Instrumentation and Sensors – Microreactor Automated Control System (MACS) and Acoustics

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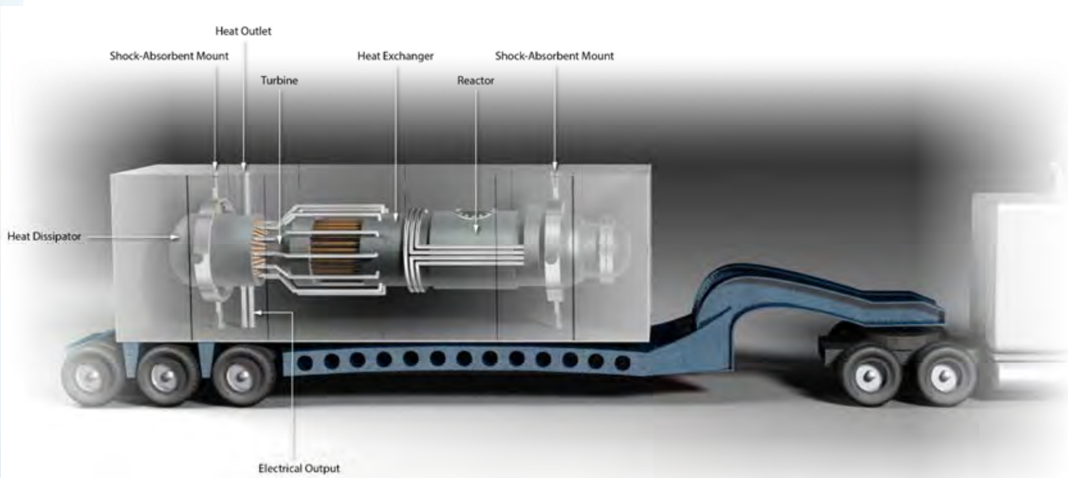
Idaho National Laboratory | Oak Ridge National Laboratory | MRP Microreactor Program | Los Alamos National Laboratory | Argonne National Laboratory

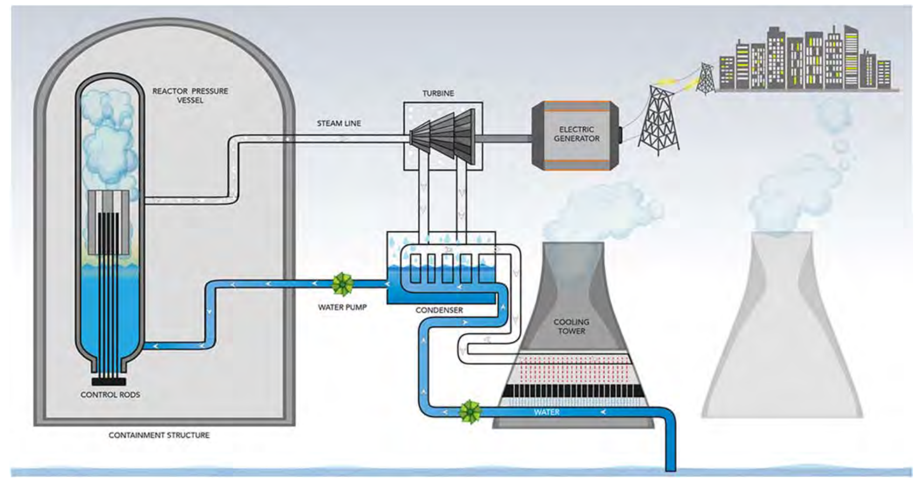
Microreactors

MACS task

- Smaller size, factory assembled, need for more automated or autonomous operation to reduce O&M costs without economies of scale
- Critical components such as pumps, heat exchangers and turbines may be located closer to the core in a harsher environment with limited access
  - Challenging to monitor or inspect, could benefit from advanced monitoring techniques
  - Harsher environment also more challenging for sensors **Acoustics task**



