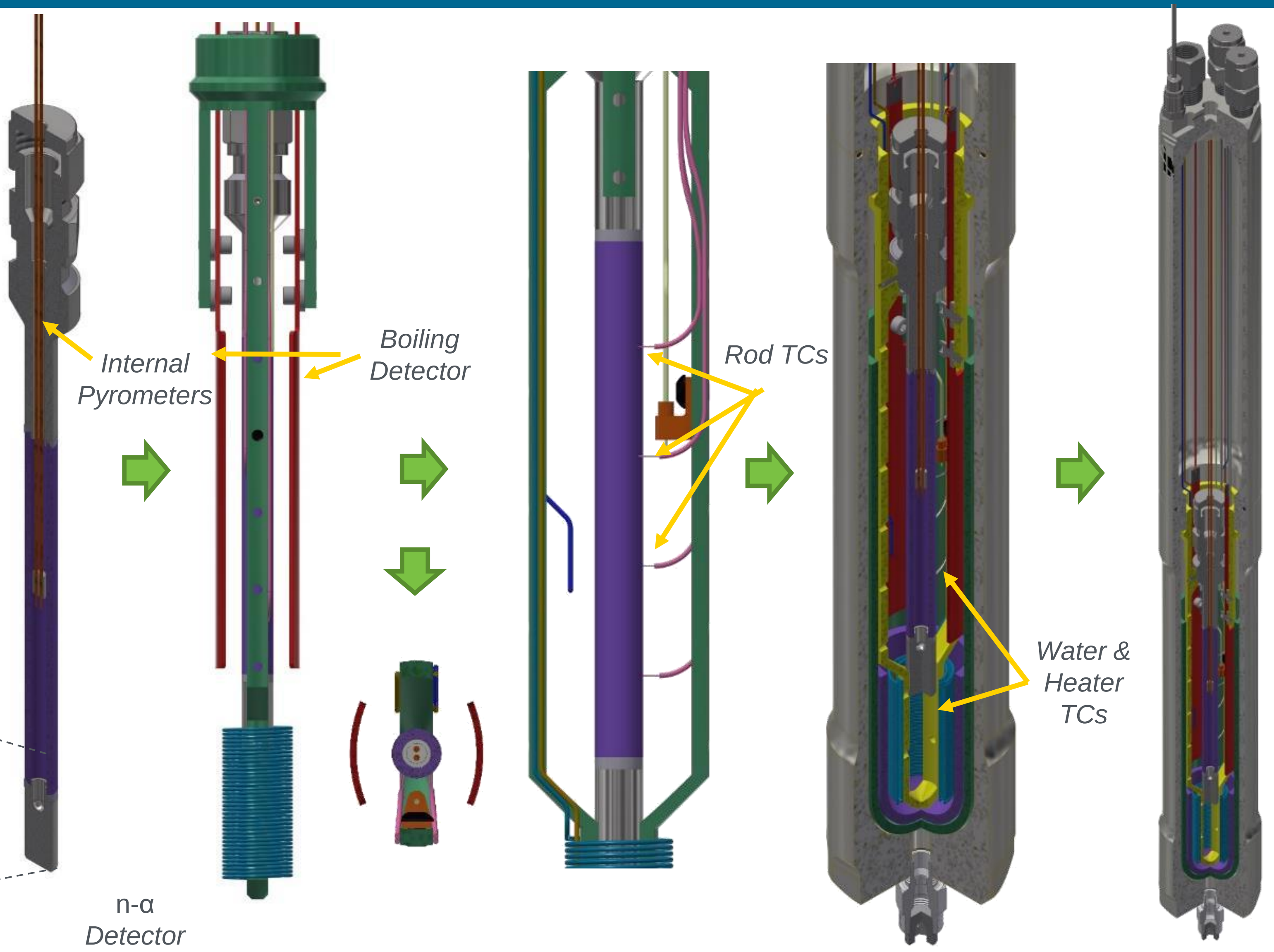


HERA

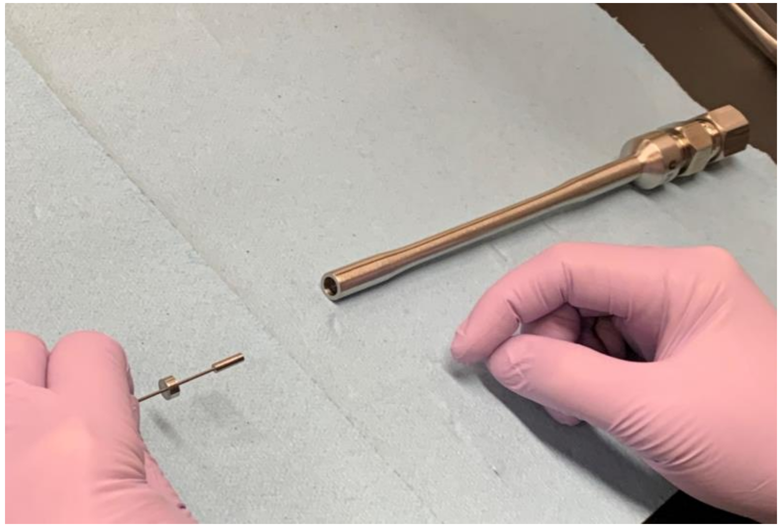
Critical Heat Flux Experiment

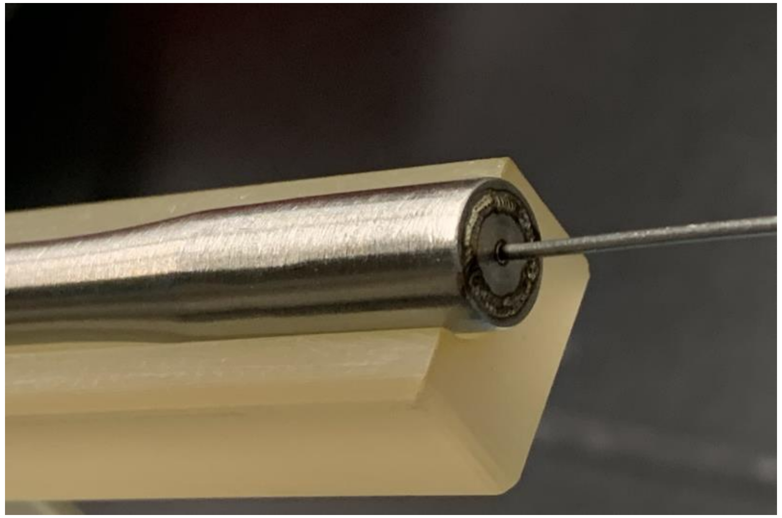
- Cladding-to-coolant heat transfer during transient irradiation conditions remains a critical area of uncertainty in fuel performance predictive capability
- Key safety limits for LWRs are intended to avoid critical heat flux (CHF)
- Fuel performance predictions for RIA events conservatively predict behaviors but with significant margin in many cases due to inadequate CHF correlations
- **Extensive instrumentation package was required**

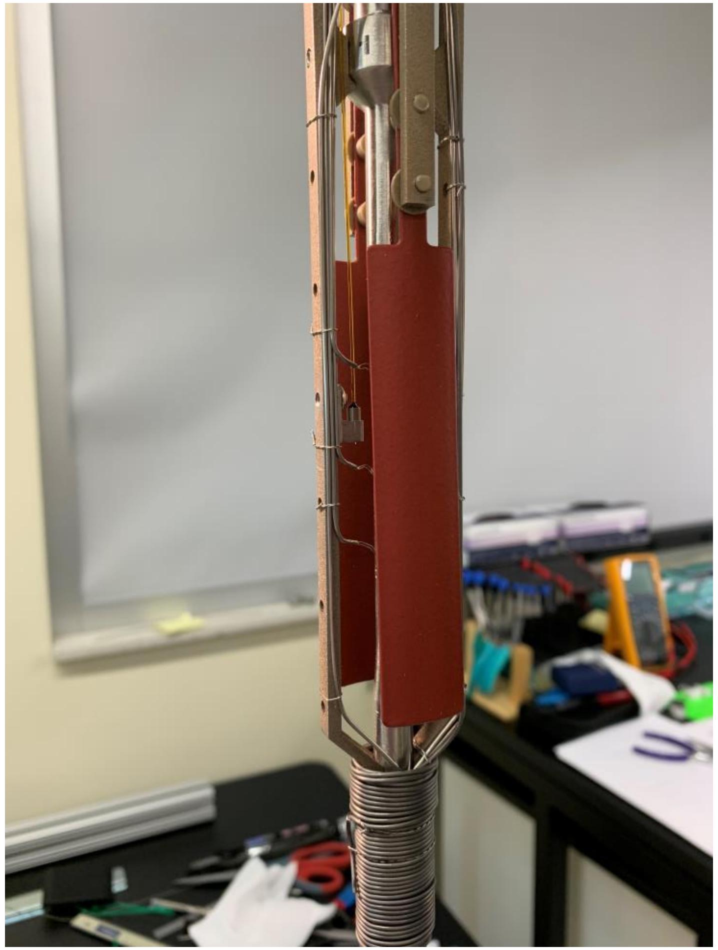




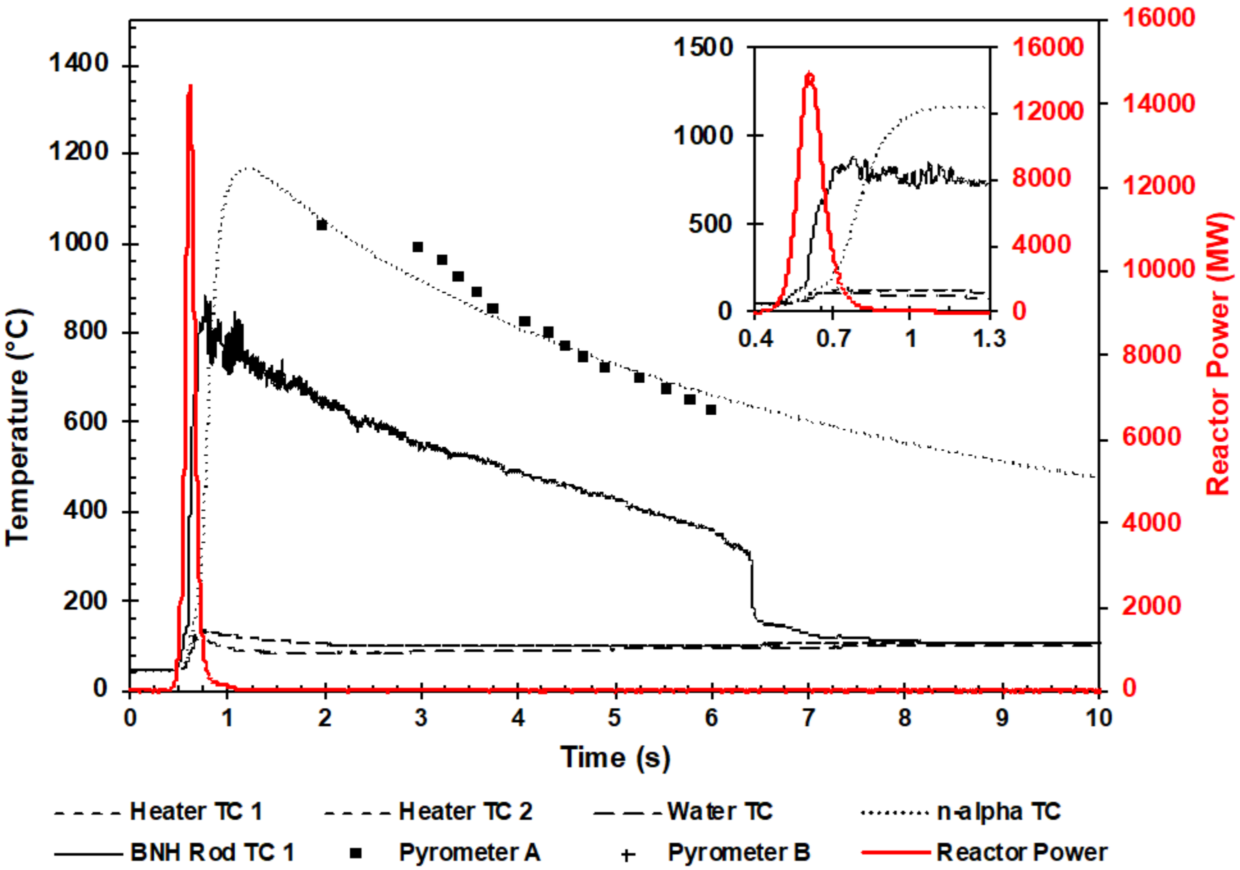
CHF Experiment Assembly

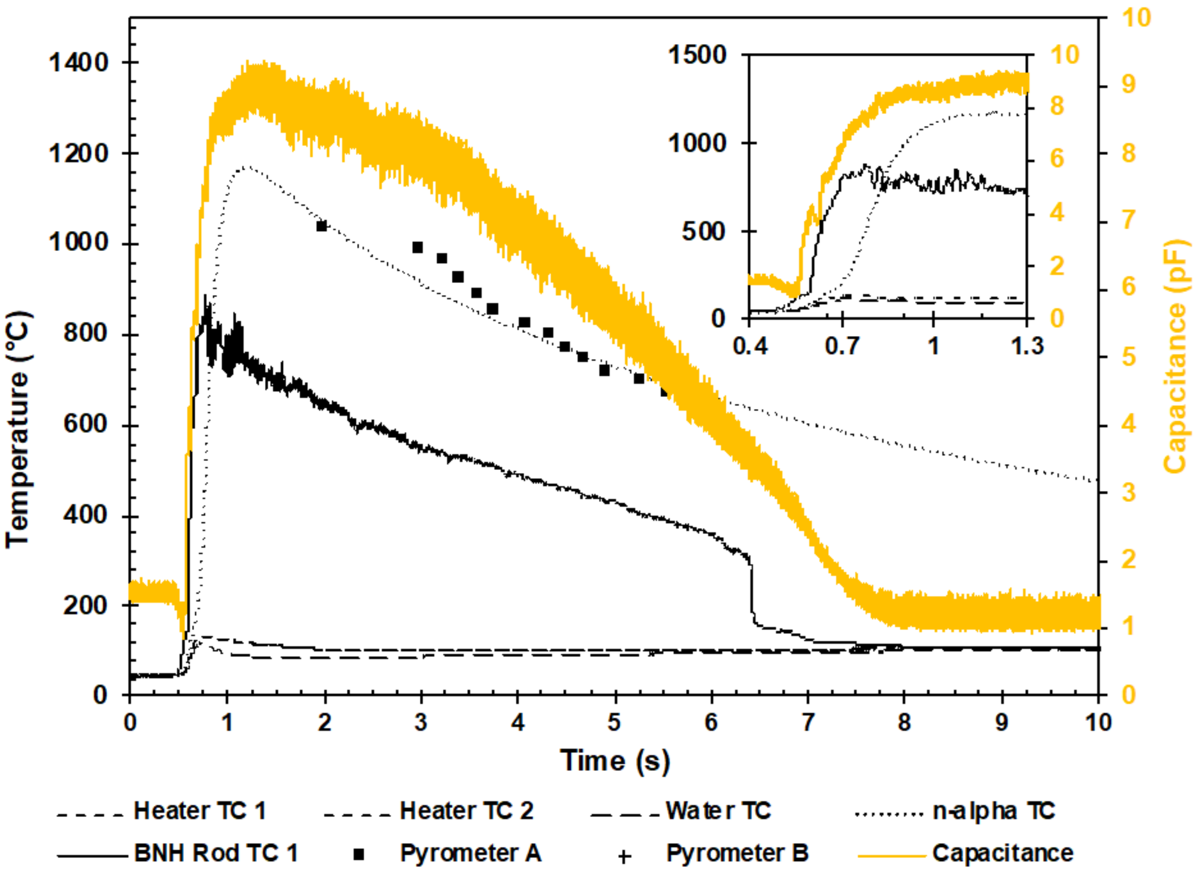






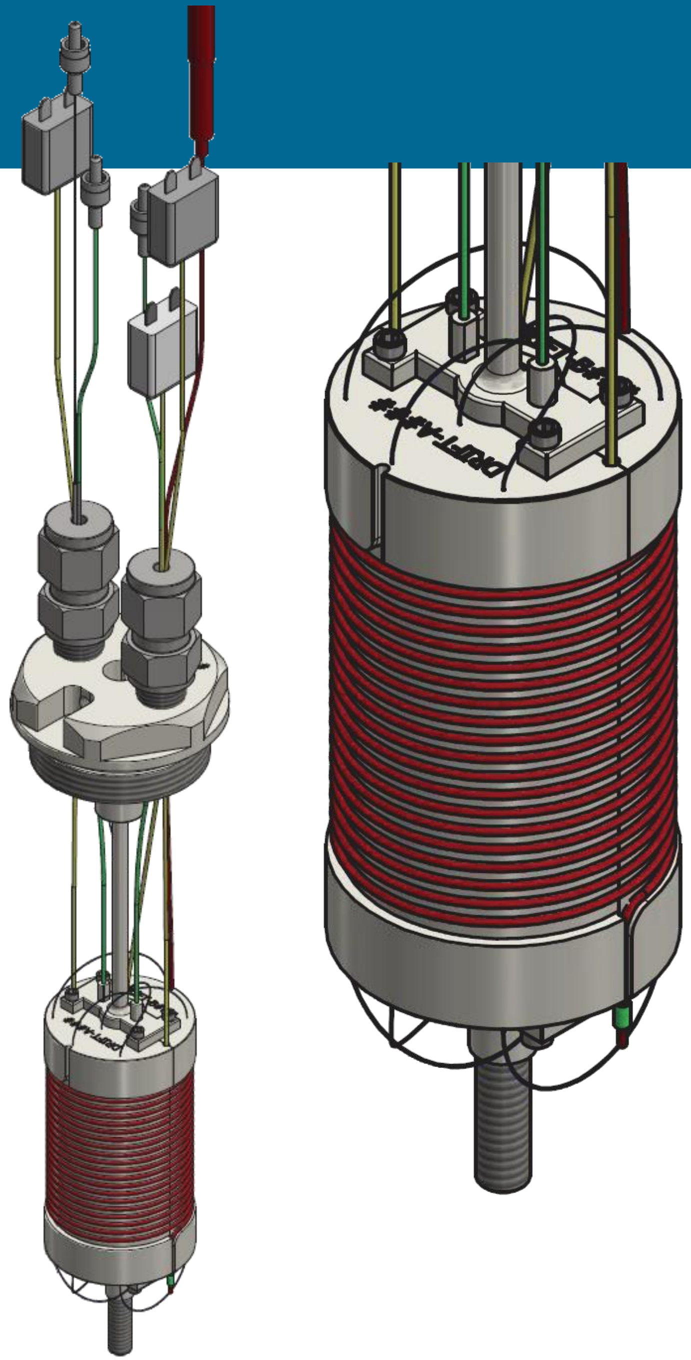
CHF Data


Temperature (°C)
Reactor Power (MW)
Time (s)
Heater TC 1
Heater TC 2
Water TC
n-alpha TC
BNH Rod TC 1
Pyrometer A
Pyrometer B
Reactor Power

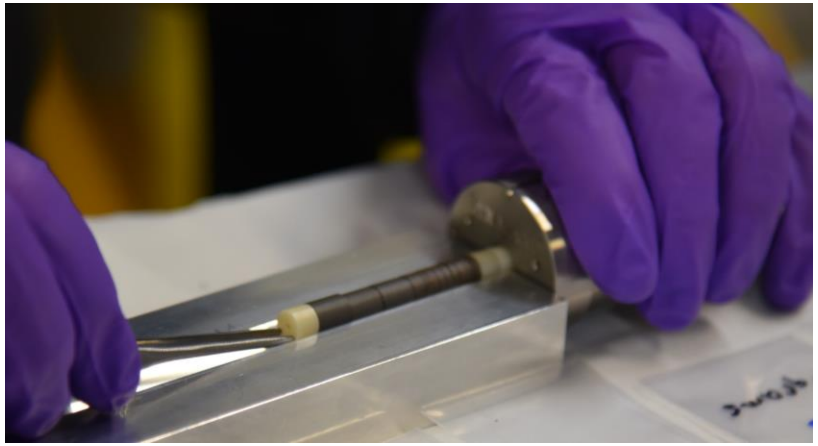

Temperature (°C)
Capacitance (pF)
Time (s)
Heater TC 1
Heater TC 2
Water TC
n-alpha TC
BNH Rod TC 1
Pyrometer A
Pyrometer B
Capacitance

DRIFT Experiment

- Experiment is designed to test cracking behavior due to the temperature profile as a benchmark for NEAMS codes
- Sample was inserted into heatsink for appropriate heat rejection
  - Preheat, coupled with transient shape and heat rejection results in desired temperature profile at the end of the transient
- Instrumentation package:
  - 2 Pyrometers viewing specimen 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 experiment)



DRIFT Assembly

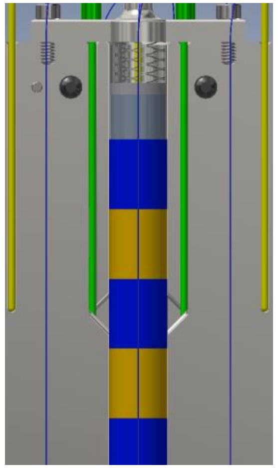


Loading Samples

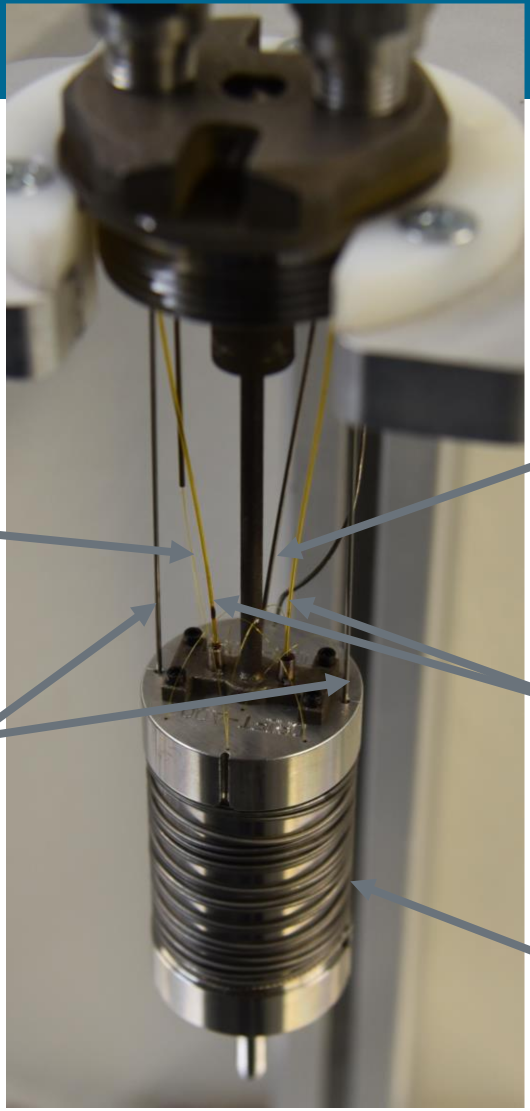
Inserting into capsule

DTS Fiber
(wrapped several times through the heat sink also)

Heat Sink TCs (2)



One half of heat sink removed



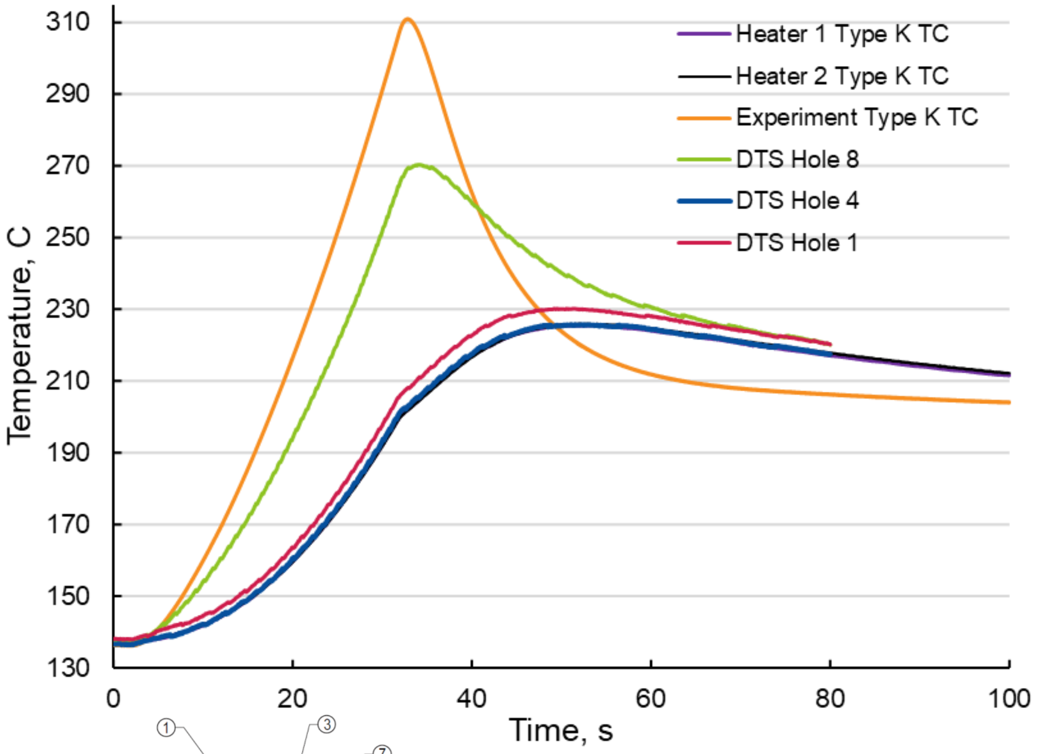
Top of specimen TC

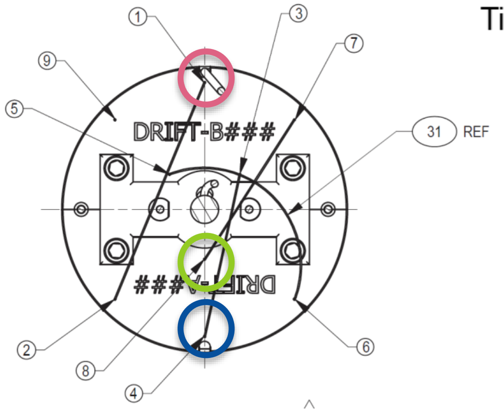
Pyrometers (2)

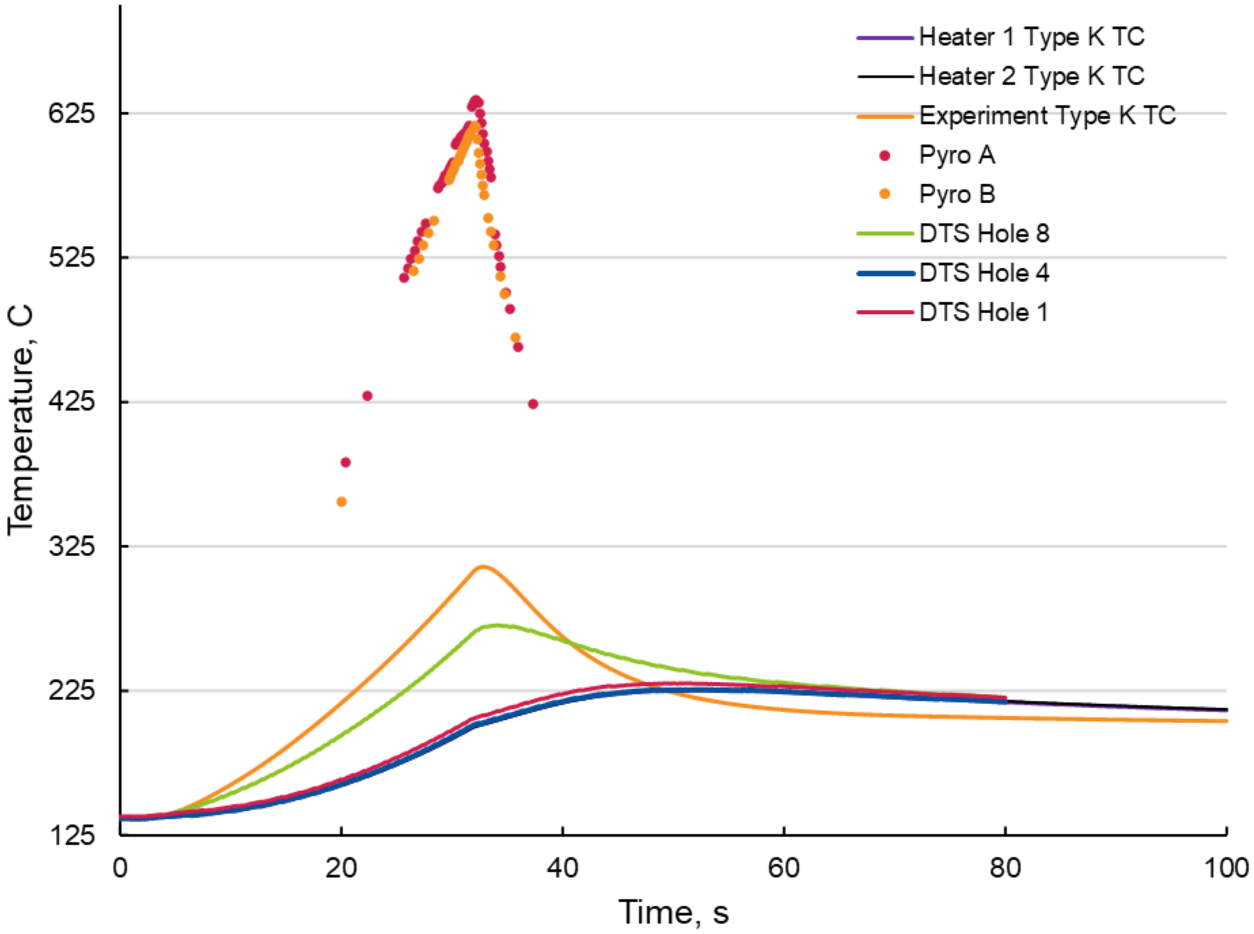
Cable Heater

Internal components all assembled

Data Overview

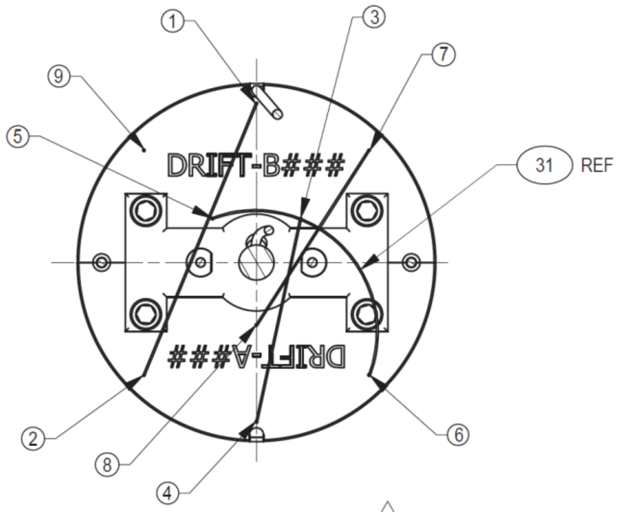


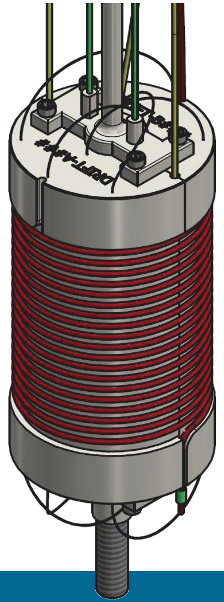


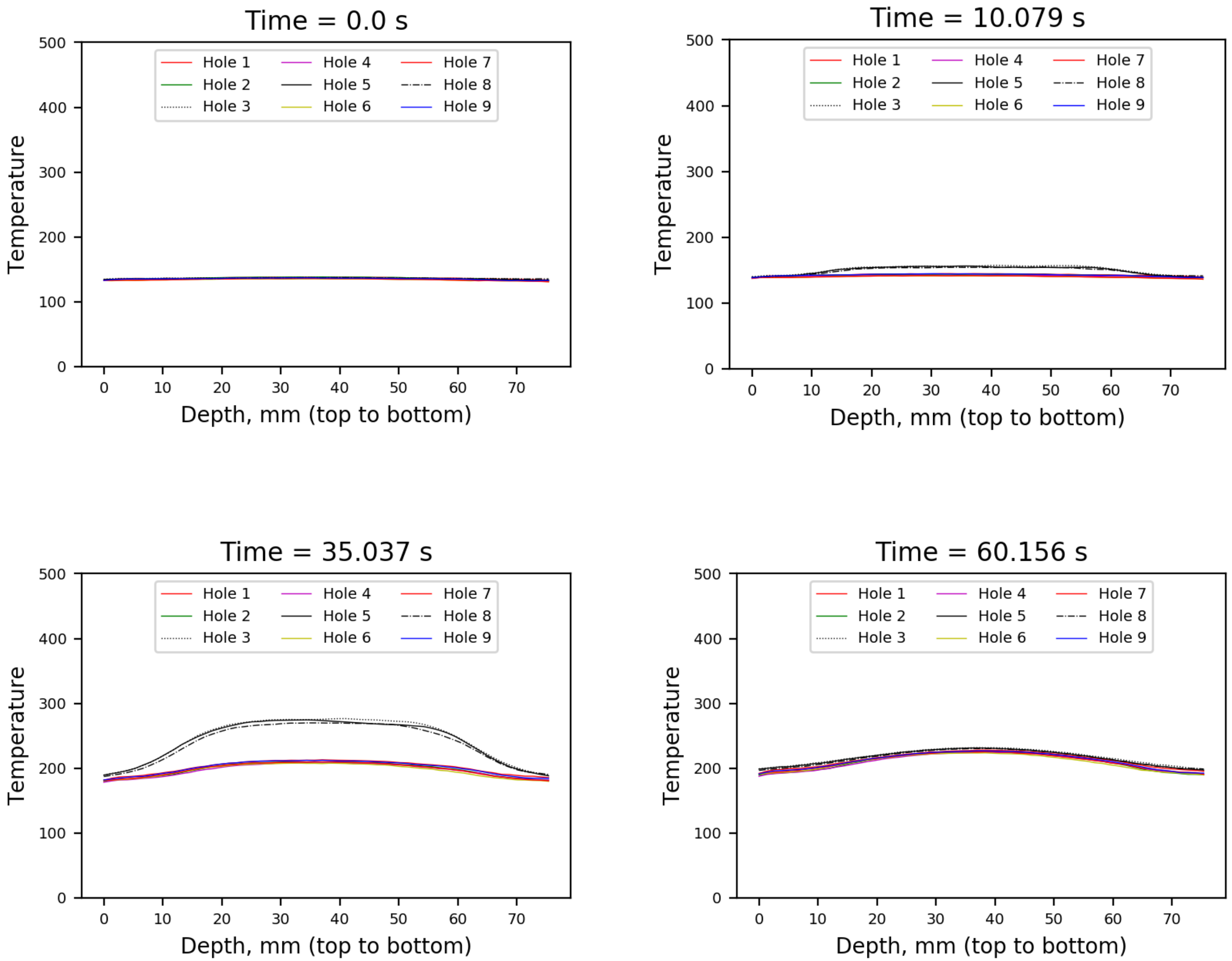


Temperatures Plotted Across Heat Sink

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







Summary & Conclusion

- Correct implementation and deployment of a sensor is as important as the qualification
- To cross the sensor "Valley of Death" an eye towards the end customers application is needed
- By establishing more stakeholders in a sensor, the long-term viability of the sensor is significantly improved.
- Even if irradiation experiments is not the end goal for the sensor, they can still provide an excellent opportunity to test and demonstrate sensor capability

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Questions?

Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

LVDT Design Integration and Calibration

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Principle Investigator: Kurt Davis

Work Package Manager: Malwina Wilding

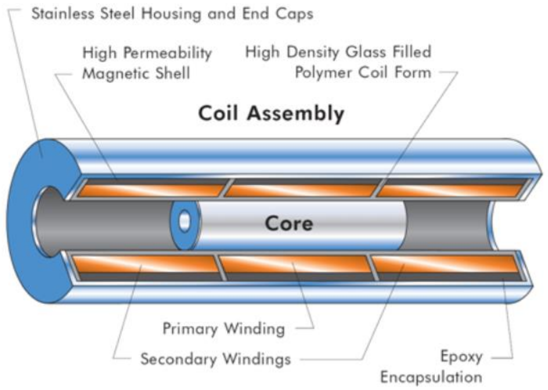
Idaho National Laboratory

Project Overview

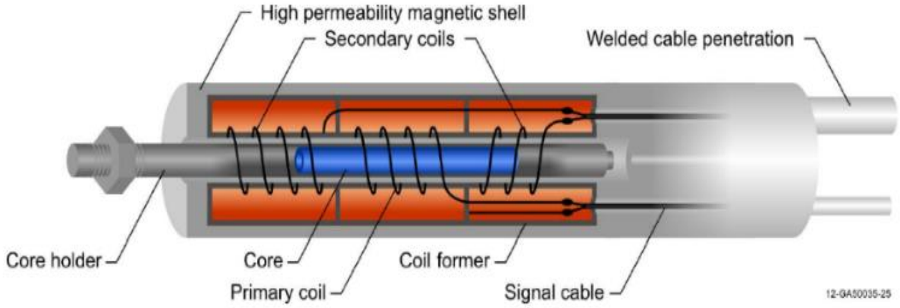
Backgroud

- An LVDT (Linear Variable Differential Transformer) is an electromechanical transducer that converts motion of object into a corresponding electrical signal. Sub-micron motions are resolvable.
- Many phenomena produce, or can be used to produce, length changes which in turn can be measured and converted into a measurement of the phenomenon. For example, pressure or temperature can be measure this way.
- The commercial LVDT device has proved to be a robust and versatile sensor, but it falls short when used at elevated temperature or when irradiated because of the materials used in construction.
- Since 1965, IFE under the Halden Reactor Project has been developing irradiation resistant high temperature LVDTs. They are the world leader when it comes to manufacturing LVDTs for irradiation testing.

Commercial LVDT



Halden LVDT



Halden Reactor Project Closure

- The Halden Reactor Project has been considered the standard supplier of high temperature, high radiation resistant, LVDTs for the international irradiation testing community
- While the supply chain is currently intact, the closure of the HRP has threatened the availability of these specialized LVDTs
- LVDTs are considered one of the most reliable measurement devices for in-pile applications with many uses in fuel performance/qualification testing
  - Directly measure displacements/elongations (fuel stack growth/cladding elongation)
  - Pressure measurement through the use of a bellows (plenum pressure, fission gas release, detecting rod failure)

Project Overview

Completion Report

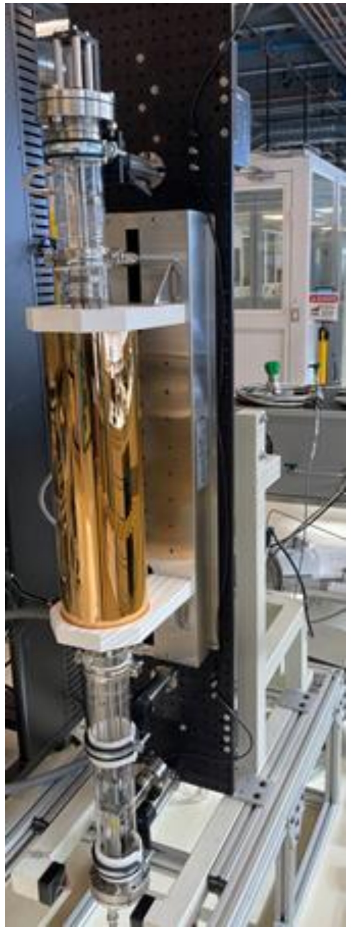
- Milestone M3CT-21IN0702046: Complete the assembly of a test rig to enable LVDT calibration in inert gas
- Milestone M4CT-21IN0702047 - Assessment of supply chain for nuclear LVDT and related components manufacture

Collaborators

- Kurt Davis, Malwina Wilding, Austin Fleming, Anthony Crawford, Russel Lewis, Kory Manning, Ashley Lambson, **Idaho National Laboratory**.

Completion of M3CT-21IN0702046: *Complete the assembly of a test rig to enable LVDT calibration in inert gas*

- 3 Calibration/Testing configuration capabilities have been established
  - Displacement: ferritic core is precisely position under well characterized thermal conditions while reading LVDT
  - Pressure: applies constant pressure to bellows coupled to LVDT core under well characterized thermal conditions. Allow direct correlation between LVDT reading and pressure at a given temperature
  - Transient pressure: Rapidly applies pressure to bellows LVDT system to test transient response of the sensor. Used to qualify for high speed measurement requirements
- All are protected by inert gas to prevent oxidation

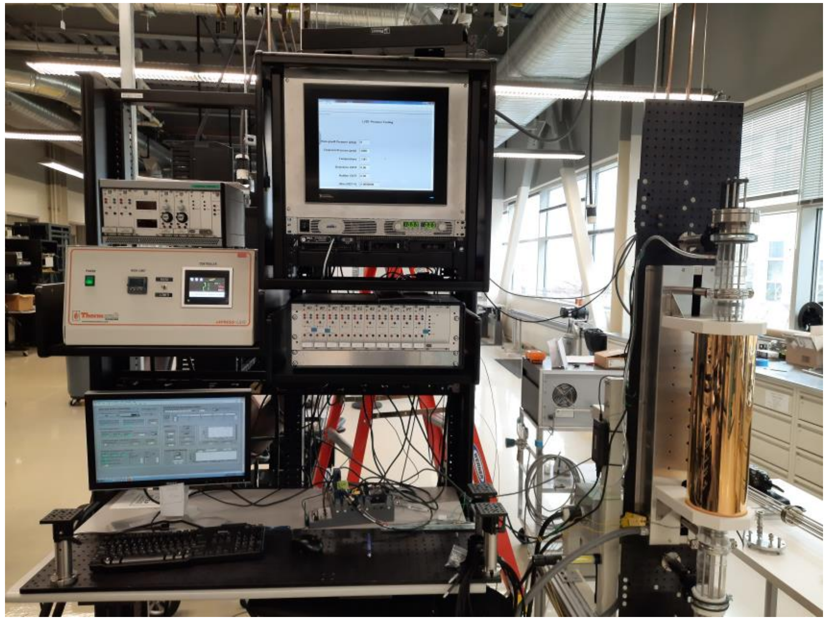


Maximum temperature 700°C

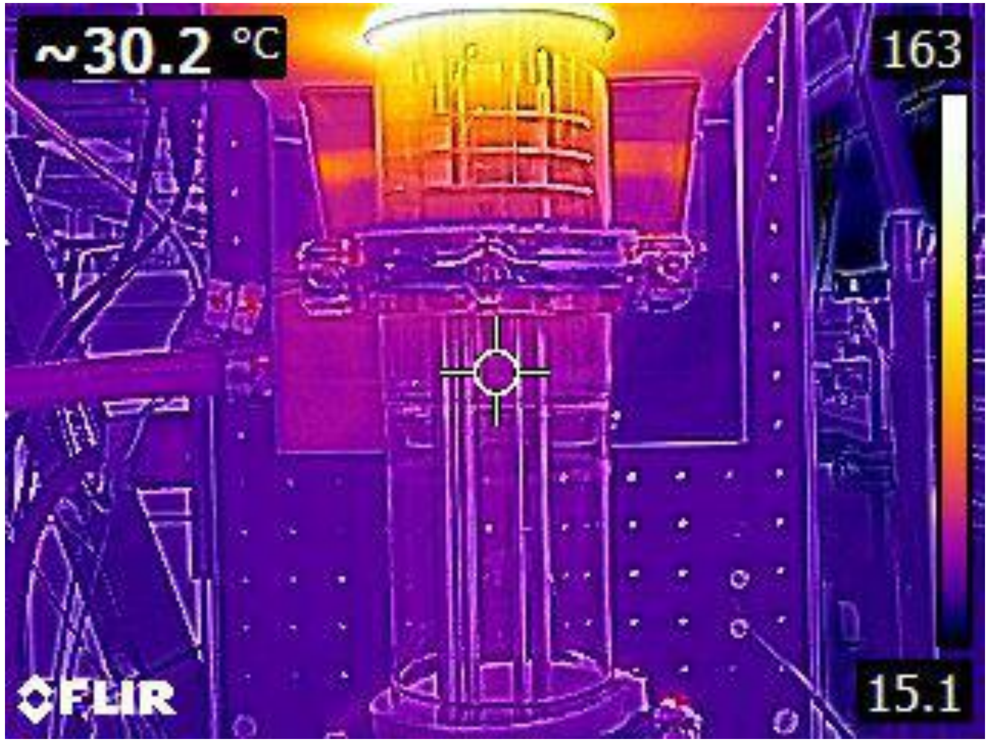
Maximum Pressure 2,800 psi

Transient pressure evaluation capable

Calibrations performed without oxidation damage to sensor

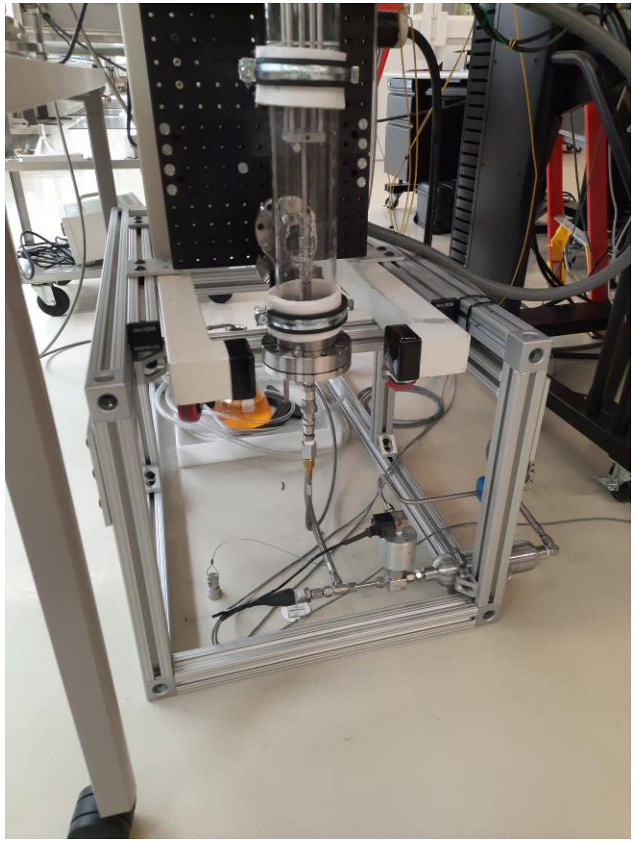


Testing

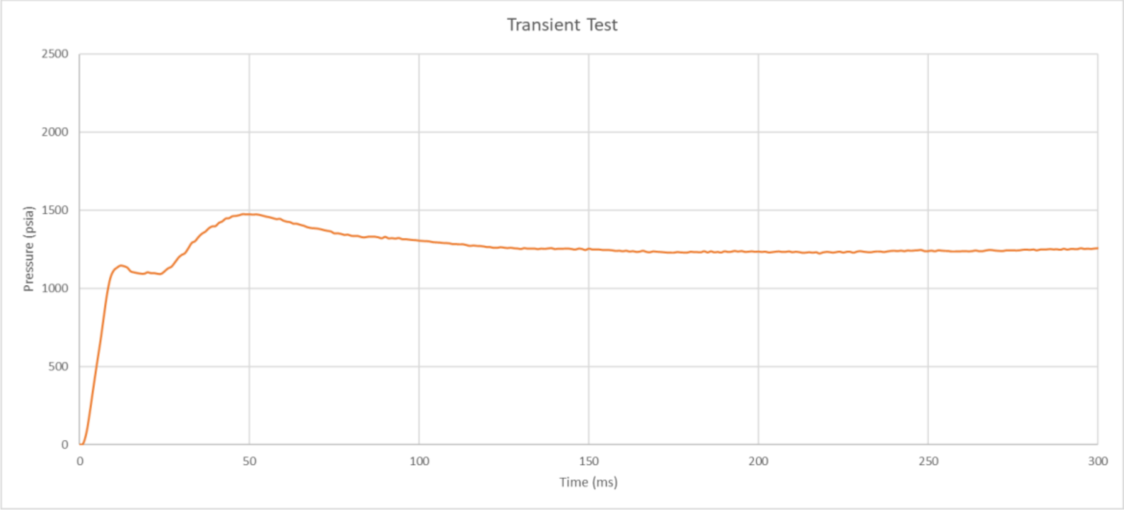


- Argon flow constant at 2 l/min
- Calibration region stable and uniform at 700°C
- Drive motor region remained near room temperature
- Acceptable oxygen uptake on Niobium detector

Pressure Transient Test

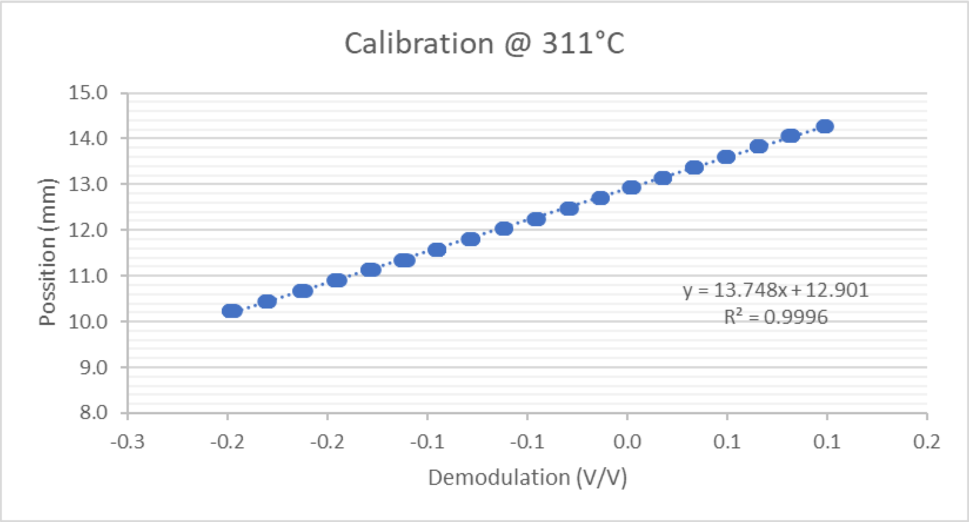


- **Accumulator loaded @ 2,000 psia**
- **First spike >1,100 psia @ 12 ms, second spike near 1,500 psia @ 49 ms**
- **No leaks or excessive rig vibrations observed**
- **Steady state pressure within calibration**
- **Ready to evaluate LVDT pressure sensor response to transient**



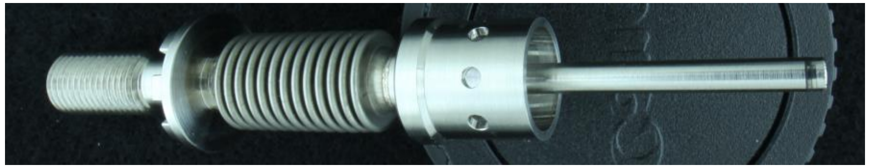
LVDT based displacement and pressure sensors calibrated for in-pile use

- **No oxidation of sensor**
- **Acceptable performance of calibration rig**
- **Have successfully calibrated LVDTs for pressure and displacement measurements at elevated temperature**

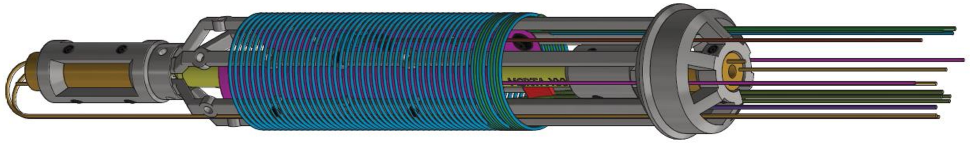


Technology Impact

- An in-pile creep test rig based on LVDT technology has been developed and will soon be deployed. Calibrations were performed using the MSL developed calibration rig.
- 5 LVDT sensors successfully deployed in the MSERTTA test fixture at TREAT. Fuel rod plenum pressure and cladding elongation were measured.
- LVDT based pressure sensor will be used in the THOR experiment to detect failure of a metallic fuel pin

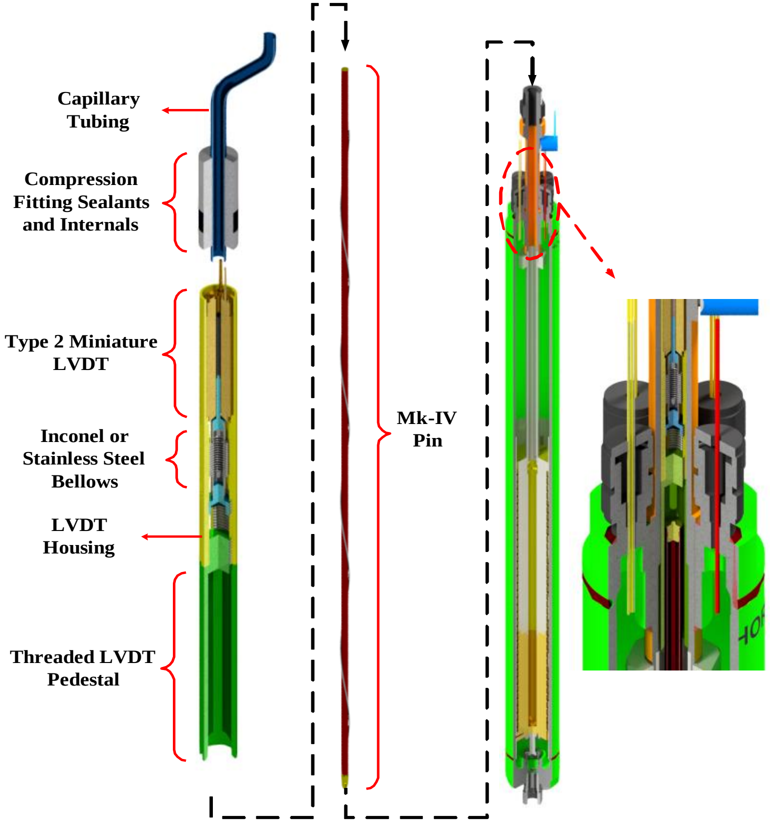


Jointly Developed LVDT Based Sensor



M-SERTTA Experiment

Micro soldering LVDT leads



THOR Experiment

Completion of M4CT-21IN0702047 - Assessment of supply chain for nuclear LVDT and related components manufacture

- An assessment of the LVDT supply chain for nuclear applications has been conducted
  - Identified potential replacement suppliers for the Halden LVDTs
- Not ALL in-pile applications require the extreme temperature and radiation capabilities of the Halden LVDTs.
- For some needs, existing commercial products may be sufficient
- For more demanding applications
  - Work with commercial vendors to improve existing designs
    - Perhaps a combination of in-house fabrication with an eye towards commercialization
- Plans to procure and benchmark various replacements against Halden LVDTs have been established


INL/LTD-21-62217

Assessment of Supply Chain for Nuclear LVDTs and Related Components Manufacturing

March 2021

Kurt Davis

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May be exempt from public release under the Freedom of Information Act (5 U.S.C. 552), exemption number and category:
Exemption 4, Statutory Exemption
Department of Energy review required before public release Name/Org: Kurt Davis, C670, Date: 4.7.21,
Guidance (if applicable) N/A

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

Conclusion

- Calibration rig provides inert environment up to 700° C
- Successful calibrations can now be performed for displacement and pressure measurements with no oxidation damage to the sensor
- Transient evaluation and steady state calibration ready

- Future work includes
  - purchasing LVDT equipment from vendors found in the assessment report and performing laboratory evaluations to benchmark against Halden LVDTs.
  - Interface with the University of Pittsburgh on the implementation of a “wireless” LVDT

Kurt Davis

Kurt.davis@inl.gov

Questions?

ASI | Advanced Sensors and Instrumentation

We will restart at 3:30 EST

3:30 Development of Radiation Endurance Ultrasonic Transducer for Nuclear Reactors (Uday Singh, X-wave Innovations, Inc)

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ASI Advanced Sensors and Instrumentation

In-Core Measurement Systems for Nuclear Materials Characterization: Codes Validation and Verification

CT-21IN070205

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Zilong Hua, Ph.D., Research Scientist

Idaho National Laboratory

Project Overview

Purpose:

Develop instruments to provide unique capabilities of measuring critical physical properties of nuclear fuels and materials **in reactor** in a **real-time** manner

- Photothermal radiometry (PTR) – thermal conductivity
- Laser-base Resonant Ultrasonic Spectroscopy for Zero-Group-Velocity plate wave detection (RUS-ZGV) – elastic property induced microstructure evolution

Participants:

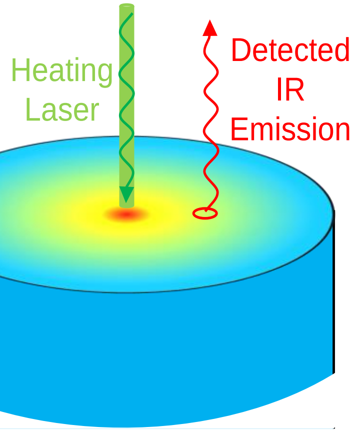
Zilong Hua, and Robert Schley (Idaho National Laboratory)

Project Overview

- Photothermal radiometry (PTR)

Thermal Wave

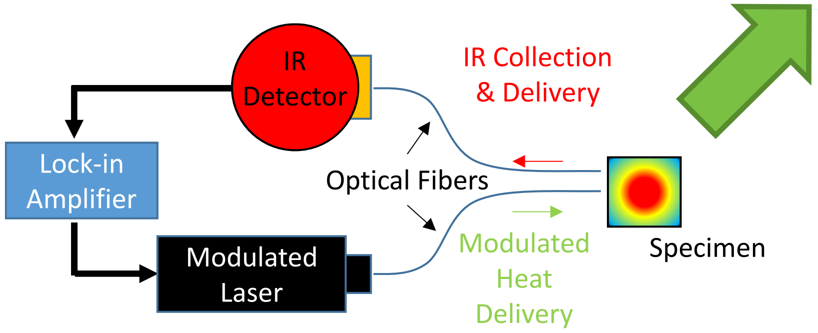
- Lock-in approach



Blackbody Radiation

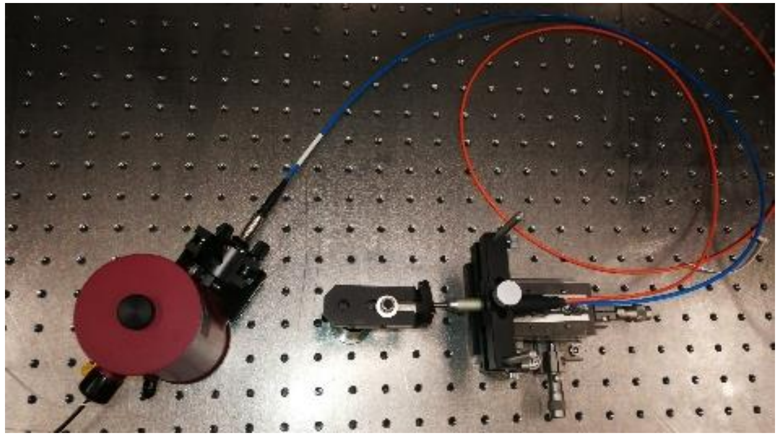
- Ideal for high temperature
- Little preparation on surface

One side-access



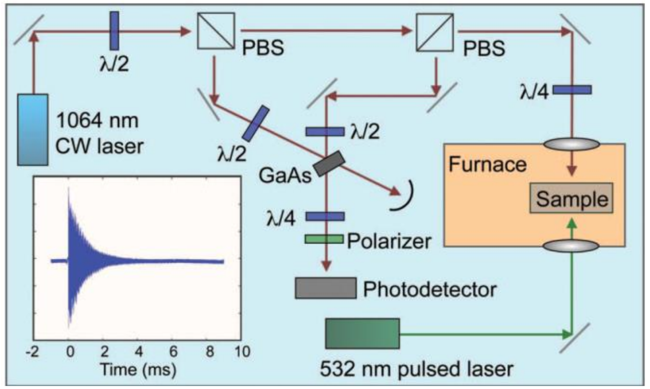
Use of Fiber

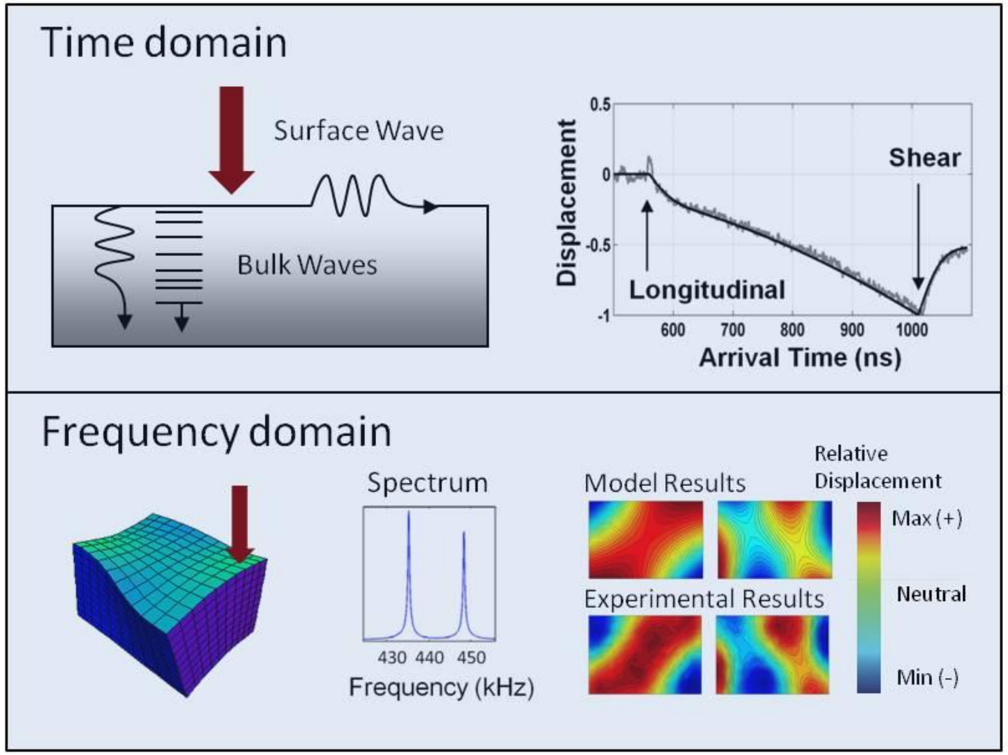
- Remote
- In-situ

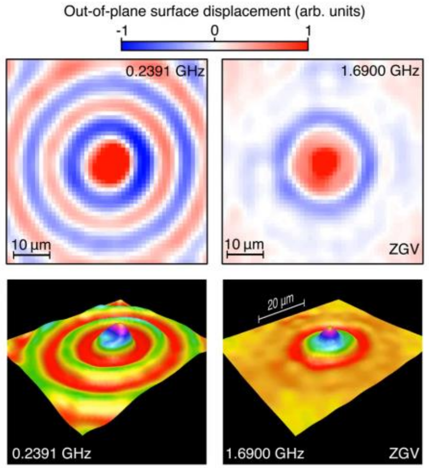


Project Overview

- Laser-base Resonant Ultrasonic Spectroscopy for Zero-Group-Velocity plate wave detection (RUS-ZGV)







Xie, Q., Imaging Gigahertz Zero-Group-Velocity Lamb Waves, Nature Communication, 10, 2228 (2019)

Technology Impact

Real-time experimental data from in-reactor measurements can

- Provide insights of dynamic microstructure evolution
- Boost the development of advanced nuclear fuels and materials
- Enable direct validation and verification for advanced fuel performance codes

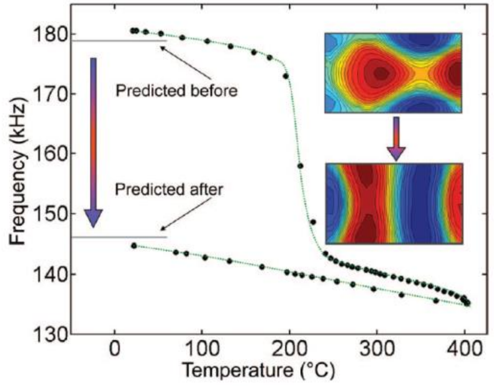


FIG. 3. (Color) *In situ* monitoring of resonant peak location as a function of annealing temperature. The center frequency changes significantly during recrystallization. The majority of this shift is due to a dramatic change in texture. Inset: Experimentally measured mode shape before and after annealing.

Hurley, D.H., In-situ Laser-based Resonant Ultrasound Measurements of Microstructure Mediated Mechanical Property Evolution, Journal of Applied Physics 107, 063510 (2010)

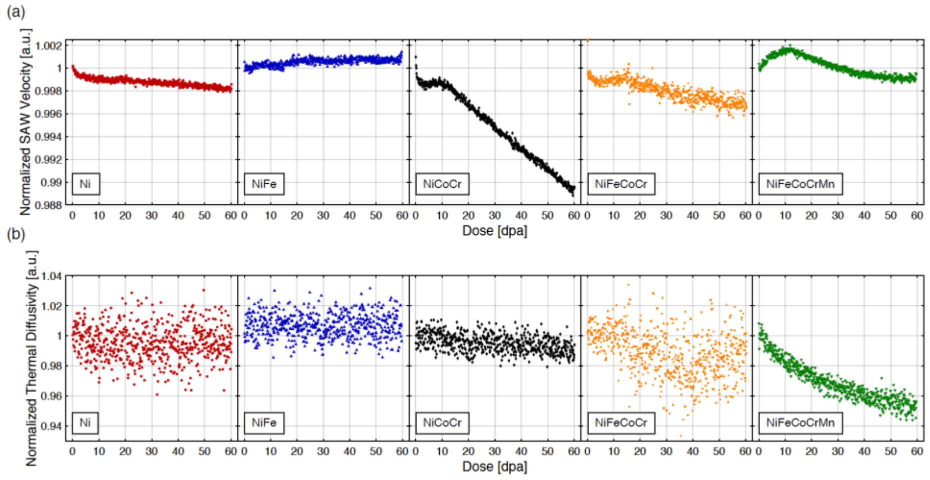
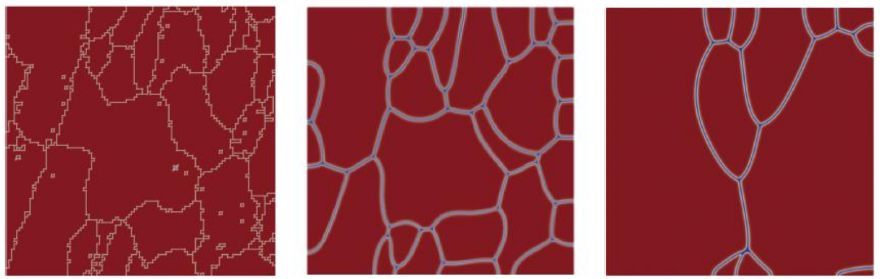


FIG. 2. *In situ* records of (a) SAW velocity and (b) thermal diffusivity evolution under irradiation. Values have been normalized to the first 5 minutes of exposure for each property set to make relative comparisons between different alloy compositions as the initial material properties vary by composition.



(a) $t = 0\mu s$ (b) $t = 16\mu s$ (c) $t = 100\mu s$

Fig. 3.4 Temporal evolution of a microstructure with 50 grains deformed with orientation dependant dislocation density. Microstructural evolution is driven by both reduction in strain energy and interfacial energy.

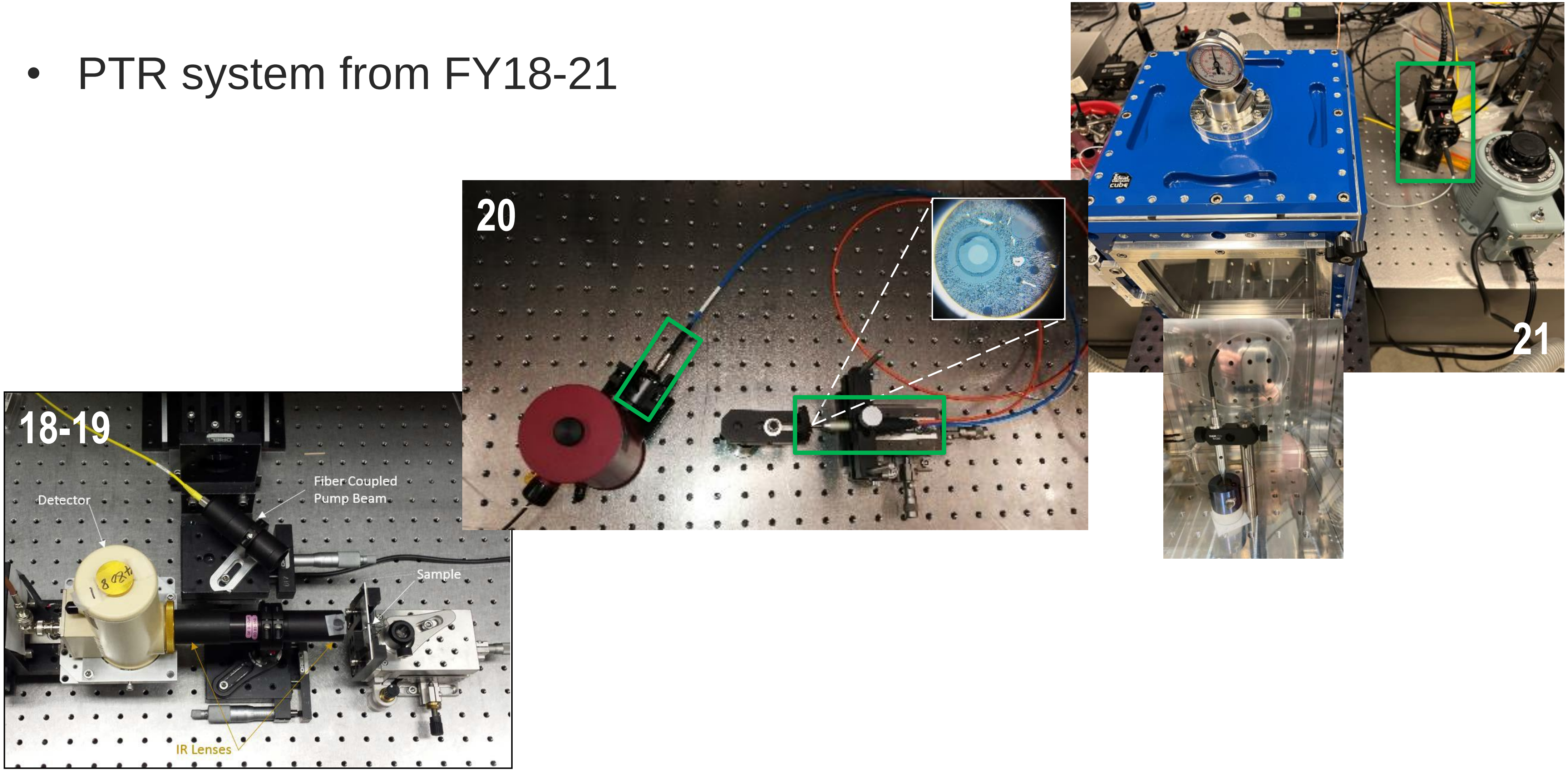
Dennett, C.A., The Dynamic Evolution of Swelling in Nickel Concentrated Solid Solution alloys Through in situ Property Monitoring, Appl. Mater. Today (2021), accepted

Results and accomplishments

- PTR
  - FY18
    - Technique validation
    - Free-space system built-up
    - Systematic errors diagnose (diffraction and non-linear effects induced overestimation)
  - FY19
    - “Complete” analytical model developed to deal with systematic errors
    - Fiber-based system designed; prototype instrument fabricated
  - FY20
    - Fiber-based system tested with reference materials at room temperature
    - System upgraded for high temperature measurements

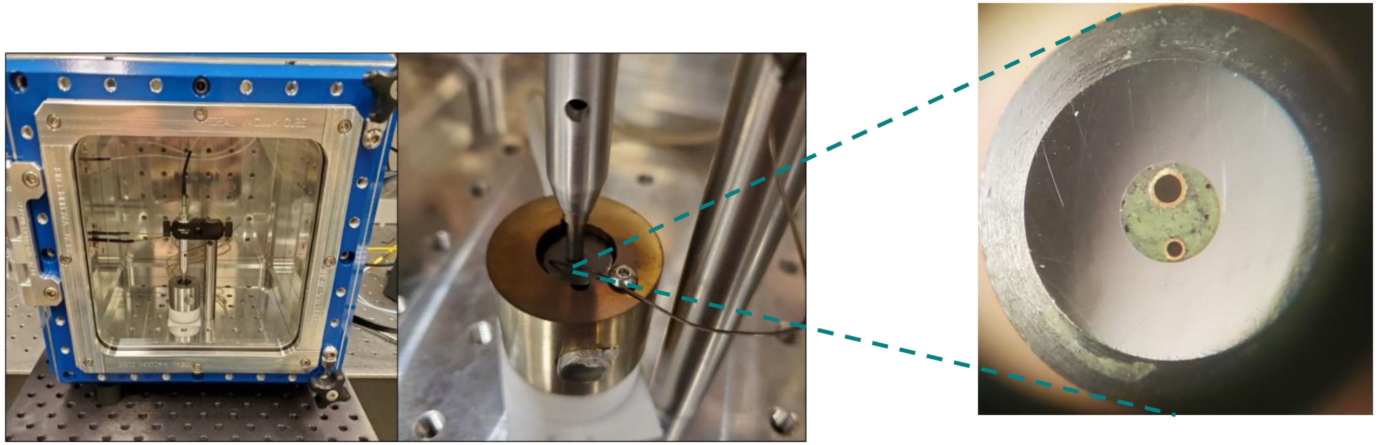
Results and accomplishments

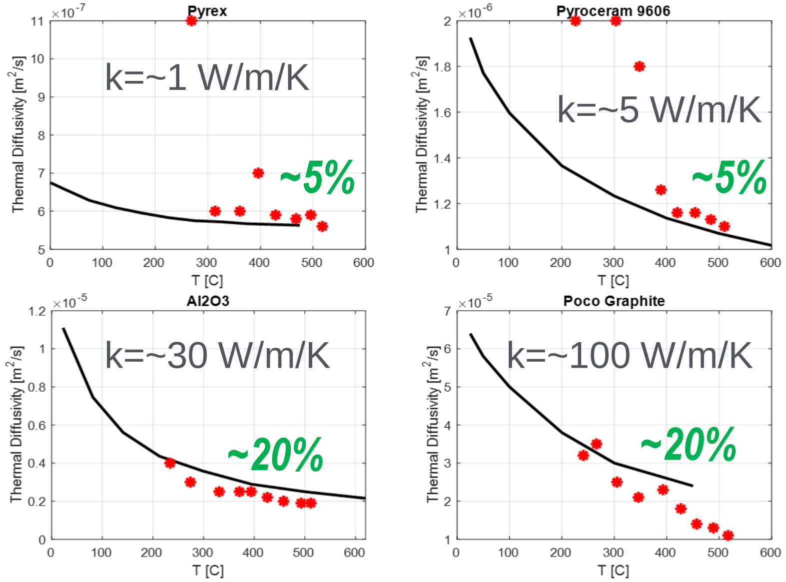
- PTR system from FY18-21



Results and accomplishments

- PTR
  - FY21
    - Fiber-based system tested in-situ at high temperature
    - Resolution adjustment and its effect on measurements studied
    - CINR-NSUF proposal awarded for MITR insertion experiment (FY22-23)

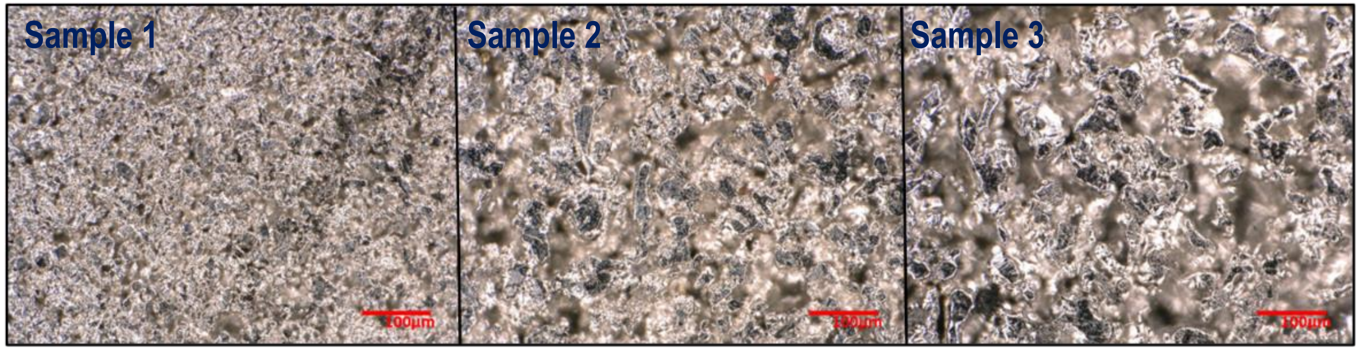




Results and accomplishments

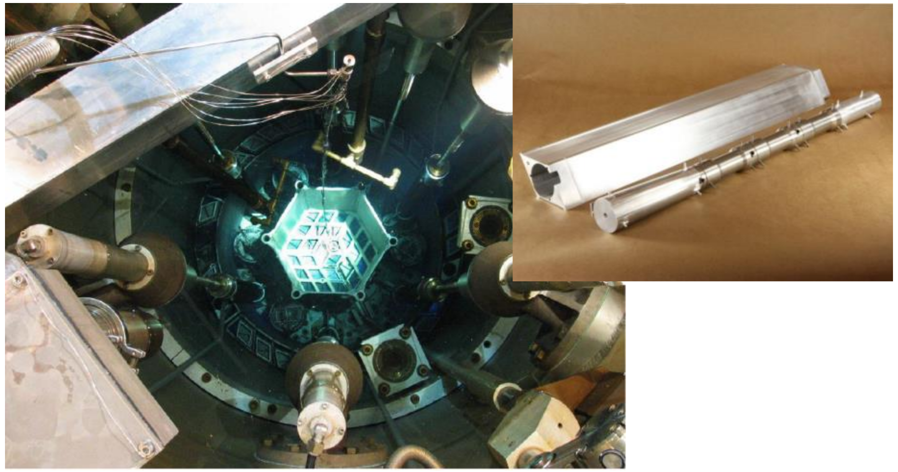
- PTR
  - FY21
    - Fiber-based system tested in-situ at high temperature
    - Resolution adjustment and its effect on measurements studied
    - CINR-NSUF proposal awarded for MITR insertion experiment (FY22-23)

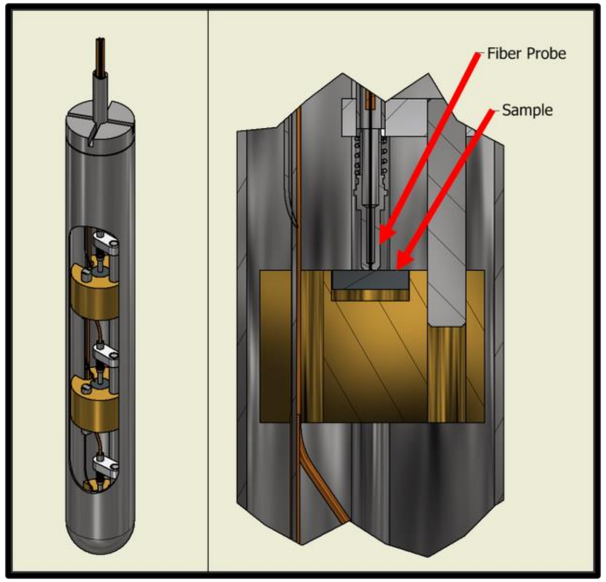
	Sample 1(#0.2)	Sample 2(#1)	Sample 3(#5)
Probe old (171μm) (470˚C)	9.8×10^{-6} m^2/s	4.8×10^{-6} m^2/s	0.72×10^{-6} m^2/s
Probe new (500μm) (470˚C)	2.4×10^{-6} m^2/s	1.4×10^{-6} m^2/s	3.5×10^{-6} m^2/s
Reference LFA (bulk) (25˚C)	2.88×10^{-6} m^2/s	2.67×10^{-6} m^2/s	2.29×10^{-6} m^2/s



Results and accomplishments

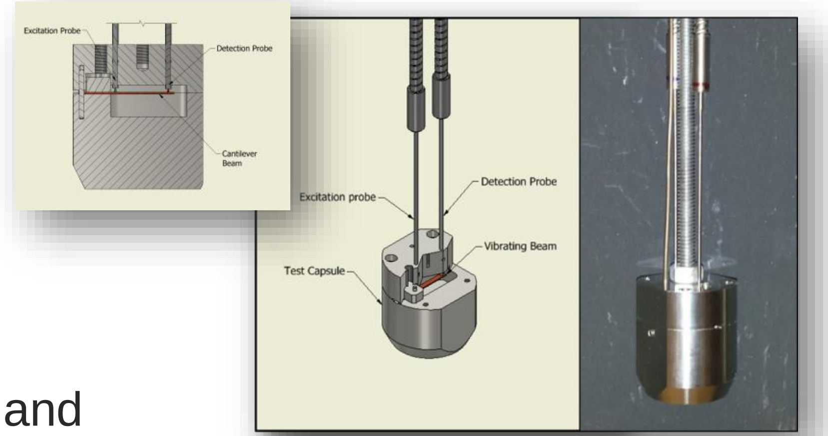
- PTR
  - FY21
    - Fiber-based system tested in-situ at high temperature
    - Resolution adjustment and its effect on measurements studied
    - CINR-NSUF proposal awarded for MITR insertion experiment (FY22-23)

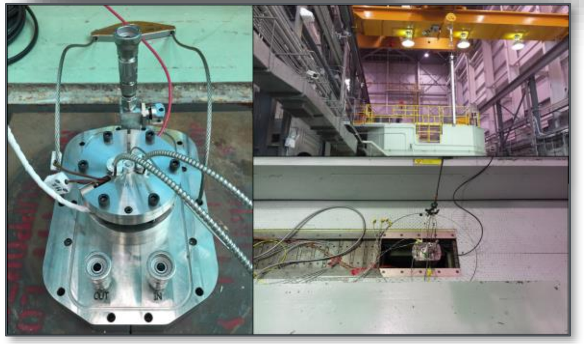


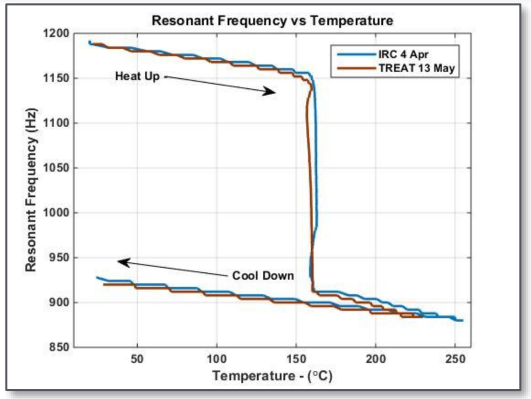


Results and accomplishments

- RUS
  - FY18
    - Fiber-system developed and tested (RUSL)
    - Cantilever beam boundary condition induced error identified and investigated
  - FY19
    - Instrument capsule for cantilever beam designed, fabricated and tested
    - Anneal process observed on a highly textured copper sample
    - Insertion experiment at TREAT (Mimic-RUSL)

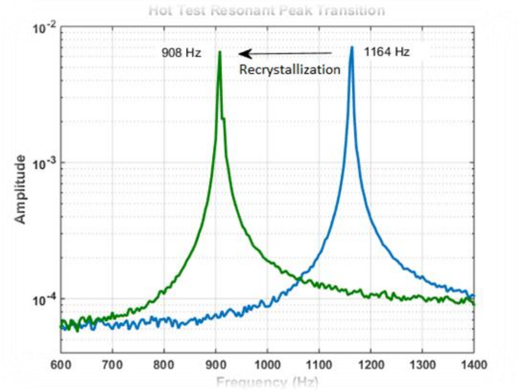


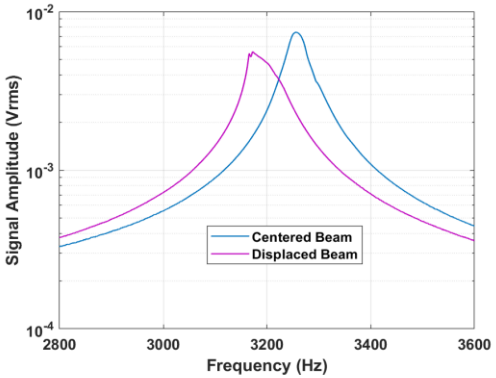




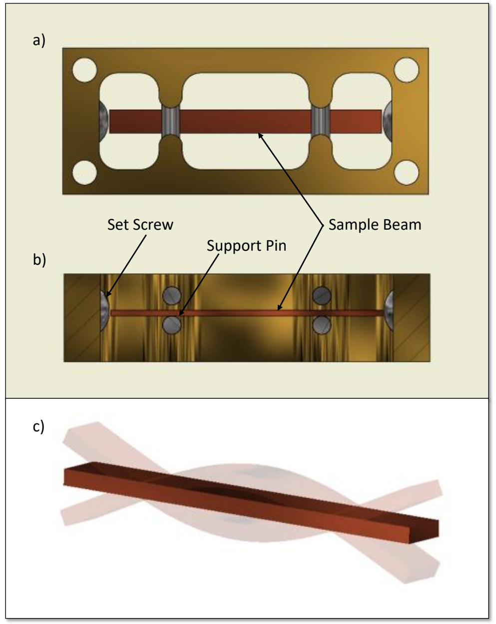
Results and accomplishments

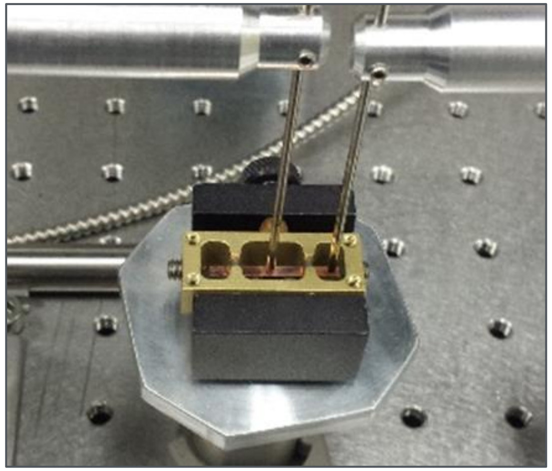
- RUS
  - FY20
    - Instrument capsule for free-free beam designed, fabricated, and tested
    - Low signal-to-noise ratio noticed and identified as induced by poorly defined boundary condition





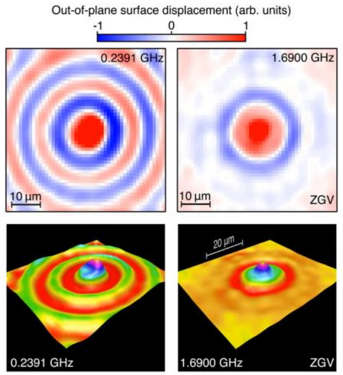
Cantilever beam vs free-free beam





Results and accomplishments

- RUS
  - FY21
    - Zero-group-velocity plate wave measurement capability tested and investigated
    - High temperature measurements conducted on reference materials



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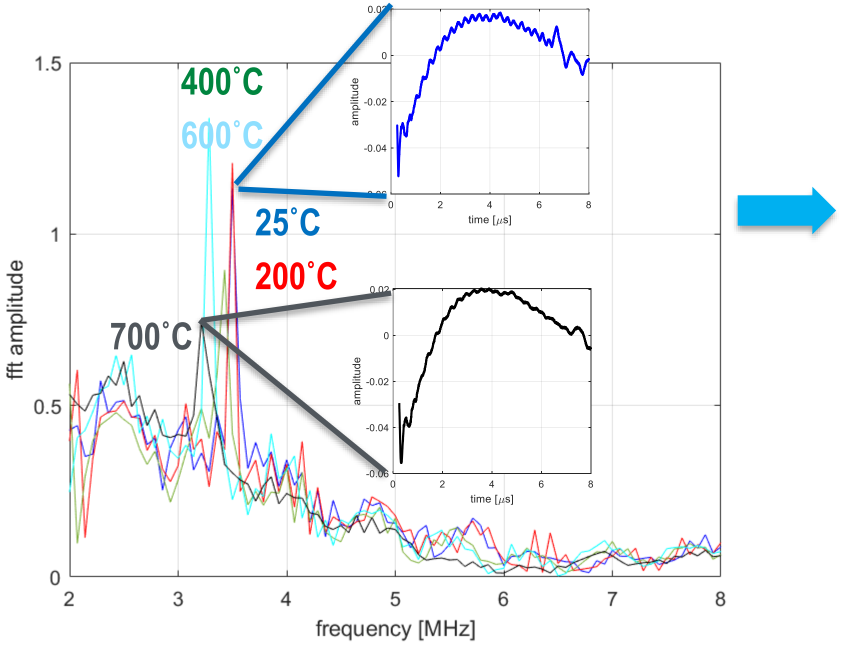

Material	ZGV f @25˚C [MHz]	ZGV f @400˚C [MHz]	ZGV f@HT limit[MHz]
Cu	**3.54**	**3.42**	**3.16@700˚C**
Mo	5.82	5.73	5.57@1000C
W	4.75	4.74	4.64@1000C
Si	6.41	6.40	6.31@800˚C

Results and accomplishments

- Challenges
  - PTR
    - Fiber/instrument survivability in high temperature, high radiation environment
    - Non-linearity issued induced by probe spot size
  - RUS-ZGV
    - Low Q-index from insufficient wave periods
    - Complicated data process

Conclusion

Continued from previous FY, more developments have been done on PTR and RUS instruments, including

- High-temperature, in-situ measurement capability test
- New measurement mode investigation and instrument optimization
- Proposal for in-reactor test at MITR awarded

Future work

- Characterize the microstructure defects that are difficult or costly to be quantified by other techniques, such as point defects and dislocations

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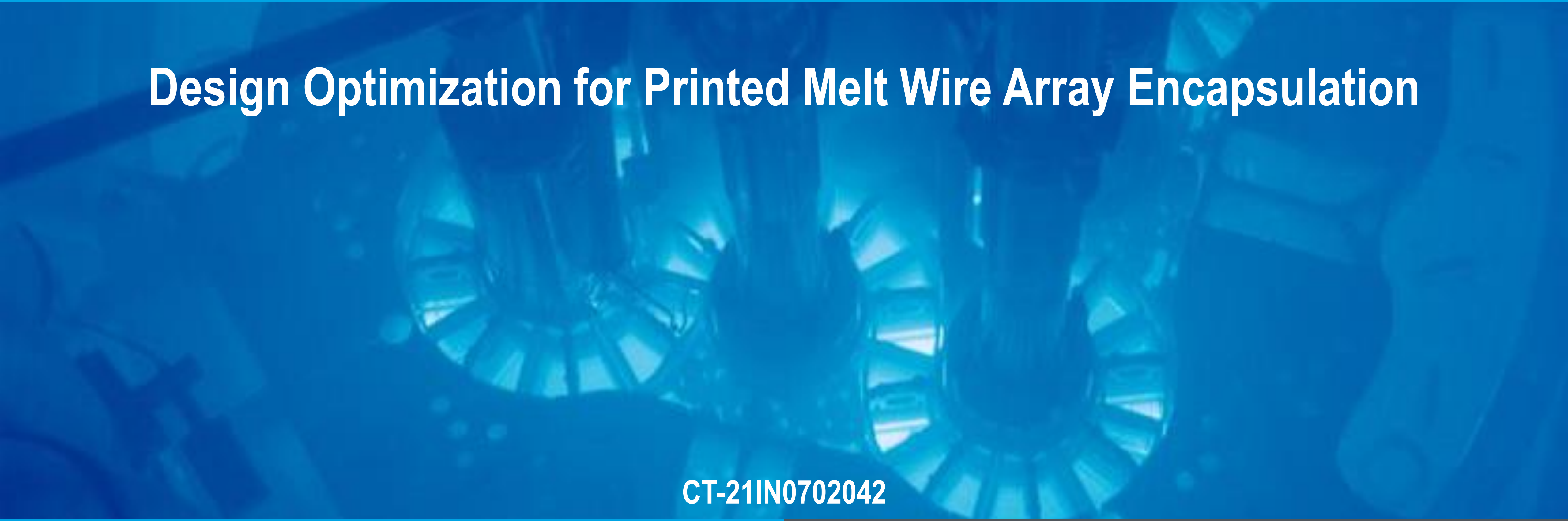
Questions?

ASI
Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Design Optimization for Printed Melt Wire Array Encapsulation



CT-21IN0702042

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

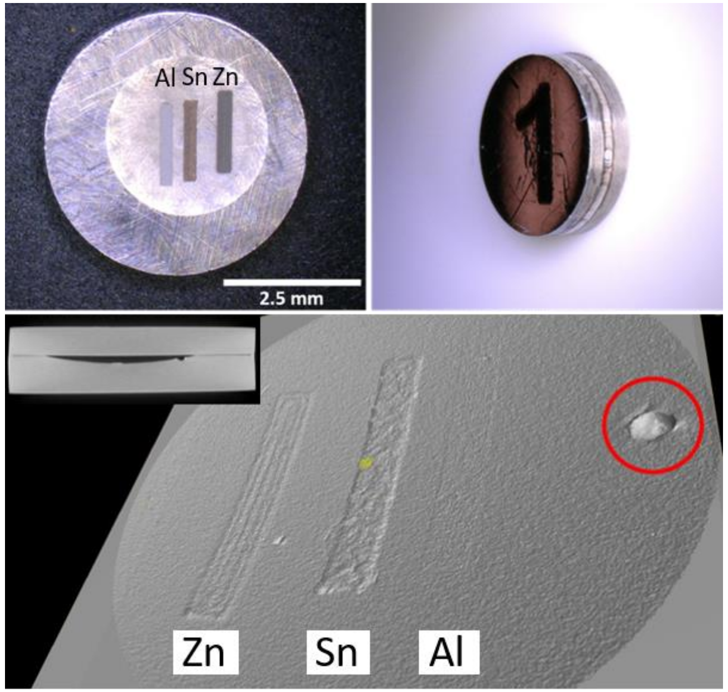
INL Graduate Fellow: Kiyo Fujimoto

Idaho National Laboratory and Boise State University

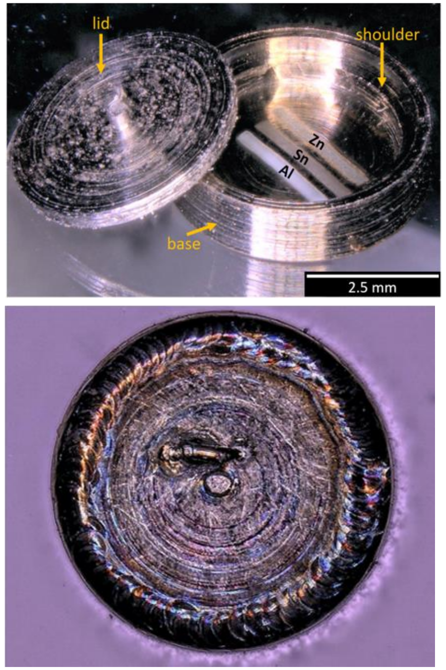
Project Overview

- **Sensor development** using **advanced manufacturing** methods enables the production of robust and miniaturized sensors for nuclear application
- **FY21 -** Develop and optimize the substrate/encapsulation design for advanced manufactured melt wires to optimize the welding process and to enhance X-ray computed tomography resolution of encapsulated printed melt wire lines

Old encapsulation design with XCT



New encapsulation design for AM melt wires



Using advanced manufacturing techniques, develop and optimize advanced manufactured melt wires to expand the range of melt wire capability

Project Overview

- **Research Schedule:**
  - FY21 technical report submitted
  - FY22 focus will be towards material optimization for welding and XCT
    - Initial planning and material identification has begun
    - Milestone report scheduled for December 2022
- **Participants**:

Kory Manning (INL)	**Kurt Davis** (INL)	**Malwina Wilding** (INL)	**James Milloway** (INL)
Kiyo Fujimoto (INL/BSU)	**Lance Hone** (INL)	**Richard Skifton** (INL)	**Robert Seifert** (INL)

Austin Fleming (INL)


INL/EXT-21-63886

Design optimization for Printed Melt Wire Arrays Encapsulation

July 2021

Lance Hone, Kiyo Fujimoto, Kory Manning, Malwina Wilding
Idaho National Laboratory

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

Technology Impact

Technology Application

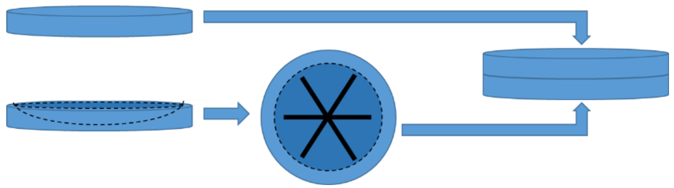
- Within irradiation experiments…
  - To support melt wire development for peak temperature monitoring within irradiation experiments.
  - To enhance passive peak temperature monitoring capabilities within irradiation experiments

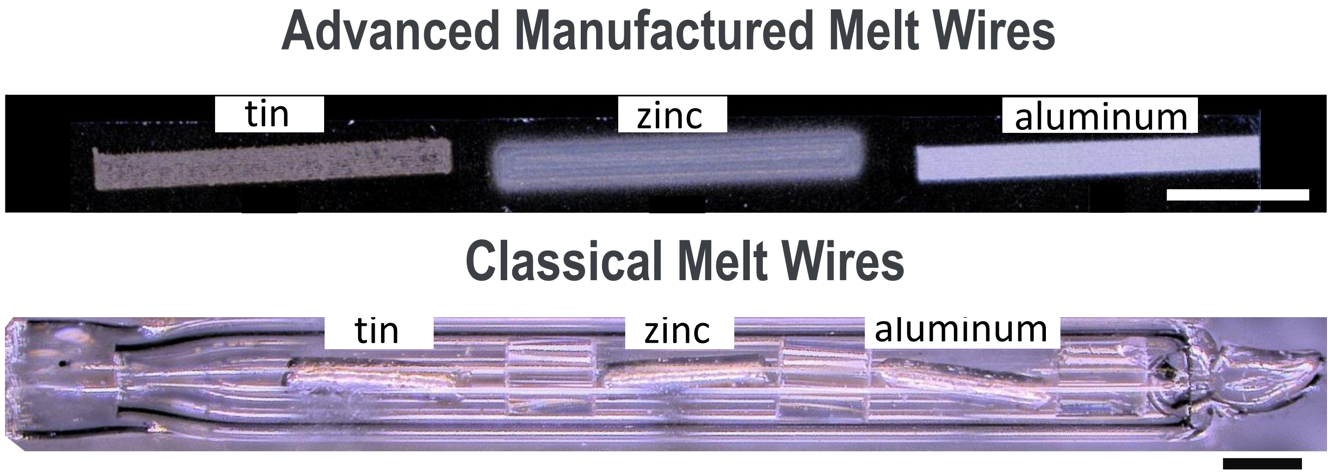
Support to NE Industry

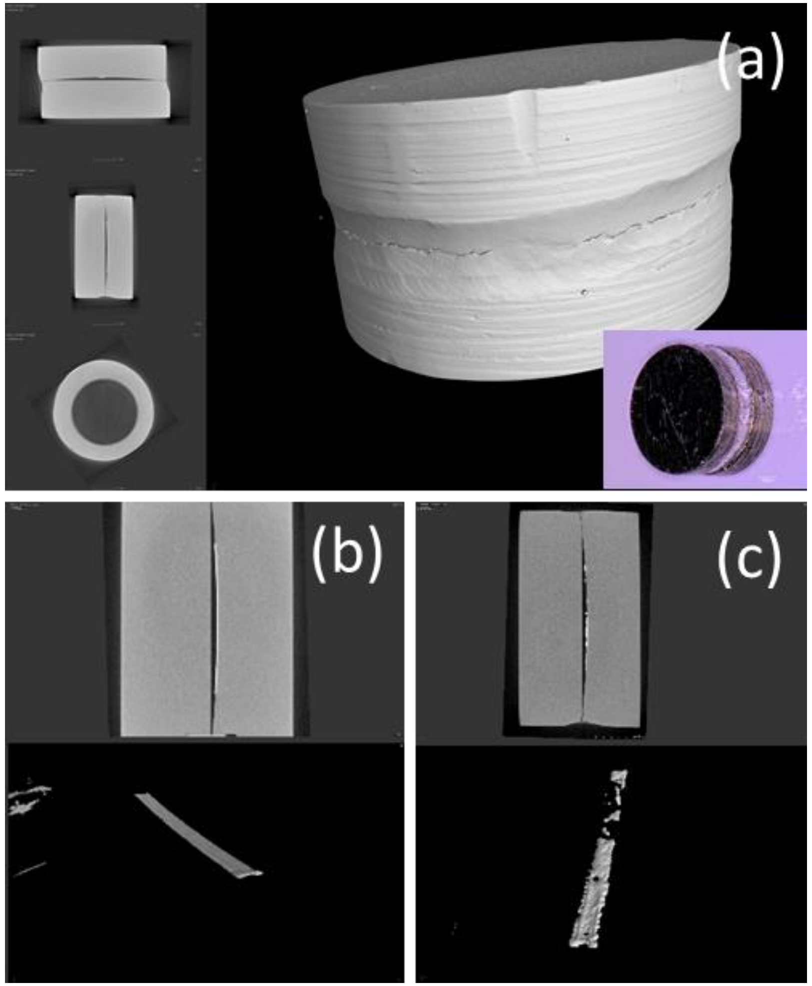
- Customer base - Anyone conducting irradiation experiments in MTRs where real time temperature monitoring is not required.
  - DOE, NSUF, National Laboratories, Universities, Commercial Nuclear entities, etc.
- Potential to expand outside of NE industry to include passive temperature monitoring of high energy systems.

