Summary of Structural Health Monitoring Activities at INL

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Structural Health Monitoring/ Acoustic Sensors

OVERVIEW

Purpose: Advance SHM technologies for nuclear use via development of high temperature, irradiation resistance sensors/transducers and develop/quantify new methods of embedding sensors in structural materials/components.

Objectives:
- M3CT-24IN0702072-(Carryover) Report on performance of updated INL ultrasonic thermometer design
- M3CT-24IN0702073-(Carryover) Complete testing of acoustic emission/vibration commercial sensor
- M3CT-24IN0702074-(Carryover) Complete testing of commercial sensor and assess needed design changes
- M4CT-24IN0702077-Development of acoustic emission and vibration sensors-Due 7/31/2024
- M4CT-24IN0702078-Design irradiation test for SHM sensors and methods for performance assessment-Due 9/30/2024
- M3CT-24IN0702079-Embedded optical fiber using Electric Field Assisted Sintering (EFAS) for SHM-Due 9/30/2024
- M2CT-24IN0702076-Report on all FY-24 activities-Due 12/31/2024

IMPACT

Logical Path:
- EFAS: Optical
  - Embed Sample>Test with OBR and He Leak>Machine Part>Test with OBR and He Leak>Heat Cycle with active OBR>Repeat to refine
- EFAS MS
  - Embed MS>Test with coil and LDV>Temperature Cycling to Curie Point>Repeat to refine
- AE/Vibration sensors: Base designs on near term TREAT needs to focus design criteria>Procure parts>Fabricate prototypes>Test in relevant conditions>Refine design as needed
- SHM Rig Design: Select likely irradiation locations/positions>Identify bounding dimensions/temperatures/flux rates>Design/develop signal input mechanism>Identify bounding sensor characteristics (dimensions/leads/temperature limitations/etc)>Use all data to inform design
- Report: Collect input from all collaborators, collate into comprehensive report

Outcomes: Advancement of ultrasound/acoustic based sensors for acoustic emission/vibration sensing. New methods of embedding sensors. Design of irradiation vehicle for testing/comparison of SHM technologies

DETAILS

Principal Investigator: Joshua Daw, Team: Bibo Zhong, Xinchang Zhang, Jorgen Rufner, Dan Deng

Institution: Idaho National Laboratory

Collaborators: BSU, PNNL

Period of performance: **FY24**

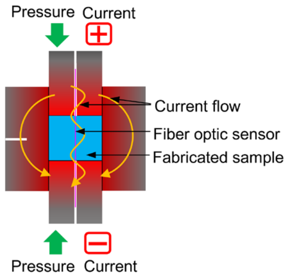
Funding: **$680K New+$100K Carryover**

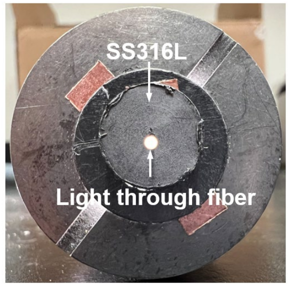
TPOC (Technical Point of Contact): Chris Petrie

Milestones/deliverables:

ACCOMPLISHMENTS

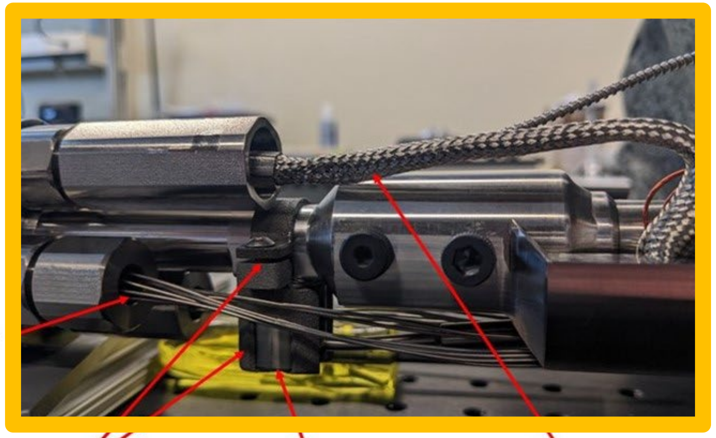
Oct 2023-Jan 2024:
- M3CT-24IN0702072 (UT Report): Complete
- M3CT-24IN0702073 (Commercial AE/Vibration Testing): Complete
- M3CT-24IN0702074 (Commercial Pressure Testing): Complete
- M3CT-24IN0702079 (EFAS):
  - Meetings held with INL and PNNL collaborators
  - Fiber embedding activity started at INL
    - Waiting for sample to test
- M4CT-24IN0702077 (AE/Vibration Sensors):
  - Following slides
- M4CT-24IN0702078 (SHM Test Rig Design):
  - Not started
- M2CT-24IN0702076 (Report)
  - Not started