Microreactor
https://inl.gov/trending-topic/microreactors/

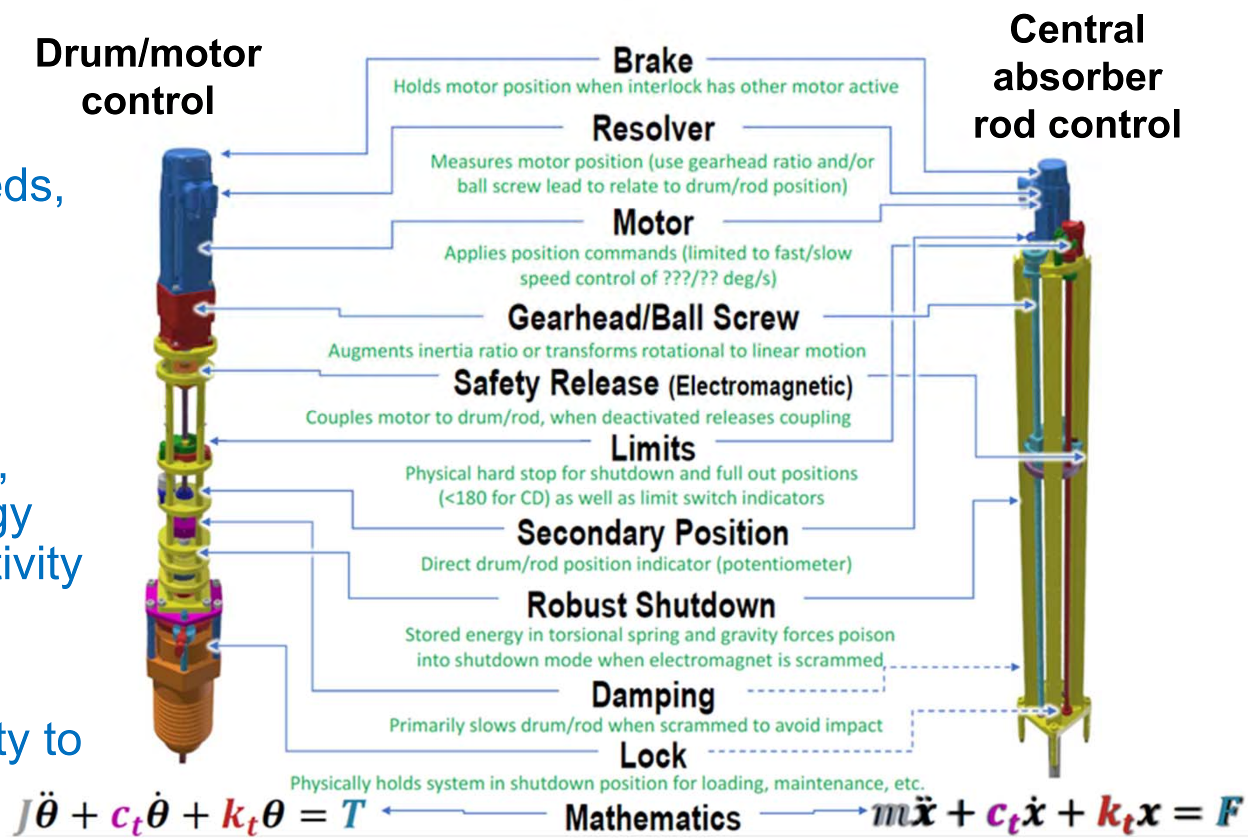


Conventional reactor
https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work

MRP Microreactor Program

Microreactor Automated Control System (MACS)

- Objective: Leverage prior efforts to develop, test and implement a high fidelity and robust MACS to minimize need for human-in-the-loop (HIL)
- Approach:
  - Leverage existing designs for microreactors, available testbeds, and prior research on control systems
  - Expected data/measurements: Reactor temperature, control element (drum or rod) position, coolant temperature and energy transfer to heat sink, and reactivity feedback
  - HIL simulator, including heat transfer and simulated reactivity to demonstrate capability



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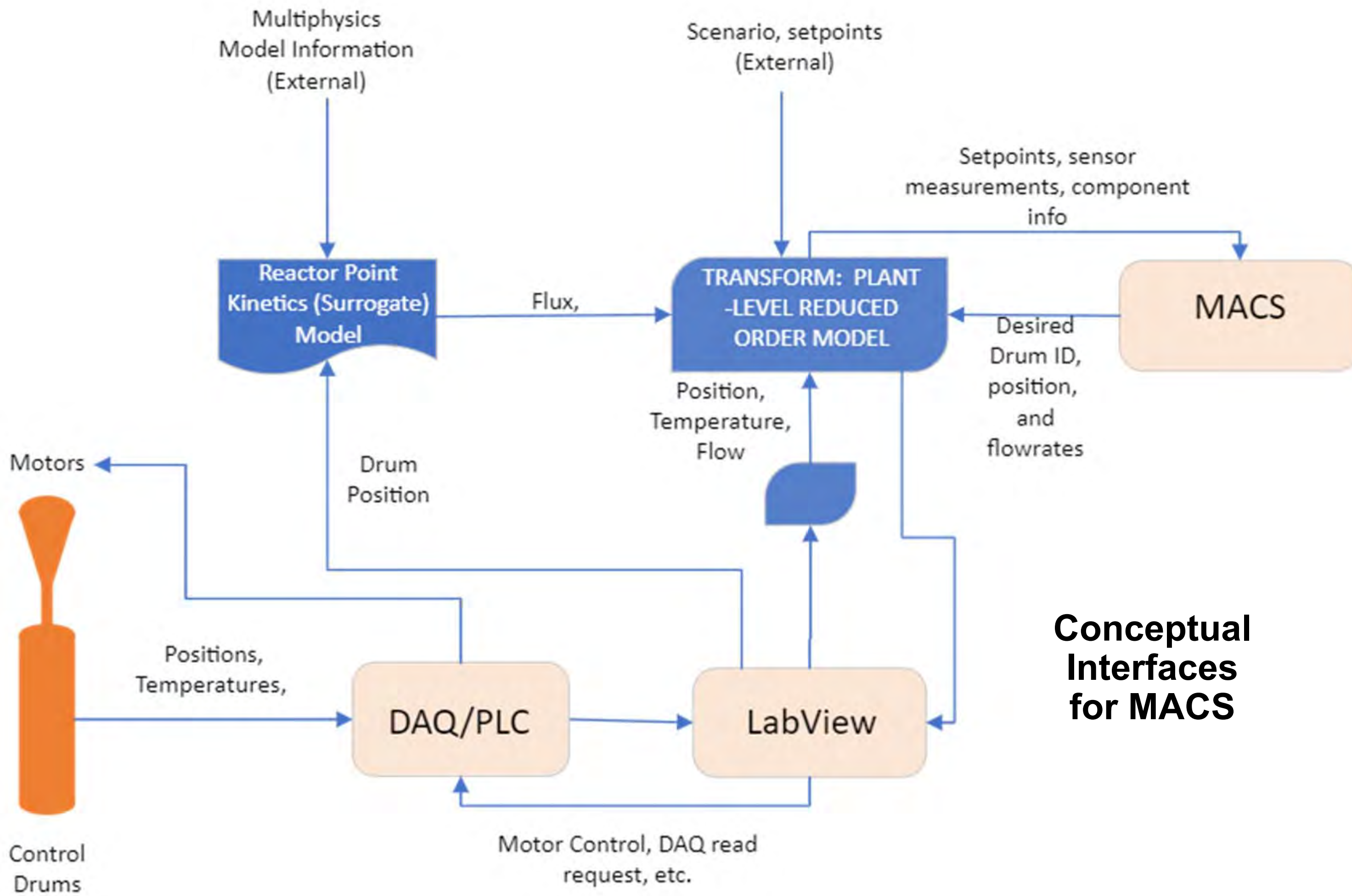
MACS status