Advanced manufacturing for passive monitor development - Background

- **Previously demonstrated X-Ray computed tomography as a tool to "read" sealed melt wire chips.**
  - Included in efforts towards miniaturizing melt wire package
- **Benchmarked printed melt wires against classical melt wires**
  - Differential scanning calorimetry and furnace testing performance of advanced manufactured and classical melt wires was consistent

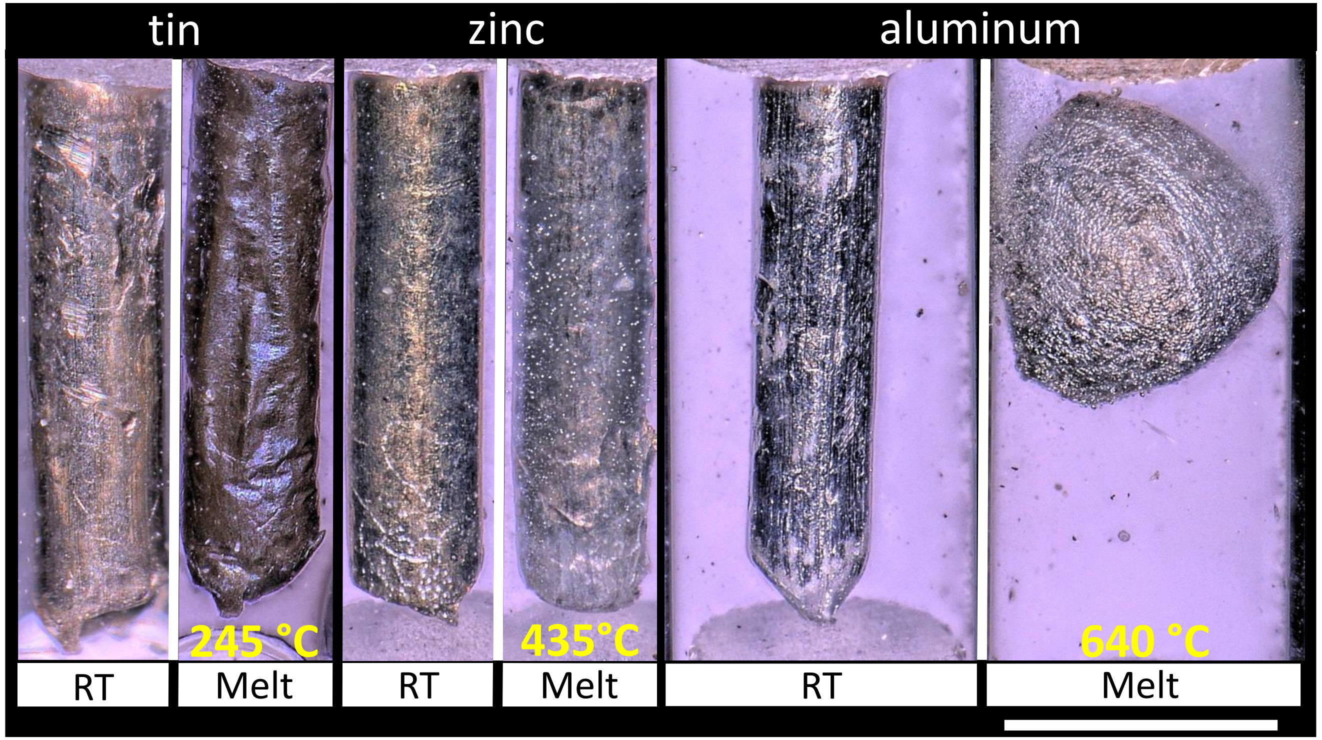


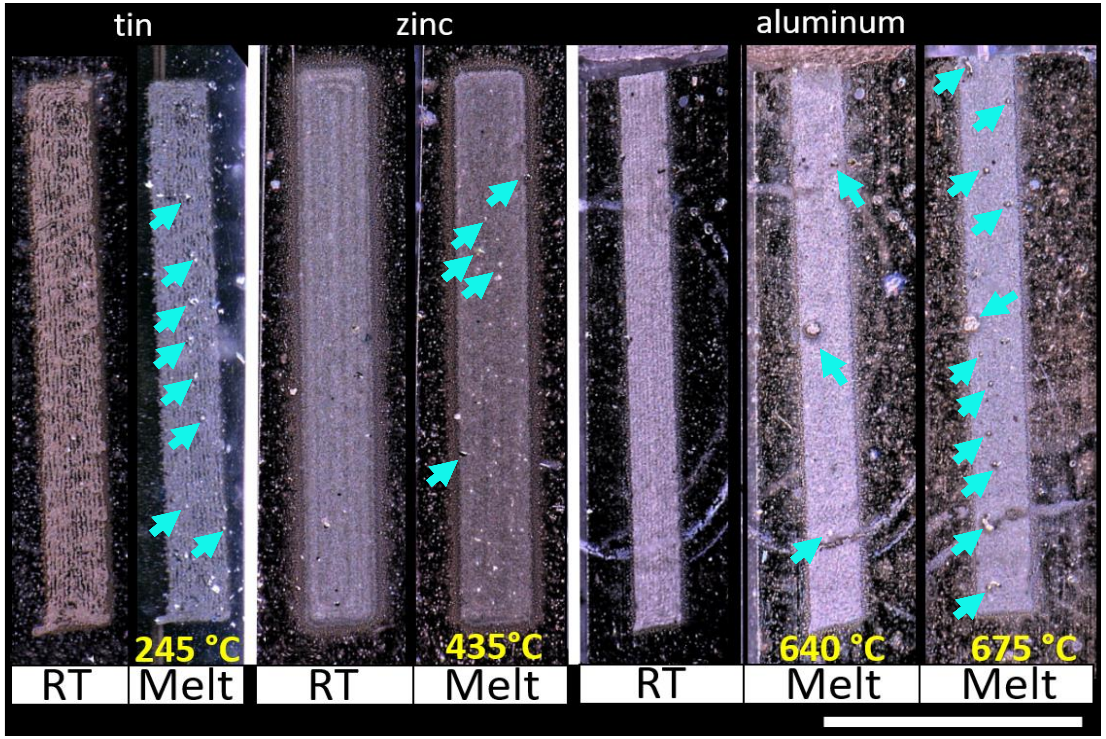




Advanced manufacturing for passive monitor development - Background

- **Classical vs. Advanced Manufactured Melt Wire**
  - Melt behavior of classical melt wires varied with each material
  - Melt behavior of advanced manufactured melt wires was consistent with the formation of beads or bubbles with each material



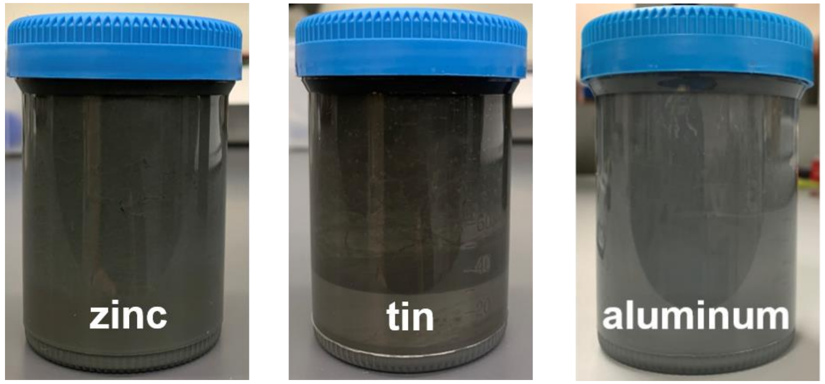


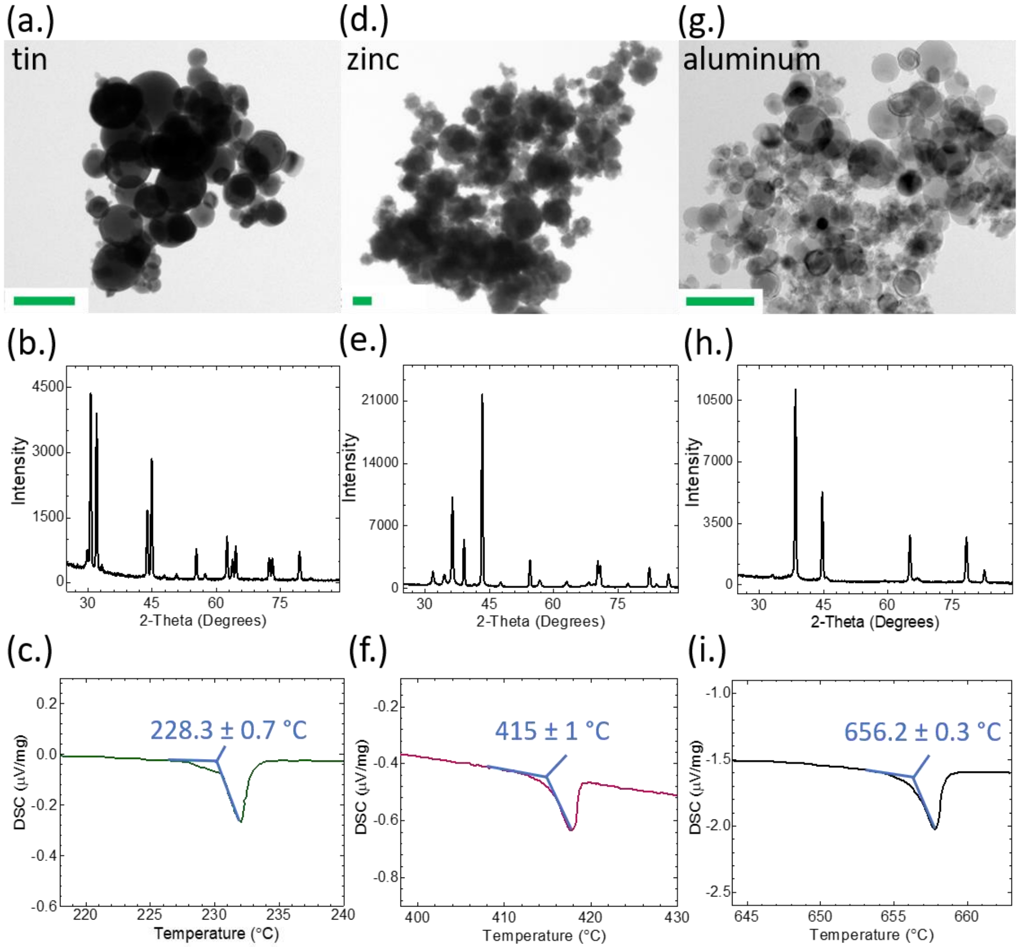
Results and accomplishments

Melt Wire Feedstock Development

- Using top-down method for ink synthesis Zn, Sn and Al inks were created for melt wire fabrication.
- Melt wires were printed using Aerosol Jet Printing (AJP)
- Composition and melting point of the powder feedstock confirmed via XRD, EDS and DSC

Feedstock used to create AM melt wires





Characterization of melt wire feedstock. Melt wire feedstock powders of (a.)-(c.) tin, (d.)-(f.) zinc and (g.)-(i.) aluminum were characterized for particle size with TEM [(a.),(d.),(g.)], composition with XRD [(b.),(e.),(h.)], and melting point with DSC [(c.),(f.),(i.)]. Scale bars are 200 nm.

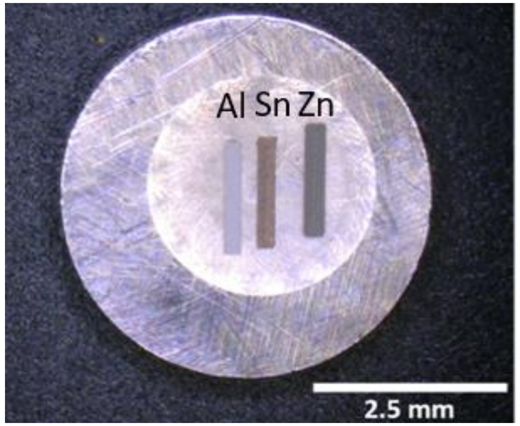
Results and accomplishments

Re-Design and Sealing Process

- Minimize thickness of encapsulation material
  - Side wall thickness reduced to 0.6 mm
  - Floor thickness reduced to 0.2 mm
- Need for inert atmosphere and to minimize premature melting of wires during sealing process
  - Addition of shoulder into the wall of the base
  - Addition of top lid
  - Small extrusion placed on center of lid to assist with handling

Old encapsulation design with XCT

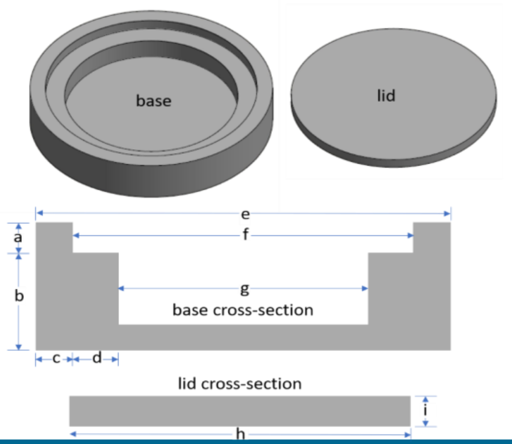
Melt wire base



Sealed melt wire capsule

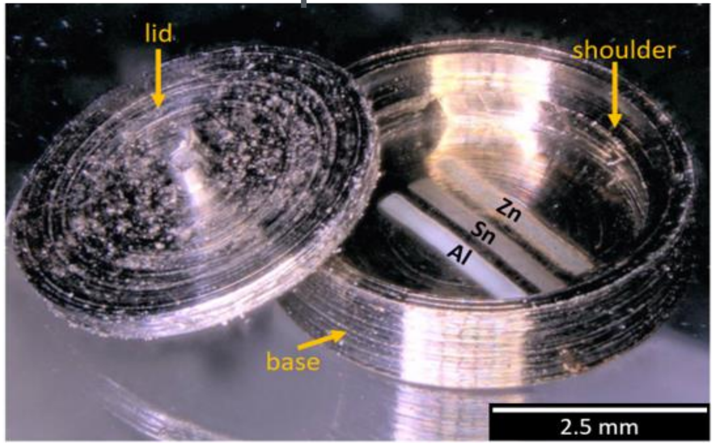
New encapsulation design

Schematic of new AM melt wire encapsulation and dimensions



Variable	Dimensions (mm)
a	0.25
b	0.76
c	0.32
d	0.39
e	5.00
f	4.37
g	3.57
h	4.34
i	0.25

Melt wire capsule lid and base

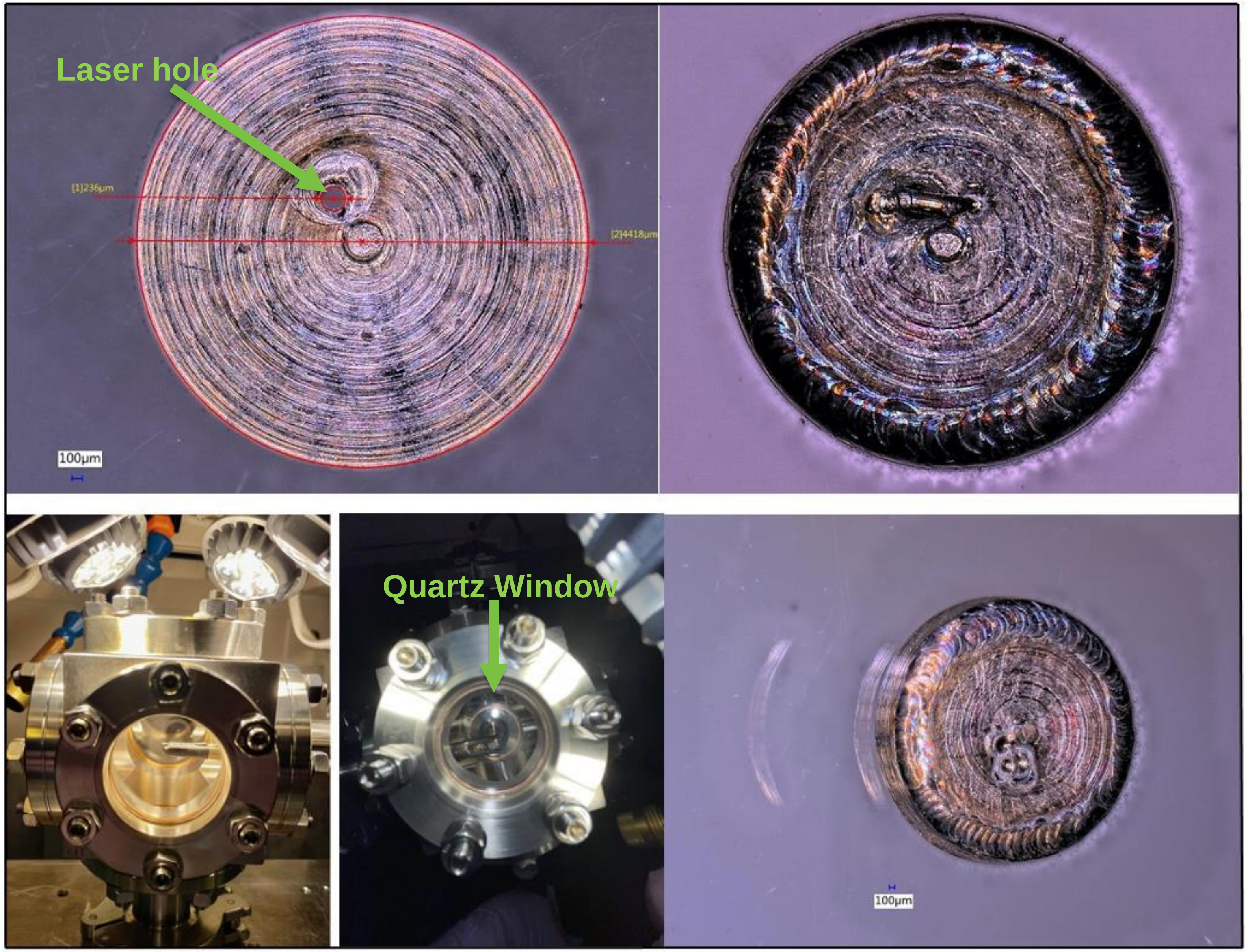


Sealed melt wire capsule

Results and Accomplishments

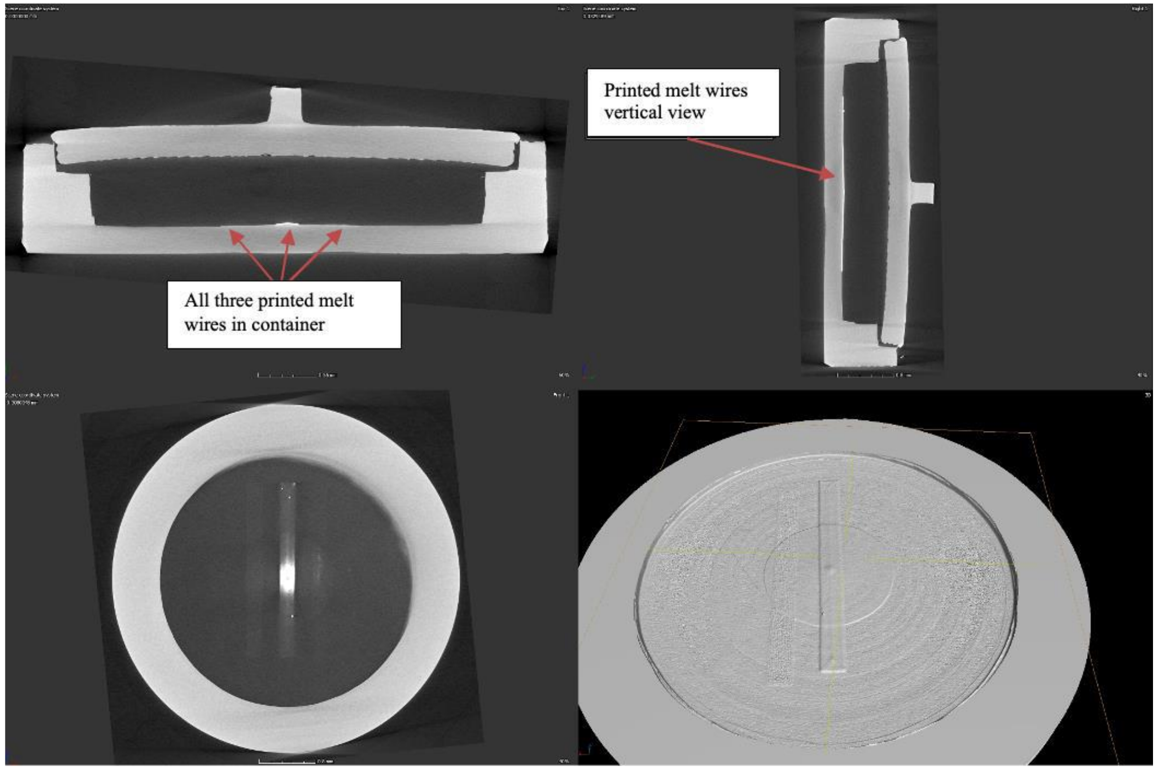
Creating an inert atmosphere within melt wire capsule

- 250 µm hole created with laser in lid
- Sealed capsule to contain an inert atmosphere

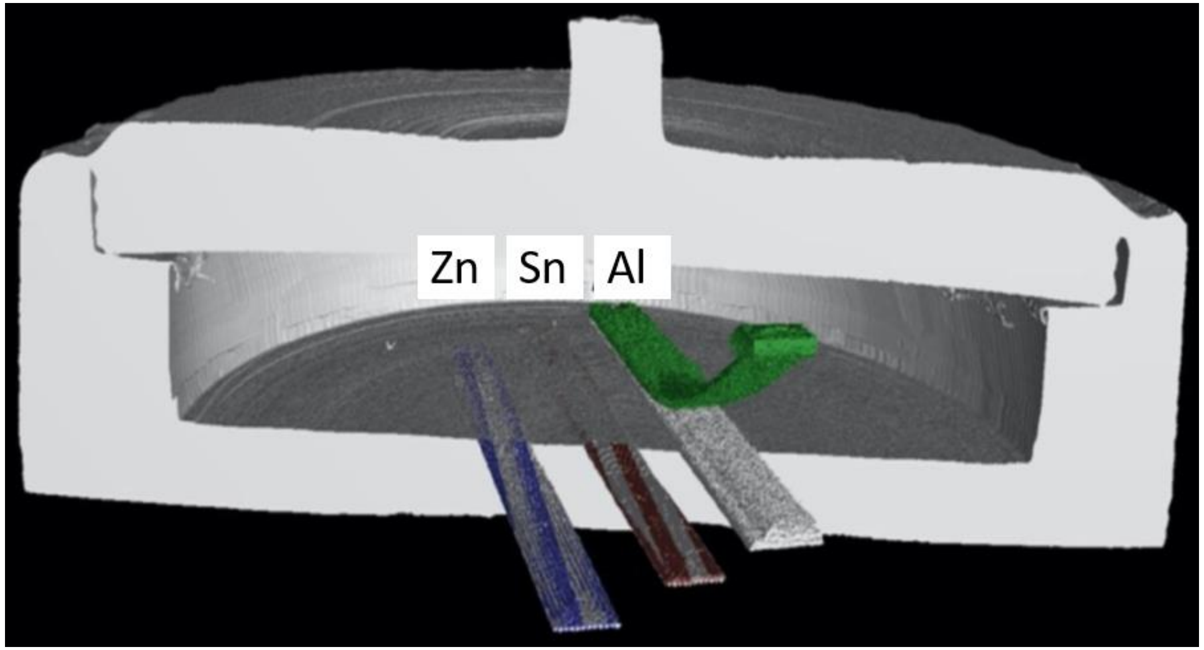


Results and Accomplishments

Pre-Test XCT of Melt Array



Cross section of a post furnace XCT image (air encapsulation)



- **Imaging melt wires through SS316 encapsulation**
  - Using SS316 eliminated the ability to use traditional evaluation methods for melt response of wires.
  - XCT enables imaging of melt wire array
  - XCT of wires before furnace testing to serve as a reference point

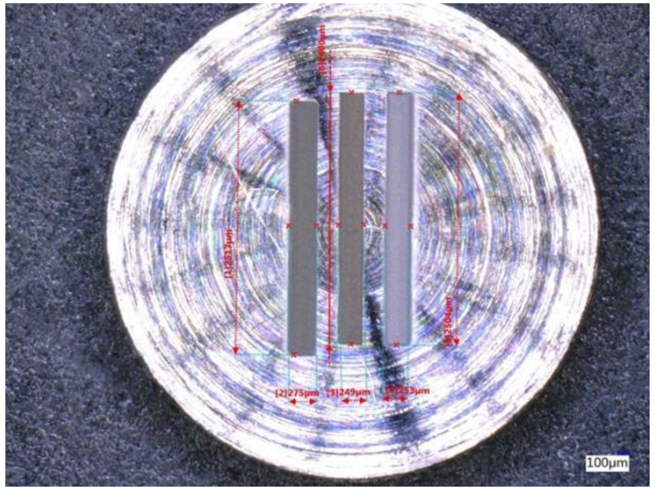
Results and Accomplishments

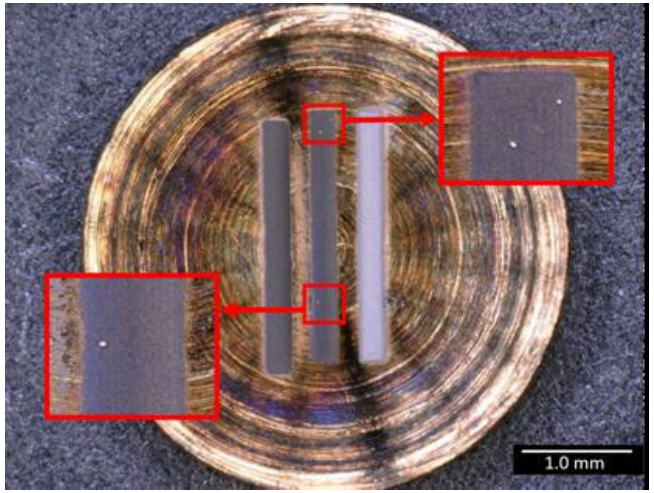
Inert Atmosphere Testing

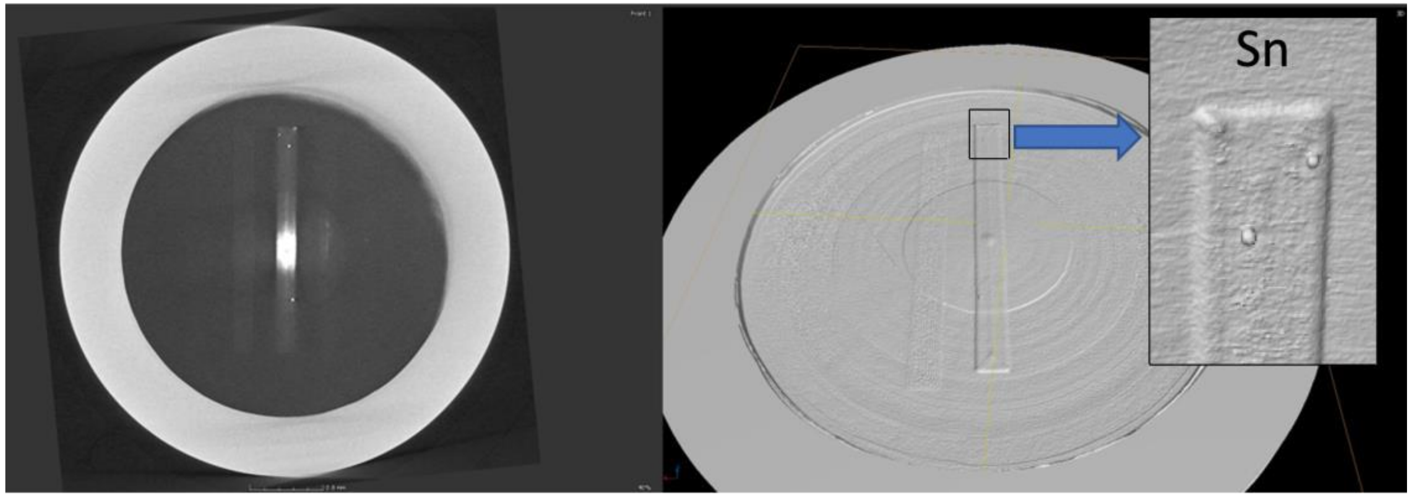
- Bead formation on tin print (post-test)
- Beads are recognizable with both optical microscope and XCT
- Comparison of air to inert gas environments demonstrates the significance of inert atmosphere encapsulation for reliable material performance.

Comparison of air to inert gas environments demonstrates the significance of inert atmosphere encapsulation for reliable material performance.

Images of Tin Melt





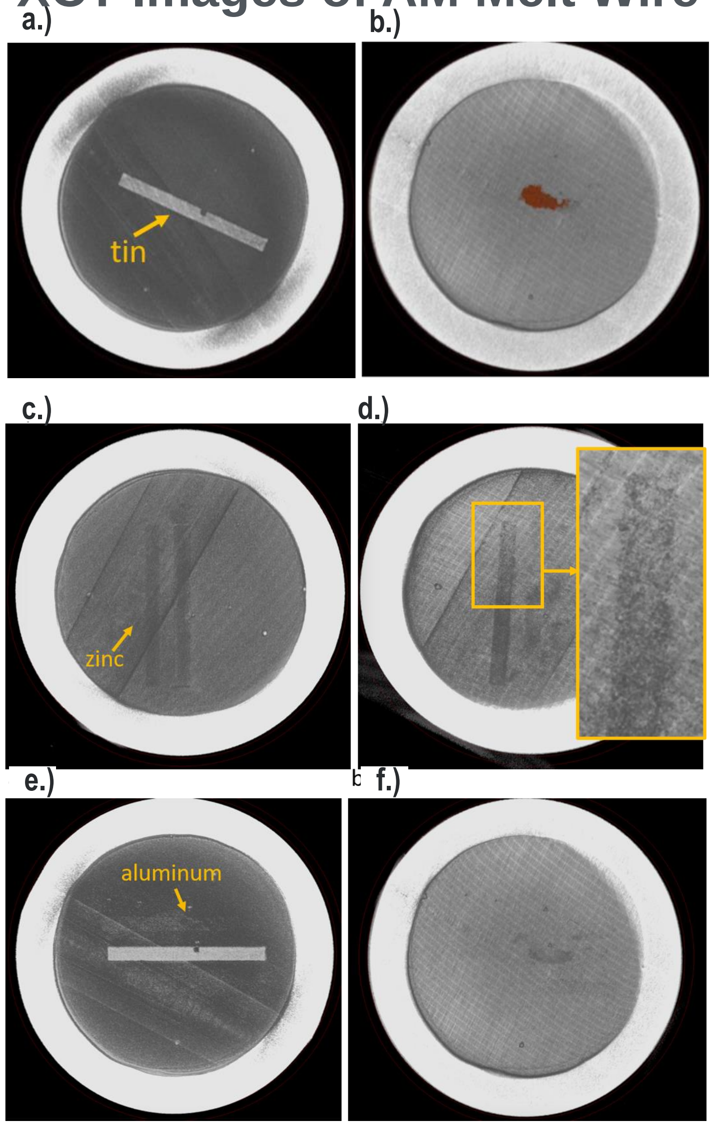


Results and accomplishments

Inert Atmosphere Encapsulation

- Assembly exposed to temperature exceeding melting point of all materials (680 ℃)
- Melt wires encapsulated in helium atmosphere
- Melt wire behavior:
  - Tin: pooled in center
  - Zinc: material separation
  - Aluminum: unidentifiable

XCT Images of AM Melt Wire

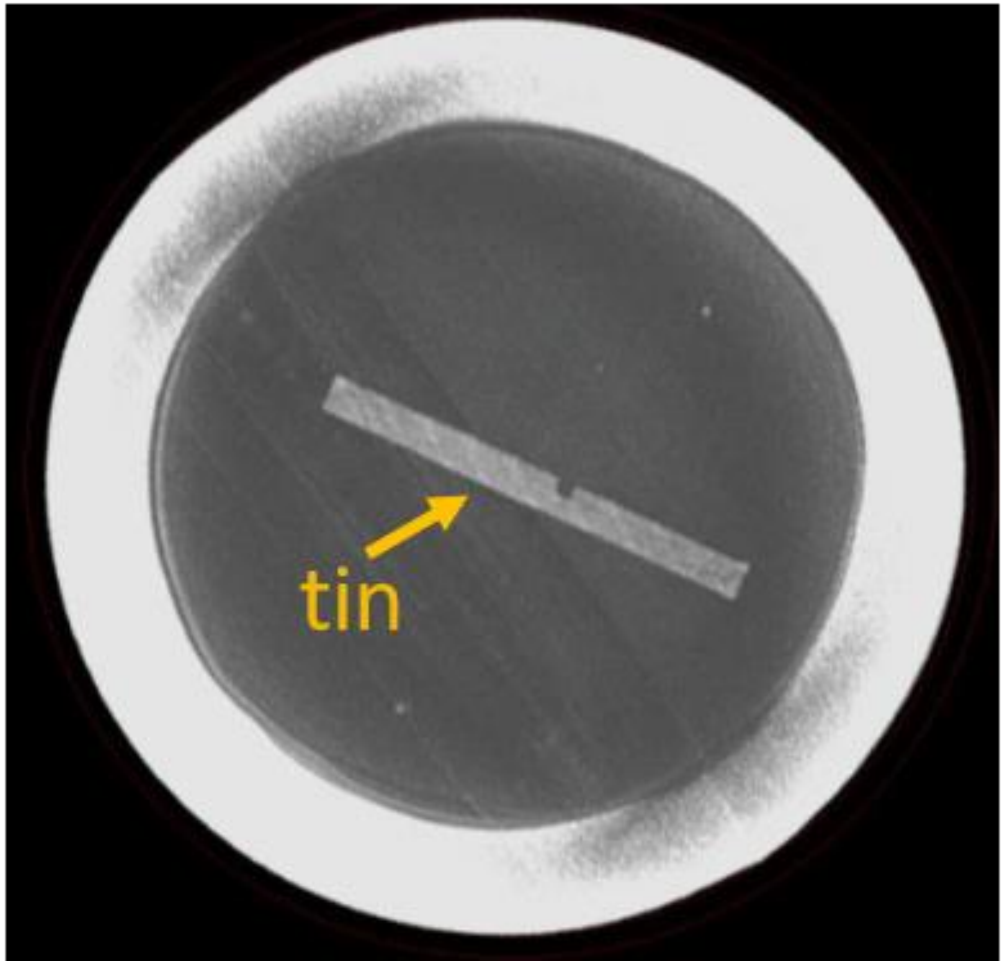


(a.) Original XCT image of tin encapsulated in helium, (b.) post-furnace image of melted tin enhanced with color, (c.) Original XCT image of zinc encapsulated in helium, (d.) Post-furnace image of zinc with enhanced image highlighting material separation, (e.) Original XCT image of aluminum encapsulated in helium, (f.) Post-furnace image of melt wire capsule with the aluminum wire not discernable against the SS316 substrate.

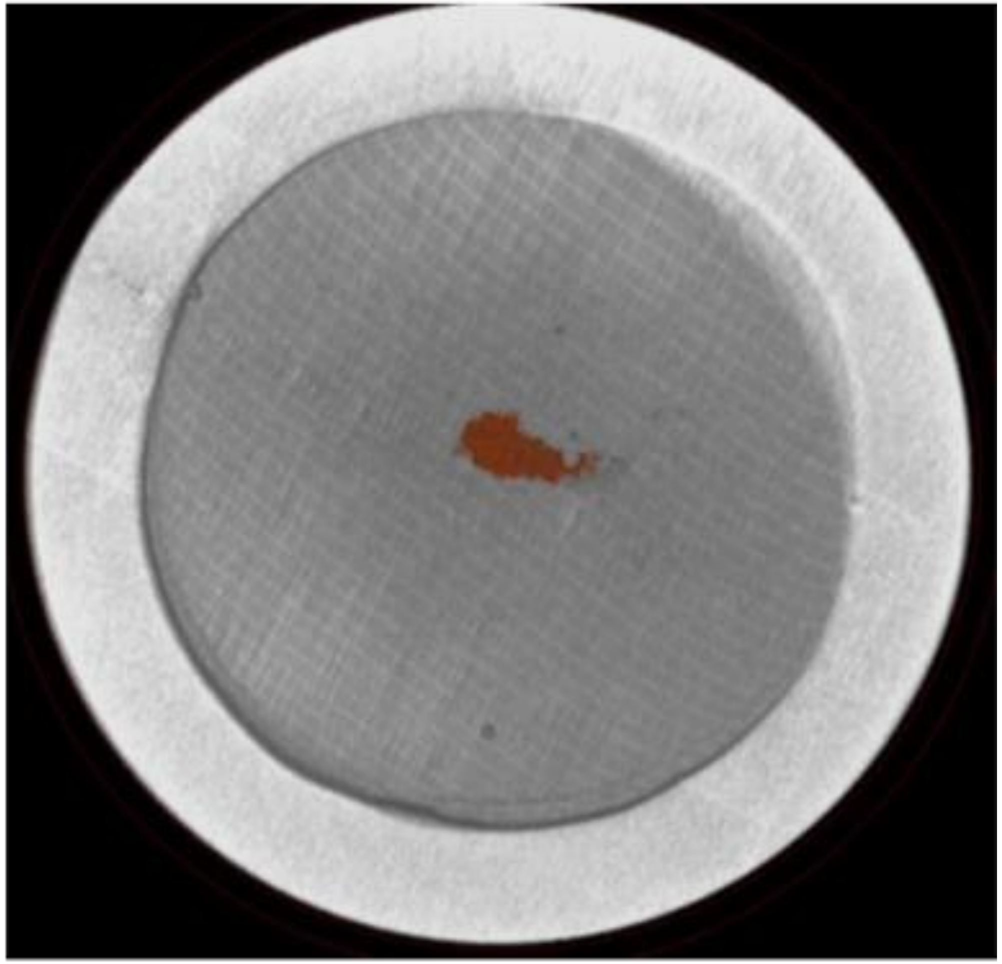
Results and accomplishments

XCT Images of Tin

Pre-Test



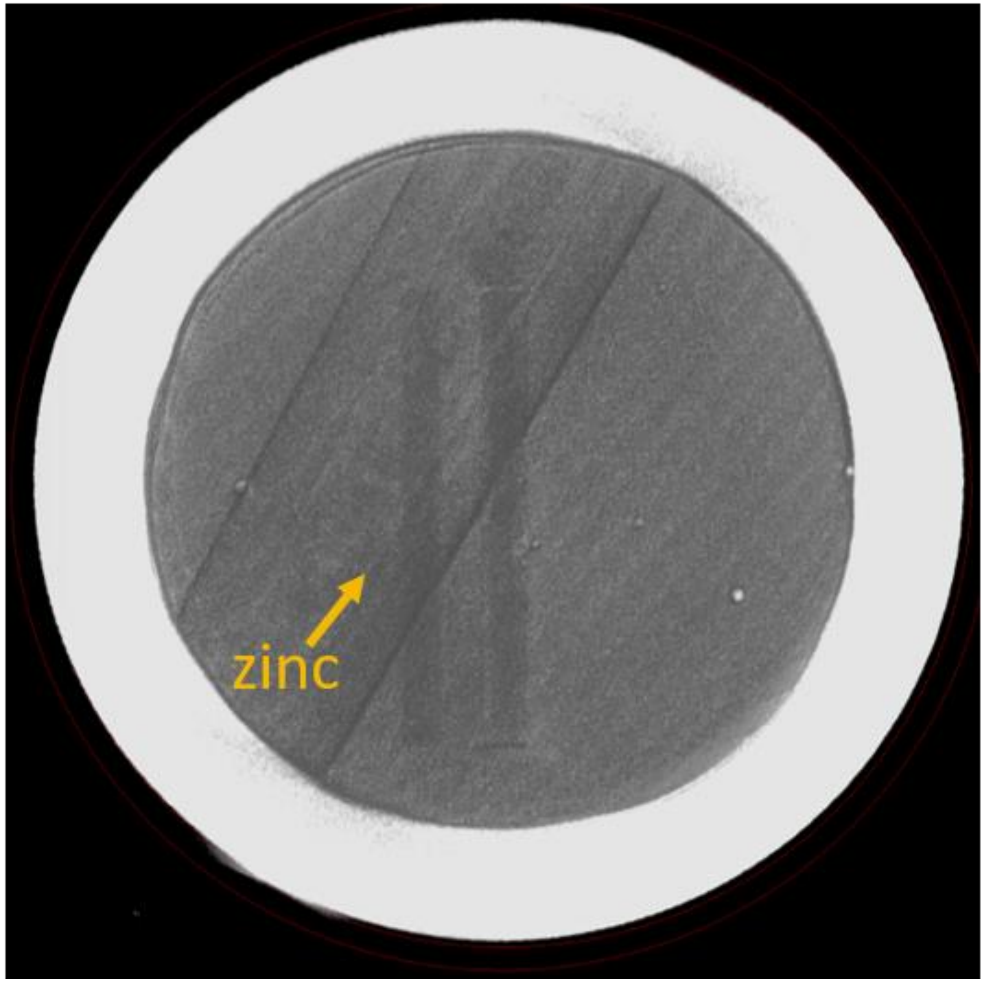
Post-Test



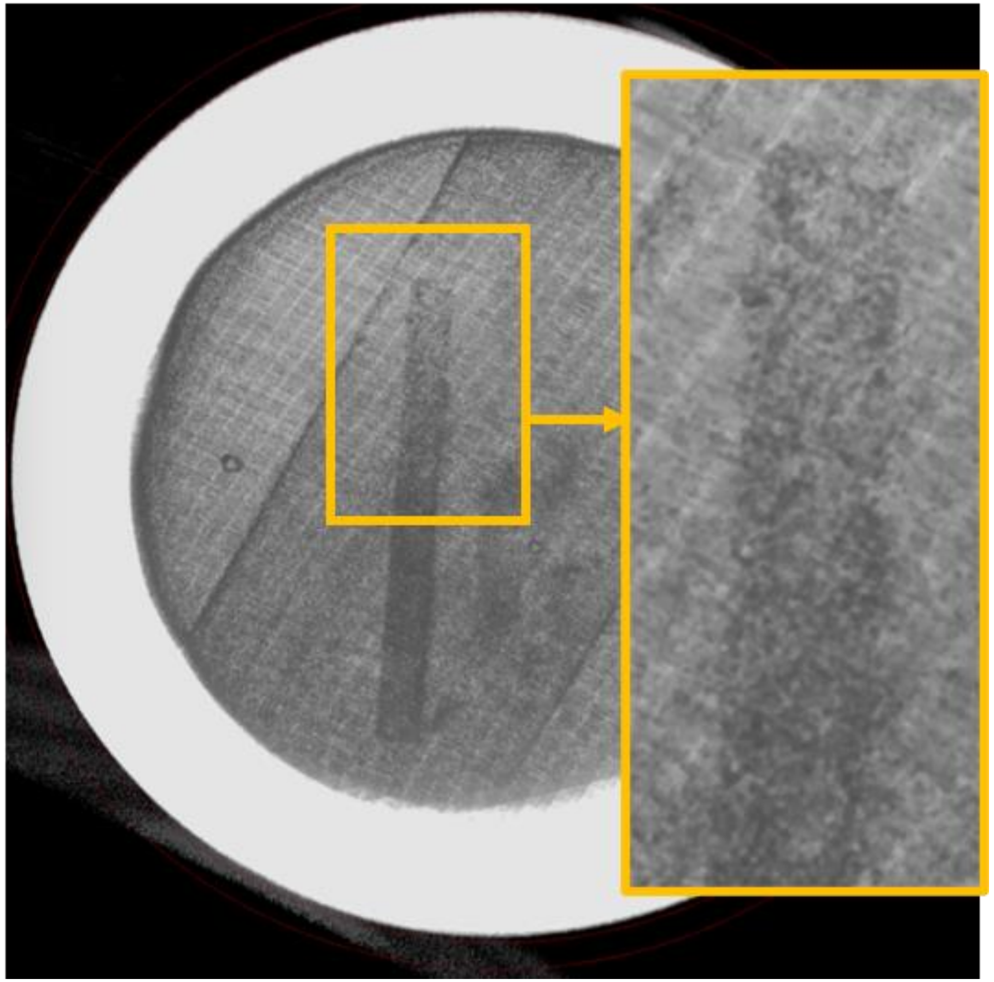
Results and accomplishments

XCT Images of Zinc

Pre-Test



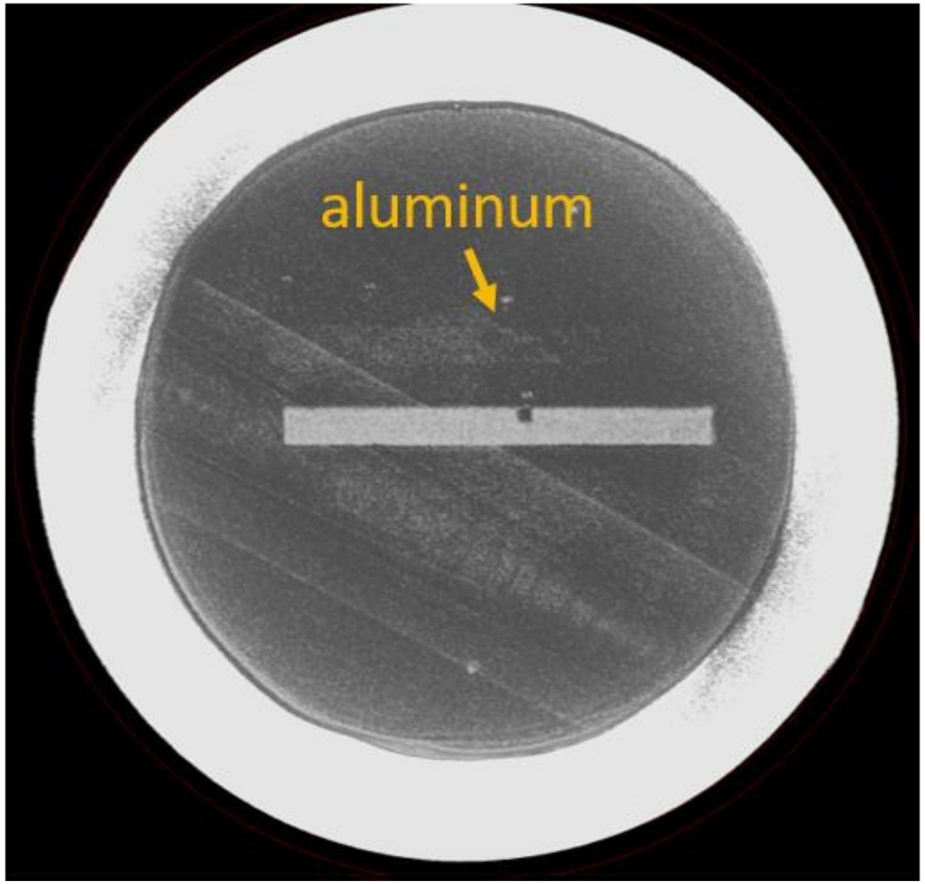
Post-Test



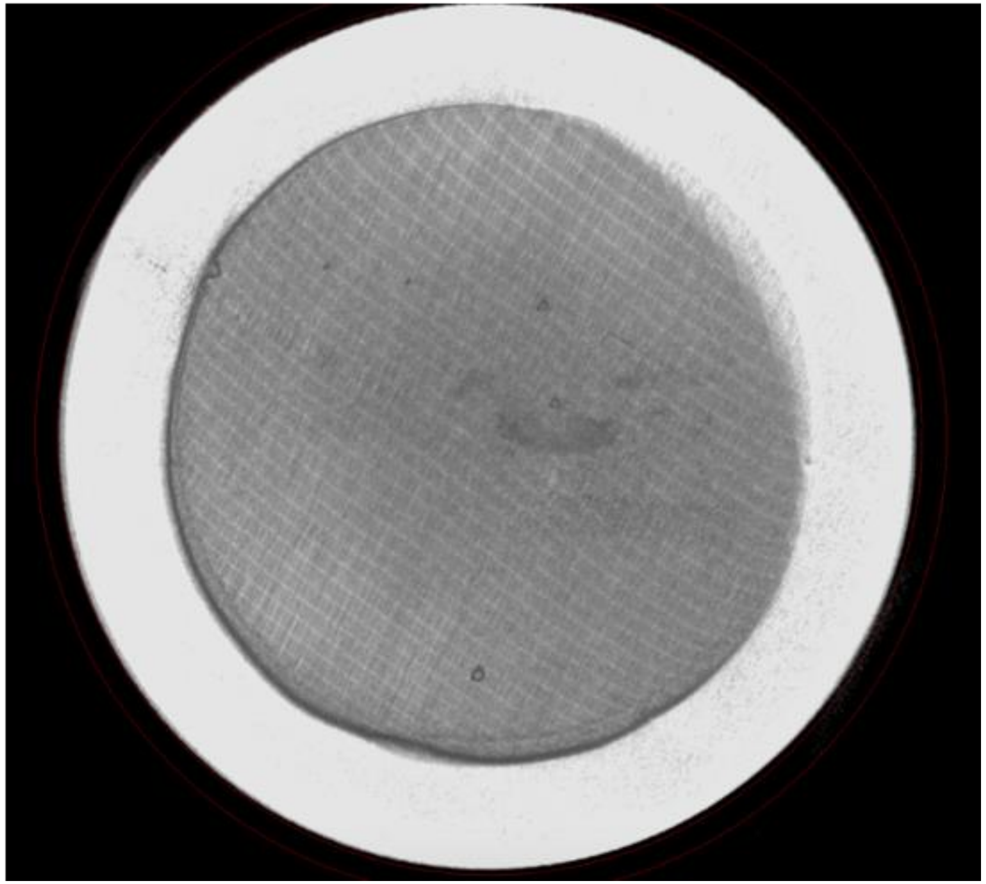
Results and accomplishments

XCT Images of Aluminum

Pre-Test



Post-Test



Conclusion

- **Challenges**
  - Low contrast between melt wire material and encapsulation material (XCT)
  - Optimizing laser welding process (temperature control to avoid premature melting)

- **Summary**
  - To improve performance reliability of AM melt wires, a process was developed and tested to identify the significance of encapsulating melt wires with an inert atmosphere when packaging of melt wire arrays.
  - Initial melt wires that were sealed with air encapsulation did not show distinguishable signs of melting after exceeding expected melting temperatures more than 50 ℃
  - Design changes and a new sealing process facilitated inert gas encapsulation for melt wires
  - Evaluation of encapsulated melt wires was accomplished pre and post melt with XCT
  - Results from inert encapsulation testing provide promise for a path forward for AM melt wires

Conclusion

Patents, Publications, etc.

- Manuscript Accepted (November 17, 2021)
  - MDPI – Sensors: *Additive Manufacturing of Miniaturized Peak Temperature Monitors for In-Pile Applications*

Future Work

- Broaden the material selection and geometries for encapsulation.
- Broaden the material selection and geometries for AM melt wires
  - Feedstock development for AM melt wires to target specific melting ranges
  - Design specific print patterns advantageous to specific material melting characteristics

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LinkedIn

Questions?

ASI | Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

Advanced Laser Ultrasonic Sensor for Fuel Rod Characterization

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Principal Investigator: Marvin Klein, Ph.D.

Intelligent Optical Systems

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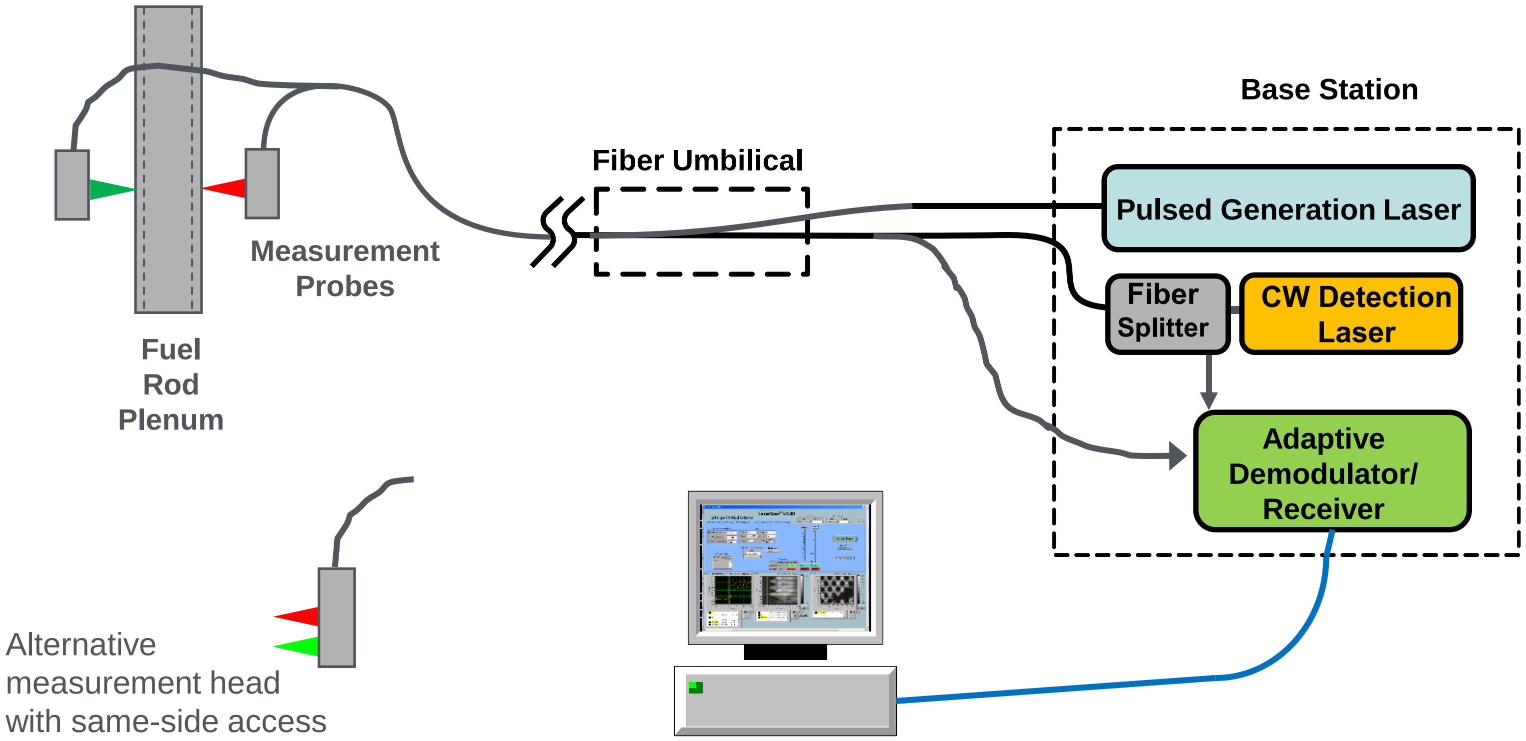
www.intopsys.com/laserultrasonics

Motivation

- There is an unfilled need to measure fuel rod pressure without removing the rods
  - Large savings in time and cost
- Current methods for internal pressure measurement of nuclear fuel rods in a cooling pool require partial or complete removal of rods from their array
- Conventional transducer-based ultrasonic testing can make measurements without rod removal, but only senses the presence of internal water when a leak is present
- Our method allows a direct measurement of pressure without removing the rods
  - Underpressure from gas leakage
  - Overpressure from excessive generation of fission gases
- Our method additionally provides measurement of rod wall thickness
  - Accuracy <0.2% demonstrated
  - May be useful for assessing corrosion or oxide buildup

Measurement Method

- Apply laser ultrasonic testing (LUT) to generate and detect circumferential ultrasonic waves without contacting the surface
- Standing waves are created, forming a series of resonances
- Correlate internal pressure to resonant frequency shifts with internal pressure, relative to a reference standard
- Benefits of LUT
  - Small laser spots on rod surface enable good spatial resolution
  - High bandwidth enables accurate frequency measurements
  - Optical fiber delivery enables easy access into small space between rods
  - Electronics-free measurement head has high thermal and radioactivity resistance



ProjectBackground and Participants

Project Background

- Phase II SBIR, funded by DOE
- Now in second quarter of two-year project

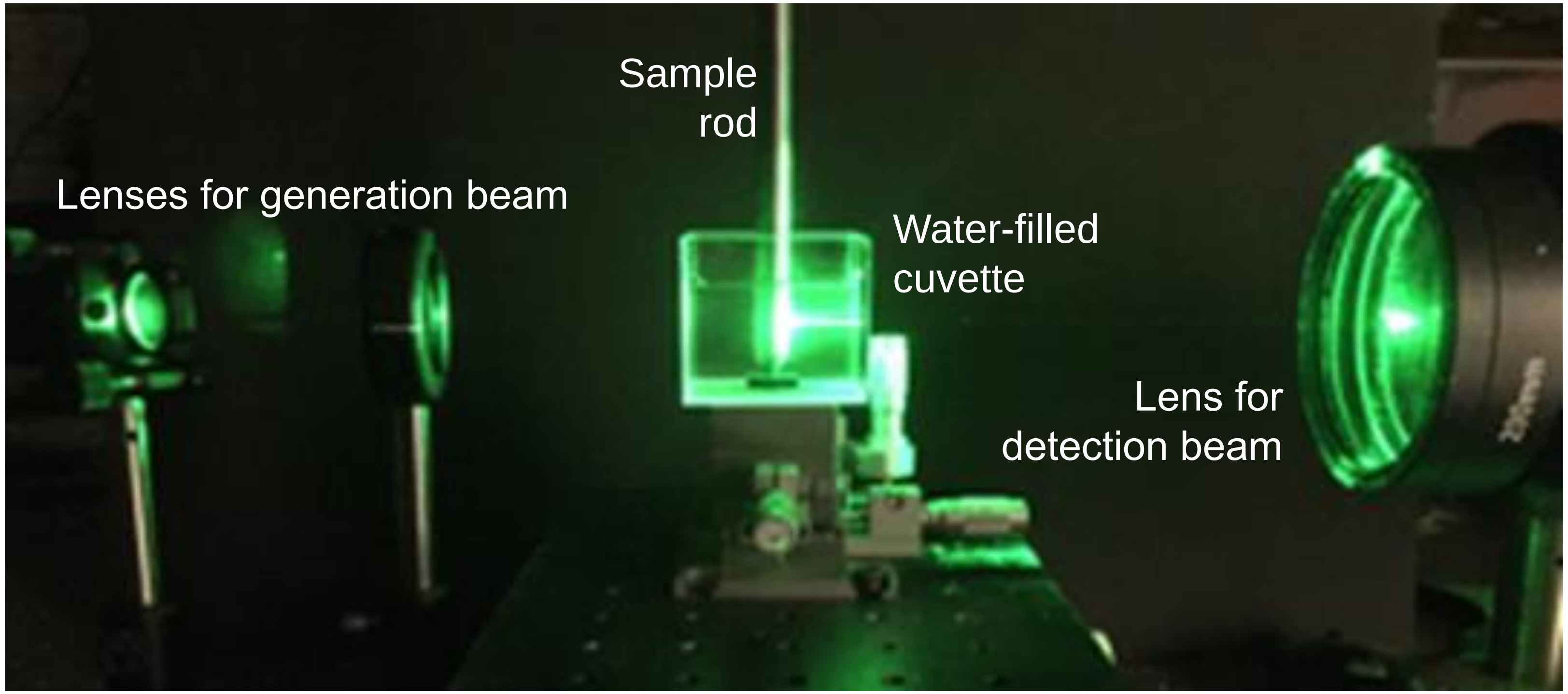
Participants

- Intelligent Optical Systems: PI Marvin Klein
- Consultant: Dr. Peter Nagy, Univ. of Cincinnati
- Advisors
  - Exelon
  - GE/GNF
  - EPRI

Technology Impact

- Pressure measurement in cooling pool enables improved safety for rods removed for servicing, and also allows comparison with simulation results
- Interest spans service companies and fuel vendors
- Stakeholders are the service companies and nuclear utilities

Setup For Proof-of-Concept Tests



Free-space laser beams

Infrared (1064 nm) generation beam

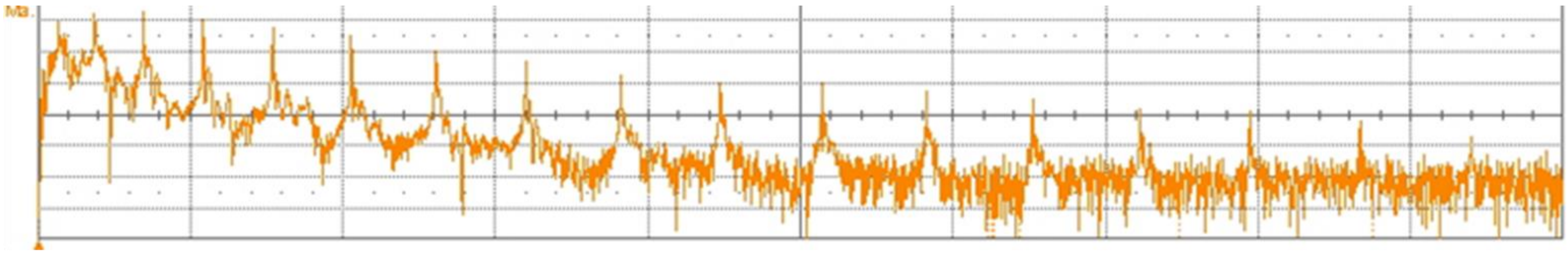
Visible (532 nm) detection beam

Laser Ultrasonic Methodology

- Excite standing wave deformations in wall

Exaggerated deformations in tube wall for 10th order resonance:

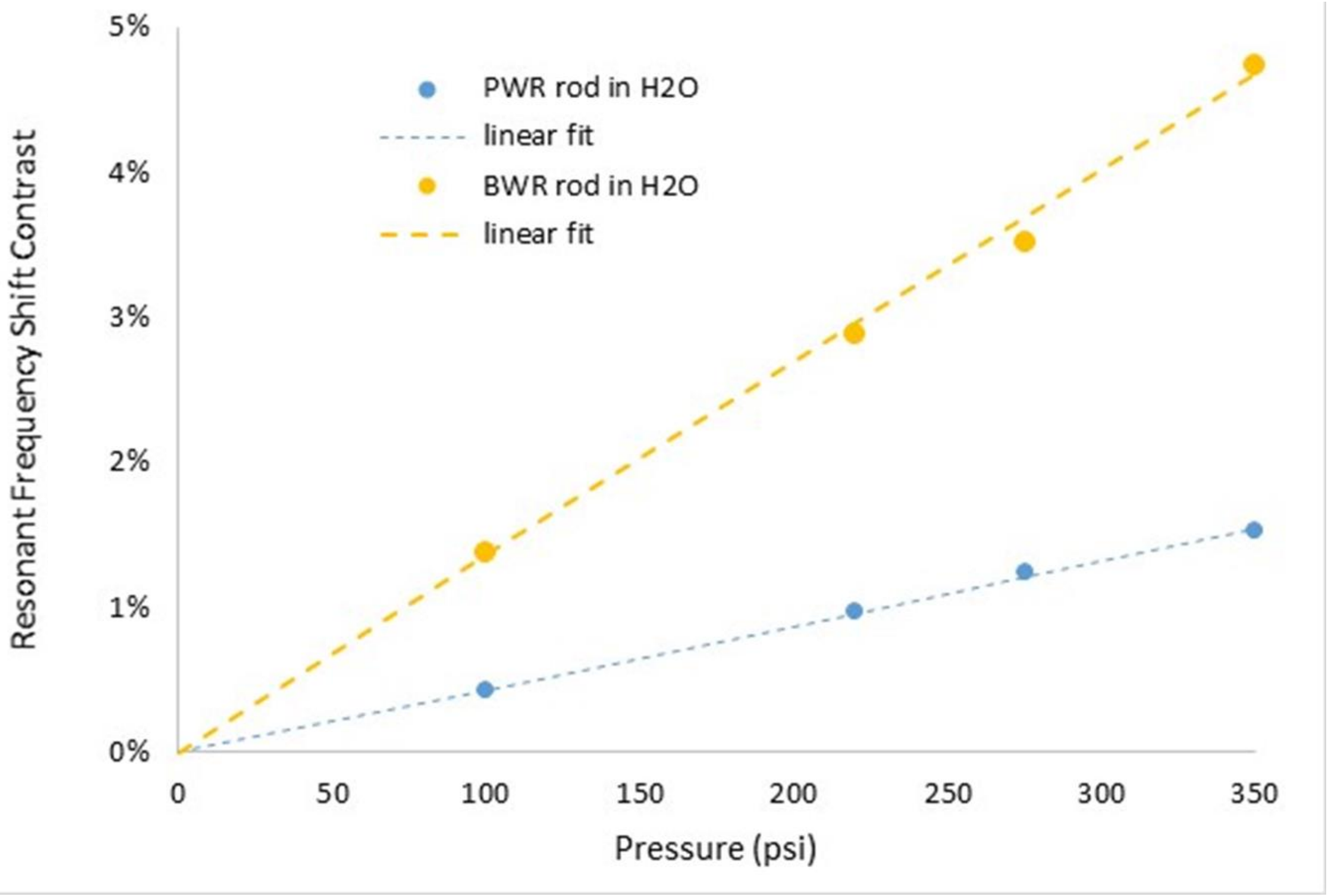
- Typical frequency spectrum for orders 2-17:



Rod Internal Pressure Measurement Results

Series of surrogate rods (BWR and PWR types) with known internal pressure, loaned by EPRI

Processing the frequency shifts leads to linear dependence on internal pressure



Conclusion

- Proof-of-concept experiment yields linear plot of calibrated metric vs. internal pressure
  - Additionally provides measurement of wall thickness with demonstrated accuracy <0.2%
- Extensive simulations have elucidated analysis of experimental data, while data provide validation of models
- Future work
  - Develop surrogate rod with controllable internal pressure and variable fill gases
  - Extend simulations and measurements to include fission gases (Kr and Xe)
  - Design and test ultra-miniature, underwater probe for access between rods in array
  - Pursue commercialization
- I welcome comments and questions!

Marvin Klein

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Questions?

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ASI Advanced Sensors and Instrumentation

Irradiation Testing of Neutron Flux Sensors

CT-22IN070208

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

Reactor Experiment Designer: Joe palmer

Idaho National Laboratory

Project Overview

- Objective

  Test and demonstrate in-pile instrumentation in conditions similar to those expected to be seen in service (i.e., the conditions they would see in either in irradiation experiments supporting advanced reactors, or ultimately, in advanced reactors themselves)

- Participants
  - Joe Palmer – Project lead and test rig designer
  - Kevin Tsai – PI for Self Powered Neutron Detectors (SPNDs) and concurrent testing in TREAT
  - Dr. Michael Reichenberger – PI for miniature fission chambers
  - Calvin Downey – ATRC test rig designer
  - Kory Manning – Lead technician for retractable sensor development
  - Dr. David Carpenter (MIT) – Project lead at MIT for irradiation of neutron sensors in MITR (NSUF collaboration)
  - Dr. Ge Yang (NCSU) – Project lead at NCSU for retractable sensor development team

Project Overview

Timelines of project activities FY-21 and FY-22

FY21

Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep

- Initial irradiation of SPNDs in NRAD to work out bugs prior to ATRC irradiation (Nov)
- Irradiation of optical fibers in ATR as part of HDG-1 experiment (Nov)
- ATRC irradiation of SPNDs and fission chambers – verified %flux increase due to booster fuel (Feb)
- Irradiation of Rh and Hf SPNDs in Idaho State's AGN-201 Rx (collaborative effort) (Mar)
- High temperature (800ºC) sensor irradiation in TREAT (Aug)

Irradiated sensors in TREAT via "concurrent testing". This was done for every operating cycle in TREAT during FY-21

During FY-21 this project irradiated sensors in all four INL reactors plus the ISU Rx

FY22

Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep

- Perform first high-temperature NRAD irradiation (Oct)
- Irradiate neutron sensors in high-temperature test rig at MITR (NSUF collaboration) (Feb)
- Perform second high-temperature NRAD irradiation (Jul)

Develop retractable sensor mechanism and test on bench top

FY-21, FY-22 Milestones

Milestone	Due Date	Status
Test neutron flux sensors in ATRC	3/31/2021	Completed on time
Perform high-temperature neutron irradiation test on neutron flux sensors	9/30/2021	Completed on time
Complete high-temperature test of neutron flux sensors in NRAD	9/30/2022	On schedule
Develop retractable system for in-core instrumentation	10/31/2022	On schedule

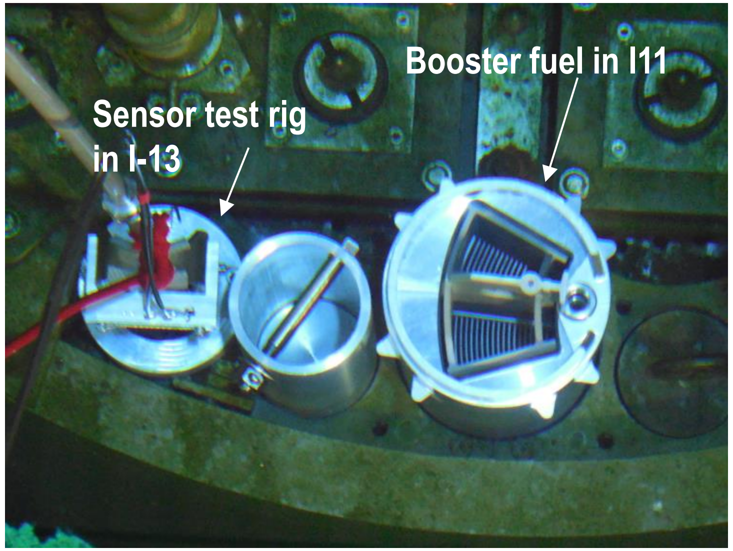
Technology Impact

- Advanced instrumentation enables 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 experience gained from in-core performance testing
- Successful completion of these activities will create new capabilities at the INL ATR and TREAT facilities that are crucial to acquiring data during irradiation testing
- Customers usually have only one shot to conduct their irradiation experiments
- Therefore, it is vital to demonstrate newly-developed sensors in operational conditions, prior to incorporating them into long-term high-value experiments

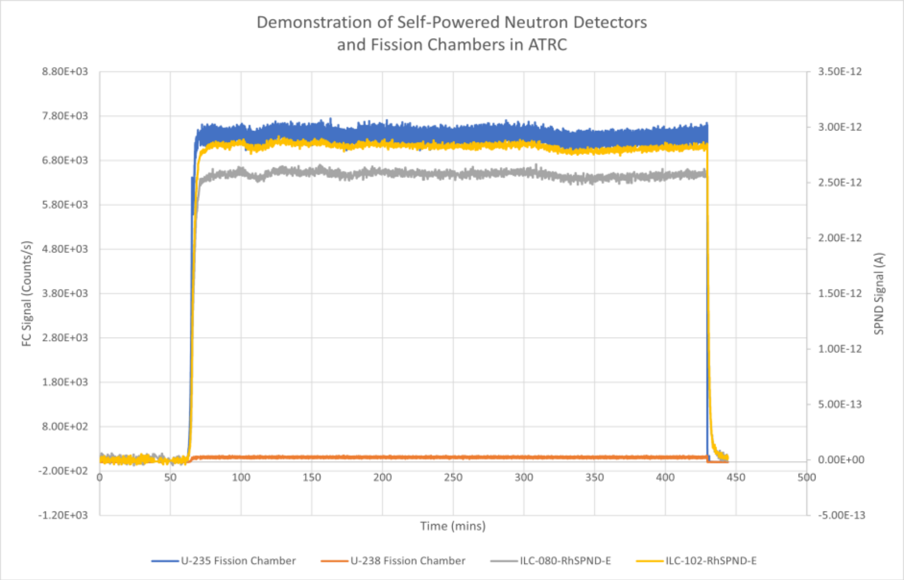
Technology Impact

- Much of the neutron sensor testing work in FY21 and FY22 is focused on testing at high temperatures
- Self Powered Neutron Detectors (SPNDs) and miniature fission chambers have been deployed in commercial reactors operating at up to 300^{o}C, and in general, their performance is well understood up to about 350^{o}C
- Advanced reactor concepts envision operating temperatures of 500^{o}C – 1000^{o}C
- Early indications are that these traditional neutron sensors may experience temperature effects at temperatures >500^{o}C
- A major effort in FY22 will be to better understand and mitigate these temperature effects (if they do indeed exist)

ATRC Test using Fission Chambers and SPNDs



Neutron experiment test rig and booster fuel installed in ATRC reactor



SPND and fission chamber data traces from 6-hour run in ATRC conducted Feb 11, 2021.

The Medium I-loop Project would like to increase thermal flux in the I-13 position of ATR by placing booster fuel in I-11. This ATRC sensor test confirmed their calculated increase.

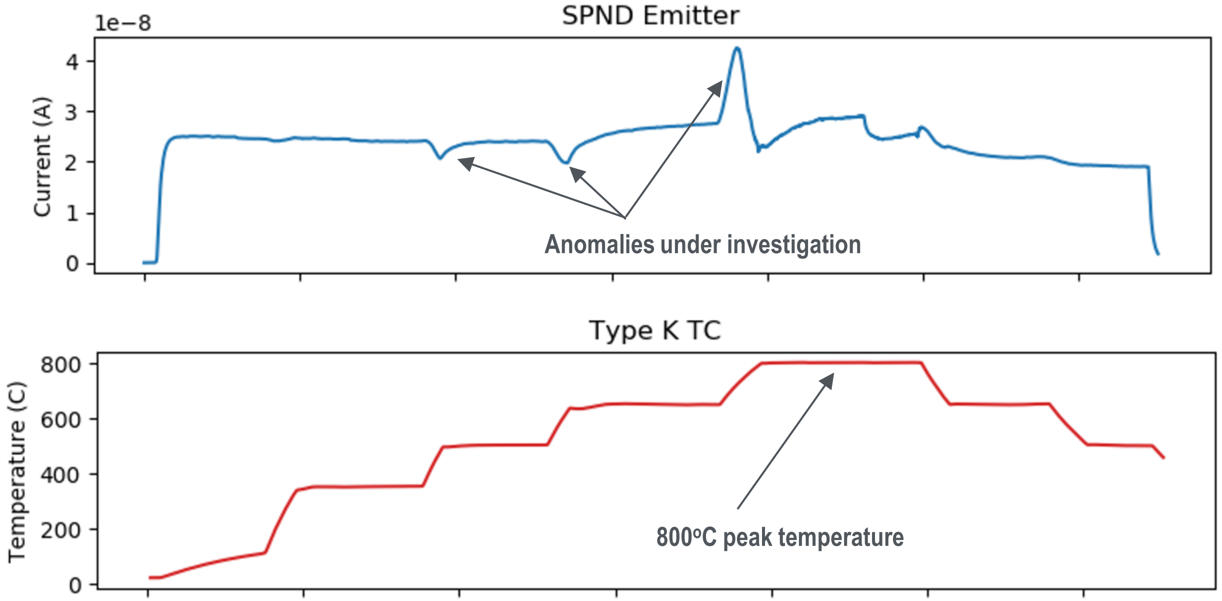
Measured increase in thermal flux due to booster fuel (this ATRC test)	Calculated increase in thermal flux (via MCNP) due to booster fuel
23%	21%

Accomplishments

High-Temperature Neutron Sensor Testing in NRAD

Installing neutron sensors (SPNDs) in NRAD

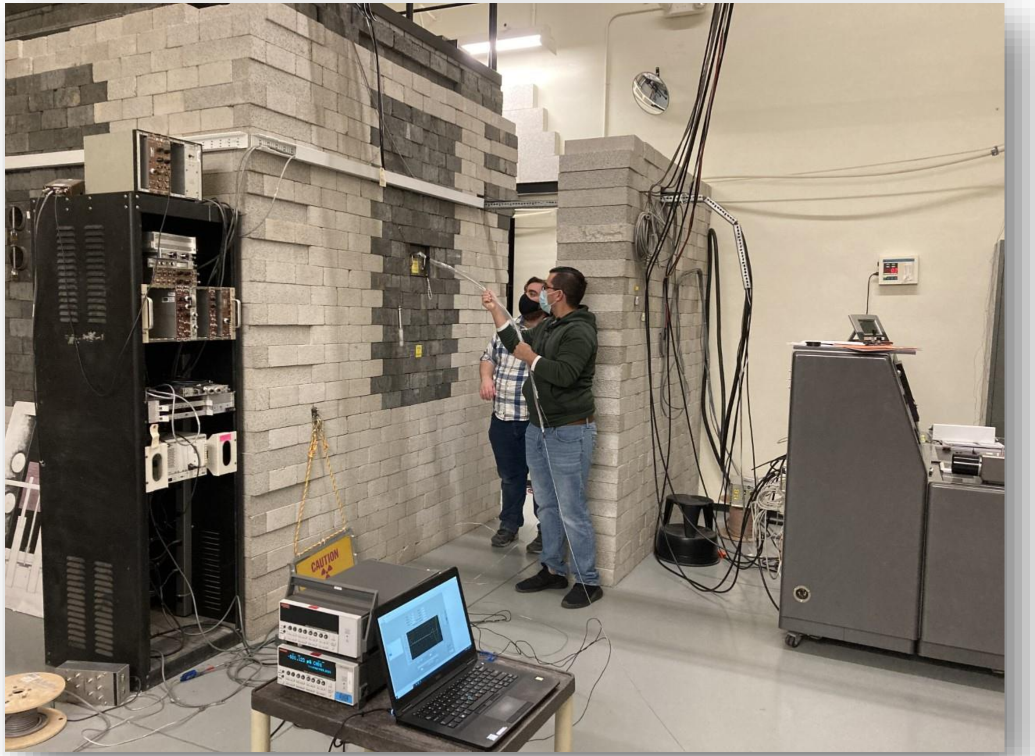
Gathering data in cask tunnel adjacent to NRAD



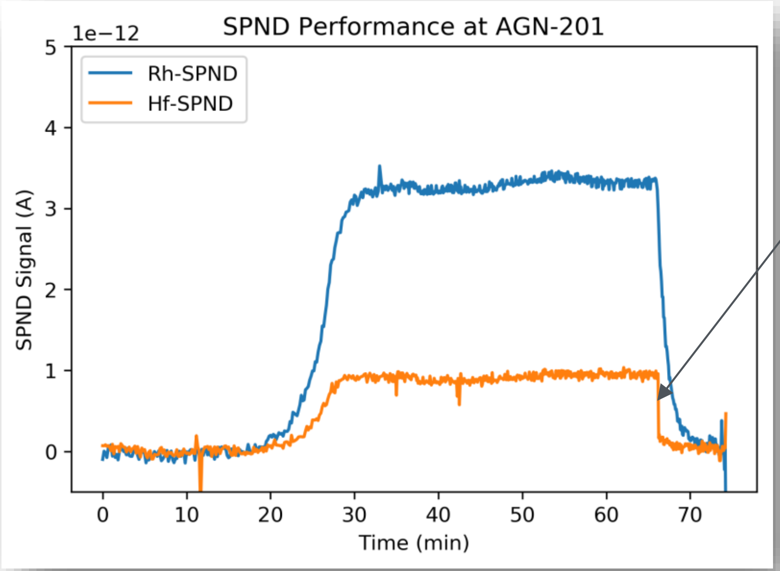
SPND signal compared to temperature profile

Accomplishments

SPND Sensors Irradiated in Idaho State University AGN-201 Reactor



Installing SPNDs in AGN-201 Rx

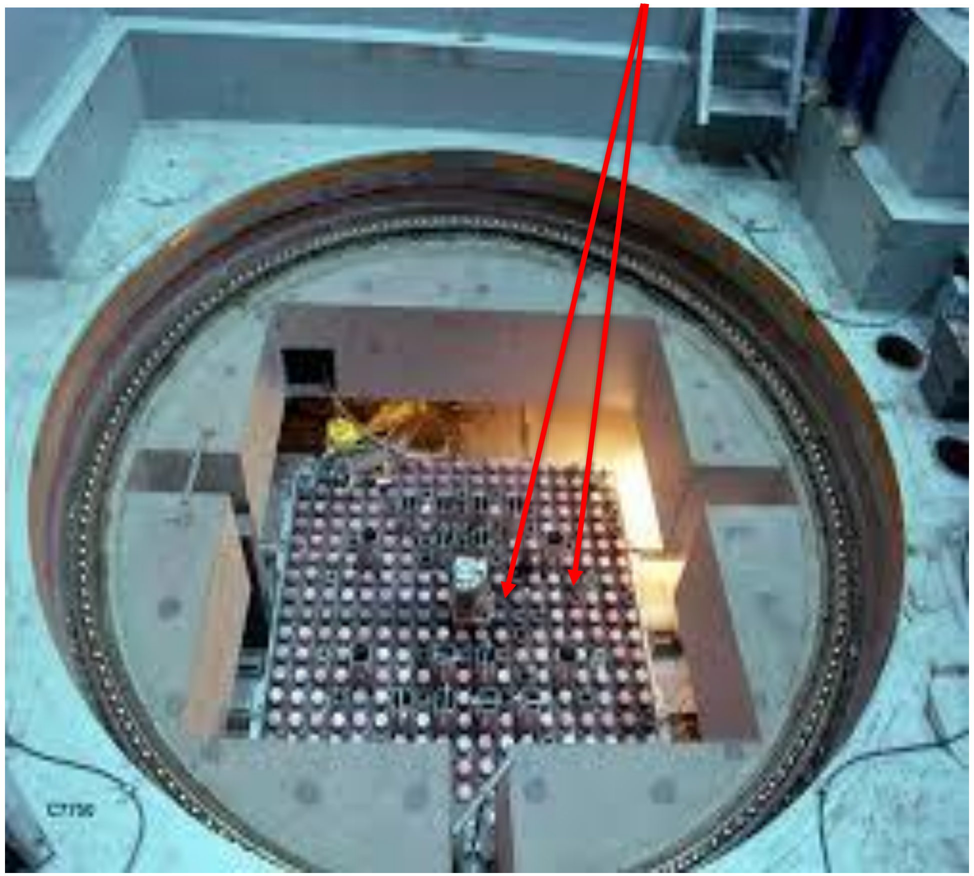


Hf-based SPND output compared to Rh-based SPND

Hf-based SPNDs have a rapid response (as illustrated above) and have been a research interest of Dr. George Imel of ISU for many years. Dr. Imel collaborated with ASI PI Kevin Tsai for this test.

TREAT Concurrent Testing

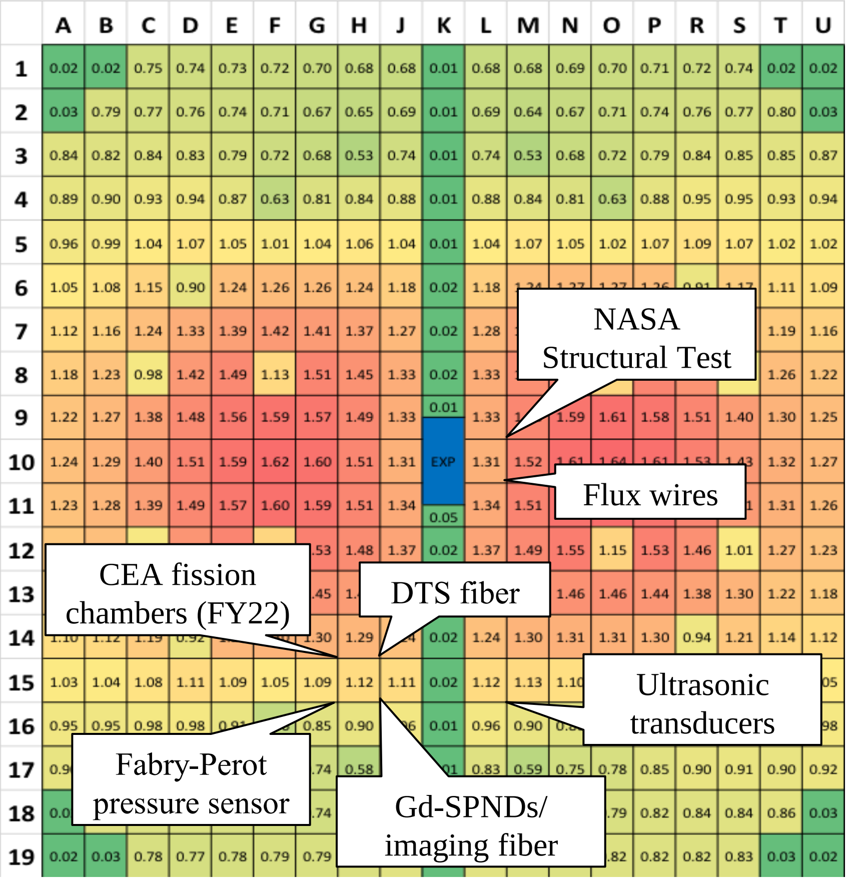
Developmental sensors are placed in cooling channels around fuel assemblies, rather than in experiments themselves. This approach lowers costs and does not interfere with high-value customer experiments.



TREAT Concurrent Testing

Concurrent Testing Sensors in FY-21

- NASA structural test
  - (non-ASI) Collaboration between NASA and TREAT to examine performance of carbon nanotube structural materials.
- DTS fiber
  - Dedicated position for FY22 fiber benchmark
- Fabry-Perot pressure sensor
  - FY-21 “Fiber Optic Fabry-Perot Pressure Sensor” activity
- Imaging fiber
  - FY-21 “In-pile Fiber Optic Based Imaging” activity
- Gd-SPNDs
  - Idaho Laboratories Corp. Gd-SPNDs follow-on testing.
- Ultrasonic transducers
  - Testing of ultrasonic transducer ceramic integrity.



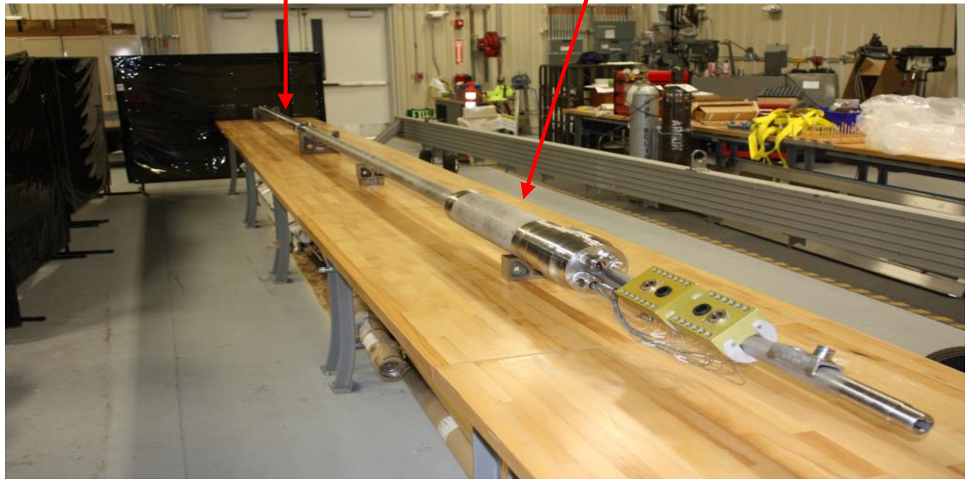
TREAT core map with relative flux ratios

Accomplishments

Retractable Sensor Development – NCSU Capstone Team

Very high temperature in-core section of experiment where sensor is periodically inserted

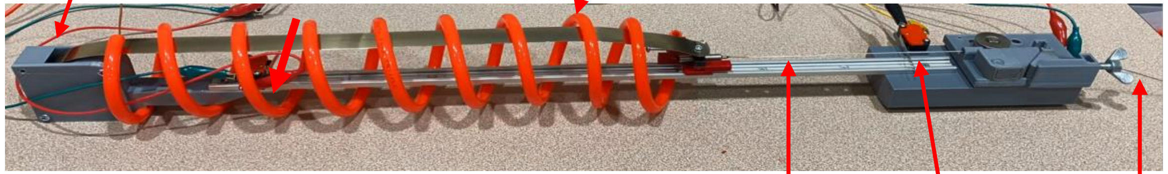
Upper part of experiment is larger (125 mm) and can accommodate drive mechanism. Temperature and radiation dose is low in this region



Complete ATR Instrumented Experiment

Constant force spring to keep tension on cable when sensor is retracted

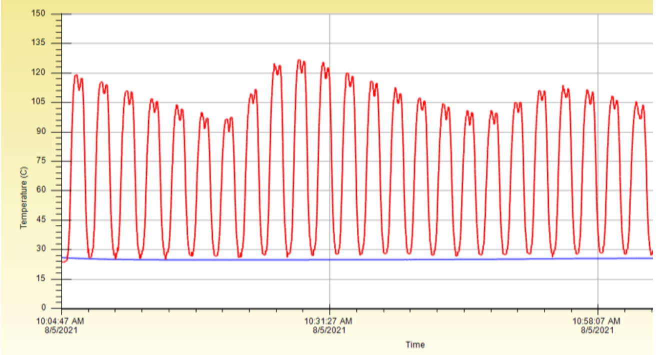
Sensor leads are placed in this plastic coil, which prevents tangles as sensor is inserted and retracted



Sensor cable

Capillary tube

Limit switches at each end tell control system that sensor is either fully inserted or retracted



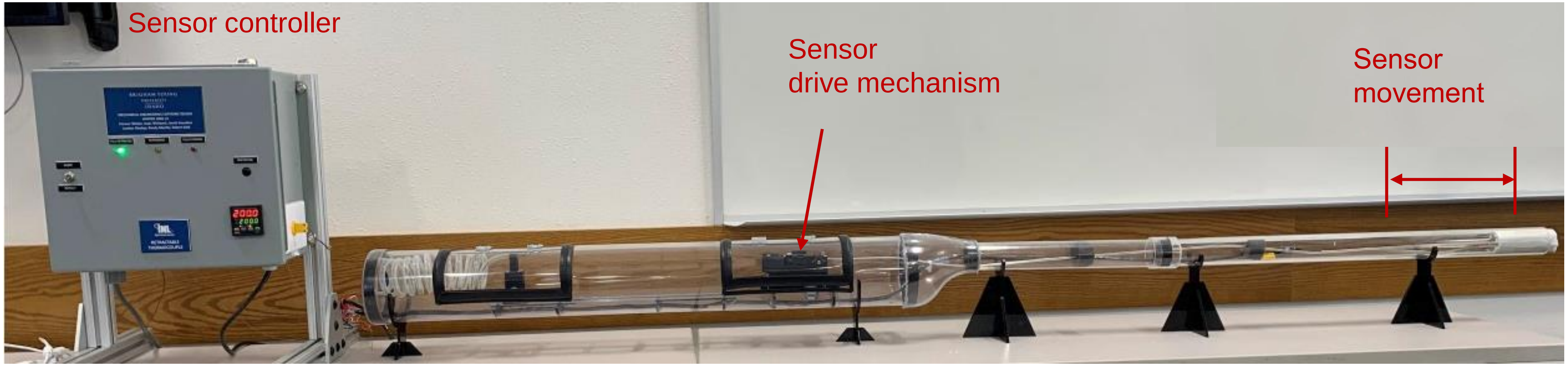
Thermocouple Response To Cycling in and Out of Furnace

The life of in-core sensors may be greatly extended by inserting them only occasionally. This can still produce a very useful data set because MTRs normally run at constant power and the corresponding conditions within reactor experiments typically evolve relatively slowly.

Accomplishments

Retractable Sensor Development – BYUI Capstone Team

- Under the direction of INL reactor experiment designers, the BYUI capstone design team developed a system capable of inserting and retracting a thermocouple sensor, which is displayed here in a transparent mockup of a reactor experiment



Retractable Sensor Demonstration System

Award-winning demonstration system created by BYUI capstone team

Conferences and Publications

- J. Palmer (INL), G. Yang, N. Fikenscher, A. Chrystler, C. Jolley, H. Osborne (NCSU); “Retractable Sensors for In-Core Service in Material Test Reactors,” 2021 Test, Research and Training Reactors (TRTR) Annual Conference, October 18-21, 2021; Raleigh, North Carolina.

Conclusion

- Advanced instrumentation enables testing of nuclear fuels and materials in support of the U.S. advanced nuclear technology industry
- It is important to demonstrate newly-developed sensors in operational conditions, prior to incorporating them into long-term high-value experiments
- In FY-21 this project irradiated neutron sensors in all four INL reactors plus the research reactor on the Idaho State University campus
- An important part of the FY-21 and FY-22 work scope is to gain experience with neutron sensors at temperatures relevant for advanced reactors i.e., 500 – 1000^{o}C
- Two university capstone design teams created functioning systems to demonstrate the retractable sensor concept during FY-21

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Questions?

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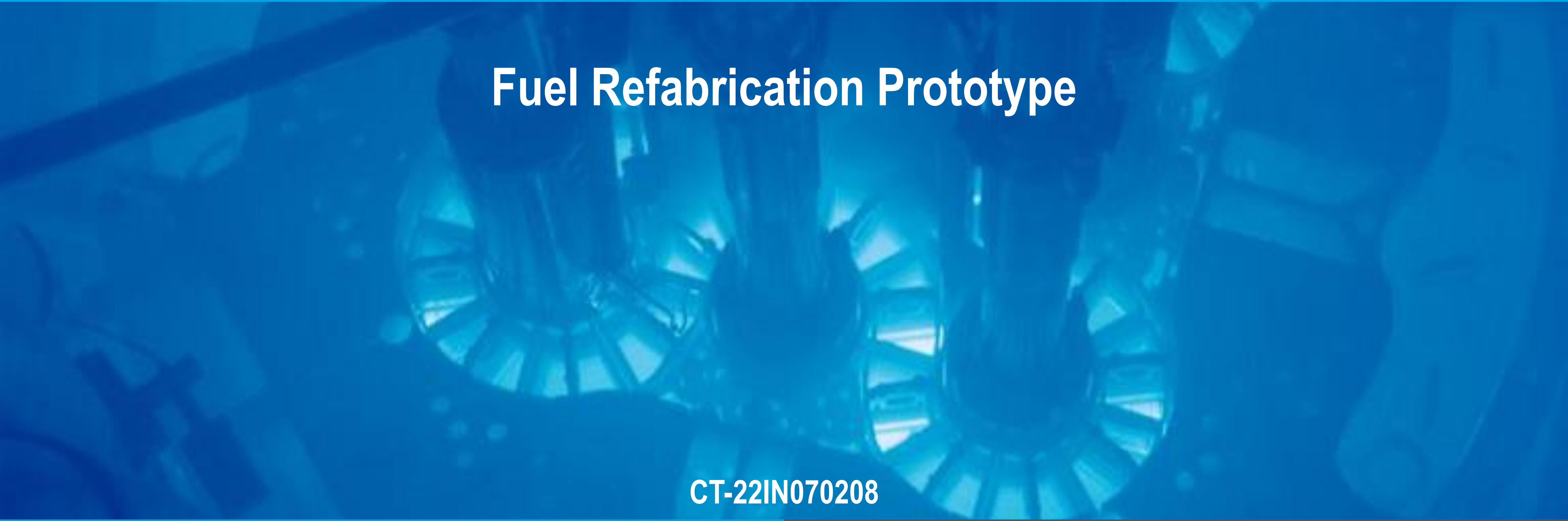


Fuel Refabrication Prototype

CT-22IN070208

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Reactor Experiment Designer: Joe palmer

Idaho National Laboratory

Project Overview

- Objective

  Capture critical technology created by Institute For Energy (IFE - formerly Halden Reactor Project) to re-instrument irradiated fuel rodlets, and further this technology to enable incorporation of advanced instrumentation: fiberoptics, LVDTs, ultrasonic based sensors

- Participants
  - ➢ Joe Palmer – Project lead
  - ➢ Dr. Austin Fleming – Technical Point of Contact
  - ➢ Kory Manning – Lead technician
  - ➢ Spencer Parker – Weld engineer
  - ➢ Steinar Solstad – Project lead at IFE (Halden, Norway)

Project Overview

Timelines of Project Activities FY-21 and F-Y22

FY21

Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep

- Received drilling and defueling modules at INL
- Completed checkout of defueling module and substantial checkout of drilling module using cryo-fluids
- Prepared, reviewed. and released Lab Instructions to operate drilling and defueling modules

FY22

Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep

- Complete checkout of drilling module
- Complete checkout of welding module
- Complete fabrication of a prototype instrumented fuel rodlet
- Update lab instructions to operate welding module
- Practice refabrication of fuel rodlets using cracked pellets and alternate instrumentation

FY-21, FY-22 Milestones

Milestone	Due Date	Status
Receive welding module for the re-instrumentation facility procured from the Institute For Energy - Halden, Norway	9/30/2021	Slipped to 11/30/2021
Complete system checkout testing of the re-instrumentation facility procured from the Institute For Energy - Halden, Norway	12/31/2021	Slipped to 3/31/2022
Complete fabrication of an instrumented fuel rodlet prototype using ceramic surrogate pellets in place of UO_2	9/30/2022	On schedule

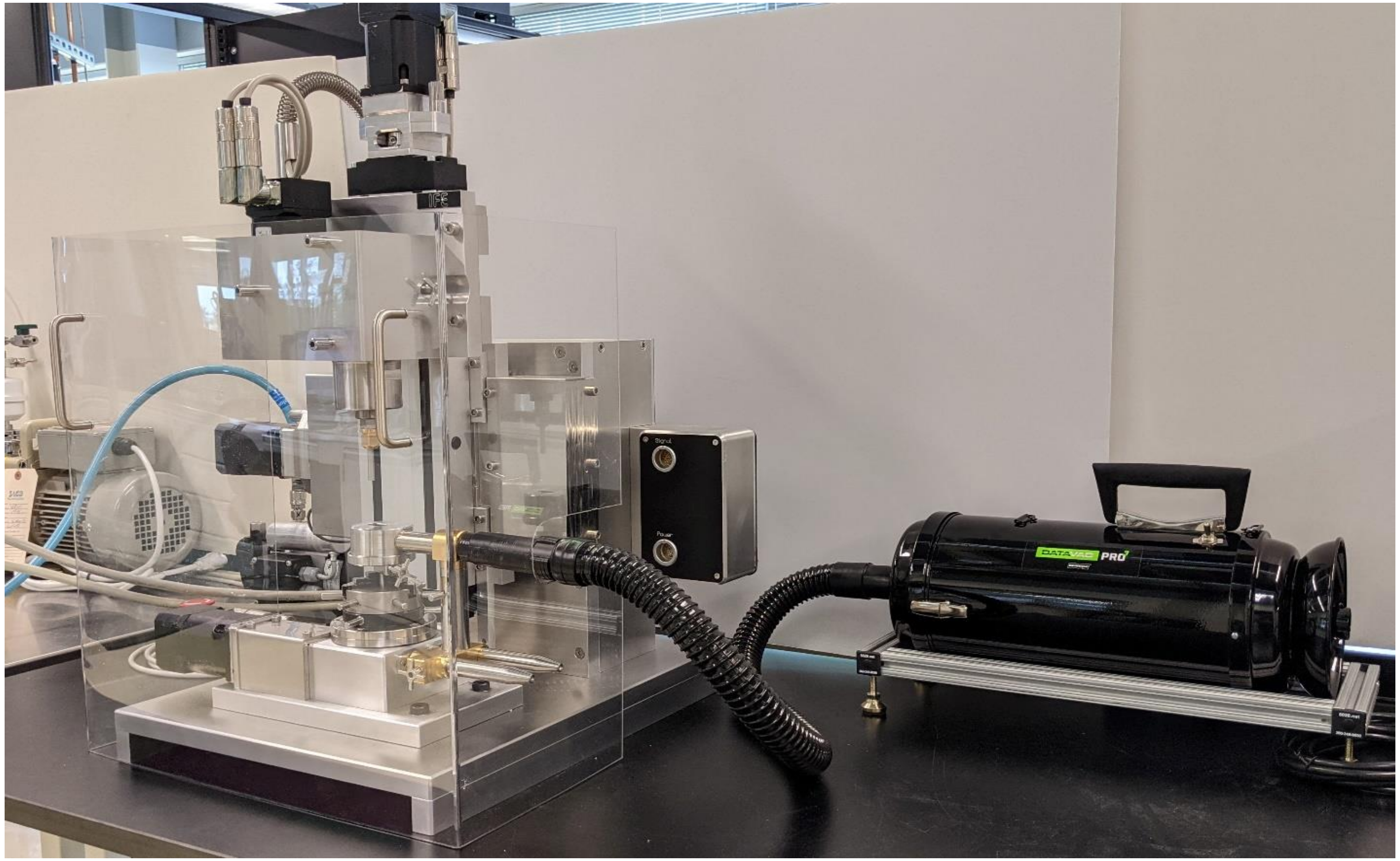
Technology Impact

- For decades, the Halden Boiling Water Reactor (HBWR) in Norway was a key resource for assessing nuclear fuels and materials behavior to address performance issues and answer regulatory questions.
- The HBWR was shut down in 2018. In order to avoid the loss of the unique experimental techniques developed at Halden, INL is procuring equipment modules designed to re-instrument sections of LWR fuel rods prior to irradiation in a test reactor.
- This is part of a broader effort to transfer the expertise developed at Halden to other relative facilities such as TREAT and ATR.
- This fuel testing is key to advancing and qualifying new light water reactor technologies.