- This work develops radiation tolerant, high temperature sensors for monitoring acoustic emission (AE) and vibration.
- As a target application to guide this work, upcoming experiments planned for the Transient Reactor Test (TREAT) facility will be used. The targeted TREAT testing includes pin burst testing at elevated temperatures, some of which will be performed in liquid sodium.
  - A commercial, piezoelectric based, acoustic emission sensor was initially selected to meet this need, and worked well for low temperature irradiations, but failed near the expected test temperatures of the higher temperature irradiations.
  - Other sensor technologies may be better suited to this need than sensors based on piezoelectric materials.
    - Three of these alternative technologies were investigated with one option selected for development.

TREAT-Current Methodology



TREAT irradiation vehicle instrumentation leads

- The AE sensor is clamped to central structural support and located above the core, several feet from the experiment.
- This location causes delay in signal receipt and additional signal noise/distortion from the many components being in close contact.

Commercial AE sensor:

- Physical Acoustics 9125D Very High Temperature AE Sensor
  - 540°C maximum operating temperature
  - 20 mm Outer Diameter × 20 mm Height
  - 50–650 KHz frequency range
  - Rated to 1×10^{9} rad and 2.23×10^{17} n/cm^2 over 40 years

Option 1: Magnetostrictive (MS) Rod Based AE Sensor

Advantages:

- High temperature capable (tested to 950° C)
- Radiation tolerant (prior testing to 8.8×10^{17} n/cm^2 (>1 MeV))
- Construction very similar to ultrasonic thermometer transducer
- MS transducer can be made smaller than commercial piezoelectric sensor
- Potentially better acoustic coupling as all parts are metallic

Disadvantages:

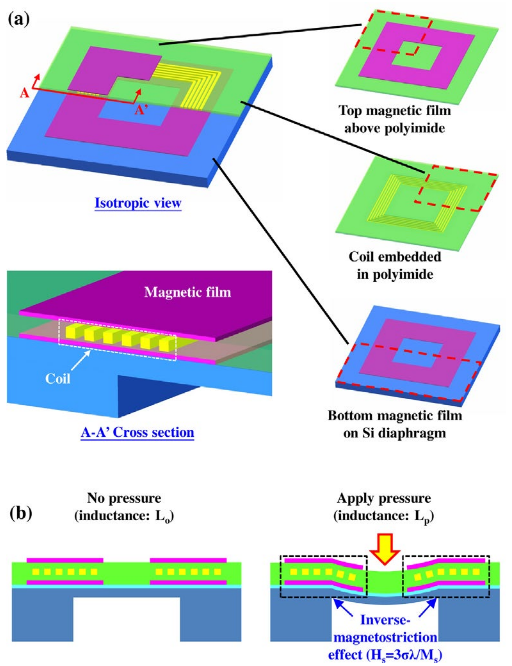
- Possible electromagnetic interference
- MS material may contain cobalt:
  - Concept tested to 950°C (Fe-Co Curie Temp.)
- Shock heating of coil causing open circuit failure
- Not thoroughly tested in TREAT
  - 3 MS transducers and gamma thermometer have been tested successfully

Advantages

- Radiation tolerant
- High temperature capable
- Good performance at low frequencies (<10Hz)
  - Better for low frequency applications such as pressure or force measurement

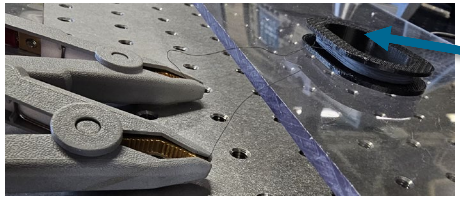
Disadvantages

- High frequency (>20 kHz) signals have low sensitivity
- Best foil materials contain cobalt: Fe-Mn and Fe-Cr alloys were also tested
- Sensitivity to nearby conductors
  - Careful sensor and experiment design required
- May need biasing magnets or coils to maximize signal
  - High temperature magnets contain cobalt
  - DC coils add size and complexity

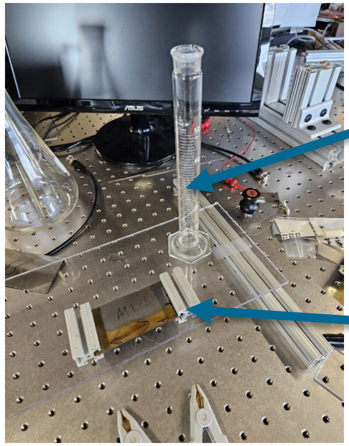


Heng-Chung Chang, Sheng-Chieh Liao, Hsieh-Shen Hsieh, Jung-Hung Wen, Chih-Huang Lai, Weileun Fang, Magnetostrictive type inductive sensing pressure sensor, Sensors and Actuators A: Physical, Volume 238, 2016, Pages 25-36, ISSN 0924-4247, https://doi.org/10.1016/j.sna.2015.11.023.