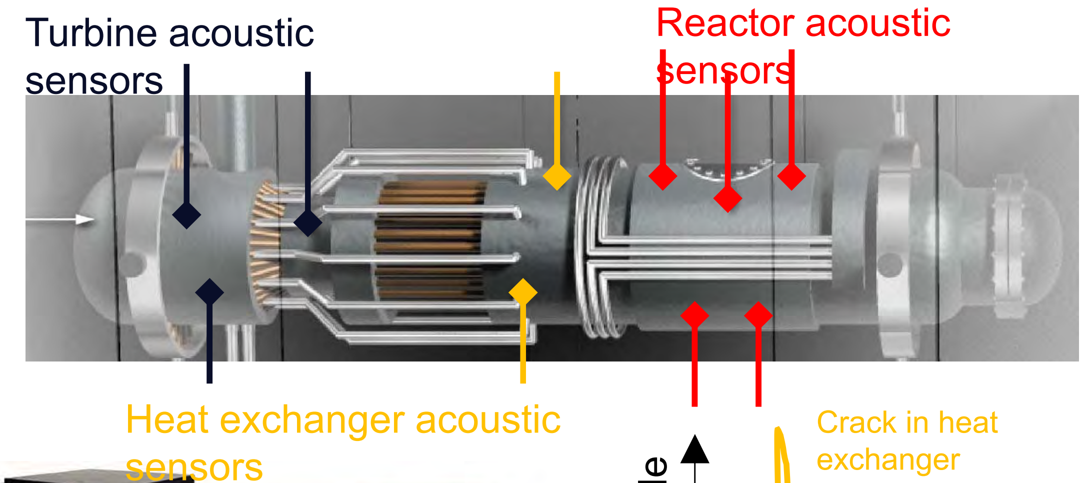
- Preliminary set of requirements defined in FY22
  - Reactor power control
  - Cooling medium
  - Power conversion unit
  - Surveillance and diagnostics
- MACS concept and design defined; implementation underway
- Demonstration hardware at INL being leveraged for MACS implementation and demo