Accomplishments

Defueling Module Setup

- **Received Defueling Module**
  - Installed transparent personnel protection shield
  - Incorporated vacuum to collect fines
  - Practiced “defueling” a surrogate rodlet

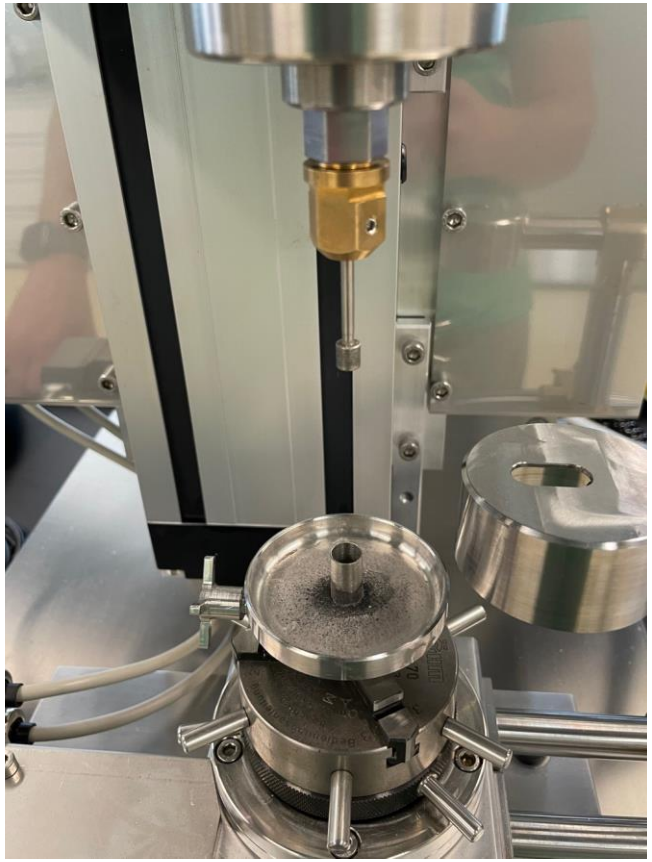


“Defueling” module with guard and vacuum pump integrated

Accomplishments

Defueling Practice

Mullite pellets glued inside oxidized (sst) cladding



Top pellet removed and oxidation cleaned from inner and outer surfaces of the cladding (this is prep for welding)

Accomplishments

Drilling Module Setup

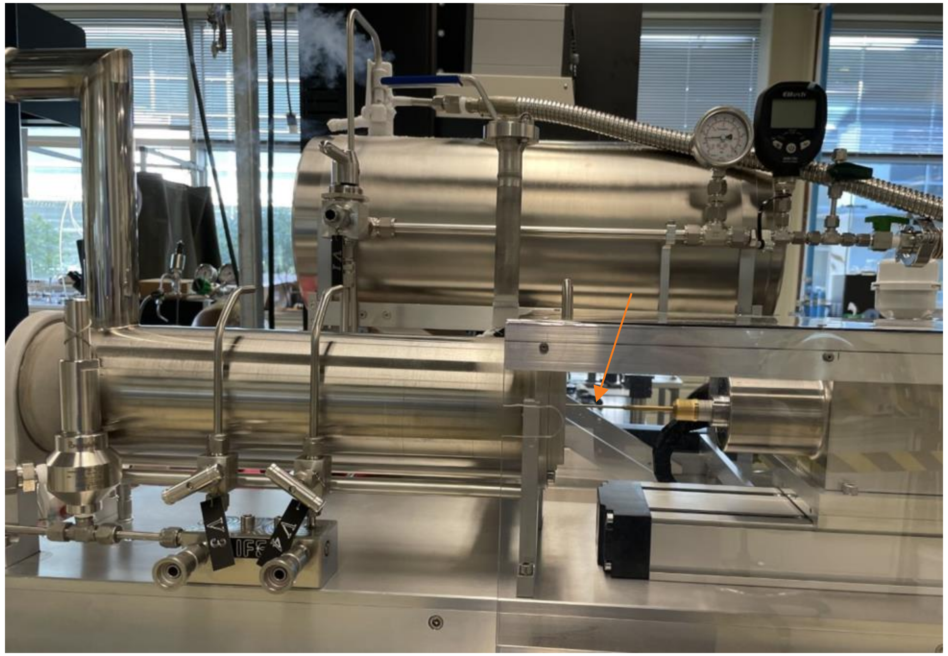
- **Received Drilling Module**
  - Installed transparent personnel protection shield
  - Incorporated two vacuum systems: 1) to collect fines and 2) to establish vacuum jacket for dewar
  - Practiced drilling with cryo-system active

Cryo-drilling unit with vacuum pumps and guards in place

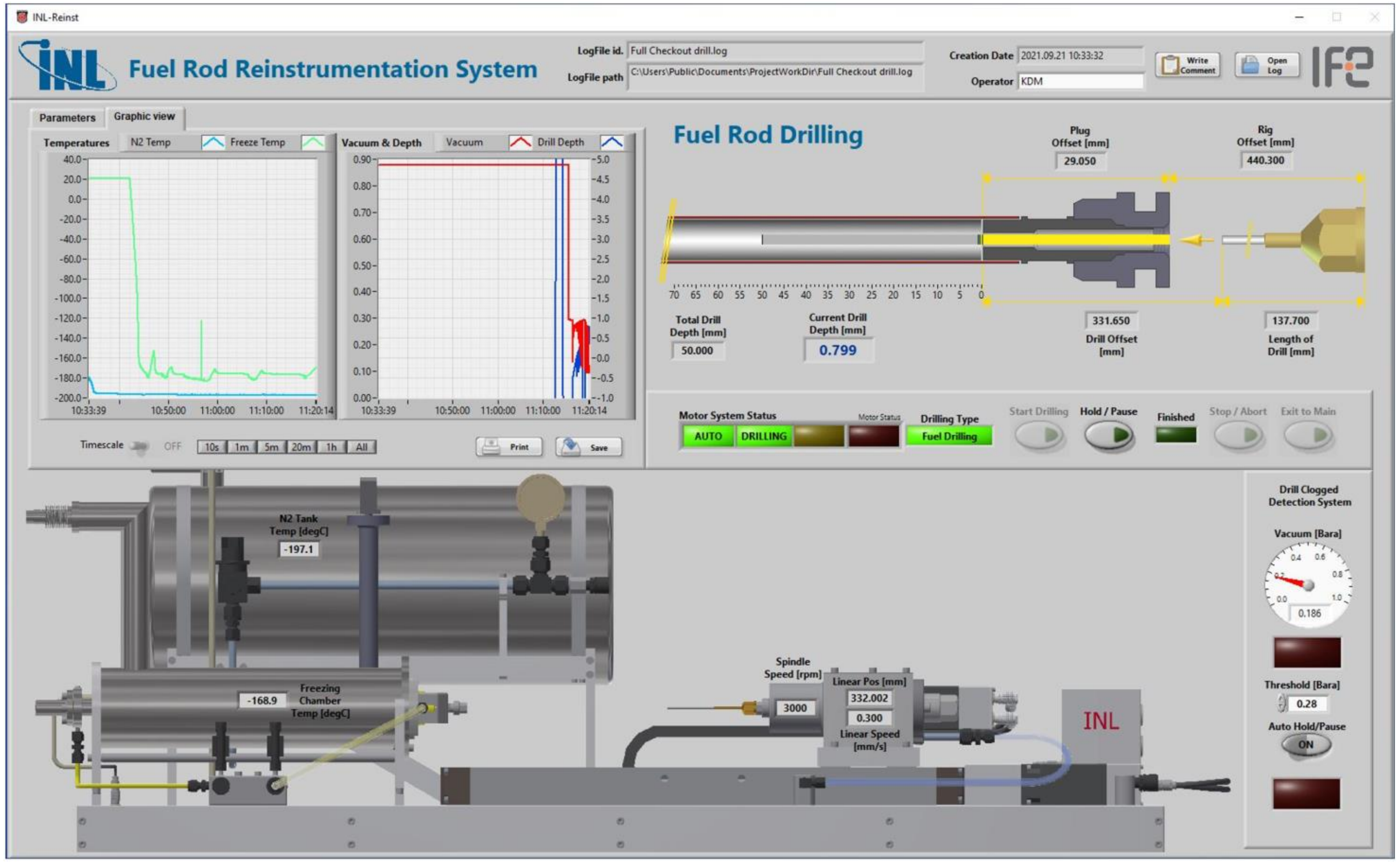
Accomplishments

Drilling Practice

Several practice runs – still learning how to not break diamond bits during drilling



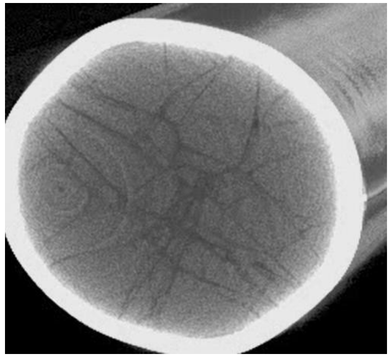
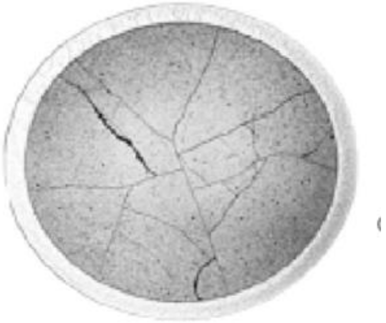
Start of a cryo-drilling practice run



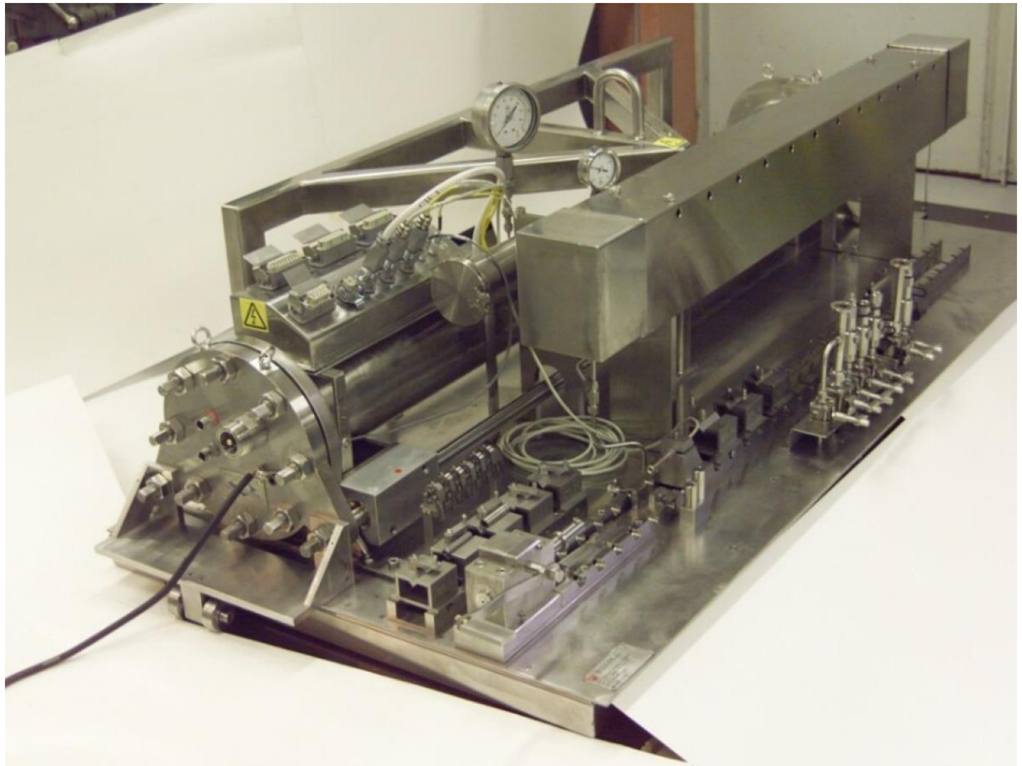
Control system display during drilling process

Outlook for FY-22

- Receive welding module and perform checkouts (practice welding)
- Prepare rodlets with both cracked and uncracked pellet stacks

- Finally, prepare a complete instrumented rodlet using all three equipment modules



Halden welding module with drying and leak check chambers

Conclusion

- INL is capturing critical technology developed at IFE in Halden, Norway by procuring three equipment modules, which are designed to take sections of commercial fuel rods and prep the ends for welding (defueling module), drill a hole in the fuel pellet stack (drilling module), and weld end plugs on each with accompanying instrumentation (welding module).
- The defueling and drilling modules were received in FY-21 and substantial experience was gained with them.
- The welding module is expected to arrive at INL early in FY-22.
- By the end of FY-22 the project will produce a fully instrumented prototypical fuel rodlet (using surrogate ceramics in the place of UO_2).

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Questions?

ASI Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

A Two Cycles Automated Approach to Electrical Resistivity Measurement of SiC Monitors for Peak Irradiation Temperature

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

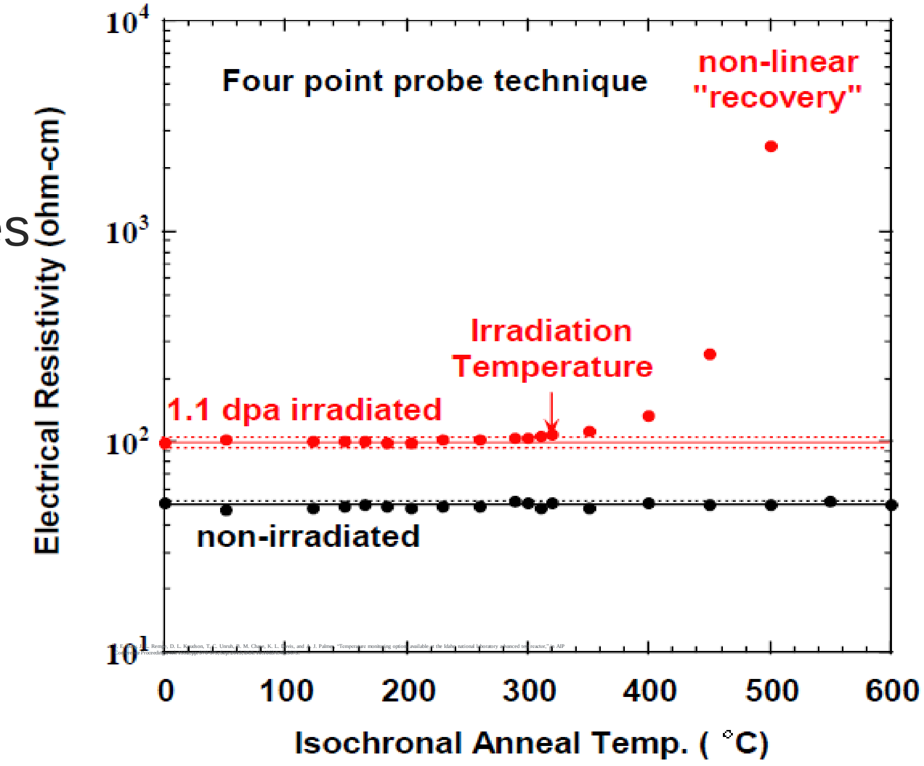
November 15 – 18, 2021

Ahmad Al Rashdan, Ph.D.
Senior R&D Scientist

Idaho National Laboratory

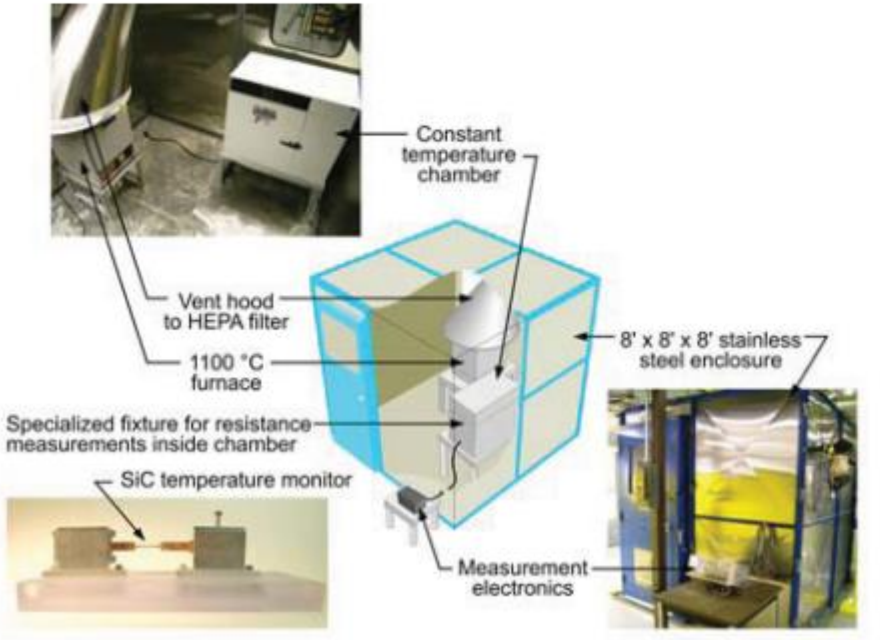
Peak Irradiation Temperature- Manual Post-Irradiation Examination

Irradiation of SiC monitors at a specific temperature causes lattice structural changes that are removable via isochronal annealing.



Electrical resistivity was found to provide one of the highest measurement accuracy (i.e., <20ºC).

Recovery of the irradiation temperature from SiC monitors during post-irradiation examination (PIE) is currently accomplished using a manual and time-consuming isochronal annealing process.



K. L., Davis, A. Gusarov, T. C. Unruh, P. Calderoni, B. J. Heidrich, K. M. Verner, A. Al Rashdan, A. Lambson, S. Van Dyck, and I. Uytdenhouwen, "Evaluation of Low Dose Silicon Carbide Temperature Monitors," in IEEE Transactions on Nuclear Science, vol. 67, pp. 585-591, Dec. 2019, EDP Sciences, DOI. 10.1109/TNS.2019.2957972.

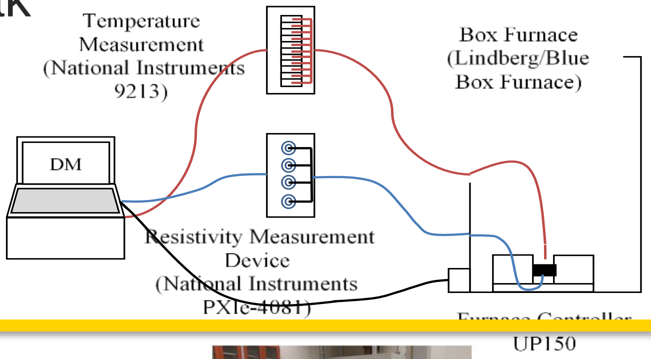
Peak Irradiation Temperature- Automated Post-Irradiation Examination

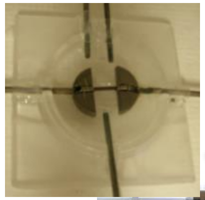
An automated setup and process were designed and optimized to acquire the peak irradiation temperature.

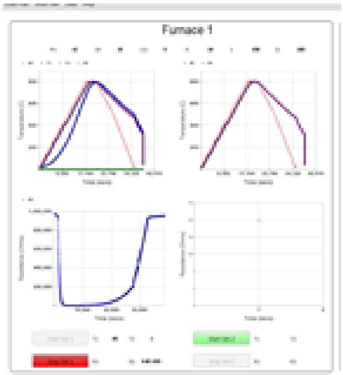
R&D Team:

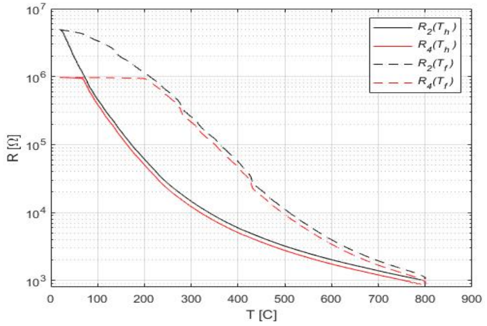
- Ashley Lambson
- Joshua Daw
- Kurt Davis
- Malwina Wilding
- Mitchell Plummer
- Pattrick Calderoni
- Troy Unruh

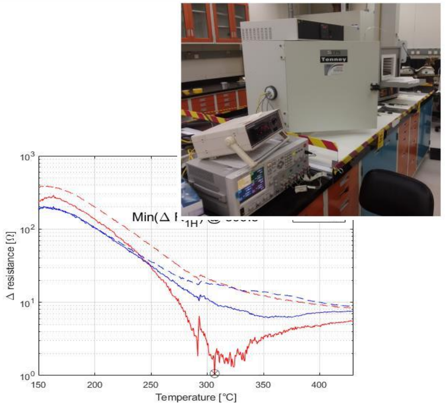
2017







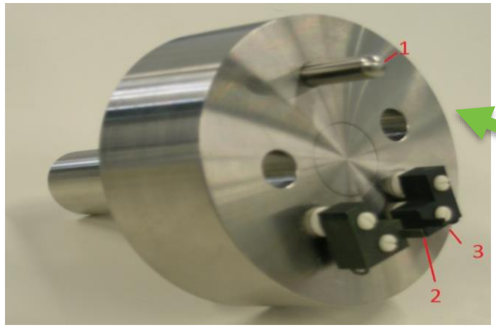


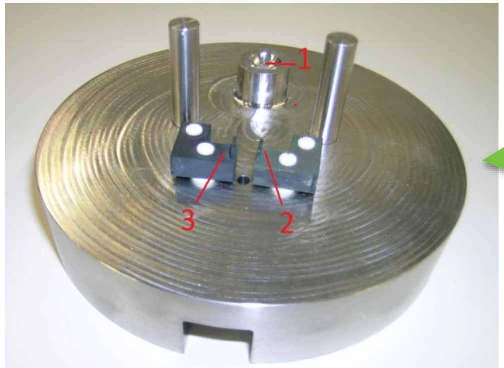


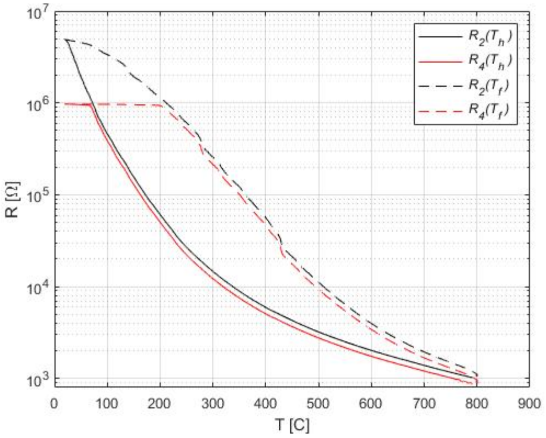
2021

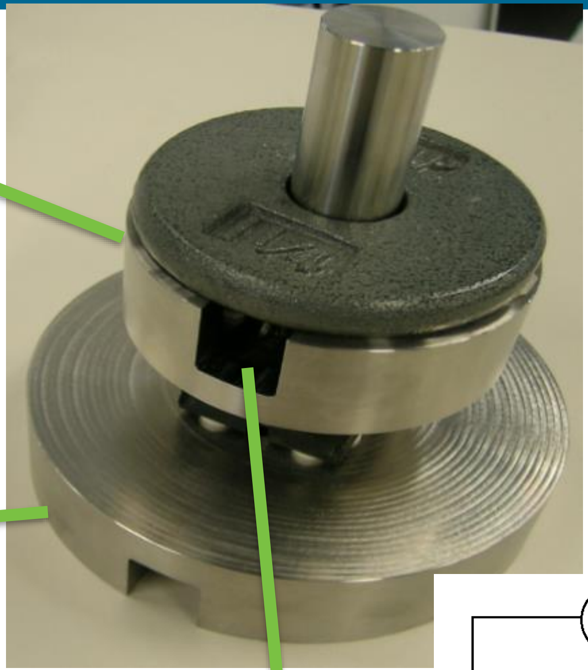
Experiment Setup and Qualification

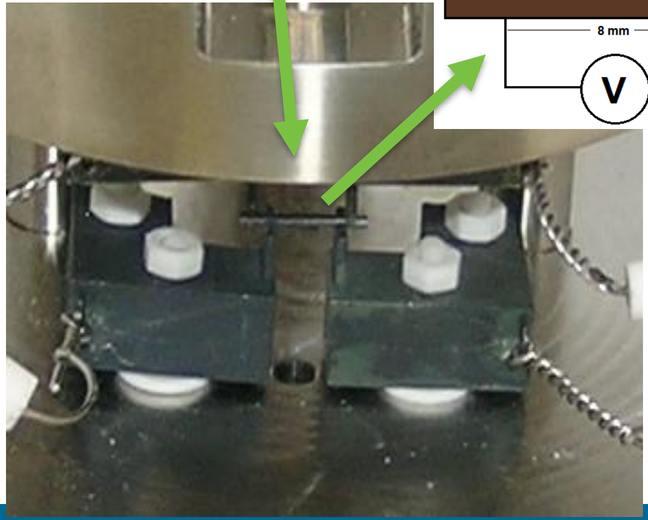
- Contact resistance was found to significantly drop early in the heating process.
- The thermal expansion effect on the experiment was almost eliminated by using sustainable pressure via the weights.
- The thermal transient was significantly decreased by applying a constant low heating rate.
- Oxidation was found to not affect measurement repeatability when using Pt-coated peripherals.

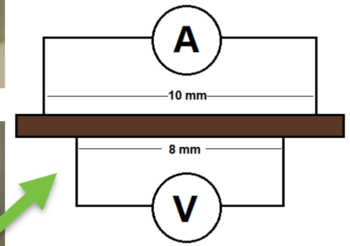








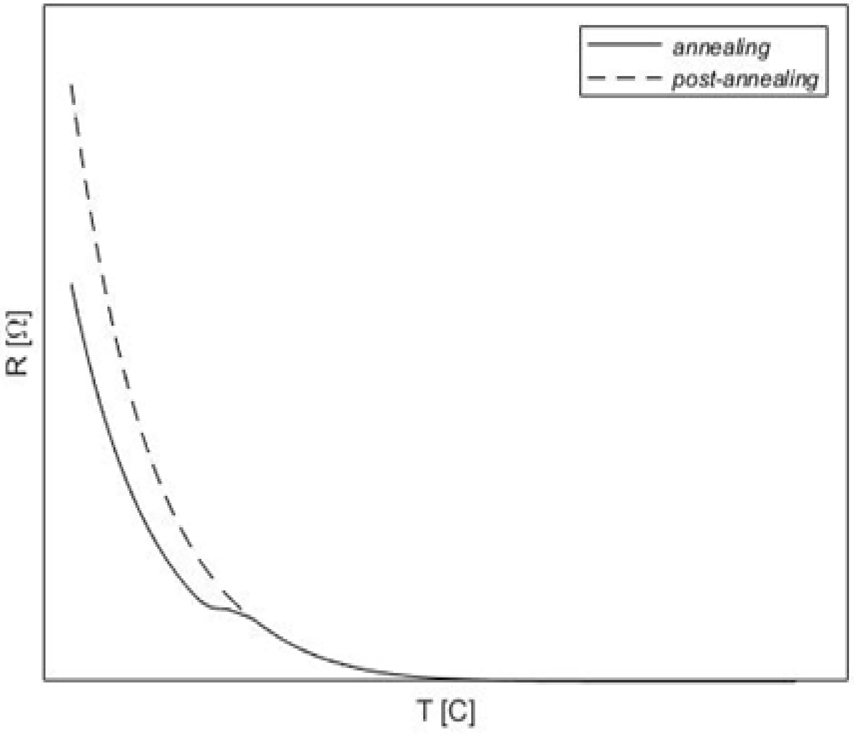




Inferring Irradiation Temperature From Resistance Measurements

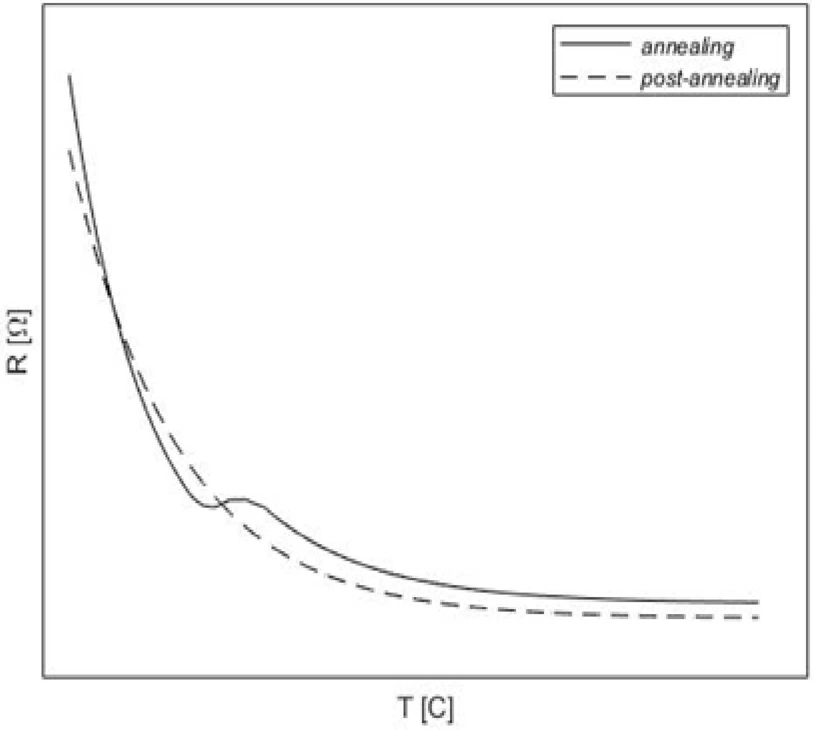
Comparing the resistance (R_a) against the mean of all other resistances (R_b)

$R_a < R_b, T < T_r$
$R_a \to R_b, T \approx T_r$
$R_a = R_b, T > T_r$



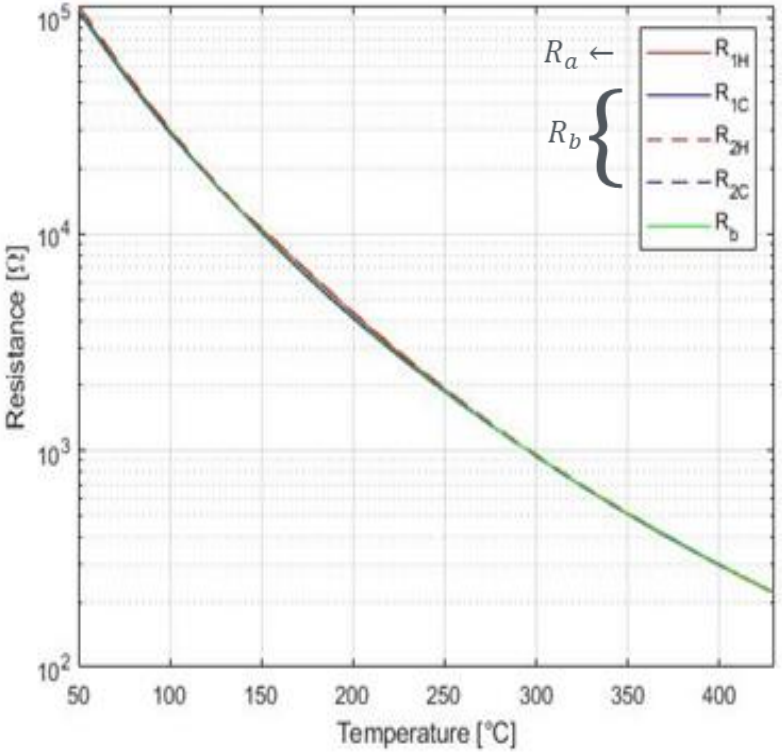
Ideal Measurement

$R_a < R_b, T < T_r$
$R_a \to R_b, T \approx T_r$
$R_a = R_b, T > T_r$



Expected Measurement

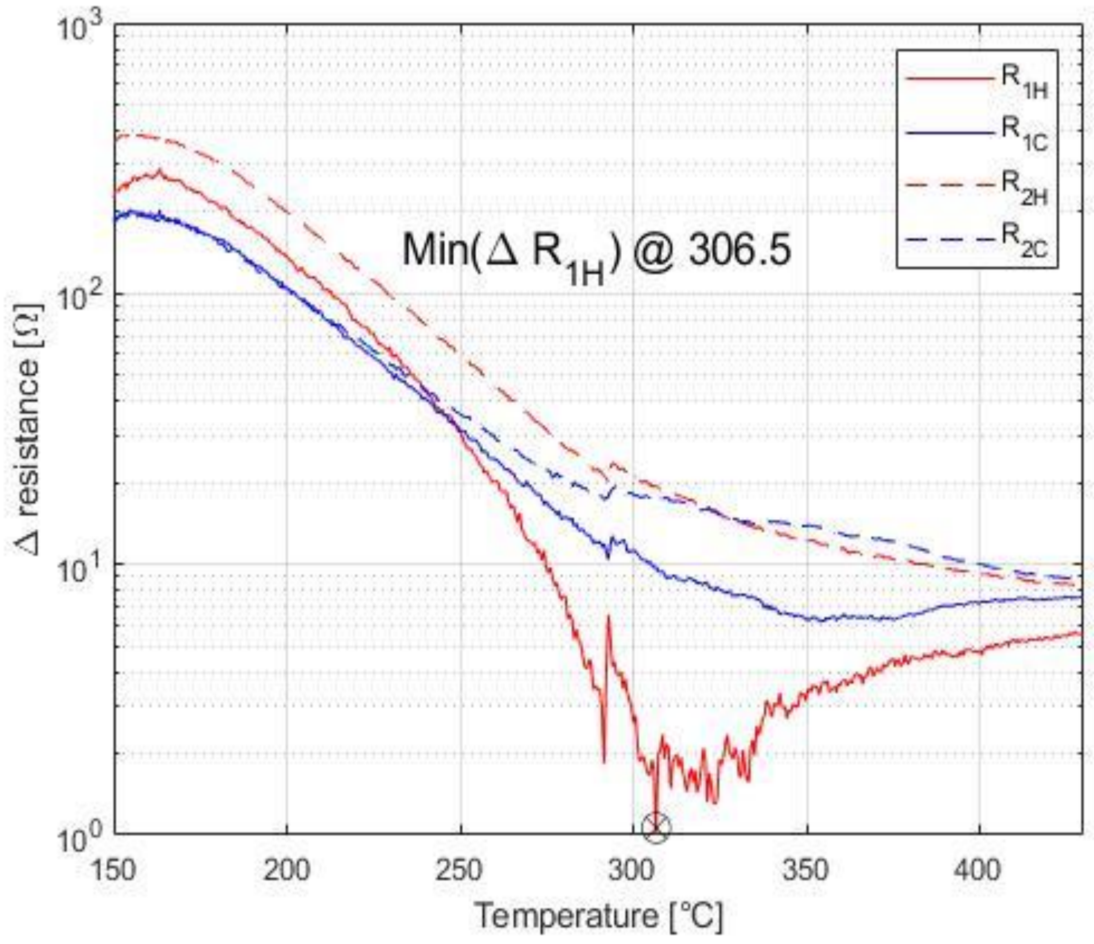
$R_a < R_b, T < T_r$
$R_a \to R_b, T \approx T_r$
$R_a = R_b, T > T_r$



Real Measurement

Inferring Irradiation Temperature From Resistance Measurements

$$T_r = T(\min[\,\mathrm{sign}\{R_{a,0} - R_{b,0}\}(R_a - R_b) + \alpha\,])$$



Sample Name	T_p (°C)	Dose (dpa)	T_e (°C)	$T_{m,A}$ (°C)	$T_{m,M}$ (°C) for pair	$T_{m,M}$ (°C)
M1-High-B	NPA	0.5	310	306.5	320	
M1-Med-B	490	0.5	410	Undetermined	390	
M2-High-B	490	1.1	310	314.9	330	
M2-Low-B	NPA	1.1	255	Undetermined	Undetermined	
M2-Med-B	NPA	1.1	410	406.3	380	
M1-High-A	380	0.5	310	312.5		320
M1-Med-A	490	0.5	410	342.4		390
M2-High-A	390	1.1	310	323.8		330
M2-Med-A	430	1.1	410	379.0		380

NPA= Not previously annealed

Conclusions

- Seven monitors resulted in comparable results to the manual isochronal annealing approach.
- Resulted in a standard deviation error of 15.2°C, whereas that achieved via the manual isochronal annealing method was 23.8°C.
- The approach was still able to detect residual defects that had not been annealed out. The exception was pre-annealing of 490°C and a dose of 0.5 dpa (i.e., high temperature and low dose).
- At the rate of 26% power, each cycle of heating and cooling took around 15 hours.
- A real continuous range of temperature measurement (i.e., higher accuracy).
- Journal paper was submitted and is being reviewed.

Questions?

ASI Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

TREAT Concurrent Testing

CT-22IN070208

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

Kevin Tsai

Nuclear Instrumentation Engineer

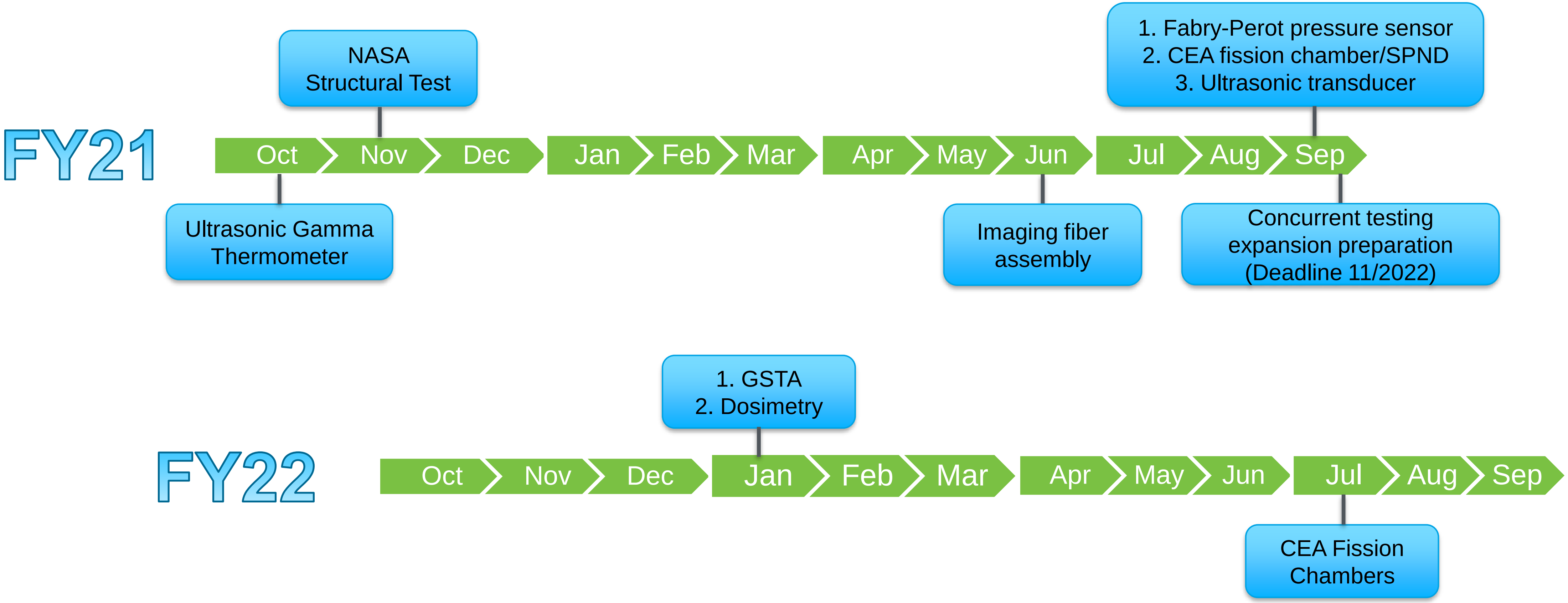
Idaho National Laboratory

Project Overview

- Objective
  - To enable in-pile irradiation testing of instrumentation in the Transient Reactor Test (TREAT) facility.
    - Evaluate the impacts of the irradiation environment to sensors
    - Demonstrate sensor integration within the TREAT facility.
  - The overall strategy is to perform irradiation testing alongside other planned experiments and operations at the TREAT facility—termed *concurrent testing*.
- Participants
  - ASI
  - TREAT Team
  - External Collaborators

Project Overview

- Timeline of activities in FY-21 and FY-22



Technology Impact

- Advanced instrumentation are needed for qualifying nuclear fuels and materials.
  - TREAT has unique capabilities to neutronically simulate postulated accidents in nuclear plants.
  - Unique sensor technologies needs to be developed and tested to support TREAT experiments.
- Concurrent testing enables the evaluation of sensors in near-identical nuclear conditions prior to their deployment in TREAT experiments.
- These activities will ensure successful sensor integration and deployment to support nuclear testing at TREAT.

Details of Concurrent Testing

- TREAT titanium holders are used to suspend sensors in TREAT cooling channels.

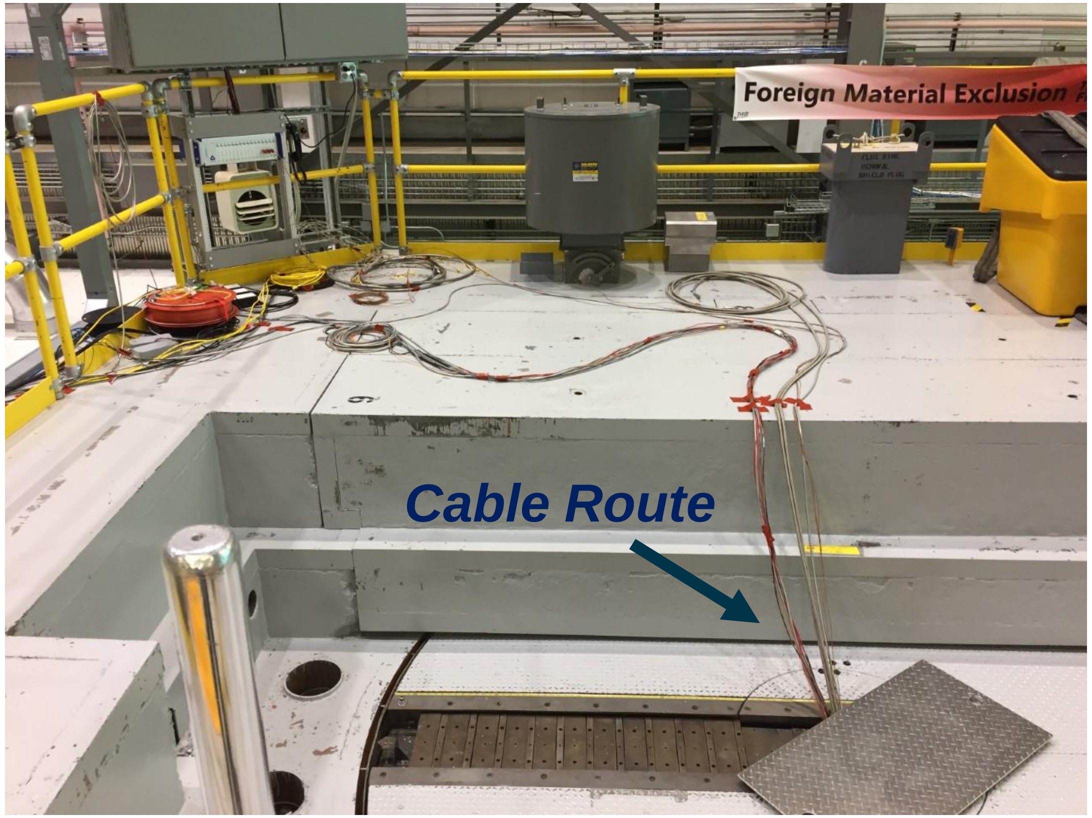
Sensors ready for Insertion in TREAT 1/4” and 3/8” holders.

Insertion of sensors into TREAT cooling channels

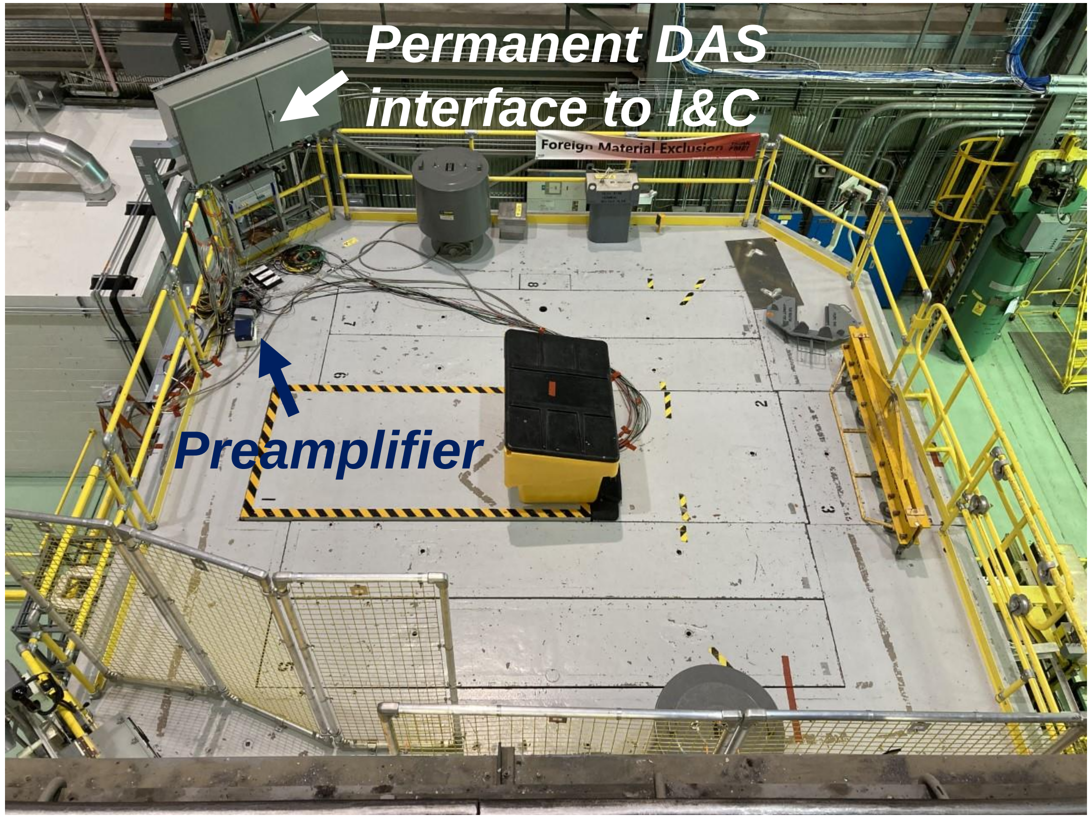
TREAT assembly top/down view w/ sensors inserted

Details of Concurrent Testing

- Cables routed to reactor top for connection with permanent DAS or preamplifiers



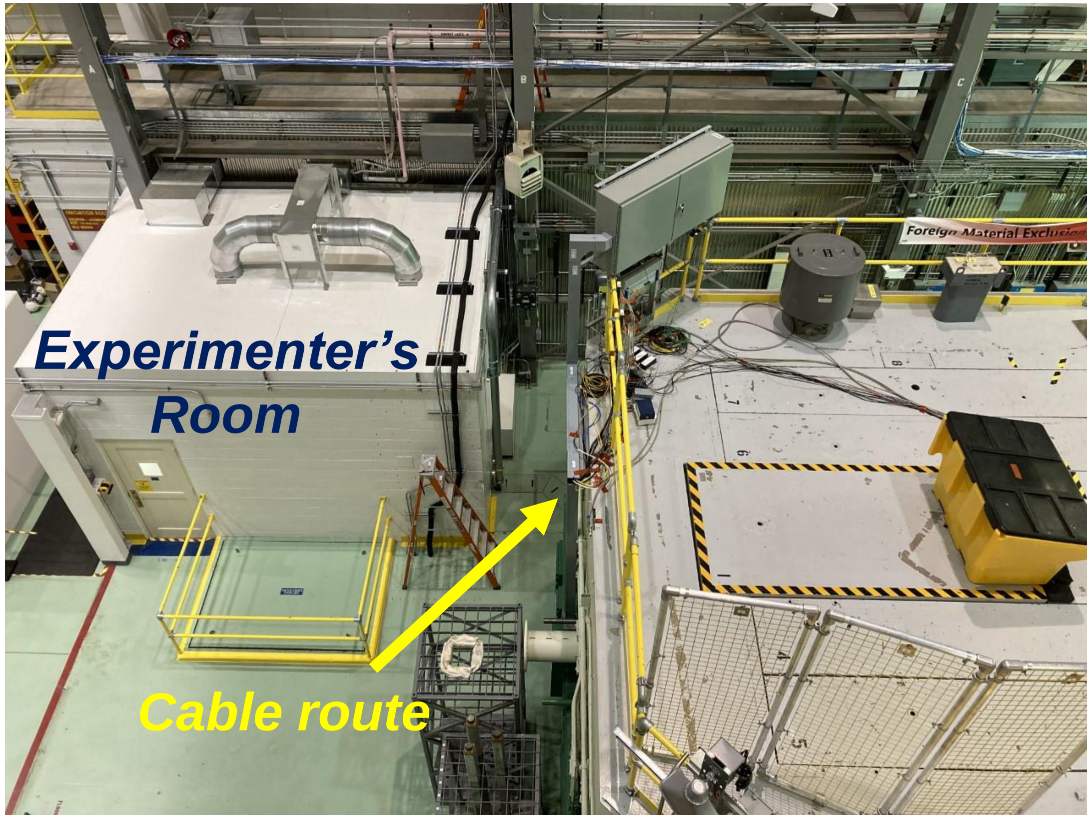
Cable route to EIP with shield blocks off



Cable route to EIP with shield blocks on

Details of Concurrent Testing

- Cable route to the experimenter's room



Top view of cable route to experimenter's room

Side view of cable route to experimenter's room

Details of Concurrent Testing

- Cable route to the experimenter’s room and electronics are operated in the control room

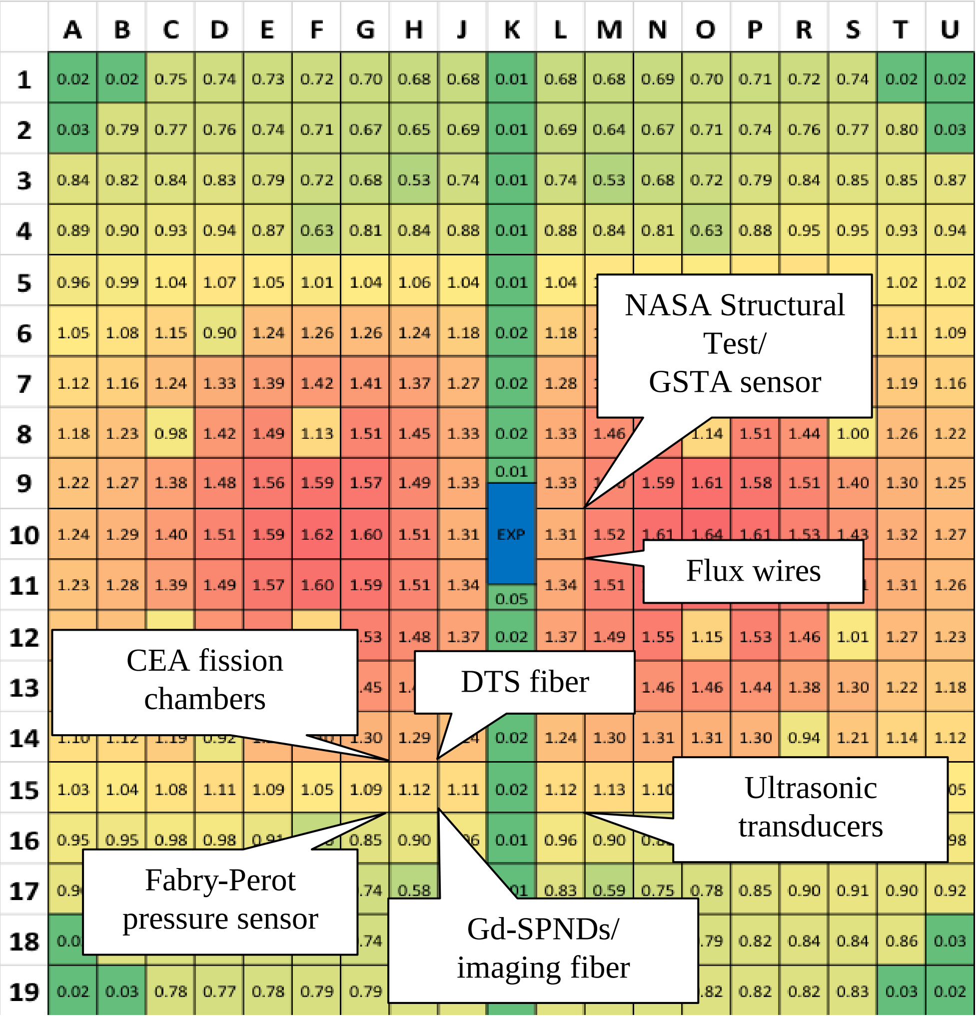
Experimenter’s room with developmental DAS

Control room

Accomplishments

Concurrent Testing Sensors in FY-21

- NASA structural test
  - (non-ASI) Collaboration between NASA and TREAT to examine performance of carbon nanotube structural materials.
- Fabry-Perot pressure sensor
  - FY-21 “Fiber Optic Fabry-Perot Pressure Sensor” activity
- Imaging fiber
  - FY-21 “In-pile Fiber Optic Based Imaging” activity
- Gd-SPNDs
  - Idaho Laboratories Corp. Gd-SPNDs follow-on testing.
- Ultrasonic transducers
  - Testing of ultrasonic transducer ceramic integrity.
- Dedicated positions for FY22 irradiation testing
  - DTS Fiber
  - CEA Fission chambers
  - GSTA sensor



TREAT core map with relative flux ratios

Conclusion

Summary:

- Concurrent testing is a crucial component of sensor qualification needed for successful deployments
- Many sensors have gone through successful testing through concurrent testing

Future work:

- Concurrent testing is a continually evolving process as sensors reach the demonstration phase
- Concurrent testing expansion preparation:
  - Reduce turnaround time
  - New positions and access dimensions (up to 2.5” diameter)

Kevin Tsai

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Questions?

ASI | Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

Development of Radiation Endurance Ultrasonic Transducer for Nuclear Reactors

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Project Manager: Uday Singh, Ph.D.

Vice President: Dan Xiang, Ph.D.

X-wave Innovations, Inc.

555 Quince Orchard Road, Suite 510, Gaithersburg MD 20878

Project Overview

Motivation

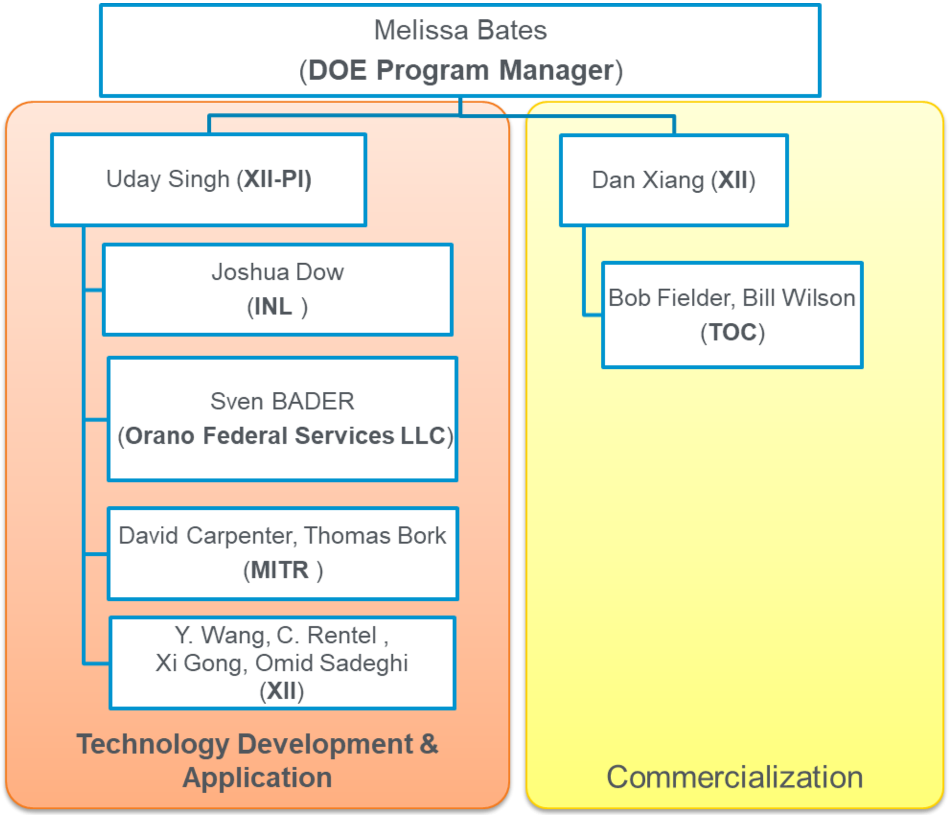
Development of sensors and nondestructive evaluation technologies, capable of surviving in substantial radiation fields is necessary to advance nuclear plant control and mentoring systems, data analysis and other nuclear applications.

Thus, DOE seeks a sensor technology that in nuclear environment,

- Demonstrate greater accuracy
- Reliability
- Resilience
- Ease of replacement and upgrade

And can directly support existing power reactors, material test reactors and other similar systems.

Participants



Our Solution

Radiation Endurance Ultrasonic Transducer (REUT) for nuclear applications. It is a contact type of ultrasonic transducers.

REUT development is based on selecting radiation resilient materials, material engineering and harnessing knowledge of acoustic propagation in materials.

Project Overview

REUT and sensor development target

- Improve REUT design
- Develop REUT sensor system
  - Temperature sensor
  - Pressure sensor
  - AE sensor
  - Liquid Level sensor
  - Making REUT wireless
- Testing and Validation

Tasks	2020		2021				2022		Participants
	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	
1. Finalize project requirements	X								**XII, Orano, INL, TOC**
2. Refine REUT design and performance	X	X							**XII, Orano, INL, MITR,**
3. Develop REUT-based ultrasonic sensors		X	X	X	X				**XII, INL, MITR**
4. Modify REUT design to support wireless interrogation			X	X	X				**XII**
5. Conduct irradiation tests and performance evaluation			X	X		X	X		**XII, INL, MITR, Orano**
6. Demonstrate prototype abilities							X		**XII, Orano, INL, TOC**
7. Transition/commercialize the technology	X	X	X	X	X	X	X	X	**XII, Orano, TOC,**

- **Milestone 1.** Complete REUT modifications (month 6)
- **Milestone 2.** Develop REUT-based ultrasonic sensors (month 15)
- **Milestone 3.** Develop REUT wireless interrogation support (month 15)
- **Milestone 4.** Irradiation testing (month 20)
- **Milestone 5.** Demonstrate prototype ability and develop Phase III work plan (month 24)

Current achievements

We have,

- Improved REUT design and tested it performance with $LiNbO_3$ and ZnO piezoelectric crystal
- Used New REUT design to develop, Temperature sensor, Viscosity monitoring sensor, AE and GW structural health monitoring systems.
- We developed application software and developing electronic hardware to accompany these sensor systems
- Developing test plans to perform high temperature and irradiation testing, as well as to validate its performance

Technology Impact

REUT sensor applications:

2016 report from Oak Ridge National Lab (ORNL/TM-2016/337 R1), Assessment of sensor technology for advanced reactors, expresses,

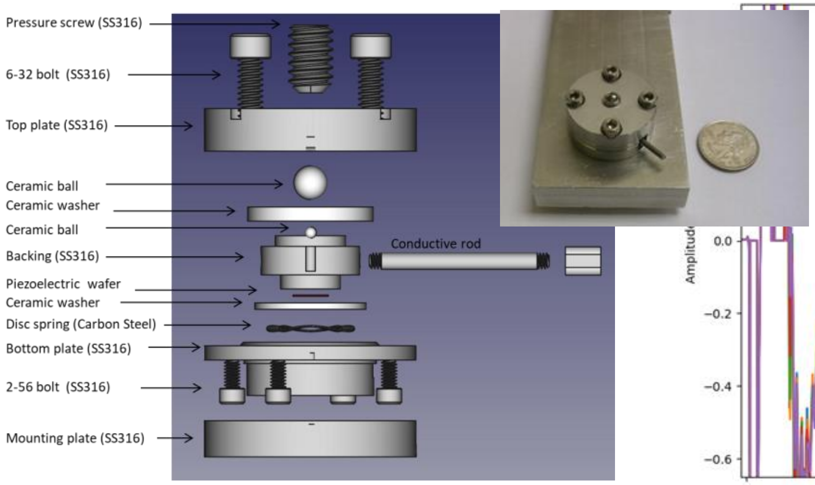
“*Flow measurement in liquid salt has been problematic. Work is currently proceeding on ultrasonic, time-of-flight methods for measuring flow velocity. High temperature is the challenge from two perspectives: (1) the ultrasonic transducers fail at the elevated salt temperatures and therefore must be isolated from the process via waveguides, and (2) the waveguides act as efficient heat sinks that cool the salt flow piping, which can lead to salt freeze. There are work arounds to the heat sinking dilemma; however, other flow measurement technologies need investigation such as thermal pulse. Additionally, the development of ultrasonic transducers that fully operate at 750 °C is needed*.”

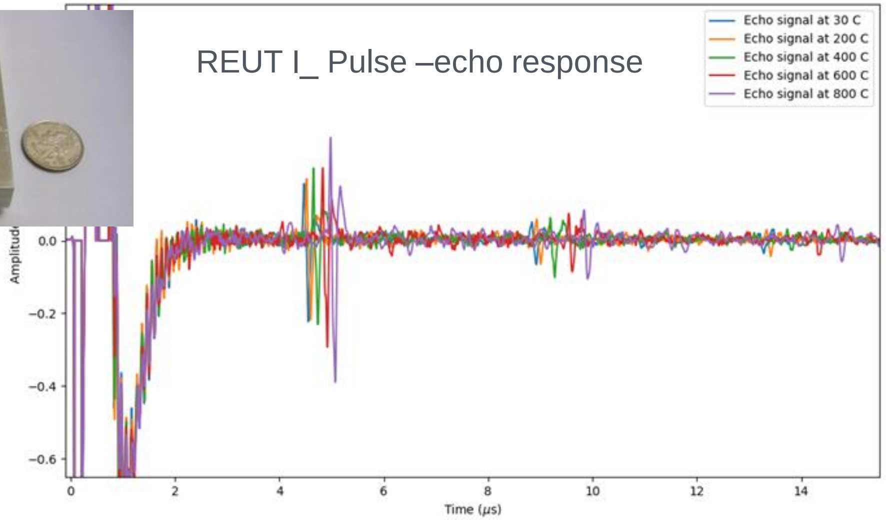
REUT is simply an ultrasonic transducer sensor which offers capability of operating at high temperatures along with potentially being radiation tolerant. Many ultrasonic sensors can be built using this REUT which can offer ultrasonic sensing capabilities at higher temperatures and other harsh conditions.

Technology Impact

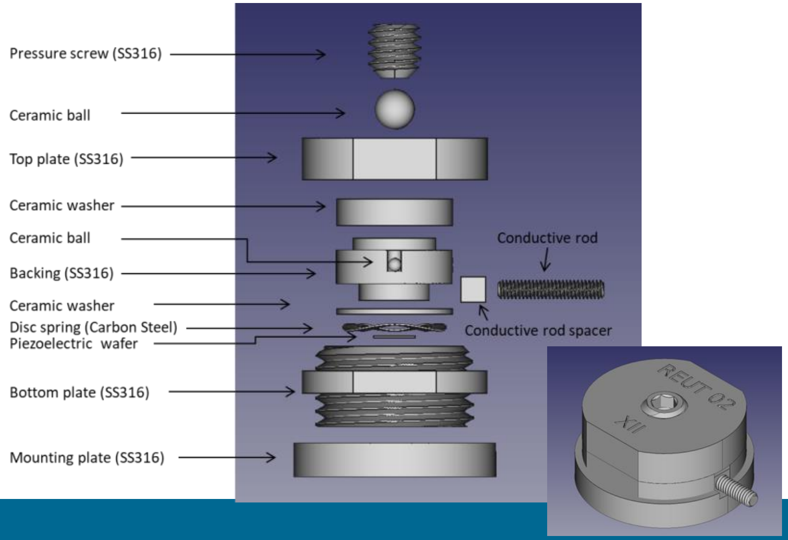
Phase I outcome :

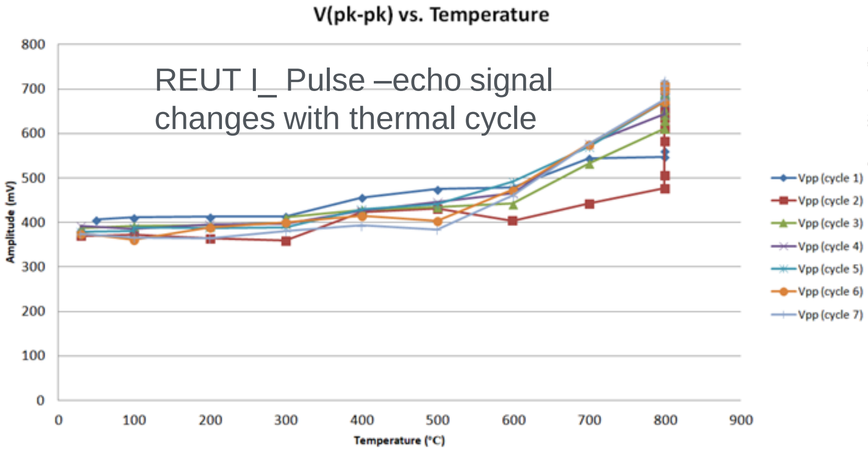
We developed REUT I and REUT II design and tested their performance at higher temperatures



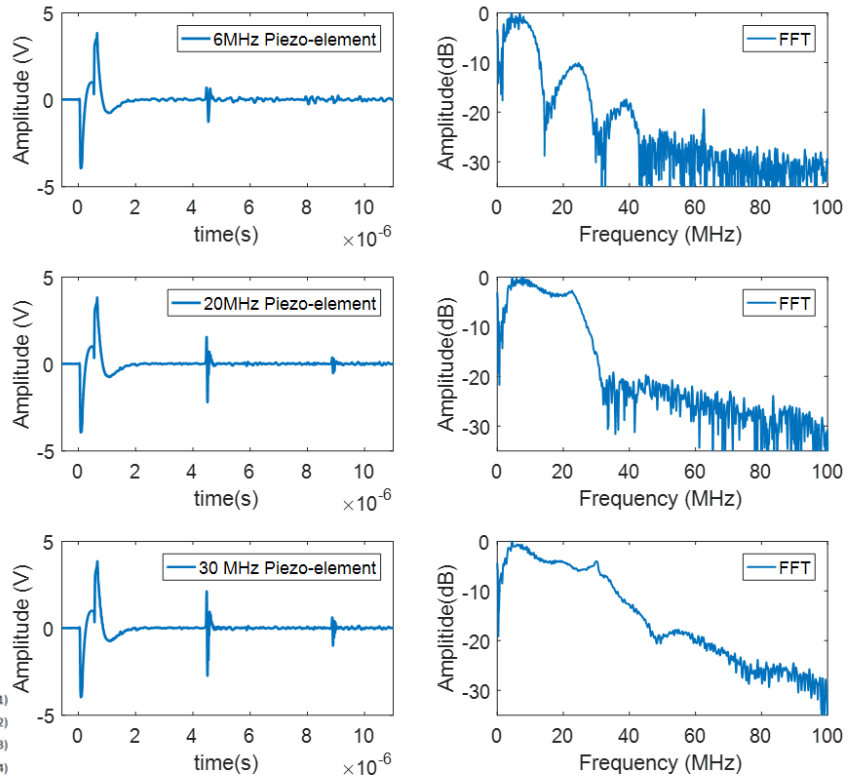


REUT I_ Pulse –echo response





REUT I_ Pulse –echo signal changes with thermal cycle

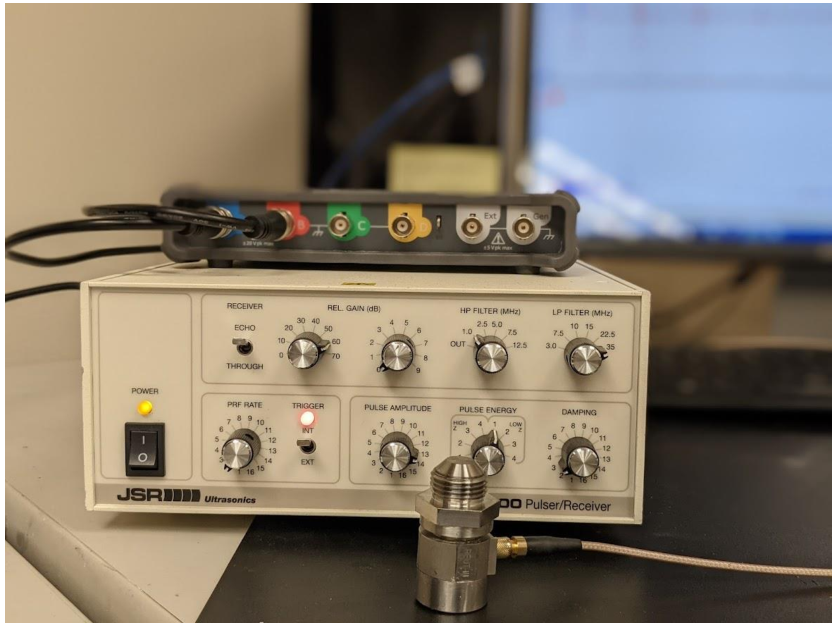


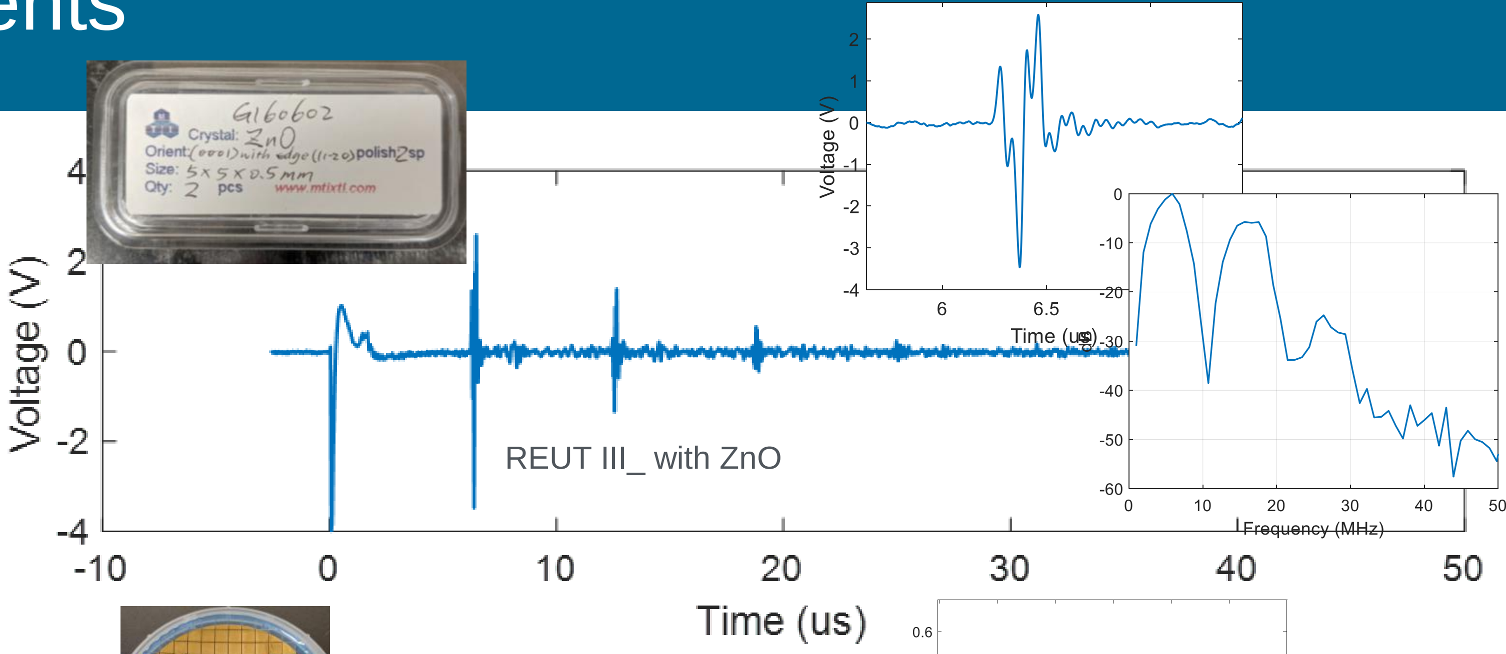
REUT I_ Pulse –echo response with different piezoelectric element

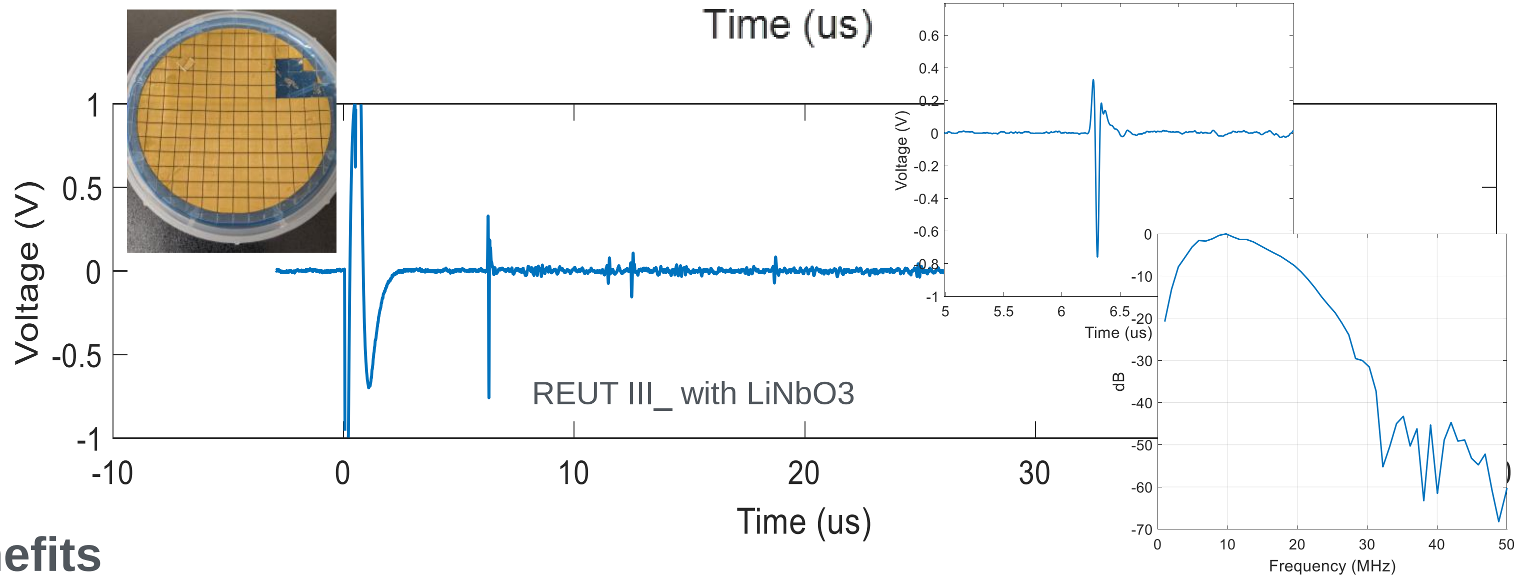
Results and accomplishments

REUT improved design :

- ¾-8 thread connectors for easy installation and maintenance
- 10-32 (microdot) rf connectors for electrical connection. We also have simple threaded rod configuration for rf connection to meet very high temperature application need.







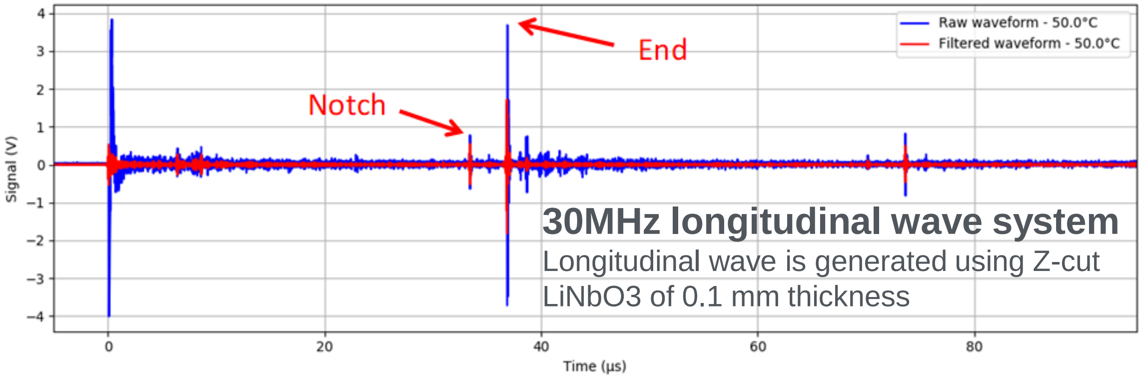
Benefits

•Any piezoelectric can be used (for best operation choose operation frequency 2 MHz or higher)
•Any ultrasonic pulser system can be used

Results and accomplishments

REUT Temperature sensor:

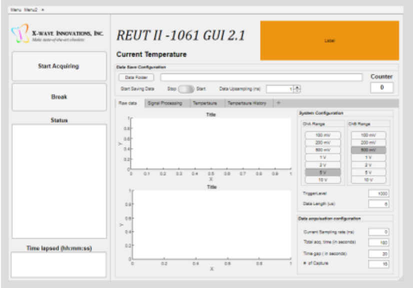
- Flange and ¾” NPT style temperature sensor with SS316 waveguide
- Waveguide length is 110mm
- Presently, we are using $LiNbO_3$ to generate longitudinal or shear wave in the waveguide
- We have developed application suite for temperature sensing

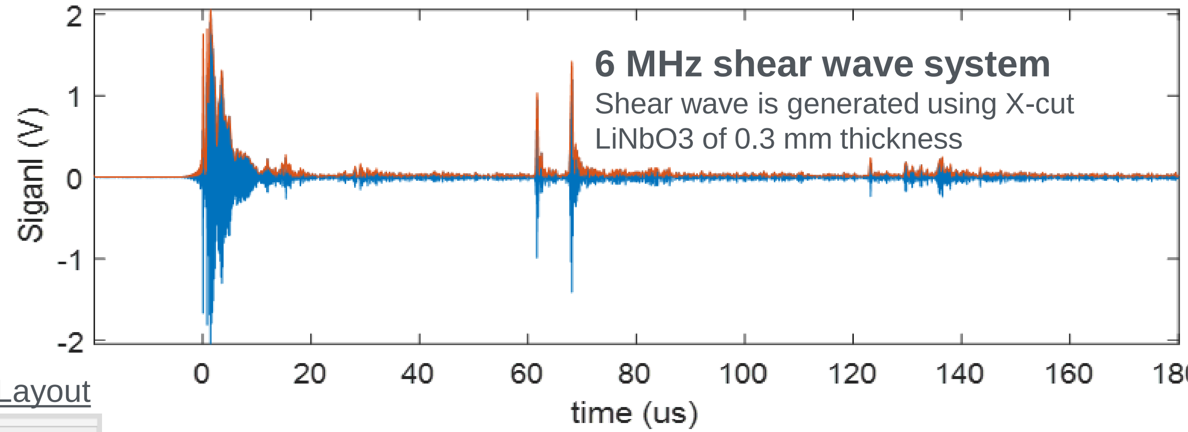


30MHz longitudinal wave system

Longitudinal wave is generated using Z-cut LiNbO3 of 0.1 mm thickness

Data Acquisition Layout



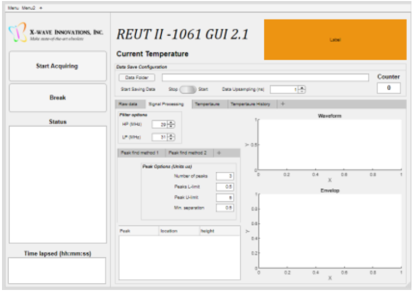


6 MHz shear wave system

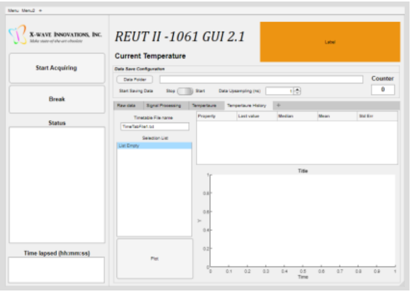
Shear wave is generated using X-cut LiNbO3 of 0.3 mm thickness

¾” NPT style connector for high pressure applications

Signal Processing Layout



Temperature history Layout

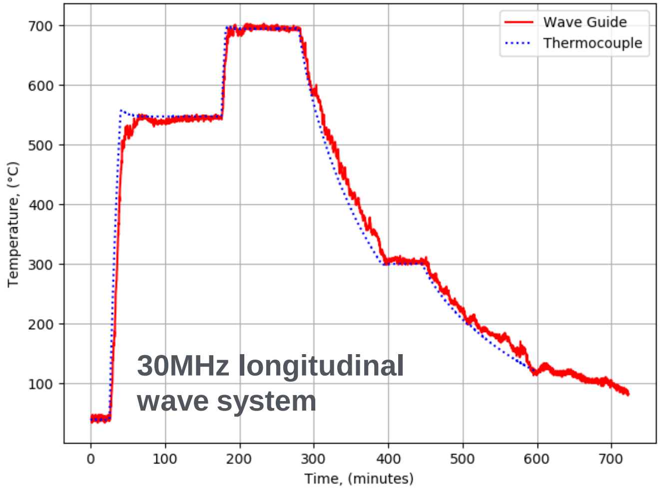


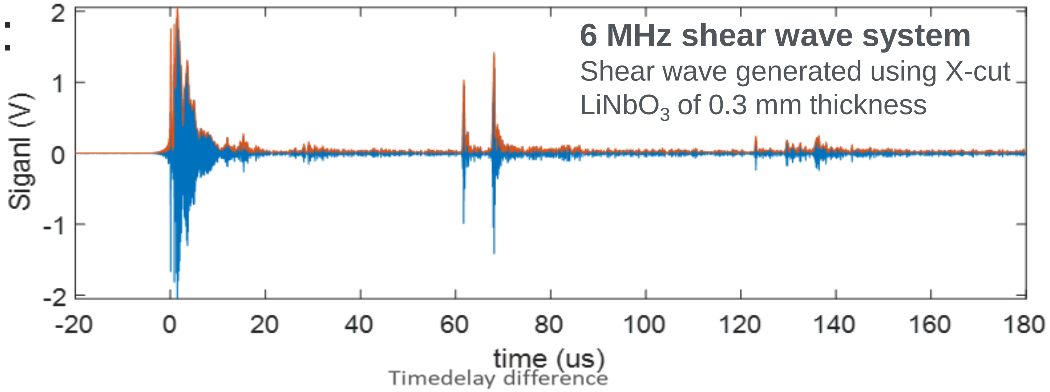
Benefits

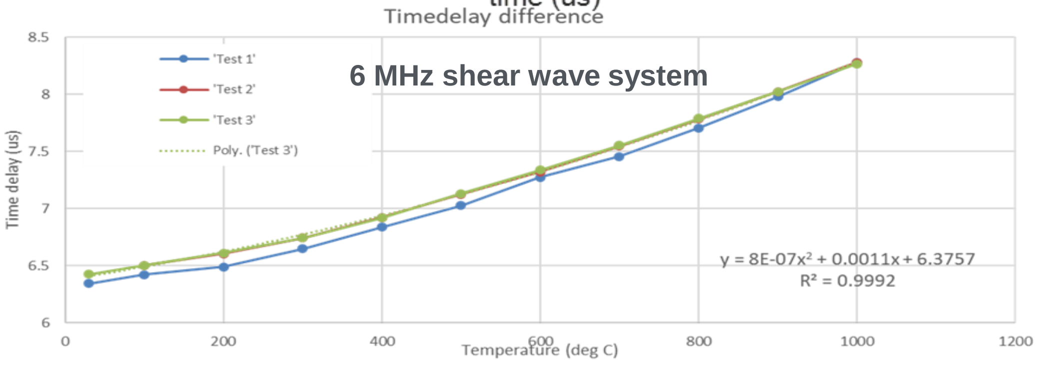
- Any piezoelectric can be used (for best operation choose operation frequency 2 MHz or higher)
- Any ultrasonic pulser system can be used
- Application specific waveguide materials and its length can be used

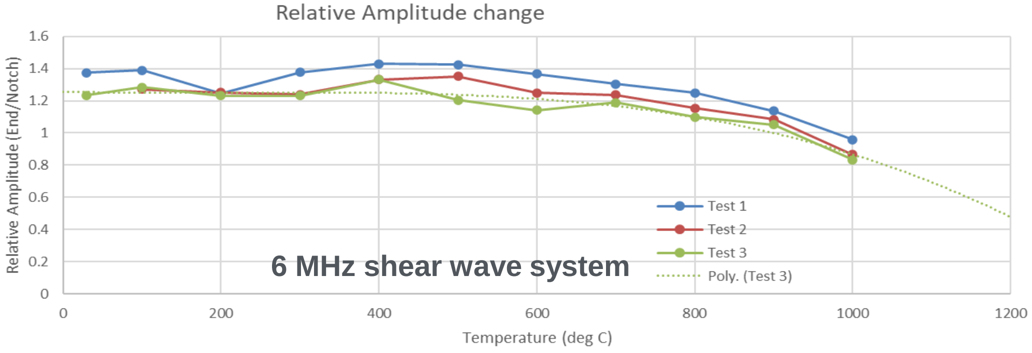
Results and accomplishments

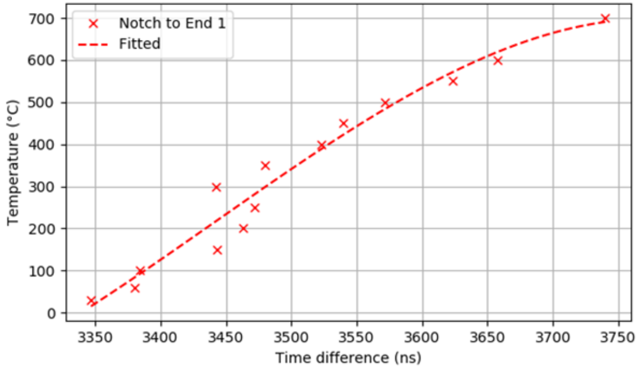
REUT Temperature sensor:

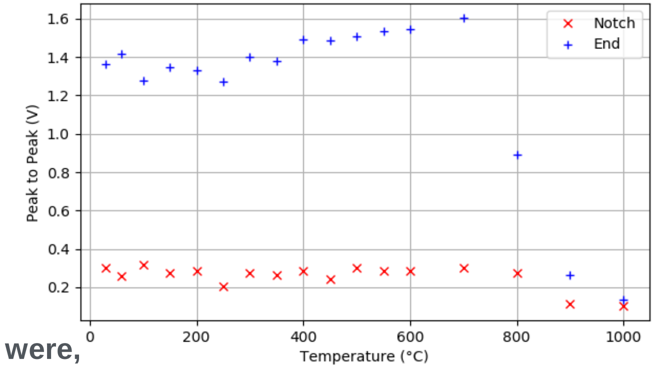












We were,

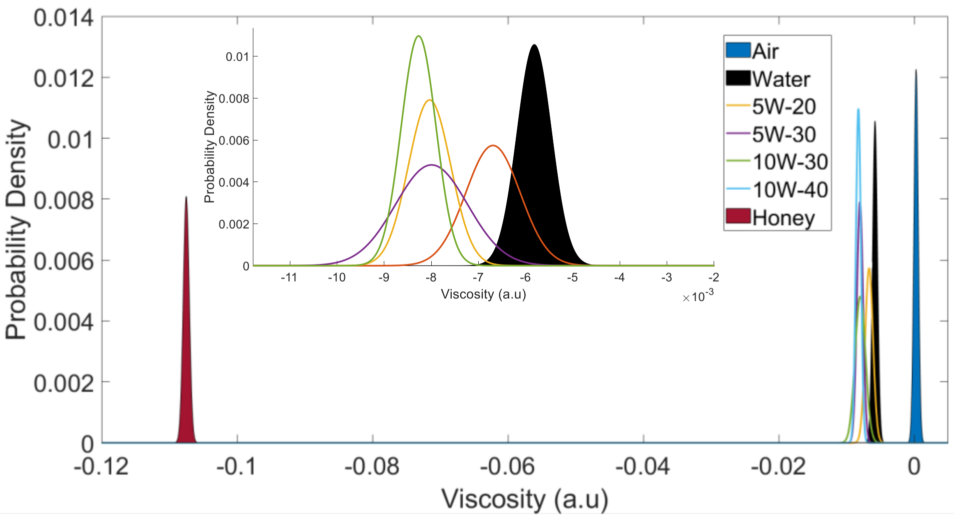
- **Unable to measure time delay beyond 700 ºC due to phase change in Ti**
- **Unable to reproduce performance at different thermal cycle due to oxidation**

Results and accomplishments

REUT viscosity monitoring system:

- ¾”-8 thread and ¾” NPT style viscosity sensor with SS316 ¾” delayline
- Presently, we are using X-cut 0.3 mm $LiNbO_3$ to generate 6MHz shear wave
- We have developed application suite for viscosity monitoring

¾” NPT style connector for high pressure applications

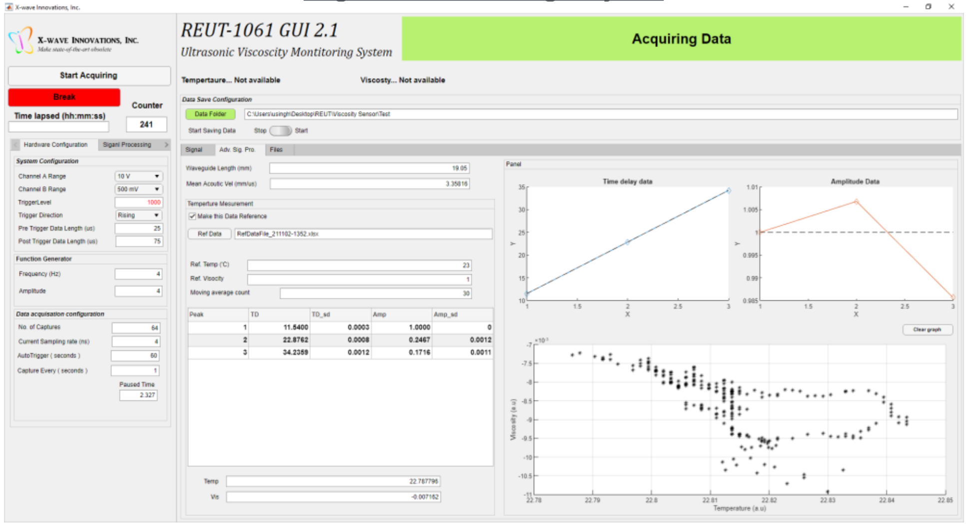


Benefits

•Suitable for viscosity and temperature monitoring at high temperatures
•Current state of fluid can be used as a reference and viscosity and temperature changes with respect to reference can be monitored

Data Acquisition Layout

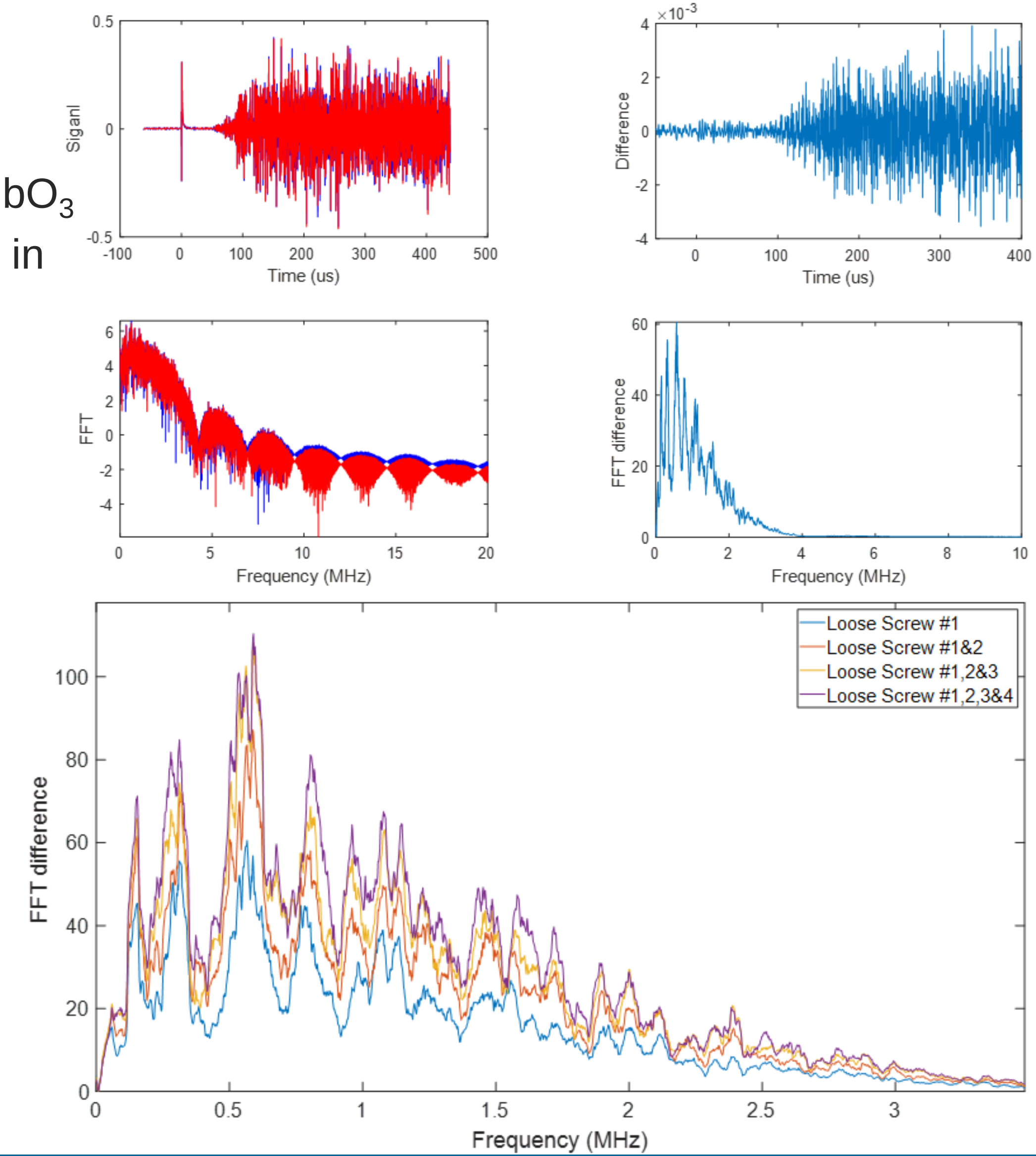
Signal Processing Layout



Results and accomplishments

REUT guided wave SHM :

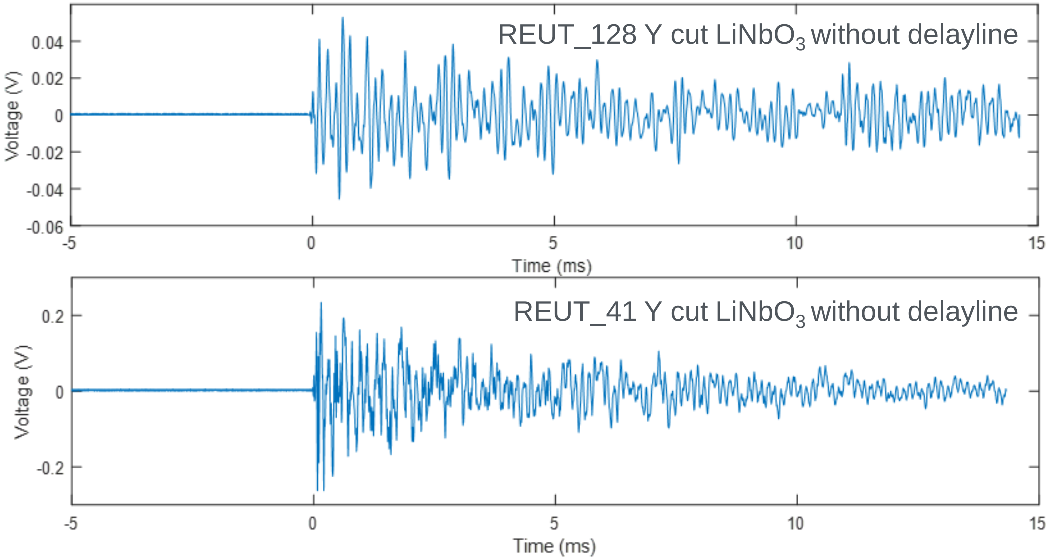
- ¾"-8 thread mounting sensor
- Presently, we are using 128 Y-cut 0.5 mm and 41 Y-cut 0.5 mm $LiNbO_3$
- We have developed signal processing technique to detect changes in the system and determine its location.

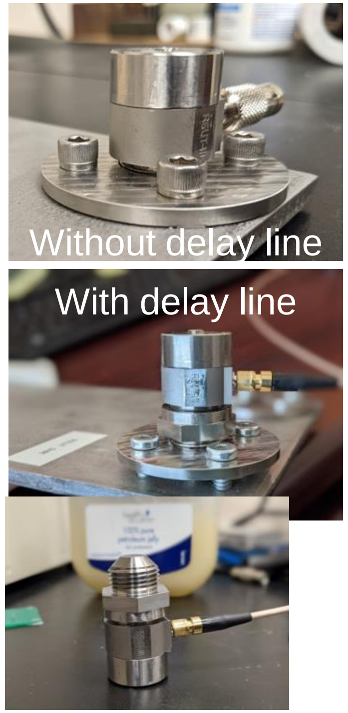


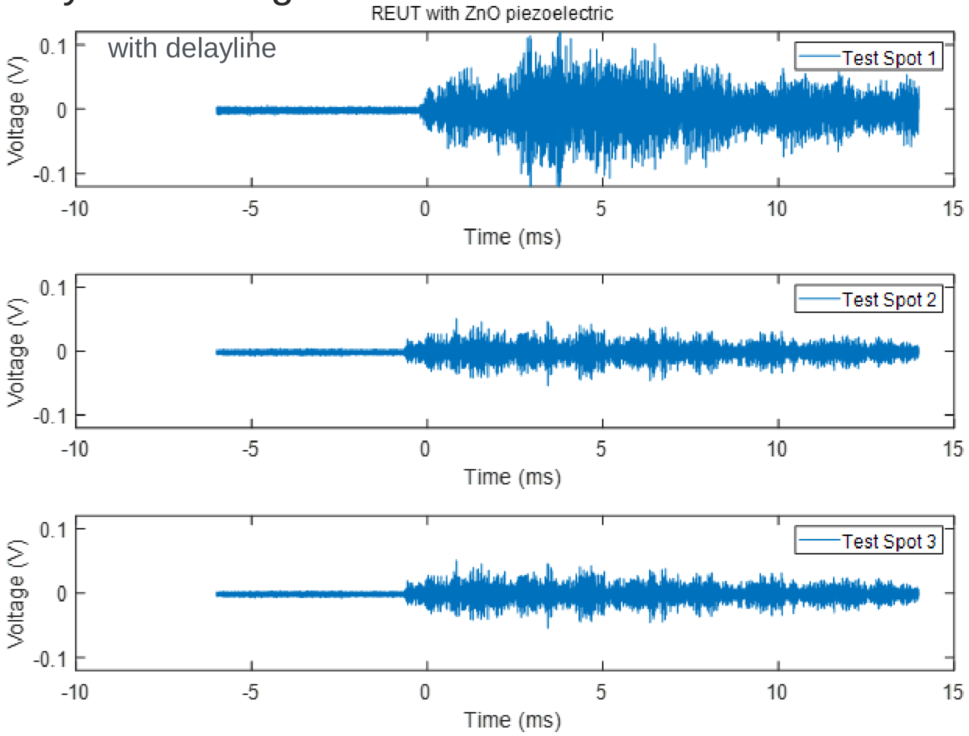
Results and accomplishments

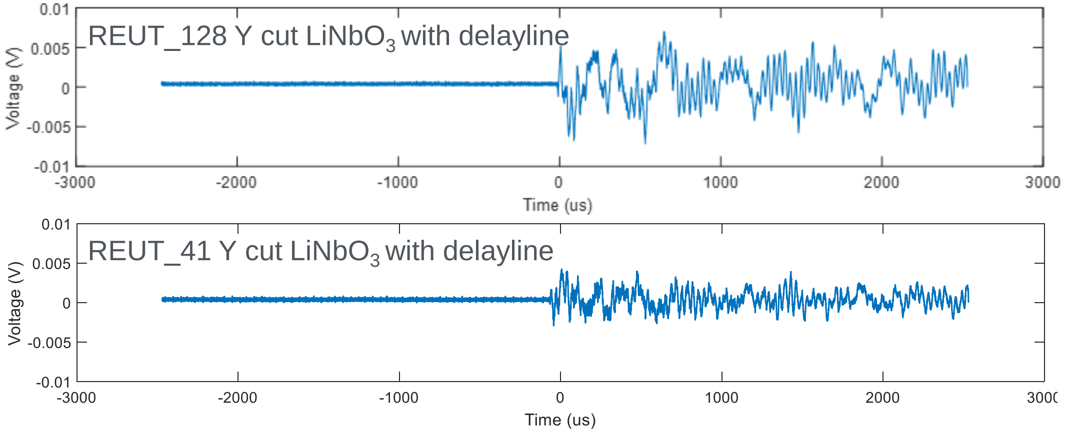
REUT AE system :

- ¾"-8 thread mounting sensor
- Presently, we are using 128 Y-cut 0.5 mm, 41 Y-cut 0.5 mm $LiNbO_3$ and 0.5mm ZnO piezoelement
- We have developed signal processing technique to suite for viscosity monitoring







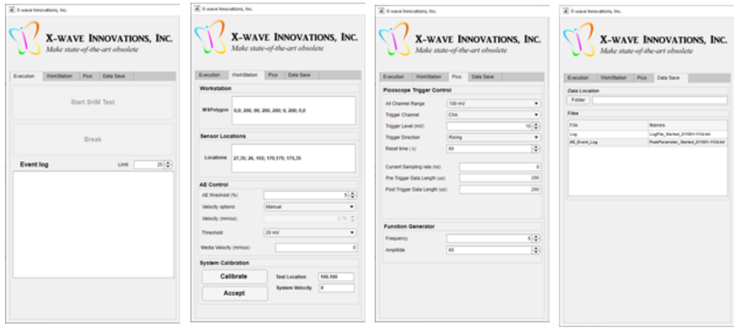


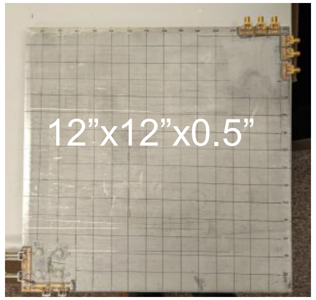
Results and accomplishments

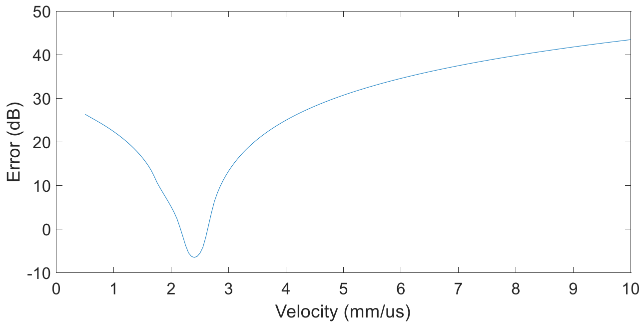
REUT AE signal processing and software development:

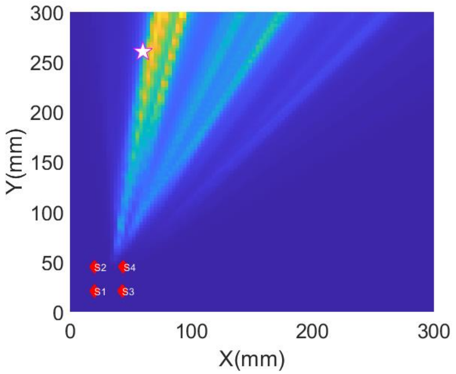
- We started with 4 (four)128 Y-cut 0.5 mm piezoelectric for data acquisition
- We have developed signal processing technique using maximum likelihood estimation, providing better estimation of defect location.
- The signal processing algorithm contains the ability to estimate ultrasonic velocity.