- Proof of concept testing with electrical impedance meter
- Clear change in DC inductance proportional to loading

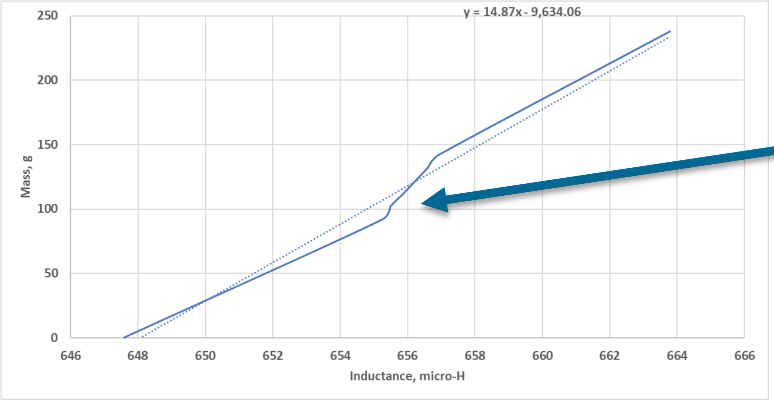


Coil



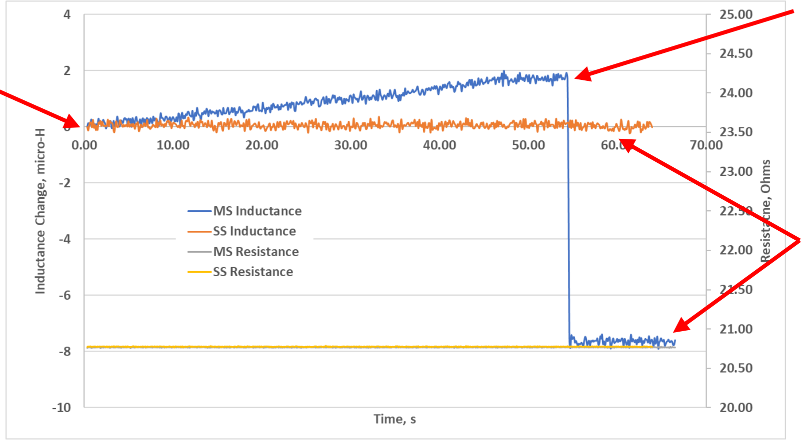
Beaker

Magnetostrictive sheet



Non-linearity due to oscillation of beaker

92 grams, mass of beaker



142 grams, mass of full beaker

0 grams, no load

Advantages

- Non-contact measurement
- No electromagnetic interference issues
- High sensitivity
- Wide frequency range (DC to 24 MHz with current Vibroflex)
- Differential measurement eliminates system vibration effects
- Small “footprint”

Disadvantages

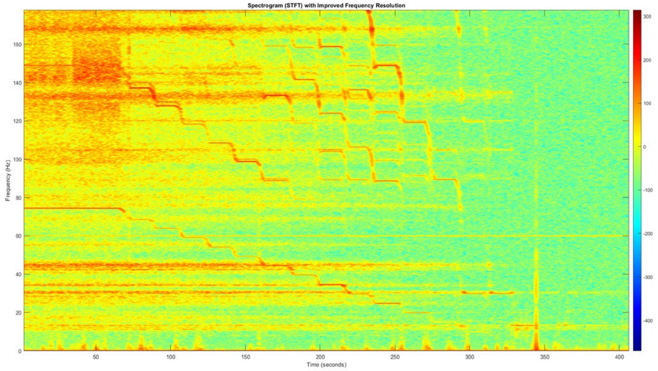
- Need infrared laser measuring head to avoid fiber darkening
- Fiber coupling requires end lenses and diffuse reflecting surface, installation into experiment requires precise placement of fibers relative to observed sample

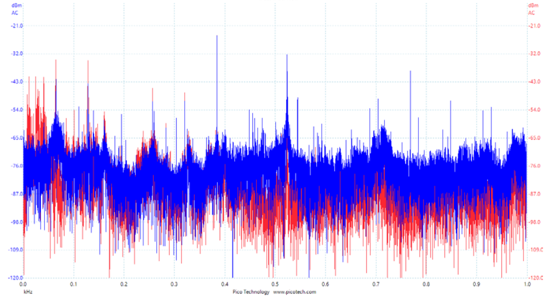
Fibers used in LDV are not useful for in-core testing, rad hard fibers with custom lensed ends require development