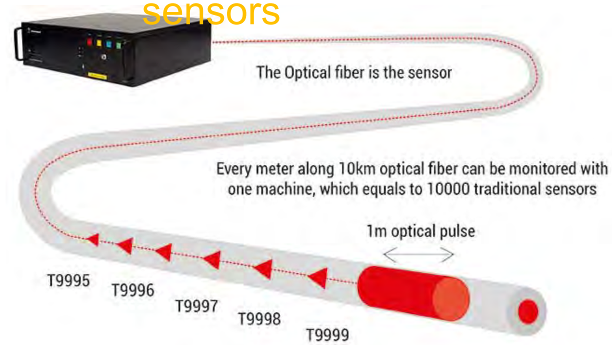


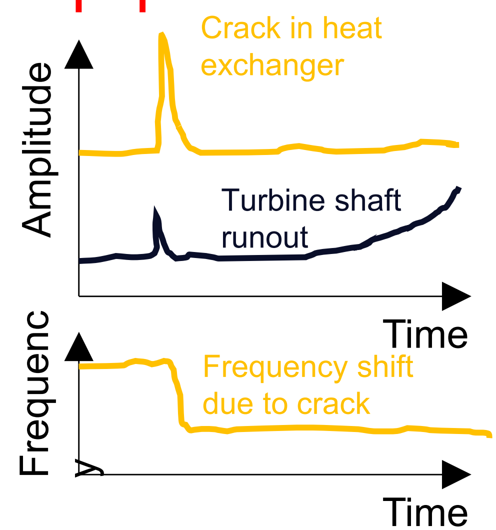
Conceptual Interfaces for MACS

Fiber-optic acoustic sensors for health monitoring

- Fiber optic sensors: Many different interrogation techniques
  - High frequency (~MHz or higher)
  - High accuracy (~nm displacements)
  - Spatially distributed measurements (~cm resolution)
- Small diameter (~100 μm)
- Immunity to electromagnetic interference
- High temperature tolerant (< 1,000°C)
- Radiation tolerant
- Many applications within nuclear power plants
  - Structural damage (cracking, debonding, corrosion, creep)
  - Components in need of maintenance
  - Vibrations
  - Loose parts or acoustic emissions







Distributed acoustic sensing to determine not just the timing but the location of a potential reactor issue

https://www.bandweaver.com/wp-content/uploads/2016/07/t-laser_beam-01-web.jpg

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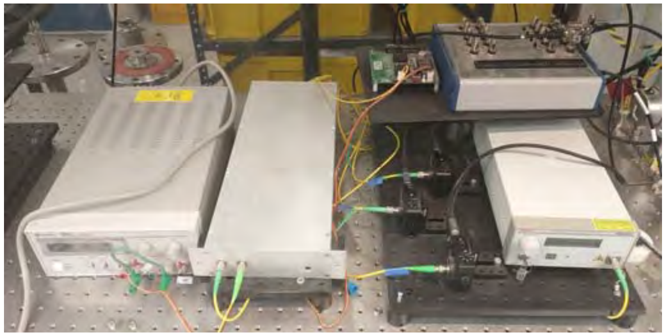
Interrogation systems for nuclear applications

- Distributed acoustic sensing (DAS)
  - Uses ordinary optical fiber
  - ~1 meter spatial resolution over ~10 km
  - ~10 kHz frequencies
  - Low tolerance to radiation-induced attenuation
  - No systems on hand (>$100k)
- Swept wavelength laser-based sensing
  - Can interrogate point (ordinary fibers) or distributed sensors (fiber Bragg gratings, FBGs)
  - Up to tens of FBGs per fiber, ~cm spacing
  - ~1 kHz frequencies
  - High tolerance to radiation-induced attenuation
- Low coherence interferometry (LCI) sensing
  - Point sensors
  - Custom interrogation system developed at ORNL
  - ~MHz frequencies or higher
  - Low tolerance to radiation-induced attenuation

DAS100 from Bandweaver
https://www.bandweaver.com/wp-content/uploads/2016/07/DAS-Horizon-product-640x480px.jpg

Hyperion si155 from Luna Innovations
https://lunainc.com/sites/default/files/styles/image_497/public/assets/images/products/SI155_new%20logo.jpg?itok=9nI-pN5a