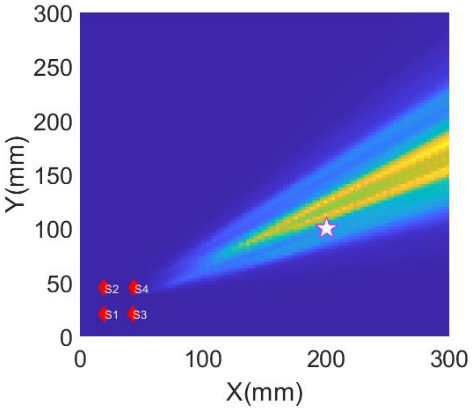
Signal Processing and Control Layout

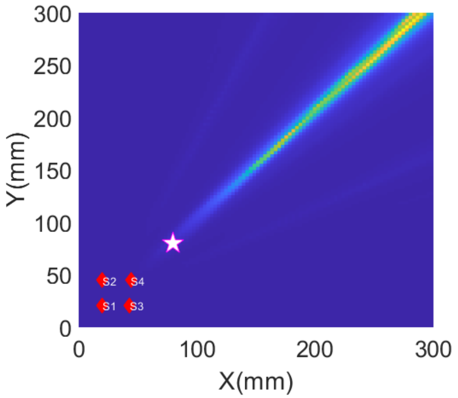


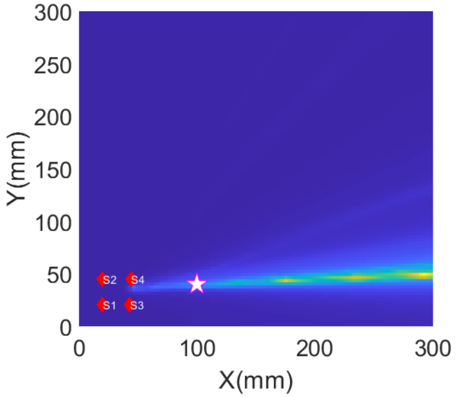


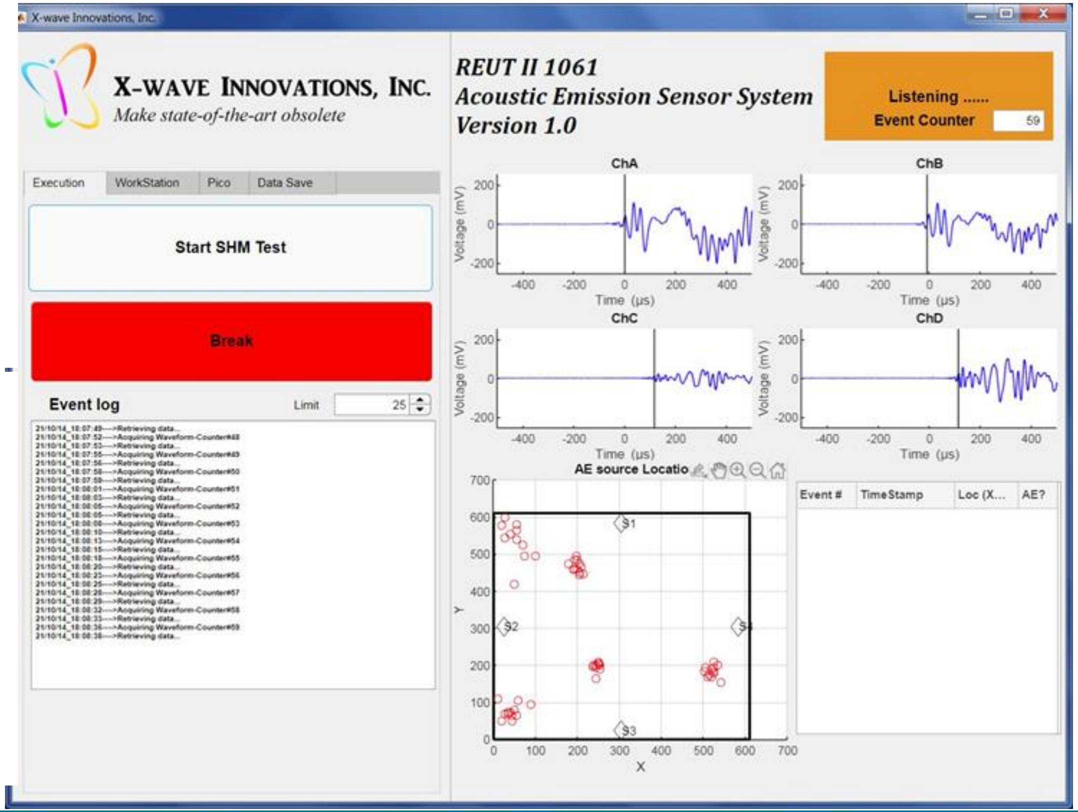








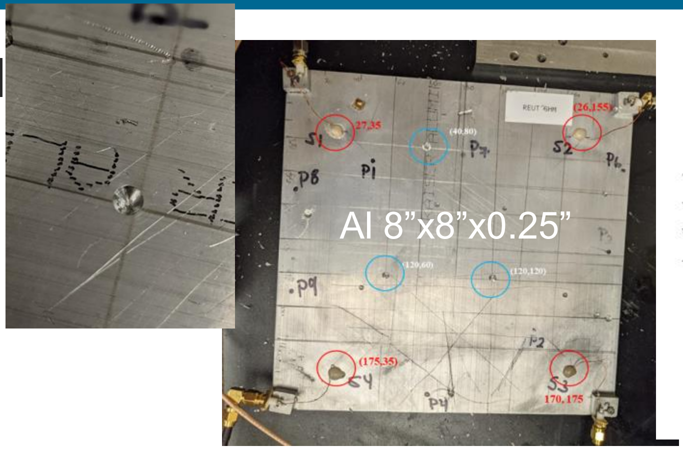


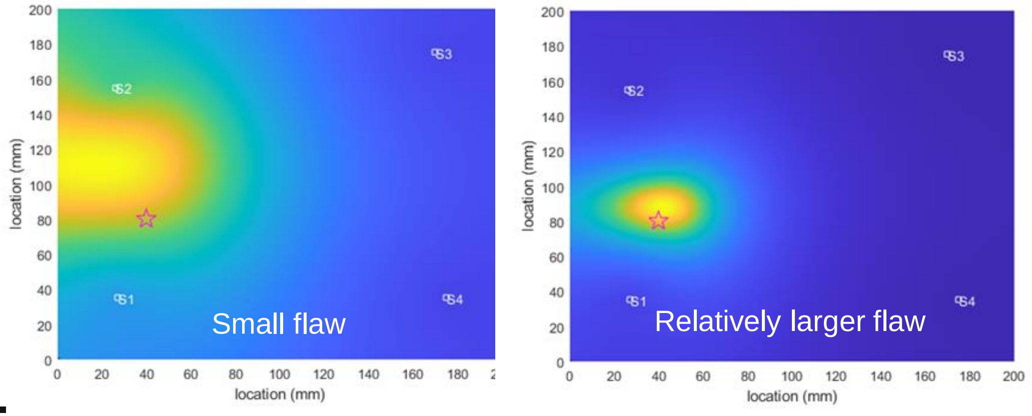


Results and accomplishments

REUT Guided Wave SHM signal processing:

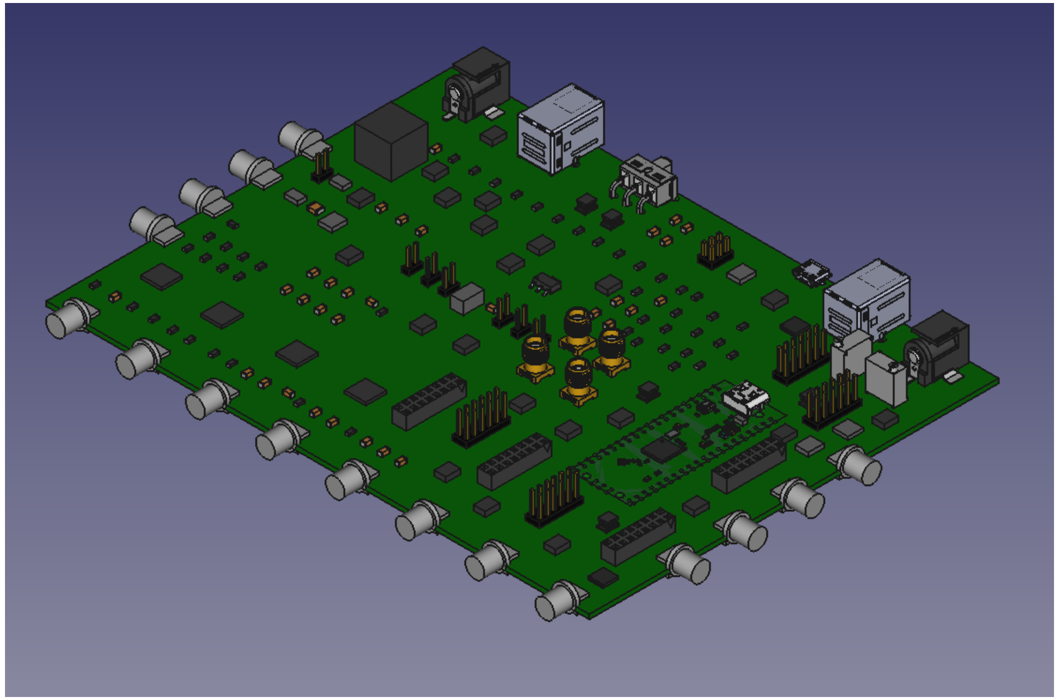
- We started with 4 (four)128 Y-cut 0.5 mm piezoelectric for data acquisition
- Develop system damage detection algorithm
- Developed algorithm to determine damage location





REUT Data Acquisition Hardware :

- 4 sensor data acquisition system
- To support,
    - 4 sensor AE and GW SHM system
    - 4 temperature sensing
    - 4 viscosity sensing
    - 4 thickness monitoring
    - 4 temperature, viscosity and thickness in any combination
- This modular hardware will be easy to program and the developed application suite will utilize this acquisition hardware



Conclusion

Advantages of REUT:

- **Radiation resilient**
  REUT design consists exclusively of components that are resilient to radiation.
- **Easy installation**
  The installation will simply require mounting the REUT on the subject surface using screws, and removing all the screws to take it off.
- **No organic couplant required**
  REUT uses soft metals (e.g. gold, silver, aluminum, etc.) as couplant
- **Easy to upgrade**
  Simply requires changing the piezoelectric element to better suit the application environment
- **Compatible with existing system**
  REUT is simply a better ultrasonic transducer suitable for radiation environments.
- **Low maintenance**
  Only element which can possibly degrade in the REUT system is the piezoelectric element.

Towards commercialization:

- Attended DOE i-corps to learn more about the market research and commercialization
- Approached Nuclear and O&G to get insight about sensor needs

Summary:

- We have developed a modified REUT
- We have developed REUT with delayline and tested its potential application in,
  - Viscosity monitoring
  - Thickness monitoring
- We have developed REUT based waveguide temperature sensors system
- We have developed REUT based SHM sensor system, including AE and guided wave

Future work:

- Complete the sensor development (design, acquisition system and software) based on end user recommendation
- Performance evaluation and validation
- Performance evaluation in radiation environment

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LinkedIn

Questions?

ASI | Advanced Sensors and Instrumentation

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ASI Advanced Sensors and Instrumentation

Analytics-at-Scale of Sensor Data for Digital Monitoring in Nuclear Plants

Advanced Sensors and Instrumentation (ASI)

November 18, 2021

Vivek Agarwal, PhD
Senior Research Scientist

Idaho National Laboratory

Project Overview

Scope (Project Duration: 2018-2022, includes 12 months no cost extension)

To advance online monitoring and predictive maintenance in nuclear plants and improve plant performance (efficiency gain and economic competitiveness)

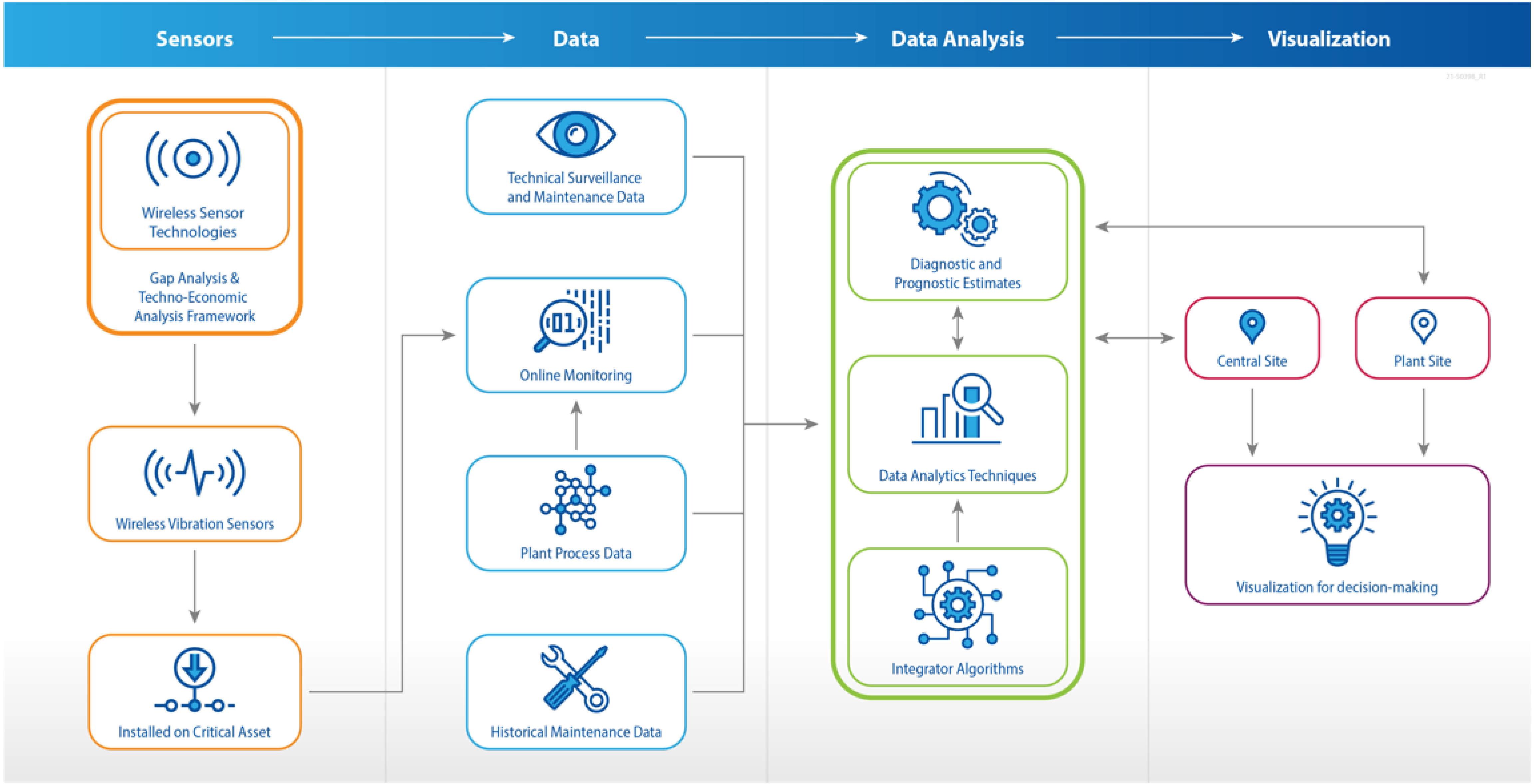
Objectives

- Techno-economic analysis of wireless sensor modalities
- Develop integrative algorithms for diagnostic and prognostic estimates using structured and unstructured heterogeneous data
- Develop visualization algorithms and guidelines
- Validate the developed methodologies

Project Team

- Idaho National Laboratory – Vivek Agarwal (PI), Nancy Lybeck, Cody Walker, and Koushik A. Manjunatha
- Oak Ridge National Laboratory – Pradeep Ramuhalli
- Electric Power Research Institute – Michael Taylor
- Exelon Generation Company – Charlotte Geiger

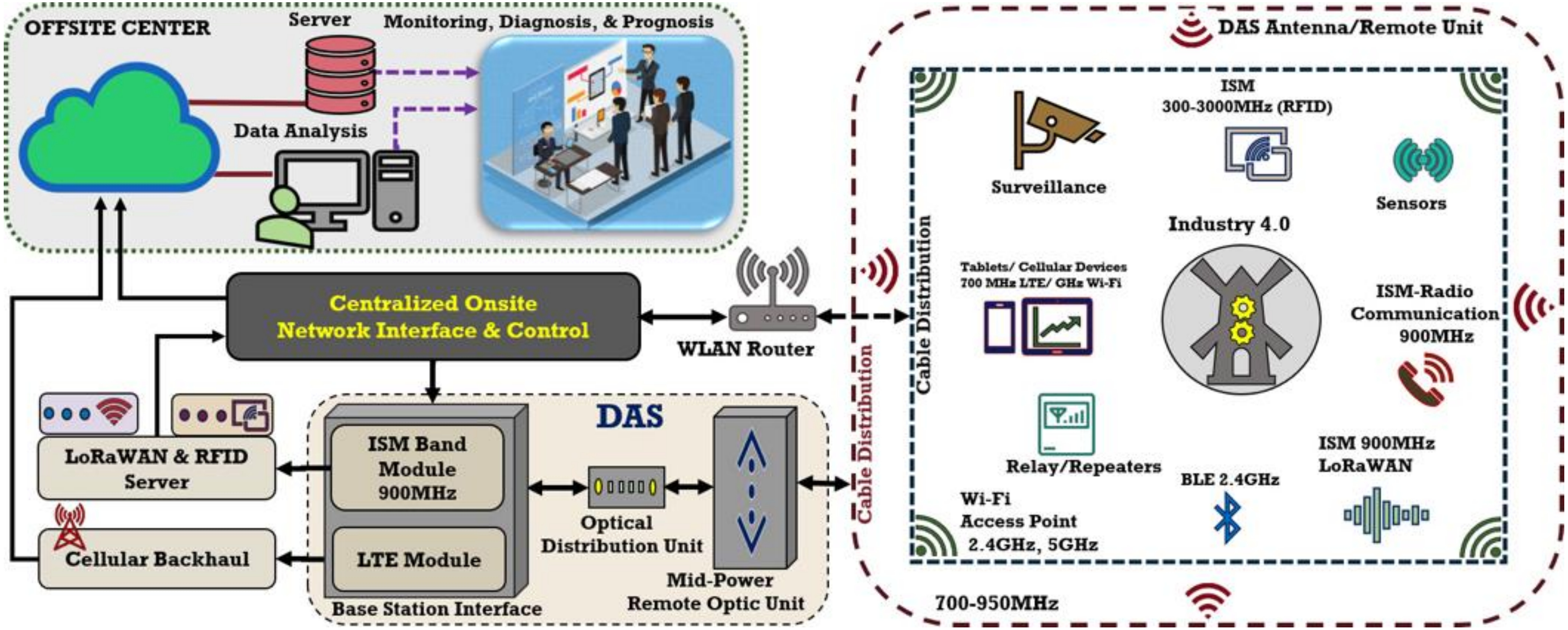
Approach



Sensors
Data
Data Analysis
Visualization
Wireless Sensor Technologies
Gap Analysis & Techno-Economic Analysis Framework
Wireless Vibration Sensors
Installed on Critical Asset
Technical Surveillance and Maintenance Data
Online Monitoring
Plant Process Data
Historical Maintenance Data
Diagnostic and Prognostic Estimates
Data Analytics Techniques
Integrator Algorithms
Central Site
Plant Site
Visualization for decision-making

Techno-Economic Analysis Framework

- A "one-size-fits-all" solution cannot be applied
  - application needs, quality of ser-vice requirements, and economic restrictions.



K. Manjunatha and V. Agarwal, “Multi-Band Heterogeneous Wireless Network Architecture for Industrial Automation: A Techno-Economic Analysis,” Accepted for Publication in Wireless Personal Communication Journal.

Preventative Maintenance Optimization to Lower Maintenance Costs

Milestone: Nuclear Power Fault Diagnostics and Preventative Maintenance Optimization (Completed January 2021)

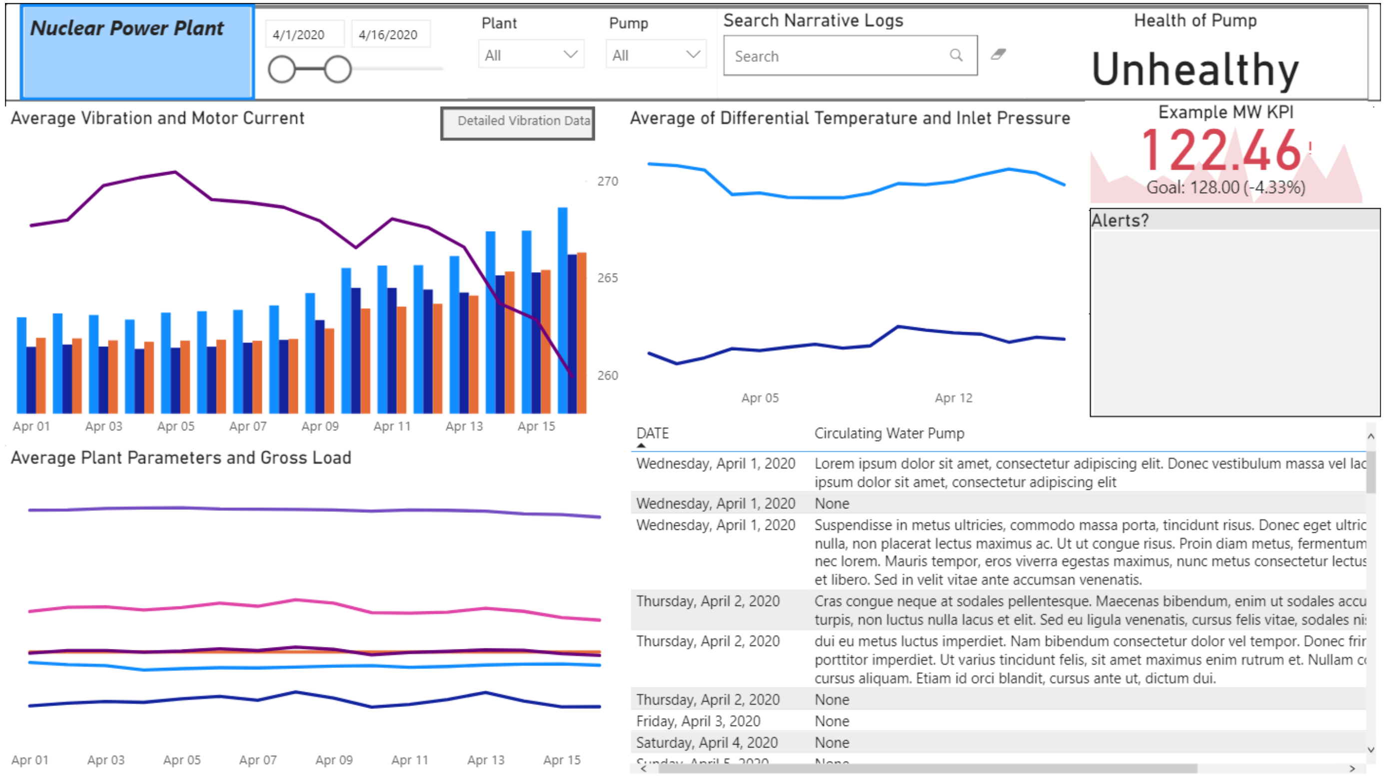
- Different forms of data was obtained from two Exelon Plants
  - Work order data
  - Plant process data
  - Maintenance records
- Healthy components were determined through process data and maintenance records.
- Current Preventative Maintenance (PM) frequencies for healthy components were compared to industry averages using EPRI's Preventative Maintenance Basis Database (PMBD).
- Several candidates were found for frequency extension.

Component	PM Task	Current PM Frequency	EPRI PMBD	Recommendation
Condensate pump and Condensate Booster pump	Refurbishment	8 years	As required	Good candidate for frequency extension
	Vibration Monitoring	3 months	3 months	Keep
	Oil Analysis	6 months	6 months	Keep
Motor	Vibration Analysis	3 months	3 months	Keep
	Fan Cleaning	6 months	2 months	Keep
	Oil Analysis	6 months	6 months or 1 year	Good candidate for frequency extension
	Electrical Testing/ Inspection	5 years	4 years	Keep

Data Visualization to Support Decision-Making

Milestone: Nuclear Power Fault Diagnostics and Preventative Maintenance Optimization (Completed: May 2021)

- Goals of visualization guidance
  - Usability
  - Saliency
  - Error prevention
- Visualization recommendation
  - Highlight consequential information
  - Group related types of information
  - Ensure navigability of information
  - Clearly delineate actual and predicted information
- Visualization tools
  - Microsoft Power BI
  - Tableau
  - Custom solution

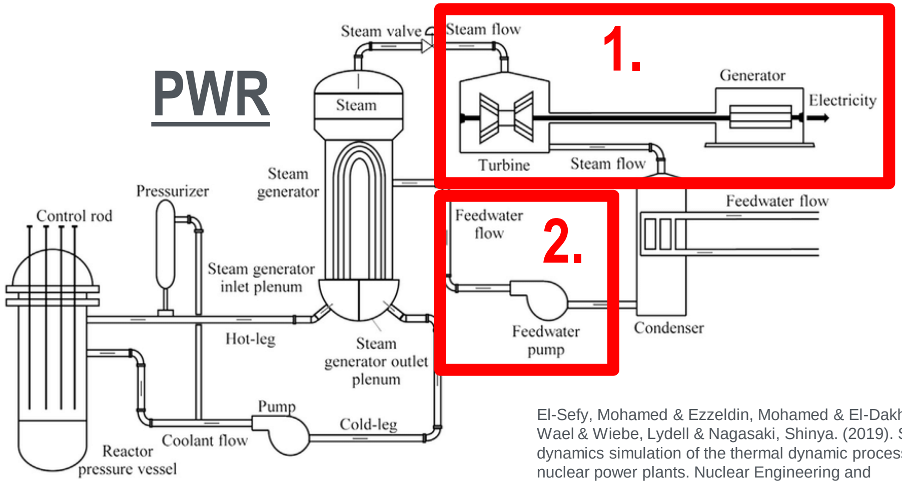


Validation & Verification (V&V) of Short-Term Forecasting Models

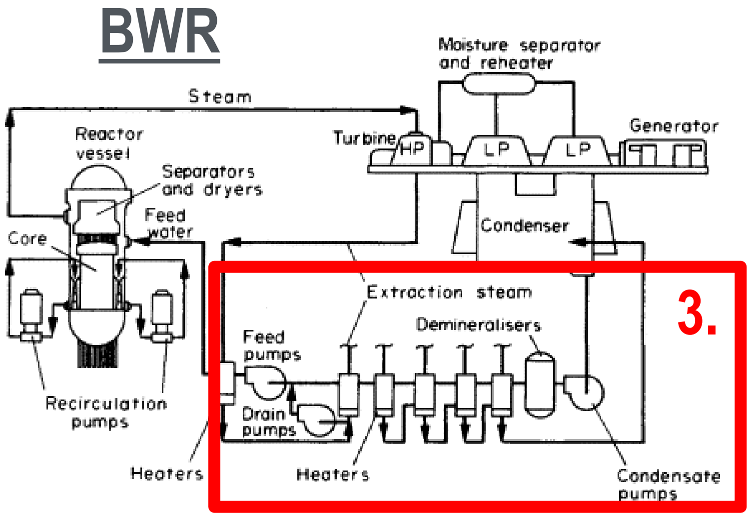
- Data was taken from three nuclear plant system (2 PWR and 1 BWR):
  1. PWR main turbine system
  2. PWR steam generator feed pump
  3. BWR condensate and feedwater system

- Recorded plant parameters and features to be forecasted varied depending on the system.

- V&V was not on a single model, but rather on the methodology from processing raw data until prediction (i.e., data preprocessing, feature selection, model optimization, and forecasting).



El-Sefy, Mohamed & Ezzeldin, Mohamed & El-Dakhakhni, Wael & Wiebe, Lydell & Nagasaki, Shinya. (2019). System dynamics simulation of the thermal dynamic processes in nuclear power plants. Nuclear Engineering and Technology. 51. 10.1016/j.net.2019.04.017.

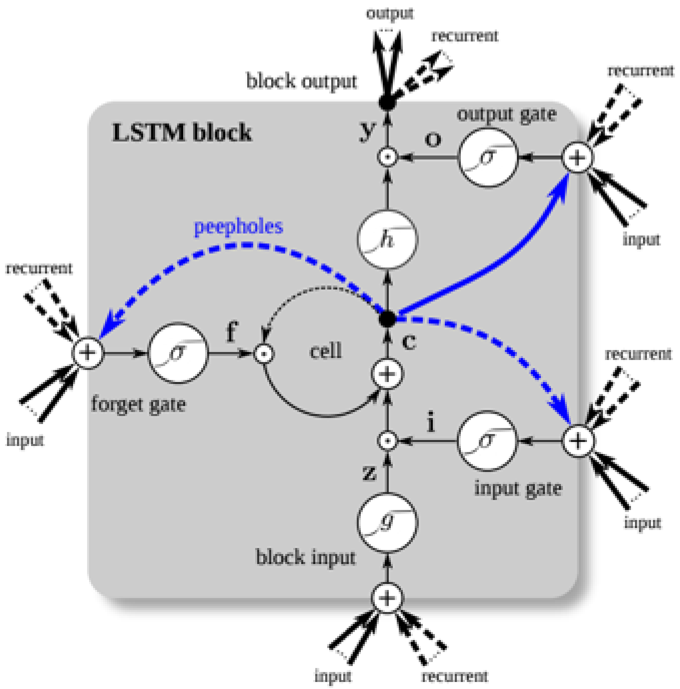


Source: Jeffery Lewins PhD (Cantab), PhD (MIT), in Nuclear Reactor Kinetics and Control, 1978

Validation & Verification (V&V) of Short-Term Forecasting Models

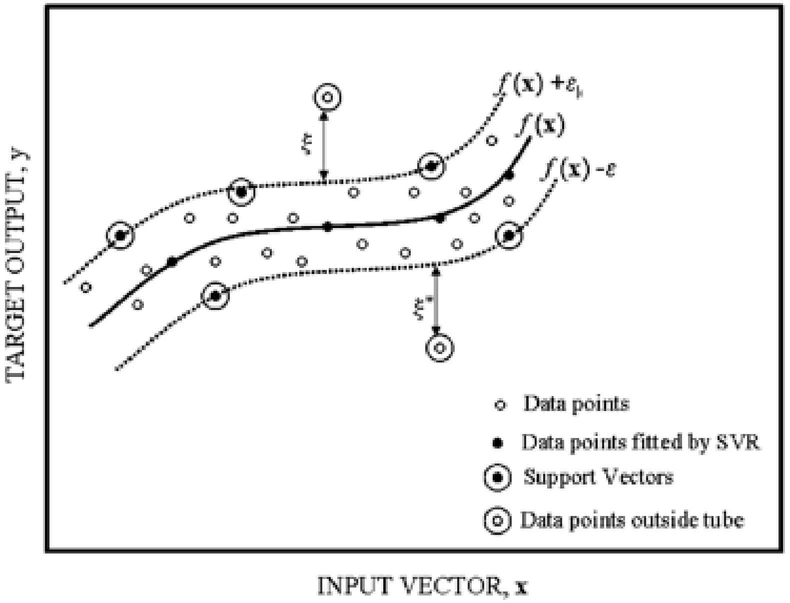
- Forecasting focused on two ML models, Long Short-Term Memory (LSTM), and Support Vector Regression (SVR), for predicting both 1-hour and 1-day ahead.

LSTM



NVIDIA Corporation. “Long Short-Term Memory (LSTM). Online. 2020.

SVR



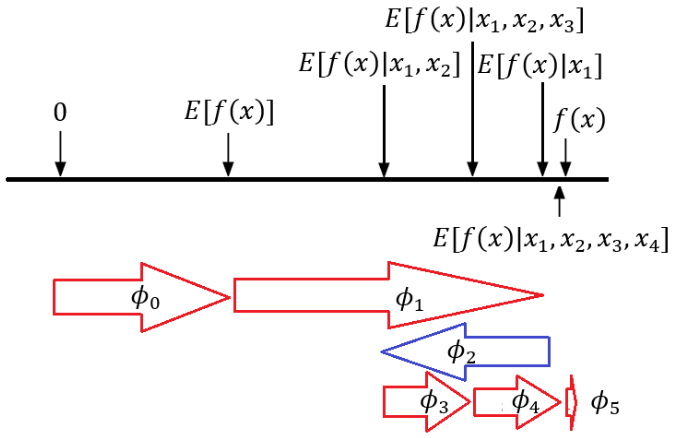
Gandhi, Ankit B., et al. "Development of support vector regression (SVR)-based correlation for prediction of overall gas hold-up in bubble column reactors for various gas–liquid systems." *Chemical Engineering Science* 62.24 (2007): 7078-7089.

Data Preprocessing and Feature Selection

- Data Preprocessing included:
  - Addressing missing values
  - Outlier Detection
  - Data smoothing
  - Normalizing data to zero mean and variance

- Feature selection utilized the mean Shapley additive explanations (SHAP) values to determine input features based on importance.

- A dynamic threshold was used to determine the importance cutoff. Any value smaller than one order of magnitude than the most importance feature was cut. On the right, shell expansion was cut from the model input.



SHAP is an additive feature attribution method

$$f(x) \simeq g(x') = \phi_0 + \sum_{i=1}^{M} \phi_i x'_i$$

- f(x) is the original model
- g(x') is the explanation model
- Φ_0 represents the constant value when all inputs are missing
- M is the number of input variables
- Φ_i is the feature attribution values
- x_i' are the simplified inputs.
- inputs related through mapping function, x = h_x(x')

Feature	Importance	Φ_i
Turbine Speed	0.608	Φ_1
Turbine Rotor Expansion	0.309	Φ_2
Turbine Differential Expansion	0.161	Φ_3
Flow to Turbine	0.151	Φ_4
Shell Expansion	0.029	Φ_5

Feature selection for predicting bearing vibration based on SHAP importance values

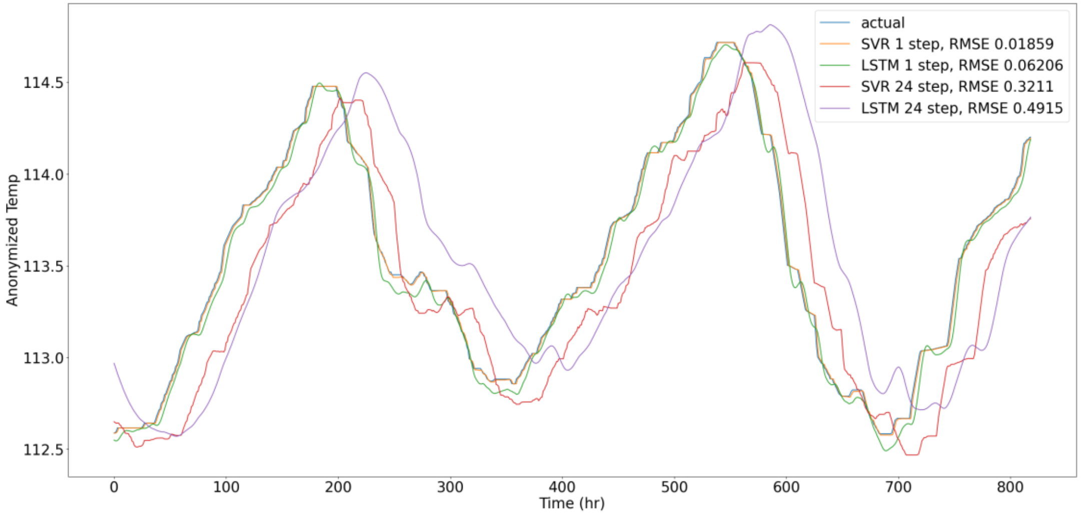
Accomplishments

Milestone: Verification and Validation of developed short-term forecasting models (Completed November 2021)

- Tested multiple methods for multi-step forecasting:
  - Direct, Recursive, and Direct-recursive.
- LSTM and SVR were used to predict 4 different plant parameters across 3 different plants using 2 prediction horizons (1-hour and 1-day).
- V&V was accomplished using a 10-fold cross validation approach then comparing the mean and standard deviation of the root mean square error (RMSE).
- For this analysis, SVR outperformed LSTM, but further improvements could potentially be made to the LSTM architecture that would improve its results.

Verification and Validation model results.

Comparison of LSTM and SVR for predicting bearing temperature 1-step and 24-steps ahead.



Data set			1-step ahead		24-steps ahead	
Plant	Parameter Predicted	Model	Mean RMSE	Std Error	Mean RMSE	Std Error
PWR 1	Main Turbine Bearing Temp	LSTM	0.0796	0.0411	0.7932	0.5450
		SVR	0.0214	0.0080	0.3194	0.1202
PWR 1	Generator Output	LSTM	0.2871	0.2031	2.2636	2.8338
		SVR	0.0806	0.0422	1.5611	1.2424
PWR 2	Steam generator flow	LSTM	2.4792	3.0455	12.435	17.333
		SVR	1.4070	2.4270	5.6299	5.3154
BWR	Condensate Pump Bearing Temp	LSTM	0.0792	0.0722	0.2991	0.2724
		SVR	0.0323	0.0496	0.2238	0.2184

Publications

Journal Article:

- K. Manjunatha and V. Agarwal, “Multi-Band Heterogeneous Wireless Network Architecture for Industrial Automation: A Techno-Economic Analysis,” Accepted for Publication in Wireless Personal Communication Journal.

Conference Proceedings:

- Walker C.M., P. Ramuhalli, V. Agarwal, N. Lybeck, M. Taylor. "Nuclear Power Fault Diagnostics and Preventative Maintenance Optimization." Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies Conference. Providence, RI. June 13–17, 2021.

- Ramuhalli, P. C.M. Walker, V. Agarwal, N. Lybeck, M. Taylor. "Nuclear Power Prognostic Model Assessment for Component Health Monitoring." Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies Conference. Providence, RI. June 13–17, 2021.

ASI Newsletter

- Walker C.M., V. Agarwal, N. Lybeck, P. Ramuhalli, M. Taylor. "Analytics-at-scale of Sensor Data for Digital Monitoring in Nuclear Plants." 2021 NEET Advanced Sensors and Instrumentation Project Summaries. September 16, 2021.

Technology Impact

- *Advances the state of the art for nuclear application*
  - Advances online monitoring at a nuclear plant site for different plant assets
  - Provides machine learning approaches to integrate and analyze heterogeneous structured and unstructured data (i.e., analytics-at-scale)
  - Visualization of information to make informed decision-making

- *Supports the DOE-NE research mission*
  - Enable economical long-term operation of existing fleet of reactors
  - Research outcomes can be utilized to develop maintenance strategy for advanced reactors

- *Impacts on the nuclear industry*
  - Enable industry to transition from preventive maintenance strategy to predictive maintenance strategy
  - Enhance reliability and economic operation of domestic existing fleet

- *Commercialization*
  - Project team will develop a transition plan to enable transfer of research outcomes to an industrial partner

Summary

- Developed a techno-economic analysis framework to evaluate different wireless sensors
- Developed diagnostic and prognostic models based on heterogeneous data sets from different plant sites
  - Applied Shapley additive explanations (SHAP) values to understand importance of a feature
  - Applied Variance inflation factors (VIF) method to understand the level of multicollinearity among plant variables
- Identified visualization gaps and standards to present information in right format to minimize information overload, enhancing informed decision-making
- Submitted milestone on validation and verification of the developed short-term forecasting methodologies on independent data sets obtained from Electric Power Research Institute.

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

ASI Advanced Sensors and Instrumentation

Status of the Optical Dilatometer Method of Evaluating the Peak Irradiation Temperatures of SiC Passive Monitors

CT-21IN0702042

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

Malwina Wilding
Nuclear Instrumentation Engineer

Idaho National Laboratory

Project Overview

Objective

Passive temperature monitors are needed for when real-time sensors are not practical or economical to install in an irradiation test. The main purpose is to provide a practical and reliable approach to estimate peak irradiation temperature during post-irradiation examination (PIE) for direct integration in irradiation test designs.

Participants

- Idaho National Laboratory
  - Malwina Wilding (PI & WPM), Austin Fleming (TPOC), Kurt Davis, Ashley Lambson, and Kory Manning

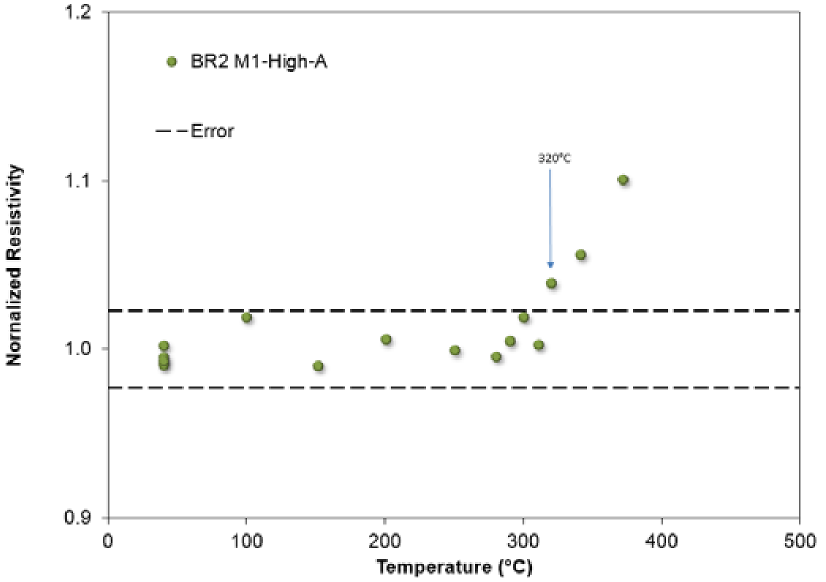
Schedule

- September 2021: Complete level 3 milestone (21IN0702044) titled “Perform comparative assessment of optical and resistivity measurement methods for the evaluation of silicon carbide peak temperature monitors”

Resistivity Method

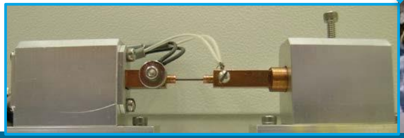
- Electrical resistivity is accepted as a robust measurement technique resulting in accuracies within 20ºC
- Very time and labor-intensive process with near-constant attention from trained staff (1 week to 3 week per sample)
  - Labor time for Technician, Engineer, Radiological Control, and Administrative Assistant
- Adds many potential sources of measurement error:
  - Potentially result in oxidizing the SiC temperature monitor
  - Measurement error due to repeatedly transferring back and forth between the furnace and the test fixture
- Currently can only process rod-shaped SiC temperature monitors

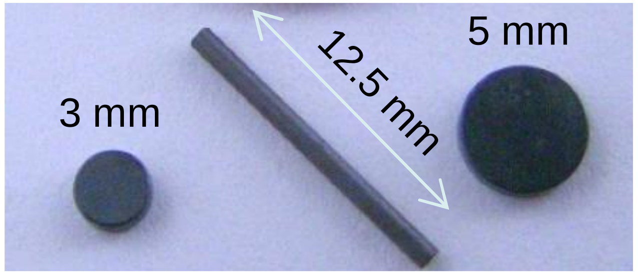
Typical Resistivity Response



Resistivity Method Set-Up

Spring loaded sample fixture.

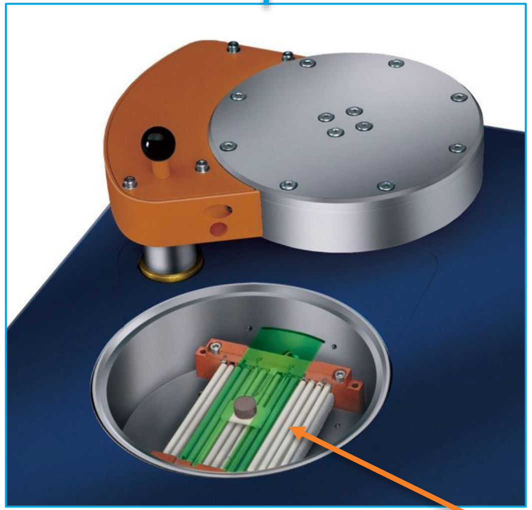


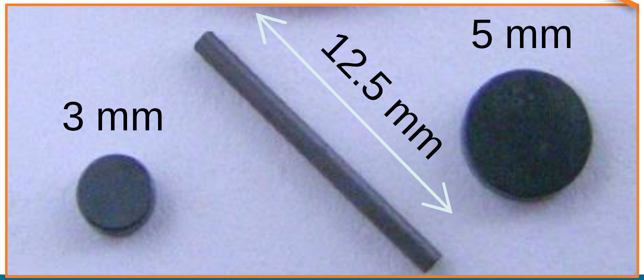


SiC temperature monitors

Optical Dilatometer Method

- Automated process requiring minimal setup time
- Dilatometer runs under vacuum or inert gas
  - key requirement for avoiding any oxidization issues involving the SiC temperature monitors
- Max. operating temperatures of 1400ºC (resolution of 0.1ºC)
  - SiC passive monitor temperatures are 200 – 800ºC (sensitivities within +/- 20ºC)
- Reduced time expense
  - Time to process each sample 2 to 3 days (irradiation target temperature dependent)
- Contactless dilatometric measurement system
  - Allows samples to freely expand/shrink without any interference from mechanical contact
- Can process all SiC temperature monitors (rod and both discs)
  - 0.3–30 mm in length with a maximum height of 10 mm





Technology Impact

- Passive monitors provide a practical, reliable, and robust approach to measure irradiation temperature during post-irradiation examination while requiring no feedthroughs/leads comparable to current more-complex real-time temperature sensors
- They have been chosen because they have a proven history for use by stakeholders for deployment and require continued development and characterization to assure successful integration with program schedules and objectives
- Further develop the temperature passive monitor capability for wider rage of temperatures, geometries and neutron damage
- Facilitates the development of advanced sensors and instrumentation with cross-cutting technology development to support the existing fleet, advanced reactor technology and advancing fuel cycle technology development

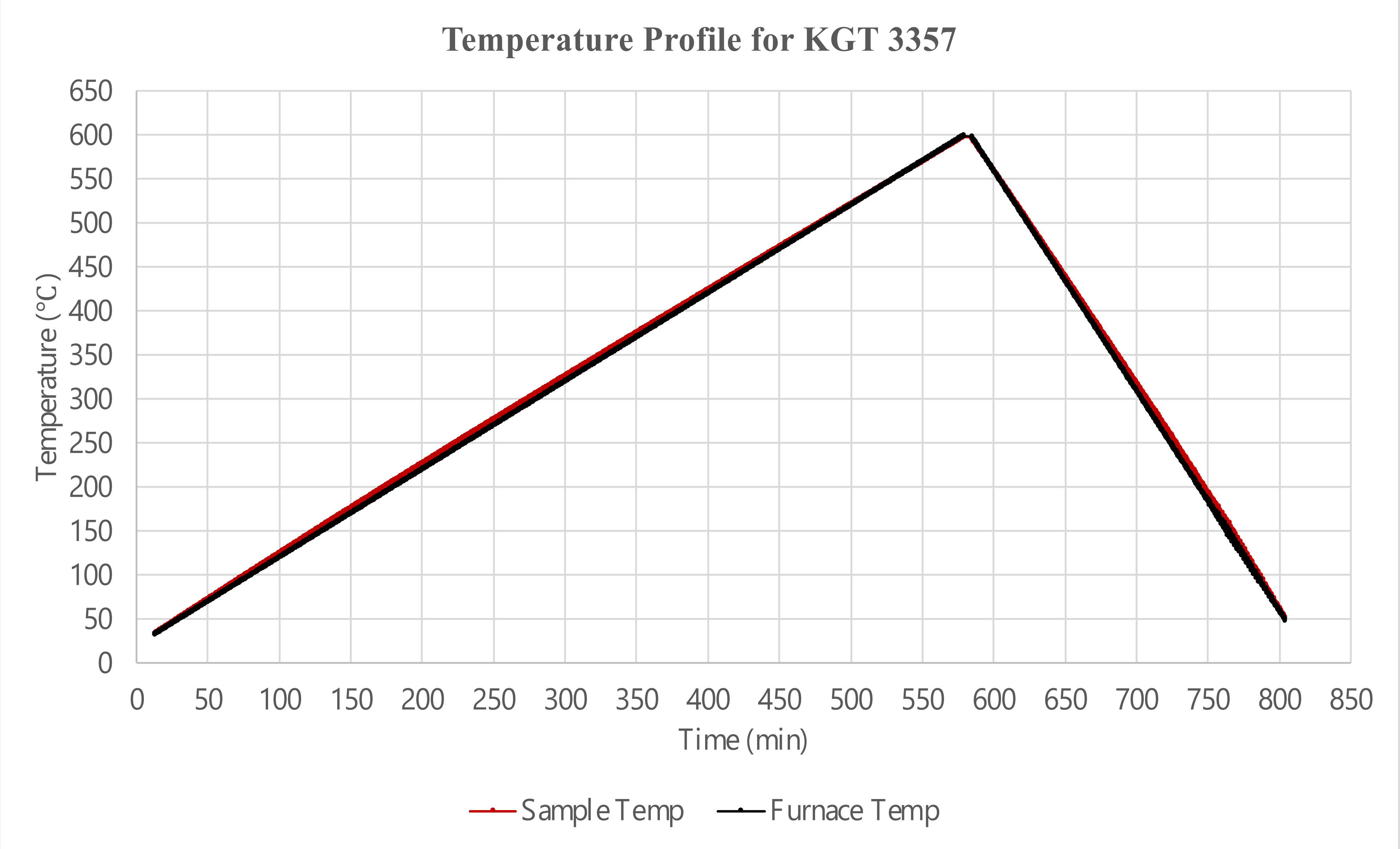
Issues (Schedule/Cost/Technical)

- NSUF planned to provide 10 SiC temperature monitors:
  - BSU-8242 with 7 SiC rods: 1-SiC rod per capsule for 7 capsules (located in the middle of the capsule)
  - GE-Hitachi with 3 SiC rods: 3-SiC rods per 1 capsule (located in the bottom, middle, and top of the capsule)
- Multiple Delays:
  - Acquiring
  - Shipping
  - Cleaning (HF wash) the SiC temperature monitors
  - Still only received one (1) SiC temperature out of the 10 initially planned for
- Highlight:
  - First SiC temperature monitor cleaned to a point of free release (no radiation above background detected)

Optical Dilatometer Results

- One NSUF SiC temp monitor:
  - BSU-8242 Experiment (300℃ and 1 dpa)
  - KGT 3357 sample ID
- Before Irradiation details:
  - Diameter: 0.98 mm
  - Length: 12.50 mm
- Melt Wire Results:
  - 238.6℃ to 271.5℃ temperature range
- Dilatometer Program:
  - 600℃ max. temp (target temp. + 300℃)
  - 1℃/min heating rate
  - Hold 5 min at 600℃
  - -2.5℃/min cooling rate

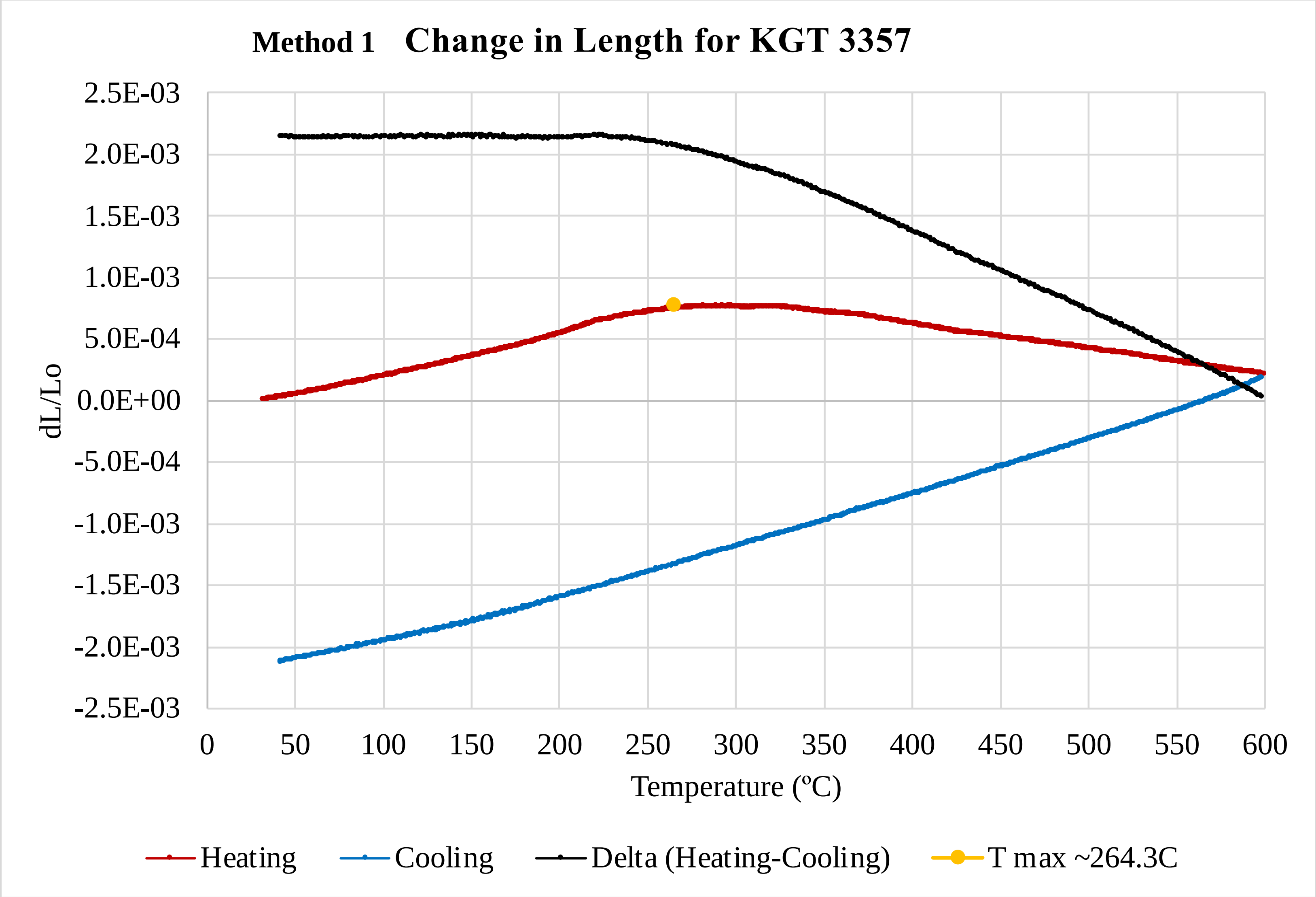
Furnace and Sample temperature control almost identical for KGT-3357



Method 1

- KGT 3357 SiC Monitor:
  - Length before annealing in dilatometer: 12.6081 mm
  - Change in length before and after irradiation of ~0.108 mm
  - Final length after dilatometer annealing: 12.5808 mm
  - Shrinkage during annealing in dilatometer of ~0.027 mm
  - Temperature at max. length change during heating is **~264.3℃**

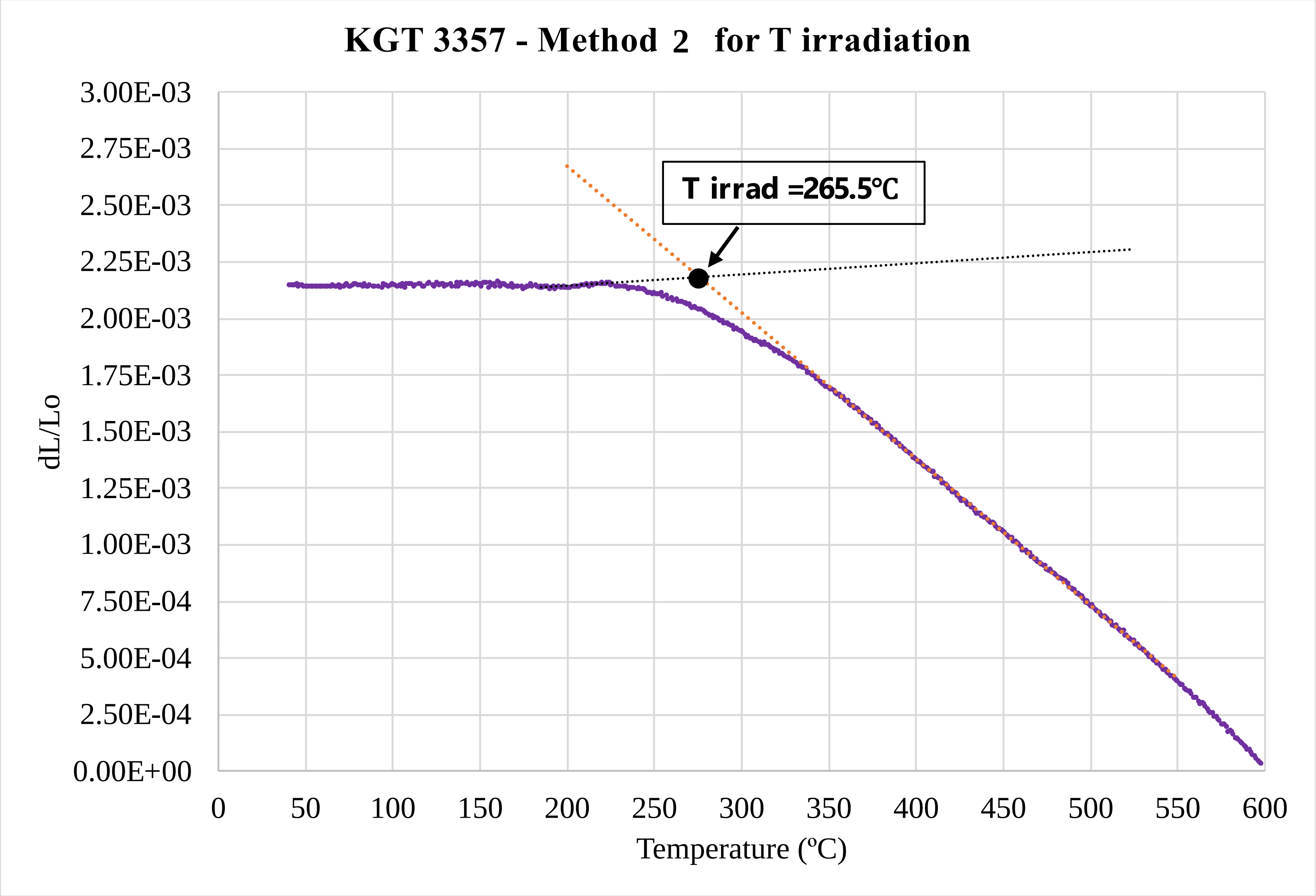
Change in Length Results for KGT-3357



Method 2

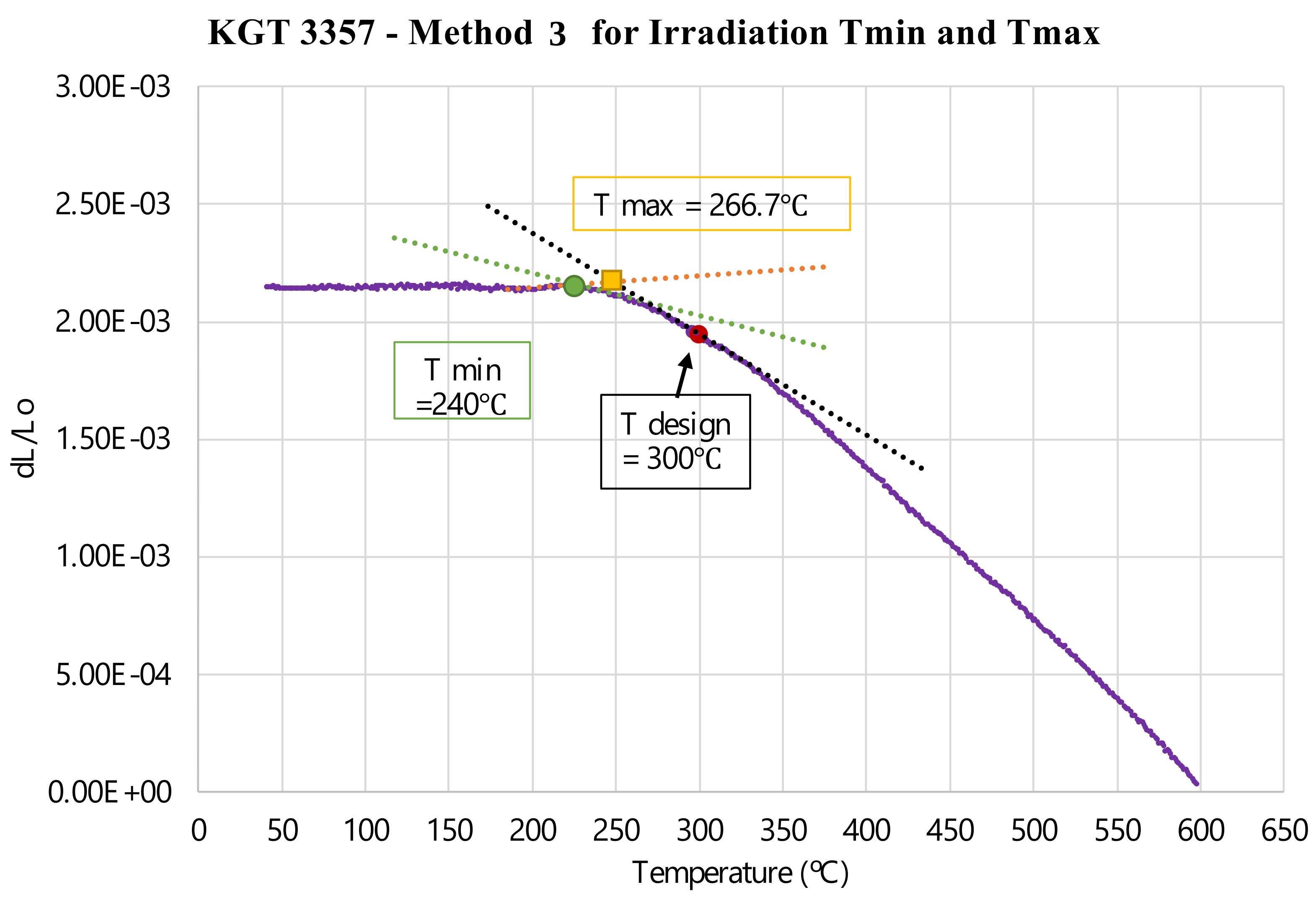
- KGT 3357 SiC Monitor:
  - Fit line below irradiation temperature (black line)
  - Fit line after irradiation temperature (orange line)
  - The intersection (black dot) of both lines is the estimated irradiation temperature of **265.5℃**
  - It agrees with melt wire temperature range of 238.6℃ to 271.5℃

Measured Irradiation Temperature from the difference of the SiC length change



Method 3

- KGT 3357 SiC Monitor: Irradiation Temp. Range from the difference of the SiC length change and T design
  - Fit line centered at design temperature of 300℃ (black line)
  - Fit line before irradiation temperature (orange line)
  - Fit line where the data begin to curve downward (green line)
  - The intersection of black and orange lines is **max. temp. of ~266.7 ℃**
  - The intersection of green and orange lines is **min. temp of ~240 ℃**
  - Both temperatures fall within melt wire temp. range of 238.6℃ to 271.5℃



Summary of Results

- Optical dilatometry annealed one (1) SiC KGT3357 sample without any issues or errors
- Both furnace and sample annealing showed linear and similar behavior
- All three methods for identifying peak irradiation temperature agree within melt wire temperature range of 238.6℃ to 271.5℃:
  - (1) T max 264.3℃
  - (2) T irradiation 265.5℃
  - (3) T min 240℃ to T max 266.7℃
- Conclusion is that the **irradiation temperature range was from 240℃ to 266.7℃**
- More than one sample required before finalizing all the capabilities information such as process time, cost, and accuracy

Conclusion

- Conduct a comparative assessment between the optical dilatometer method and resistivity method using all 10 NSUF SiC temperature monitors
- Encounter multiple delays in acquiring, shipping, and cleaning the SiC temperature monitors
- The project was only able to process one (1) SiC temperature monitor
- The optical dilatometer measurements indicated that the KGT-3357 SiC temperature monitor's peak irradiation temperature range was 240–267℃ (sensitivity of approximately ±20℃)
- Additionally, this temperature range falls within the evaluated melt wire temperature range of 238.6–271.5℃
- The remaining six (6) SiC temperature monitors from the BSU-8242 experiment and three (3) from the General Electric Hitachi experiment will be used in the future work to further validate the optical dilatometer method for measuring SiC peak irradiation temperatures

Questions?

- *Contact Info:*

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W (208)-526-1674

- References:

  - Guillen, Donna, et al. “Boise State University (BSU)-8242 Experiment Execution Plan,” PLN-5248, Rev. 1, Project 32349, April 2017.
  - Davis, Kurt L., and Hone, Lance A. “NSUF Melt Wire Evaluations for BSU 8242 and GE Hitachi-10393 Irradiation Experiments.” 2020, https://doi.org/10.2172/1633621.
  - Campbell, Anne A., et al. “Method for Analyzing Passive Silicon Carbide Thermometry with a Continuous Dilatometer to Determine Irradiation Temperature.” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, vol. 370, 2016, pp. 49–58., https://doi.org/10.1016/j.nimb.2016.01.005.
  - Rempe, J. L., Condie, K. G., and Knudson, D. L. “Silicon Carbide Temperature Monitor Evaluation,” PLN-3473, Revision 0, Idaho National Laboratory, May14, 2010.
  - “Dil 806 Optical Dilatometer.” TA Instruments, https://www.tainstruments.com/dil-806/.
  - Field, Kevin G., et al. “Evaluation of the continuous dilatometer method of silicon carbide thermometry for passive irradiation temperature determination.” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, vol. 445, 2019, pp. 46–56., https://doi.org/10.1016/j.nimb.2019.02.022.

Thank you!

ASI | Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Analytics-at-Scale of Sensor Data for Digital Monitoring in Nuclear Plants

Advanced Sensors and Instrumentation (ASI)

November 18, 2021

Vivek Agarwal, PhD
Senior Research Scientist

Idaho National Laboratory

Project Overview

Scope (Project Duration: 2018-2022, includes 12 months no cost extension)

To advance online monitoring and predictive maintenance in nuclear plants and improve plant performance (efficiency gain and economic competitiveness)

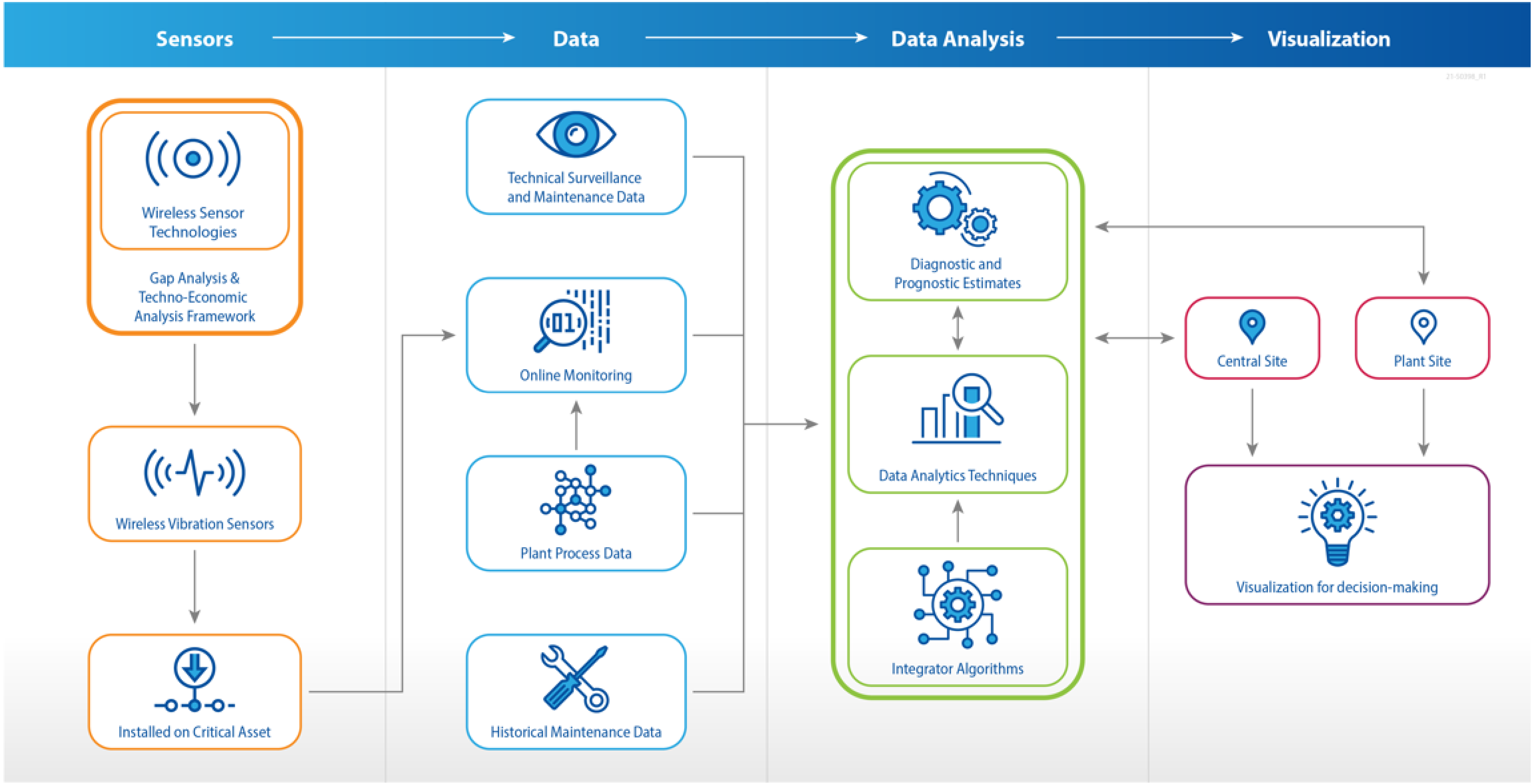
Objectives

- Techno-economic analysis of wireless sensor modalities
- Develop integrative algorithms for diagnostic and prognostic estimates using structured and unstructured heterogeneous data
- Develop visualization algorithms and guidelines
- Validate the developed methodologies

Project Team

- Idaho National Laboratory – Vivek Agarwal (PI), Nancy Lybeck, Cody Walker, and Koushik A. Manjunatha
- Oak Ridge National Laboratory – Pradeep Ramuhalli
- Electric Power Research Institute – Michael Taylor
- Exelon Generation Company – Charlotte Geiger

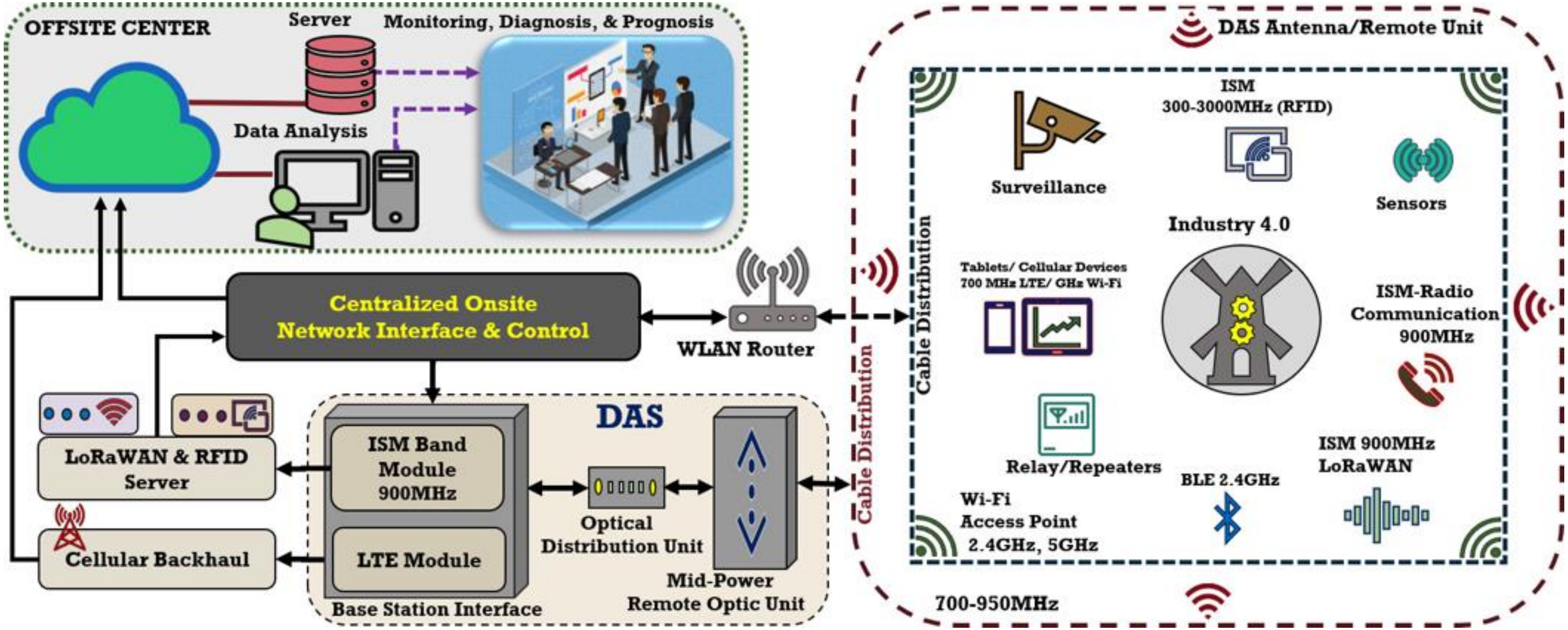
Approach



Sensors
Data
Data Analysis
Visualization
Wireless Sensor Technologies
Gap Analysis & Techno-Economic Analysis Framework
Wireless Vibration Sensors
Installed on Critical Asset
Technical Surveillance and Maintenance Data
Online Monitoring
Plant Process Data
Historical Maintenance Data
Diagnostic and Prognostic Estimates
Data Analytics Techniques
Integrator Algorithms
Central Site
Plant Site
Visualization for decision-making

Techno-Economic Analysis Framework

- A "one-size-fits-all" solution cannot be applied
  - application needs, quality of ser-vice requirements, and economic restrictions.



K. Manjunatha and V. Agarwal, "Multi-Band Heterogeneous Wireless Network Architecture for Industrial Automation: A Techno-Economic Analysis," Accepted for Publication in Wireless Personal Communication Journal.

Preventative Maintenance Optimization to Lower Maintenance Costs

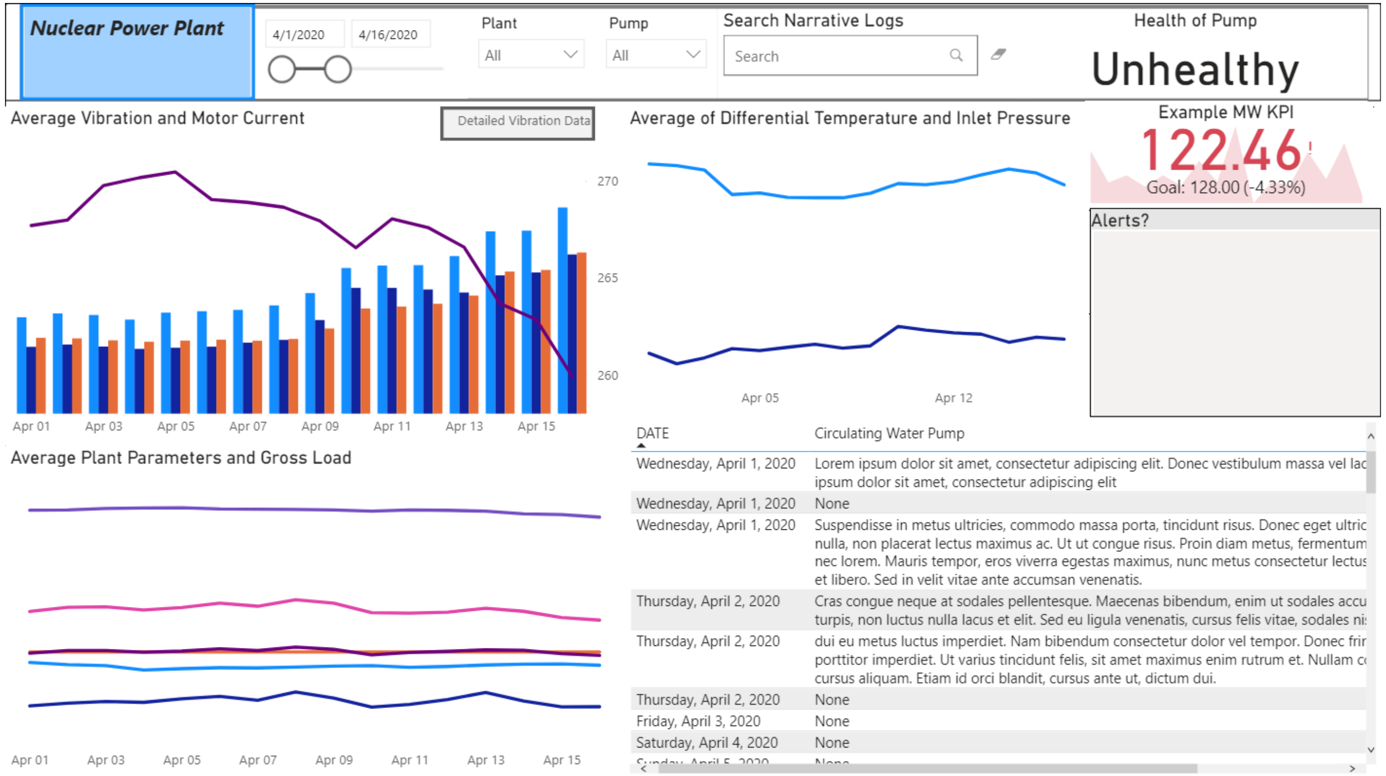
Milestone: Nuclear Power Fault Diagnostics and Preventative Maintenance Optimization (Completed January 2021)

- Different forms of data was obtained from two Exelon Plants
  - Work order data
  - Plant process data
  - Maintenance records
- Healthy components were determined through process data and maintenance records.
- Current Preventative Maintenance (PM) frequencies for healthy components were compared to industry averages using EPRI's Preventative Maintenance Basis Database (PMBD).
- Several candidates were found for frequency extension.

Component	PM Task	Current PM Frequency	EPRI PMBD	Recommendation
Condensate pump and Condensate Booster pump	Refurbishment	8 years	As required	Good candidate for frequency extension
	Vibration Monitoring	3 months	3 months	Keep
	Oil Analysis	6 months	6 months	Keep
Motor	Vibration Analysis	3 months	3 months	Keep
	Fan Cleaning	6 months	2 months	Keep
	Oil Analysis	6 months	6 months or 1 year	Good candidate for frequency extension
	Electrical Testing/ Inspection	5 years	4 years	Keep

Milestone: Nuclear Power Fault Diagnostics and Preventative Maintenance Optimization (Completed: May 2021)

- Goals of visualization guidance
  - Usability
  - Saliency
  - Error prevention
- Visualization recommendation
  - Highlight consequential information
  - Group related types of information
  - Ensure navigability of information
  - Clearly delineate actual and predicted information
- Visualization tools
  - Microsoft Power BI
  - Tableau
  - Custom solution



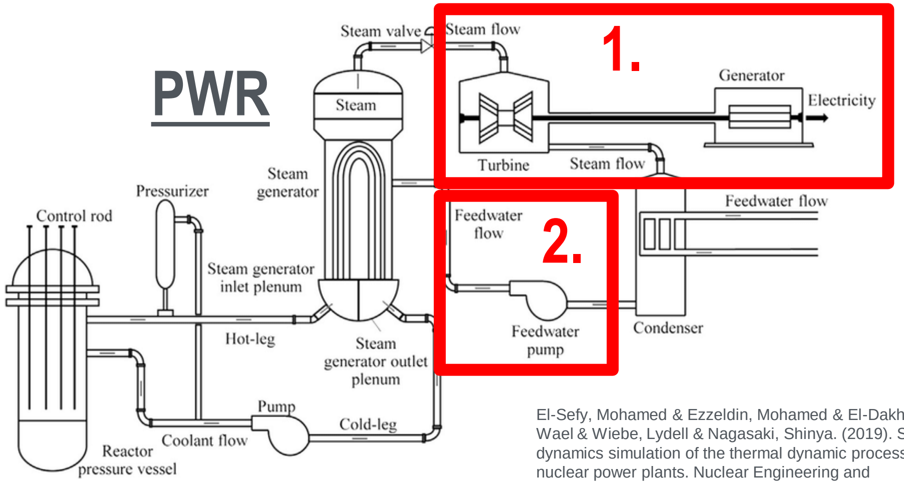
Validation & Verification (V&V) of Short-Term Forecasting Models

- Data was taken from three nuclear plant system (2 PWR and 1 BWR):
  1. PWR main turbine system
  2. PWR steam generator feed pump
  3. BWR condensate and feedwater system

- Recorded plant parameters and features to be forecasted varied depending on the system.

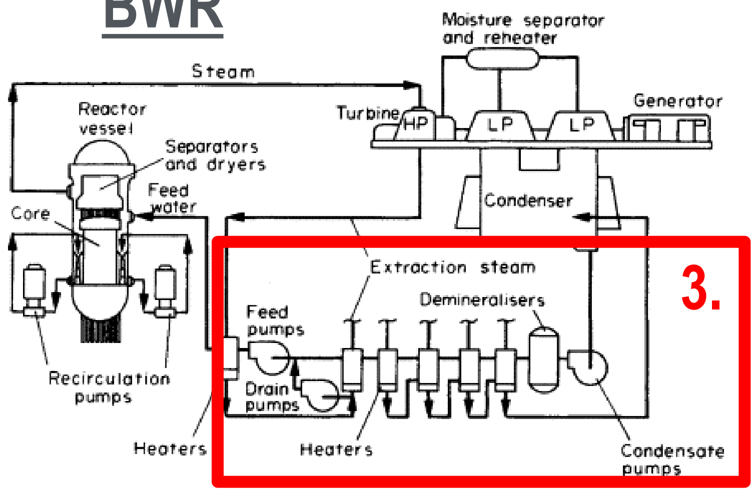
- V&V was not on a single model, but rather on the methodology from processing raw data until prediction (i.e., data preprocessing, feature selection, model optimization, and forecasting).

PWR



El-Sefy, Mohamed & Ezzeldin, Mohamed & El-Dakhakhni, Wael & Wiebe, Lydell & Nagasaki, Shinya. (2019). System dynamics simulation of the thermal dynamic processes in nuclear power plants. Nuclear Engineering and Technology. 51. 10.1016/j.net.2019.04.017.

BWR

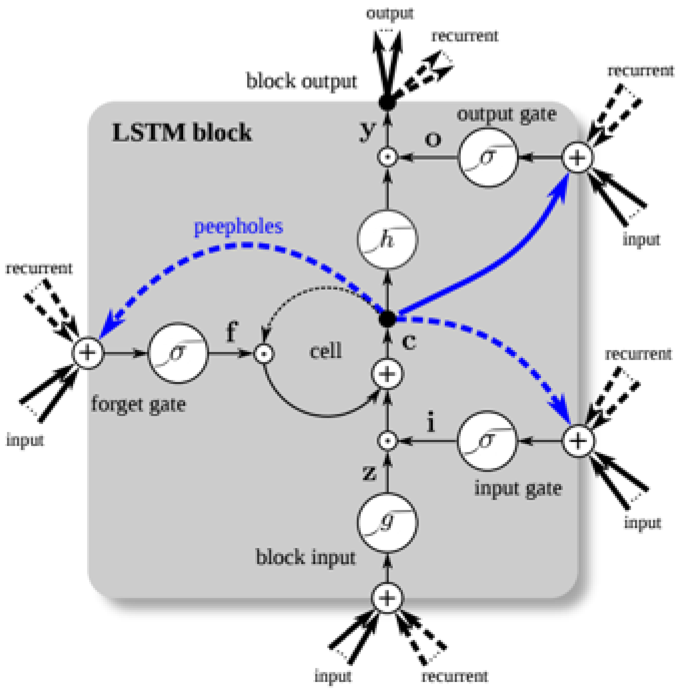


Source: Jeffery Lewins PhD (Cantab), PhD (MIT), in Nuclear Reactor Kinetics and Control, 1978

Validation & Verification (V&V) of Short-Term Forecasting Models

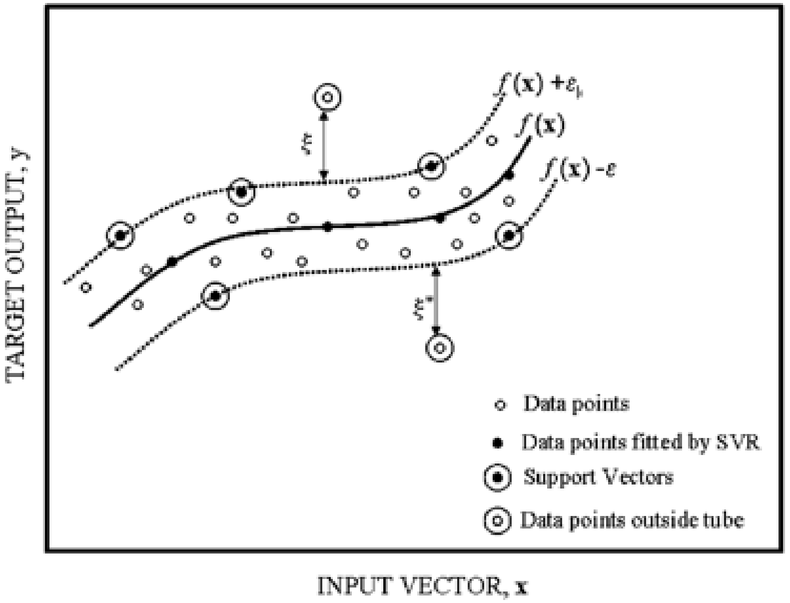
- Forecasting focused on two ML models, Long Short-Term Memory (LSTM), and Support Vector Regression (SVR), for predicting both 1-hour and 1-day ahead.

LSTM



NVIDIA Corporation. “Long Short-Term Memory (LSTM). Online. 2020.

SVR



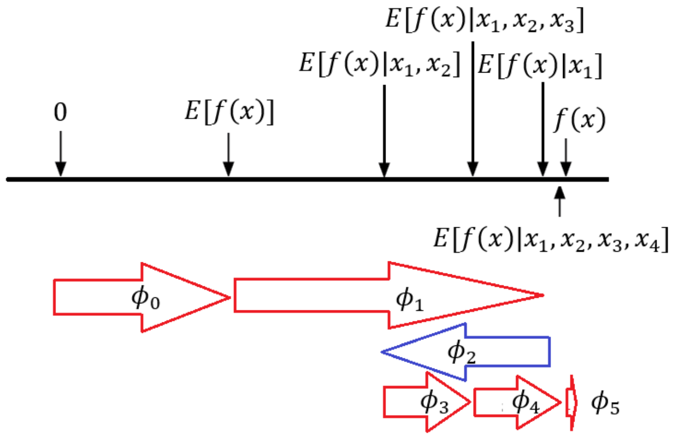
Gandhi, Ankit B., et al. "Development of support vector regression (SVR)-based correlation for prediction of overall gas hold-up in bubble column reactors for various gas–liquid systems." *Chemical Engineering Science* 62.24 (2007): 7078-7089.

Data Preprocessing and Feature Selection

- Data Preprocessing included:
  - Addressing missing values
  - Outlier Detection
  - Data smoothing
  - Normalizing data to zero mean and variance

- Feature selection utilized the mean Shapley additive explanations (SHAP) values to determine input features based on importance.

- A dynamic threshold was used to determine the importance cutoff. Any value smaller than one order of magnitude than the most importance feature was cut. On the right, shell expansion was cut from the model input.



SHAP is an additive feature attribution method

$$f(x) \simeq g(x') = \phi_0 + \sum_{i=1}^{M} \phi_i x'_i$$

- f(x) is the original model
- g(x') is the explanation model
- Φ_0 represents the constant value when all inputs are missing
- M is the number of input variables
- Φ_i is the feature attribution values
- x_i' are the simplified inputs.
- inputs related through mapping function, $x = h_x(x')$

Feature	Importance	Φ_i
Turbine Speed	0.608	Φ_1
Turbine Rotor Expansion	0.309	Φ_2
Turbine Differential Expansion	0.161	Φ_3
Flow to Turbine	0.151	Φ_4
Shell Expansion	0.029	Φ_5

Feature selection for predicting bearing vibration based on SHAP importance values

Accomplishments

Milestone: Verification and Validation of developed short-term forecasting models (Completed November 2021)

- Tested multiple methods for multi-step forecasting:
  - Direct, Recursive, and Direct-recursive.

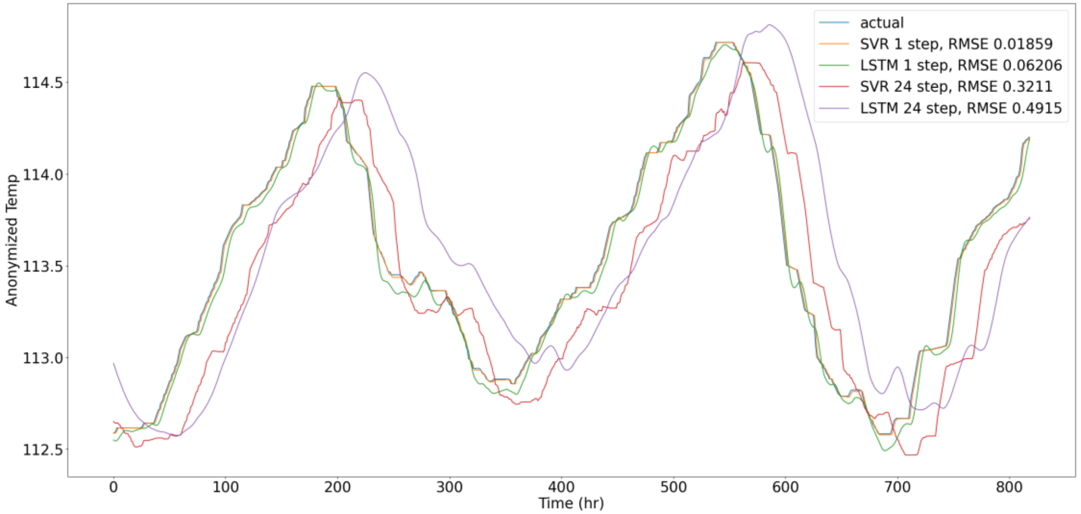
- LSTM and SVR were used to predict 4 different plant parameters across 3 different plants using 2 prediction horizons (1-hour and 1-day).

- V&V was accomplished using a 10-fold cross validation approach then comparing the mean and standard deviation of the root mean square error (RMSE).

- For this analysis, SVR outperformed LSTM, but further improvements could potentially be made to the LSTM architecture that would improve its results.

Verification and Validation model results.

Comparison of LSTM and SVR for predicting bearing temperature 1-step and 24-steps ahead.



Data set			1-step ahead		24-steps ahead	
Plant	Parameter Predicted	Model	Mean RMSE	Std Error	Mean RMSE	Std Error
PWR 1	Main Turbine Bearing Temp	LSTM	0.0796	0.0411	0.7932	0.5450
		SVR	0.0214	0.0080	0.3194	0.1202
PWR 1	Generator Output	LSTM	0.2871	0.2031	2.2636	2.8338
		SVR	0.0806	0.0422	1.5611	1.2424
PWR 2	Steam generator flow	LSTM	2.4792	3.0455	12.435	17.333
		SVR	1.4070	2.4270	5.6299	5.3154
BWR	Condensate Pump Bearing Temp	LSTM	0.0792	0.0722	0.2991	0.2724
		SVR	0.0323	0.0496	0.2238	0.2184

Publications

Journal Article:

- K. Manjunatha and V. Agarwal, “Multi-Band Heterogeneous Wireless Network Architecture for Industrial Automation: A Techno-Economic Analysis,” Accepted for Publication in Wireless Personal Communication Journal.

Conference Proceedings:

- Walker C.M., P. Ramuhalli, V. Agarwal, N. Lybeck, M. Taylor. "Nuclear Power Fault Diagnostics and Preventative Maintenance Optimization." Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies Conference. Providence, RI. June 13–17, 2021.

- Ramuhalli, P. C.M. Walker, V. Agarwal, N. Lybeck, M. Taylor. "Nuclear Power Prognostic Model Assessment for Component Health Monitoring." Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies Conference. Providence, RI. June 13–17, 2021.

ASI Newsletter

- Walker C.M., V. Agarwal, N. Lybeck, P. Ramuhalli, M. Taylor. "Analytics-at-scale of Sensor Data for Digital Monitoring in Nuclear Plants." 2021 NEET Advanced Sensors and Instrumentation Project Summaries. September 16, 2021.

Technology Impact

- *Advances the state of the art for nuclear application*
  - Advances online monitoring at a nuclear plant site for different plant assets
  - Provides machine learning approaches to integrate and analyze heterogeneous structured and unstructured data (i.e., analytics-at-scale)
  - Visualization of information to make informed decision-making

- *Supports the DOE-NE research mission*
  - Enable economical long-term operation of existing fleet of reactors
  - Research outcomes can be utilized to develop maintenance strategy for advanced reactors

- *Impacts on the nuclear industry*
  - Enable industry to transition from preventive maintenance strategy to predictive maintenance strategy
  - Enhance reliability and economic operation of domestic existing fleet

- *Commercialization*
  - Project team will develop a transition plan to enable transfer of research outcomes to an industrial partner

Summary

- Developed a techno-economic analysis framework to evaluate different wireless sensors
- Developed diagnostic and prognostic models based on heterogeneous data sets from different plant sites
  - Applied Shapley additive explanations (SHAP) values to understand importance of a feature
  - Applied Variance inflation factors (VIF) method to understand the level of multicollinearity among plant variables
- Identified visualization gaps and standards to present information in right format to minimize information overload, enhancing informed decision-making
- Submitted milestone on validation and verification of the developed short-term forecasting methodologies on independent data sets obtained from Electric Power Research Institute.

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ASI Advanced Sensors and Instrumentation

Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management Operation, and Maintenance

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

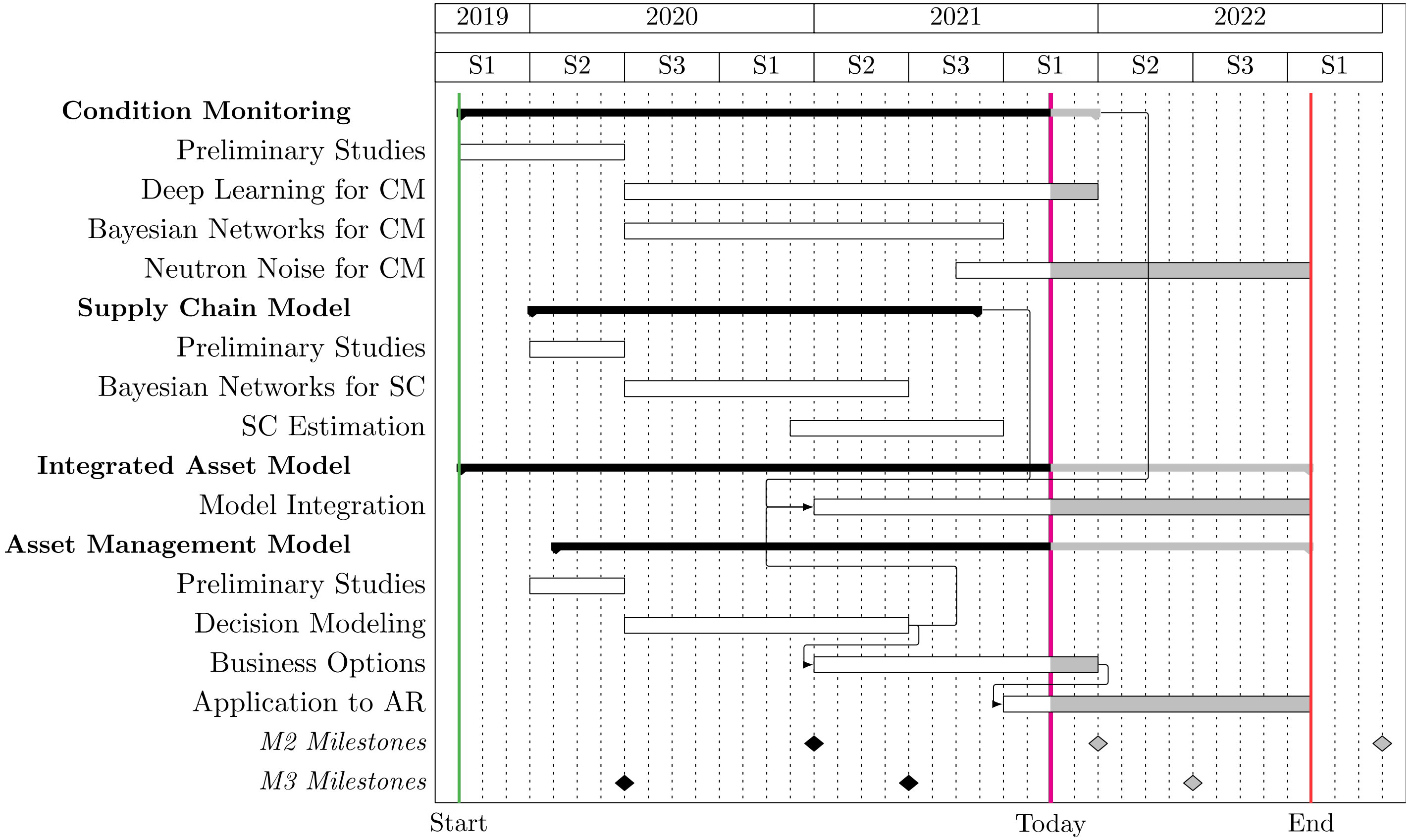
November 15 – 18, 2021

PI: Daniel G. Cole, PhD

University of Pittsburgh

Project Overview

Goal: To develop and demonstrate advanced online monitoring to better manage nuclear plant assets, operation, and maintenance.



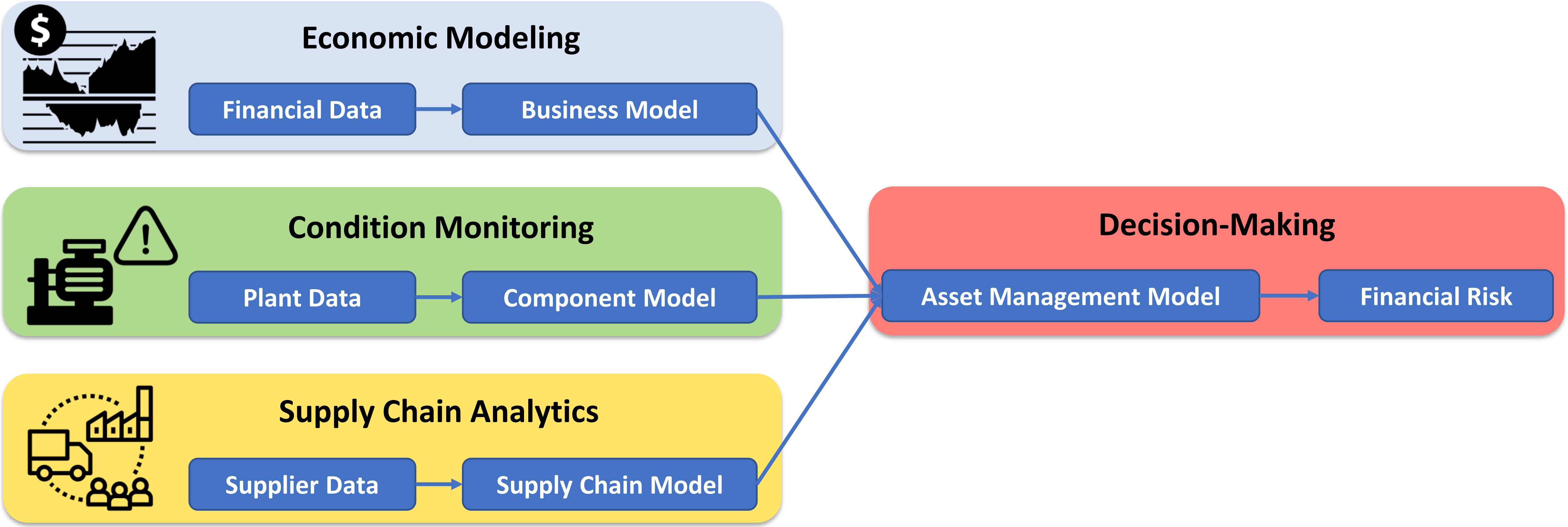
Daniel Cole (Pitt)

Heng Ban (Pitt)

Vivek Agarwal (INL)

Project Overview

Integrating condition monitoring, supply chain analytics, and decision making, we can improve asset-management for nuclear O&M



Technology Impact

This research provides an integrated approach for long-term decision-making for plant operation

Utilities would be better able to manage plant O&M

Minimize staffing levels with real financial impact.

The asset management analysis will support decision-making for

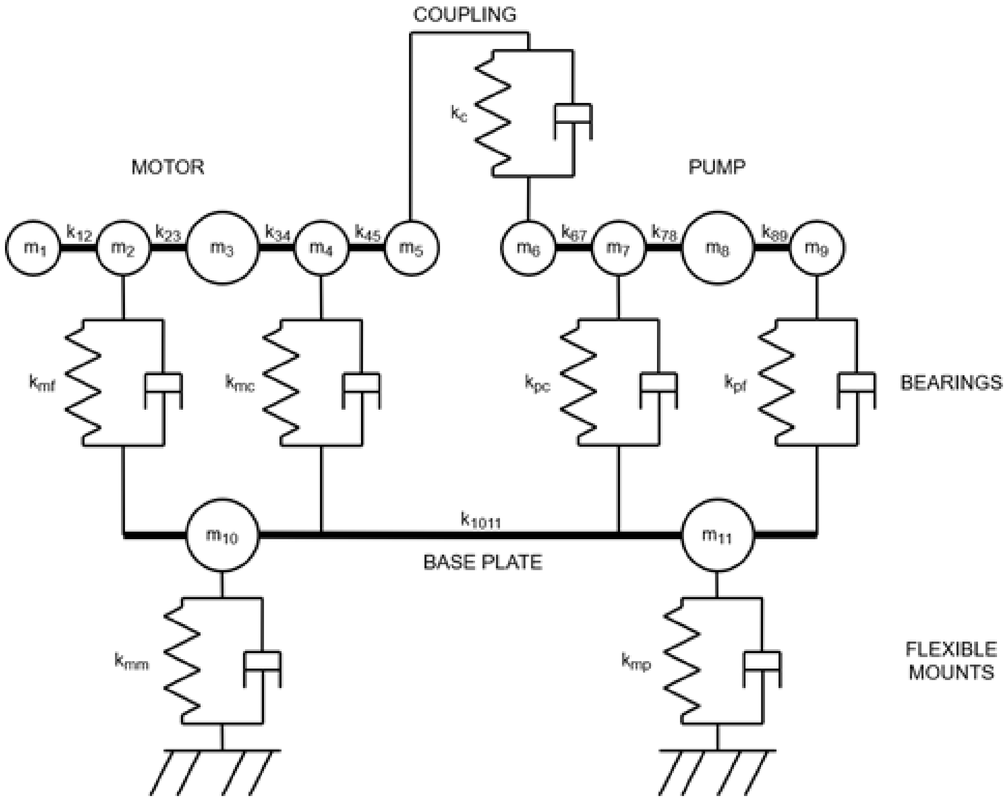
- **SSC replacement and asset management**
- **supply chain, resource availability, and outage planning**
- **license extension for long-term operation**

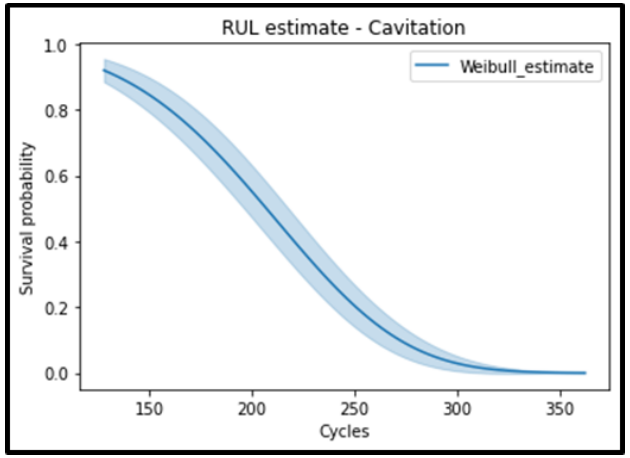
By better accounting for obsolescence and replacement in financial decision-making, utilities can optimize costs.

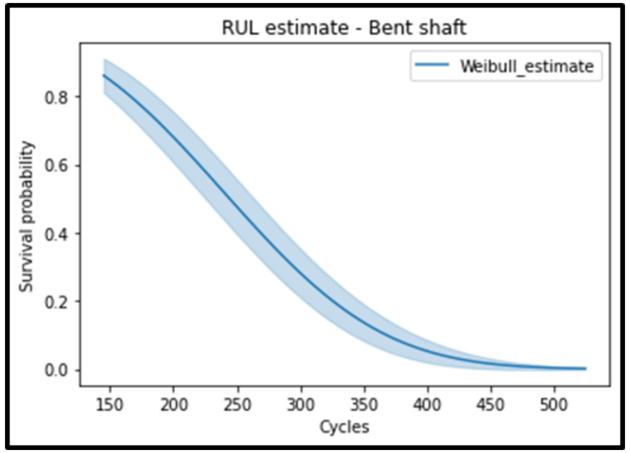
The proposed technology can be applied to different reactor designs or fuel cycle applications.