Polytec Vibroflex Located at Measurement Sciences Laboratory

- Prior year results show potential for AE and vibration measurement

Flowing Autoclave System (FAS) measurements with varying pump speed





LDV Spot

Commercial Accelerometer

- Flowing autoclave used to evaluate commercial sensor
- LDV used as basis for comparison
- Commercial accelerometer and LDV show close agreement

Flowing Autoclave System

Design is similar to ultrasonic thermometer

- Demonstrated radiation tolerance and well-developed transducer design with small form factor needing minimal modifications

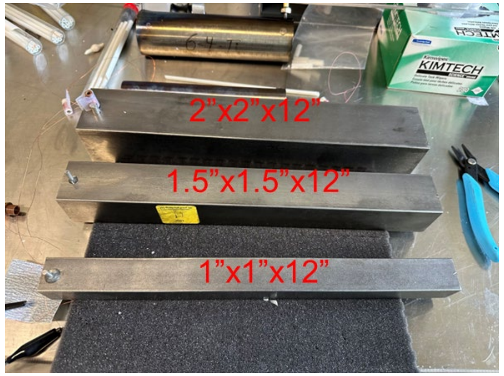
Required testing:

- Frequency response in well defined sample for comparison to simulated response
  – Needed to demonstrate broadband response needed for vibration/AE monitoring
- Passive testing at room temperature and elevated temperatures
  – Send impulse through structure and record response
  – Standard “pencil break” test is representative of brittle fracture of ceramic fuels
- Active testing to identify Curie temperature (pulse-echo ultrasonic method)
  – Demonstrate absolute temperature limit of sensor
- Simulated fuel pin bursts for comparison to commercial sensor
  – Necessary for demonstrating that sensor will work for TREAT tests

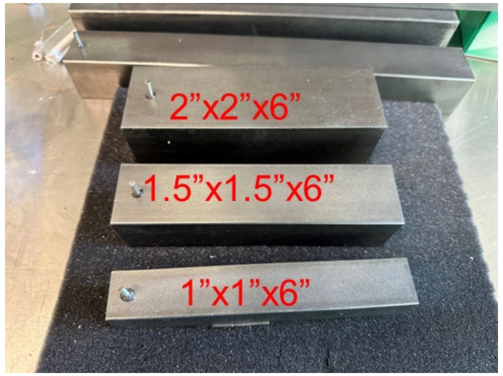
Multiple metallic specimens with different dimensions and materials were tested

- Shapes and material properties are easily modelled with predictable resonant vibrational frequencies
- By modeling the response and comparing to response measured with magnetostrictive rod-based sensor, the performance of the sensor can be validated