ORNL custom LCI system

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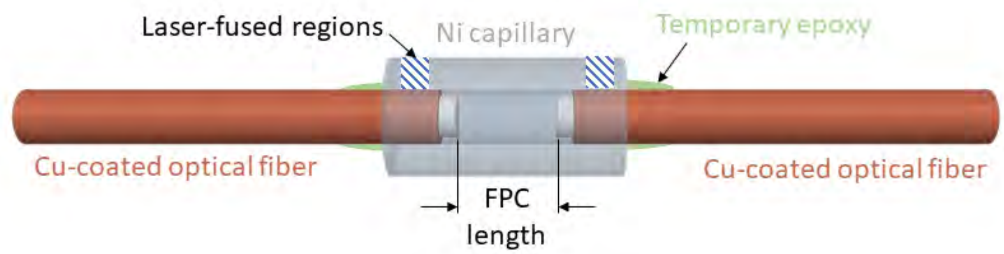
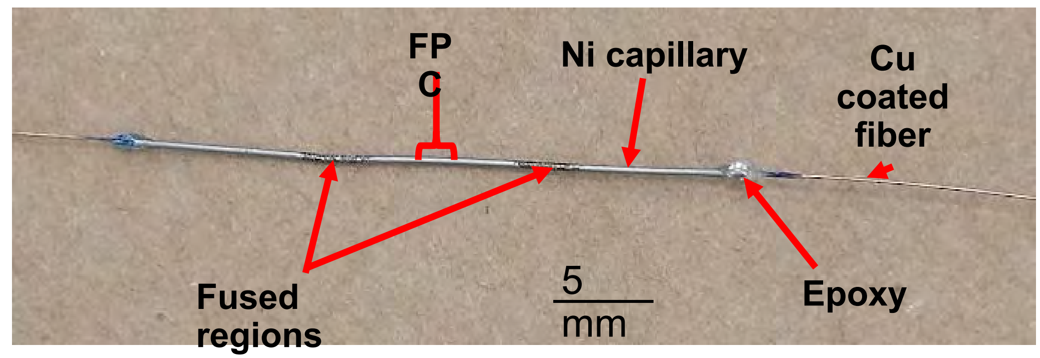
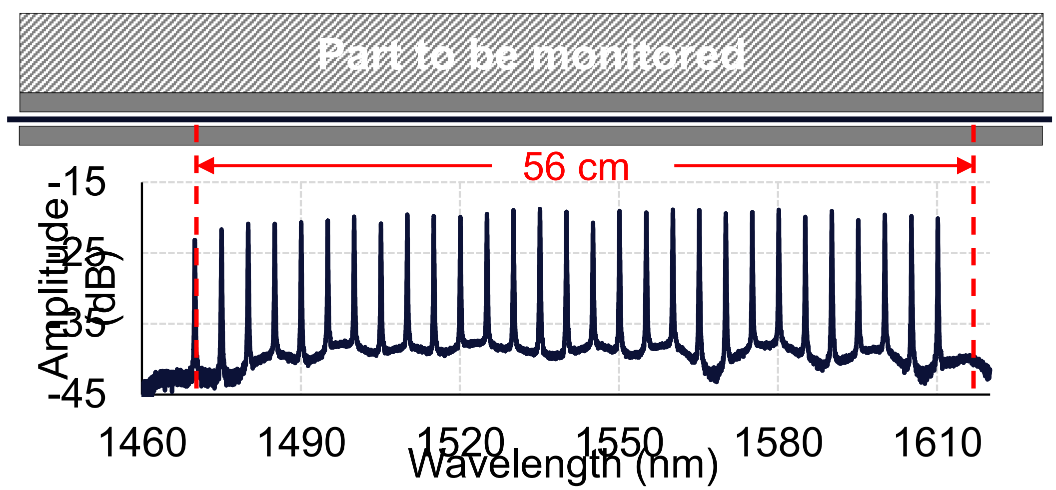
Sensors for nuclear applications

- Fibers should use pure silica core, F-doped silica cladding to minimize radiation-induced attenuation
- Single-point sensors: Fabry-Perot cavities (FPCs)
  - Two Cu-coated optical fibers bonded inside a capillary tube
  - One fiber temporarily bonded to Ni capillary using epoxy
  - 2nd fiber bonded after adjusting gap
  - Fibers fused to Ni capillary via local fusion with a laser
- Distributed sensors: FBGs
  - 29 FBGs inscribed every 2 cm over a 56 cm length of fiber
  - 5 nm wavelength spacing from 1470–1610 nm
  - Must be sheathed in a metal capillary tube (weak acoustic coupling)







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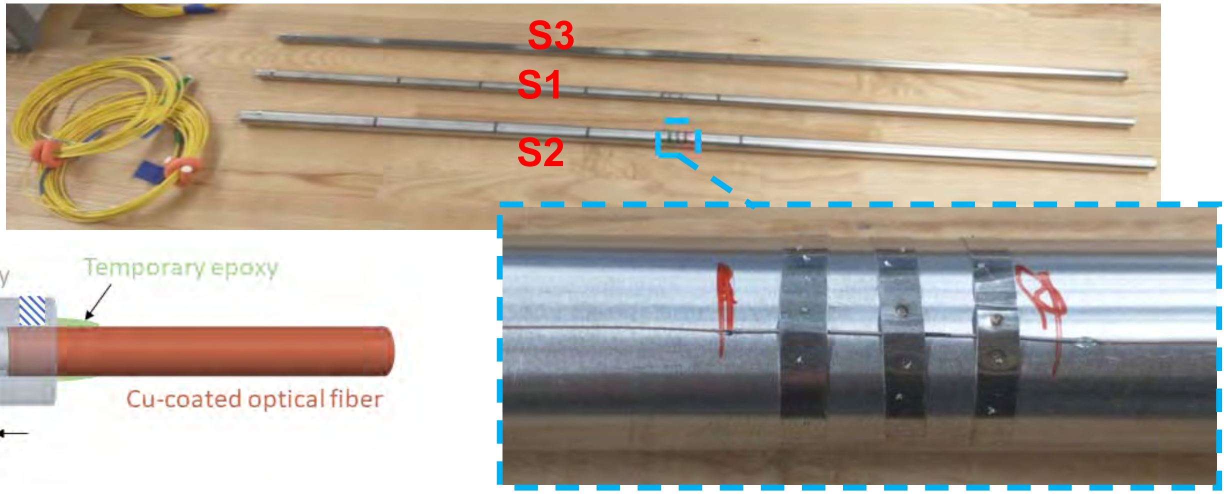
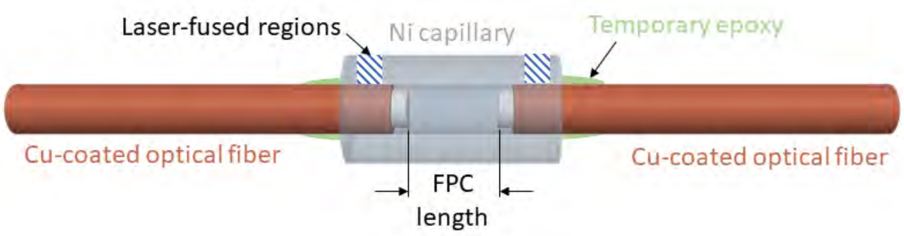
Bonding techniques for nuclear applications