Results and accomplishments

We developed vibration models and survival models to generate fault data and analyze remaining-useful-life for a pump



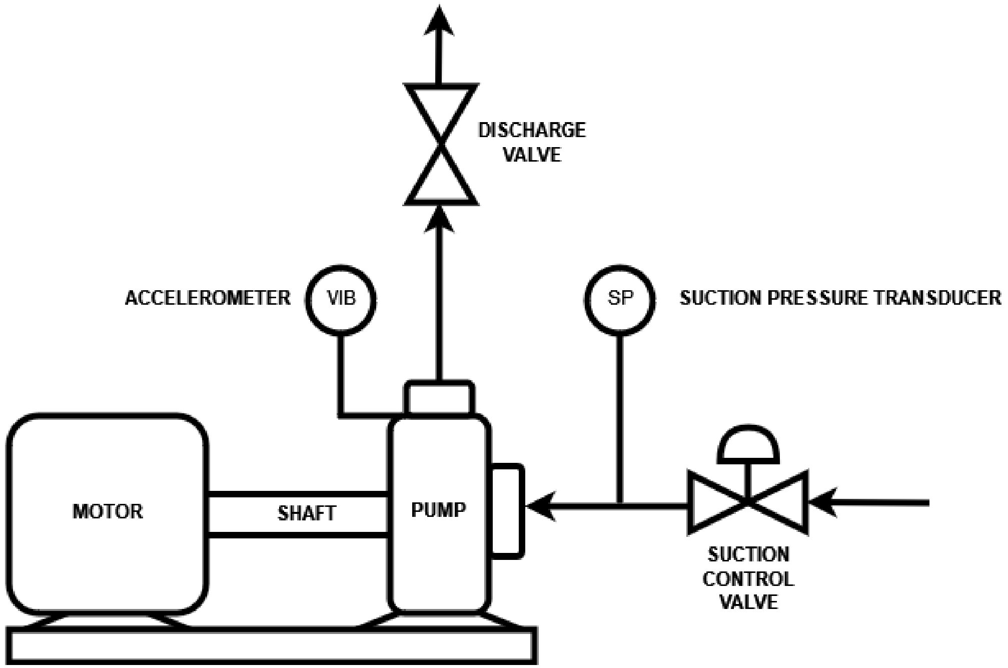


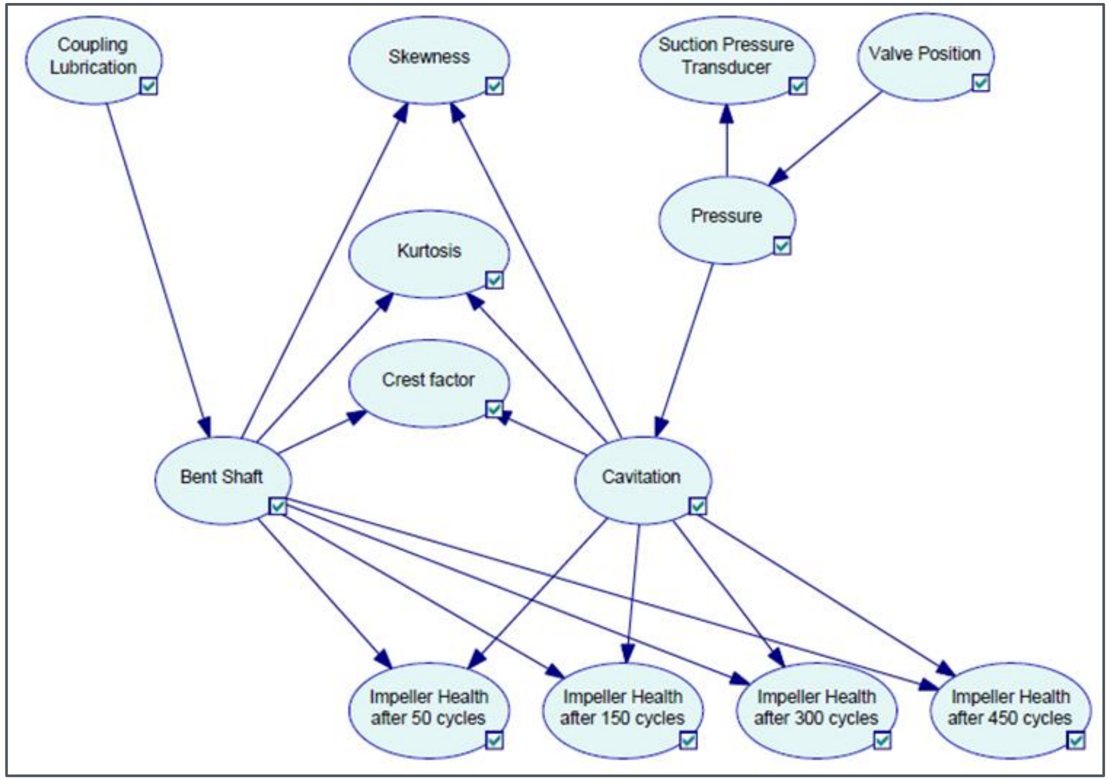


Condition Monitoring

Results and accomplishments

Using machine learning and domain expertise, we created a Bayesian network that can diagnose faults, infer their root cause, and forecast machine health

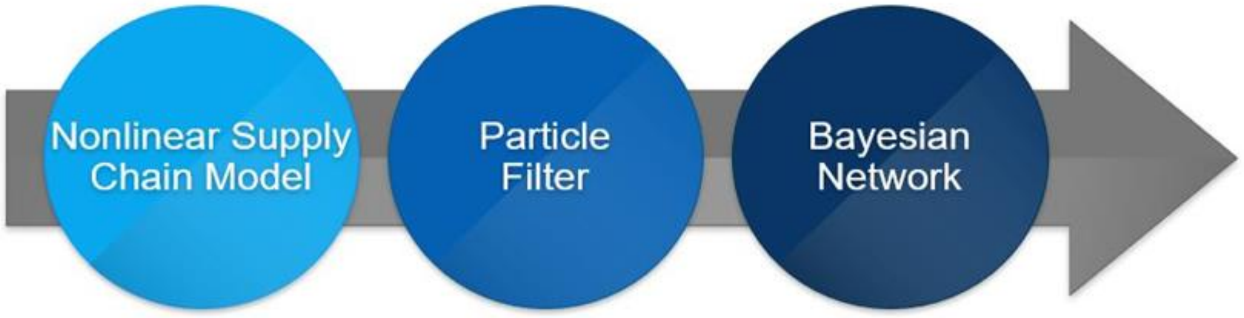




Condition Monitoring

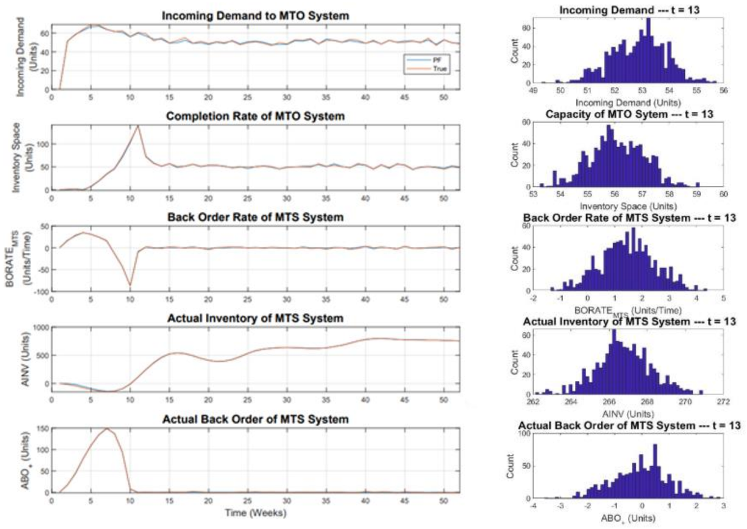
Results and accomplishments

The inventory of upstream suppliers can be estimated in order to reduce the uncertainty in available resources

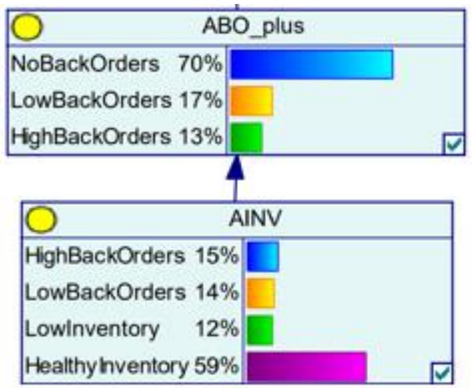


Supply Chain Modeling

State Estimation of Upstream Supplier



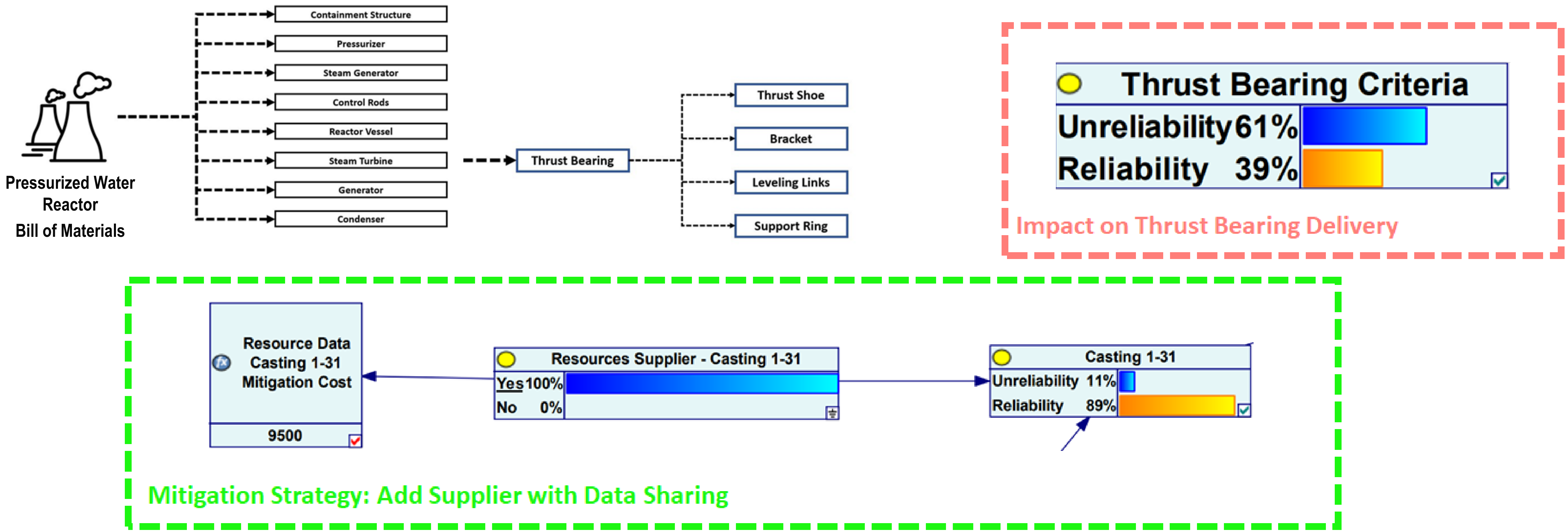
Bayesian Inference



Supply Chain

Results and accomplishments

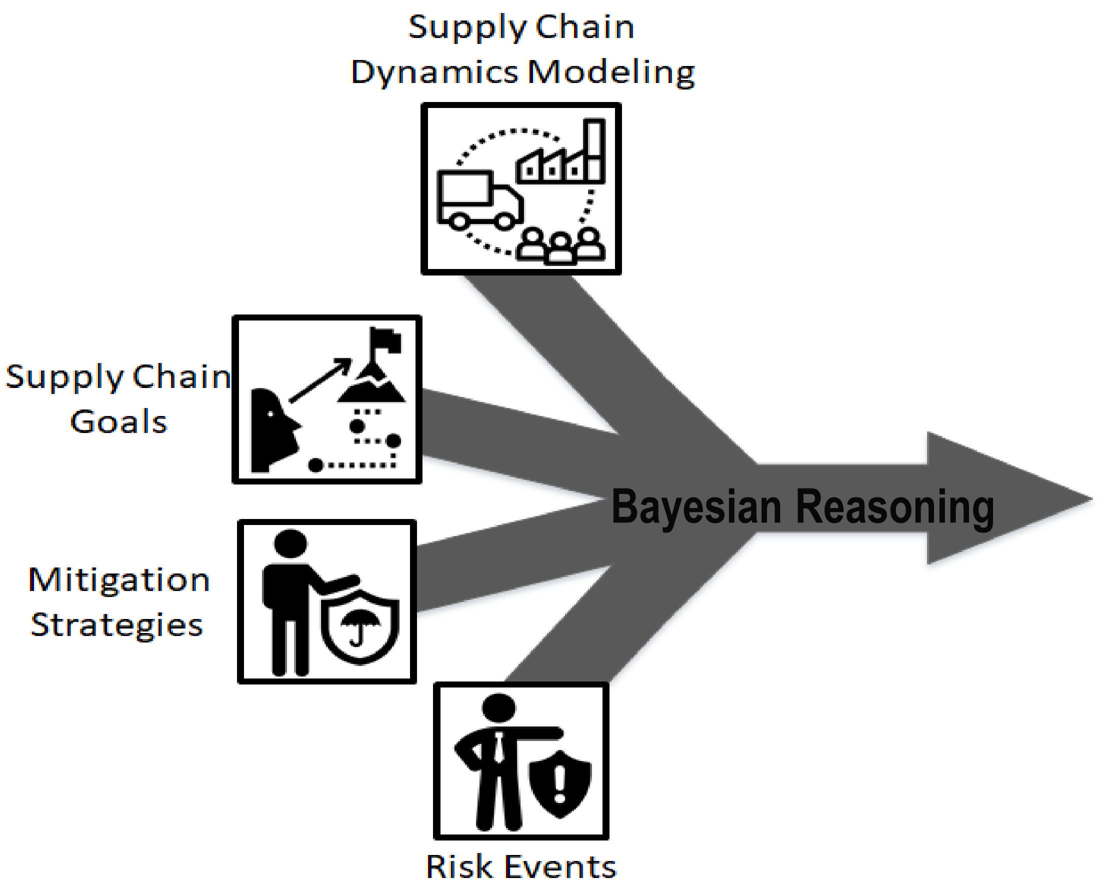
Bill of materials can be used to create Bayesian networks in order to monitor risk events and plan mitigation strategies to reduce unreliability

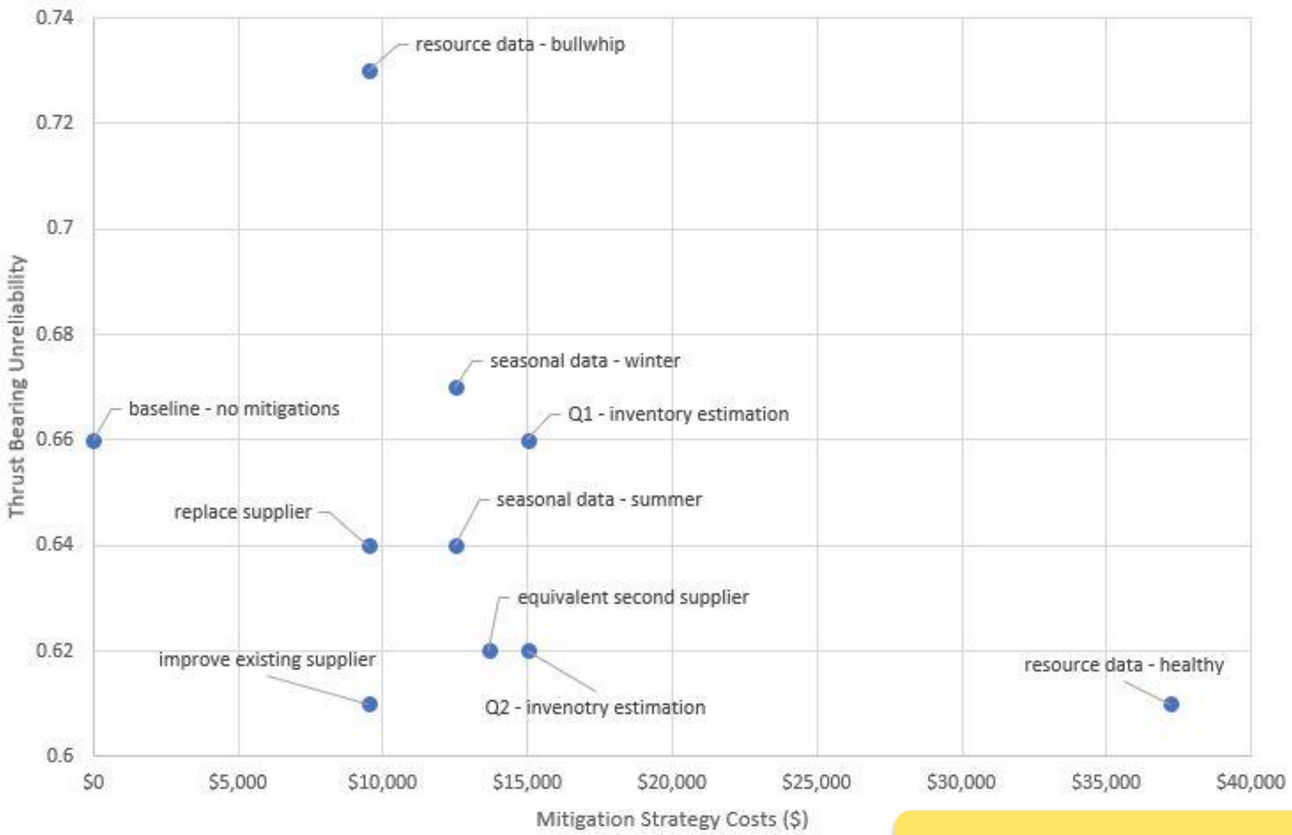


Supply Chain

Results and accomplishments

Uncertainty can be reduced by integrating big data, supply chain goals, and risk events into a Bayesian network in order to deploy mitigation strategies

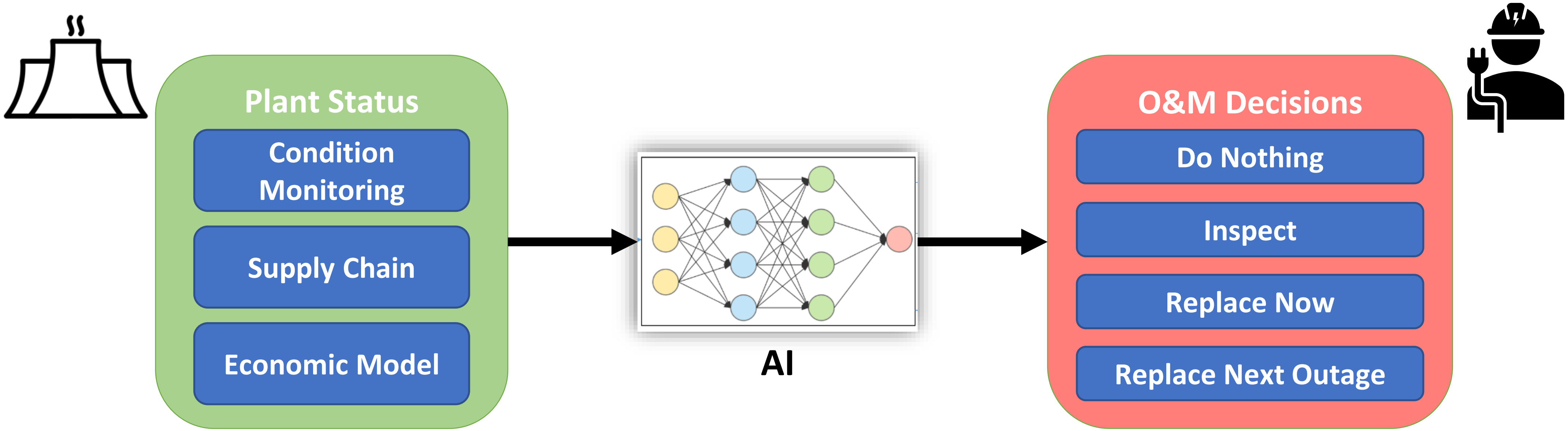




Supply Chain

Results and accomplishments

By training an AI algorithm, we can aid operators by suggesting optimal inspection and maintenance decisions

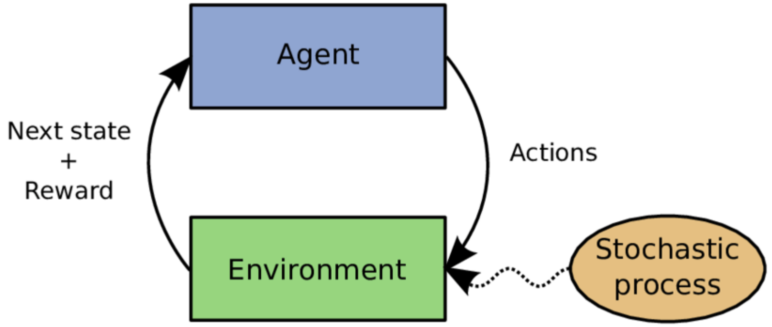


Decision Making

Results and accomplishments

Using reinforcement learning techniques, we can evaluate multiple decisions for several components over time

Reinforcement Learning

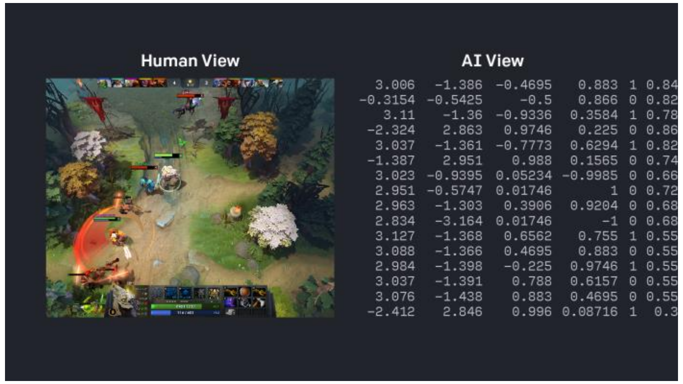


– **Long forecast horizons**
– **Partial observability (uncertainty)**
– **Large decision and action spaces**

Drone Swarms

Go (Google DeepMind)

Dota 2 (OpenAI)

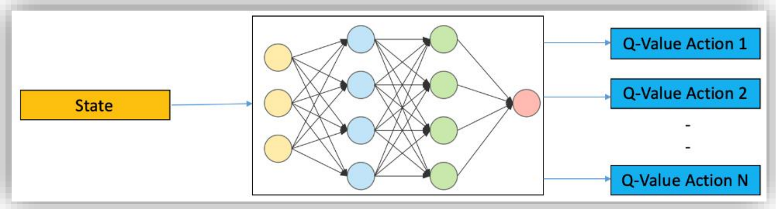


Decision Making

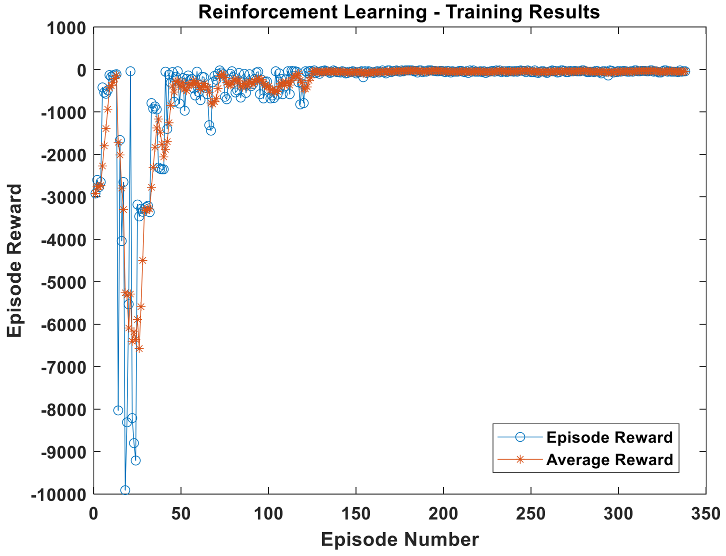
Results and accomplishments

Preliminary results using deep Q-learning have proved successful for a single-component analysis and optimization

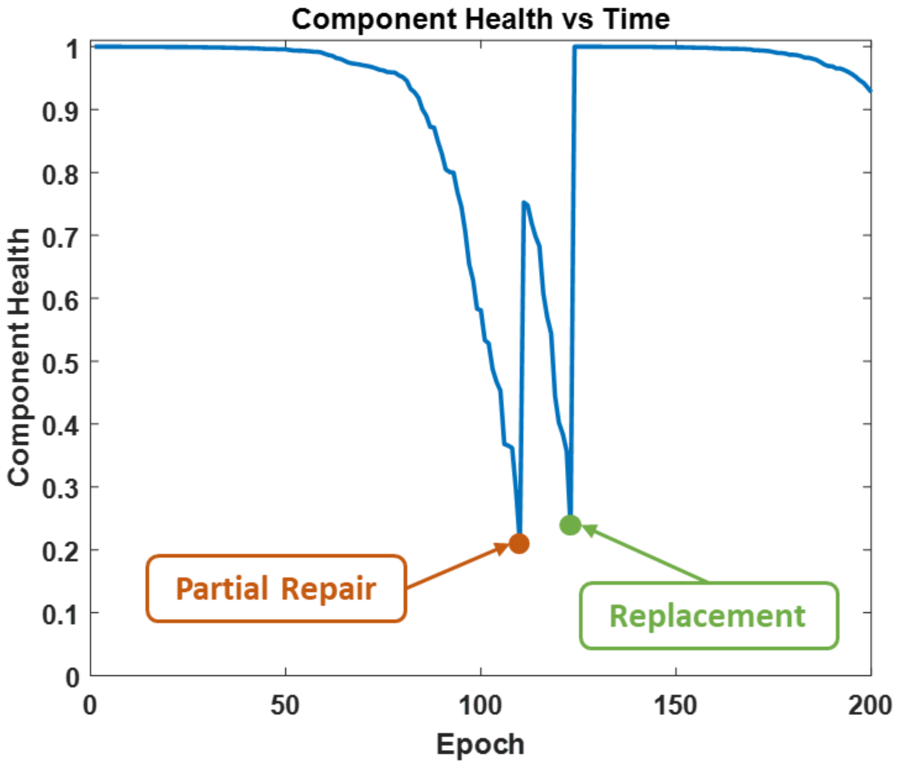
Deep Q-Learning



Training Results



Component Results



Decision Making

Conclusion

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Condition Monitoring

- **Demonstrated the effectiveness of a Bayesian network in diagnosing faults, determining root cause, and forecasting health**

Supply Chain Modeling and Estimation

- **Estimated inventory of upstream suppliers for a low-volume, high-value supply chain using a particle filter**
- **Integrated model into a Bayesian network to determine reliability of suppliers**

Decision Making

- **Used a deep-reinforcement learning algorithm to train a feedforward neural-network to predict optimal inspection and maintenance strategies**

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ASI Advanced Sensors and Instrumentation

Design of Risk-Informed Autonomous Operation for Advanced Reactors

CA-19-MA-MIT_-0703-01

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

Prof. Michael Golay[1], Ph.D.; Prof. Hyun Gook Kang[2], Ph.D.; Dr. Birdy Phathanapirom[3]; Dr. Xingang Zhao[3]; Dr. Xinyan Wang[1]; Junyung Kim[2]

[1] **Massachusetts Institute of Technology**

[2] **Rensselaer Polytechnic Institute**

[3] **Oak Ridge National Laboratory**

Project Overview

- Rationale: Reduce risks from human errors during transients – operations, accidents
- Goals: Demonstration of artificial reasoning to support operator actions
- Elements: Prognostics, Responses, Operator actions, Automated actions
- Work to-date: Prognostics – data, Bayesian model, Automated reasoning for needed response – risk reduction, system metric optimization
- Future work – Further prognostics, SFR focus and integrated modeling

Project Overview

- Milestone Schedule

Date	Topics
07/30/20	Symptom-Based Conditional Failure Probability Estimation for Selected Structures, Systems, and Components
07/30/21	Development of Candidate Reasoning Methods and Associated Decision-Making Metrics
06/30/22	Selection of SSC Degradation Scenarios and Case Studies for Demonstration of Operator Decision-support
07/30/22	Risk Analysis of PLC/FPGA System and V & V Results of PLC/FPGA System Software and Design
12/29/22	Final Report for Design of Risk Informed of Autonomous Operations for Advanced Reactors

Project Overview

Design of Risk Informed Autonomous Operation

Simulation-based Autonomous Control Algorithm Development

Safety Operation

RAVEN-RELEP5

- Physics-based machine learning-aided space-state discretization
- Formulation of prognostic capability
- Integrated artificial reasoning algorithm development
  - Dynamic Bayesian network based on functional modeling

Non-Safety Operation

Modelica (TRANSFORM)

- Fuzzy control logic development
- Diagnostics for SSC incipient failure detection

- Markov decision process formulation of a failed loop scenario
  - Exact value iteration solves for the optimal policy

Component and System Diagnostics using Real Operational Data

- Collaboration with MIT Central Utility Plant (CUP)
- Diagnostic Bayesian Network for a cooling tower fan motor
  - Monitoring data inspections and analysis.
  - Troubleshooting chart-based causalities.
  - Field expert inputs for faults pickup and probability quantifications.
  - Prediction of degradation/failure probabilities based upon observed symptoms using probability propagation.

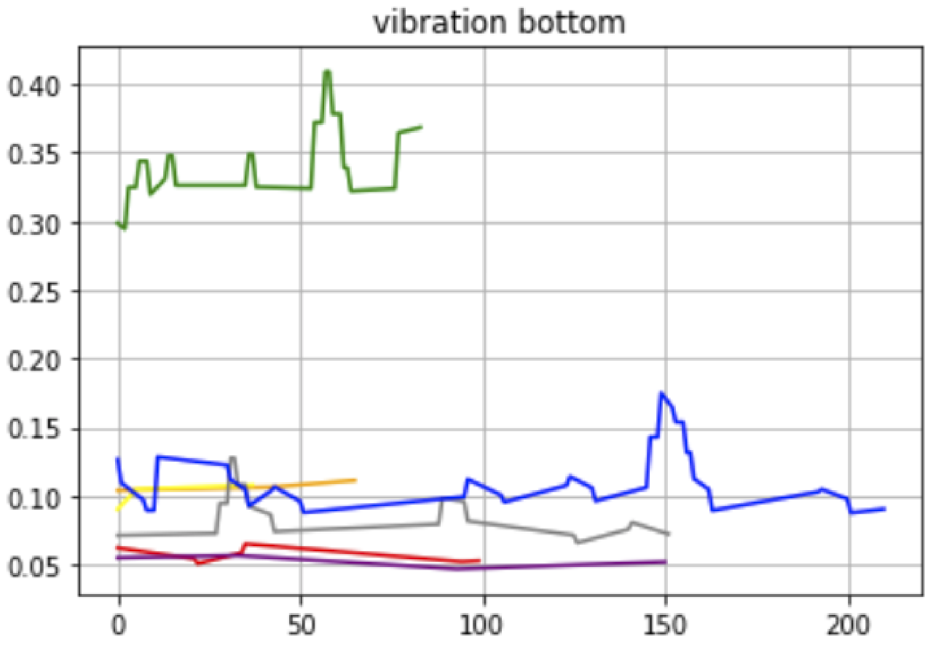
Integrated Operator Support Network

SSC Health Status Diagnostics

Results and accomplishments

Monitoring Data Analysis

- Collaboration with MIT Central Utilities Plant (CUP) for monitoring data, field experts' inputs and technical details of the components since early 2021.
- Figure below: Vibration of motor with a bad bearing (green line) is noticeably higher than that of the others.



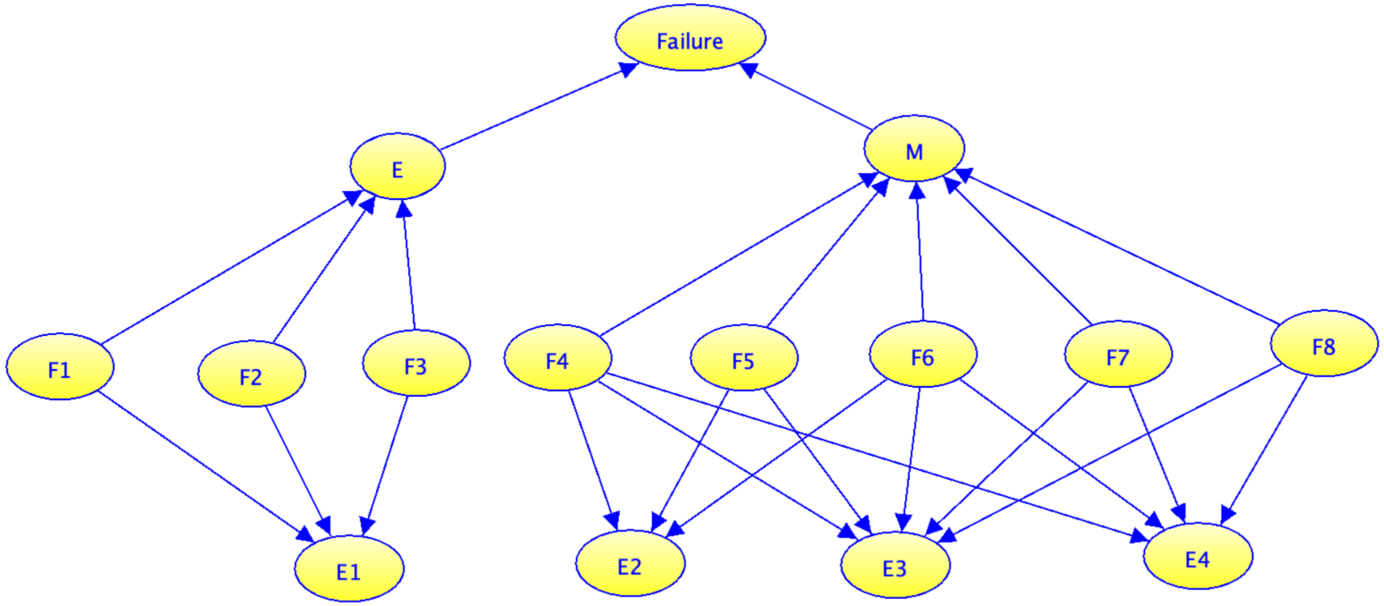
Vibration data monitored by bottom vibration sensors for 7 electric motors running at 25% of full speed steadily at the CUP.

Bayesian Network (BN) for the Electric Motor

- F_j nodes: low-level failures with 3 states <mild, moderate, severe>.
- E_i nodes: symptoms with 3 states <low, medium, high>.
- The 3 higher-level nodes have 2 states: Success and Failure. Node E: electric failure. Node M: mechanical failure.
- Detailed formulation of the model is in Appendix I.

Labels	Sensor Features (Symptoms)
E1	Motor Over Heating
E2	Bearing Over Heating
E3	Noise
E4	Vibration

Labels	Faults
F1	Unbalanced Voltage
F2	Open Stator Winding
F3	Grounded Winding
F4	Misalignment
F5	Insufficient Grease in Bearing
F6	Dirt in Bearing
F7	Rotor out of balance
F8	Bent Shaft

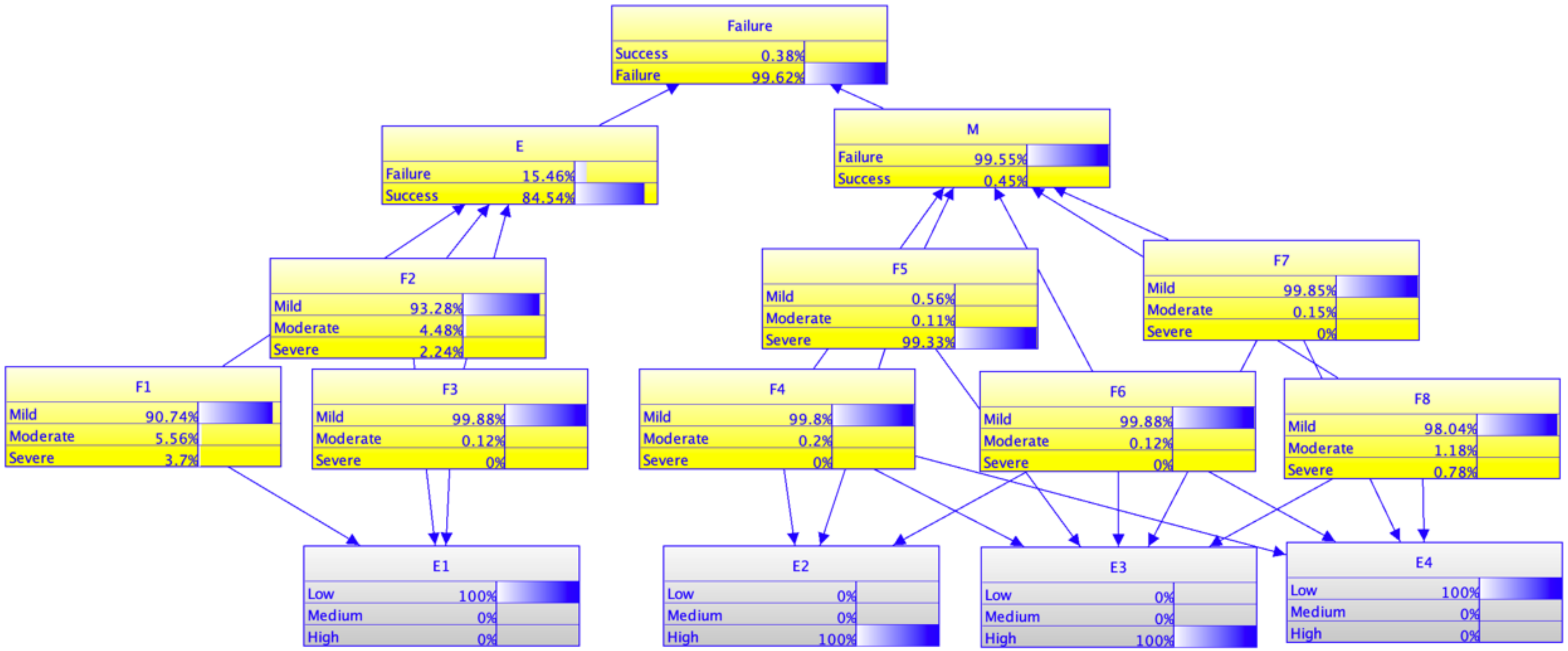


BN Diagram Drawn Using UnBBayes.

Results and accomplishments

Fault Diagnosis using Probability Propagation

- Fault Diagnosis is supported by UnBBayes's probability propagation function.
- E.g. when E_1 and E_4 are observed to be "low" while E_2 and E_3 are observed to be "high", it is predicted that F_5 is 99.33% likely to be severe and every other fault is >90% likely to be mild as shown in the figure below.



Decision Making Support: MDP

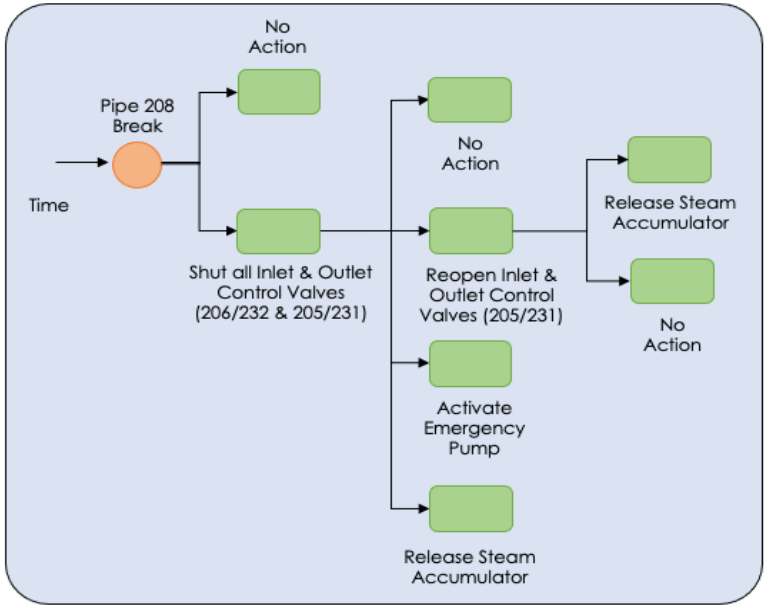
Results and accomplishments

Example System and Test Scenario

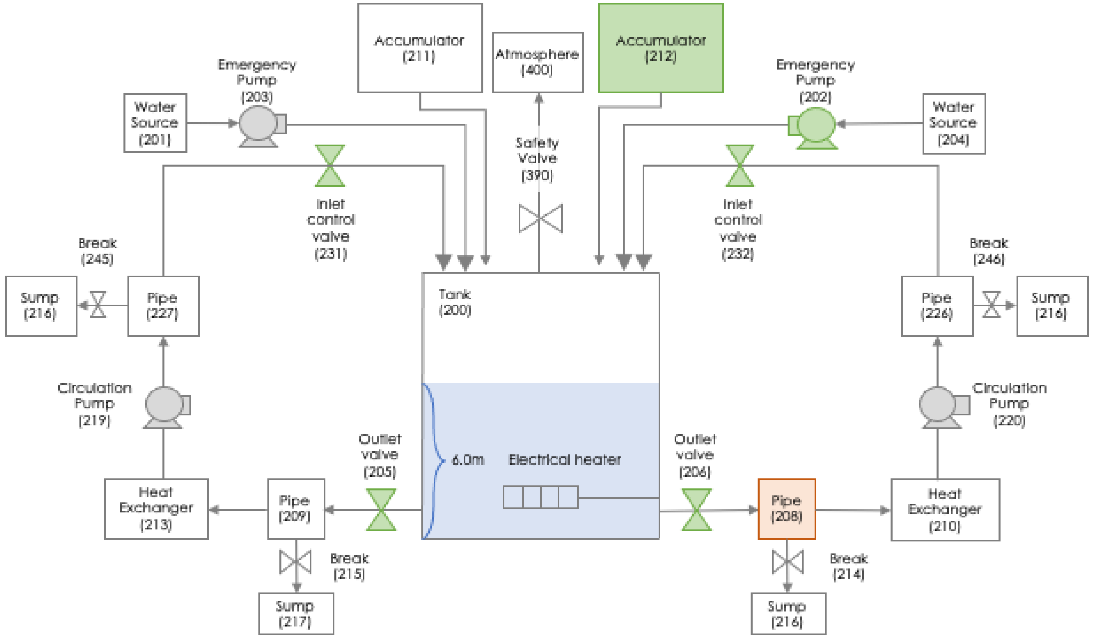
Household water heating system with two loops

Loss of flow accident initiated by a pipe break

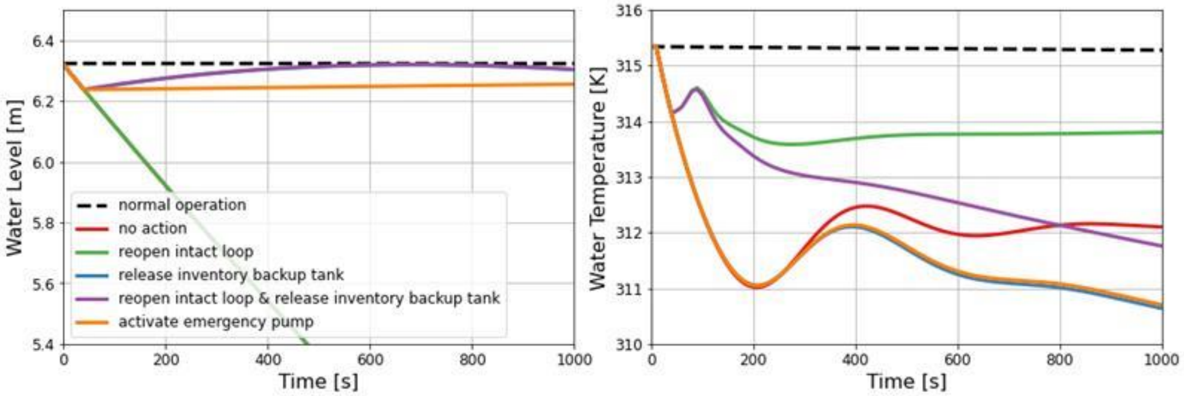
Competing objectives of (1) maintaining system within safety operating limits ("trip setpoints") and (2) continued operation



High-level depiction of evaluated decision tree.



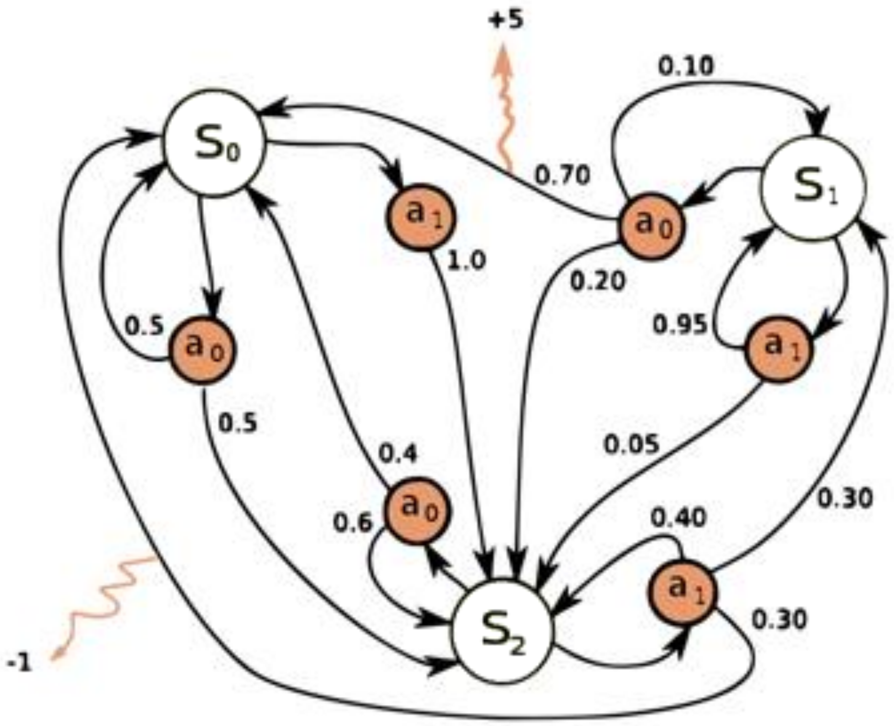
High-level sketch of heating system. Degraded SSC is marked orange and SSCs marked green are available for operator control.



System state evolution in response to loss of flow accident and corrective actions.

Results and accomplishments

Markov Decision Process (MDP)



General framework for formulating sequential decision problems

Decomposed as
1. State space
2. Action space
3. Dynamic model
4. Reward model

Objective is to maximize reward

MDP Solution Approach

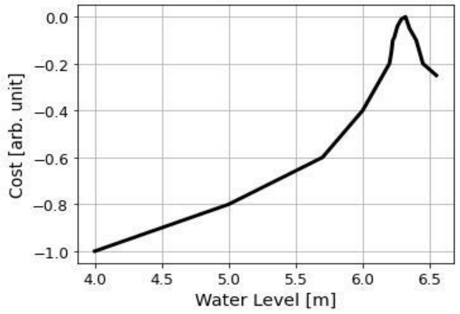
Compute the Expected Value (Bellman Update Equation)

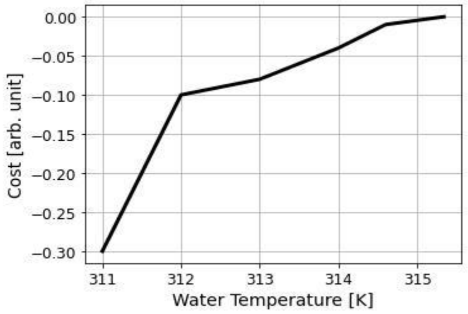
$$Q(s,a) = R(s,a) + \sum_{s'} P(s'|s,a)V(s')$$

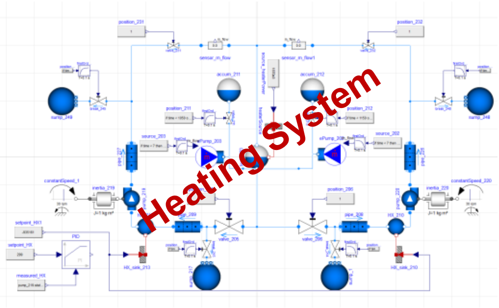
Dynamic programming

Results and accomplishments

Application to a Failed Loop Scenario







← Human effort to develop
← Reward Model & Dynamics Model

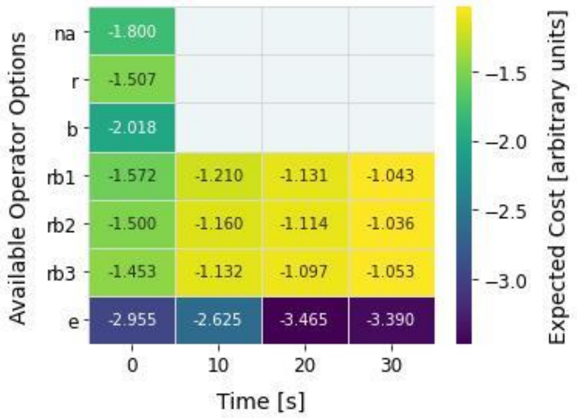
Inventory backup tank release: -0.1
Emergency pump activation: -1

MDP Solution Approach

$$Q(s,a) = R(s,a) + \sum_{s'} P(s'|s,a)V(s')$$

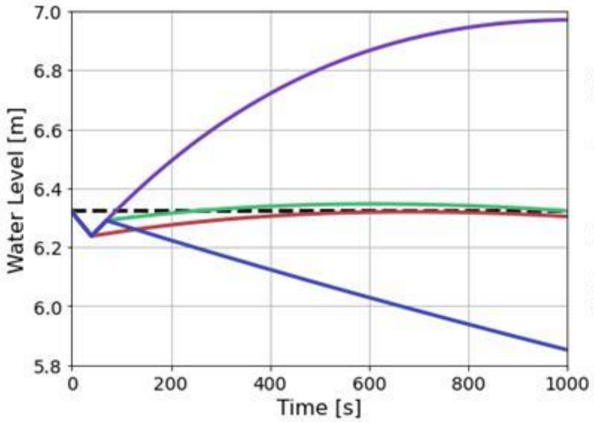
Dynamic programming

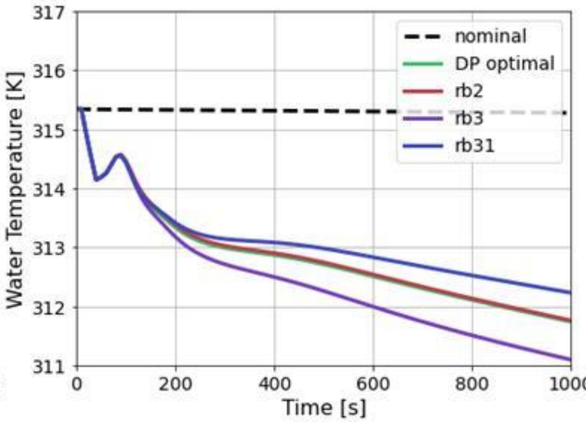
← Computer effort to solve DP Logic



Sample Results from Failed Loop Scenario
Water inventory recovery strategy

← Consistent with human logic



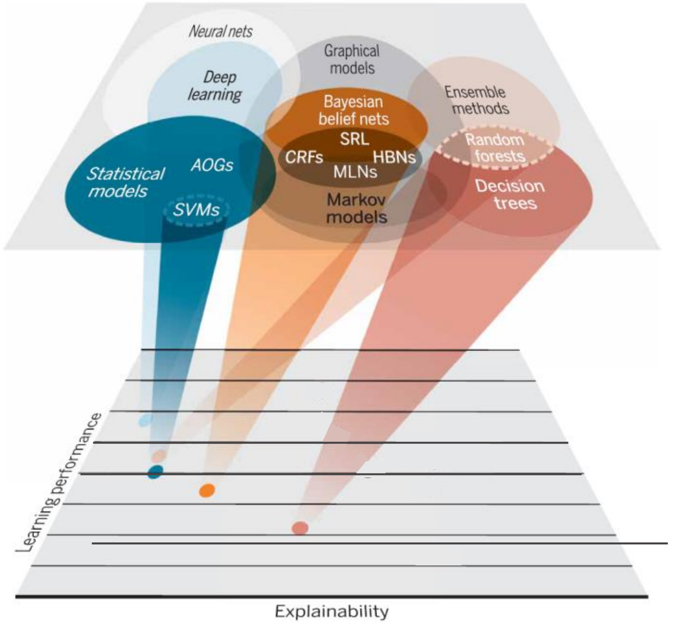


Decision Making Support: DBN

Results and accomplishments

Integrated Artificial Reasoning Algorithm: Explainable AI (XAI)

Performance vs. Explainability tradeoff [1]



- **Performace-Explainability tradeoff relationship among existing ML techniques.**
  - Often, the highest performing methods are the least explainable, and vice versa.

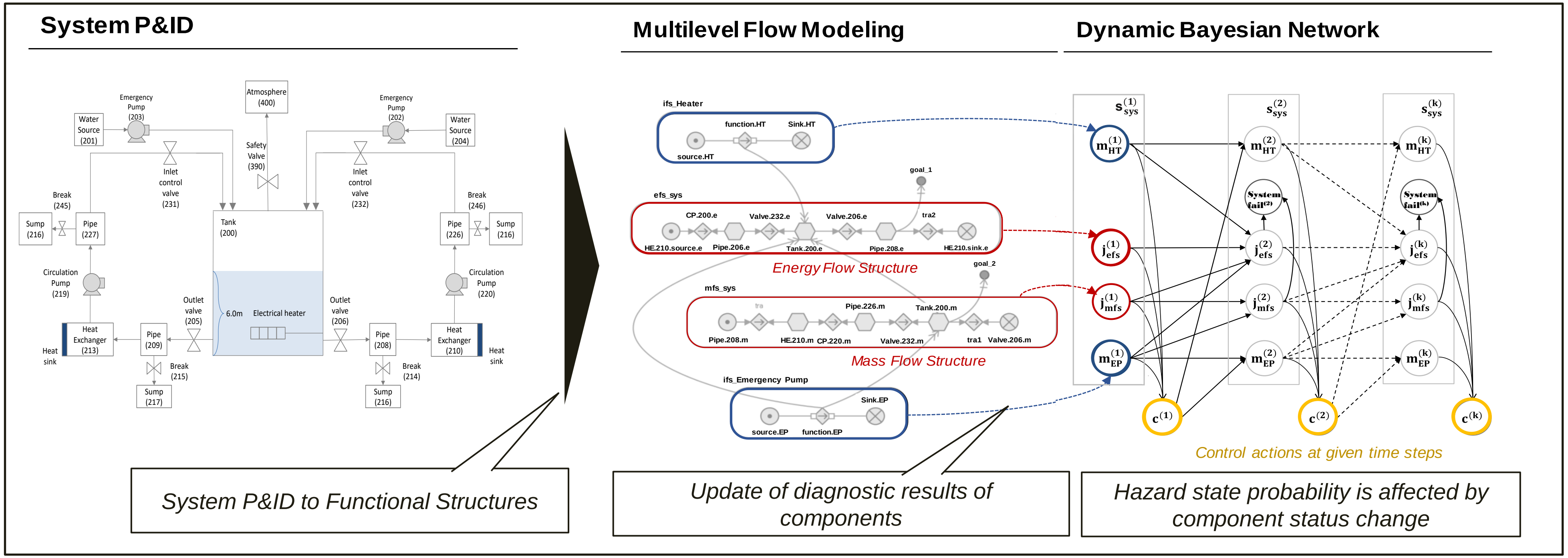
We aim at Integrated Artificial Reasoning Algorithm

	Objective	Techniques
Internal Structure Modeling	• Mathematical and graphical modeling	• Multilevel Flow Modeling (MFM) • Dynamic Bayesian Network (DBN)
System State Discretization	• State-Space discretization based on system information and data analytics	• Data-driven hyperplanes from Support Vector Machine (SVM)
Causal / Consequence Reasoning	• Graphical visualization of state transition trajectory	• Decision Tree

- **Making decisions based on quantitative evaluation of operational options**
- **Capturing merits of systematic approaches combined with techniques**

[1] Figure adopted and modified from Figure 1. in Gunning, David, et al. "XAI—Explainable artificial intelligence." Science Robotics 4.37 (2019).

Dynamic System Status & Risk Modeling



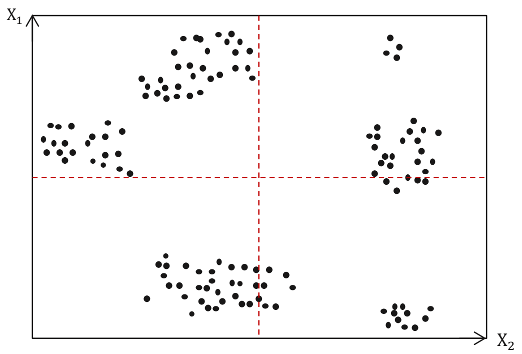
- **Objective modeling of system using functional modeling technique and dynamic Bayesian network[2] [3]**
  - System decomposition reflecting physical phenomena (the law of conservation of mass and energy)
  - State probability calculation using dependency information among subsystems
- **System state probability & risk quantification**
  - $\Pr(s_{sys}^{(k)}) = \sum_{s_{sys}^{(k-1)}} \sum_{c^{(k-1)}} \Pr(s_{sys}^{(k)} \mid s_{sys}^{(k-1)}, c^{(k-1)}) \times \Pr(c^{(k-1)} \mid s_{sys}^{(k-1)}) \times \Pr(s_{sys}^{(k-1)})$

[2] Kim, Junyung, Asad Ullah Amin Shah, and Hyun Gook Kang. "Dynamic risk assessment with Bayesian network and clustering analysis," Reliability Engineering & System Safety 201 (2020)
[3] Kim, Junyung, Hyun Gook Kang et al. "System Risk Quantification and Decision Making Support using Functional Modeling and Dynamic Bayesian Network," Reliability Engineering & System Safety (2021)

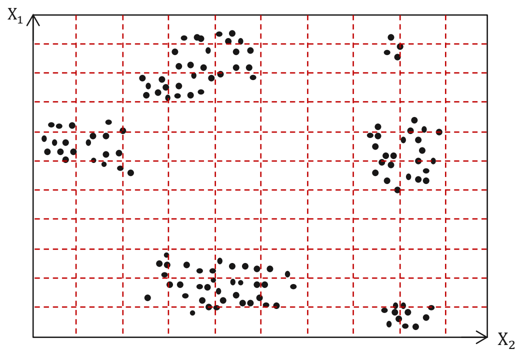
Results and accomplishments

State-Space Discretization for Physical Inference and Manageable Computational Cost

Equal Width Discretization

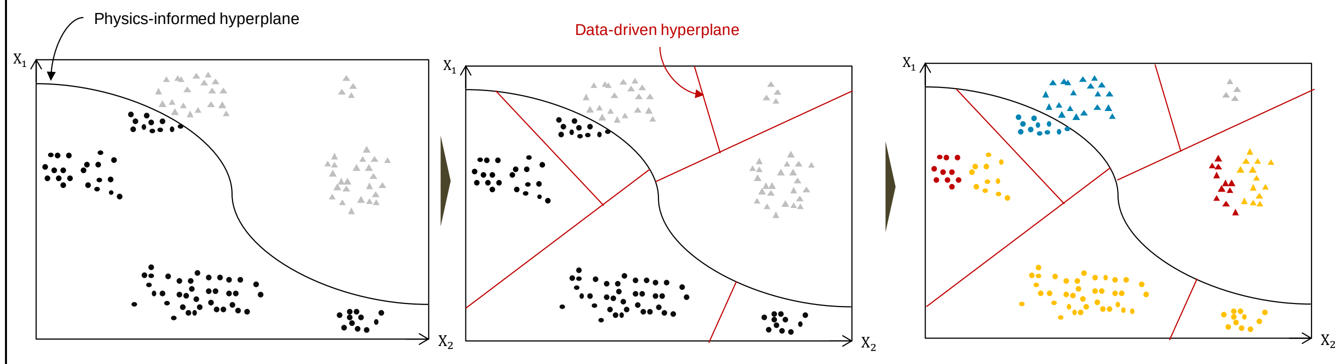


- Uncertainty Increases due to the lumped states



- High computation cost for state transition matrix

Physics-informed Machine Learning-aided State-Space Discretization



Step 1: Physics-based partitioning

Step 2: Machine Learning-based clustering

Step 3: Component Status-based partitioning [4]

- **Each state cell is tagged with physical meaning by Step 1 and 3.**
  - System space is partitioned based on physical property and component status information.
- **State size is controlled by Step 2.**
  - It minimizes the loss of state information due to lumped states.

* Different component status in system is coated with different colours.

[4] Junyung Kim, Hyun Gook Kang, et al. “Physics-informed machine learning aided system space discretization.” Proceedings of 12th NPIC&HMIT, 2021.

Results and accomplishments

Decision Making Support Metrics

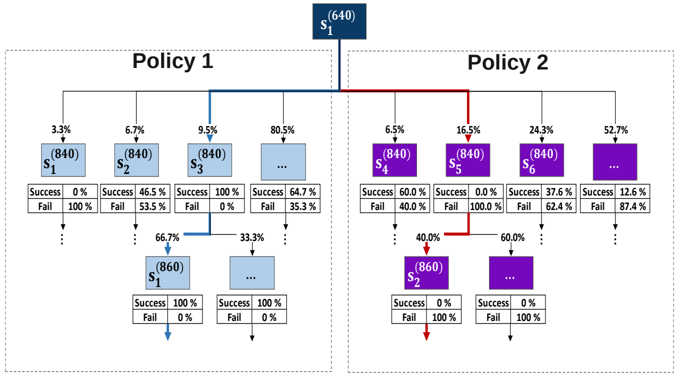
System Failure Risk based Approach (DBN)

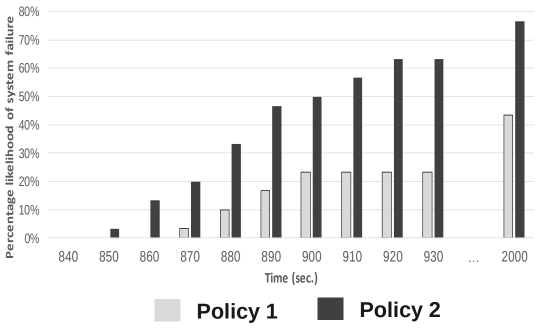
Decision Making based on System Failure Probability

$$\Pr(f^{(t)}) = \sum_{S^{(t-1)}} \sum_{c^{(t-1)}} \underbrace{\Pr\left(f^{(t)} | S^{(t-1)}, C^{(t-1)}\right)}_{\text{System Failure Risk}} \underbrace{\Pr\left(C^{(t-1)} | S^{(t-1)}\right)}_{\text{Policy}} \underbrace{\Pr\left(S^{(t-1)}\right)}_{\text{State Probability}}$$

$$\Pr(S^{(t-1)}) = \sum_{S^{(t-2)}} \sum_{c^{(k-2)}} \underbrace{\Pr(S^{(t-1)} | S^{(t-2)}, c^{(k-2)})}_{\text{State Transition}} \Pr(c^{(k-2)} | S^{(t-2)}) \Pr(S^{(t-2)})$$

Decision Tree and Risk Profile of Operational Policy





Reward-function based Approach (MDP)

Decision Making based on State Value

$$V(S^{(t)}) = \sum_{C_t} \underbrace{Q(S_t, C_t)}_{\text{Action Value}} \Pr(C^{(t)} | S^{(t)})$$

$$= \sum_{C_t, S_{t+1}} \underbrace{\left(R^{(t)} + \gamma V(S^{(t+1)})\right)}_{\text{State Value}} \underbrace{\Pr(S^{(t+1)} | S^{(t)}, C^{(t+1)})}_{\text{State Transition}} \underbrace{\Pr(C^{(t)} | S^{(t)})}_{\text{Policy}}$$

- **We tested decision-making support metrics for different operational objectives**
  - System risk for selecting mitigation options during the accident scenarios.
  - State value for choosing operating options to make continuous operation.
- **We are planning to harmonize two metrics considering both system failure risk and expected state value.**

Conclusion

Summary of Presentation

- Built a BN diagnostic model for cooling tower fan motors at the CUP.
- Developed a two-flow system simulation model using Modelica and TRANSFORM.
- Built an MFM model for the two-flow system.
- Developed an MDP for operator decision support for the two-flow system.
- Developed a DBN system based on the MFM for operator decision support for the two-flow system.

Future Work

- Build a BN diagnostic model for another component (likely a pump or a steam turbine) at the CUP.
- Develop a TRANSFORM model for a sodium-cooled fast reactor (SFR).
- Develop an integrated operator support algorithm for the SFR cases

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Conclusion

Publications in FY 2021

Conference papers presented.

1. Junyung Kim, Hyun Gook Kang, “System State Discretization with Laws of Physics and Data Analytics,” STSS & ISOFIC 2021, Okayama (Hybrid), Japan, Nov. 2021
2. Junyung Kim et al. “Physics-informed machine learning-aided system space discretization.” NPIC-HMIT ANS Conference 2021.
3. Hyun Gook Kang et al. “Risk Comparison Among Design Options of RPS with Diverse PLC and FPGA Systems.” NPIC-HMIT ANS Conference 2021.
4. Xingang Zhao and Michael Golay. “Artificial Reasoning System for Symptom-Based Conditional Failure Probability Estimation Using Bayesian Network.” NPIC-HMIT ANS Conference 2021.
5. Junyung Kim et al. “Inference Rule Generation using Multilevel Flow Modeling for Fuzzy Logic-based System Control”; “Risk assessment using MFM with dynamic Bayesian Network.” IWFM 2020 (Oct. 2020)
6. Junyung Kim and Hyun Gook Kang. “Quantitative Reasoning and Risk Assessment with Dynamic Bayesian Network.” ANS Winter Meeting (Nov. 2020)

Journal paper accepted.

1. Junyung Kim et al. “System Risk Quantification and Decision-Making Support using Functional Modeling and Dynamic Bayesian Network.” Reliability Engineering and System Safety (RESS) (2021).
2. Xingang Zhao, et al. "Prognostics and health management in nuclear power plants: an updated method-centric review with special focus on data-driven methods." Frontiers in Energy Research (2021).

Questions?

ASI | Advanced Sensors and Instrumentation

Construct the Structure BN for the Electric Motors

- Nodes and causalities were picked from troubleshooting chart in the motors' manual.
- Expert knowledge helped to refine the selection.

Symptom	Possible Causes	Possible Solutions
Motor will not start	Usually caused by line trouble, such as, single phasing at the starter.	Check source of power. Check overloads, fuses, controls, etc.
Excessive humming	High Voltage.	Check input line connections.
	Eccentric air gap.	Have motor serviced at local Baldor service center.
Motor Over Heating	Overload. Compare actual amps (measured) with nameplate rating.	Locate and remove source of excessive friction in motor or load. Reduce load or replace with motor of greater capacity.
	Single Phasing.	Check current at all phases (should be approximately equal) to isolate and correct the problem.
	Improper ventilation.	Check external cooling fan to be sure air is moving properly across cooling fins. Excessive dirt build-up on motor. Clean motor.
	Unbalanced voltage.	Check voltage at all phases (should be approximately equal) to isolate and correct the problem.
	Rotor rubbing on stator.	Check air gap clearance and bearings.
		Tighten Thru Bolts.
	Over voltage or under voltage.	Check input voltage at each phase to motor.
	Open stator winding.	Check stator resistance at all three phases for balance.
	Grounded winding.	Perform dielectric test and repair as required.
	Improper connections.	Inspect all electrical connections for proper termination, clearance, mechanical strength and electrical continuity. Refer to motor lead connection diagram.
Bearing Over Heating	Misalignment.	Check and align motor and driven equipment.
	Excessive belt tension.	Reduce belt tension to proper point for load.
	Excessive end thrust.	Reduce the end thrust from driven machine.
	Excessive grease in bearing.	Remove grease until cavity is approximately 3/4 filled.
	Insufficient grease in bearing.	Add grease until cavity is approximately 3/4 filled.
	Dirt in bearing.	Clean bearing cavity and bearing. Repack with correct grease until cavity is approximately 3/4 filled.
Vibration	Misalignment.	Check and align motor and driven equipment.
	Rubbing between rotating parts and stationary parts.	Isolate and eliminate cause of rubbing.
	Rotor out of balance.	Have rotor balance checked are repaired at your Baldor Service Center.
	Resonance.	Tune system or contact your Baldor Service Center for assistance.
Noise	Foreign material in air gap or ventilation openings.	Remove rotor and foreign material. Reinstall rotor. Check insulation integrity. Clean ventilation openings.
Growling or whining	Bad bearing.	Replace bearing. Clean all grease from cavity and new bearing. Repack with correct grease until cavity is approximately 3/4 filled.

Troubleshooting Chart from the Motors' Manual

Prior Probabilities of Low-Level Failures of the CUP's Electric Motors

- Prior probabilities of the low-level failures (F_j) are given by the experts **qualitatively:** F4 = F5 > F1 = F7 > everything else. Exact values are assigned to the low-level failure nodes based upon this rank as shown below.

Prior Probability Values for F4 and F5

States	Probabilities
Mild	0.75
Moderate	0.15
Severe	0.10

Prior Probability Values for F1 and F7

States	Probabilities
Mild	0.8
Moderate	0.12
Severe	0.08

Prior Probability Values for F2, F3, F6 and F8

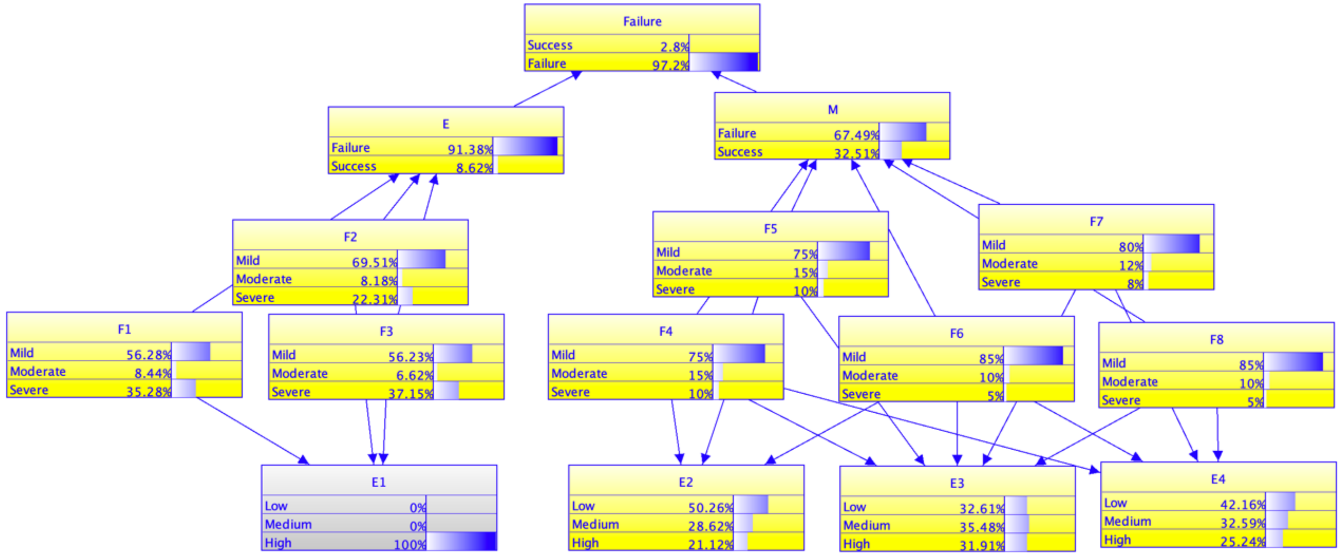
States	Probabilities
Mild	0.85
Moderate	0.10
Severe	0.05

Appendix I

CPT $P(E_i|F_j)$ of the sensor nodes

- The field experts provided $P(F_j|E_i)$ **qualitatively** as shown in the chart below.
- $P(E_i|F_j)$ is determined using the qualitative $P(F_j|E_i)$ and UnBBayes's evidence propagation function. In order to reflect the qualitative $P(F_j|E_i)$, all the $P(E_i|F_j)$ must be defined such that the posterior probabilities of F_j satisfy the $P(F_j|E_i)$ from the expert when corresponding E_i values are observed to be abnormal. For example, the CPT of node E_1 must be set up such that, when E_1 is observed to be moderate or severe, the posterior probabilities of F_1 through F_3 must be ranked as $P(F_3|E_1)>P(F_1|E_1)>P(F_2|E_1)$ as shown in the figure below.

Observed Abnormal Sensor(E_i)	Likelihood of Related Faults Rank($P(F_j|E_i)$)
E1	F3 > F1 > F2
E2	F4 > F5 > F6
E3	F4 > F5>F7 >F6> F8
E4	F4 > F7 > F6 > F8



Posterior Probabilities Given E_1.

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

ASI Advanced Sensors and Instrumentation

Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

PI: Dave Grabaskas

Manager, Safety and Risk Assessments Group
Argonne National Laboratory

Project Overview

Project Goal: Improve advanced reactor economics through:

- Optimization of the reactor sensor network design
- Intelligent asset-management decision-making during operation

Participants

Argonne National Laboratory | The Ohio State University | framatome

PI: Dave Grabaskas
Roberto Ponciroli
Vera Moiseytseva

Carol Smidts
Xiaoxu Diao
Yunfei Zhao
Samuel Olatubosun
Ragib Rownak

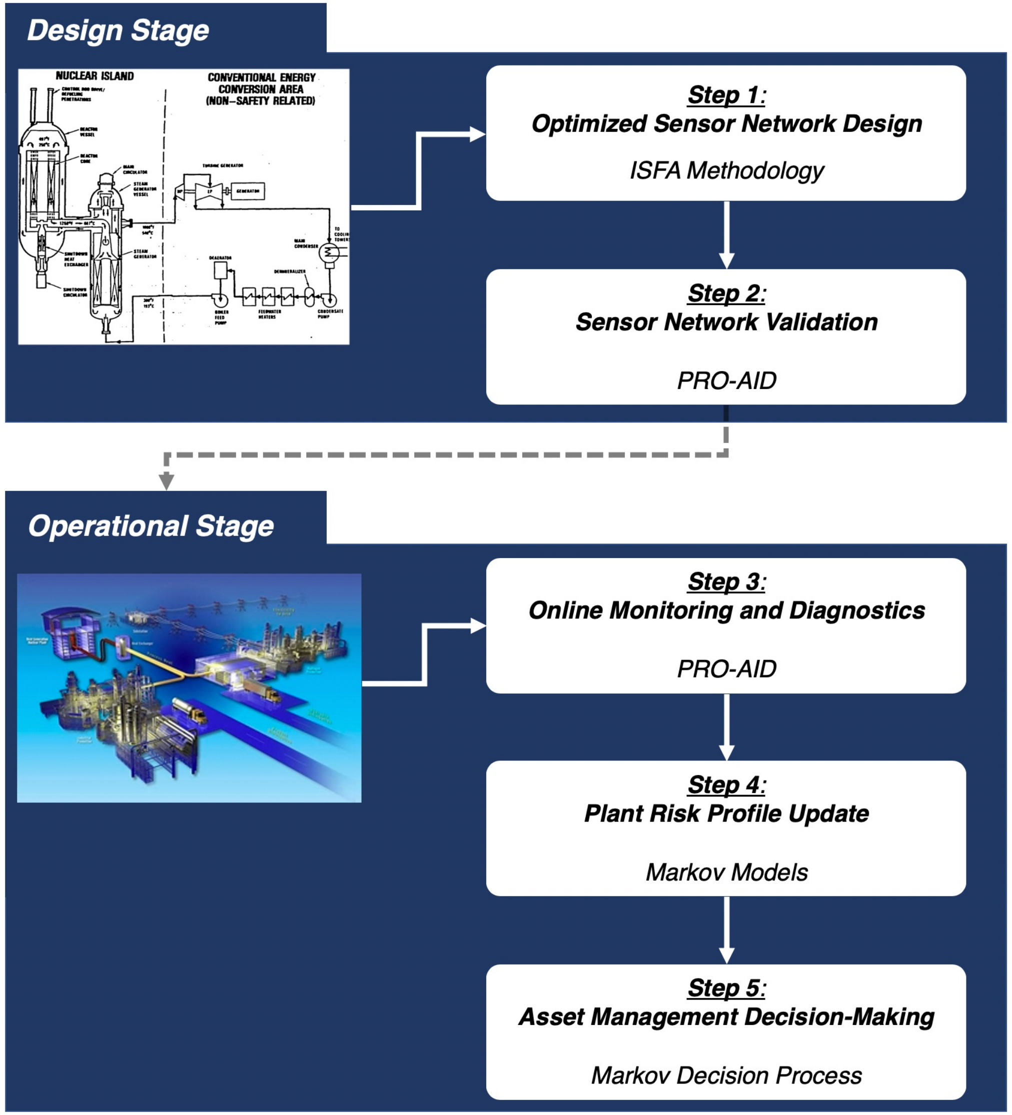
Pascal Brocheny
Many others…

Schedule: FY20 - FY22

Project Overview

- Design Phase
  - Optimize the sensor network design based on a variety of criteria (cost, reliability, etc.)
  - Ensure the diagnosability of key faults and events, such as component degradation or sensor failure

- Operational Phase
  - Utilize online monitoring and diagnostic information to create a real-time model of the plant risk profile, including:
    - **Safety**: Probabilistic Risk Assessment (PRA)
    - **Economics**: Generation Risk Assessment (GRA)
  - The real-time risk profile facilitates intelligent asset-management decision-making through…
    - The identification and ranking of those components contributing to current or potential generation issues
    - The comparison of different operational plans and the predicted cost and return of each option



Project Overview

- Schedule

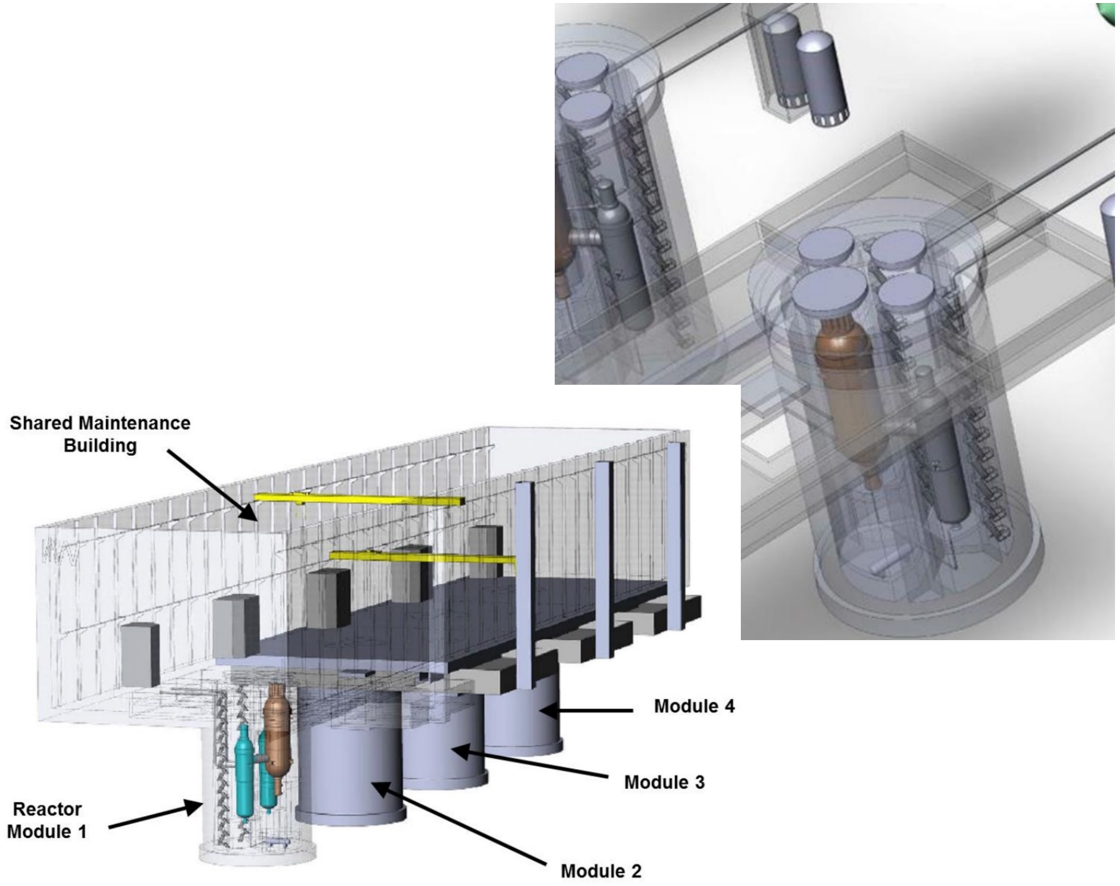
FY20
- Establishment of overall process and flow
- Identification of new capabilities and methods
- Preliminary development of linking strategies

FY21
- Expansion of tool capabilities
- Continued development of linking strategies
- Selection of demonstration analysis

FY22
- Finalize method and tool development
- Complete demonstration analysis
- Publish findings and results

Technology Impact

- This central focus is economics of advanced reactor design and operation
- Maximizing the value of instrumentation and expanding the impact of monitoring data
- Taking tools and methods that have been developed by alternate DOE programs (ARPA-E, NEET, ART) and creating an integral approach
- Working directly with industry to advance to demonstration and pursue commercialization



framatome

Results and accomplishments

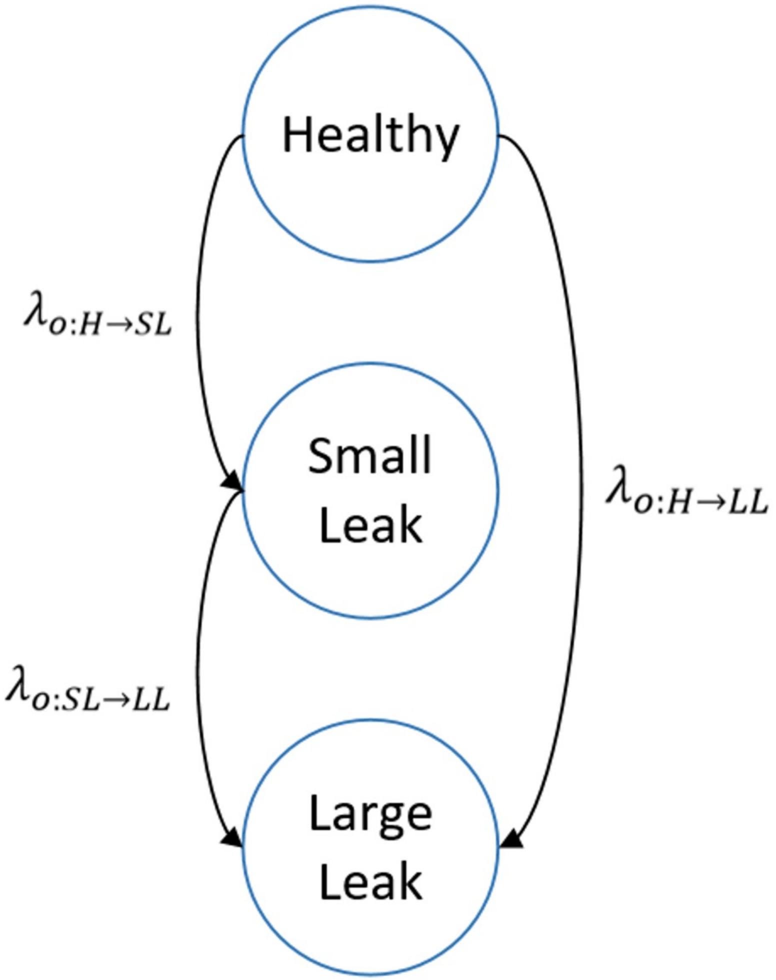
- Sensor Network Optimization
  - Integrated System Failure Analysis (ISFA) method
    - Developed by Ohio State University
    - Efficiently explores alternative sensor network designs
    - Expanding capabilities to facilitate new optimization acceptance criteria and allow sensor grading
  - New capabilities
    - Identified, defined, and instituted new optimization criteria
    - Identified, assessed, and selected optimization algorithm
    - Summarized in two completed M3 deliverables

ISFA Optimization Criteria	
Observability	Uncertainty
Reliability	Risk Resistance
Cost	Failure Prognosis
Functionality	Integrability

Evaluated Optimization Algorithms	
Evolutionary Algorithms	Genetic Algorithm
	NSGA
	NSGA-II
	Particle Swarm
	Distributed Wolf
	Microhabitat Frog-leaping
Greedy Algorithms	Greedy
	Hybrid Greedy
	Simulated Annealing

Results and accomplishments

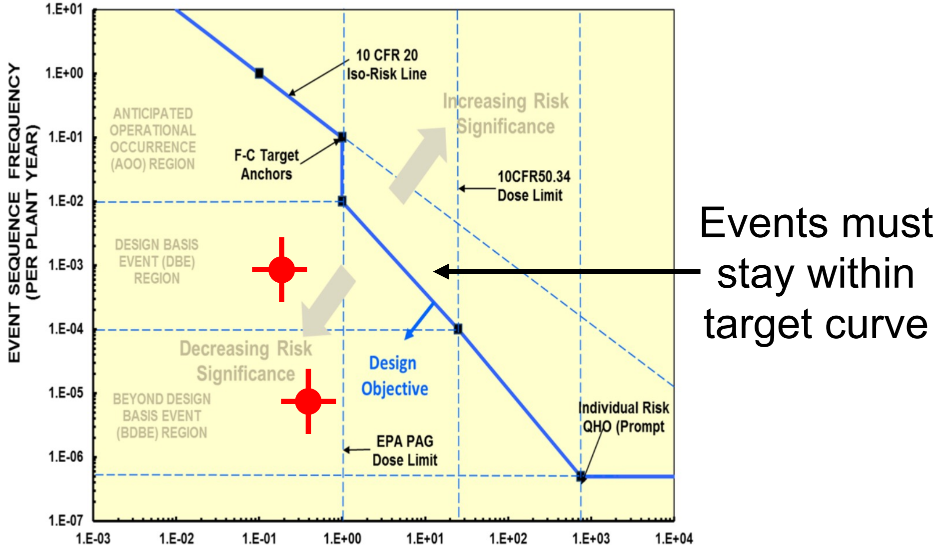
- Online Monitoring and Diagnosis
  - Utilizing the Argonne tool PRO-AID
    - Combines sensor data and physics models to diagnose plant conditions
    - Building off the development efforts of previous NEET projects
  - Coupling to Markov component models
    - Markov component models are utilized in PRA/GRA to assess the likelihood of component failure or degradation
    - The Markov component models within the PRA/GRA are linked to PRO-AID, which updates the key model parameters
    - Progress summarized in two M3 deliverables



Pipe Markov Model

Results and accomplishments

- Real-Time Risk Profile
  - Probabilistic Risk Assessment (PRA)
    - Assesses the likelihood and consequence of accident scenarios
    - Using the Licensing Modernization Project (LMP) framework, scenarios are plotted against a frequency versus consequence curve.
    - Establishes the allowable operating envelope



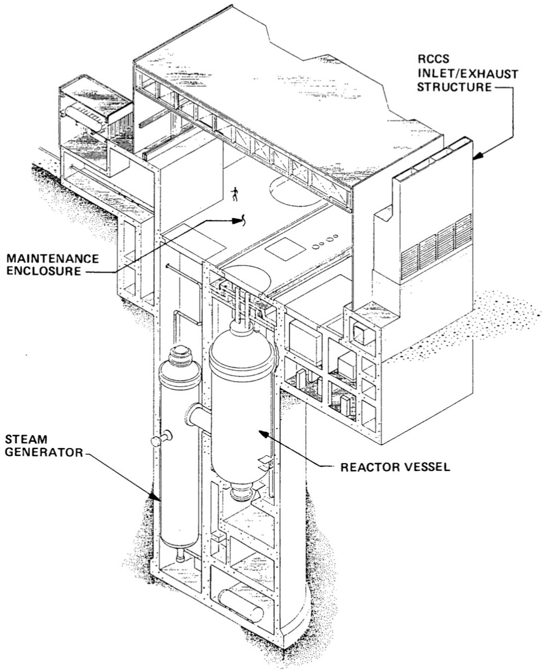
Frequency vs. Consequence Plot

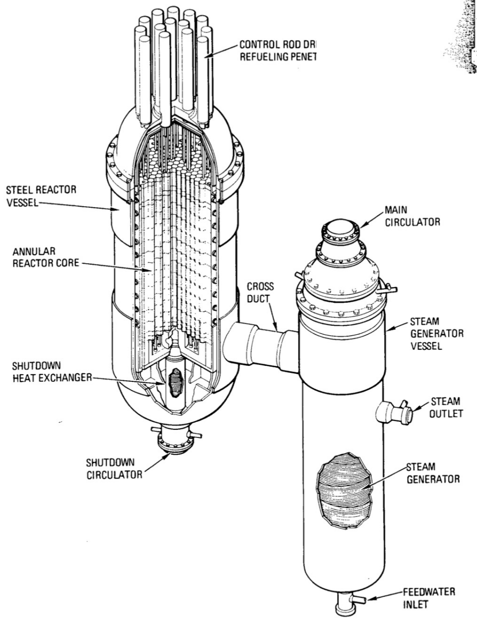
  - Generation Risk Assessment (GRA)
    - Examines risk from a generation perspective
    - Utilizes a structure similar to PRA models
    - GRA findings can be utilized to optimize operational plans (*i.e.*, minimize the likelihood of scram/de-rate)

- Asset Management Decision-Making
  - Many variables to consider…
    - Current and future status of components
    - Cost to repair or replace components
    - Loss of generation
    - Risk associated with different operational plans (safety and generation)
  - Decision-Making Process
    - Real-time risk profile provides the importance of components to generation and safety risk
    - Differing operational plans are developed for the prioritized components (repair, ignore, etc.)
    - Plans are evaluated to determine if they are within allowable safety operating window
    - For those plans that are acceptable, compare and optimize cost-benefit
      - Depending on complexity and time-scale, utilize a Markov Decision Process (MDP) reinforced learning process

Results and accomplishments

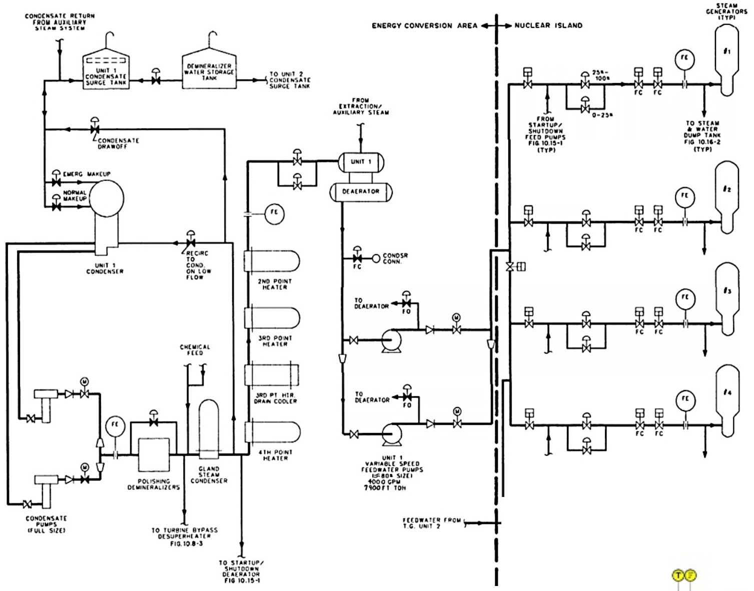
- Demonstration Analysis
  - General Atomics MHTGR
    - Similar to the Framatome SC-HTGR design concept but significant design and analysis information available in the public domain, which alleviates proprietary restrictions
      - Preliminary Safety Information Document (PSID)
      - Preapplication Safety Evaluation Report (PSER)
      - PRA and licensing basis event selection documents
      - Numerous design and operational documents (SDDs, SSDDs, maintenance plans, etc.)
    - A number of MHTGR systems were evaluated based on complexity, available data, importance to generation, and industry interest to select the demonstration problem

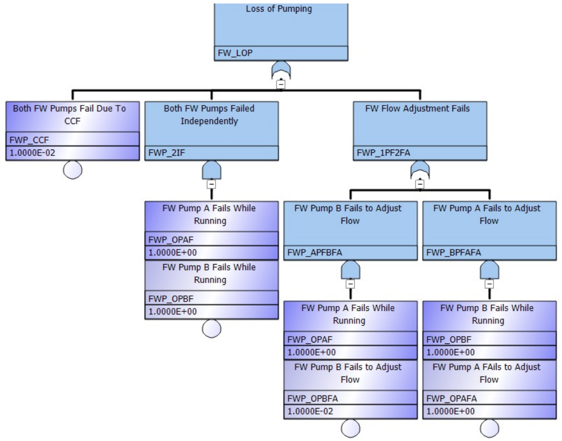


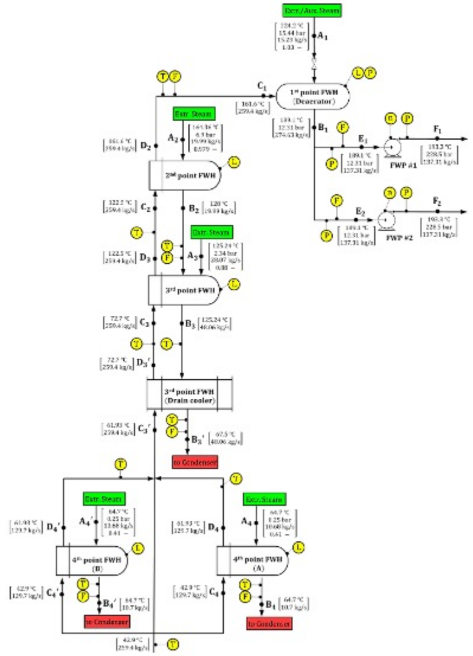


Results and accomplishments

- Demonstration Analysis
  - Feedwater System
    - High importance to both PRA and GRA
    - Complexity in design and function (support of multiple reactor modules)
    - Current data available from Framatome regarding component characteristics (cost, repair time, etc.) due to commonality with LWRs
  - Model Development
    - Developing system surrogate in Dymola, for use with PRO-AID to diagnose faulted conditions
    - Re-creating and updating the PRA and GRA in SAPHIRE to utilize for creating real-time plant risk profile







Conclusion

- Seeking to improve advanced reactor economics through advancements in sensor network design and asset-management decision-making

- FY21 Accomplishments
  - Continued to develop and refine methods and tools
  - Selected and initiated work on the demonstration analysis

- FY22 Plans
  - Finalize all methods and tools
  - Complete demonstration analysis and publish
  - Explore next steps…

Conclusion

- Future Plans
  - Contributing findings to a new NEET project on autonomous operation
  - Based on findings of the demonstration analysis, explore an expanded analysis for a complete advanced reactor system in partnership with a vendor
  - Evaluate avenues for industry to obtain access to tools and methods

Dave Grabaskas

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LinkedIn

Questions?

ASI | Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Machine Learning Enhancement of BWR Neutron Flux Measurement and Calibration

Funded under DE-FOA-0001817
Award # DE-NE0008930

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

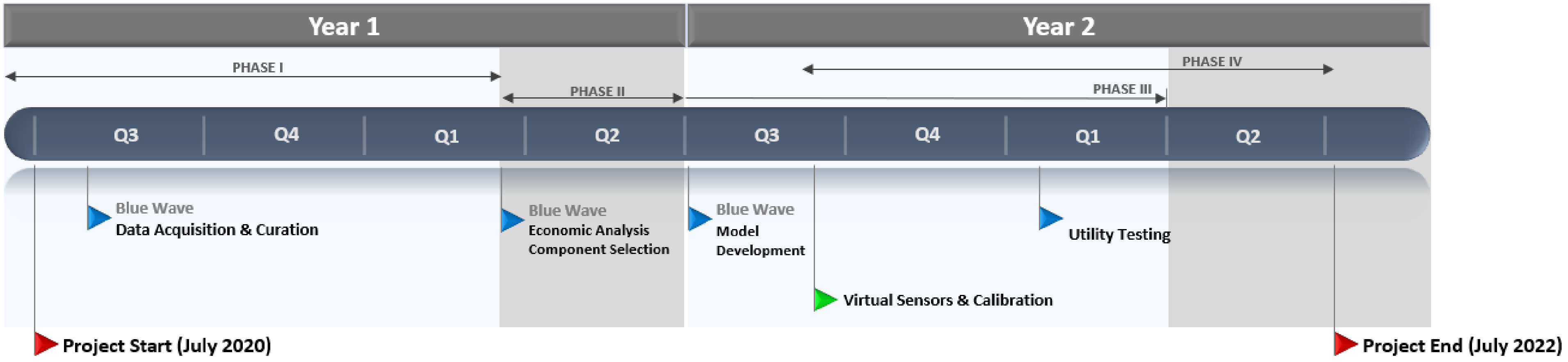
November 15 – 18, 2021

Principal Investigator, Tom Gruenwald, PhD
Chief Operating Officer

Blue Wave AI Labs

Project Overview

Schedule



Milestone	Description	Target Completion Date	Actual	Progress
Phase I	**Data Acquisition & Curation**	03/16/21	ongoing	100%
1	Pre-Data Acquisition Information Exhanged	09/24/20	09/24/20	100%
	Task ID 3: Site Visits (virtual)			100%
	Task ID 4: Exelon Conference Calls (weekly)	ongoing	ongoing	100%
	Task ID 5: Raw Data Descriptions			100%
	Task ID 6: Data Dictionary			100%
	Task ID 7: Data Transfer Protocols (via ShareFile)			100%
2	Data Acquisition - All Data Acquired	05/28/21	–	99%
	Data Acquisition - Transfer Completed (round 1)	11/24/20	11/24/20	100%
	Data Acquisition - Transfer Completed (round 2)	12/31/20	12/19/20	100%
	Data Acquisition - Transfer Completed (round 3)	05/10/21	06/11/21	100%
	Data Acquisition - Peach Bottom FW data post PB3C24 Startup	12/15/21		50%
3	Raw Data Curated	03/16/21	ongoing	100%
	Task ID 15: Raw Data Exploration (rounds 1-2)			100%
	Task ID 16-19: Data Cleaning Procedures (rounds 1-2)			100%
	Task ID 20-24: Establish Working Database (LPRM + FW Heaters)	03/01/21	02/26/21	100%

Phase II	**Component Selection & Economic Analysis**	07/14/21	ongoing	94%
1	Outage Data for Component Causes Examined	05/11/21	ongoing	88%
	Task ID 28: Examine Outage Data	05/11/21	ongoing	75%
	Task ID 30: Review data sufficiency	05/14/21	ongoing	100%
2	List of Target Components Determined	06/22/21	ongoing	100%
	Determination of Initial target components	02/08/21	01/15/21	100%
Phase III	**Model Development**	03/17/22	ongoing	50%
1	Unsupervised Learning Feature Analysis	08/13/21	ongoing	50%
	Task ID 36: Feature Analysis (LPRM, Control Blades, FW)		ongoing	50%
2	ML Component Models Constructed	12/08/21	ongoing	50%
	Task ID 38: Supervised ML on Components (LPRM, FW)	11/30/21	ongoing	50%
3	Model Testing w/ Utilities	03/15/22	–	0%
Phase IV	**Calibration & Sensor Modeling**	07/05/22		34%
1	Calibration Analysis	02/03/22	ongoing	10%
	Task ID 46: Calibration Analysis (LPRM)	01/20/22	ongoing	10%
2	Data Fusion Analysis	02/24/22	ongoing	75%
	Task ID 48: Data Fusion Analysis (LPRM)	02/10/22	ongoing	75%
3	Sensor Correlation Maps	05/18/22	ongoing	50%
	Task ID 50: Correlation Maps Established (LPRM)	04/22/22	ongoing	50%
4	Correlation Map Testing	06/06/22	–	0%
	Task ID 52: Test Sensor Correlation Maps (LPRM)	05/24/22		0%

Project Overview

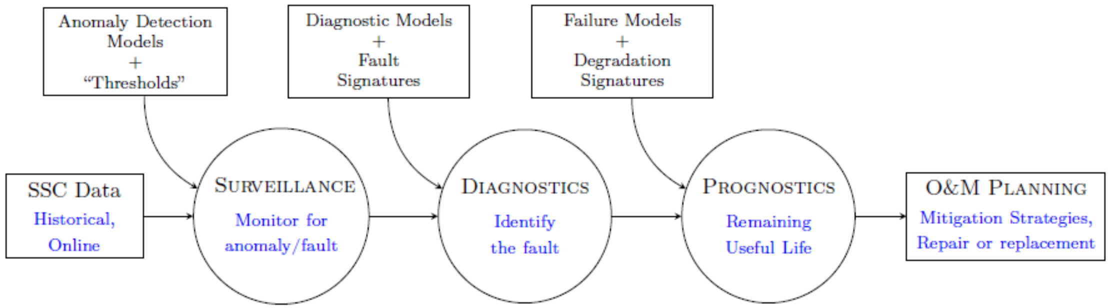
System Health Framework – Diagnostics & Prognostics

Application of Machine Learning for Enhanced Diagnostic and Prognostic Capabilities of Nuclear Power Plant Assets

PI: J. Thomas Gruenwald
Blue Wave AI Labs, Inc.

Pathway:
Advanced Reactor Development Projects

Collaborators:
Richard Vilim, Argonne National Laboratory (ANL)
Upendra Singh Rohatgi, Brookhaven National Lab (BNL)
Christopher Pelchat, Nebraska Public Power District (NPPD)
Andrew Winter, Exelon Generation



The stages of such a system include:

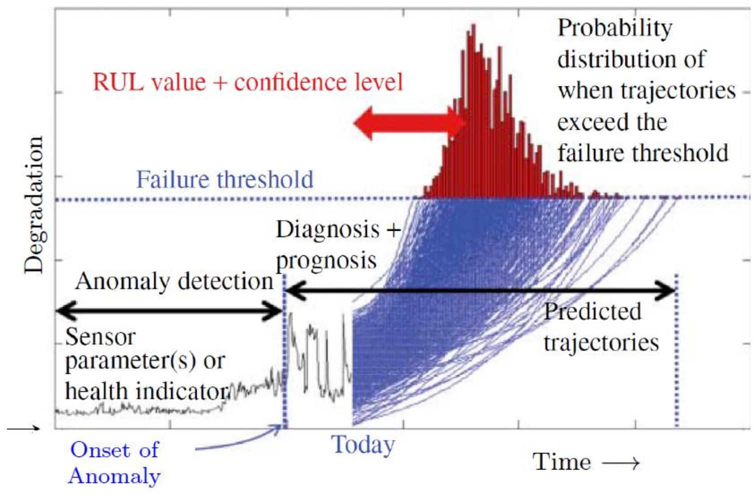
1. Collecting data on a plant asset,
2. Monitoring the data for anomalies,
3. Identifying the type of fault, and
4. Predicting RUL and probability of failure from the updated history of the SSC's, environmental conditions, and diagnoses.

Challenges for accurate assessment of health:

1. Knowledge of which features (performance indicators) determine equipment health
2. Ability to measure these features <u>frequently</u>
3. Ability to detect anomalies at the **earliest possible stage**.
4. Reliable prediction of future performance from this information!

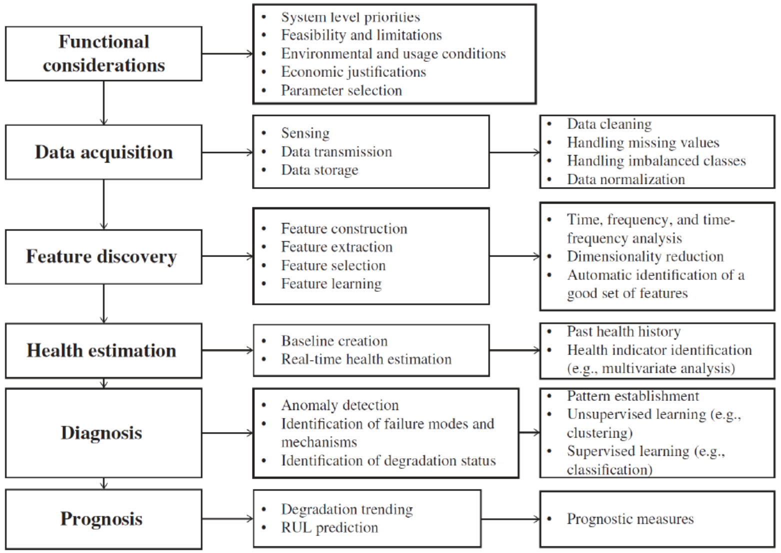
- Principle Technical Contributors (Blue Wave)
  - Tom Gruenwald, Ph.D. PI
  - Jonathan Nistor, Ph.D. Chief Scientist
  - Jordan Heim, Ph.D. Neutronics Team Leader
  - Anirudh Tunga, MS
- BW Interns
  - Gihan Mendis, Ph.D. candidate, active
  - Alina Nesen, Ph.D. candidate, assignment completed
  - Georgios Georgiopolis, Ph.D., assignment competed

➢ Condition-based maintenance
➢ Virtual sensors
➢ Virtual calibration
➢ Remaining useful life models
➢ Data management and visualization



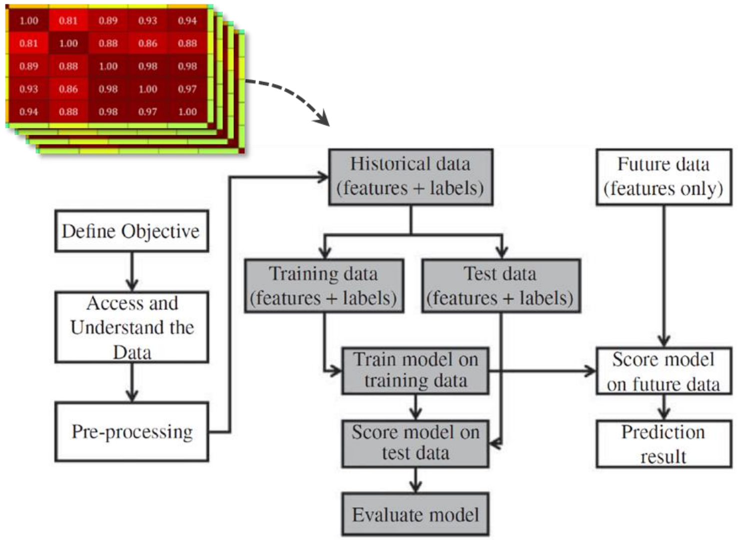
Project Overview

AI-Enabled Framework



General Concept

Supervised Learning on new feature set



Specific System/Component

Outputs

- Robust metrics for current/forecasted system or component health
- Virtual Sensors
- **RUL** (remaining useful life) of SSCs

Benefits — Significant Cost Savings

- Reduce unplanned downtime/outages
- Eliminate unnecessary maintenance
- Intelligent maintenance scheduling + allocation of resources
- Extend maintenance/replacement/inspection intervals
- Increase visibility through more frequent, reliable "health" readings

This framework is now being applied to:

- **Feedwater Heater System**
- **Feedwater Heater Level Control**
- **EHC Tuning**
- **FAC (Flow-accelerated Corrosion)**
- **LPRMs** (Local Power Range Monitors) in BWRs
  - Dynamic thresholding for LPRM trip units (reduce the need to bypass an LPRM)
  - More accurate LPRM lifetime estimation (extend replacement intervals)
  - Virtual LPRMs for use when one is in BY/CAL mode (bypassed or being calibrated)
- **TIPs** (Traversing In-core Probes)
  - Trace Alignment
  - Power Adaption

Project Overview

LPRM Monitoring Calibration, and EOL Determination Methodology

Objectives

- **Provide Virtual Measurements**
  - Offline / bypassed LPRM readings (redundancy)
  - Anomaly detection (early failure indication)
  - Increased effective service life
- **Enable Virtual Calibration of LPRMs**
  - On-demand
  - Quick calibration for new LPRMs
  - Improved nodal flux characterization
- **Improve RUL determinations & Replacement Schedule**
  - Higher accuracy
  - Reduce premature LPRM replacement
- **Streamline bookkeeping and workflow**
  - Easy review of detector history (interactive UI)
  - Visual insights (layout / heatmaps / graphs)

Problem statement: The LPRMs are critical for monitoring the thermal neutron flux within a boiling water reactor (BWR). Their reliability and accuracy are crucial to accurately assess thermal limits and monitor the core. Problems include:

- Infrequent calibrations leading to periods of inaccurate readings
- Lack of visibility when an LPRM goes offline / bypassed
- Premature replacement due to inaccurate end-of-life (EOL) determination

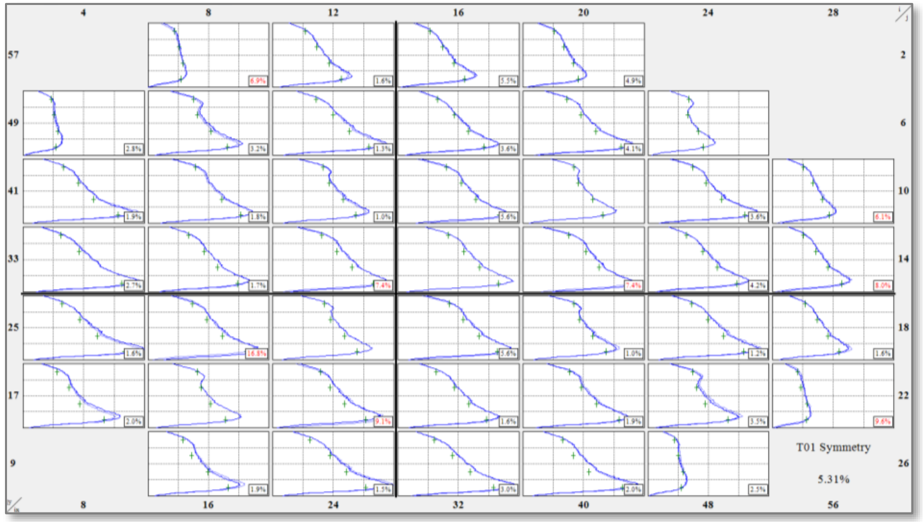
Overview

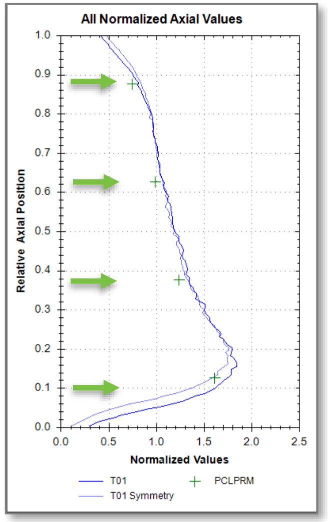
TIP Alignment Methodology and Flux Adaptation

Objectives

- **ML Detection of when auto alignment is performed incorrectly**
  - Historical trace review for past few cycles
  - Tool integration into customer process for identification of issues going forward
- **Develop new methodology for high fidelity TIP trace adaptation**
  - Train classifiers to more accurately adjust and adapt TIP traces than the current state-of-practice
  - Correct misaligned traces
- **Detect other spurious TIP data for increased visibility by Reactor Engineering**
  - Use to validate LPRM calibrations from TIP traces

Problem statement: The auto TIP alignment feature (in fuel vendor software) occasionally incorrectly shifts the local flux profile (by more than a full node) resulting in higher thermal limits (e.g. MFLPD). Higher thermal limits challenge operations due to inadequate margin and may result in a power derate if a limit is reached.