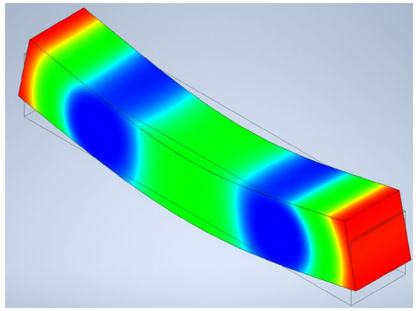
6061 aluminum alloy specimens



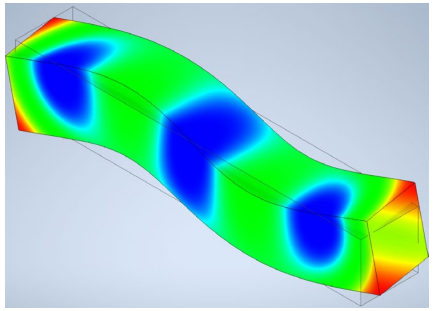
Long carbon steel specimens



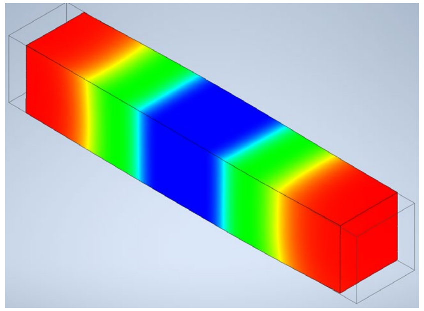
Short carbon steel specimens



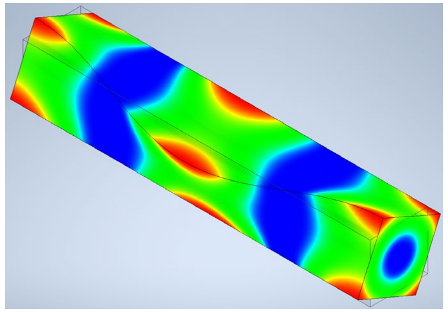
2599.66 Hz first order bending mode



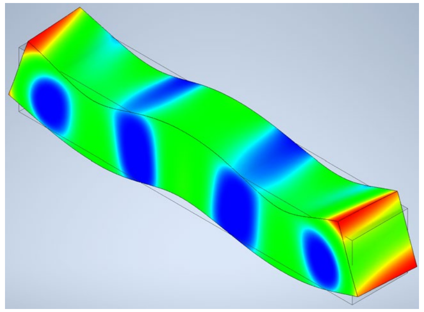
6316.37 Hz second order bending mode



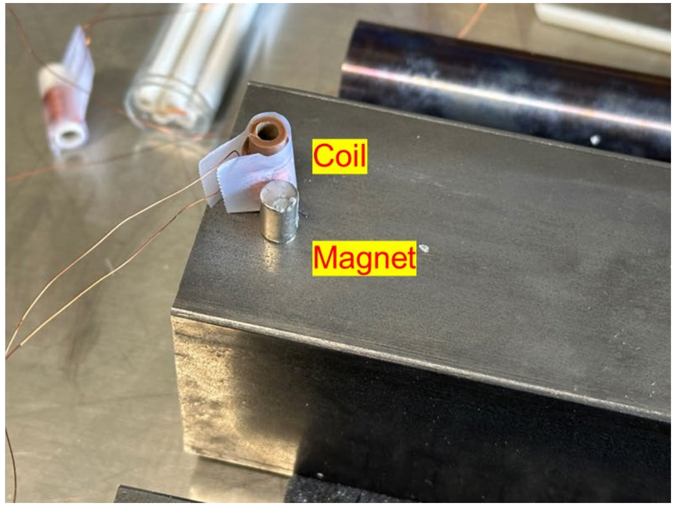
8265.38 Hz first order longitudinal mode