- Acoustic sensing is much more effective if the fiber is directly bonded to the component
  - Challenging for fiber to remain bonded despite large static strain due to differential thermal expansion and/or radiation-induced dimensional changes
- FBGs can be contained in tight-fitting capillaries
  - Relies on friction
- FPCs tack-welded to SS304 pipes or rods
  - Interrogated with LCI and reference piezo-electric accelerometer
  - Compared acoustic resonant frequencies with theoretical values at low and high temperature

FPC sensors bonded to SS304 pipe or rods for acoustic testing





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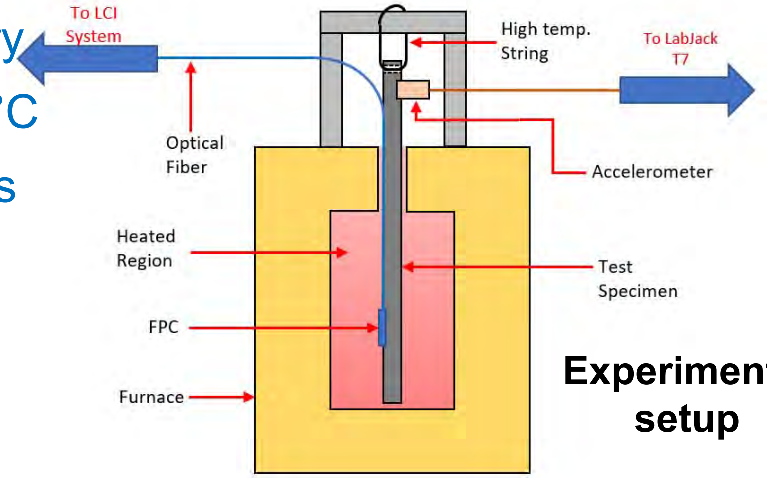
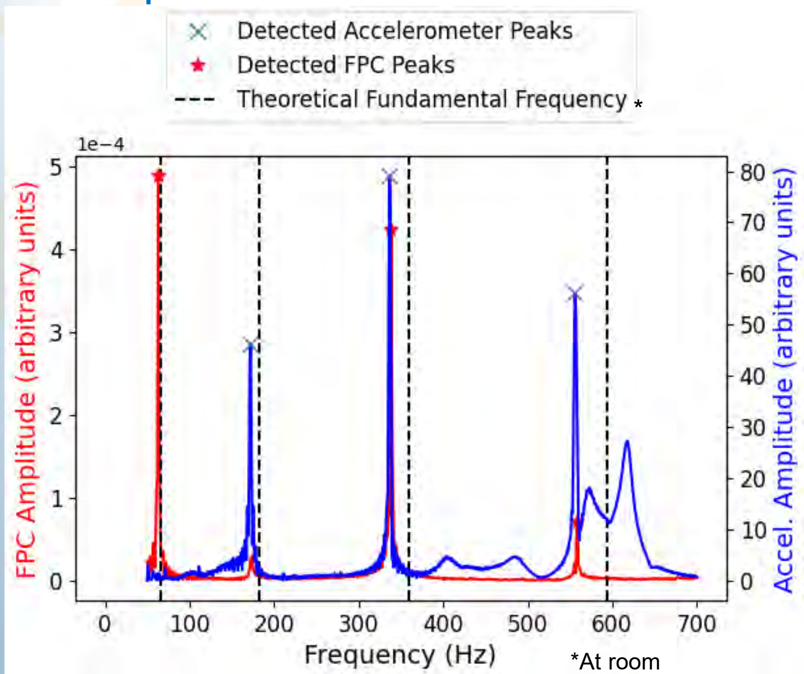
Initial testing of bonded FPCs

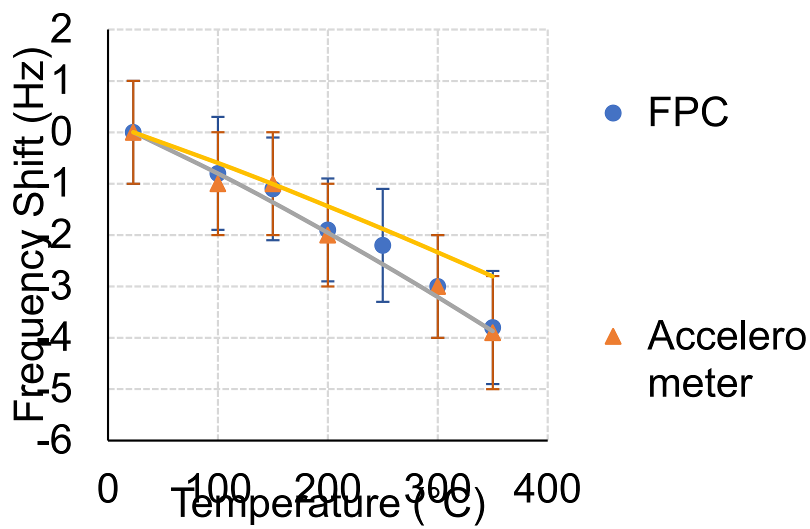
- FPC frequencies consistent with accelerometer and theory
- FPC temperature trends consistent with theory up to 350°C
  - Furnace trip prevented testing at higher temperatures
  - Accelerometers only provided data outside high temperature region
- Results encouraging but require further testing at higher temperatures