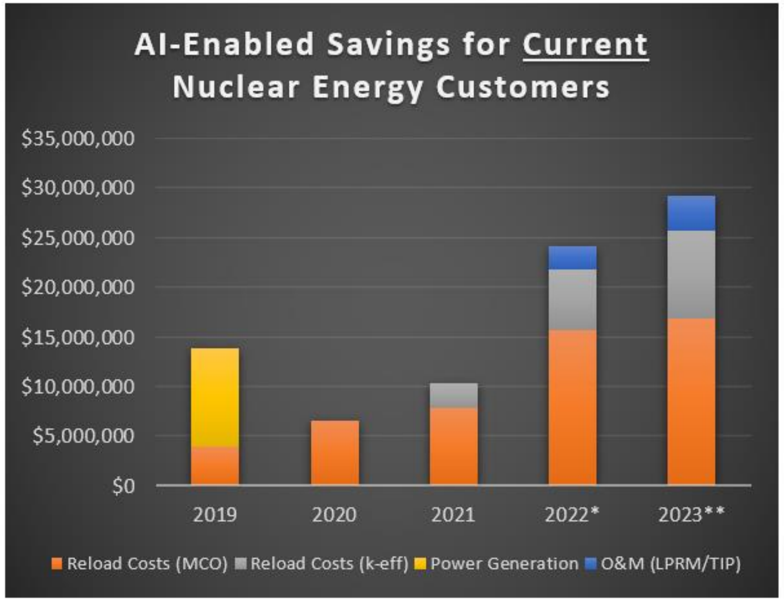


Improved characterization of axial power distribution

LPRM Location

Technology Impact

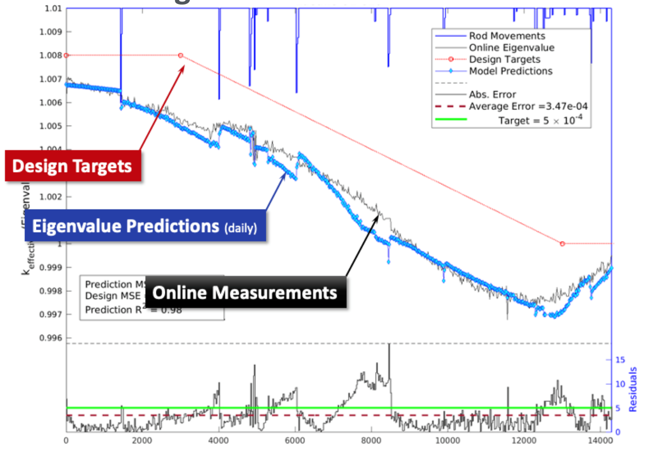
- AI-Enabled Solutions to optimize Nuclear Power Operations, Planning, and Maintenance
- For increased safety, reliability, cost-optimization, and visibility in NPP systems for Nuclear Engineers



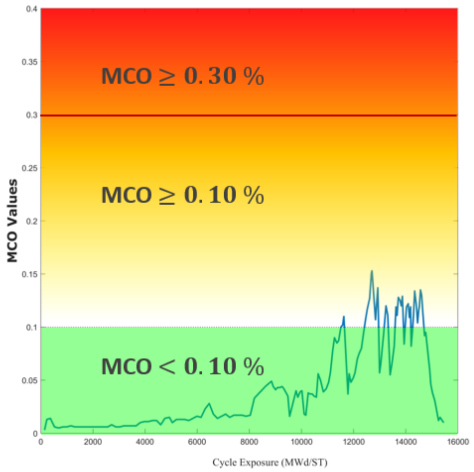
* Figure only includes savings from reload designs already completed

** Projected (expected) savings for current customers only

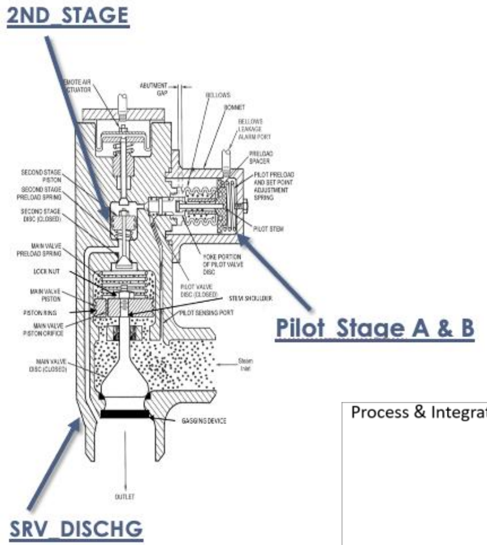
BWR Eigenvalue Prediction

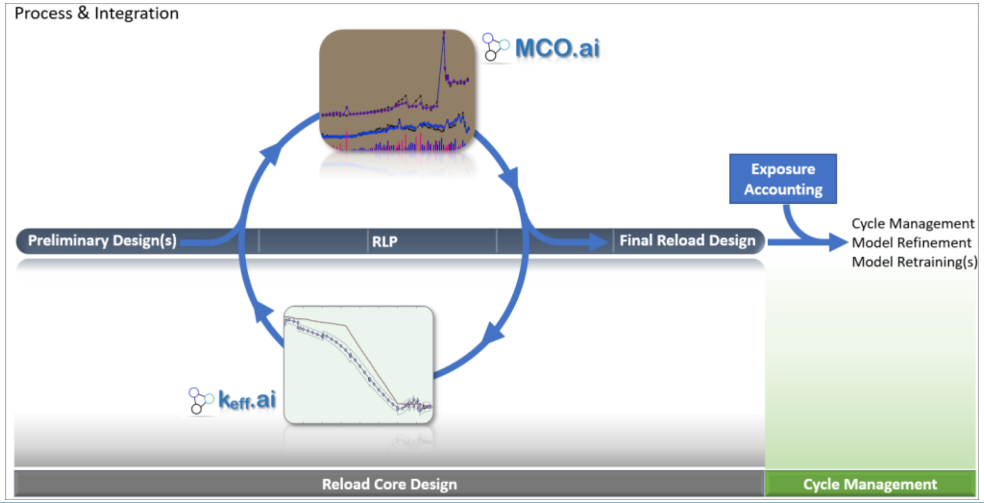


BWR MCO Prediction

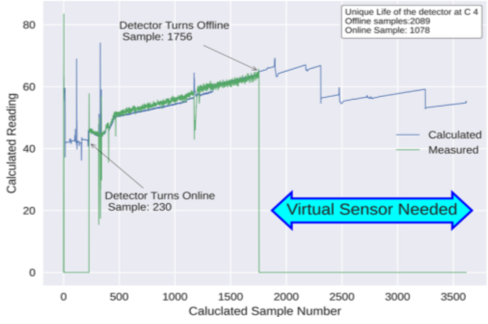


Chattering Valve

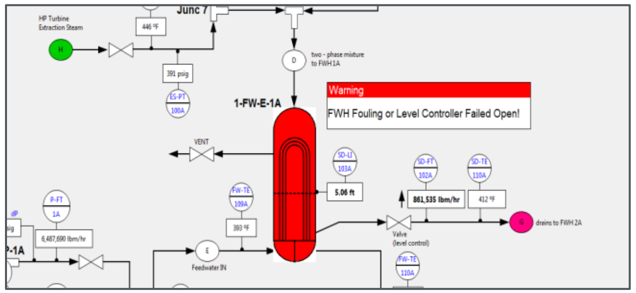




LPRM Virtual Sensor

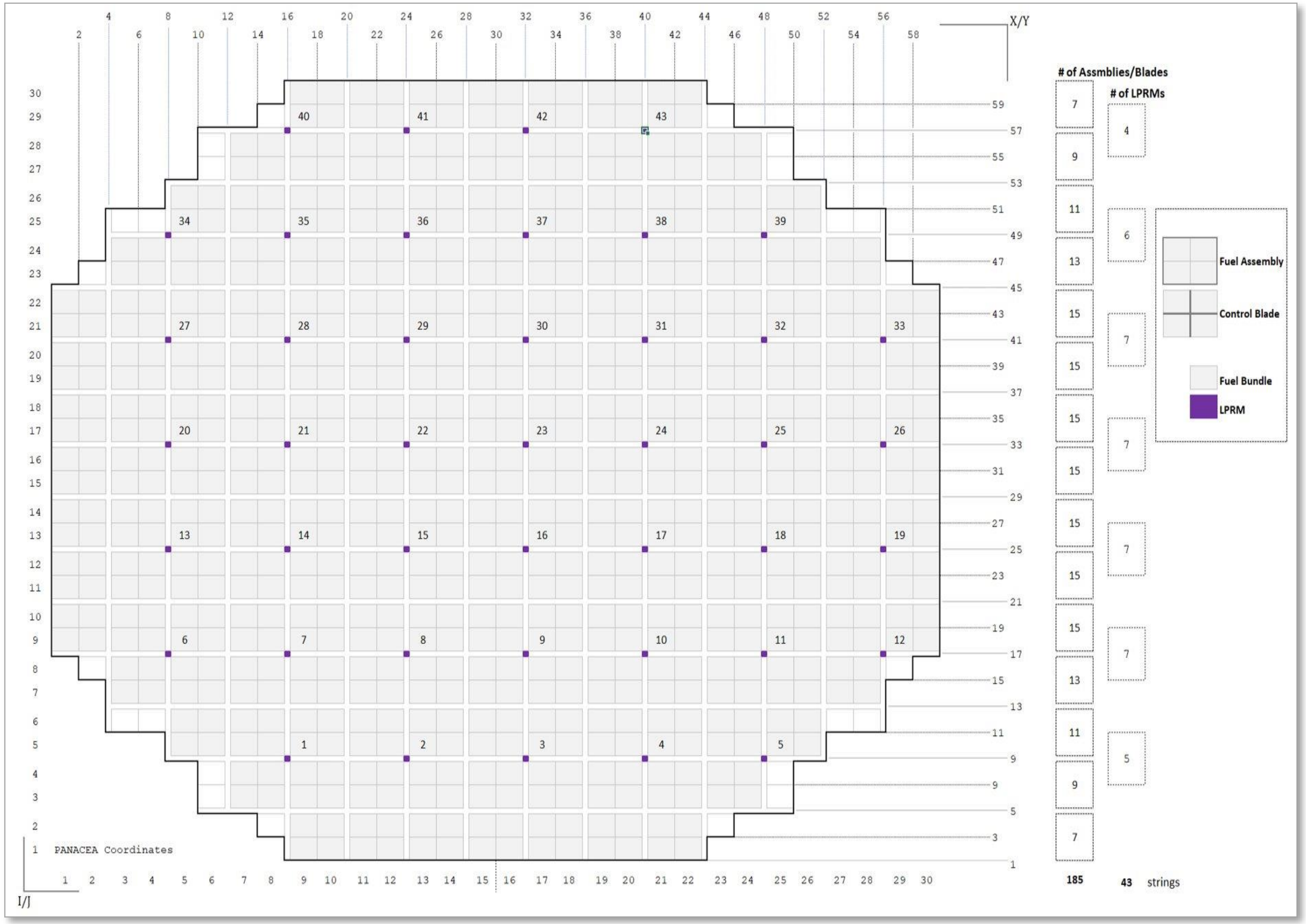


Feedwater Heater Control



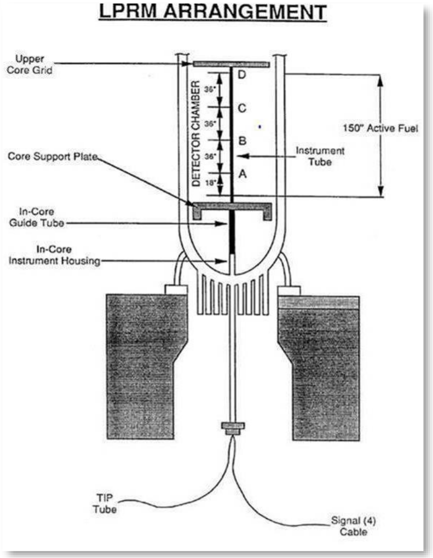
Results and accomplishments

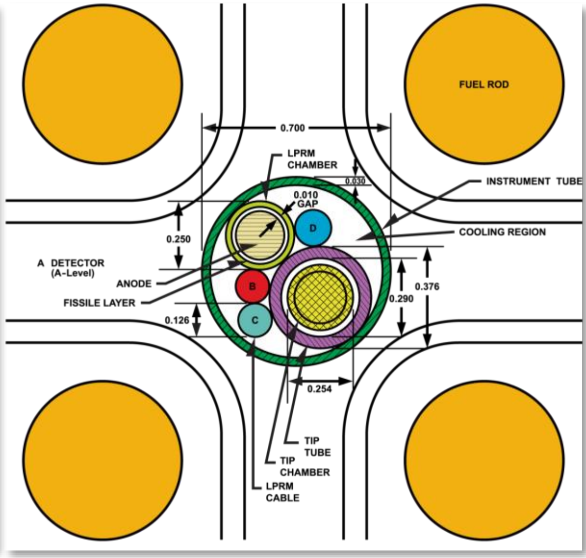
TIP & LPRM Overview



Geometry & Layout:

- LPRMs strings (4 fission chamber detectors) are installed within instrument tubes in the core
- Large BWR core will have up to 43 strings (172 detectors)
- Replacement of one LPRM requires replacement of entire string
- TIPs are periodically inserted (every few months) within the TIP tube to produce 1-inch integrated power trace along the entire length of active fuel





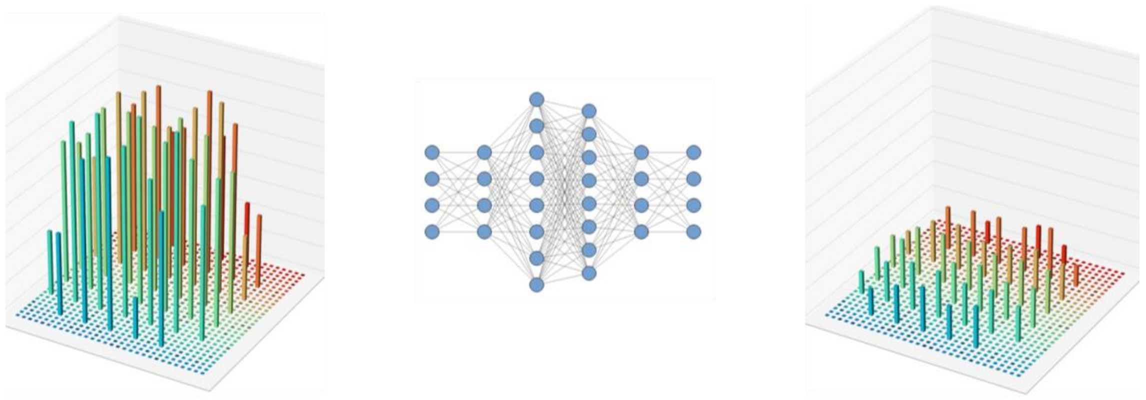
Results and accomplishments

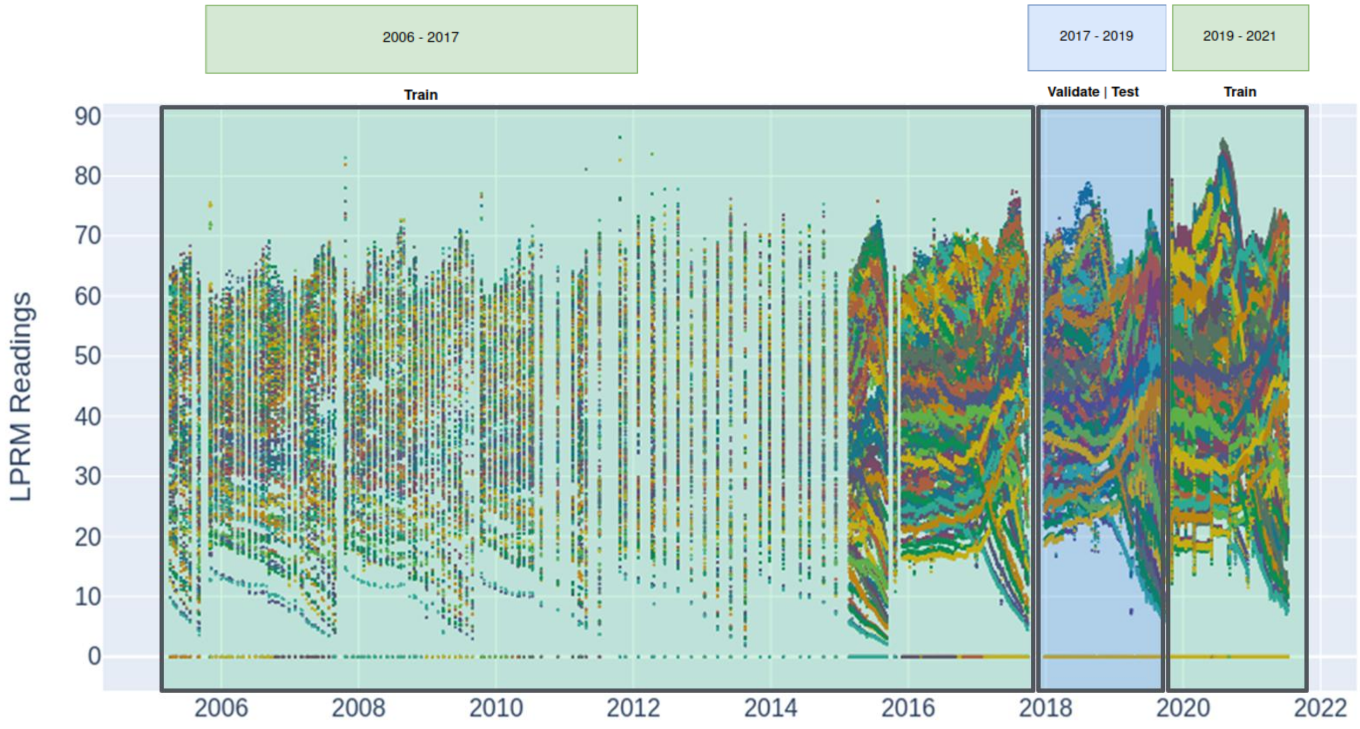
LPRM Modeling (Data from operating NPPs)

- **Data Coverage**
  - 5 Large (30 x 30 core size) Generating Stations
  - 2 operating units at each station
  - 15+ years of historical operational & cycle data
- **Types of Data (varies by unit)**
  - LPRM readings, location data
  - Power and replacement histories
  - EOL Determination Worksheets
  - Incident Reports
  - PPC points, mappings
  - Diagrams

- **Summary for Generating Station A**
  - 11,770 statepoints for Unit 3
  - Each Statepoint includes:

– Blade nodal Depletion Ratio	[30 x 30 x 24]
– Calculated LPRM Readings (Core Simulator)	[43 x 4]
– Dome Pressure	[scalar]
– Core Flow	[scalar]
– Core Inlet Subcooling	[scalar]
– LPRM Gains	[43 x 4]
– LPRM Sensitivities	[43 x 4]
– LPRM Rejected	[43 x 4]
– Measured LPRM Readings	[43 x 4]
– **Core Parameter**	
– Nodal Iodine Worth	[30 x 30 x 25]
– Nodal Xenon Worth	[30 x 30 x 25]
– Rod Pattern	[30 x 30]
– Thermal Power	[scalar]
– Cycle Exposure	[scalar]
– LPRM Mapping	[30 x 30]
– Nodal Power	[30 x 30 x 25]





Results and accomplishments

LPRM Modeling (virtual sensors)

Application

- **Surrogate LPRM Models**
  - **Input:** LPRM String | **Output:** LPRM String
  - **Input:** Multiple LPRM Strings| **Output:** LPRM String

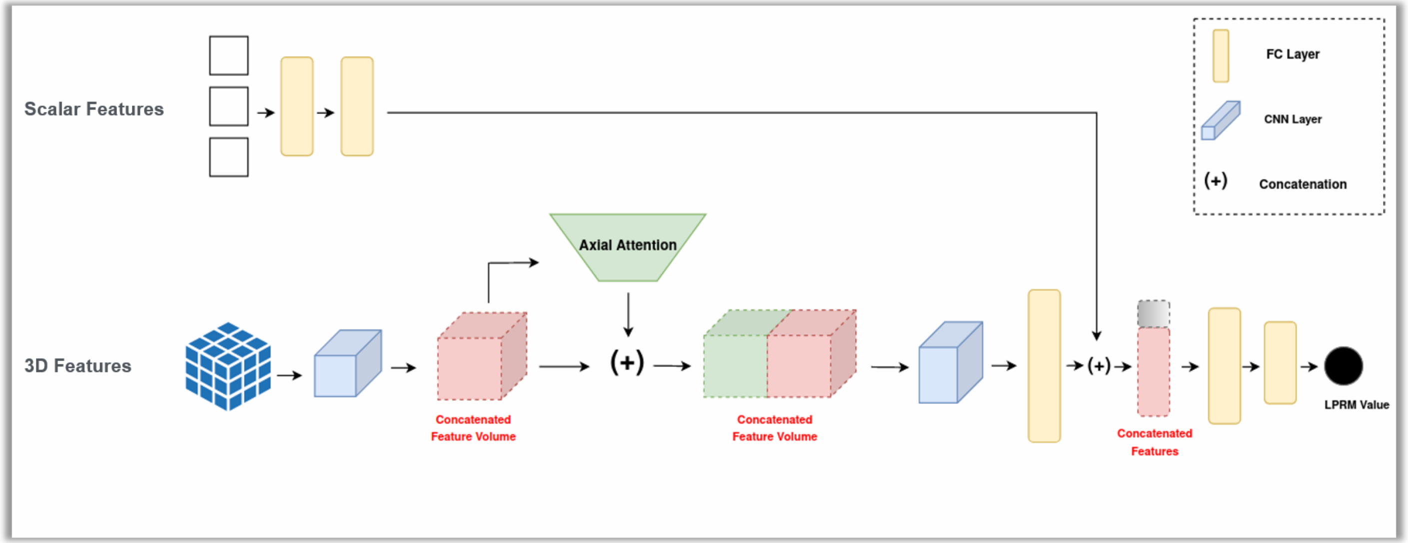
  Real-time virtual readings (dashboard), Virtual calibration

- **Cycle Parameters Model**
  - **Input:** Nodal Power, Rod Variables, Core Flow, Core Power, Thermal Power
  - **Output:** Single LPRM Reading
  - Most robust but complex model, requires block data transfer

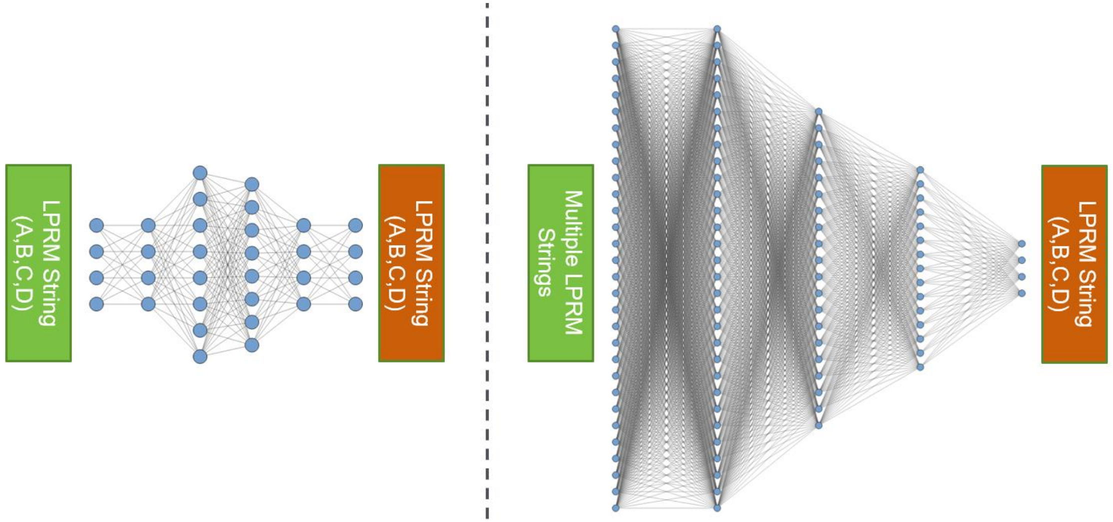
  ~Real-time or future predictions, Virtual calibration, Anomaly detection

- **Panacea Error Correction Model**
  - **Input:** PANACEA Calculated LPRM Values
  - **Output:** Set of LPRM Readings

  Future LPRM predictions



- Data include:
  - Blade Nodal Depletion Ratio
  - Calculated LPRM Readings (PANACEA)
  - Core Dome Pressure
  - Core Flow
  - Core Inlet Subcooling
  - LPRM Gains
  - LPRM Rejected
  - LPRM Sensitivities
  - Measured LPRM Readings
    - Rod Pattern
    - Thermal Power
    - Cycle Exposure
    - LPRM Mapping
    - Nodal Power



Utilized in Model:

Surrogate LPRMs | PANACEA Correction | Cycle Parameters

Results and accomplishments

Performance

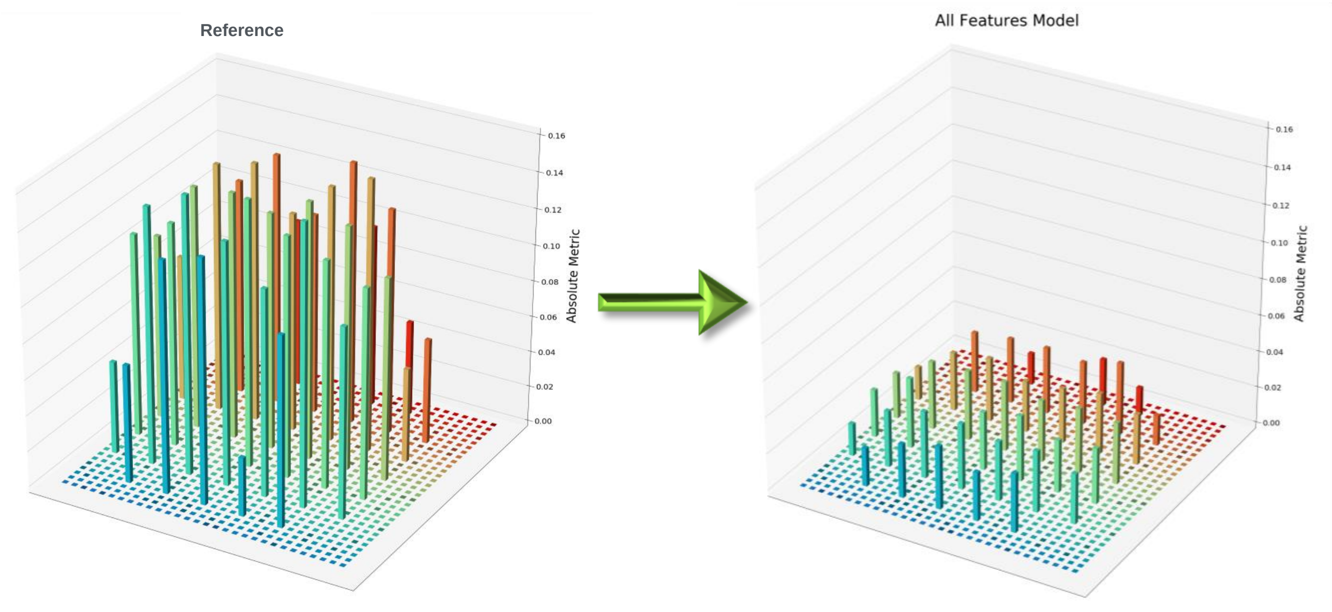
Accuracy:

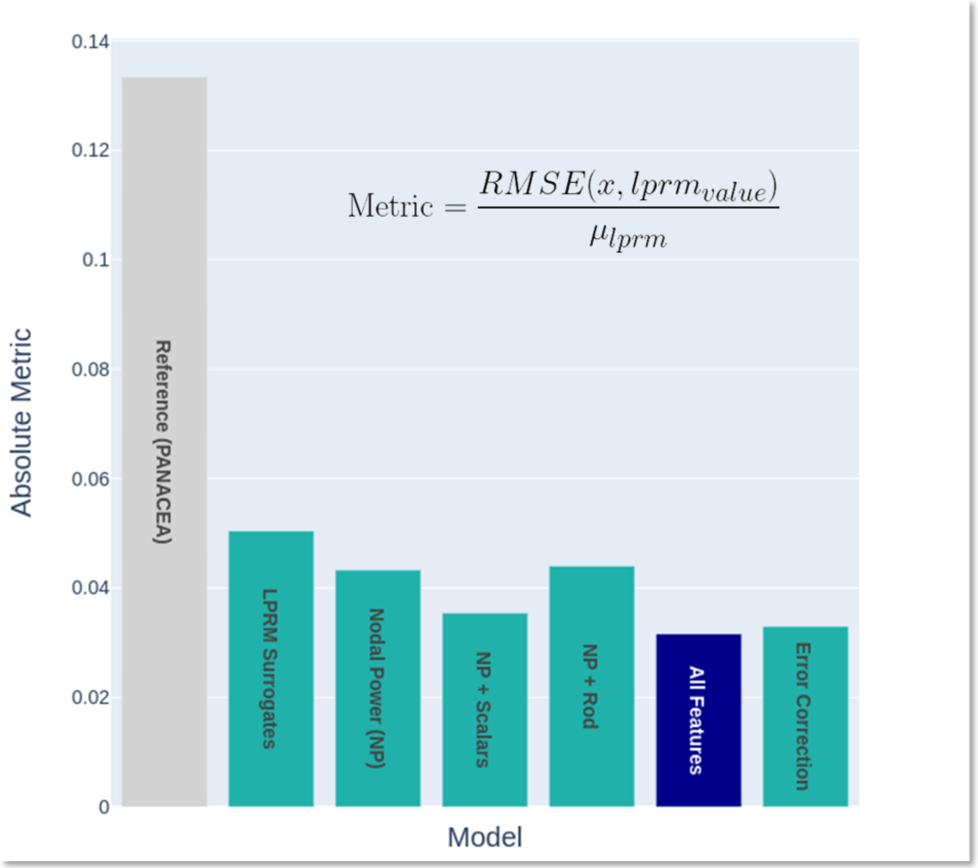
- Virtual LPRMs can predict actual LPRM readings to within ±3% on average over all 172 detectors

  → **This represents 4x reductions in uncertainty from current state-of-practice**

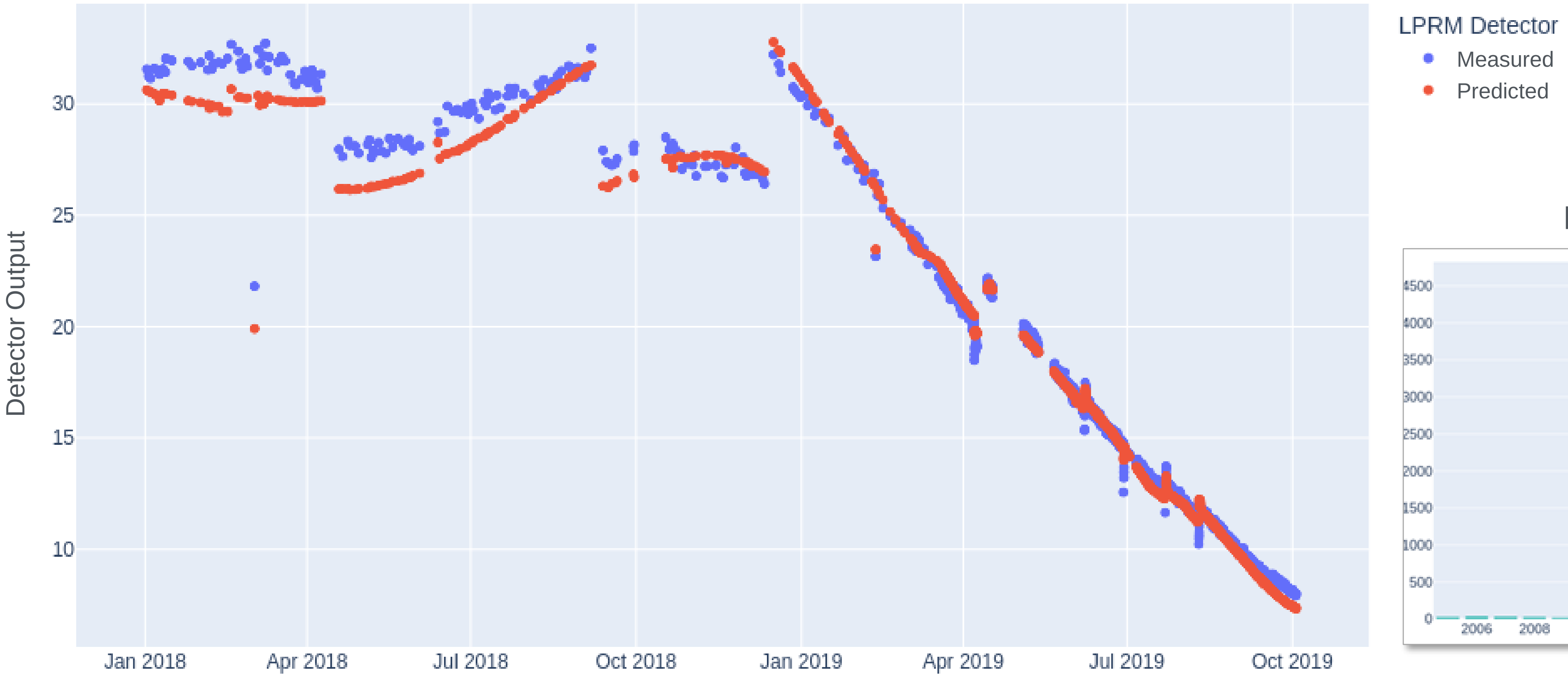
- This is with a model trained from 1 Reactor unit
- Currently expanding training set to several multi-unit generating stations

  → **This will drive down uncertainty even further**

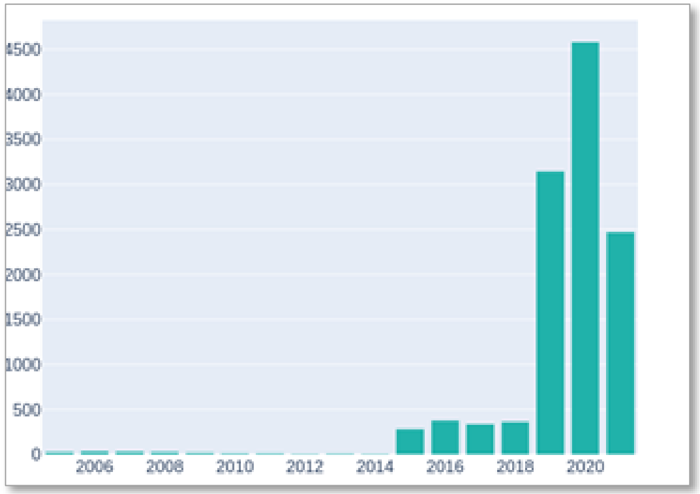




Visualization of Results



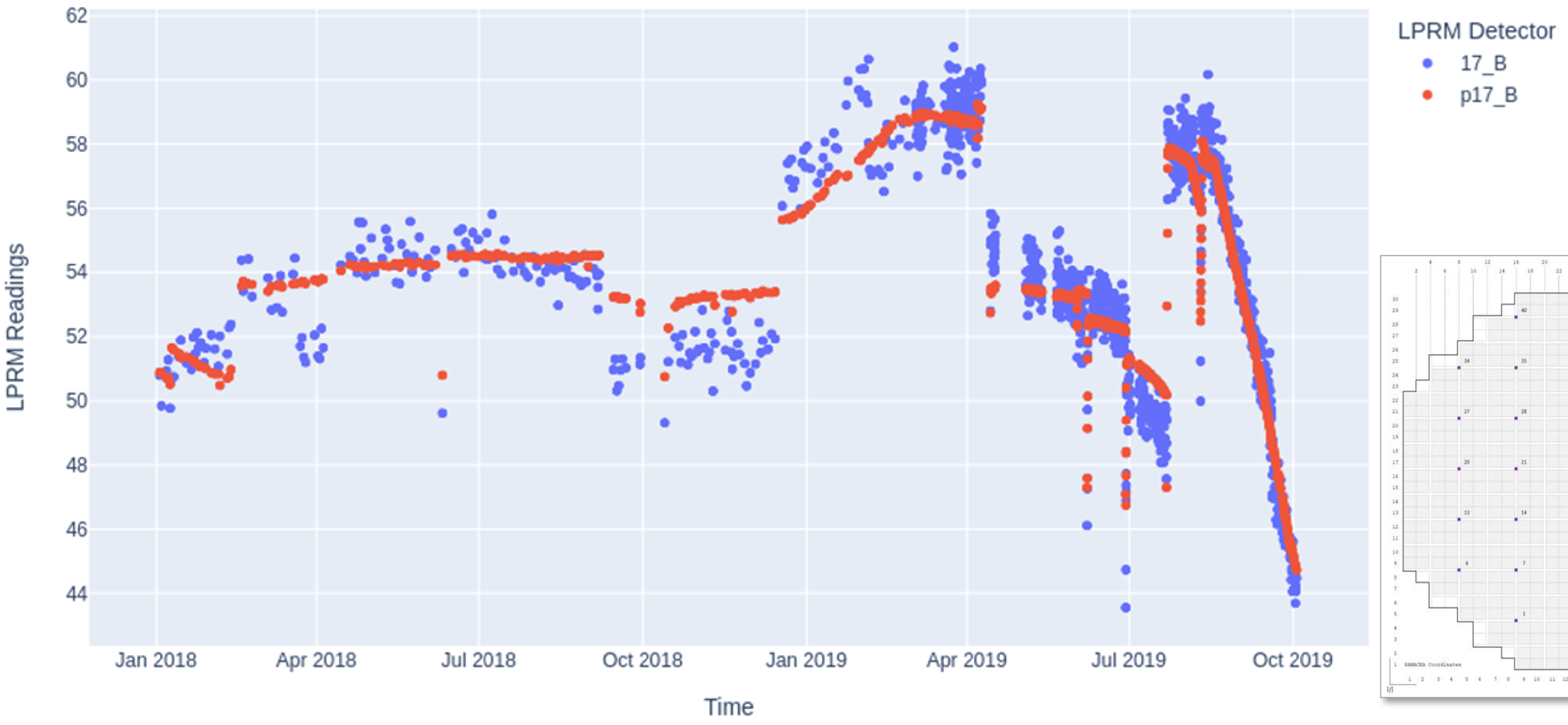
Data Distribution

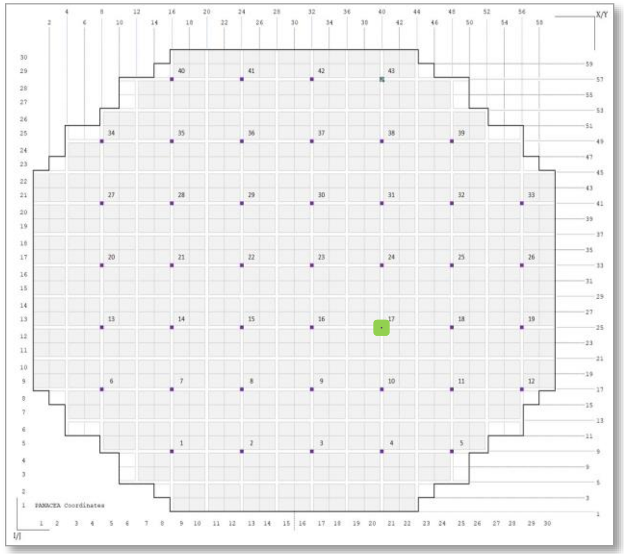


>85% of data from 2019-2021

Visualization of Results

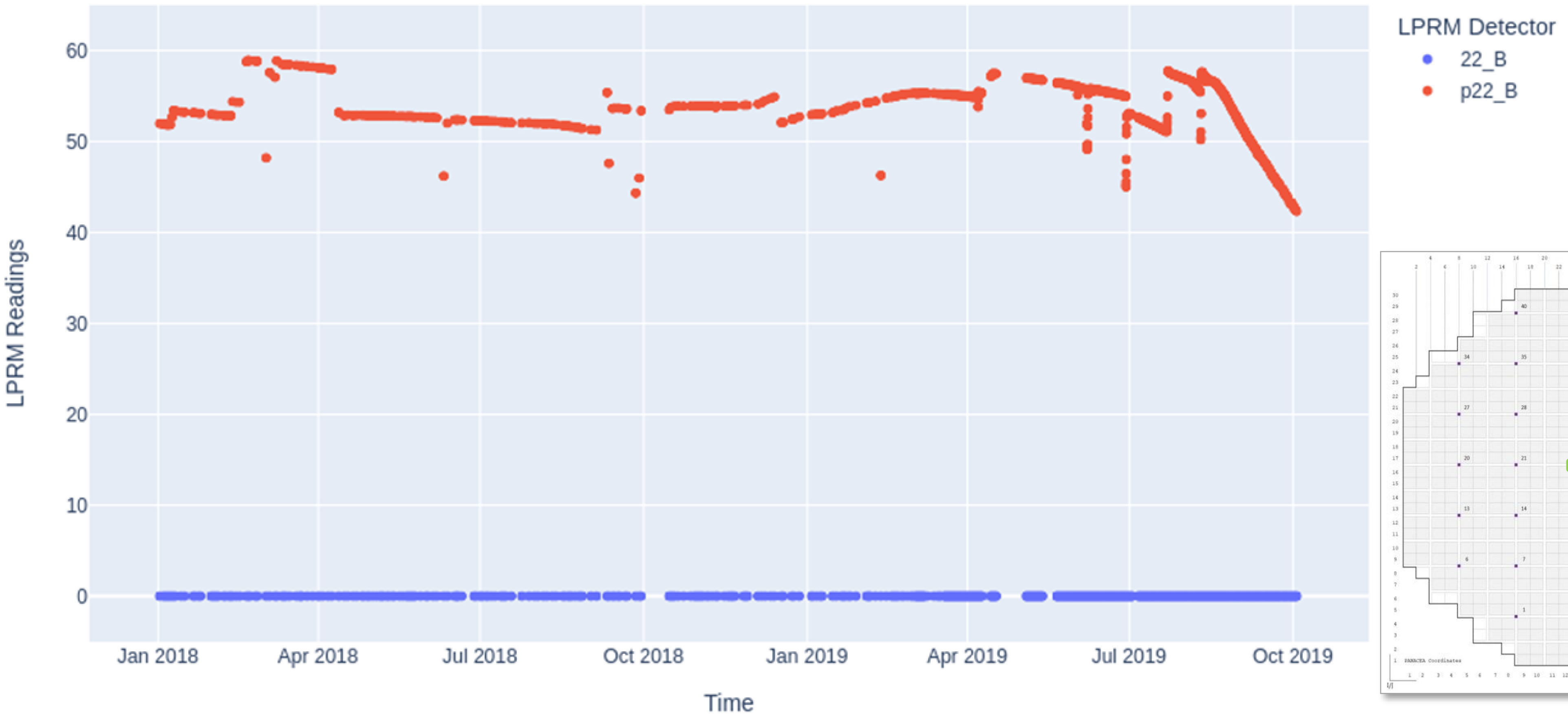
LPRM 17B – All Features Model

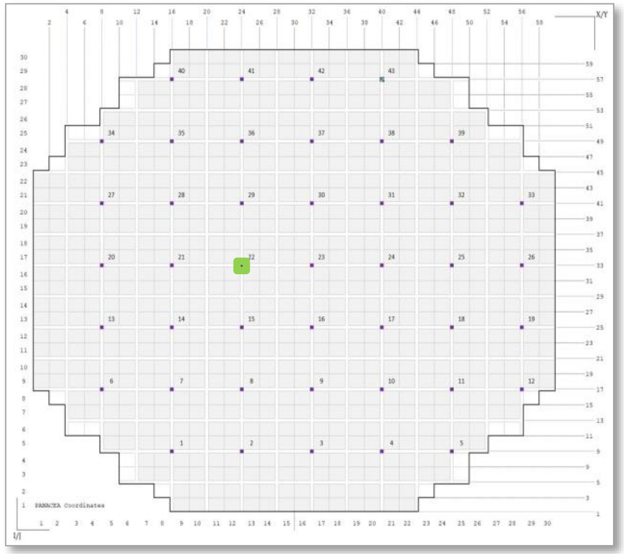




Sample Scenarios

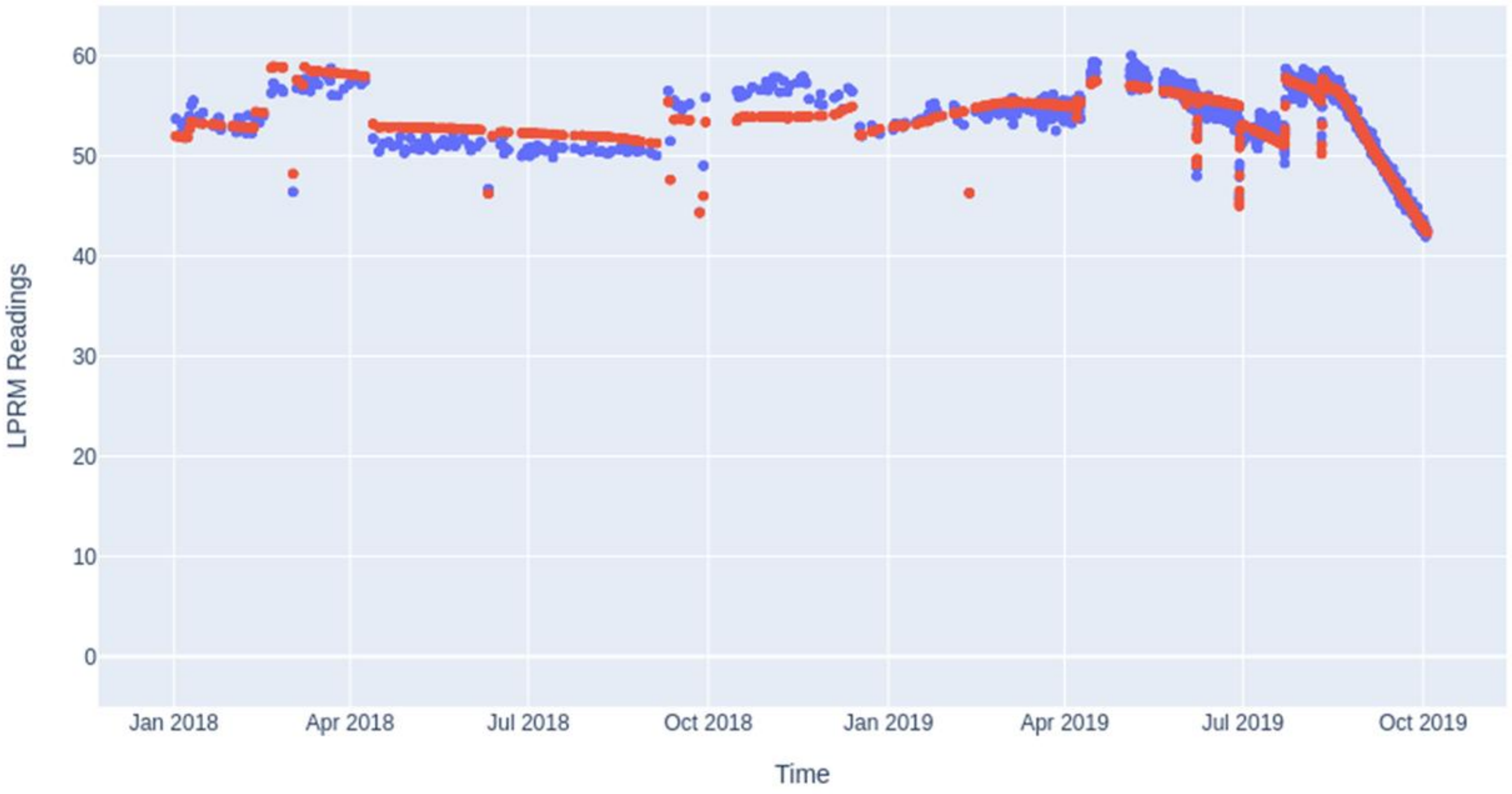
LPRM Detector 22 B Simulated Bypass | Model Predictions

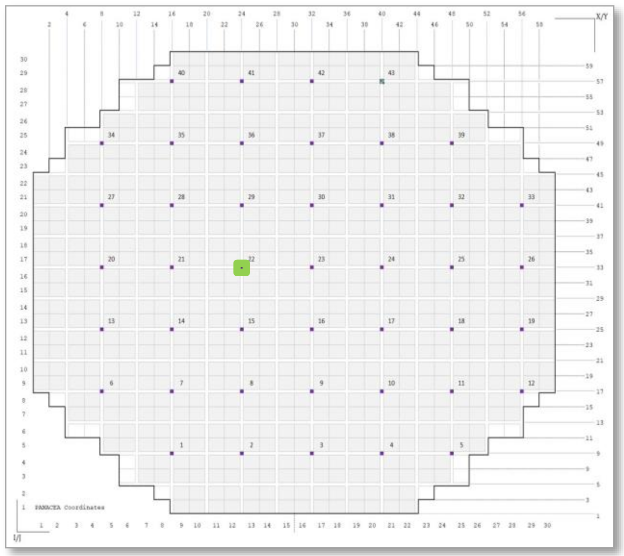




Sample Scenarios

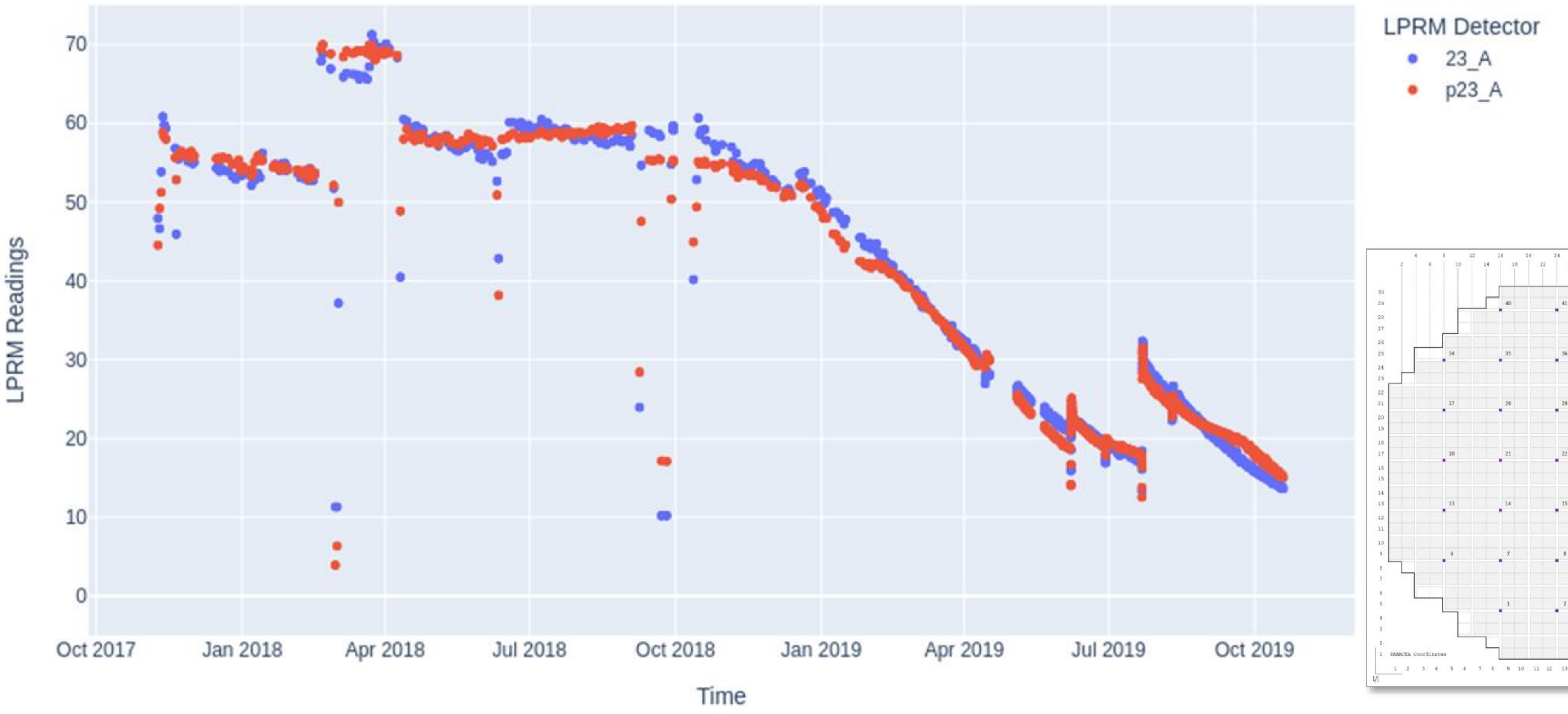
LPRM 22 B Measured Values and Predictions

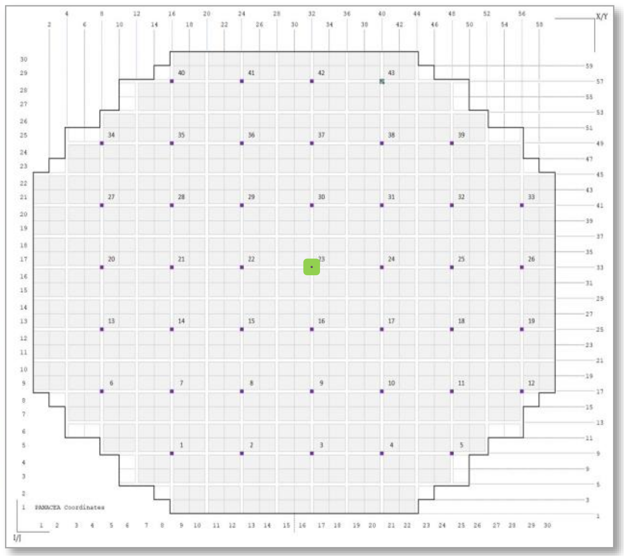




Sample Scenarios

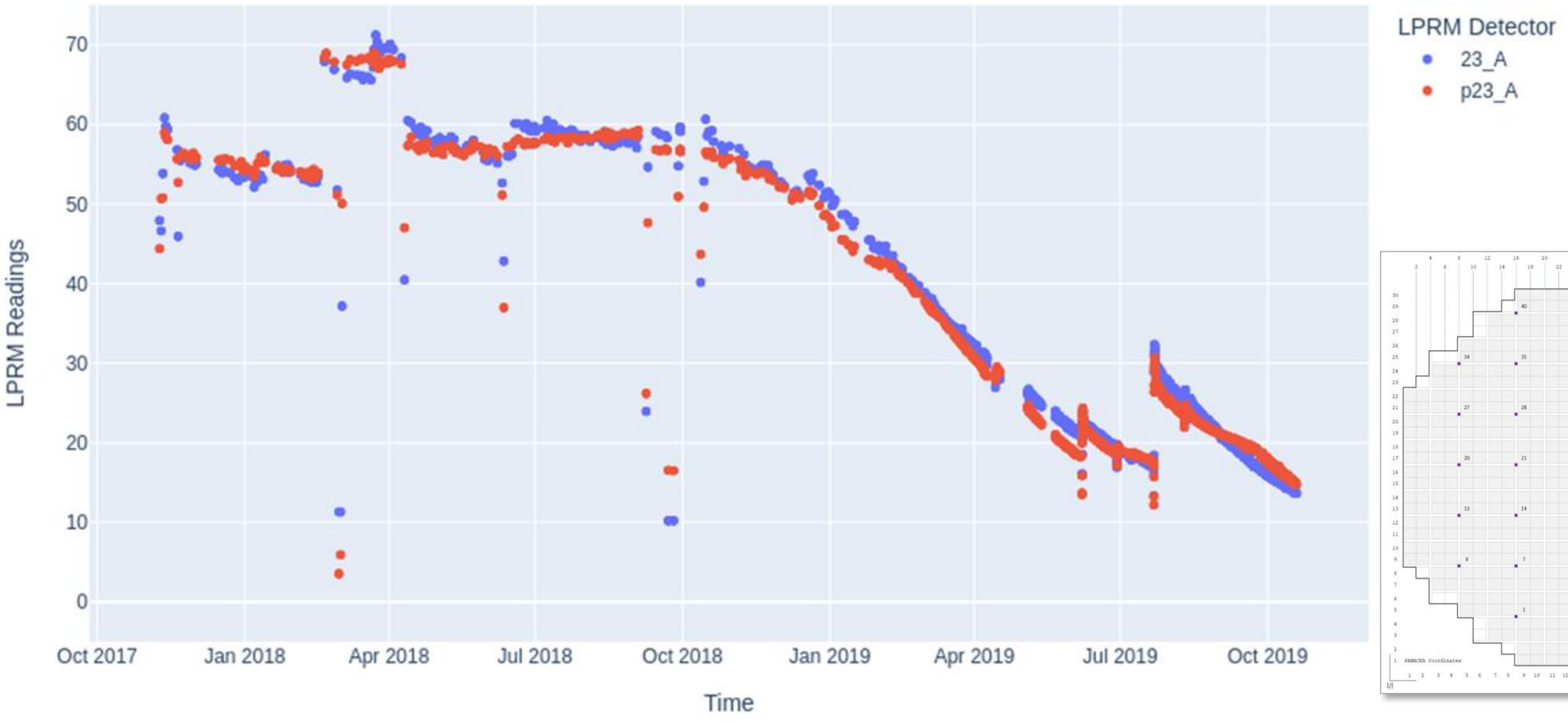
LPRM 23 A | LPRM Surrogate Model

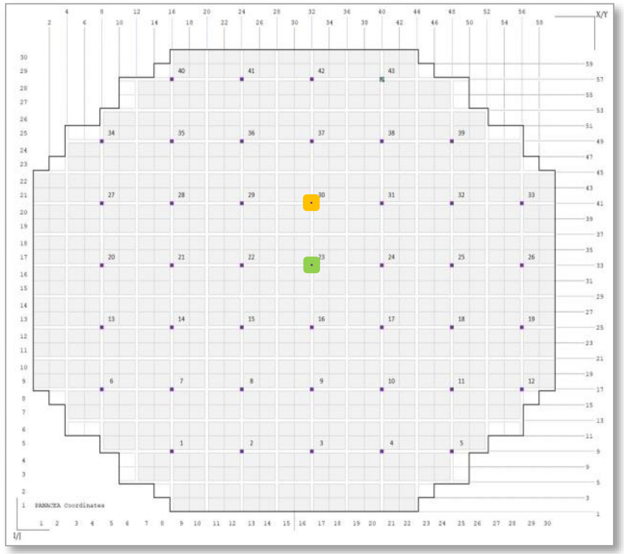




Sample Scenarios

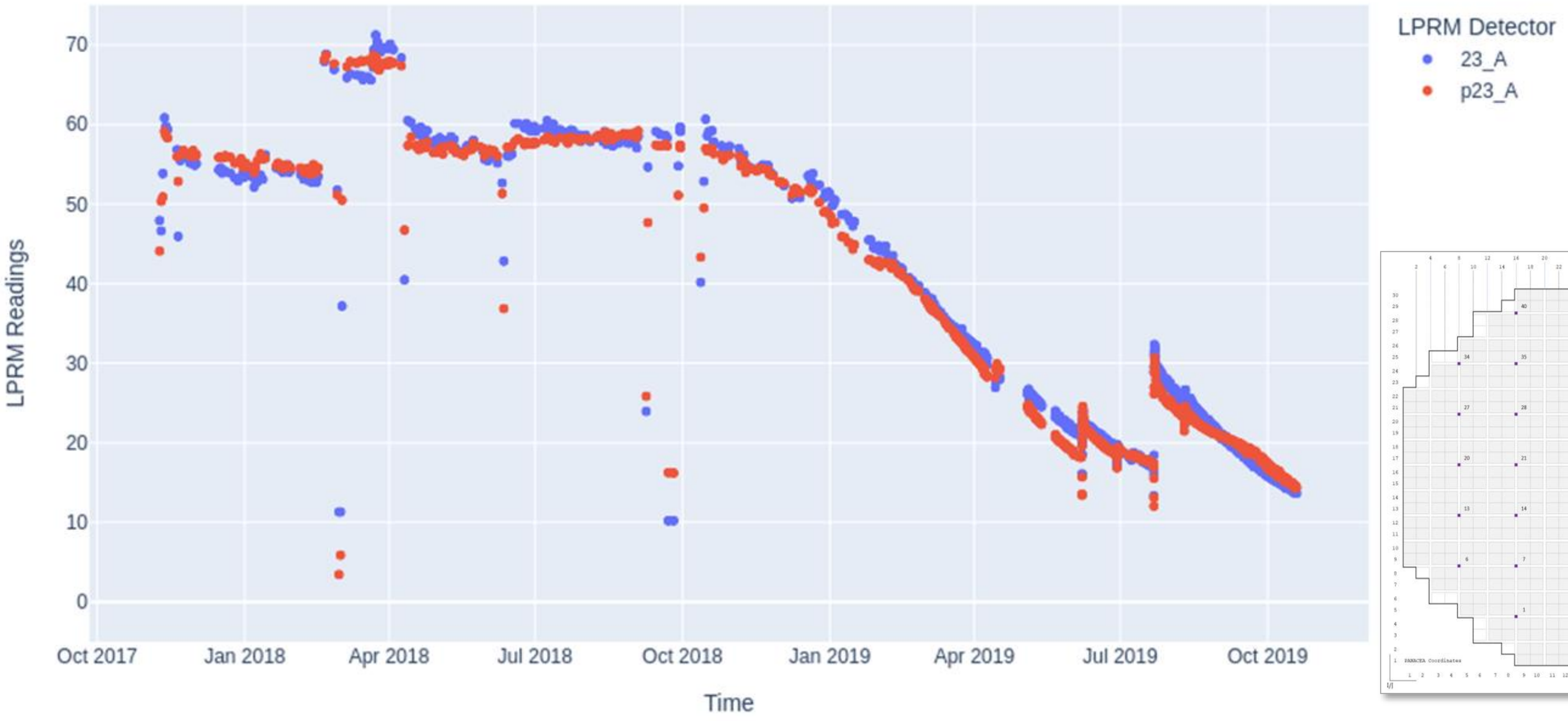
LPRM 23 A | LPRM Surrogate Model | 30 A Bypassed

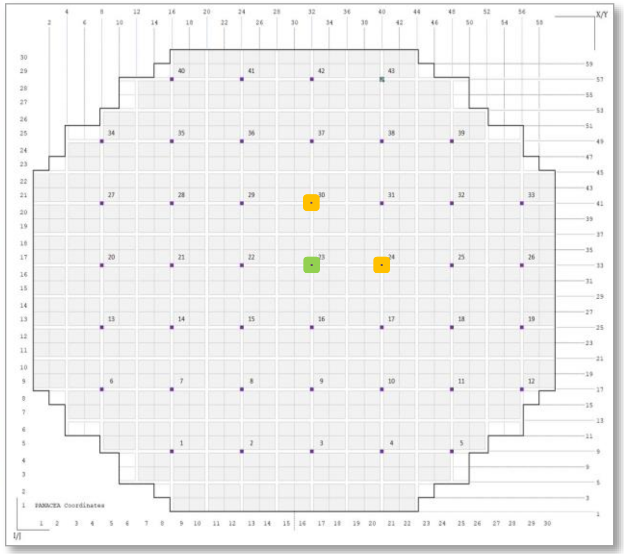




Sample Scenarios

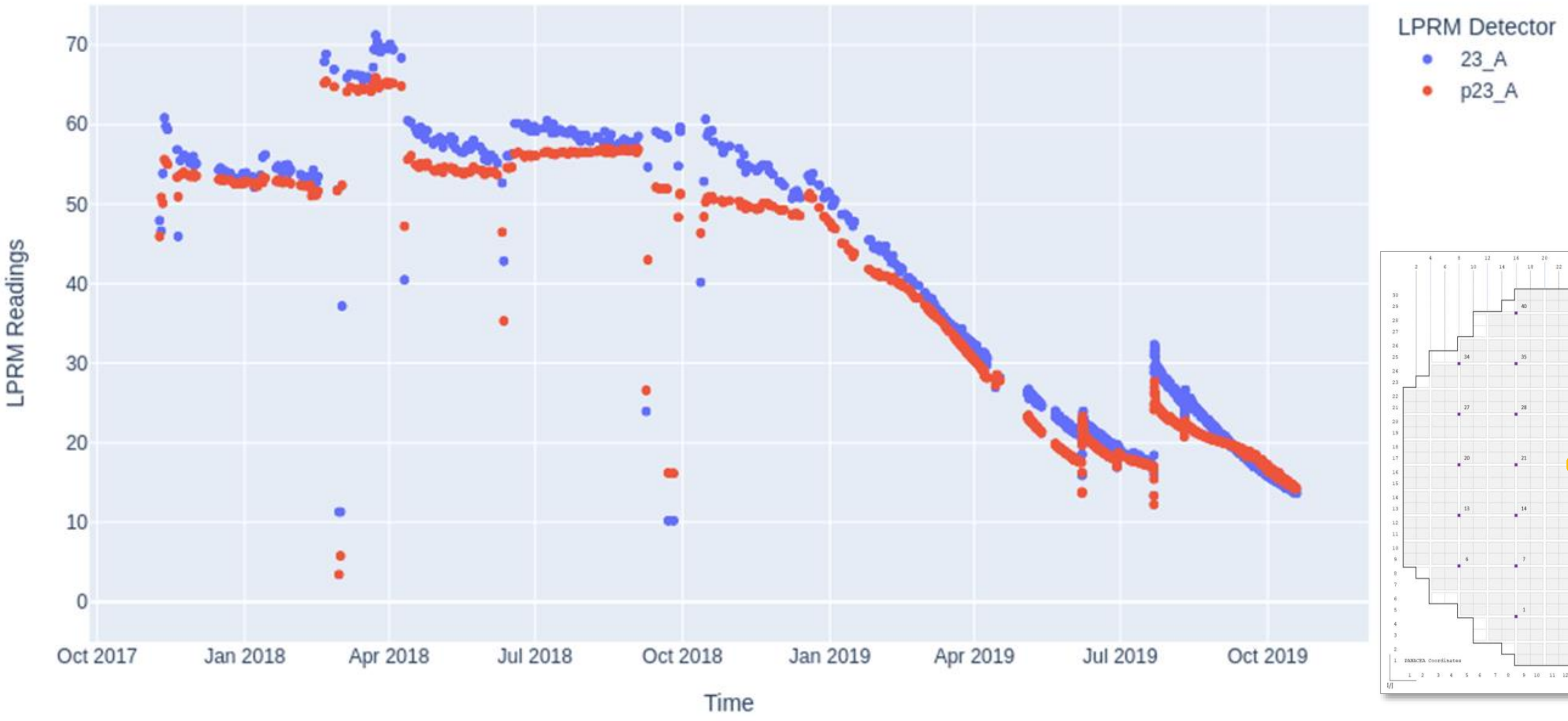
LPRM 23 A | LPRM Surrogate Model | 30 A and 24 B Bypassed

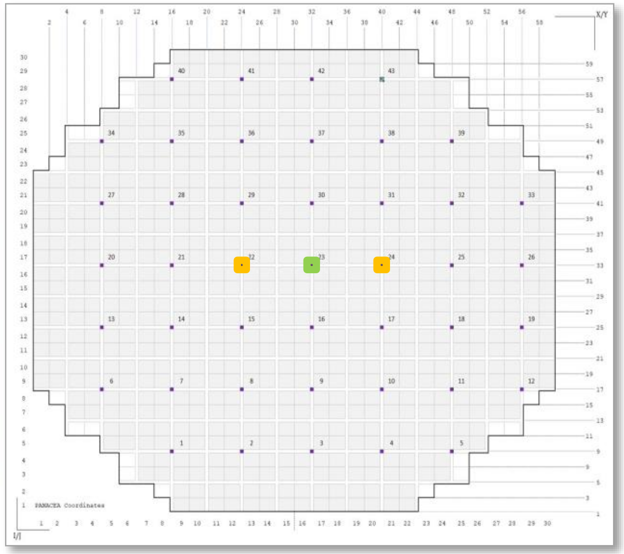




Sample Scenarios

LPRM 23 A | LPRM Surrogate Model | 22 A and 24 B Bypassed

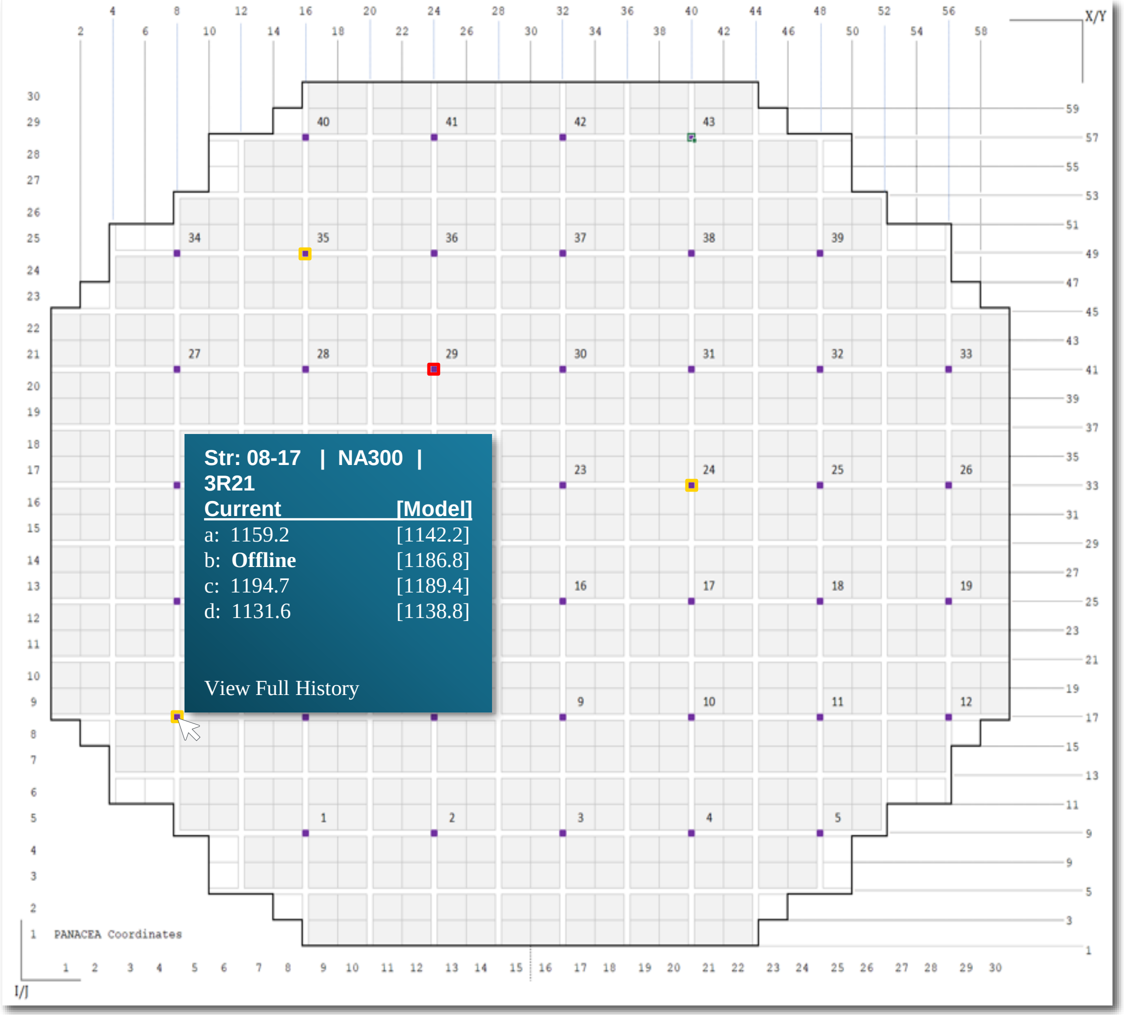




Commercialization

Features

- Real-time Interactive UI -> Individual LPRM Info
  - LPRM ID
  - Date installed / time-in-service
  - Last calibration date / cal. current / GAF
  - Status (online / offline)
  - Latest measured flux / current
  - PANACEA calculated value
  - Offline and Anomaly / out-of-range indicators
- Real-time & Projected
  - Accumulated exposure / SNVT / fluence
  - Virtual reading (model prediction)
  - RUL
- Visualizations
  - Flux / nodal power with notching
  - Axial power shape (vs. PANACEA)
- Report Generation:
  - List of offline LPRMs
  - List of out-of-range / anomalous readings by LPRM ID
  - Suggested / scheduled replacement cycle
  - Replacement Summary (signature request email option)



Conclusion

- Summary of accomplishments
  - Developed suite of Machine Learning models to enable virtual calibration, virtual measurement of neutron flux
  - Developed visualization tool that will automate cumbersome data organization/spreadsheets
  - Initial stages of Remaining Useful Life model development completed
  - Began Machine Learning model for TIP calibration issues

- Future work (for FY22)
  - Continue model development for LPRM remaining useful lifetime
  - Develop TIP trace alignment and power adaption models
  - Continue modeling Feedwater heater sub-systems: Flow-induced corrosion in pipes, spurious oscillations
  - Test and validate model performance with partnering utilities
- Publications:
  - *LPRM machine Learning for Virtual Measurement and Calibration* *[in preparation]*
  - *Using AI to Improve Equipment Reliability* *[invited talk, ERWG and PMWG, EPRI, INPO, and Nuclear Utilities]*
  - *AI-Enabled Solution in NPPs* *[invited talk, BWR Owner's Group (BWROG)]*
- Commercialization
  - ***n*****Fluence**©- A tool for visualizing and managing neutron flux instruments.

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Questions?

ASI Advanced Sensors and Instrumentation

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

ASI Advanced Sensors and Instrumentation

Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 15 – 18, 2021

PI: Roberto Ponciroli

Principal Nuclear Engineer

Plant Analysis & Control & NDE sensors

Argonne National Laboratory

Project Overview

Project Goal: Improve economic competitiveness of advanced reactors through

- Enhanced operational flexibility by coupling advanced reactor concepts with thermal energy storage (TES) technologies.
- Integration of control, diagnostics, and automated reasoning in a suitable architecture ensuring semi-autonomous operation.
- Reduction of O&M costs by optimizing plant availability and maintenance schedule.

Participants

Argonne NATIONAL LABORATORY

PI: Roberto Ponciroli
Akshay Dave
Haoyu Wang
Dan O'Grady
Richard B. Vilim

UNIVERSITY OF MICHIGAN

Brendan Kochunas
Shai Kinast
Deep Patel

Kairos Power

Anthonie Cilliers

Schedule: FY21 - FY23

Project Overview

- Schedule

FY21
- Definition of the Integrated Energy System reference configuration
- Development of the High-fidelity simulator

FY22
- Selection of Control and Diagnostics algorithms
- Adaptation of the diagnostics and control capabilities
- Derivation of necessary Digital Twins

FY23
- Implementation of selected algorithms in the designed Architecture
- Cost-benefit analysis

Project Overview

- System definition and Simulator development
  - Selected the Integrated Energy System (IES) configuration that will serve as the reference case.
  - Identified the most appropriate TES technology that can be driven by a fluoride salt-cooled, high temperature reactor (FHR).
  - Developed a high-fidelity simulator by using SAM (System Analysis Module) code.

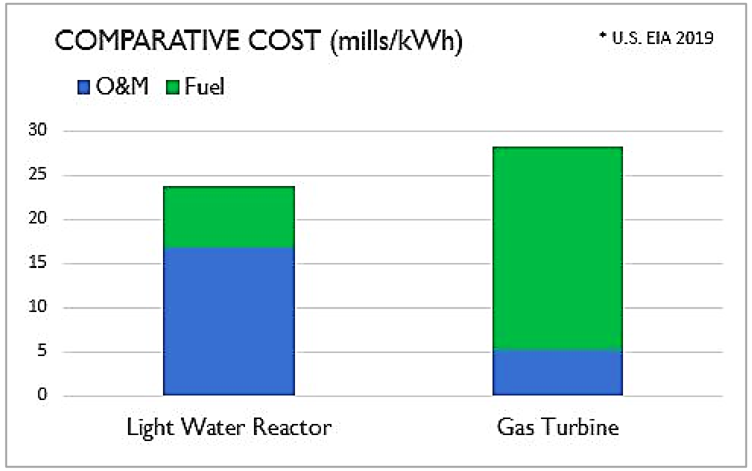
- Diagnostics and Control methods Development
  - Simulation of operational transients, e.g., charging/discharging, load-following, etc.
  - Implementation of regulators foreseen by the control strategy, finite-state machines, Supervisory control layer.
  - Selection of diagnostics algorithms.

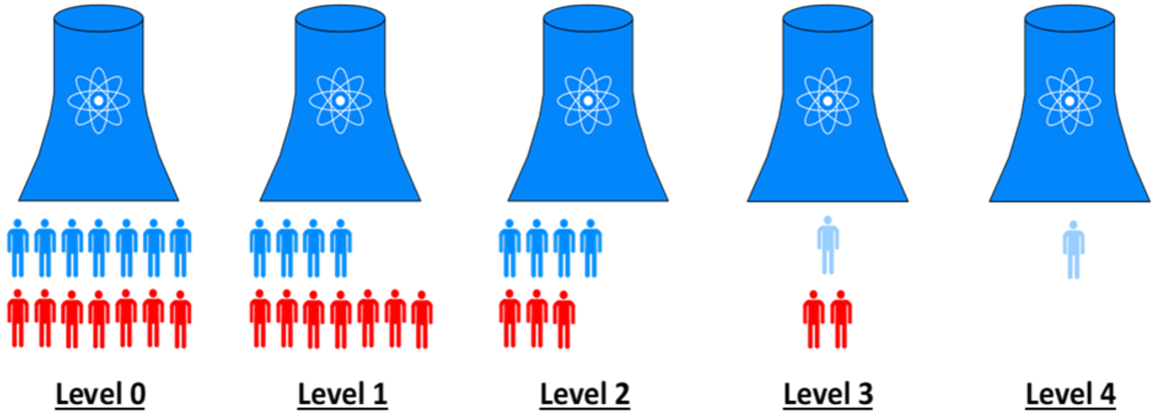
- Demonstration of the performance of the proposed Architecture
  - Formulation of the Markov decision process that will constitute the heart of the decision-making capabilities.
  - Coupling the different components of the architecture and validation by adopting the developed high-fidelity simulator.

Results and accomplishments

- How exactly can Autonomous Operation help saving on O&M costs?
  - Limits the number of operators in the Main Control Room does not significantly reduce costs.
  - Most of the savings by optimizing the maintenance schedule (less time-consuming interventions), reduced number of technicians on-site, promptly detected performance degradation).

- Application of AI/ML algorithms to Normal Operation ONLY
  - When adapting the operational paradigms from other industrial applications (e.g., self-driving cars, etc.), peculiar features of nuclear reactors need to be accounted for (separation of Control and Safety).





No automation
Traditional controllers implemented (PIDs). Plant indicators and alarms are monitored by operators in the control room.

Automated control
A supervisory control scheme coordinating feedback regulators during complicated sequences is implemented.

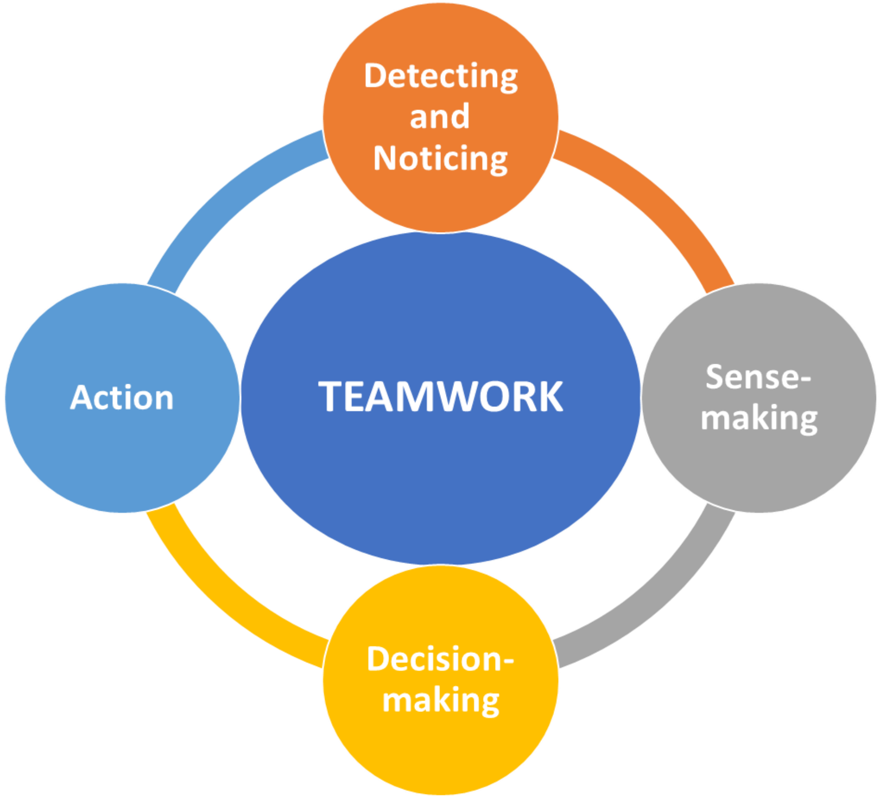
Semi-autonomous operation
A diagnostics algorithm closely interacts with supervisory control. Health monitoring reduces maintenance staff requirement.

Autonomous operation
The NPP can be remotely operated. A minimum staffing on-site is required.

Self-regulated with remote monitoring
The NPP is remotely monitored. Design allows robotic maintenance to be accommodated.

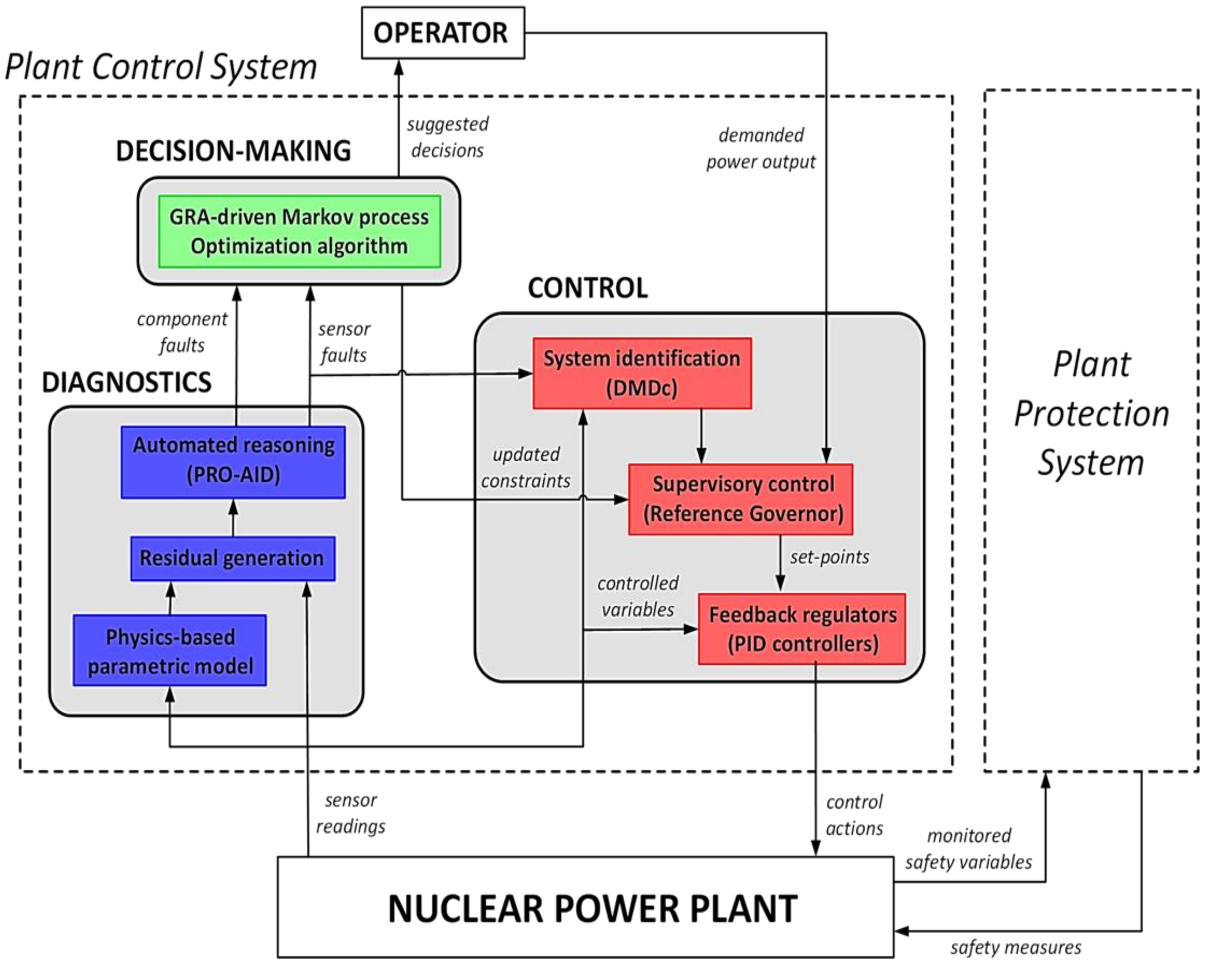
Results and accomplishments

- Teams without teamwork defeat the purpose of teams
  - When collaboration is correctly applied, it is one of the best ways for NPPs to produce power with fewer errors, events, and improved performance that is sustainable.
  - The U.S. NRC organized a team of researchers to review literature in psychology, cognition, behavioral science and apply it to human performance in NPP operation (NUREG-2114, January 2016).
  - Cognitive framework consists of five cognitive functions. It focuses on the nature of human performance "in the field," where decisions must be made quickly, in risky situations. If one of these aspects is missing, errors might occur.



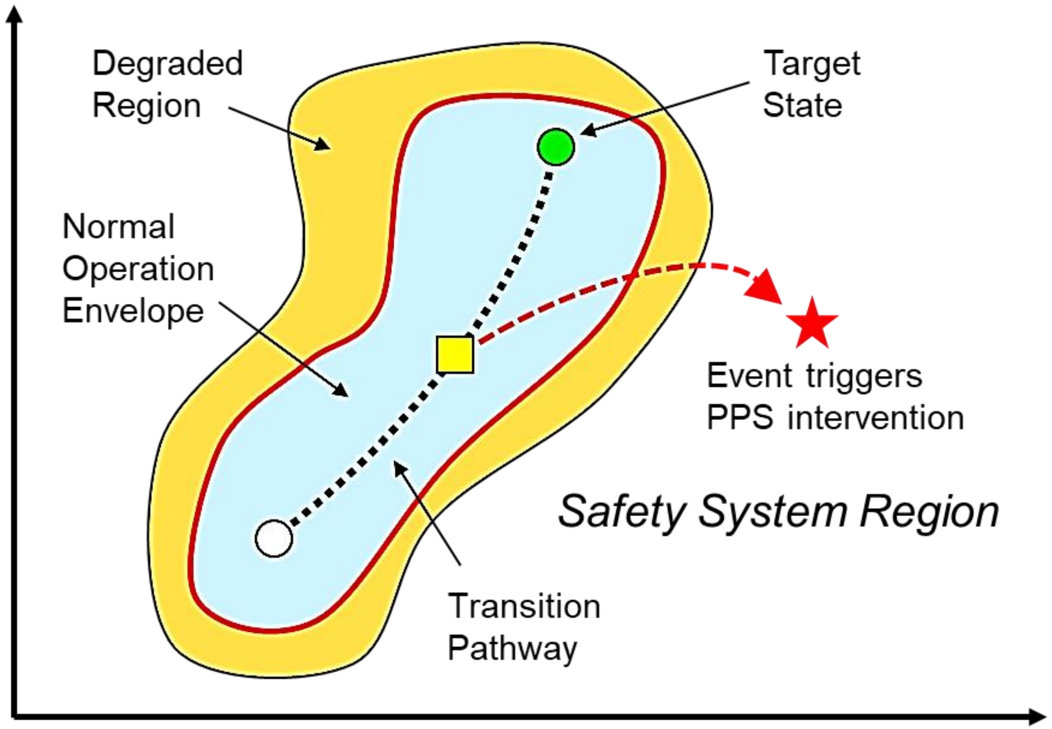
Results and accomplishments

- Features of Autonomous Operation control system architecture
  - Strong role played by Digital Twin. Control actions and decisions are based on predictions of plant response.
  - Diagnostics capability of discriminating between sensor-level and component-level faults is crucial.
  - Control, Diagnostics and Decision-making modules need to be integrated.
  - Plant Protection System (PPS) <u>must be allowed</u> to take over in case of violation of limits on safety variables.



Results and accomplishments

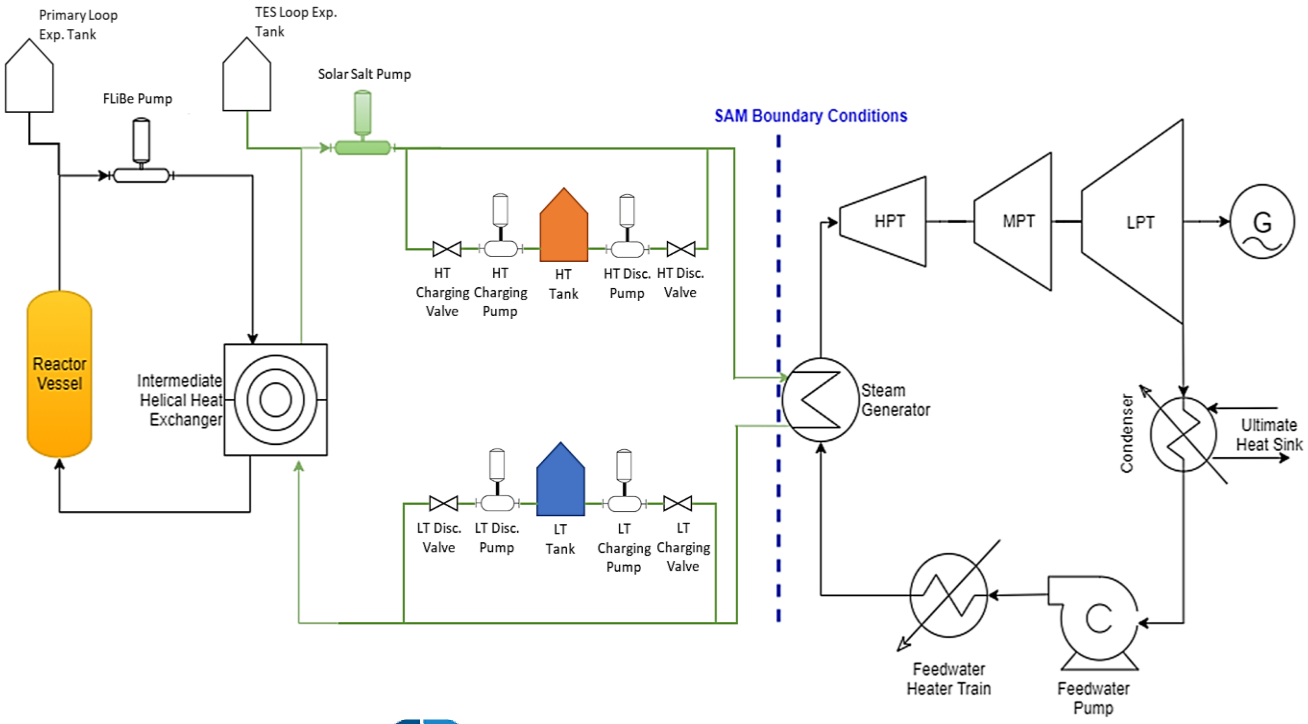
- Need to monitor the bounds of Normal Operation Envelope
  - To improve the profitability of units through Autonomous Operation, the performance of the units has to be exploited to the full extent.
  - Plants can be operated as long as safety-imposed bounds are not violated.
  - Diagnostics algorithm provides the Decision-making algorithm with updates about the performance of the components. Bounds of Normal Operation and Degraded regions evolve in time.
  - A control algorithm confirming plant trajectories are within these bounds is necessary.



Results and accomplishments

- Definition of the Integrated Energy System reference configuration
  - A pebble-bed, fluoride salt-cooled, high temperature reactor (PB-FHR) coupled with a thermal energy storage was selected as a reference test-case.
  - ANL developed a generic FHR SAM model (gFHR) to foster commercial development of FHRs.
  - gFHR design specifications based on the University of California, Berkeley (UCB) Mk1 design.

D. O'Grady et al. "*SAM Code Enhancement, Validation, and Reference Model Development for Fluoride-salt-cooled High-temperature Reactors*", ANL/NSE-21/15. Argonne National Laboratory (2021).

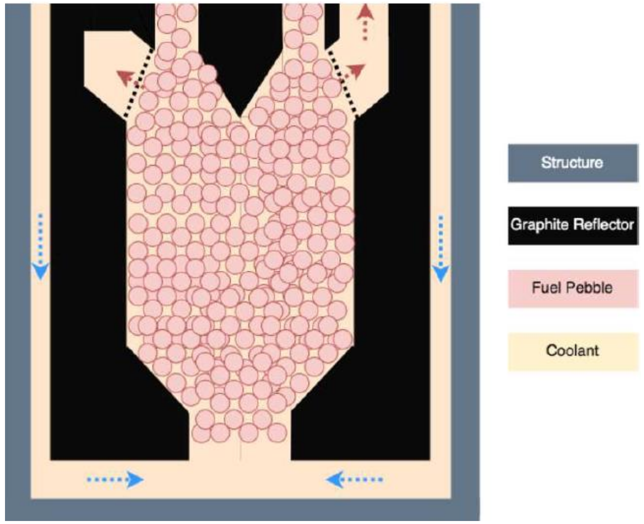


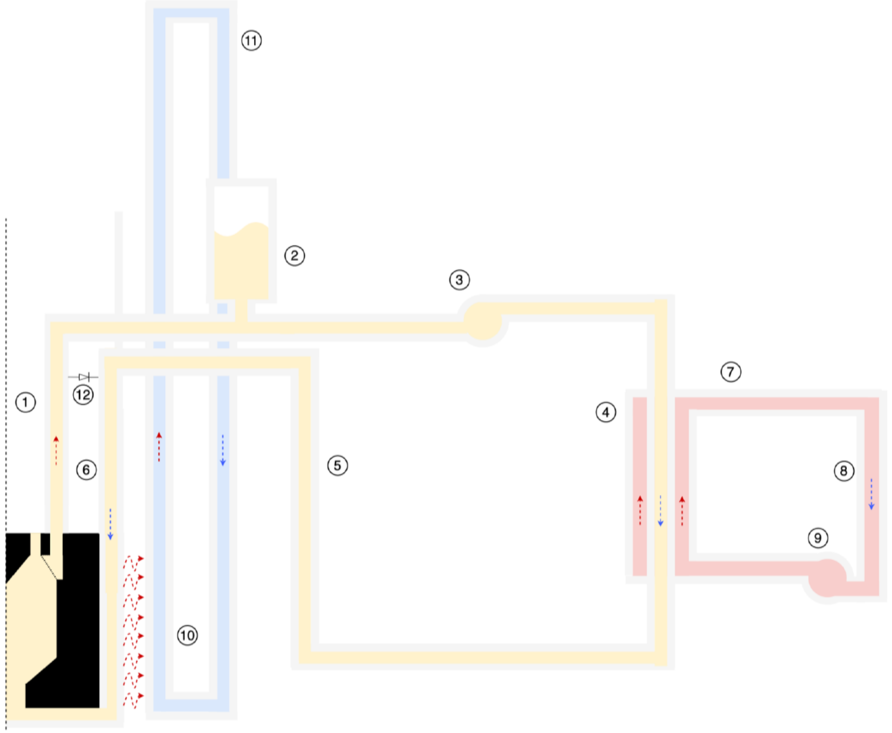
Kairos Power

Results and accomplishments

- Modeling of the Primary Circuit
  - SAM (System Analysis Module) code was used
  - 320 MW_{th} core power with point-wise kinetics equation
  - Thermal-hydraulics closure models for packed-bed geometry are implemented

D. O'Grady et al. "*SAM Code Enhancement, Validation, and Reference Model Development for Fluoride-salt-cooled High-temperature Reactors*", ANL/NSE-21/15. Argonne National Laboratory (2021).





List of Components

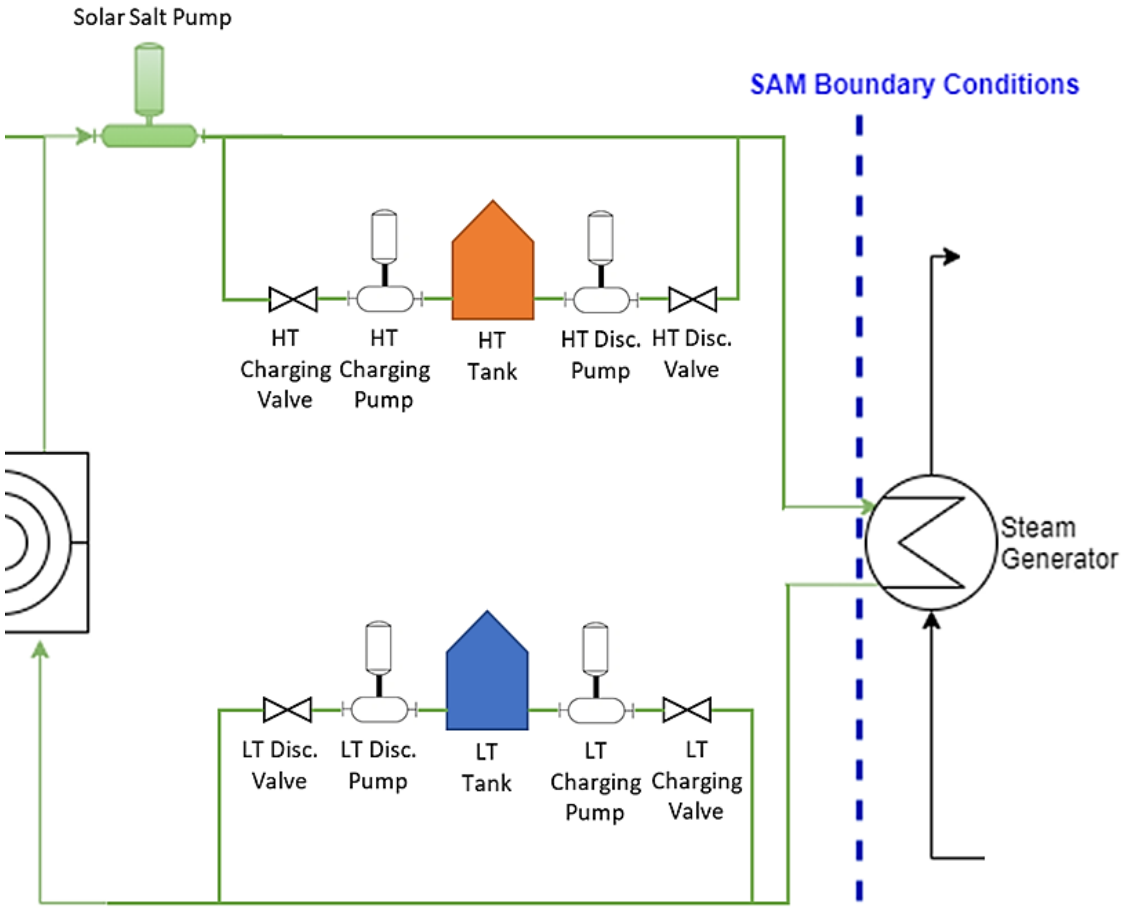
1. Reactor Outlet
2. Expansion Tank
3. Primary Coolant Pump
4. Helical (Tube & Shell) Heat Exchanger
5. Rest of Primary Loop
6. Downcomer
7. Intermediate Loop (Hot Side)
8. Convective BC for Steam Generator
9. Intermediate Loop Pump
10. RCCS Radiative Heat Transfer from Vessel
11. RCCS Air Dump Heat Exchanger
12. Fluid Diode (for natural recirculation)

Results and accomplishments

- Modeling of the Intermediate Circuit
  - Addition of expansion tank to address coolant expansion/contraction during transients.
  - PID controllers governing the pumps.
  - Boundary conditions (thermal flux imposed) to mimic the presence of the SG.
  - Implementation of thermo-physical properties of the solar salt.