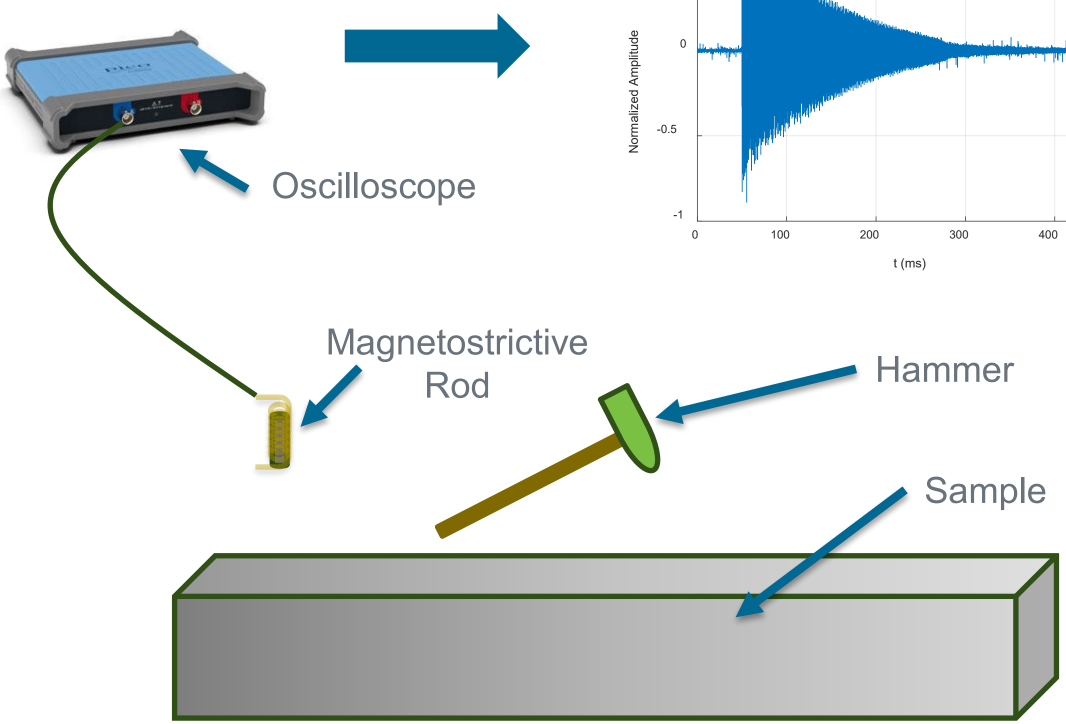
9433.66 Hz second order torsional mode

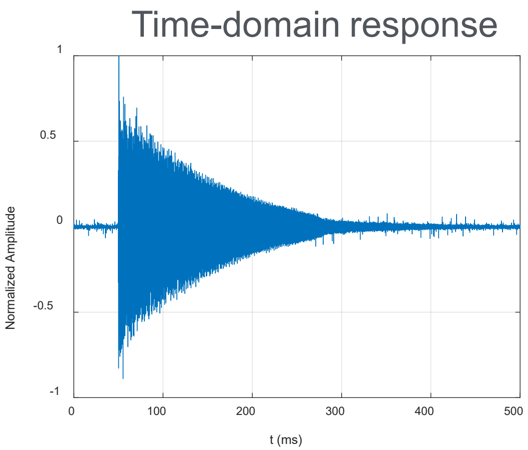


10823.82 Hz third order bending mode

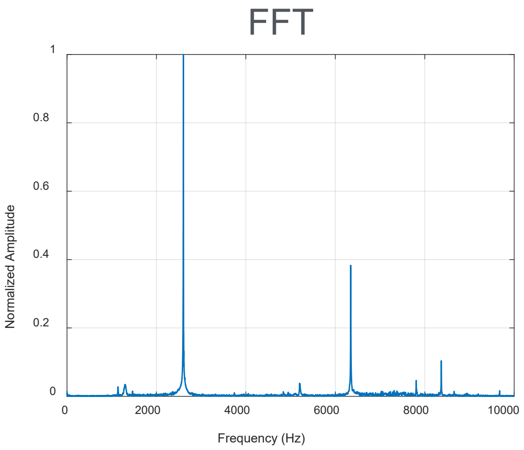


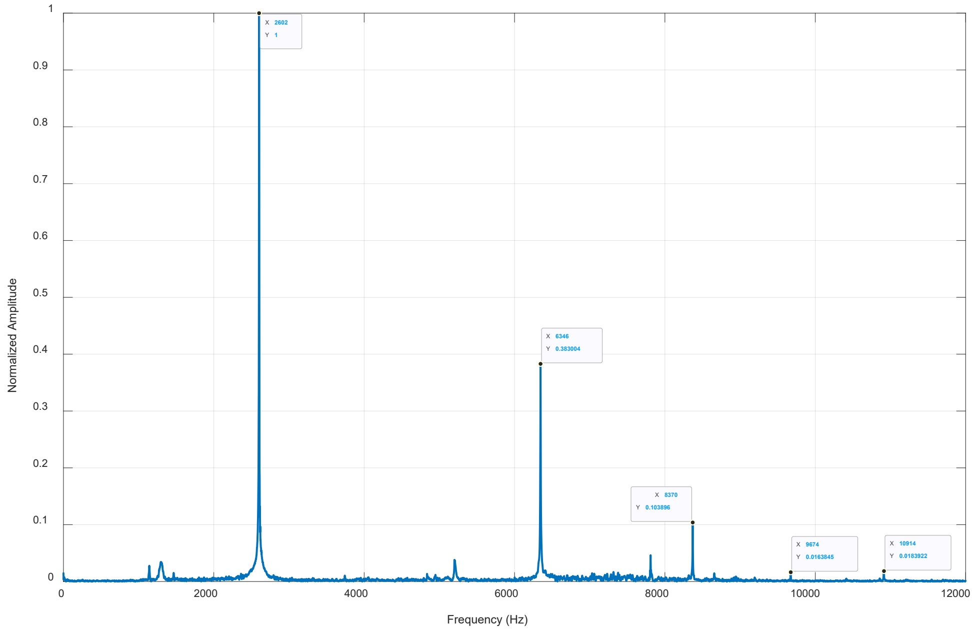
- Magnetostrictive rod rigidly attached to specimen using epoxy
- Sensing coil placed over rod and biasing magnet placed adjacent to coil





Impulse load is imparted to center of specimen using small hammer. Time-domain signal is recorded using oscilloscope and converted to frequency-domain via fast Fourier transform (FFT).

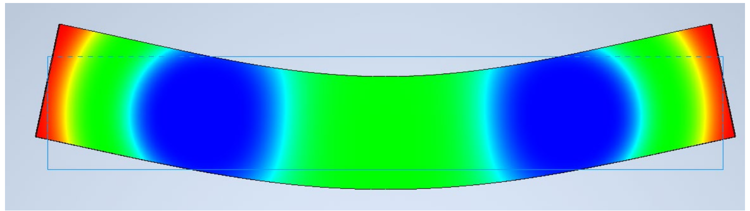




Experiment	Simulation
2600 Hz	2602 Hz
6316 Hz	6346 Hz
8265 Hz	8370 Hz
9434 Hz	9674 Hz
10824 Hz	10914 Hz

- Recorded data shows close agreement to modeled response.
- Minor differences and smaller frequency peaks are attributable to differences between idealized model geometry/material properties and real sample:
  - Rounded corners
  - Non-parallel cuts
  - Microstructure