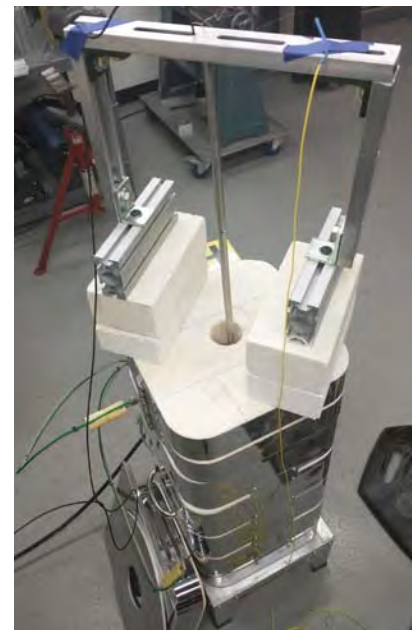


Experimental setup



*At room temperature





Milestones and future work

MACS

- M3: Complete conceptual design for MACS (6/30/2023)
  - Requires integration with INL efforts to stand up non-nuclear demonstration capabilities
  - INL has a M2 to demonstrate actuation of a non-nuclear control system using MACS

Acoustics

- M3: Investigate and demonstrate acoustic and high temperature sensing to support structural health monitoring for microreactors (7/28/2023)
  - Evaluate sensitivity to damage (e.g., bonded vs. debonded heat pipes)
  - Higher temperature testing to quantify sensor limitations
  - Evaluate potential for spatially distributed measurements using FBGs at high temperatures
  - Closely connected to LANL efforts on flaw detection toward acoustic demonstration in a relevant component

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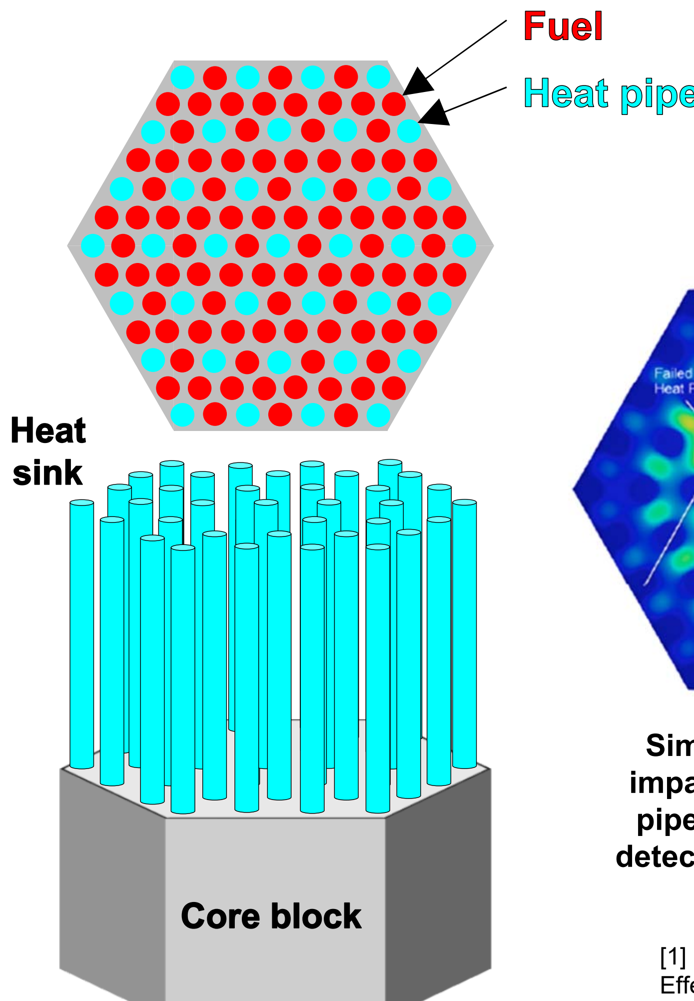
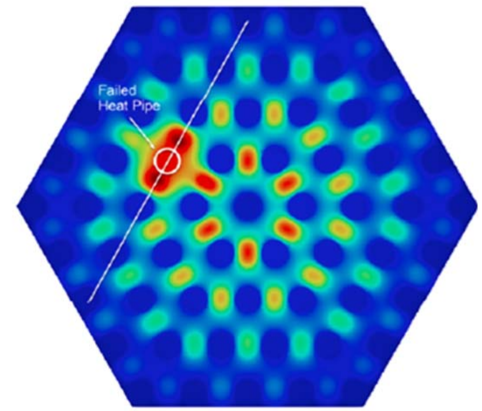
Backup slides

Approach

- Develop sensors and attachment techniques for monitoring acoustic vibrations of microreactor components
  - Goal is to detect signs of damage or required maintenance
  - Cracking, debonding, corrosion, creep, etc.
- Sensors must be compatible with typical microreactor materials and expected operating conditions
  - Stainless steels, nickel-based alloys, etc.
  - Temperatures approaching 800°C or higher
  - Fast neutron exposure
  - Potentially compatibility with corrosive media (sodium vapor, molten salt, lead, etc.)