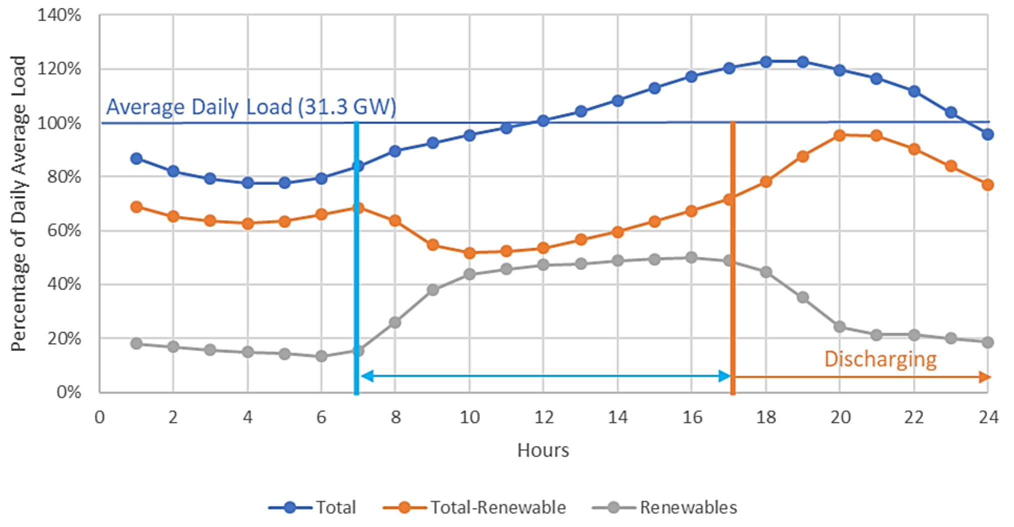
Temp. (°F)	Density (lb_m/ft^3)	Specific Heat (Btu/lb_m-F)	Absolute Viscosity (lb_m/ft-hr)	Thermal Conductivity (Btu/hr-ft-F)
500	120.10	0.356	10.506	0.285
550	118.98	0.358	8.607	0.288
600	117.87	0.359	7.085	0.291
650	116.76	0.360	5.894	0.294
700	115.65	0.361	4.987	0.297
750	114.54	0.362	4.320	0.300
800	113.43	0.363	3.845	0.303
850	112.32	0.364	3.518	0.307
900	111.21	0.366	3.291	0.310
950	110.10	0.367	3.121	0.313
1000	108.99	0.368	2.960	0.316
1050	107.88	0.369	2.762	0.319
1100	106.77	0.370	2.483	0.322

Temp. (°C)	Density (kg/m^3)	Specific Heat (Joule/kg °C)	Absolute Viscosity (mPa-sec)	Thermal Conductivity (W/m-c)
260	1924.64	1488	4.343	0.492
288	1906.97	1492	3.558	0.498
316	1889.31	1497	2.929	0.503
343	1871.64	1502	2.436	0.508
371	1853.97	1507	2.062	0.514
399	1836.31	1512	1.786	0.519
427	1818.64	1516	1.589	0.524
454	1800.97	1521	1.454	0.529
482	1783.31	1526	1.361	0.535
510	1765.64	1531	1.290	0.540
538	1747.97	1535	1.223	0.545
566	1730.31	1540	1.142	0.550
593	1712.64	1545	1.026	0.556



Results and accomplishments

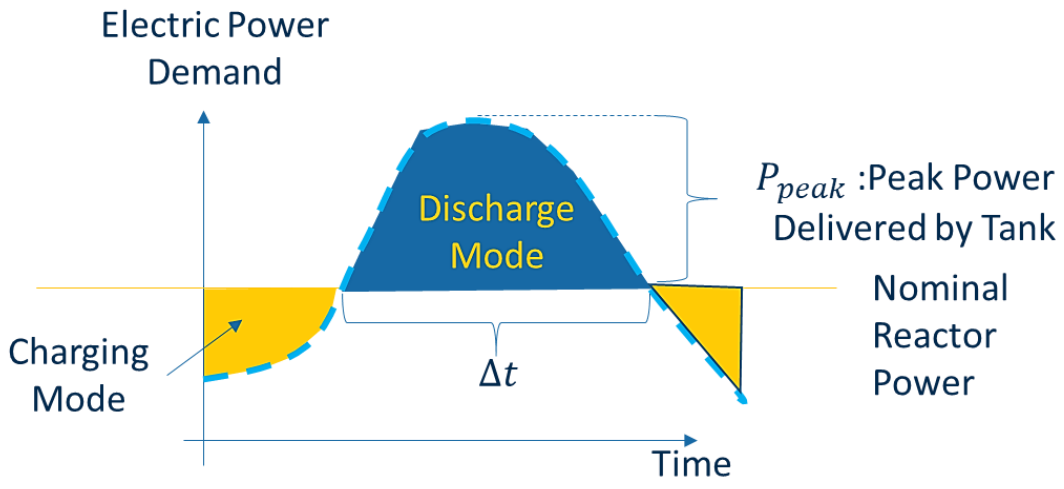
- Design of the TES circuit (tank sizing)
  - The reactor operates in base-load mode, tanks are energy storing device that provide the power surplus that the reactor cannot provide.
  - Representative Normalized Daily Demand Profile Data from CA-ISO grid (large penetration of renewables).



Energy Requirement	Hot Tank Volume
48 MW @ 30 min	2,389 m^3
48 MW @ ~31.5 min	2,500 m^3
48 MW @ 1 hr	4,778 m^3
48 MW @ 3 hr	14,333 m^3
48 MW @ 6 hr	28,666 m^3
48 MW @ 12 hr	57,333 m^3

← Olympic Swimming Pool (48 MW @ ~31.5 min)

← 23 Olympic Swimming Pools (48 MW @ 12 hr)

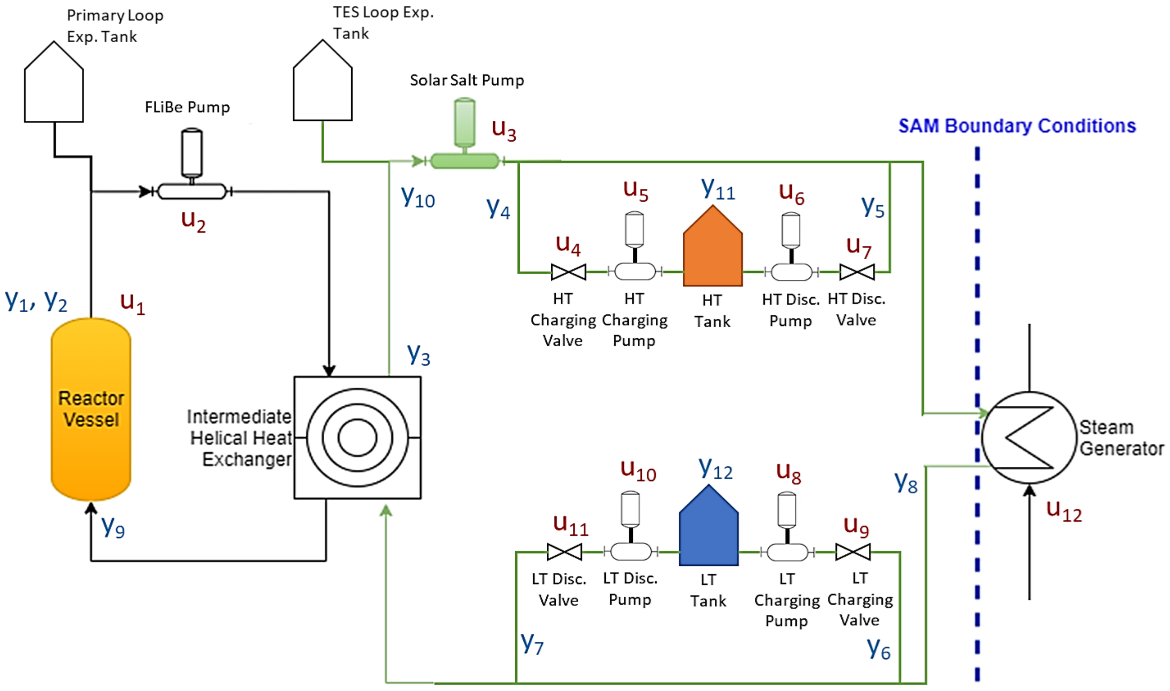


Results and accomplishments

- Definition of the IES Control Strategy
  - Definition of the P&ID for the IES system
  - Selection of pairings between Input variables and a tentative set of Variables to be controlled
  - Definition of a tentative set of Constrained Variables (variables whose evolution needs to be limited between upper/lower bounds)

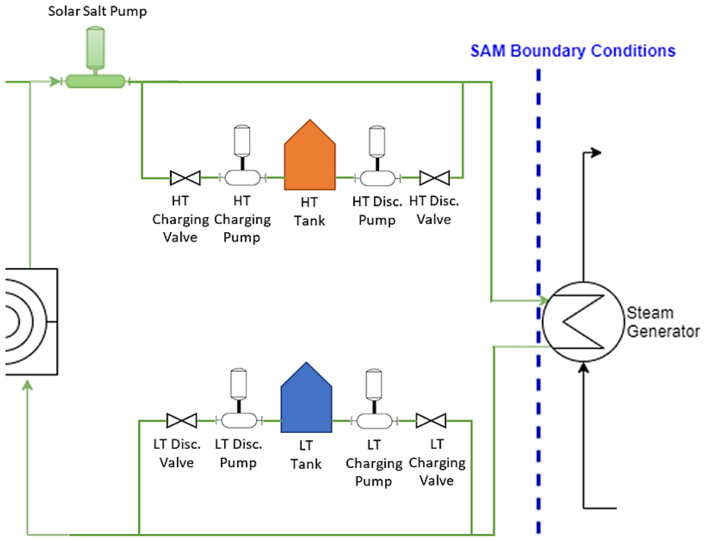
Constrained variables
Reactor Power (y_1)
Core flow rate (y_9)
Core outlet temperature (y_2)
TES flow rate (y_{10})
HT tank level (y_{11})
LT tank level (y_{12})

Input variables	Controlled variables
Reactivity insertion (u_1)	Reactor power (y_1)
FLiBe salt pump (u_2)	Core outlet temperature (y_2)
Solar salt pump (u_3)	IHX outlet temperature (y_3)
HT tank charge pump/valve (u_4, u_5)	HT tank charging rate (y_4)
HT tank disc. pump/valve (u_6, u_7)	HT tank discharge rate (y_5)
LT tank charge pump/valve (u_8, u_9)	LT tank charging rate (y_6)
LT tank disc. pump/valve (u_{10}, u_{11})	LT tank discharge rate (y_7)
SG (Rankine side) flow rate (u_{12})	SG (TES side) outlet temperature (y_8)

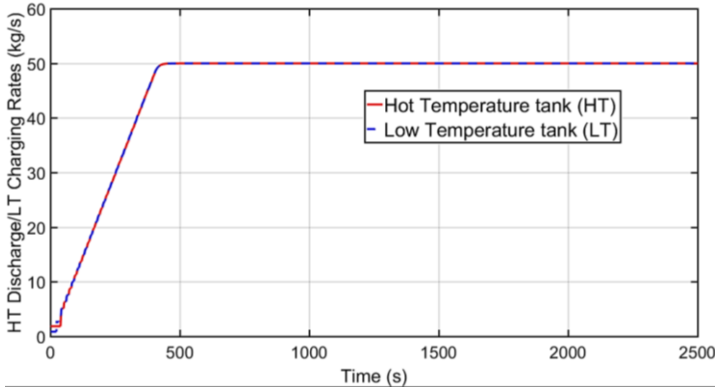


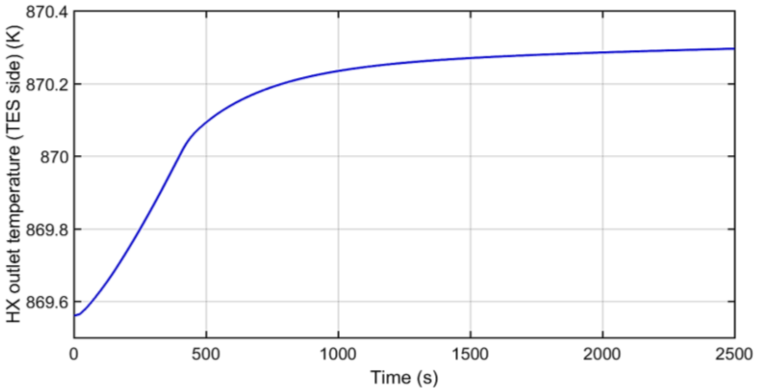
Results and accomplishments

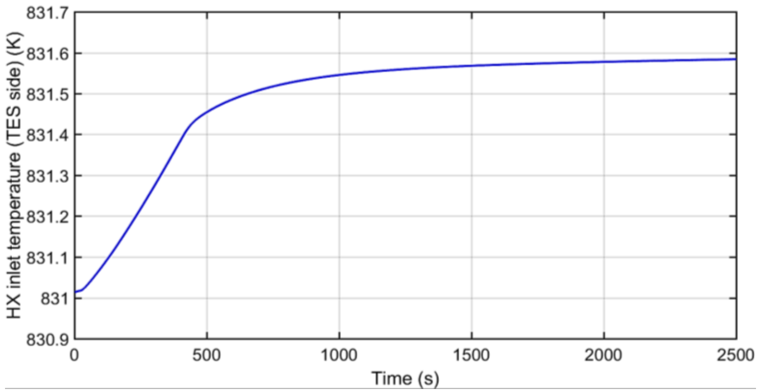
- Simulation of “TES Discharging” transient
  - Salt flows from the HT tank to the LT tank through the SG by producing an additional power output.
  - PID controllers regulate the head provided by HT/LT discharge/charging pumps
  - Crucial role played by the presence of the expansion tank to address coolant expansion/contraction during transients

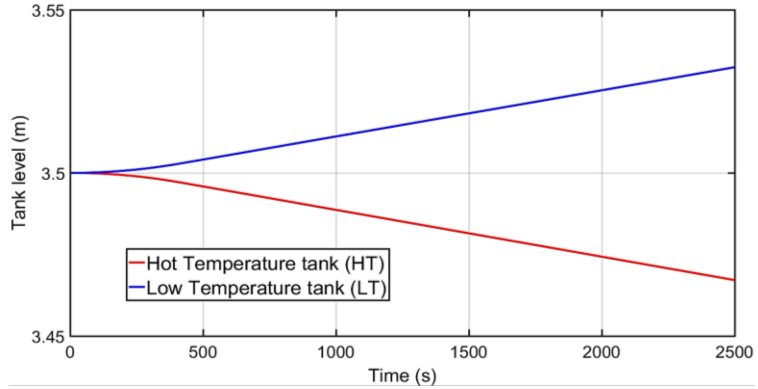


Control actions initialing the transient (HT/LT tanks flow rate variations)



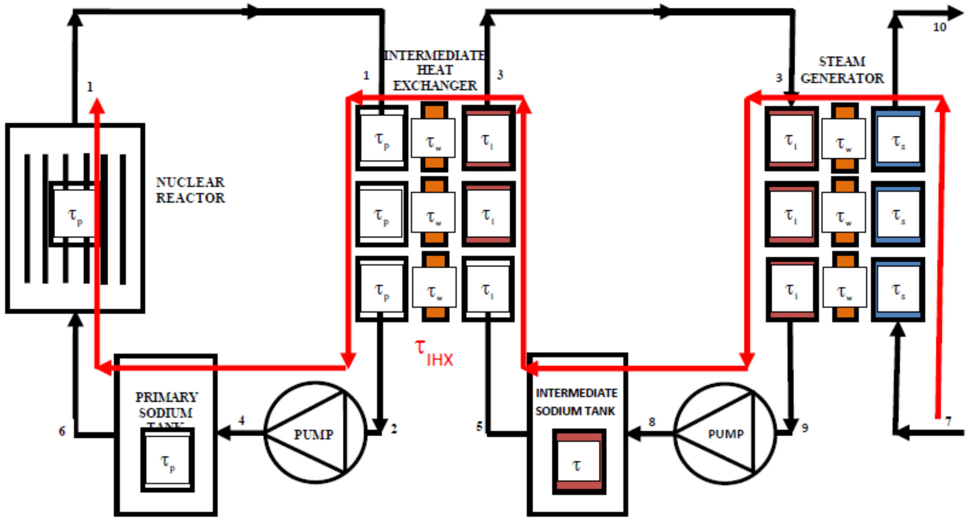




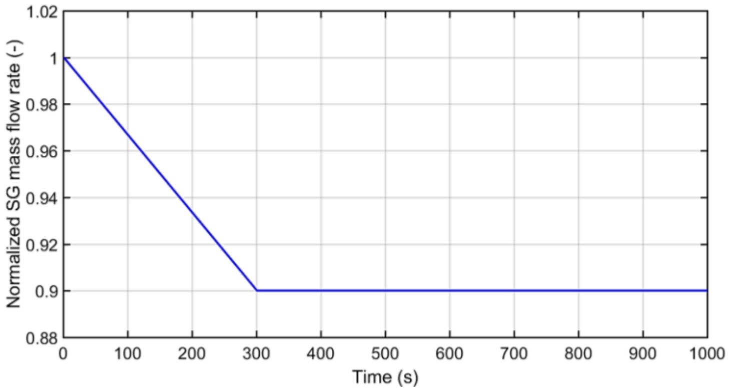


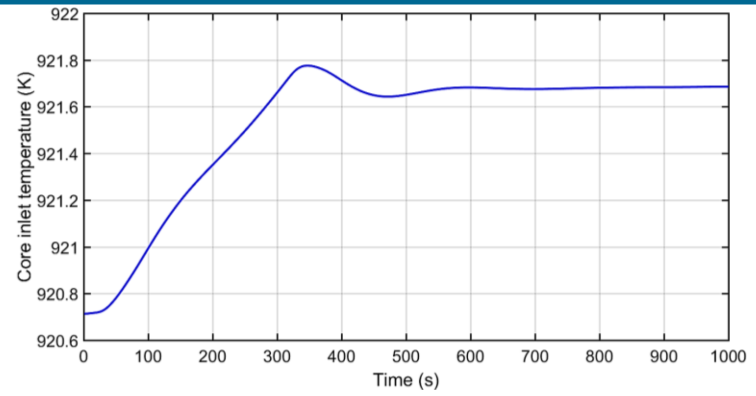
Results and accomplishments

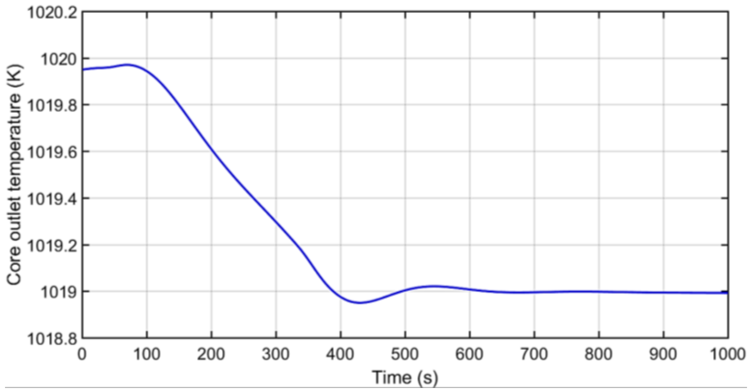
- Simulation of “Load-following” transient
  - The load variation was simulated by altering the imposed thermal boundary conditions (feedwater flowrate reduction).
  - Characteristic time constants can be evaluated
  - “Reactor-follows-turbine” behavior observed

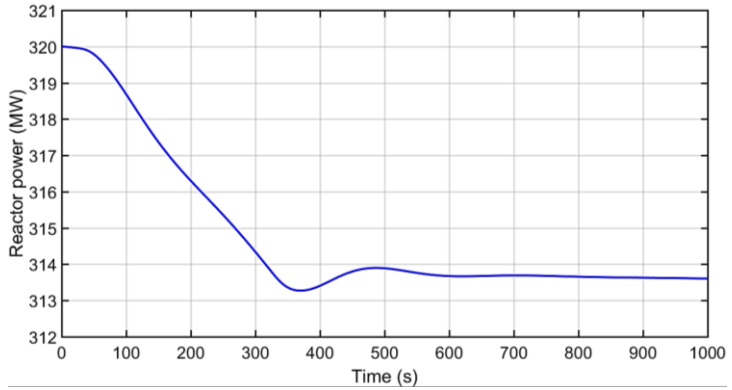


Control action initialing the transient (SG feedwater flow rate reduction)









Conclusion

- Future Plans
  - Implementation of the System Identification scheme to derive the Digital Twin for control algorithm ("rolling window" DMDc)
  - Implementation of the Finite State Machine to synchronize the control actions during complex operational transients (load-following, TES charging/discharging, etc.)
  - Started the literature review about the savings in terms of O&M costs ensured by the adoption of autonomous control architecture

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LinkedIn

Questions?

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ASI Advanced Sensors and Instrumentation

Advanced Sensors and Instrumentation (ASI) Program Research Overview

November 15 – 18, 2021

Pattrick Calderoni – National Technical Director

Measurement Science Department

Idaho National Laboratory

ASI FY21 Annual review meeting

ASI Advanced Sensors and Instrumentation

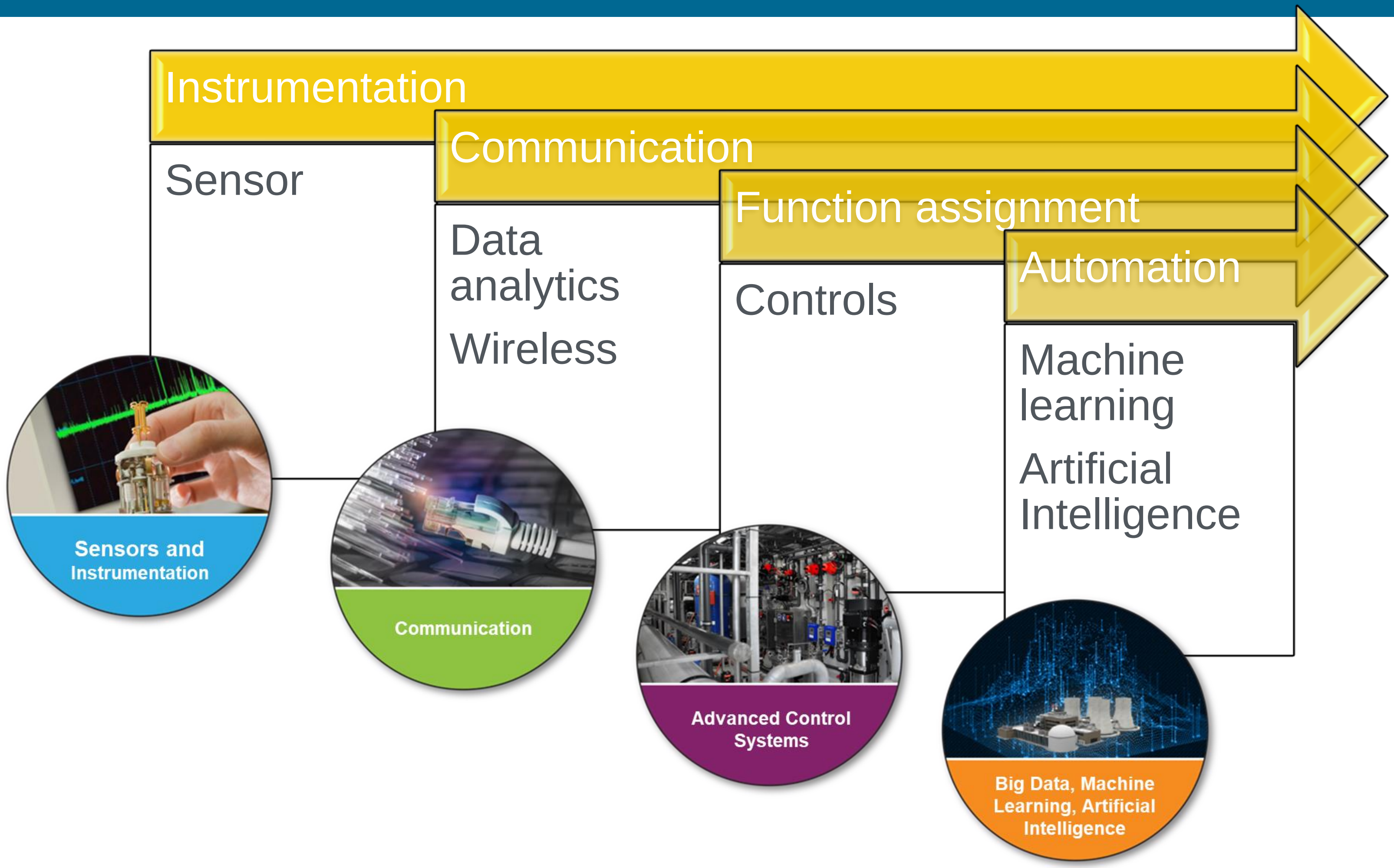
Webinar Agenda
Advanced Sensors and Instrumentation (ASI)
FY21 Annual Review meeting
(All Times are Eastern Standard Time)

Thursday, November 18, 2021

Session 4: Digital technology

10:00 am	The approach to development of digital technology for advanced reactors I&C (Craig Primer, INL)
10:15 am	Process Constrained Data Analytics for Sensor Assignment and Calibration (Rick Vilim, ANL)
10:45 am	Design of Risk-informed Autonomous Operation for Advanced Reactors (Michael Golay, MIT)
11:15 am	Analytics at scale of Sensor Data for Digital Monitoring in Nuclear Plants (Vivek Agarwal, INL)
11:45 am	Cost-Benefit Analysis through Integrated Online Monitoring and Diagnostics (Dave Grabaskas, ANL)
12:15 pm	***Break***
12:30 pm	Develop Methods and Tools using NSUF Data to support Risk-Informed Predictive Analytics (Vivek Agarwal, INL)
1:00 pm	Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance (PI – Daniel Cole, University of Pittsburgh)
1:30 pm	Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid (Roberto Ponciroli, Argonne)
2:00 pm	Context-Aware Safety Information Display for Nuclear Field Workers (Pingbo Tang, George Gibson, ASU)
2:30 pm	Rad-hard electronics for data communication and advanced controls – (Kyle Reed, ORNL)
3:00 pm	***Break***
3:20 pm	Fault Detection of Digital Instrumentation and Control Systems using Integrated Electromagnetic Compatibility and Automated Functional Testing (Greg Morton, Analysis & Measurement Services Corp.)
3:40 pm	Video Camera for Harsh Environments in Nuclear (Esen Salcin, Alphacore Inc.)
4:00 pm	Machine Learning Enhancement of BWR Neutron Flux Measurement and Calibration (Tom Gruenwald, Jonathan Nistor, Blue Wave AI Labs)
4:30 pm	Moderated discussion on Session 4 (Moderator: Craig Primer, INL)
4:50 pm	Concluding Remarks (DOE)
5:00 pm	***Adjourn***

Technology integration in plant I&C



Commercial Microreactors

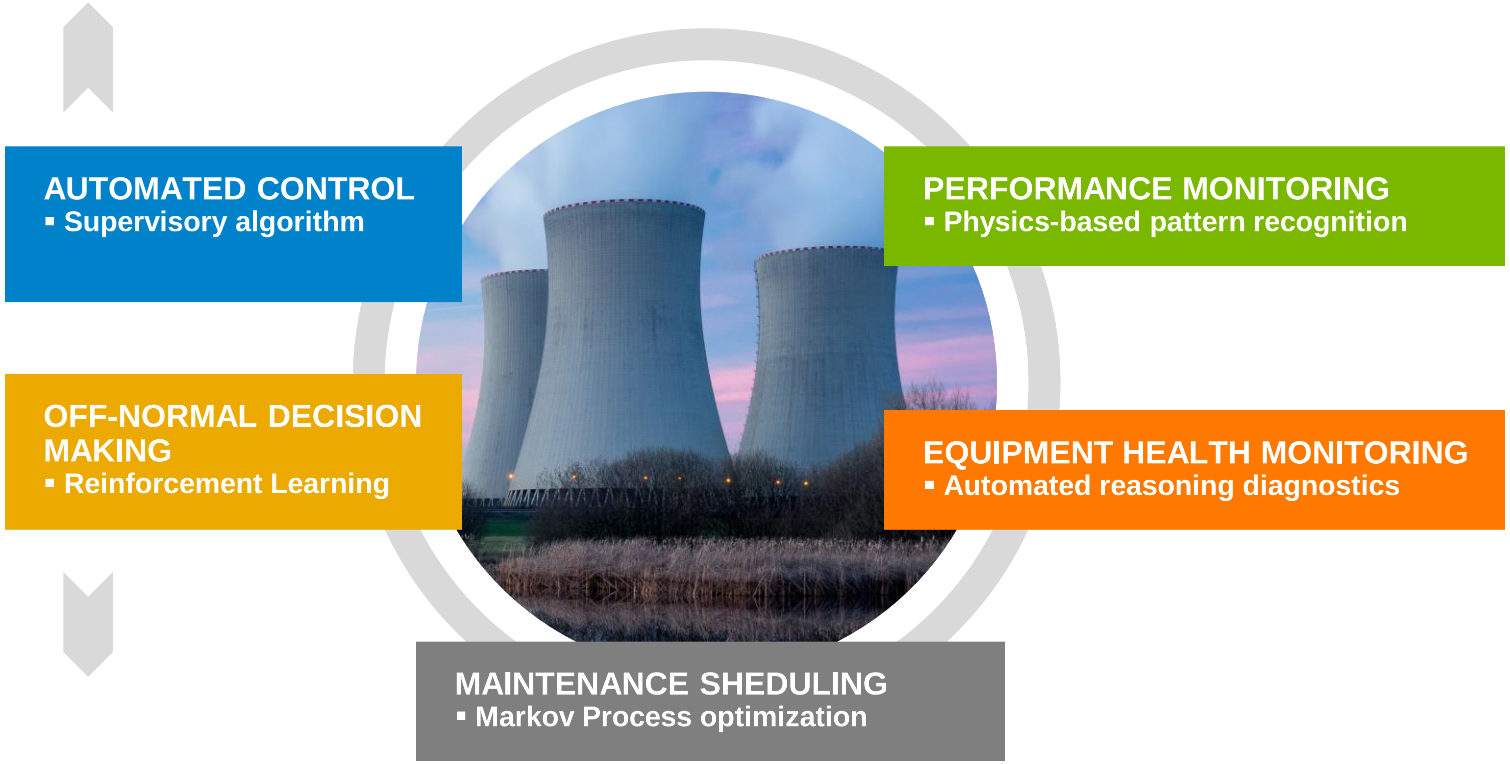
NEET ASI Research results in **advanced sensors and I&C technologies** that are qualified, validated, and ready to be adopted by the nuclear industry

Program objectives FY22-25

Digital Technology for advanced reactors

- Develop condition monitoring technologies for anomaly detection, diagnostics, prognostics, and decision making that can operate on streaming data
- Integrate advanced sensors and instrumentation in Nuclear Digital Twins (NDT) with Hardware in the Loop simulation for the phased demonstration of performance-based control algorithms to enable autonomous operation
- Develop modeling and simulation tools for communication technologies to support integration with control systems

A logical progression towards sensor-based autonomous operation of advanced reactors

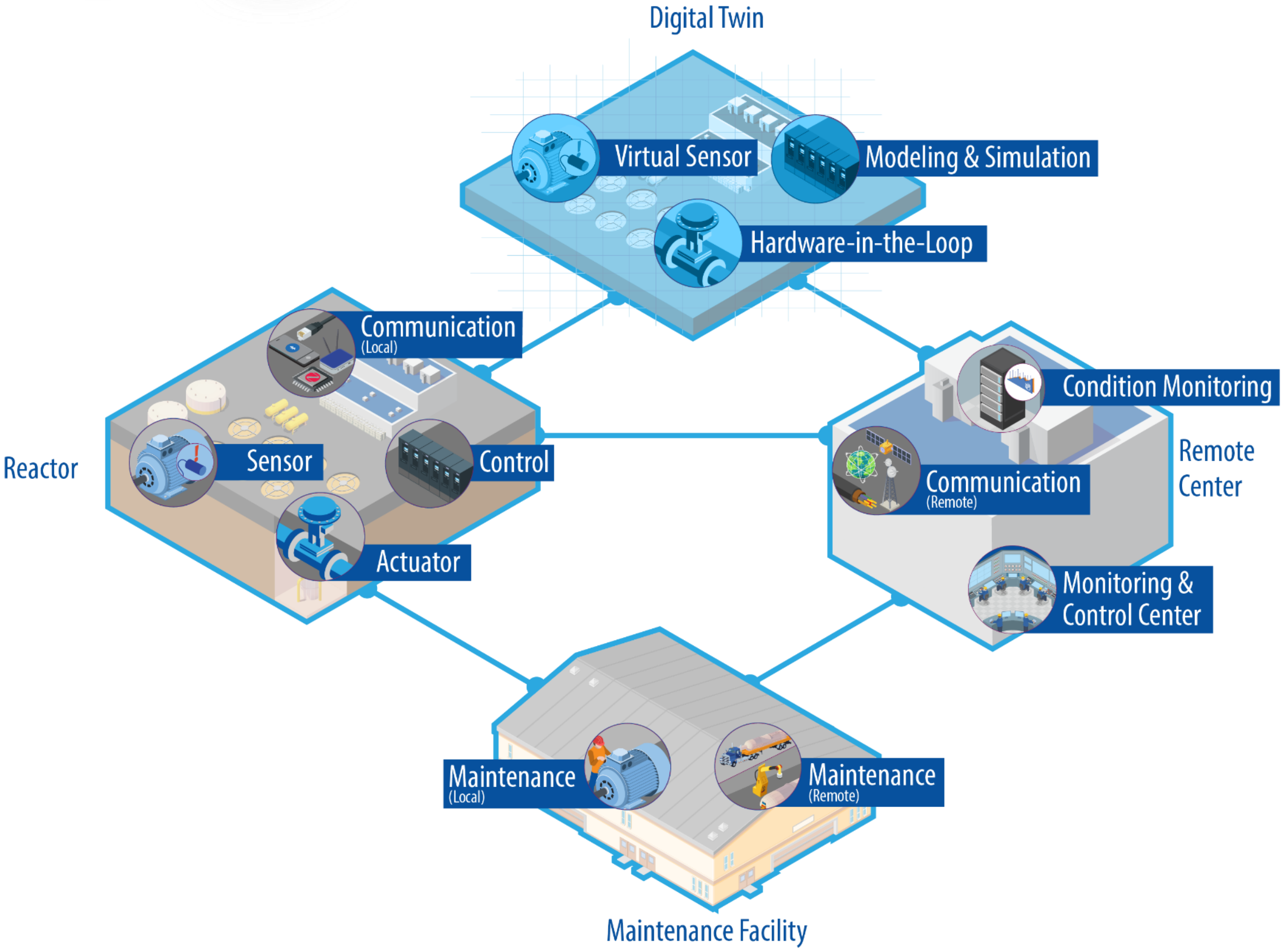


Digital technology for advanced reactors

5 years objectives

Develop the approach to integrate advanced control algorithms in nuclear digital twins

- Develop Nuclear Digital Twins (NDT) with Hardware in the Loop simulation for **advanced controls demonstration**
- Develop technologies for anomaly detection, diagnostics, prognostics, and decision making that can **operate on streaming data**
- Develop modeling and simulation tools for **communication technologies** to support integration with predictive control systems
- Develop performance-based control algorithms to **enable autonomous operation**

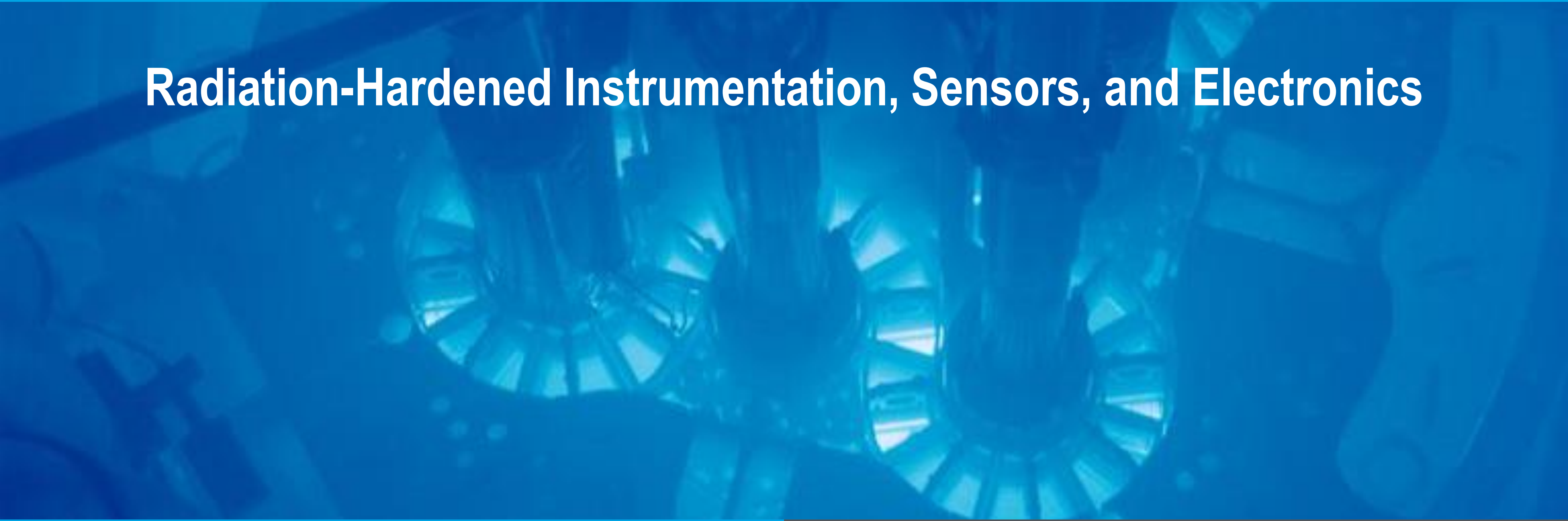


Thank You!

ASI

Advanced Sensors and Instrumentation

Radiation-Hardened Instrumentation, Sensors, and Electronics



Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

F. Kyle Reed

Oak Ridge National Laboratory

Project Overview

- Goal and Objective
  - Survey state-of-the-art (SOA) radiation-hardened electronic components and systems for reactor communication, instrumentation, and controls. This survey identifies gaps in technology and suggests future research directions in radiation-hardened electronic systems.
- Participants (2020-2021)
  - Nance Ericson, PI, Oak Ridge National Laboratory
  - Kyle Reed, Oak Ridge National Laboratory
  - Dianne Bull Ezell, WPM, Oak Ridge National Laboratory
  - Chuck Britton, Oak Ridge National Laboratory
- Schedule
  - July 1st, 2020 – September 30th, 2021

Summary of Accomplishments

- FY20:
  - Radiation effects of electronics associated with reactor environments are reviewed
  - Survey of commercial and research SOA rad-hard electronics is presented
  - Gaps in technology space are identified
  - Suggestions for establishing future research directions of research are given
- FY21:
  - JFET-based sensing and communications circuit irradiated to beyond 100 Mrad (Si)
  - Frequency error correction established
  - Report detailing wide bandgap transistor technologies and their radiation-hardness was completed


A 100 Mrad (Si) JFET-Based Sensing and Communications System for Extreme Nuclear Instrumentation Environments

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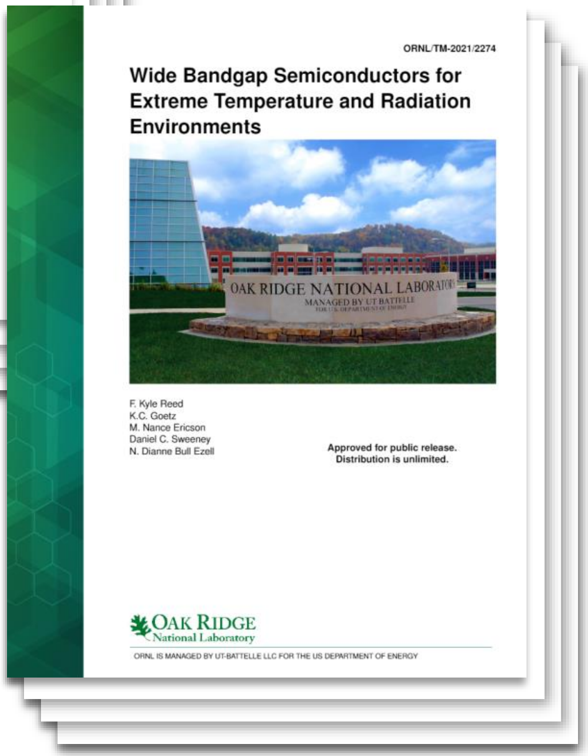
Number of figures: 10


ORNL/TM-2021/2274

Wide Bandgap Semiconductors for Extreme Temperature and Radiation Environments

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K.C. Goetz
M. Nance Ericson
Daniel C. Sweeney
N. Dianne Bull Ezell

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OAK RIDGE National Laboratory

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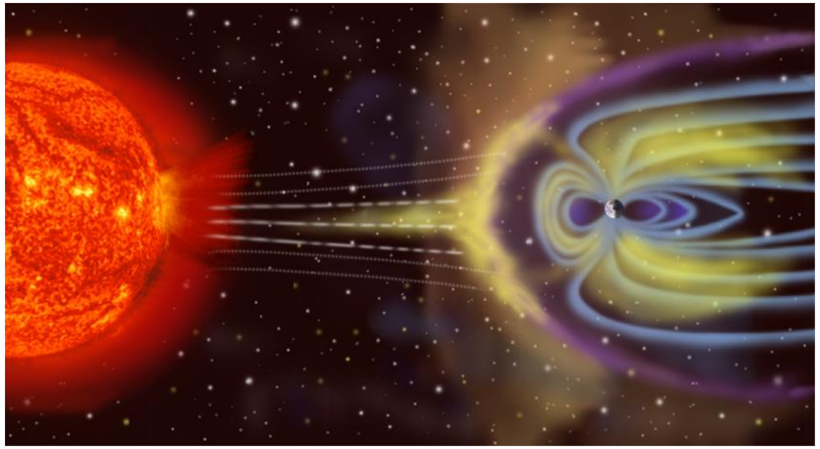
Technology Impact

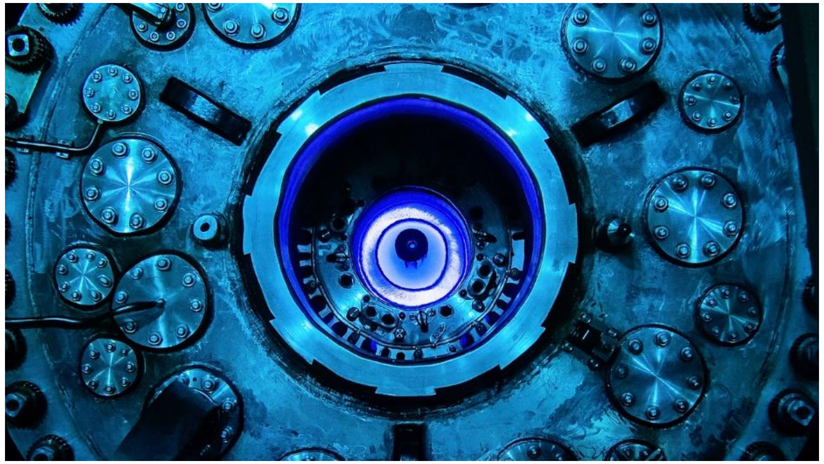
- *Advances the state of the art for nuclear application*
  - The current SOA is identified and can be used to guide research opportunities in both short- and long-term goals. First reported 100 Mrad sensing and communications circuit irradiated.
- *Supports the DOE-NE research mission*
  - A course of research for radiation-hardened electronics that support increasing safety and efficiency is identified.
- *Impacts the nuclear industry*
  - Placing sensors and associated electronics closer to a nuclear reactor core will improve reactor control and operation through increased signal accuracy, precision, and fidelity resulting in safer and more efficient energy production.
- *Will be commercialized*
  - This research identifies technology gaps and directions which will benefit researchers and industry to work more cohesively to promote commercialization.

Space Vs. Nuclear Environments

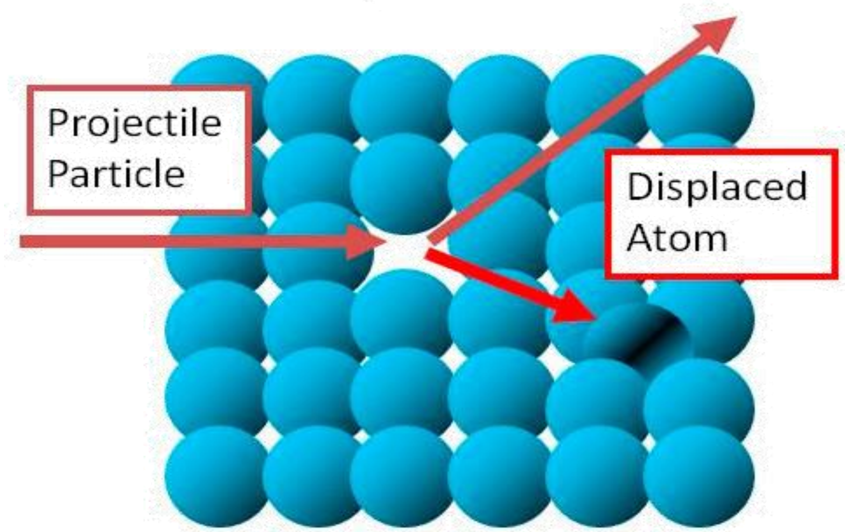
- Space environments
  - Space-rated electronics dominate the radiation-hardened (rad-hard) market
  - The radiation environment in low earth orbit (LEO) and deep space consists of:
    - Galactic cosmic rays and solar winds comprised of **protons** and **electrons (β)**
    - Solar flares and coronal mass ejections generate **protons**, **x-rays**, and **heavy atomic nuclei (α)** with energies ranging from MeV to tens of MeV
    - **Neutrons** if reactor is used for power and/or propulsion
- Terrestrial nuclear environments
  - Nuclear ratings are unclear or omitted from commercial electronic device data sheets
  - **Neutrons** and **ionizing radiation** are associated with terrestrial nuclear environments



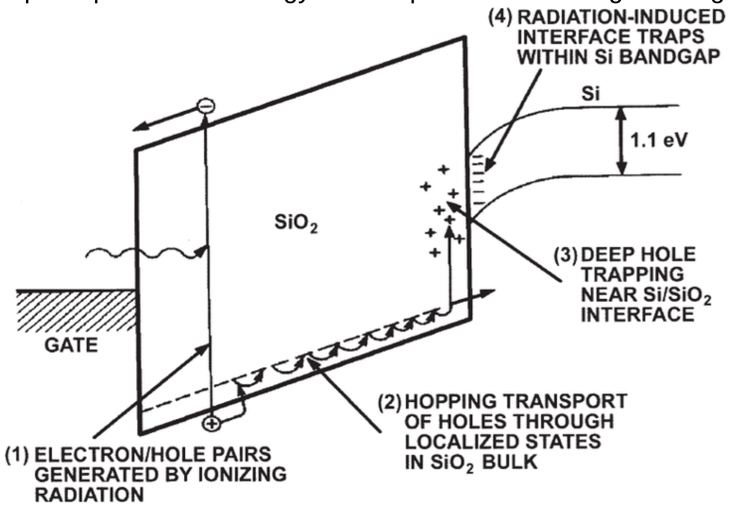
https://www.inverse.com/article/8216-space-radiation-is-quietly-stopping-us-from-sending-humans-to-mars



Radiation Effects in Electronic Components



https://wpo-altertechnology.com/displacement-damage-testing/



A. Dawiec, Development of an ultra-fast X-ray camera using hybrid pixel detectors, HumanComputer Interaction [cs.HC], Universite de la Mediterranee — Aix-Marseille II, Marseille France (2011)

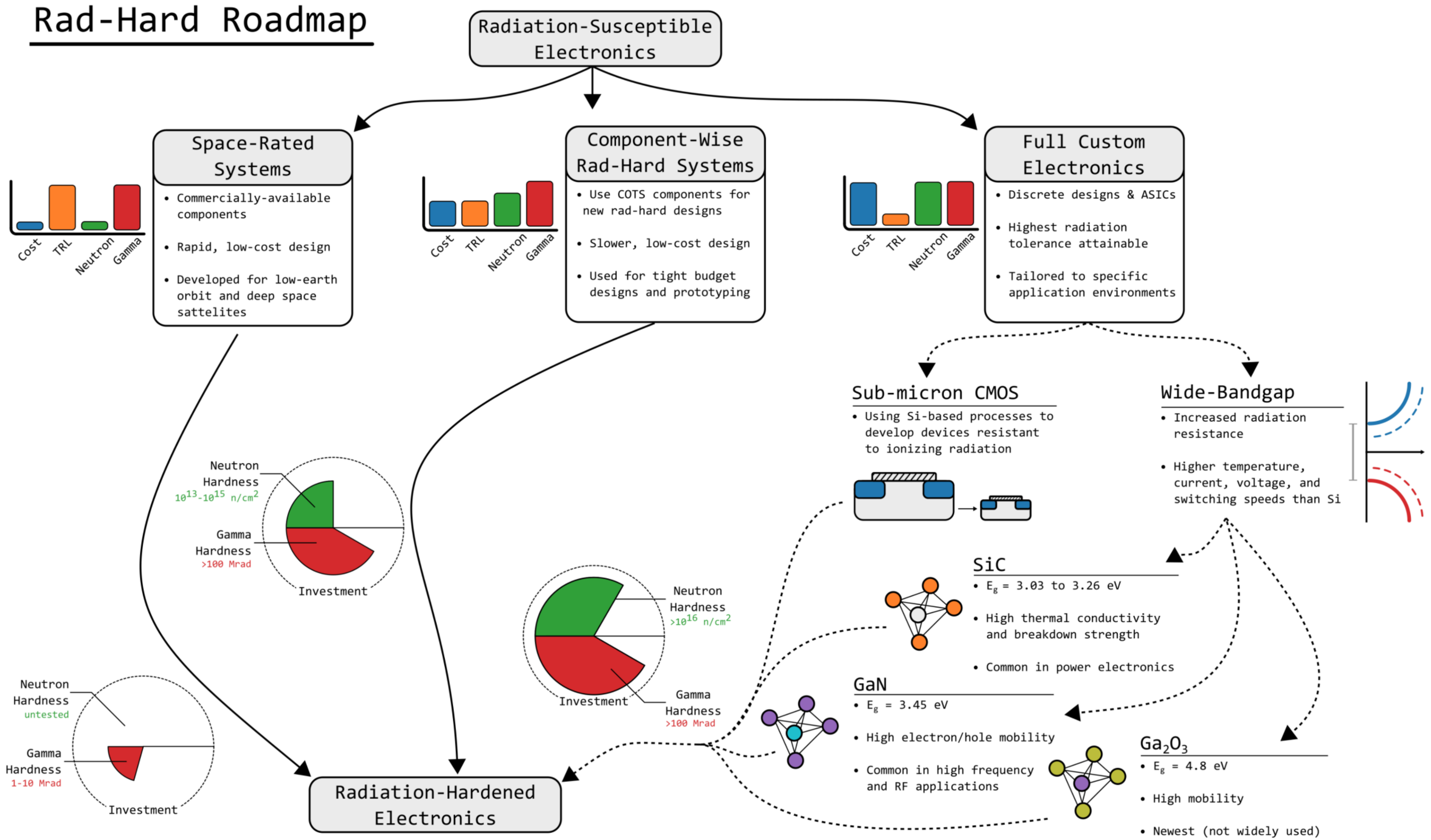
- Neutrons
  - Neutrons will transfer energy to interstitial atoms displacing atoms which may recombine with dopant or impure atoms producing stable defects
  - Minority carrier removal and increased material resistivity are associated with neutron displacement damage
- Ionizing Radiation
  - Compton effect and pair creation from high energy photons create ions in the incident materials
  - Charges are trapped in electrical insulators that generate electric fields and induce currents
  - Dose rates contribute to single event errors such as single event upsets or latch ups

Electronic Component Dose Degradation Limitations

	Neutron Displacement Damage [1]		**Total Ionization Dose (TID) Damage** [2]	
	Max Fluence (n/cm^2)	Displacement effect	TID (rad)	TID effect
Diodes/ Photodiodes	10^{13}-10^{15}	↑ leakage current; ↑ forward voltage threshold	10^{6}-10^{8}	↑ photocurrents
LEDs	10^{12}-10^{14}	↓ light intensity	10^{7}-10^{8}	0.25 dB attenuation
BJTs	10^{13}	Current gain degradation	10^{5}-10^{7}	Current gain degradation; ↑ leakage current
JFETs	10^{14}	↑ channel resistivity; ↓ carrier mobilities	$>10^{8}$	Minimal effects
SiC JFETs	10^{16}	↑ channel resistivity; ↓ carrier mobilities	$>10^{8}$	Minimal effects
MOSFETs	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^{6}	↑ threshold voltage; ↑ leakage current
CMOS	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^{8}	variation in threshold voltage; variations in leakage current

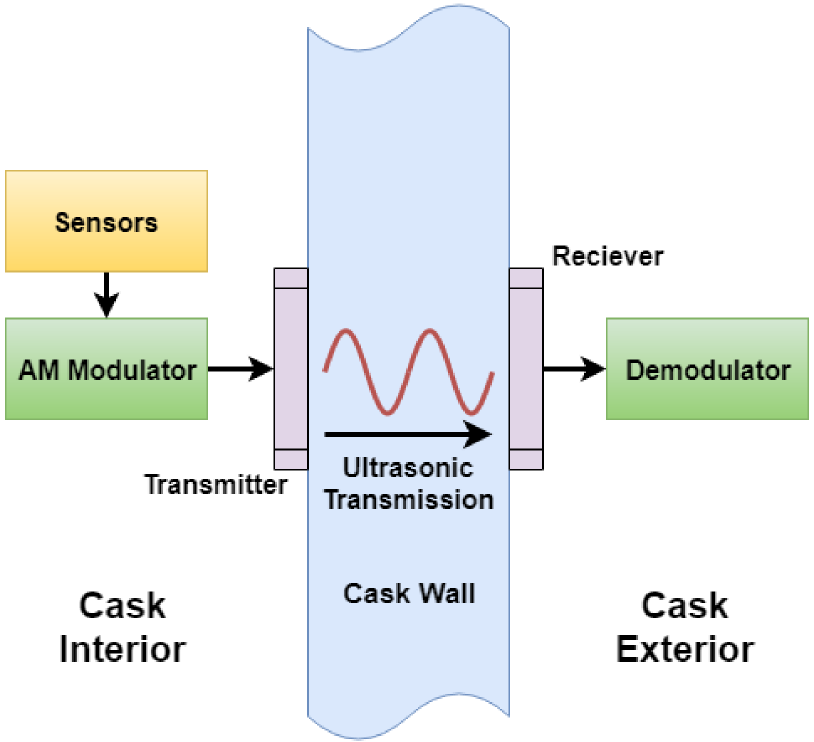
[1] Neamen, Donald A. Semiconductor physics and devices: basic principles. New York, NY: McGraw-Hill,, 2012.
[2] H. Spieler, "Introduction to radiation-resistant semiconductor devices and circuits." AIP Conference Proceedings. Vol. 390. No. 1. American Institute of Physics, 1997.

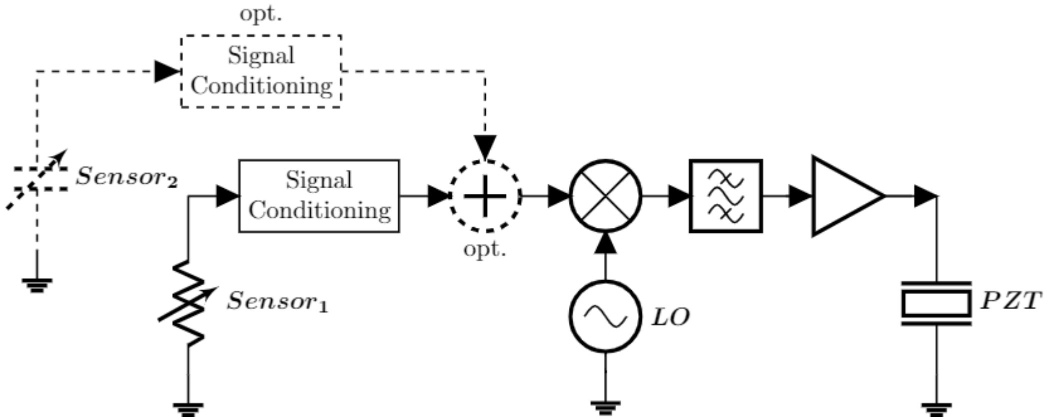
Pathways to Rad-Hard Electronic Systems



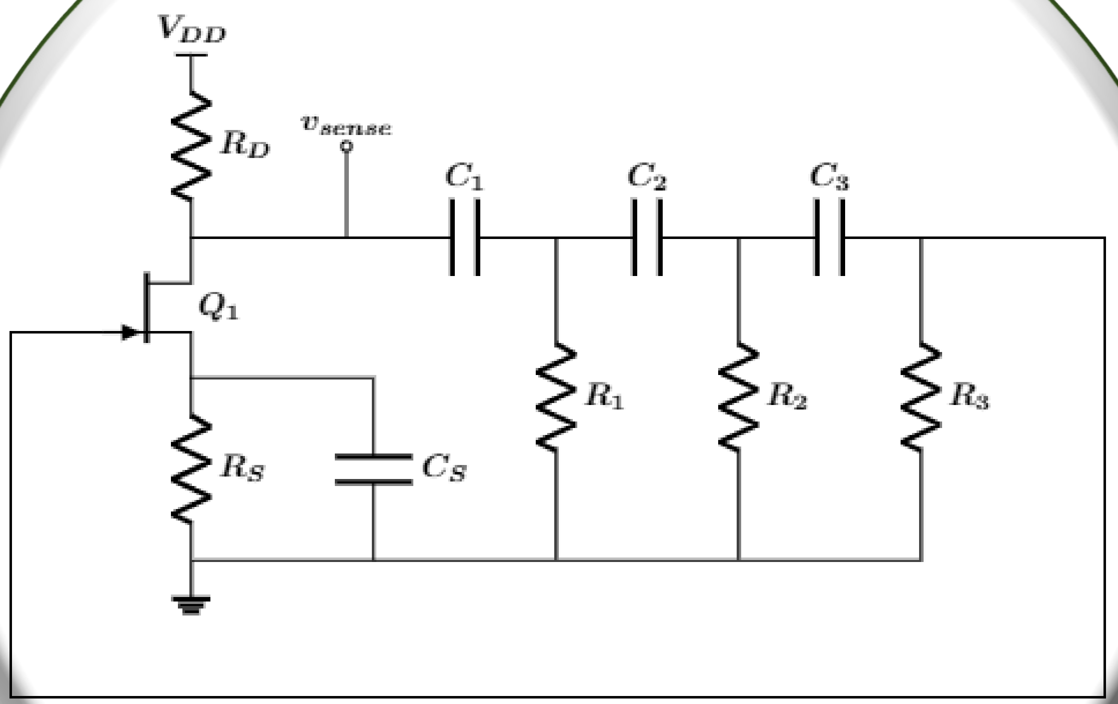
Rad-Hard Electronics Design Considerations

- Utilizes analog-based approach to minimize active device count
- Suitable for use with temperature and pressure sensors
- Each sensor's information is encoded into an independent frequency – both signals are summed
- Summed sensor output frequencies are mixed with a carrier wave matched to the PZT resonance
- The mixer output is filtered and amplified to drive the PZT
- Utilizes straightforward methods on the cask exterior for signal detection



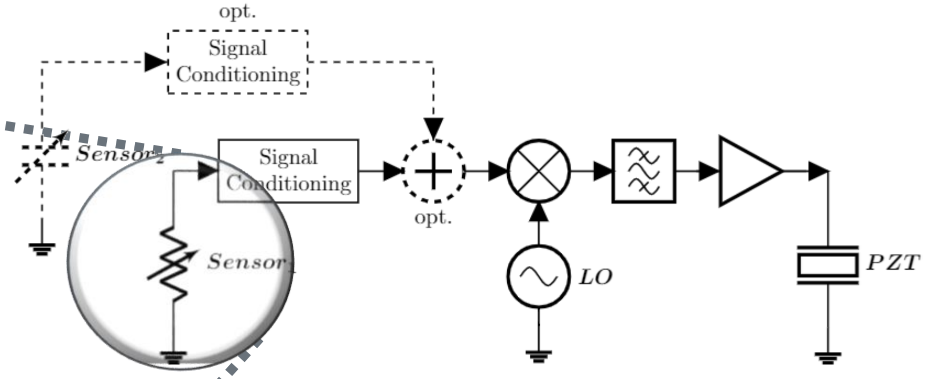


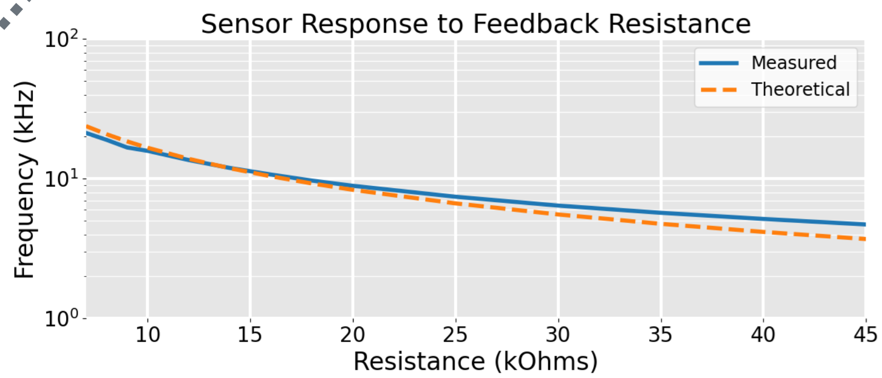
RC Sensor Oscillator

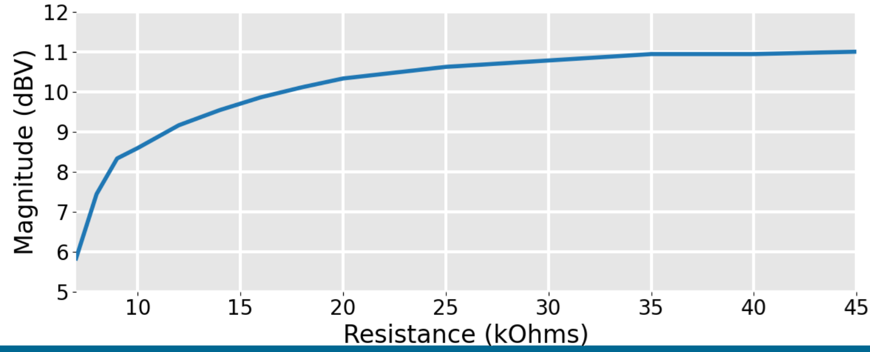


$$f_{RC} = \frac{1}{2\pi RC\sqrt{6}}$$

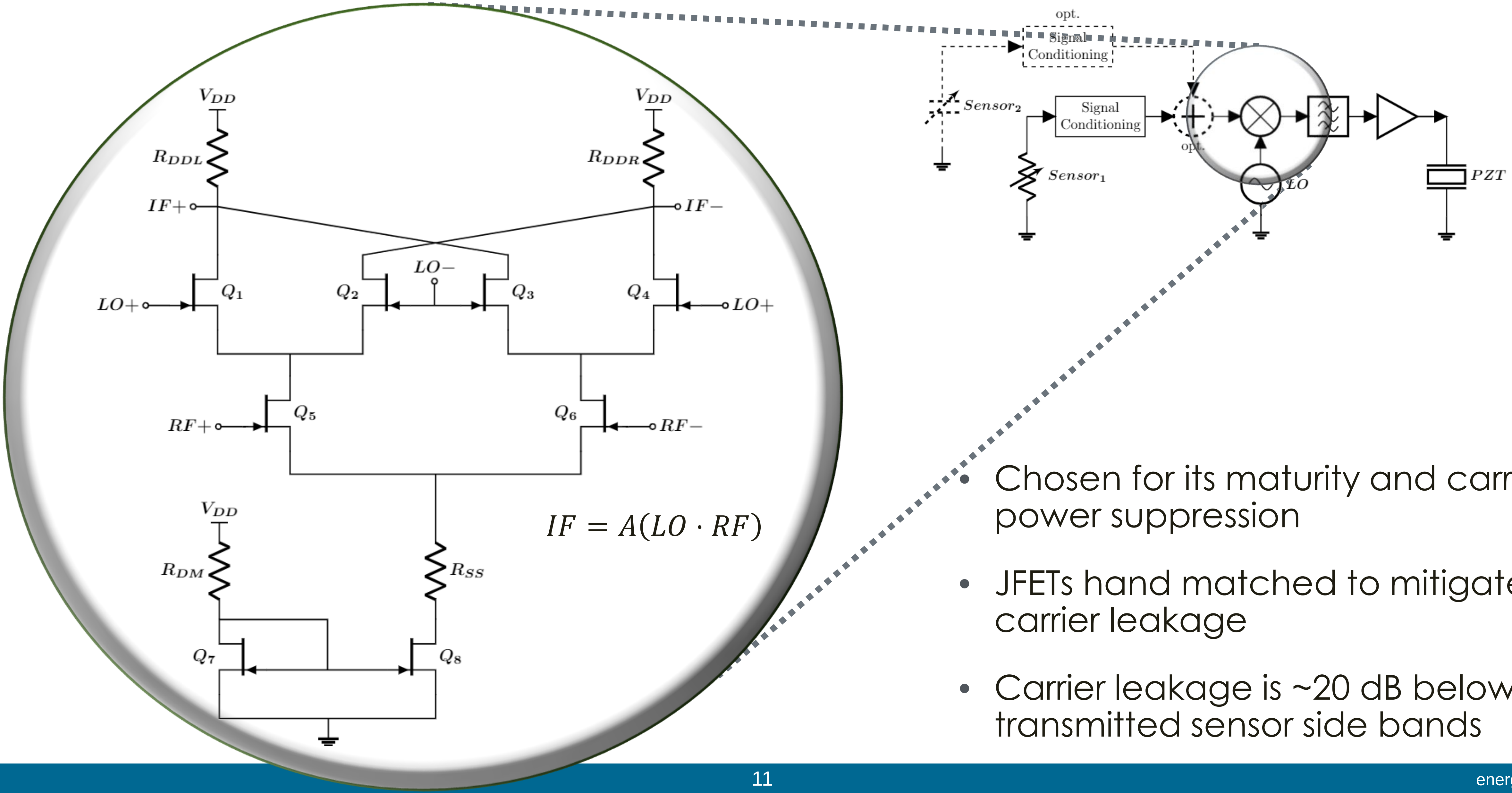
when, $R = R_1 = R_2 = R_3$ & $C = C_1 = C_2 = C_3$





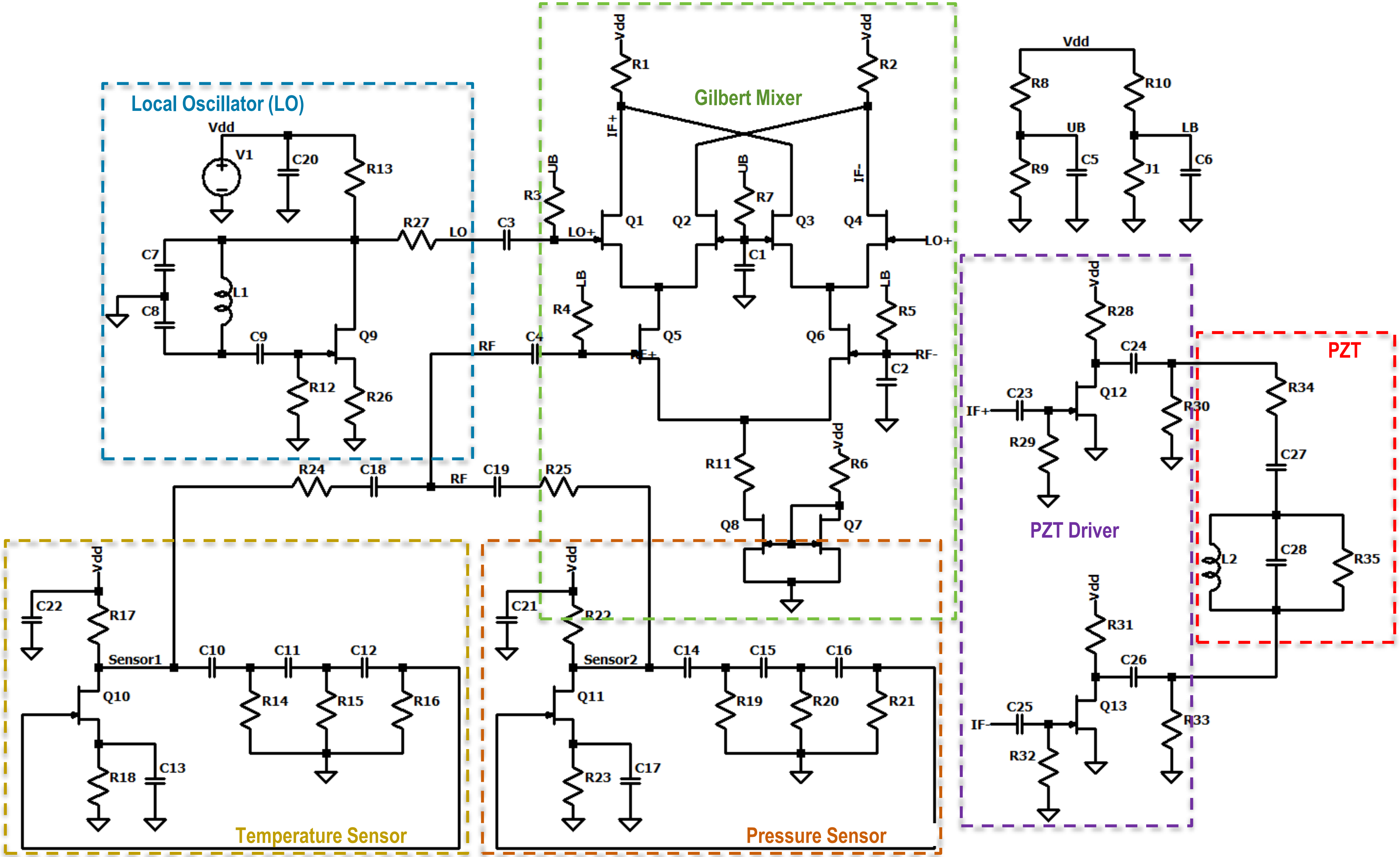


Gilbert Mixer



- Chosen for its maturity and carrier power suppression
- JFETs hand matched to mitigate carrier leakage
- Carrier leakage is ~20 dB below transmitted sensor side bands

JFET System Schematic



Modulation and Signal Theory

- The multiplication (mixing) of two sinusoids in frequency domain is written as

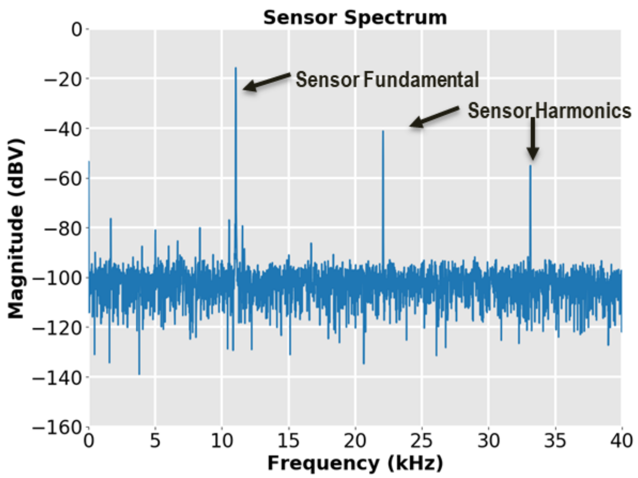
$$\mathcal{F}\{\cos(2\pi f_{RC}t)\cos(2\pi f_{LO}t)\} = \frac{1}{4}[\delta(f + f_{LO} + f_{RC}) + \delta(f + f_{LO} - f_{RC}) + \delta(f - f_{LO} + f_{RC}) + \delta(f - f_{LO} - f_{RC})]$$

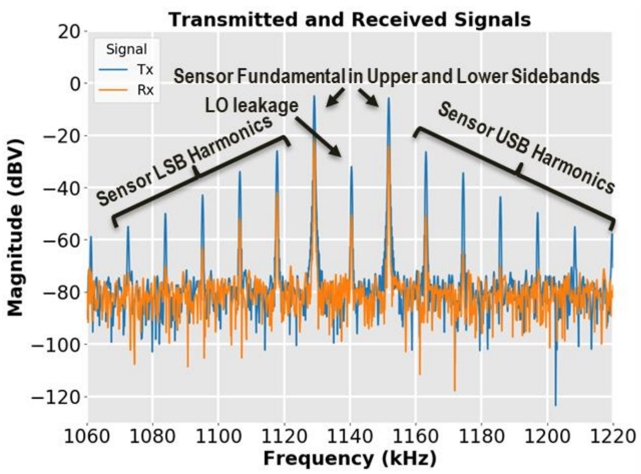
- The sensor frequency estimate $\hat{f}_{RC}$ can be obtained by the upper and lower sideband impulses corresponding to the mixed sensor frequency as follows

$$\hat{f}_{RC} = \frac{1}{2}[f_{USB} - f_{LSB}] = \frac{1}{2}[f_{LO} + f_{RC} - (f_{LO} - f_{RC})]$$

- Multiple sensors can be added due to the linearity of the Fourier transform when exploiting frequency orthogonality

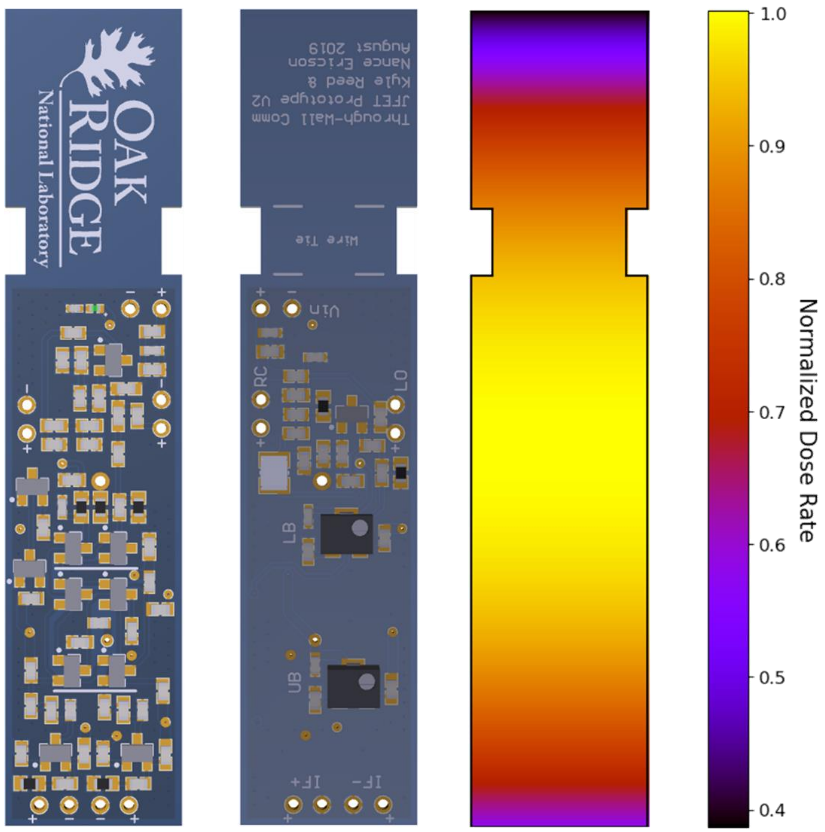
$$\mathcal{F}\left\{\left(\sum_{i=1}^{N}\cos(2\pi f_{RC_i}t)\right)\cos(2\pi f_{LO}t)\right\} = \frac{1}{4}\sum_{(i=1)}^{N}[\delta(f + f_{LO} + f_{RC_i}) + \delta(f + f_{LO} - f_{RC_i}) + \delta(f - f_{LO} + f_{RC_i}) + \delta(f - f_{LO} - f_{RC_i})]$$



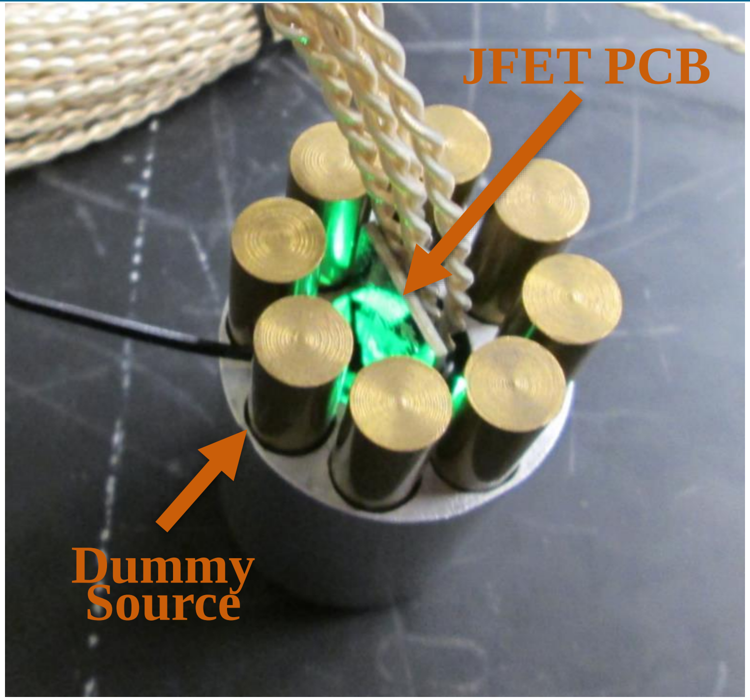


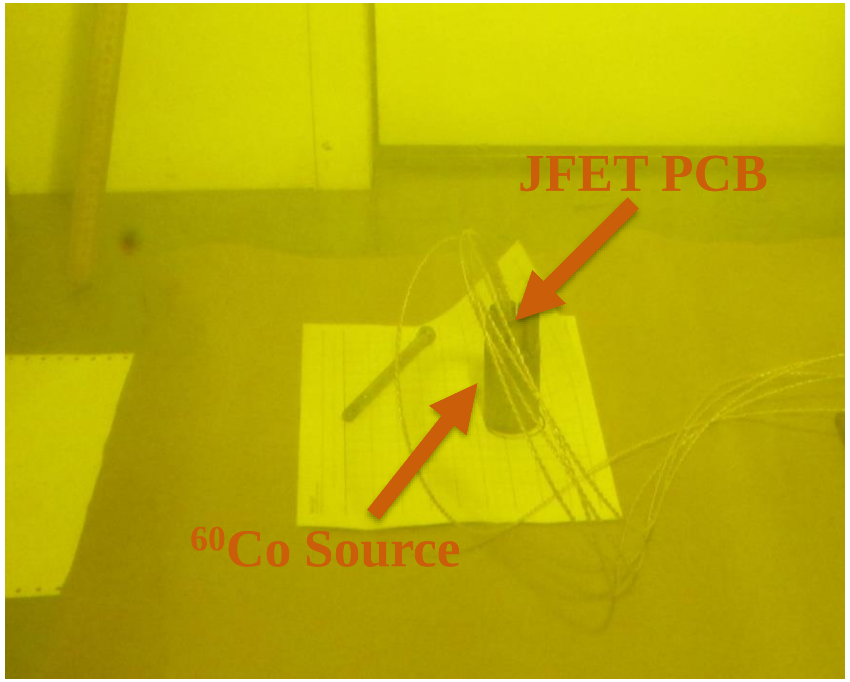
100 Mrad (Si) Irradiation Test Procedure

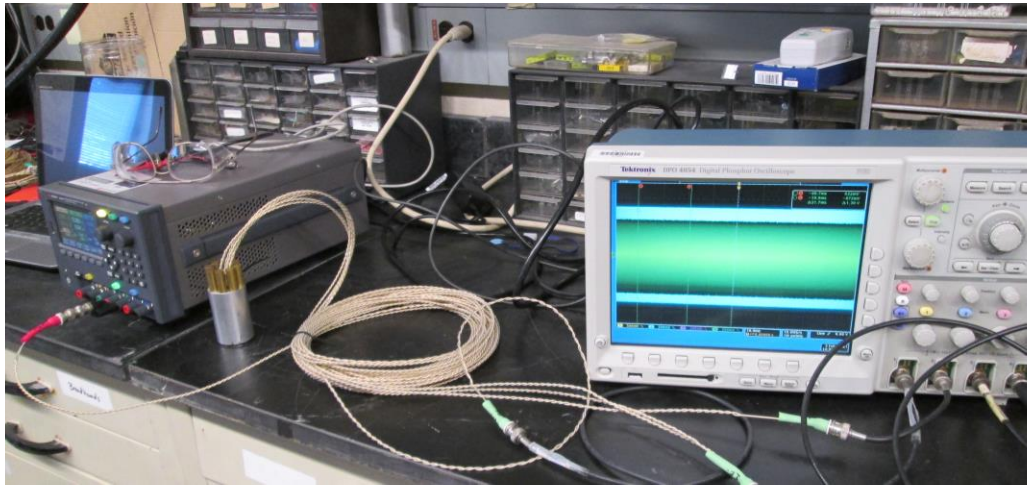
- Four JFET boards where irradiated and monitored continuously at Westinghouse using a Co-60 source at a rate of about 500 krad/hr (Si) for a total of 100 Mrad at the board edges
- Each board was supplied with 12 VDC and consumed ~50 mA
- Signals were passed through 20 ft of PEEK cabling to an oscilloscopes controlled by a custom LabVIEW program
- The scope were set to acquire 1 MSamples/capture on each channel at a 10 MHz sample rate
- One capture was triggered every 10 minutes, timestamped, and saved to an external hard drive
- The scope channels monitored:
  - CH1: RC oscillator
  - CH2: Colpitts Local Oscillator
  - CH3: IF+ (the Gilbert mixer positive differential post amplifier)
  - CH4: IF- (the Gilbert mixer negative differential post amplifier)



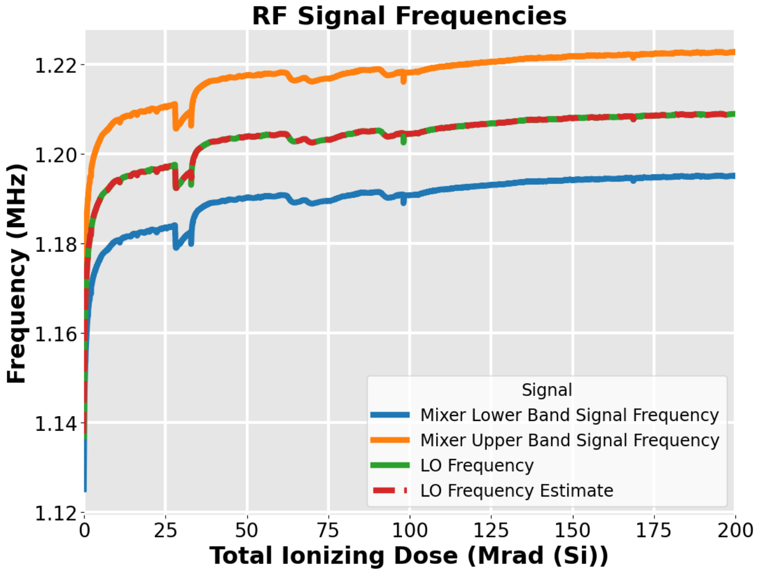
Board Revision and 100 Mrad Irradiation

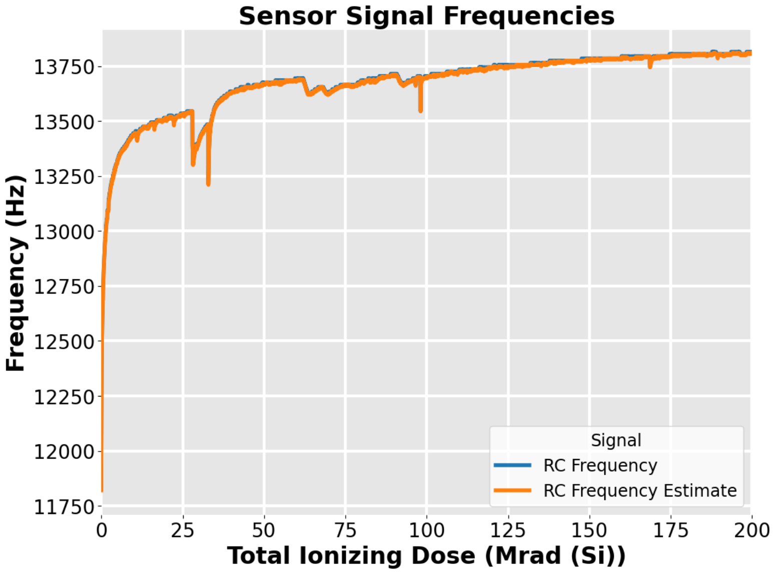


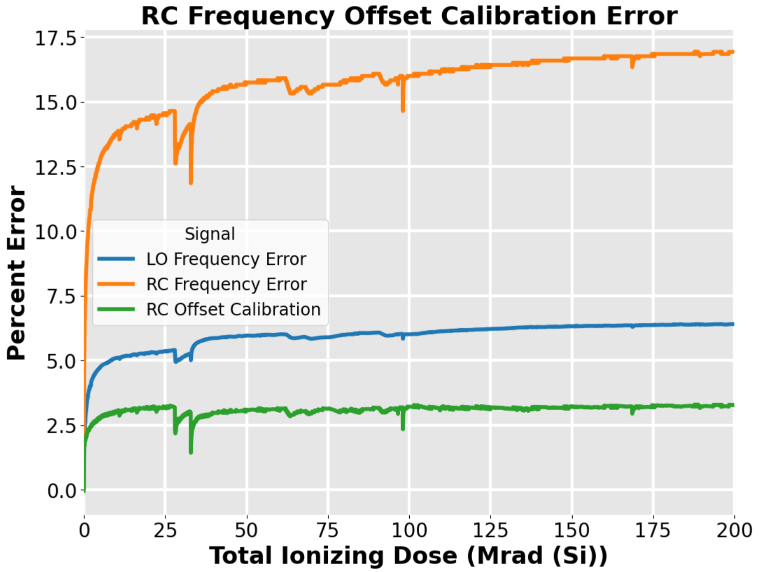


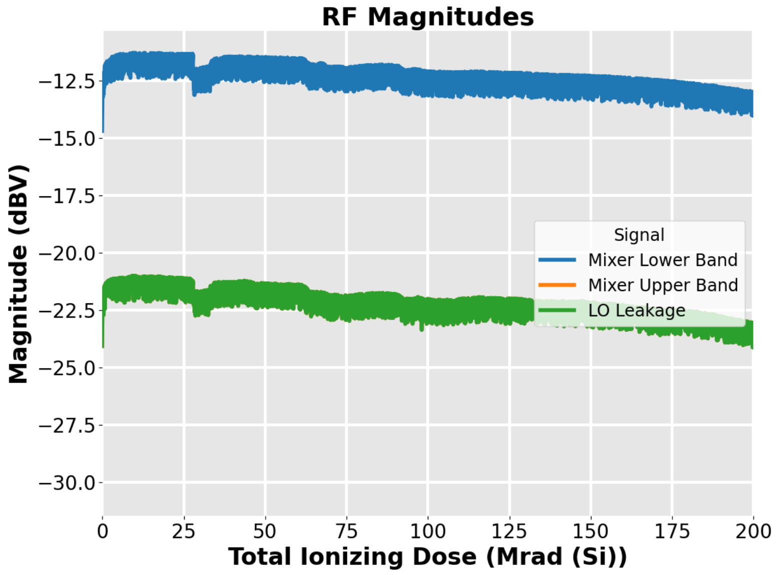


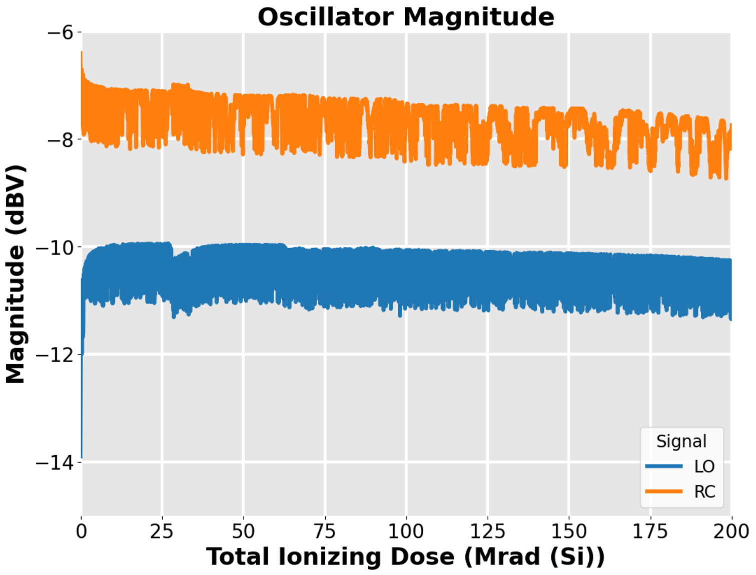
200 Mrad (Si) Irradiation Results of JFET Board 1

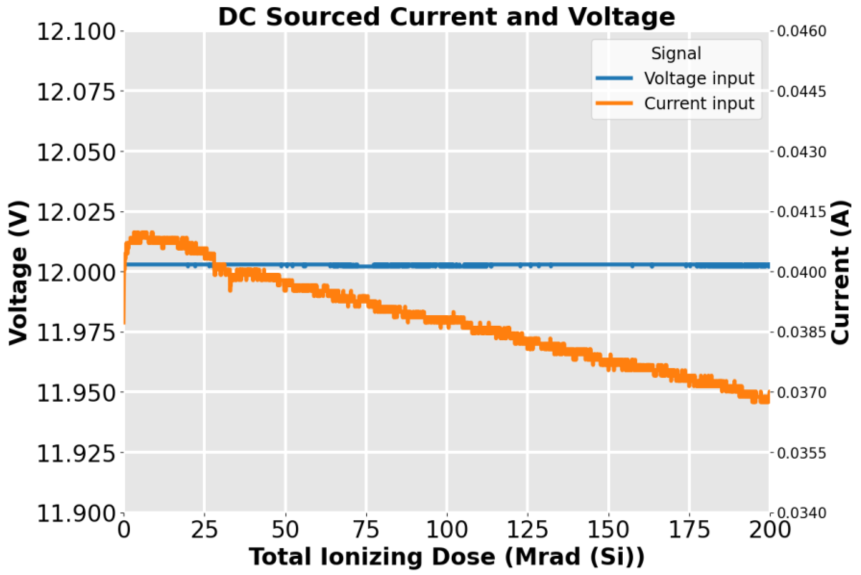










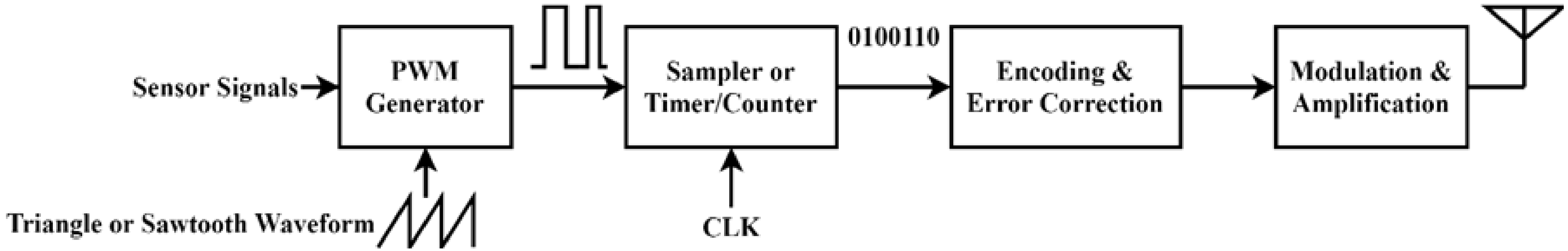


Conclusions

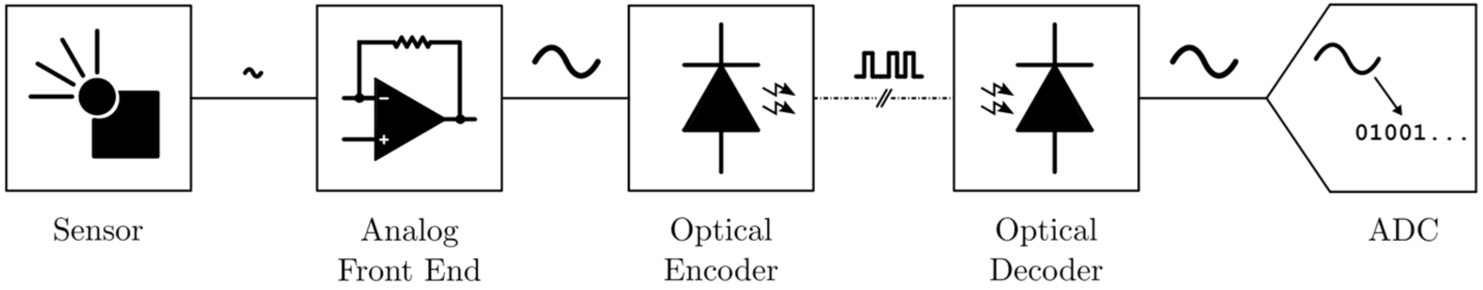
- Even with frequency and minor magnitude shifts, the circuits remained operational to 100 Mrad (Si) at the board edges (~170 Mrad at the board center)
- Frequency drifts are mostly attributed to feedback capacitance variations (charge traps change dielectric properties) and JFET parameter drifts
- Investigations into frequency drift compensation mechanisms are underway
- A journal paper titled, "A 100 Mrad (Si) JFET-Based Sensing and Communications System for Extreme Nuclear Instrumentation Environments" has been submitted to ANS, and another journal publication plus a PhD dissertation are being written
- Invention disclosures are being submitted over frequency error correction of the circuits
- Technical memo titled "Wide Bandgap Semiconductors for Extreme Temperature and Radiation Environments" is under internal review

Future Works

- Radiation-hardened electronics research will continue at ORNL in
  - A recently funded NE-NEET project collaboration with OSU: "GaN-based 100-Mrad Electronics Technology for Advanced Nuclear Reactor Wireless Communications"
    PI: Nance Ericson (ericsonmn@ornl.gov)



  - A direct funded project: "Radiation-Hardened Front-End Digitizer (FREND)"
    PI: Callie Goetz (goetzkc@ornl.gov)



Questions?

ASI | Advanced Sensors and Instrumentation

F. Kyle Reed

reedfk@ornl.gov

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

Clean. Reliable. Nuclear.

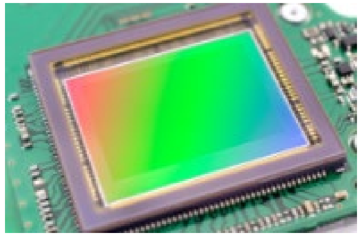
Video Camera for Harsh Environments in Nuclear Energy Applications (SBIR Phase II)

Advanced Sensors and Instrumentation
Annual Webinar
November 18, 2021

Principal Investigator: Esen Salcin, PhD
Presented by: Esko Mikkola, PhD
Alphacore, Inc.

Project Overview

Technical Objective: Develop and test *high-frame rate* video sensor and camera that is capable of operating high radiation environments. The video camera will improve the state of the art of cameras available for nuclear energy research.



In the field of nuclear-heated transient testing, one of the experiments needing this type of camera is "reactivity-initiated accident simulation with video observation of transient water boiling".

Phase II Additional Goal: We are working with a partner whose intention is to *commercialize* the technology in the field of nuclear reactor inspection and plant monitoring.

We are also hardening the image sensor to be suitable for use in the *space radiation* environment to increase the commercial potential.

Subcontractor: A Large Nuclear Industry Camera and Robotics Manufacturer (small sub-contract)

Motivation 1/3: Frame Rate

Alphacore's image sensor provides *50X higher Frame Rate* than existing rad-hard cameras used in Nuclear Energy applications. It also provides *Array Resolution vs Frame Rate Programmability*.

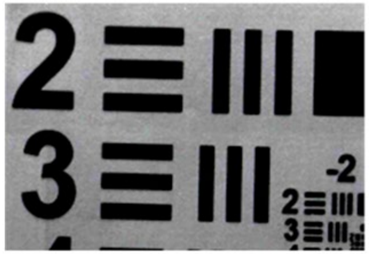
Selected Pixel Array Configuration	Frame rate [fps]		
	Alphacore Sensor A (1Mrad)	Alphacore Sensor B (1Grad)	Diakont D40 (200Mrad)
1,024 x 768	N/A	120	30 fps (eff.) for 728 x 492 (eff.)
640 x 512	1,500	288	
512 x 512	1,880	360	
384 x 384	3,330	640	
320 x 256	6,000	1,150	
256 x 256	7,500	1,440	

Motivation 2/3: Radiation Hardness

c)

d)

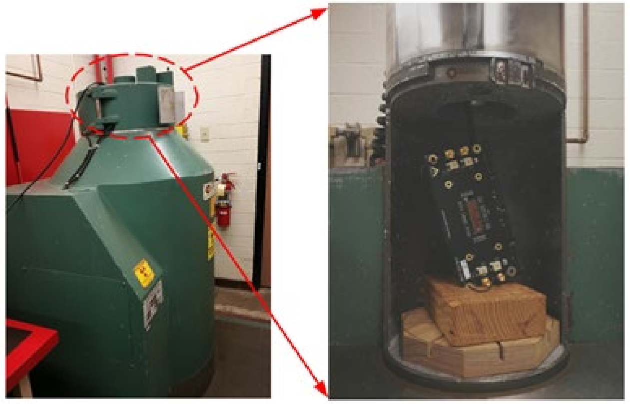
Radiation hardness of high-frame rate commercial cameras is poor

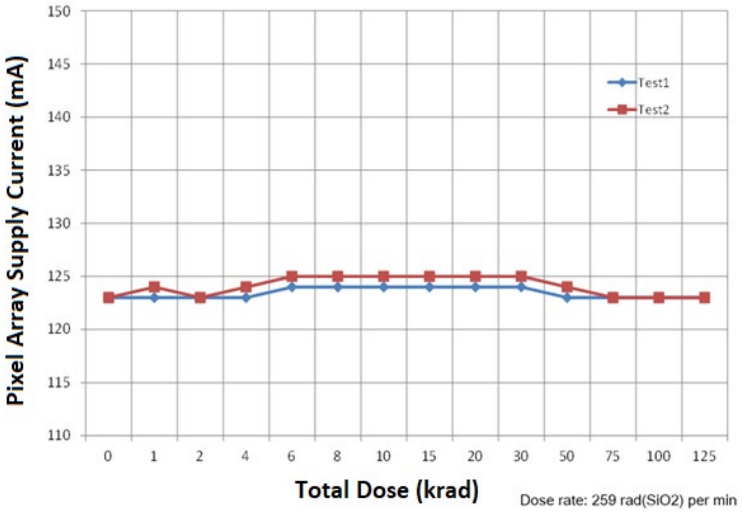


a)

b)

- **Figure a)** COTS high-speed camera image at 0 krad(Si).
- **Figure b)** Same sensor, after 3.2 krad(Si). Image degradation was seen already at 900 rads(Si).
- Custom-hardened cameras are needed for imaging in radiation environments.





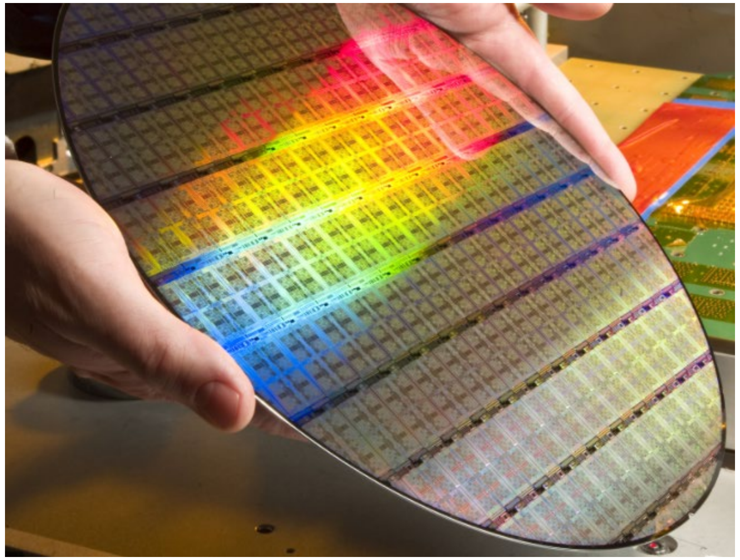
Alphacore's Rad-Hard Image Sensor

Figure c) shows Alphacore's high frame rate rad-hard image sensor prototype in the Gammacell Co60 radiation test chamber

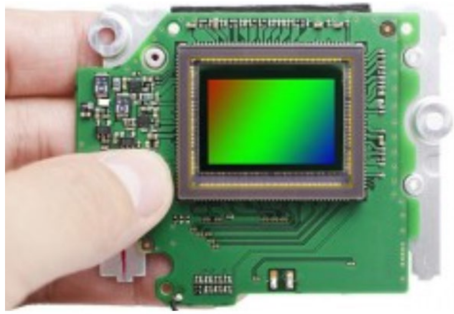
Figure d) shows no change in baseline pixel array current due to leakage during testing to 125 krad TID

Motivation 3/3: Upgrading Old Technology

Vidicon Tube used in radiation Hard Cameras



CMOS wafer



CMOS Image Sensor

Technology Impact

- Alphacore's image sensor and camera provide *50X higher Frame Rate* than existing ultra-rad-hard cameras used in Nuclear Energy applications. It also provides *Array Resolution vs Frame Rate Programmability*.

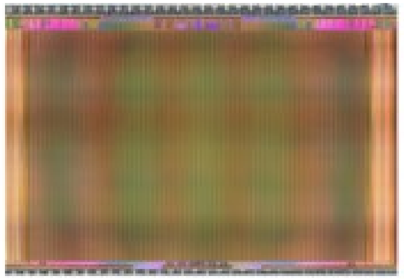
- Enables new types of tests/research in *Nuclear Reactor Research*.

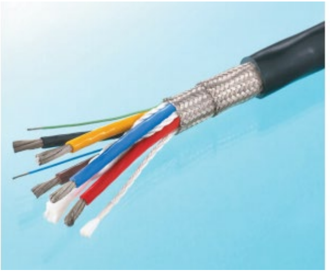
- Novel CMOS Image Sensor will be offered to the *Nuclear Facility Inspection/Monitoring* market sector. Higher performance, higher radiation hardness, better manufacturability and lower cost than existing solutions.

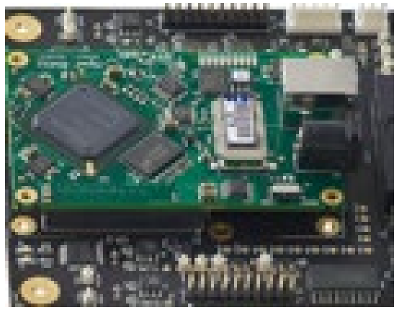
- Image sensor with potentially the highest level of radiation hardness will be offered to the booming *Space* market sector.

Accomplishments (1/3): Full System Architecture Development and Optimization

Good progress has been achieved in the development of all five system building blocks.







1) Image Sensor (CIS)
- Rad-hard 1Mrad – 1Grad
- 640 x 512
- 1.5 kfps
- *<u>Built-in signal interface capable of driving a long cable</u>*

2) Image Sensor enclosure and Optics
- Hosts Image sensor
- Rad-Hard Optics

3) Cable from CIS to Camera Board
- Rad-hard cable is needed.