Results for 1st Flexural Vibration Mode



Carbon steel

Dimensions	2” × 2” × 12”	1.5” × 1.5” × 12”	1” × 1” × 12”	2” × 2” × 6”	1.5” × 1.5” × 6”	1” × 1” × 6”
Experiment	2602 Hz	2020 Hz	1382 Hz	8584 Hz	7058 Hz	5098 Hz
Simulation	2600 Hz	2021 Hz	1385 Hz	8680 Hz	7157 Hz	5201 Hz

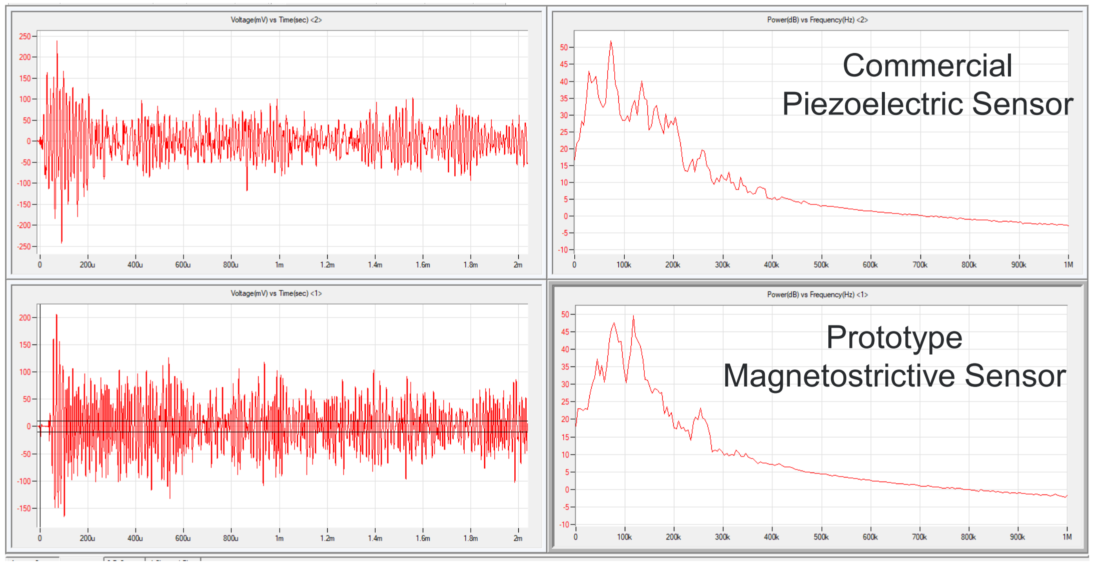
Aluminum 6061

Dimensions	2” × 2” × 12”	1.5” × 1.5” × 12”	1” × 1” × 12”
Experiment	2592 Hz	2024 Hz	1384
Simulation	2600 Hz	2021 Hz	1386

Passive AE Sensor Testing At Room Temperature

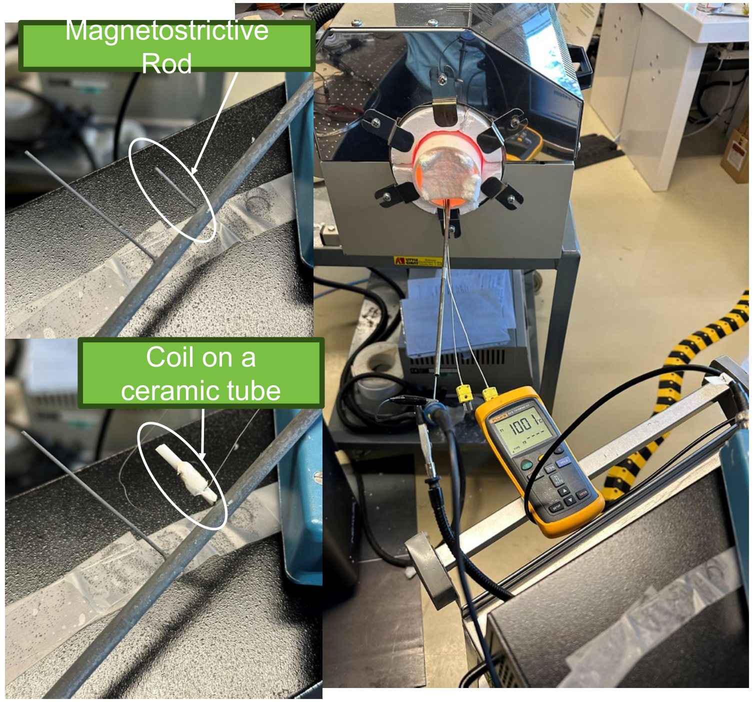
Prototype Magnetostrictive Sensor | Commercial Piezoelectric Sensor

Both the magnetostrictive sensor and commercial piezoelectric sensor are attached to the steel bar. A pencil break is used to generate an acoustic event at the middle of the bar, which then detected by both sensors.