Potential application: Monitoring debonding of heat pipes to a microreactor core block

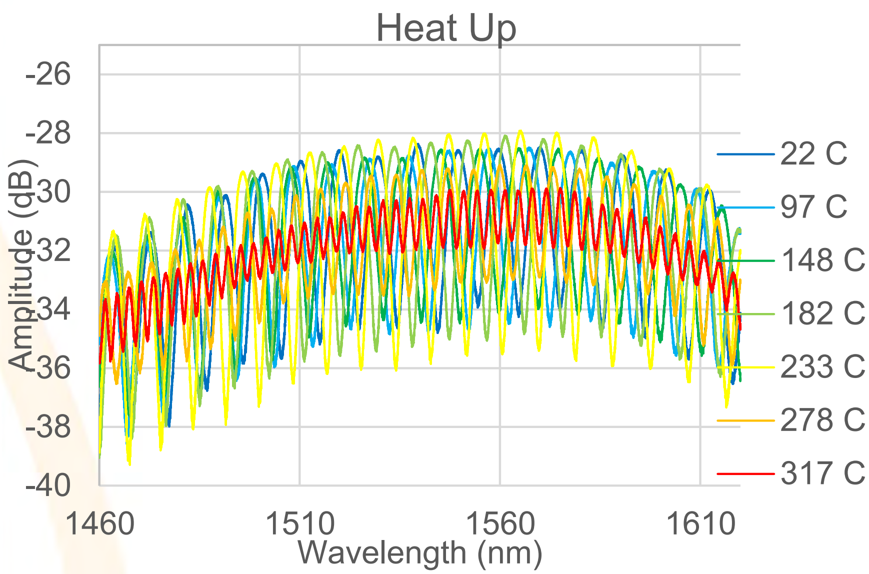


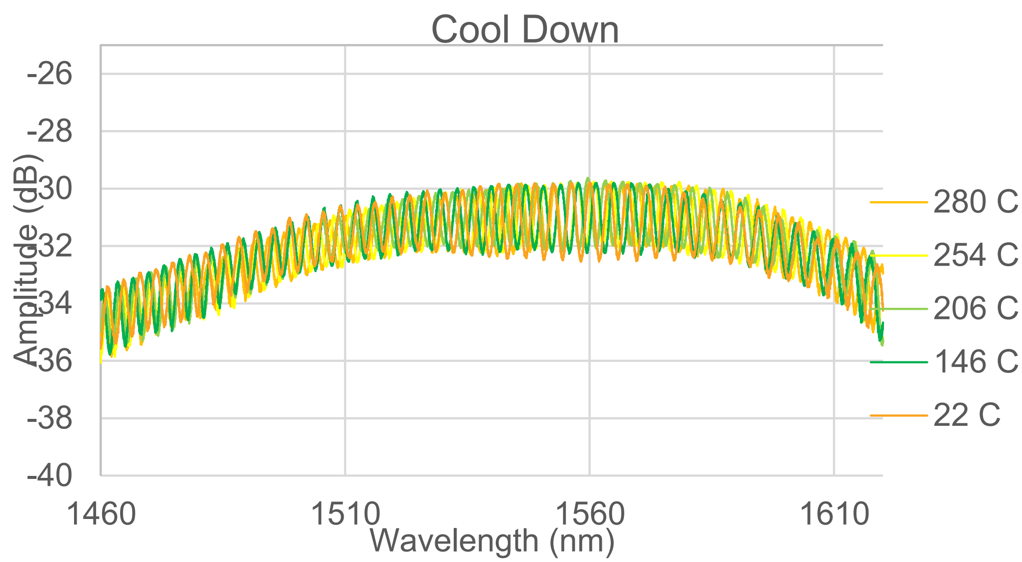
Simulation showing impact of a failed heat pipe [1] that could be detected using acoustic techniques

[1] Galloway J.D. et al. (2020) Effects of Heat Pipe Failures in Microreactors. LA-UR-20-23798

Full spectra obtained at high temperatures

- Spectral features maintained during high temperature testing, but amplitudes did decrease, indicative of the cavity length expanding
- Cool down data shows that the cavity size does not return to pre-test size
- If the fiber/sheath interface yields but still allows for acoustic measurements to be made, that is encouraging for the potential of the sensor to survive higher temperatures and static strains





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