4) Camera Board/System
- Receives high data rate from CIS
- Interfaces with a PC
- Non-rad-hard

5) Firmware and Hardware
- FPGA functionality
- GUI

Accomplishments (2/3): Rad-Hard High Frame Rate Image Sensor Development

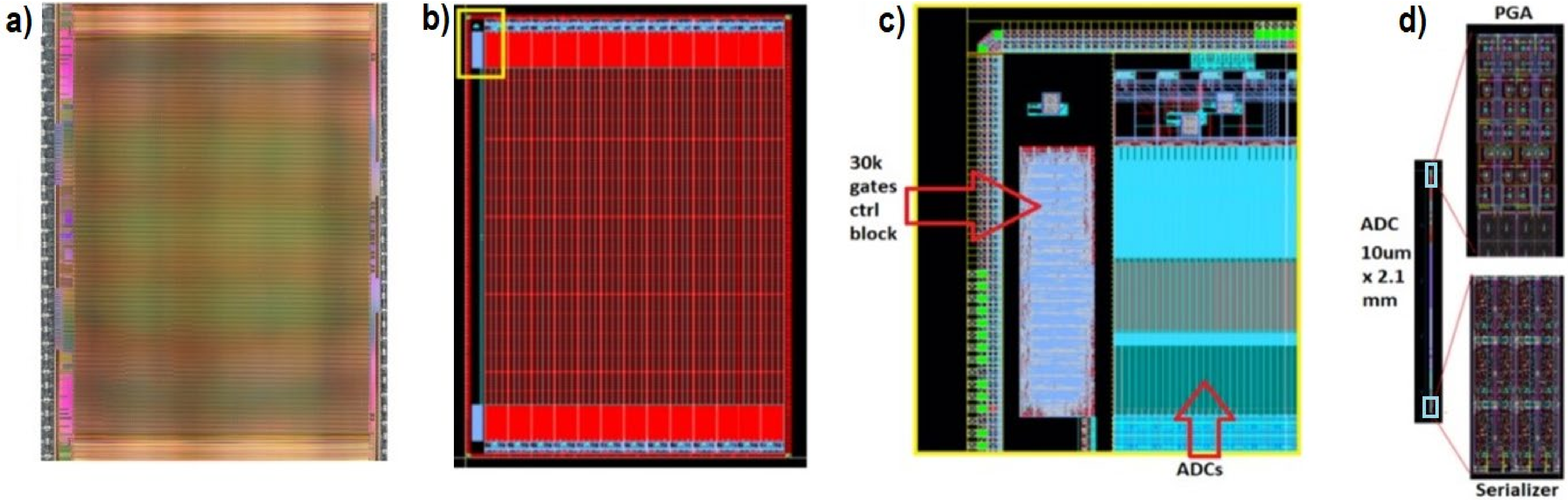


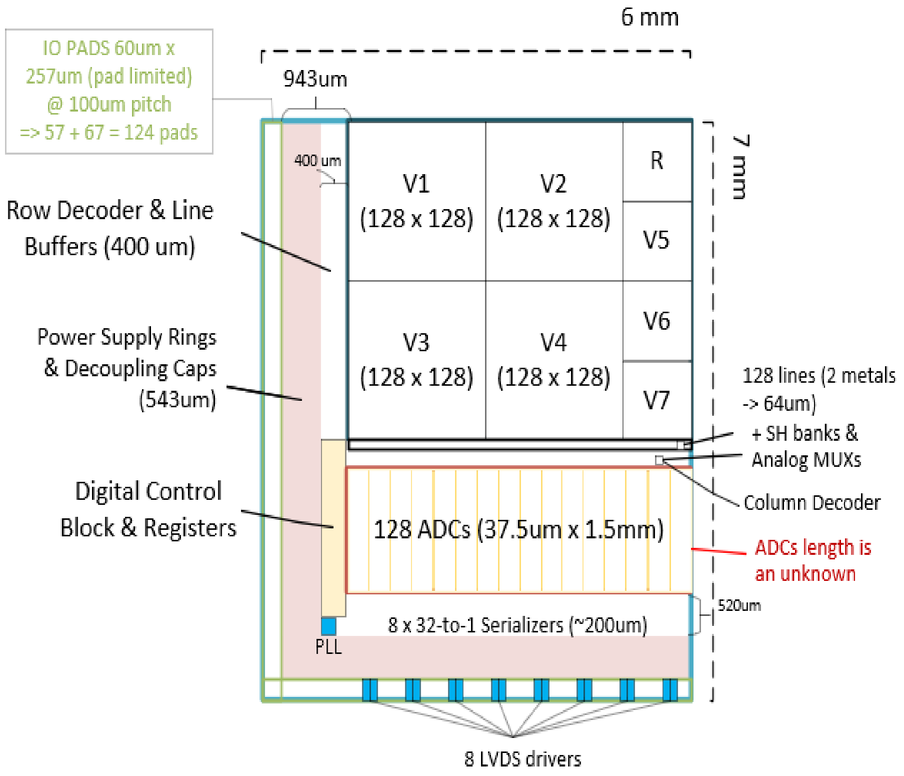
Image Sensor A) VGA (640 x 512)-pixel, 1,500fps, scalable radiation-hardened CMOS image sensor and full camera system. This camera provides 6,000fps at QVGA (320 x 256). Image sensor hardened to 1 Mrad.

Image Sensor B) XGA (1,024 x 768)-pixel, 120fps, scalable radiation-hardened CMOS image sensor and full camera system. This camera provides 1,150fps at QVGA. Image sensor hardened to **1 Grad**.

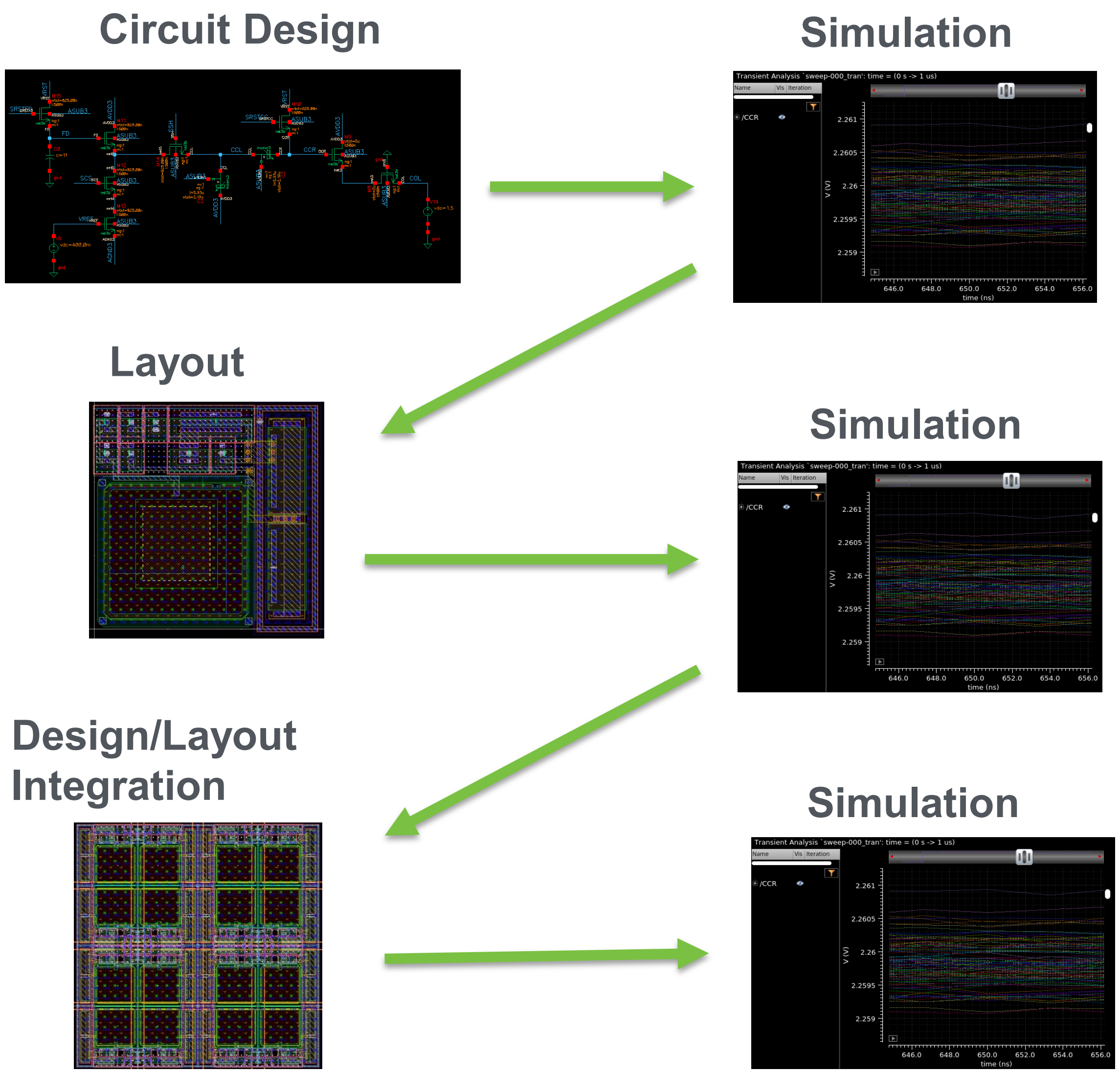
- Sensor #B1: Analog signal output interface
- Sensor #B2: Digital outputs (ultra-rad-hard ADC included on the chip)

Accomplishments (3/3): Test Chip Development

Engineering Wafer Fabrication Run for four Image Sensors scheduled for early 2022.

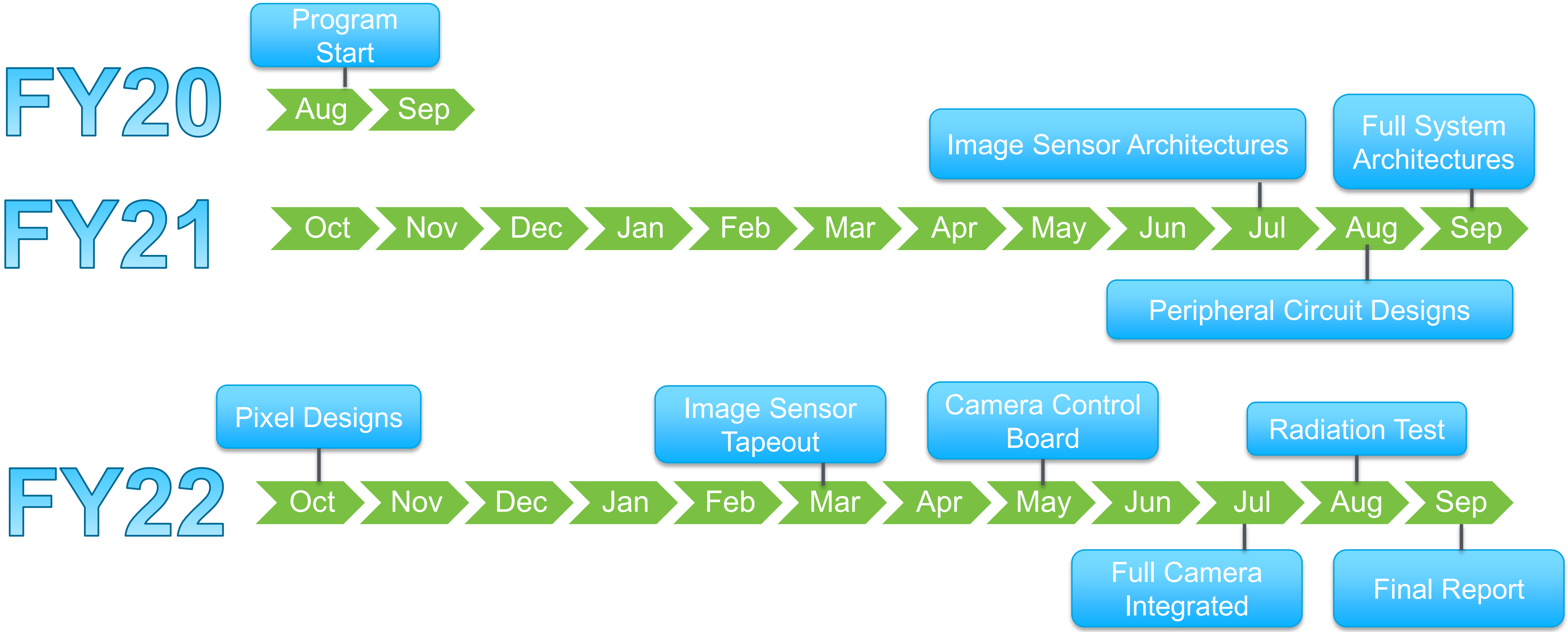


Floorplan: High Frame Rate Image Sensor, One Quarter, Test Pixels



Project Schedule

Timeline of activities in FY-21 and FY-22



Summary

- Alphacore's image sensor and camera provide *50X higher Frame Rate* than existing ultra-rad-hard cameras used in Nuclear Energy applications. It also provides *Array Resolution vs Frame Rate Programmability*.
- Enables new types of tests/research in *Nuclear Reactor Research*.
- Novel CMOS Image Sensor will be offered to the *Nuclear Facility Inspection/Monitoring* market sector. Higher performance, higher radiation hardness, better manufacturability and lower cost than existing solutions.
- Image sensor with potentially the highest level of radiation hardness will be offered to the booming *space market sector*.
- Alphacore has made good progress on all five technical areas of the program: Rad-hard Image Sensor, Enclosure/Optics, Rad-hard Cable with rad-hard Interface Circuit, Camera Control Board and Firmware/Software.
- Image Sensor Tapeout Scheduled for March 2022.
- Full camera will be integrated and evaluated by September 2022.

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esko.mikkola@alphacoreinc.com

Context-Aware Safety Information Display for Nuclear Field Workers

Principal Investigator: Dr. George Edward Gibson, Jr., Arizona State University
Co-Principal Investigator: Dr. Pingbo Tang, Carnegie Mellon University
Co-Principal Investigator: Dr. Alper Yilmaz, The Ohio State University
Collaborator: Dr. Ronald Laurids Boring, Idaho National Laboratory
Collaborator: Mr. Thomas Myers, Duke Energy

Presenter: Pingbo Tang

November 2021

Operation of Nuclear Power Plant

Predefined lists of information that need to be verified or collected

Inaccurate

Communicate/ report the collected information

Field operator

Control room operator

Human errors, miss critical information or collect wrong information

Operator rounds - Collect information
e.g., Component status, Temporary modifications in the field

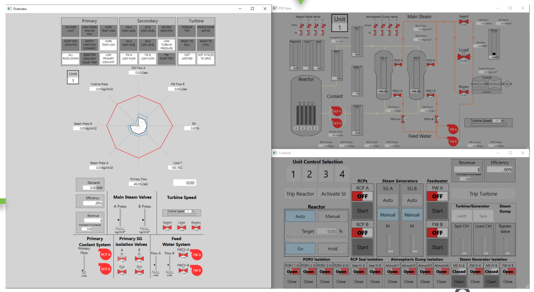
Control decision making and execution

Sensor data are not reliable, some information can’t be captured by sensors

Information collected by field sensors

Control signals

Nuclear plant field



Control room

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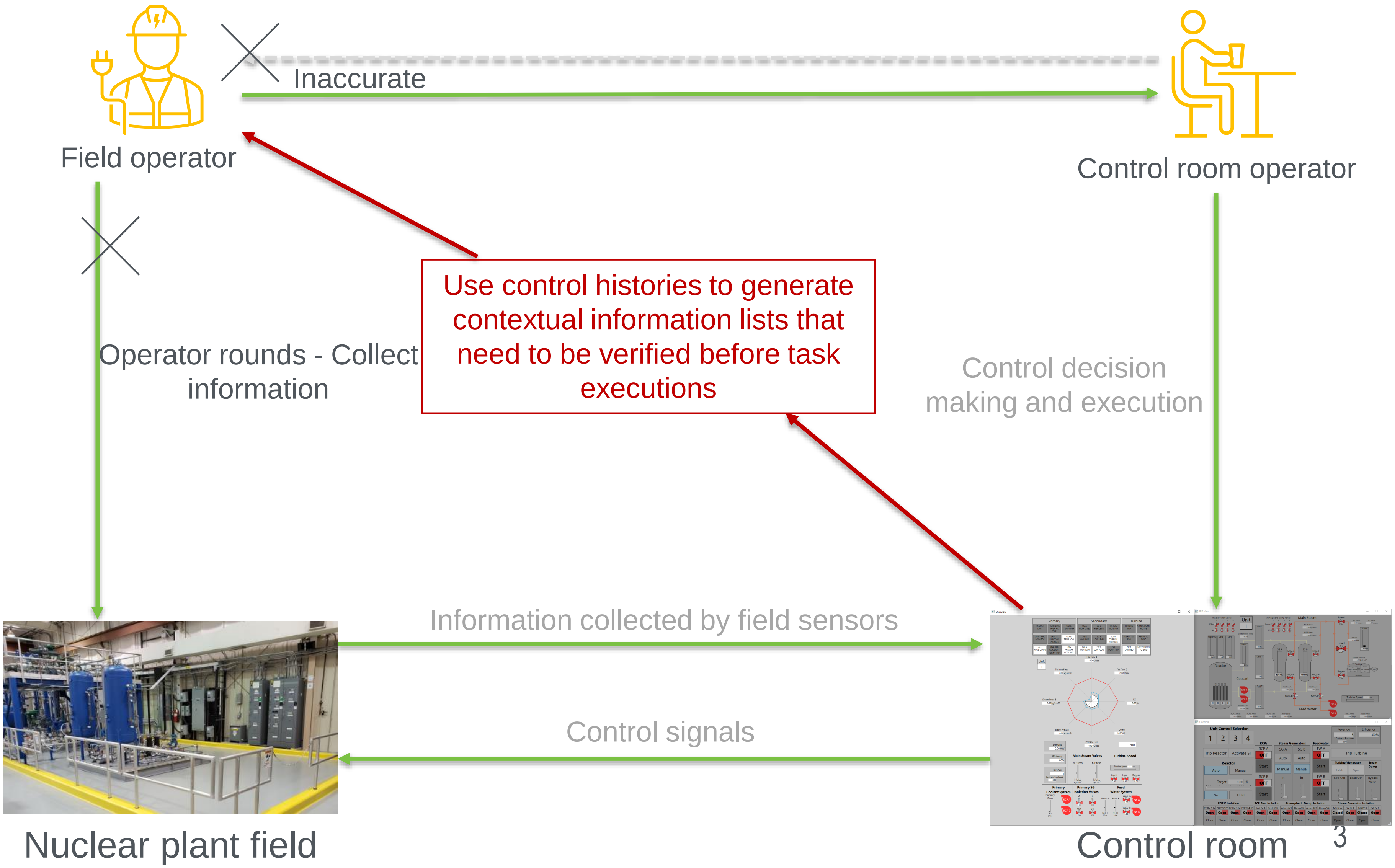
Clean. Reliable. Nuclear.

Operation of Nuclear Power Plant



Identifying Field Operators’ Needs

Field operator

Operator rounds - Collect information
e.g., Component status, Temporary modifications in the field

Operator Navigation

- Locate and navigate operators to targeted work locations

Highlight Critical Objects

- Identify critical sensors associated with each steps

Flow Trend Prediction

- Predict the likely condition of a typical flow and detect anomalies

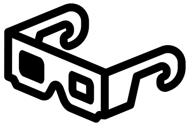
Nuclear plant field

Information matching

Information matching

Computer vision

Information display



Augmented Reality Glasses

Intelligent Context-Aware Safety Information Display

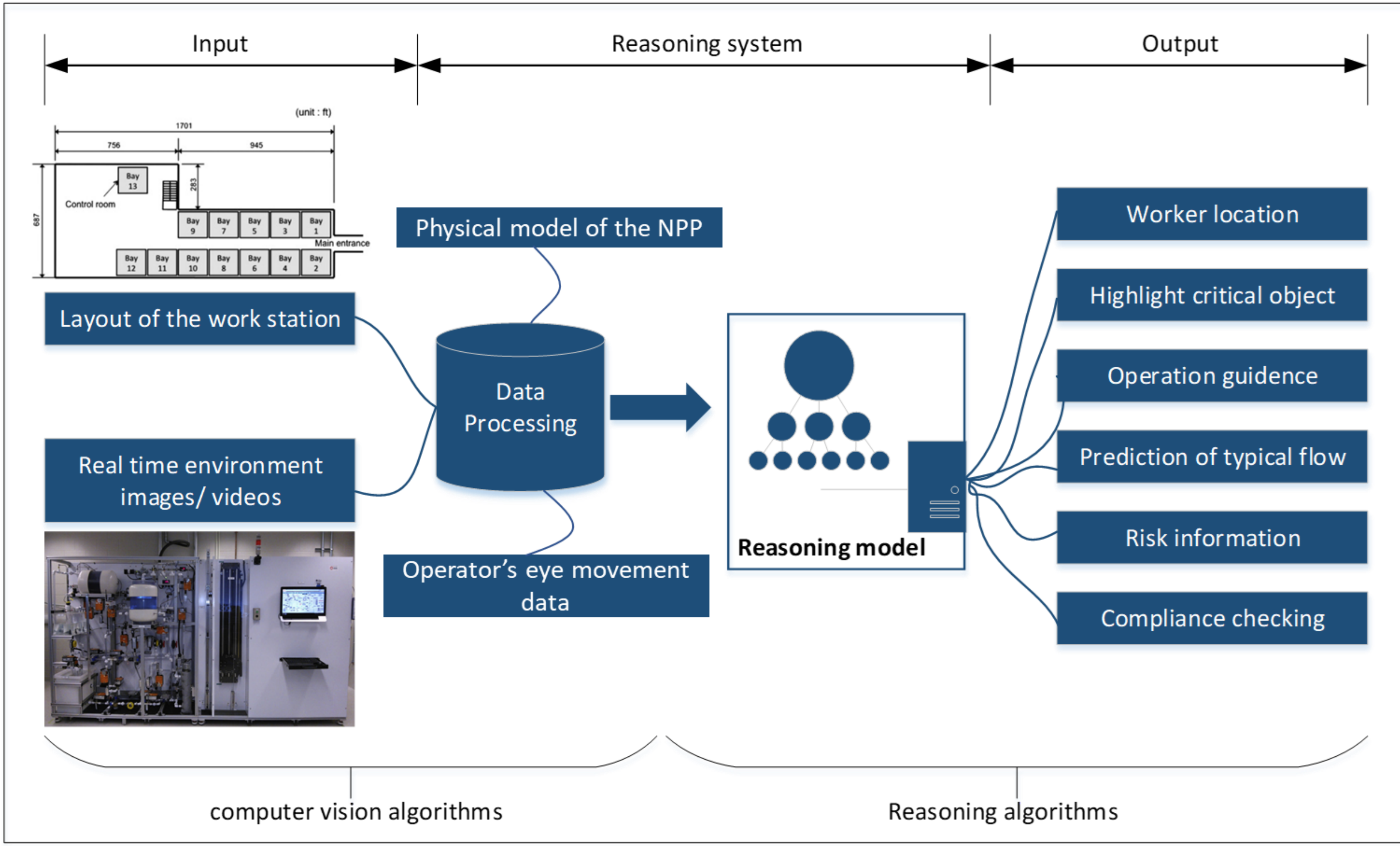
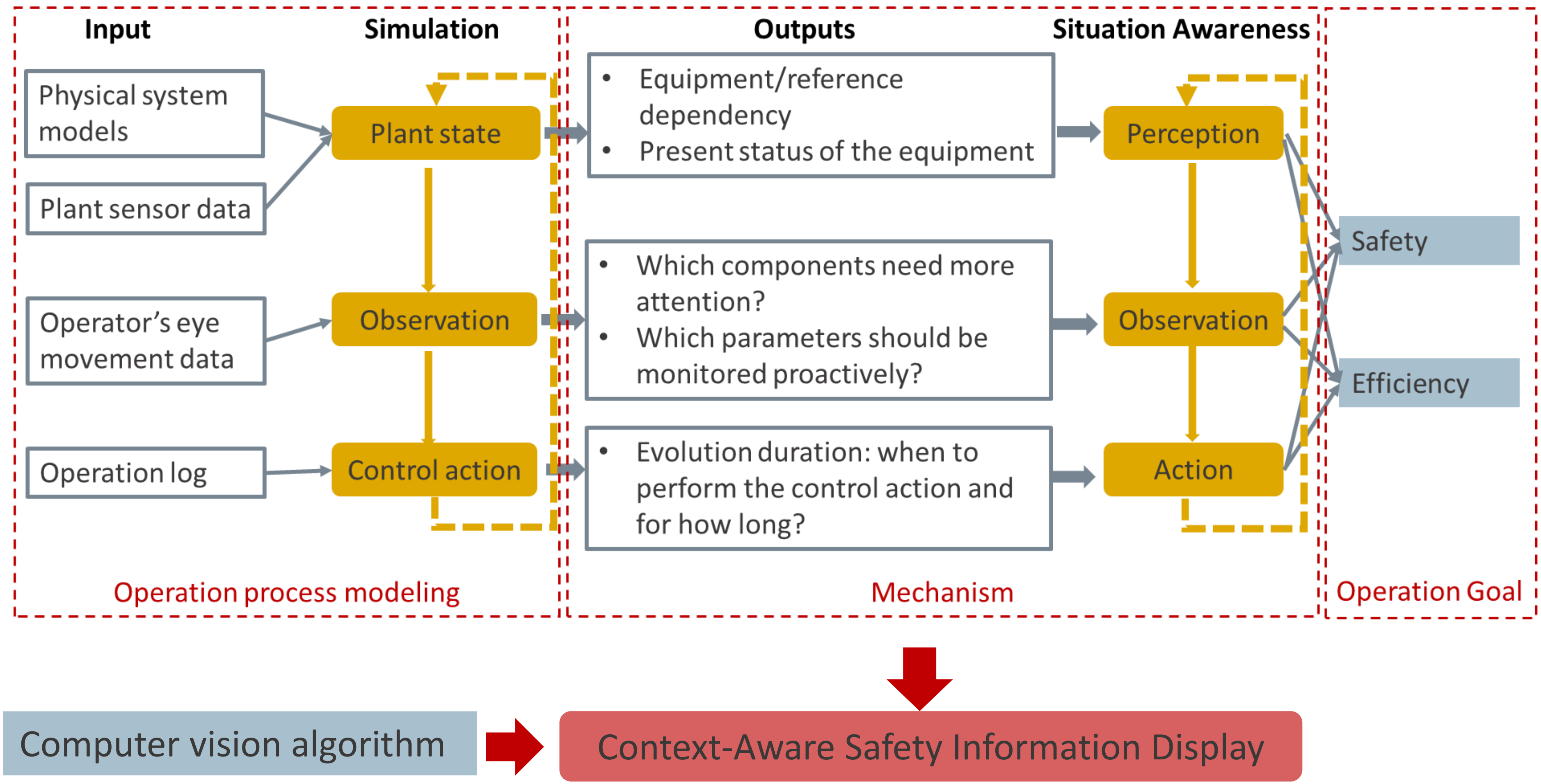


Fig.1. A conceptual framework of the "Intelligent Context-Aware Safety Information Display" (ICAD) system

Context-Aware Safety Information Reasoning



Safety Control Object Detection: Computer Vision

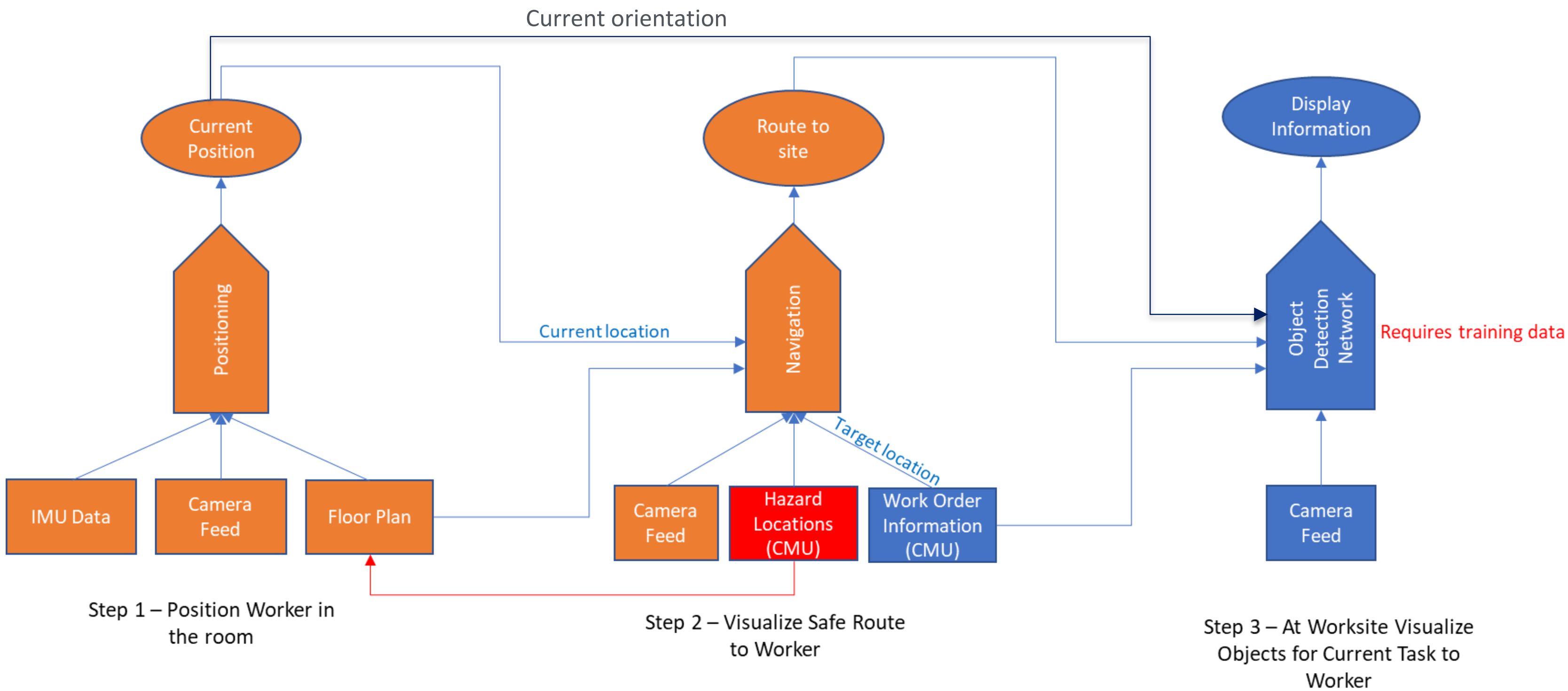


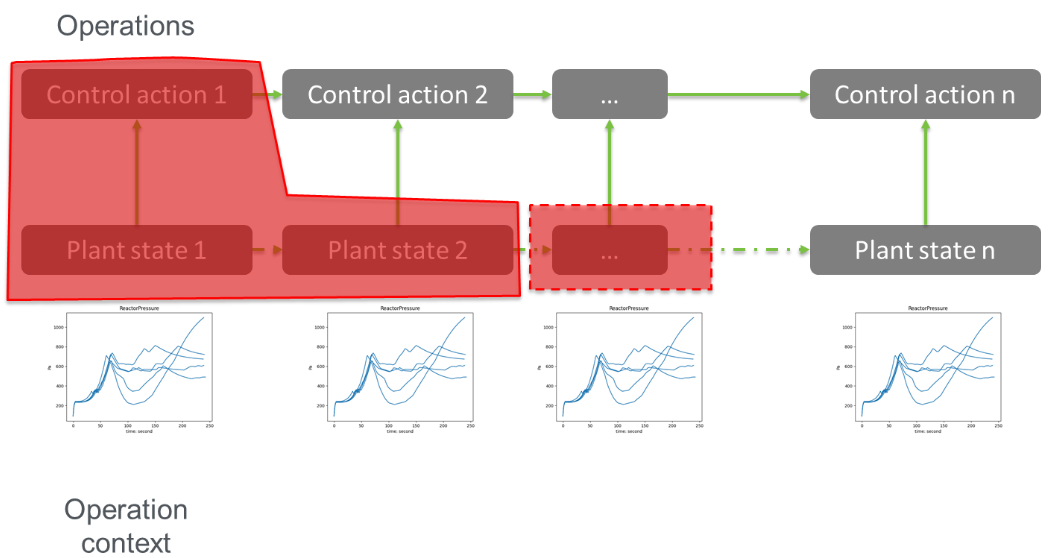
Fig. 2. Computer vision algorithm

Worker location → Safe path navigation → Critical object detection

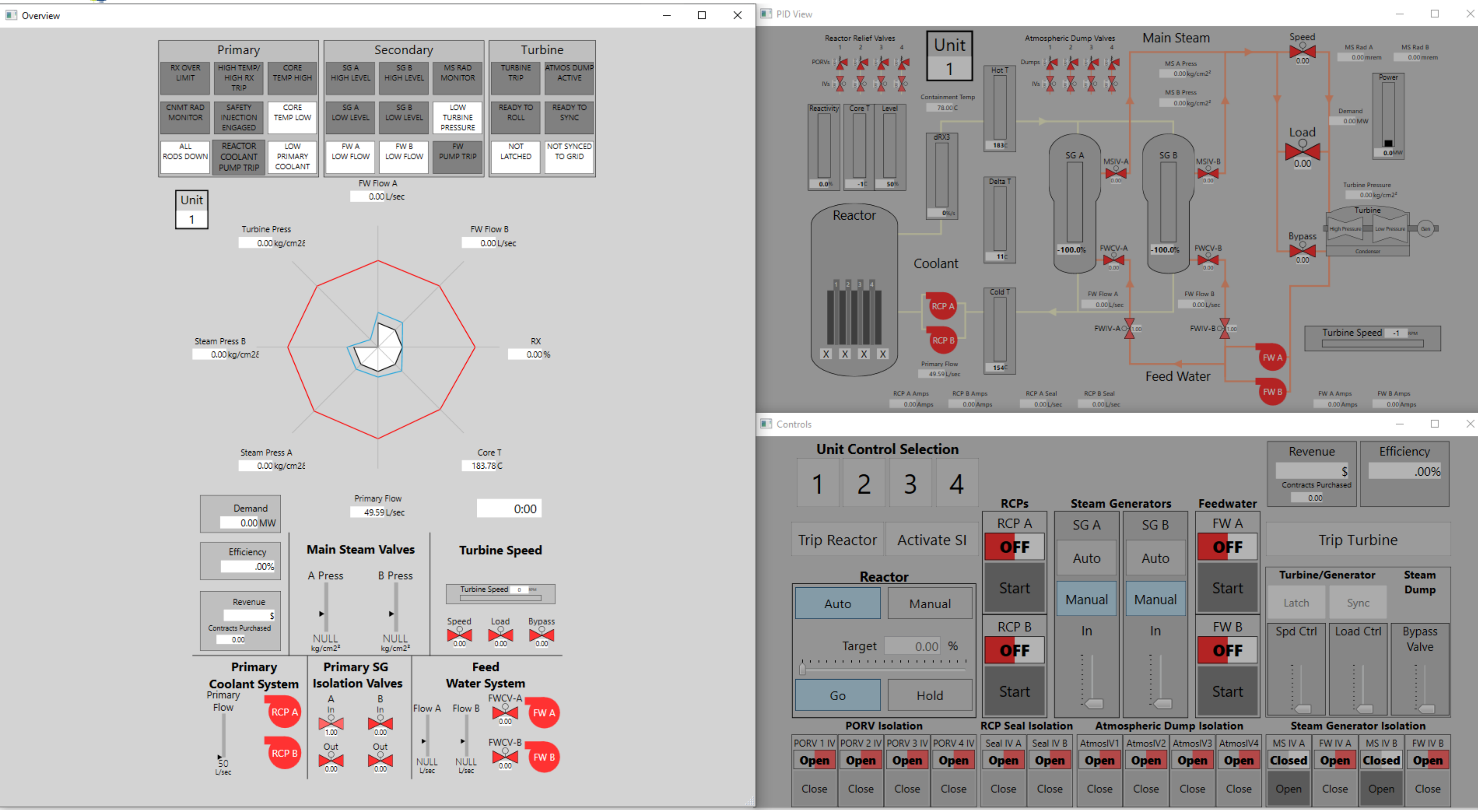
Context-aware Operations

Operation histories

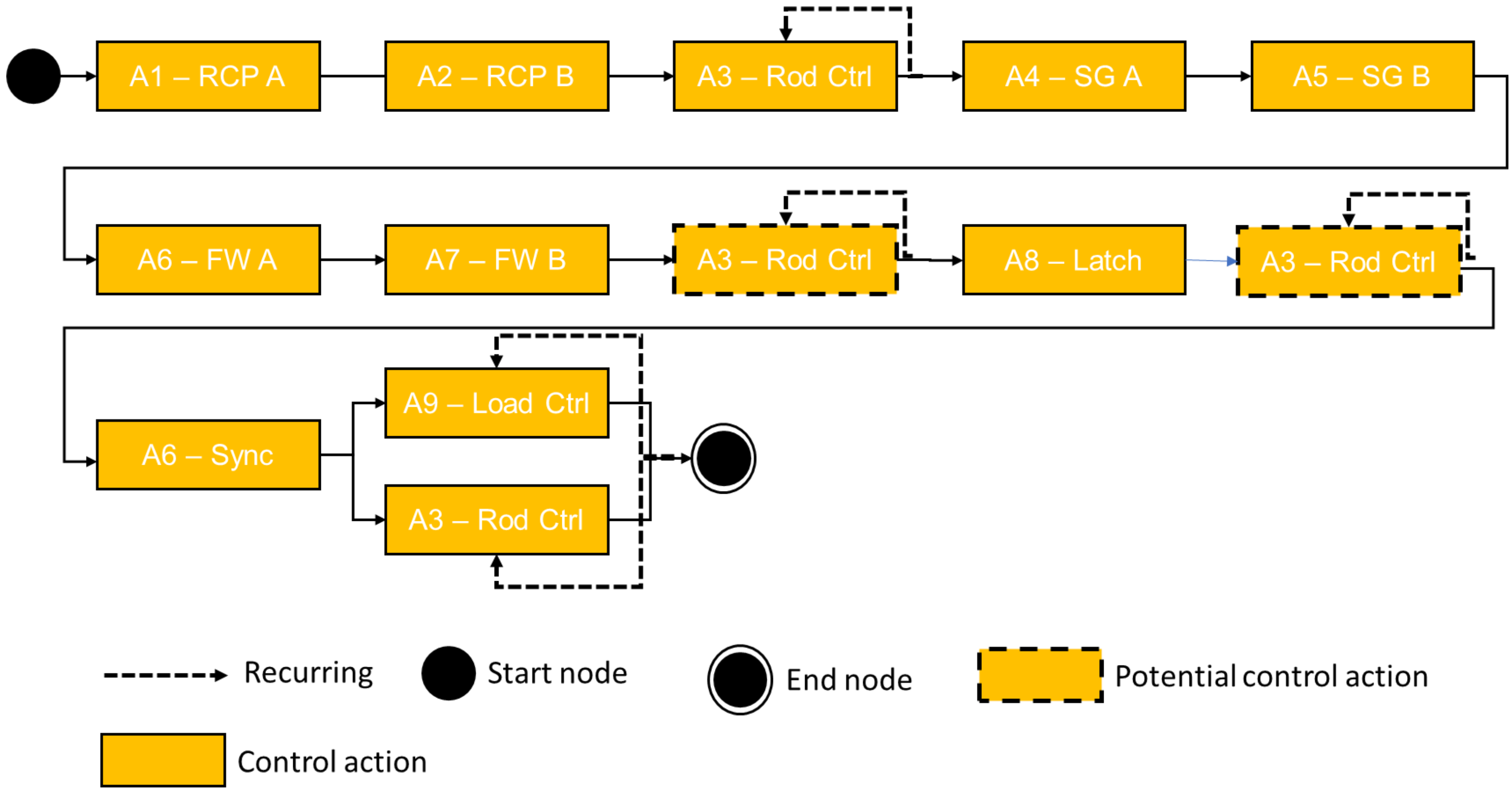
- Learn possible control action sequences from operation history
- Determine when to perform control action:
  - When single sensor reached a setpoint
  - When a combination of several sensors form certain patterns
- Build a model to predict when the operator should perform what type of control actions



Physical System Simulator: Rancor

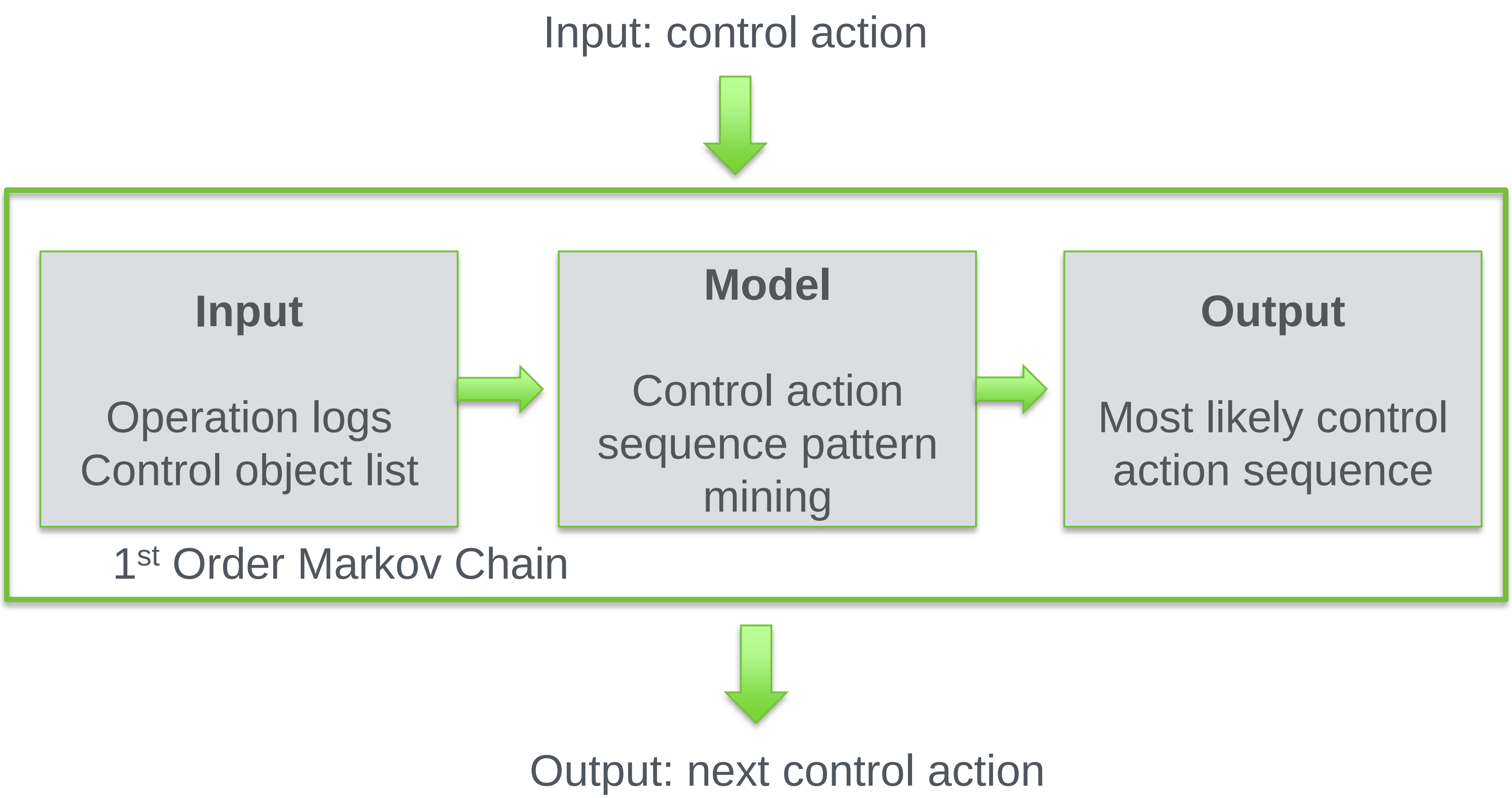


Experiment: Reactor Startup



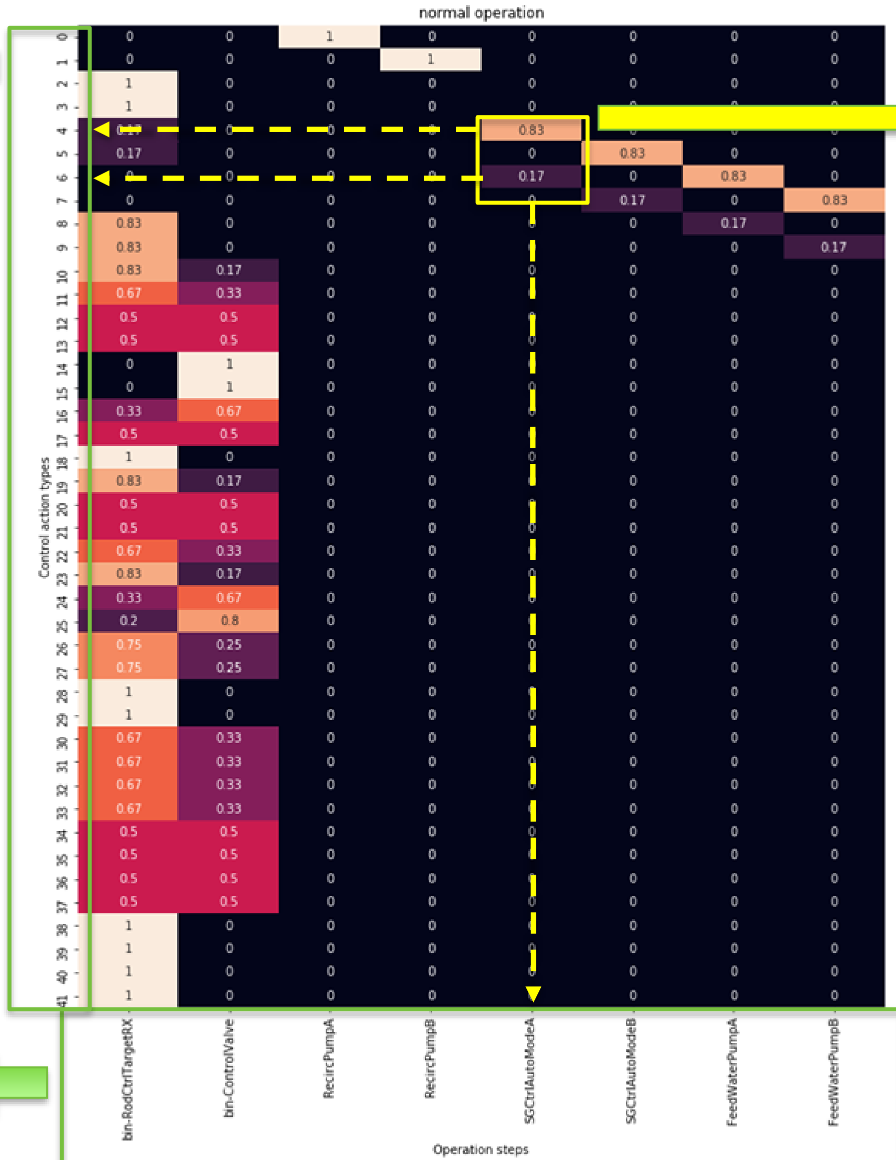
Workflow structure for the startup task

Control Action Sequence Generation



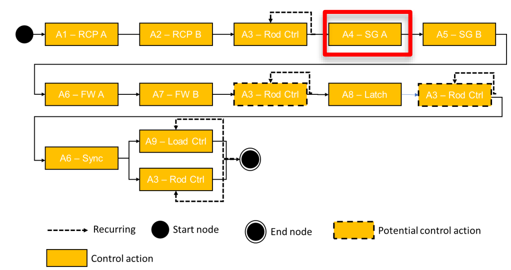
Control Action Sequence Generation

Control action order

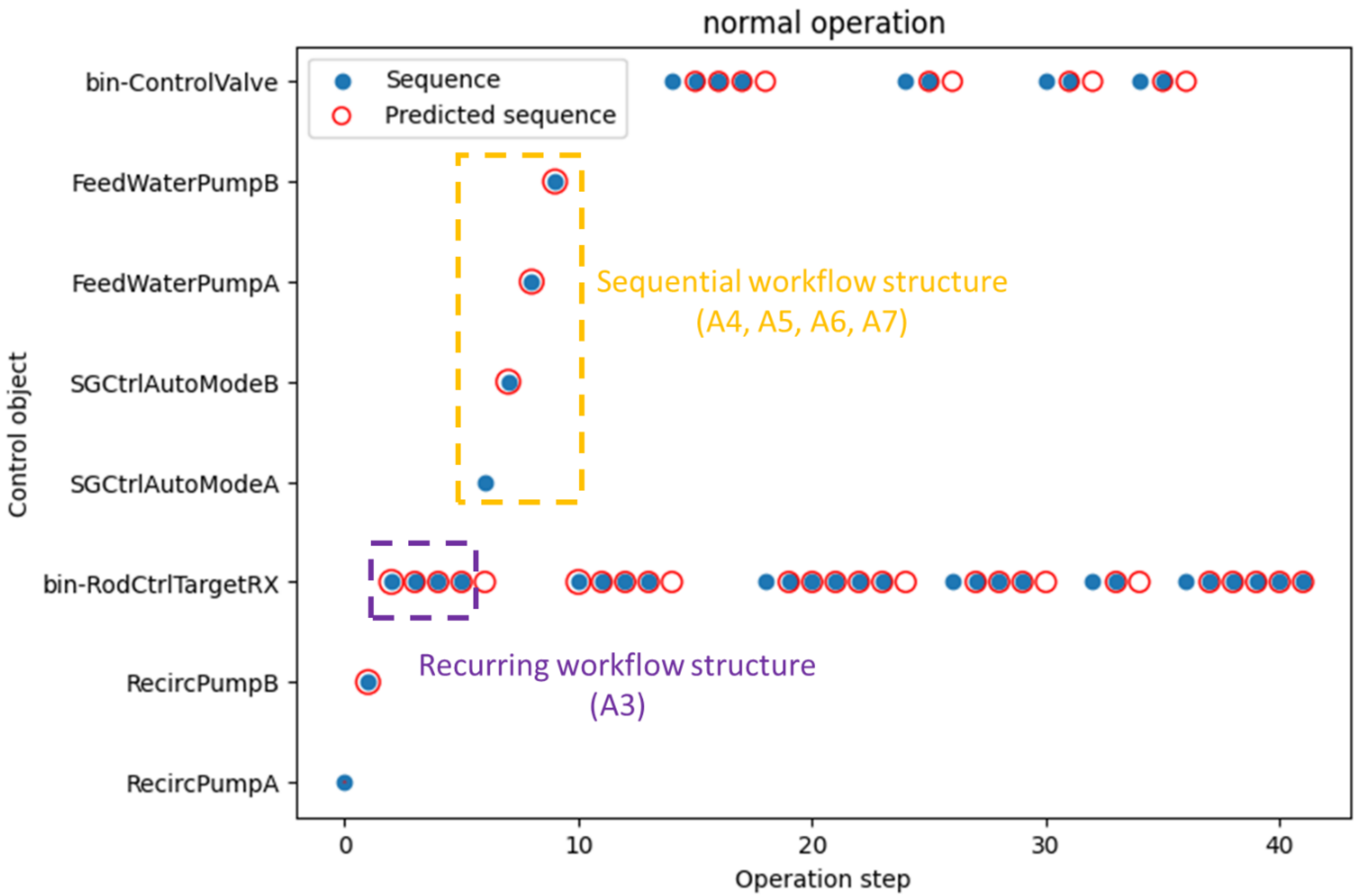


Control object list

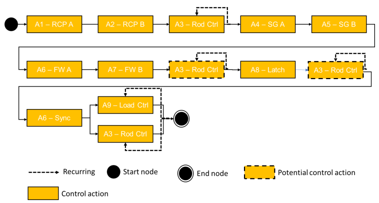
In the experiment, 83% of the operators perform steam generator A control at step 4, and 17% at step 6.



Control Action Sequence Generation

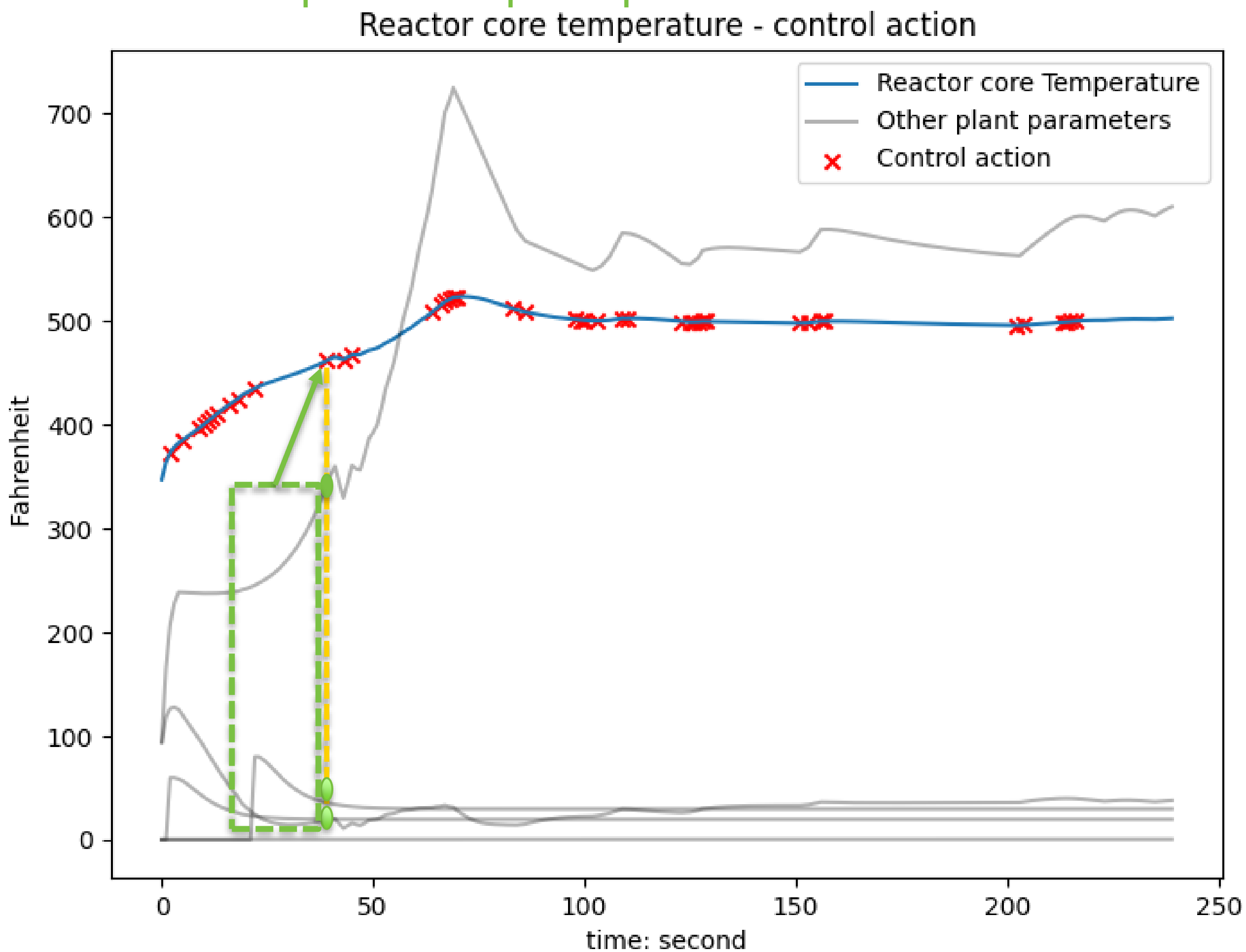


The predicted control action sequence



Operation Context Modeling

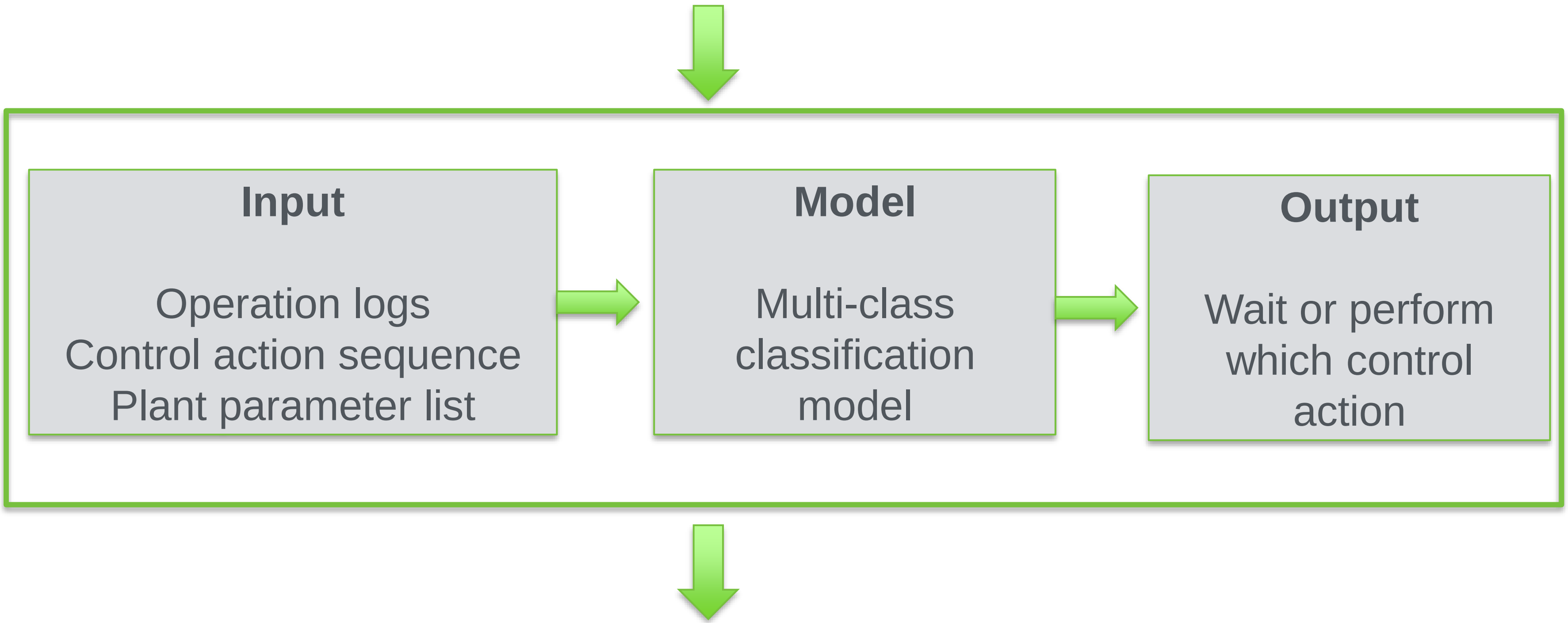
- The baseline model: point to point prediction
- Time window model: sequence to point prediction



Operation context

Operation Context Modeling

Input: Plant parameter(s)



Output: wait or perform which control action

Operation Context Modeling

Input: 5 reactor startup operation logs

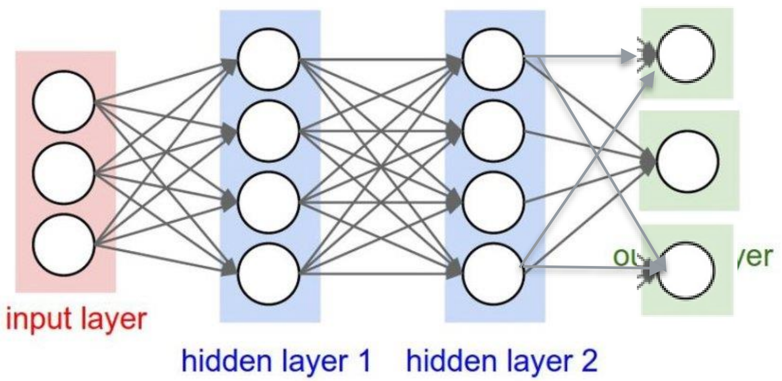
↓

Data normalization

↓

Feature selection - F score analysis

↓



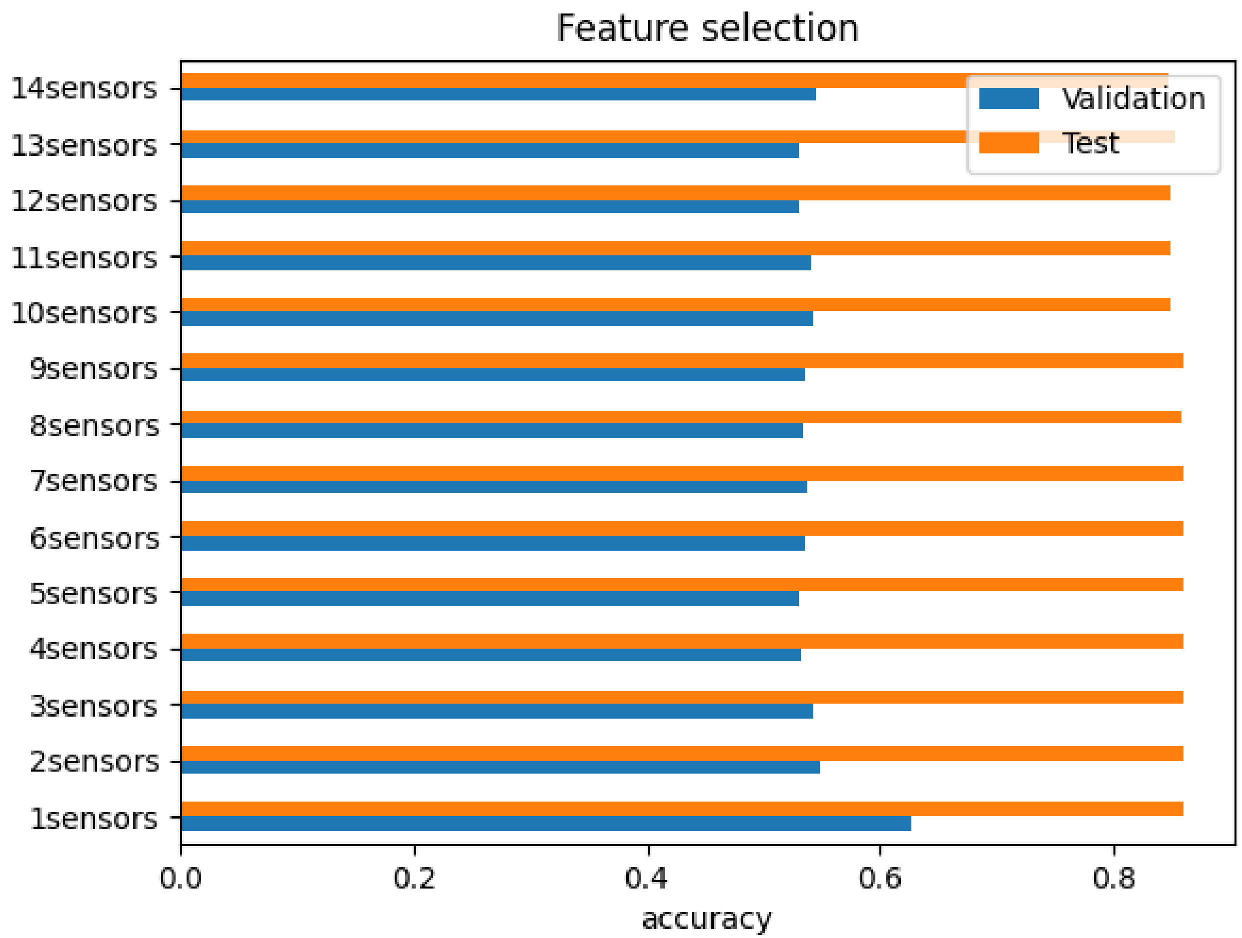
sensors | 64 units | 64 units | 11 units

CNN

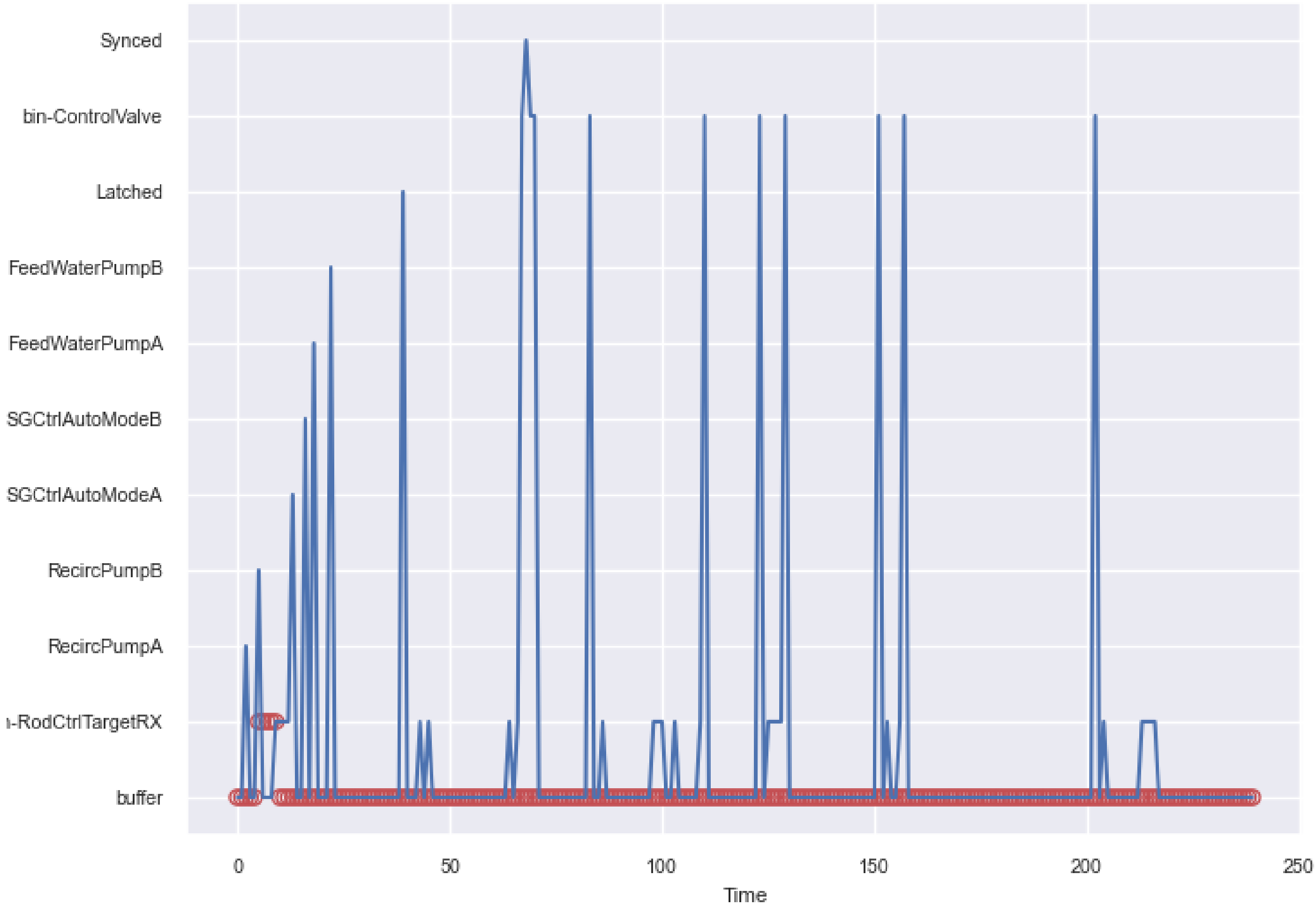
Operation Context Modeling

Prediction accuracy:

- When selecting one sensor (DelteT), the validation and test have the highest prediction accuracy.



Operation Context Modeling



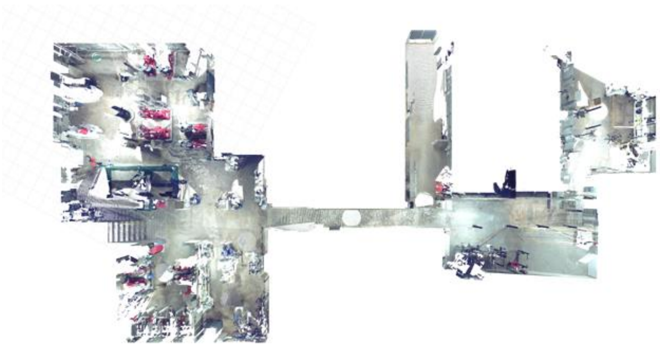
Context based control action prediction

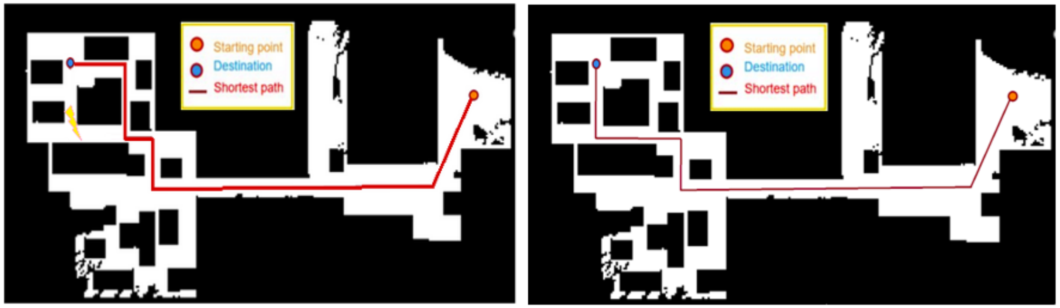
Computer vision - Navigation

- Navigation pipeline:
  - Positioning
  - Path planning
- The worker positioning part provides instantaneous rotational and positional information w.r.t an arbitrary coordinate system
  - Operating on images and inertial measurements
- The path planning part uses that information to generate the shortest path between starting and destination points
  - Considering safety constraint provided through the labelling on the map of the environment

Computer Vision - Navigation

- While the second part operates on maps

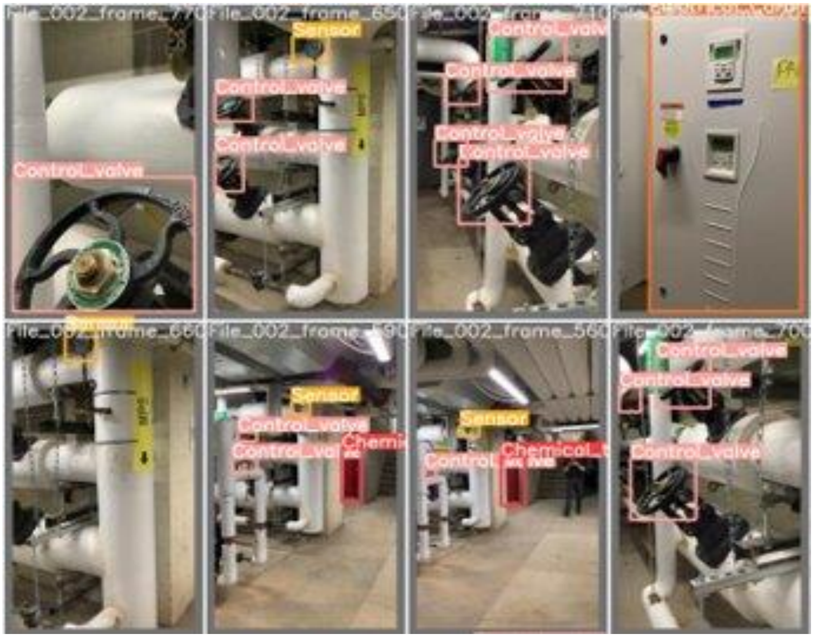




- In progress on navigation side:
  - Transferring the navigation to Robot Operating System (ROS)
    - ROS nicely integrates on different hardware
  - Using a 3D laser scanning and video navigation dataset collected in a mechanical room for ROS development
  - Integration of two parts of the navigation algorithm

Computer vision – Object detection

- The developed method were trained on a limited number of dataset (1500 manually labelled frames) including:
  - Chemical tanks
  - Control valves
  - Sensors
  - Electrical carbines and etc.



- The model leverages from transfer and semi supervised learning scheme

Computer Vision - Findings

- The object detection algorithm trained in mechanical rooms and water treatment plant's data can work on video data collected from nuclear training facilities
  - We can use industrial control facilities having similar environments as nuclear power plants to produce computer vision models suitable for nuclear applications
  - Caveat: if the environment drastically differs from what the model was train on both in terms of structure and objects in the scene, the accuracy will be dropped significantly
- Nevertheless, the accuracy achieved on the Duke Energy' training facility data set is 95%.

Computer vision

- Model transferring capability
  - Example of the model performance trained on water plant dataset but applied to the duke energy power plant

Conclusion and Future work

Conclusion

- A process data analysis methods:
    - Aim to capture and analyze control histories in order to identify critical control objects' states and evolutions in different operation scenarios.

- Developed and tested computer vision techniques:
    - Aim to support NPP field operator positioning, navigation, and real-time detection of process-safety-critical objects

Conclusion and Future work

Future work

- Context-aware reasoning:
  - Improve the performance of process analysis by integrating the control action sequence model and operation context model.
  - Include field operator’s eye movement into the reasoning model to infer the field control objects that need the most attention.

- Computer vision:
  - Improve the model's performance on previously unseen power plants
  - Dynamically safety path planning: improve the integration between object detection and navigation

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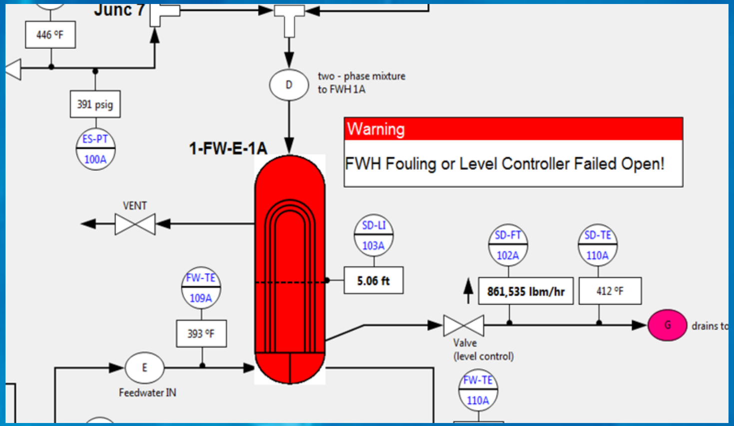
ASI Advanced Sensors and Instrumentation

Process-Constrained Data Analytics for Sensor Assignment and Calibration



Work Package ID: CA-18-IL-AN-0703-02

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar

November 15 – 18, 2021

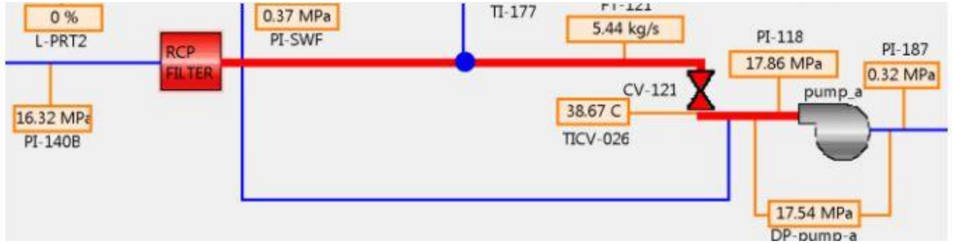
PI: Richard Vilim, PhD, Senior Nuclear Engineer

Argonne National Laboratory
University of Michigan
Xcel Energy

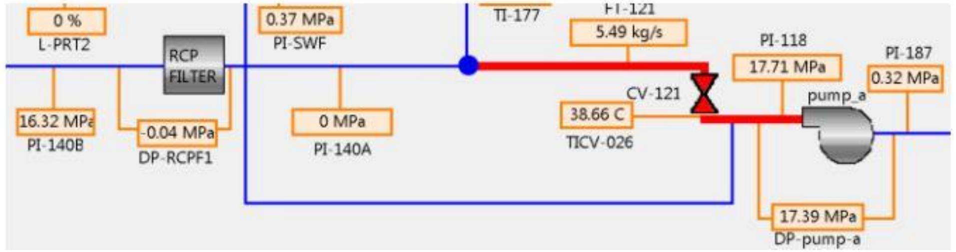
Project Overview

Objectives

- How to select a sensor set for equipment and sensor health monitoring for advanced O&M tasks?
  - Given a list of faults to be diagnosed to a prescribed degree of spatial resolution, find the sensor set that will accomplish this goal at the least cost
- Incorporate domain knowledge (physics-based digital twin) to provide for
  - Virtual sensors to reduce physical sensor requirements
  - More reliable and explainable diagnoses



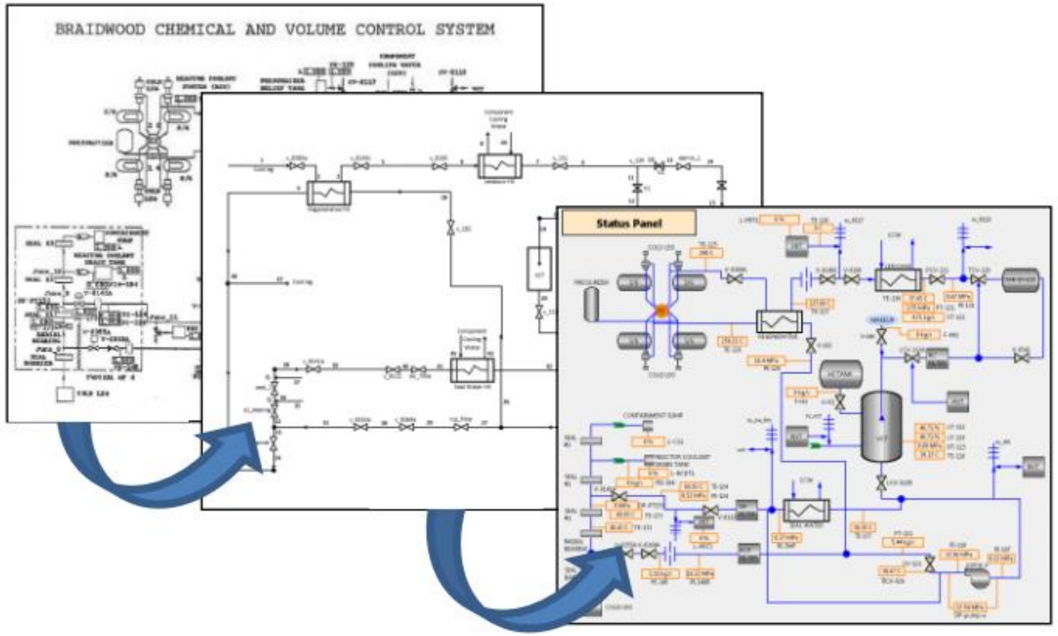
Increased fault spatial resolution obtained by addition of sensors



Project Overview

Approach

- Diagnostic Algorithm - Digital Twin based
  - Use automated reasoning to look at difference between digital twin prediction and what sensors are reporting
  - Digital twin constructed from domain knowledge and represents components communicate with each other providing richer information than components treated in isolation
- Sensor Assignment Algorithm
  - Iteratively call diagnostic algorithm
  - Assignment of sensors is cast as a mixed-integer programming (MIP) problem where a sensor in a specific location is 0 or 1
  - Minimize the cost of satisfying a set of diagnostic objectives for a given set of sensors



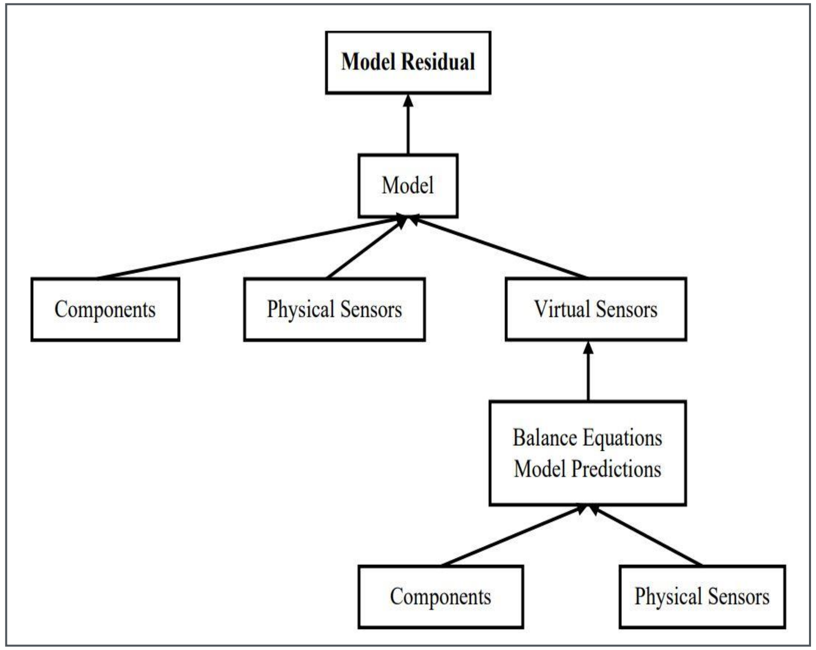
Creation of Physics-Based Digital Twin from P&ID

Project Overview

Schedule

FY20

Methods and Algorithm Development



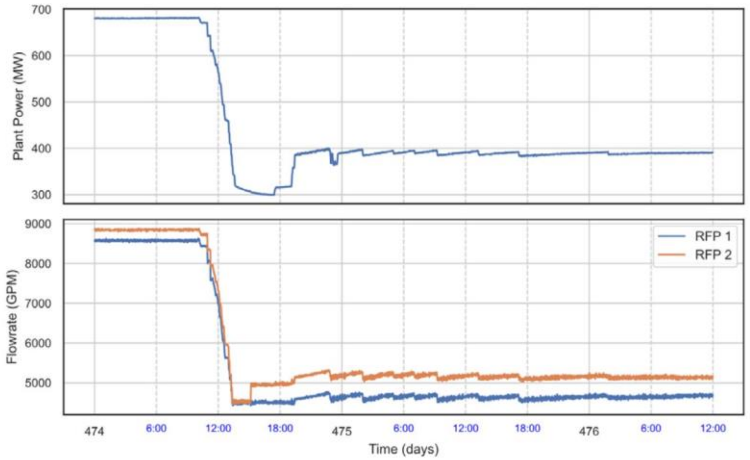
FY19

Analysis and Sensitivity Studies

Residuals	Component Faults			Sensor Faults				
	Motor	Bearings	Pump	P_m	I	n	Q	p_{in}/p_{out}
$r_{m,P}$	1	0	0	1	0	1	0	0
$r_{m,I}$	1	0	0	0	1	1	0	0
$r_{p,\Delta p}$	0	0	1	0	0	1	1	1
$r_{c,P}$	1	1	1	1	0	1	1	0
$r_{m,P2}$	1	0	0	1	1	0	0	0
$r_{c,P2}$	1	1	1	1	0	1	0	1

FY21

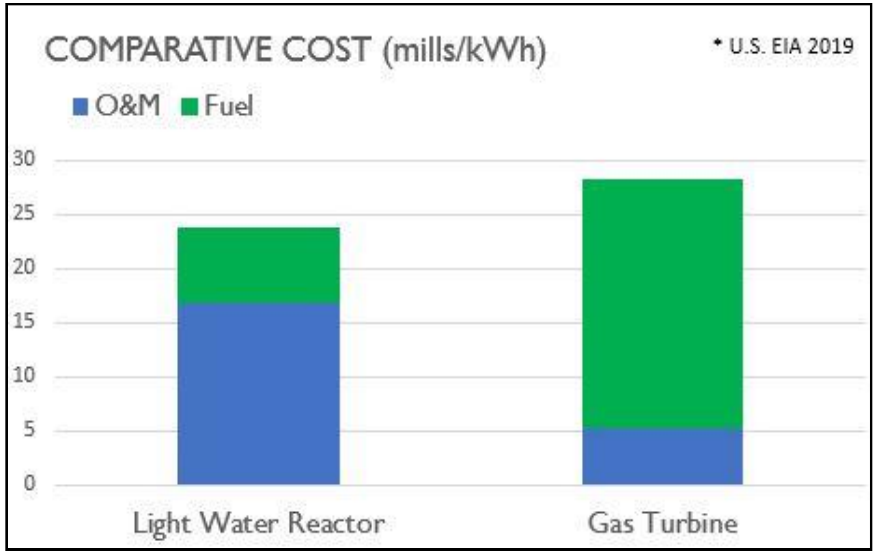
Demonstration with Utility Data

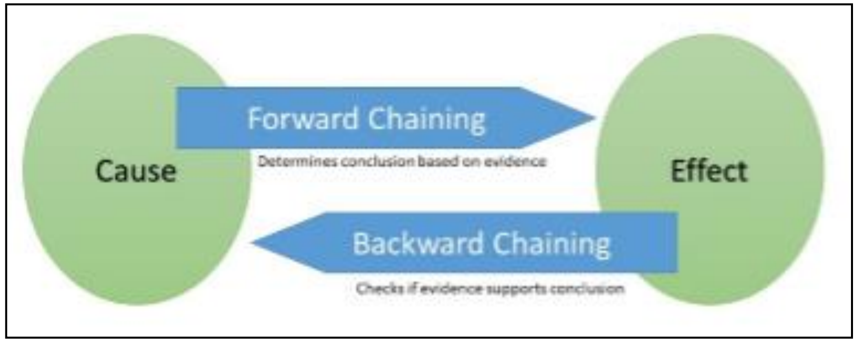


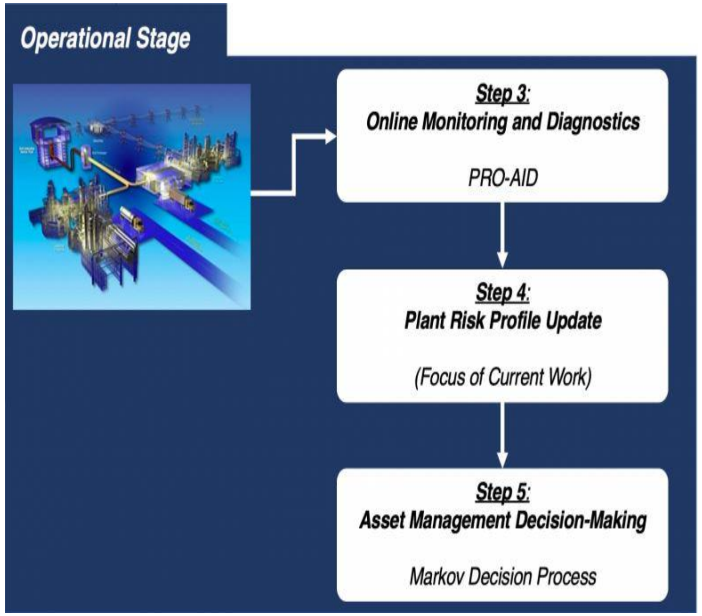
Technology Impact

Industry Interest

- Advanced reactor developers are looking at streamlining O&M procedures
- Our approach realizes explainable condition-based monitoring
- Enables transition to predictive from periodic maintenance for improved scheduling







Technology Impact

Advantages of Physics-Based (PB) Digital Twin

- Overcomes problems of pure Data Driven (DD) approach
- Improves business case

Supports the Nuclear Industry

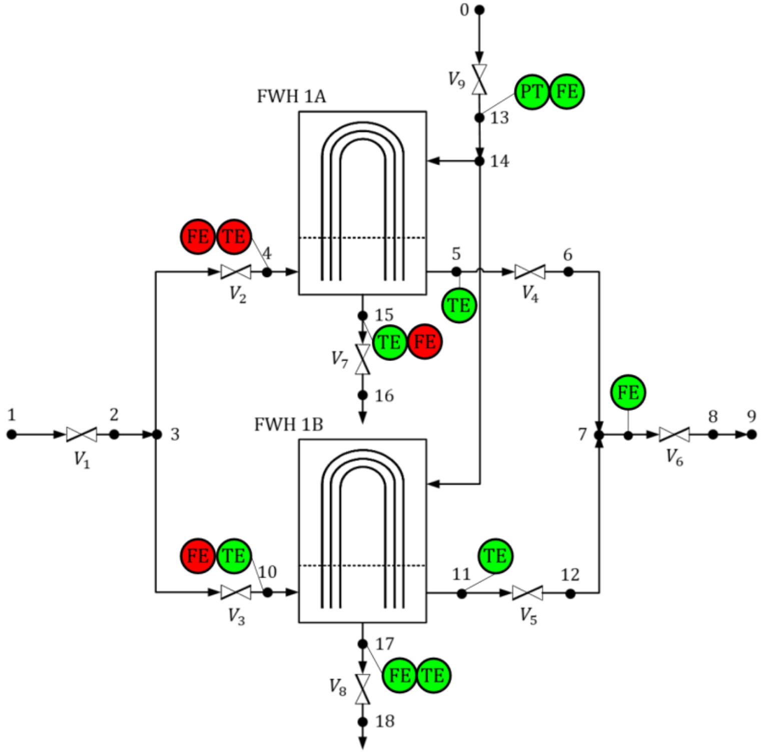
- Lifetime extension applications for life beyond 80 are being planned for with digital upgrades
- Understanding how the selection of an upgraded sensor set contributes to improved monitoring and control can provide for more informed staffing reductions and reliable operation.

CAPABILITY	DD	PB
Immune to operating point change?	N	Y
Diagnosis resolved to specific fault?	N	Y
Rank ordering of likelihood of faults?	N	Y
Applicable to engineering systems?	—	Y
Free of need for library of fault signatures?	N	Y
Generates virtual sensors?	N	Y
Adapts upon dropped sensor?	—	Y
Yields component performance index?	N	Y
Supports design of optimal sensor set?	N	Y

Results and Accomplishments

1. Developed virtual sensor capability for an engineered system based on the concept of a physics-based digital twin

- Combined with physical sensors, provides for richer set of measurements with which to make diagnoses
- Description of engineered system taken from the Piping & Instrument Diagram (P&ID)
- Decompose engineered system into building-blocks whose operations can be described by first principles
- Each of these models may contain one or several parameters left to be determined by fitting against plant data



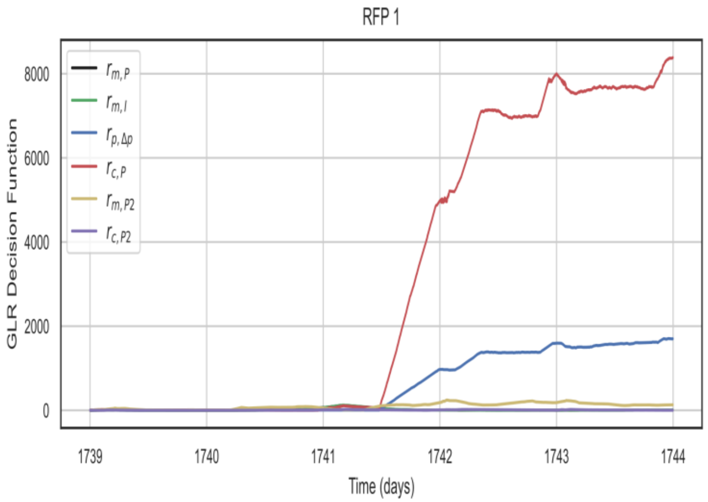
Optimal sensor set (green) and virtual sensors (red) created in PRO-AID

Results and Accomplishments

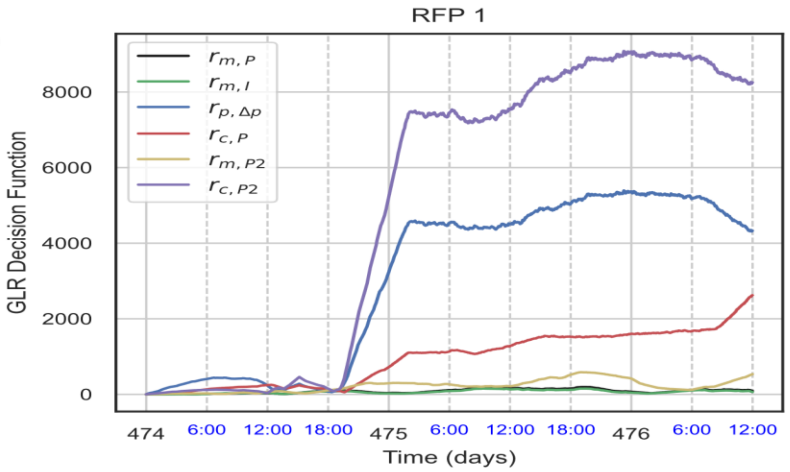
2. Diagnosed blind faults in utility data for feedwater pump-motor set

- Utility collaborator provided plant data for three blind events
  - Plant load change only; no fault
  - Flow straightener breakoff damaging impeller
  - Bias of 2% on pump flow measurement
- Successfully diagnosed all events

Flow sensor bias correctly diagnosed



Impeller performance degradation correctly diagnosed

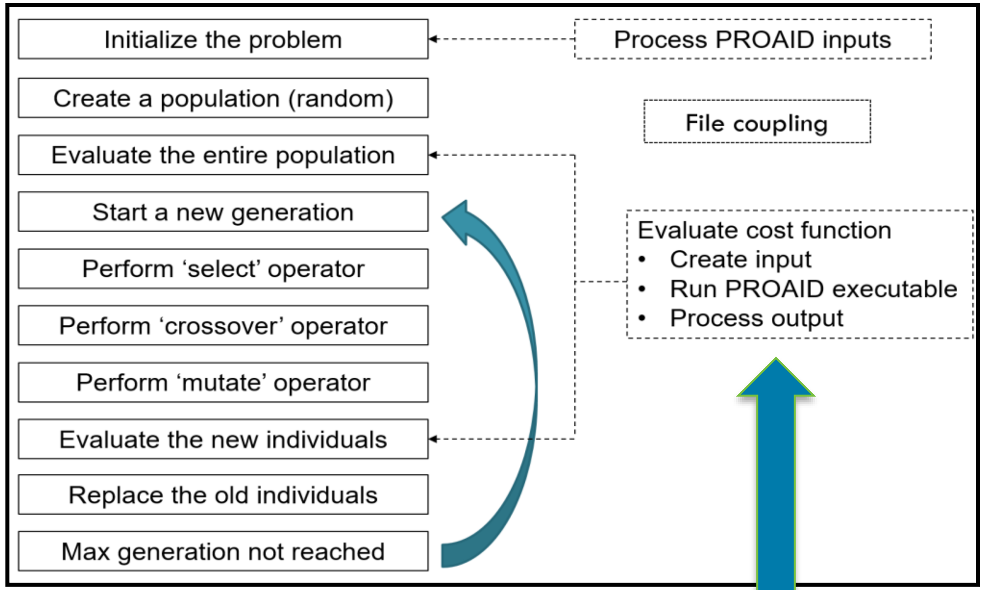


Results and Accomplishments

3. Developed and implemented sensor assignment GA-based optimization algorithm

```
#1. PID input file
PID    PID_input.txt

#2. FAULT LIST
# List of faults in a scenario to consider
# Line format: FAULT Fault-type Component-name
# Component names must match those in the P&ID
# Valid fault types: Leakage, Blockage, Fouling for components
#                    SensorFault for sensors

FAULT    Fouling       hx_shell          30000    15000
FAULT    Leakage       hx_tube           30000    15000
FAULT    SensorFault   hx_tube:temp:in   30000    15000

# 3. Options for the reasoning process
# (Optional, set to default if no user input is provided)

# NUM_FAULT_CO: upper limit on the number of faults per diagnosis
# In general, there could be cases where multiple-fault diagnoses, although less
# likely, are mathematically valid. This variable sets the cutoff limit on the
# number of faults per diagnosis in the diagnostic output. Default value is 3.

NUM_FAULT_CO    3


# 4. Parameters for the optimization problem

NUM_INDIVIDUALS 100
NUM_GENERATIONS 10
CROSSOVER_PROB  0.5
MUTATE_PROB  0.1 0.03
SELECT_TOURNSIZE 3
NUM_BEST 10
NUM_PROC 16
RANDOM_SEED 1
```

Input file for Cost Minimization by Genetic Algorithm



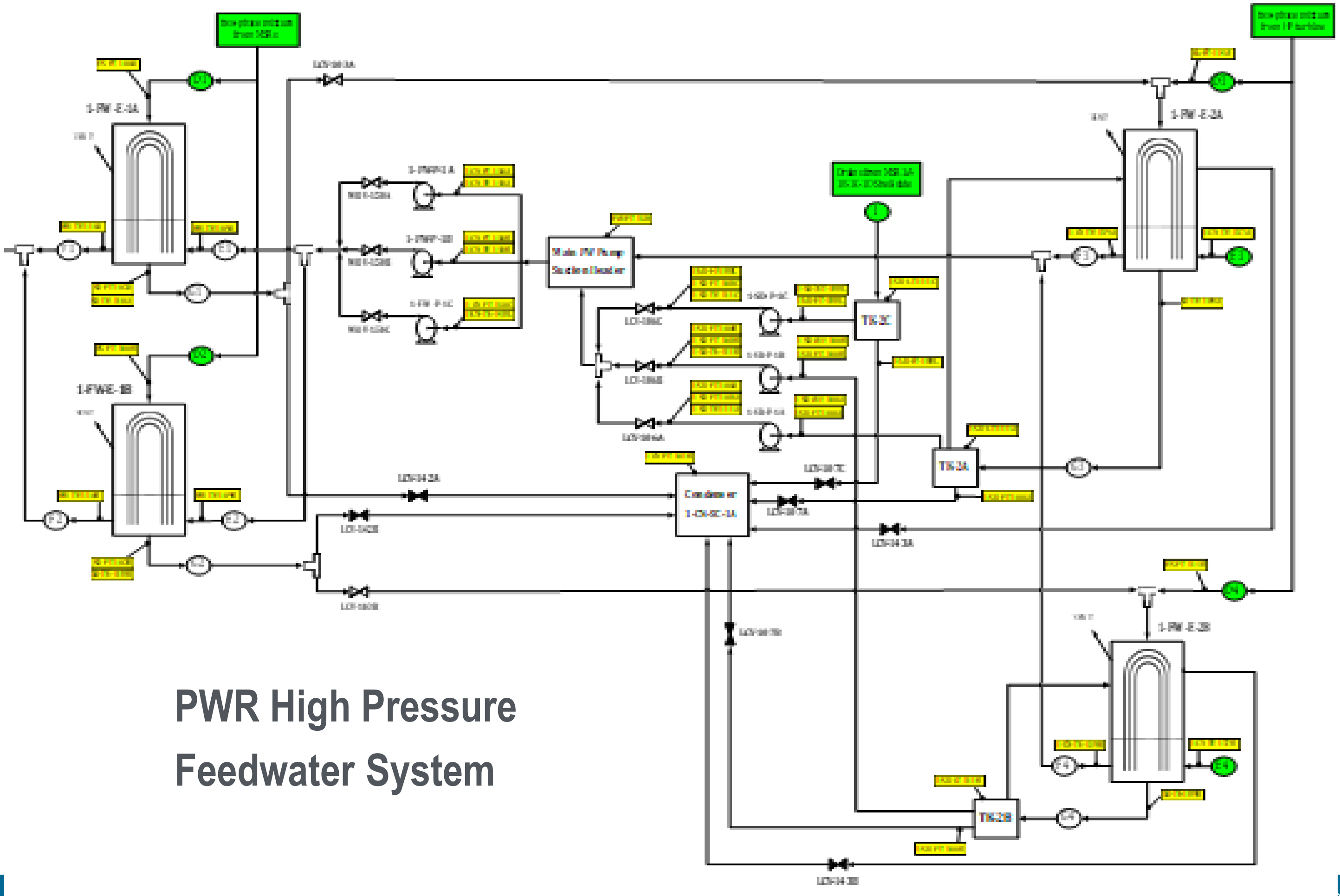
Genetic Algorithm Optimization Code

PRO-AID Diagnostic Code

Results and Accomplishments

4. Successfully applied sensor assignment algorithm to utility use case

- What is the minimum sensor set needed to diagnose the faults that are currently diagnosable with the installed sensor set? i.e., is there a more optimal sensor set from a cost standpoint?



PWR High Pressure Feedwater System

Results and Accomplishments

4. Successfully applied sensor assignment algorithm to utility use cases (cont'd)

- Greater fault resolution capability is achievable with fewer sensors
  - 38 versus 47
- Demonstrates the importance of sensor type and placement when considering the condition monitoring task

Comparison of Optimized Sensor Set with Installed

ID	Fault		Installed Set (47 sensors)		Optimal Set (38 sensors)	
	Comp.	Type	Detect	Uniquely Diagnose	Detect	Uniquely Diagnose
1	FWH 1A	Fouling	Y	N	Y	Y
2	FWH 1A	Tube Leak	Y	N	Y	N
3	FWH 1A	Tube Block	Y	N	Y	N
4	FWH 1A	Shell Leak	Y	N	Y	N
5	FWH 1B	Fouling	Y	N	Y	Y
6	FWH 1B	Tube Leak	Y	N	Y	N
7	FWH 1B	Tube Block	Y	N	Y	N
8	FWH 1B	Shell Leak	Y	N	Y	N
9	FWH 2A	Fouling	N	N	Y	Y
10	FWH 2A	Tube Leak	N	N	Y	N
11	FWH 2A	Tube Block	N	N	N	N
12	FWH 2A	Shell Leak	N	N	Y	N
13	FWH 2B	Fouling	N	N	Y	Y
14	FWH 2B	Tube Leak	N	N	Y	N
15	FWH 2B	Tube Block	N	N	N	N
16	FWH 2B	Shell Leak	N	N	Y	N
17	FWP 1A	Pump	N	N	Y	N
18	FWP 1A	Motor	N	N	Y	N
19	FWP 1A	Bearings	N	N	Y	Y
20	FWP 1B	Pump	N	N	Y	N
21	FWP 1B	Motor	N	N	Y	N
22	FWP 1B	Bearings	N	N	Y	Y
23	SDP 1A	Pump	Y	N	Y	N
24	SDP 1B	Pump	Y	N	Y	N
25	SDP 1C	Pump	Y	N	Y	N

Conclusions

- Developed virtual sensor capability for an engineered system based on the concept of a physics-based digital twin
- Diagnosed blind faults in utility data for feedwater pump-motor set
- Developed and implemented sensor assignment GA-based optimization algorithm
  - Deployed on parallel computing for scale up to multi-node clusters and solved a nuclear utility sensor assignment problem
- Successfully applied sensor assignment algorithm to utility use cases
  - Obtained physically explainable optimal sensor sets in reasonable runtimes

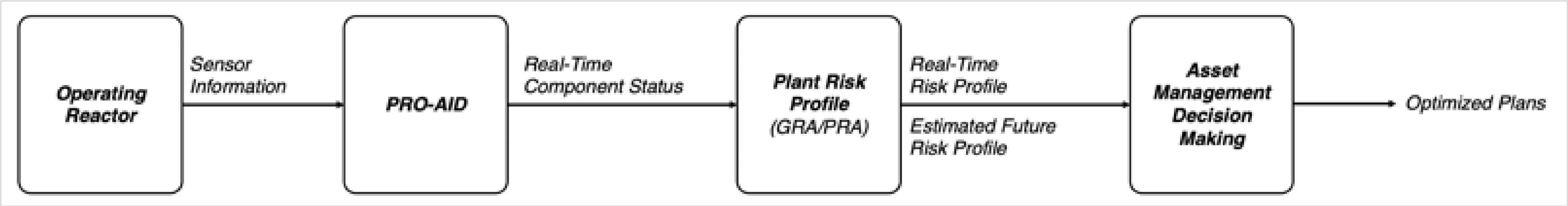
Future Work

Next-generation diagnostic capability

- Integrate two approaches, one for incipient detection, other for detailed diagnosis
  - Data-driven algorithm - High sensitivity but limited to anomaly detection (prior work)
  - Physics-based digital twin algorithm - Detailed and explainable diagnosis but lesser sensitivity (present work)
- Work collaboratively with utility to assess method on plant data sets

Leverage for longer term end goal of maintenance optimization and asset management

- Provides prior probabilities to Markov process model



Publications

Journal Papers

- Nguyen, T., and R.B. Vilim, “A Probabilistic Model-Based Diagnosis Framework for Fault Detection and System Monitoring in Nuclear Power Plants,” Annals of Nuclear Energy, August 25, 2020.
- Nguyen, T., Roberto Ponciroli, R., Vilim, R., “A Physics-Based Parametric Regression Approach for Feedwater Pump System Diagnosis,” accepted for publication, Annals of Nuclear Energy, August 2021.
- Nguyen, T., and R.B. Vilim, “A Digital-Twin Approach to System-Level Health Monitoring for Increased Diagnosis Specificity,” under revision, Annals of Nuclear Energy, October 2021.

Conference Papers

- Vilim, R. “Explainable Diagnostics Achievable Using Process-Based Automated Reasoning,” NPIC HMI Conference, June 2021.
- Vilim, R. “A Physics-Based Automated Reasoning Approach for Sensor Set Assignment,” NPIC HMI Conference, June 2021.

Patent Applications

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Questions?

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