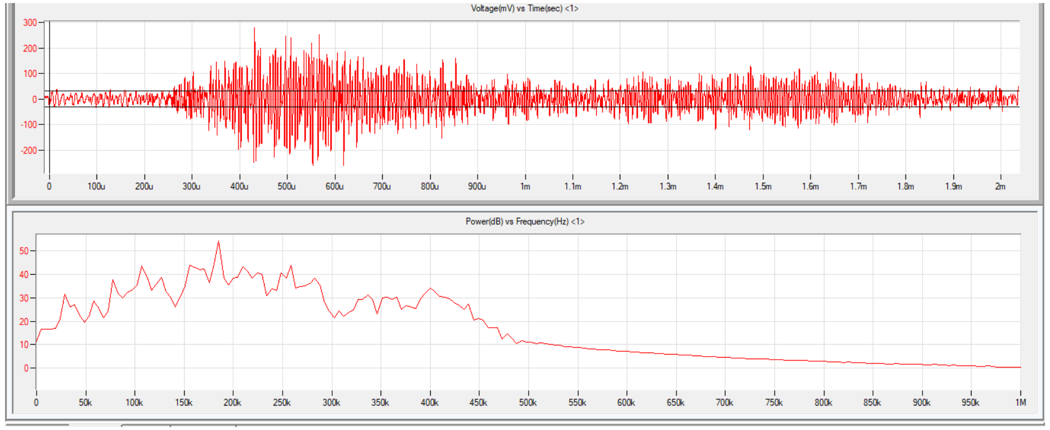


AE signals and frequency spectra

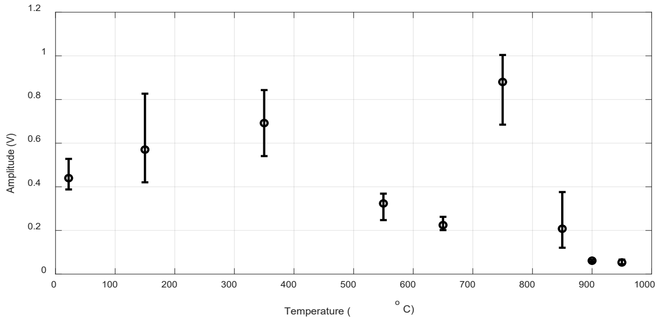
- Magnetostrictive sensor response matches commercial sensor closely



- A 1 mm diameter, 20 mm long magnetostrictive rod was laser-welded to a 1-meter-long stainless-steel tube
- Acoustic signals are detected via a high temperature capable coil
- Acoustic signals are introduced to the tube outside the furnace using pencil break and impact, propagate into the furnace, and are detected by the sensor inside
  - Pencil break simulates fuel cracking, but is low amplitude
  - Impact provides higher amplitude

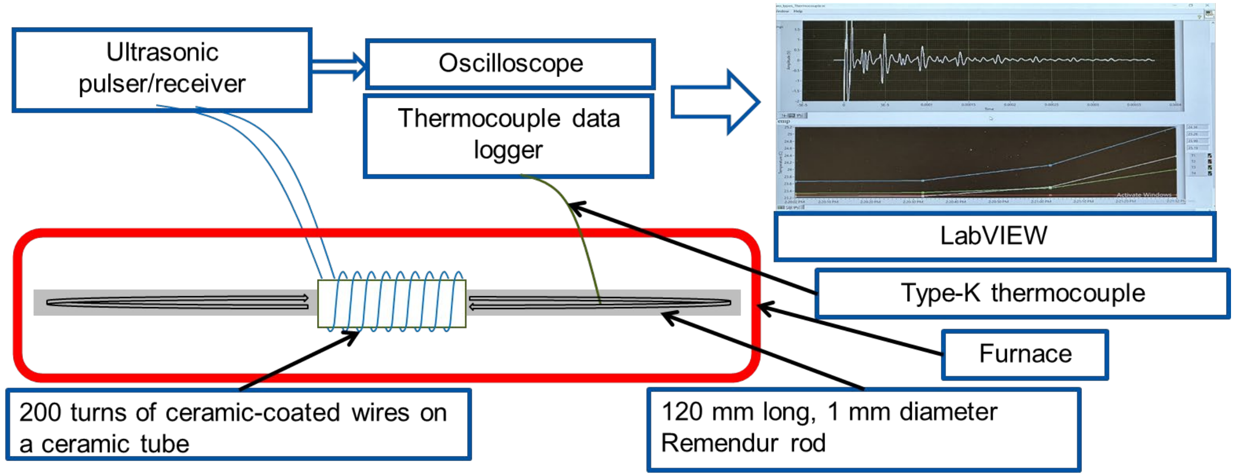


Sample of an AE signal and frequency spectrum collected by magnetostrictive sensor.



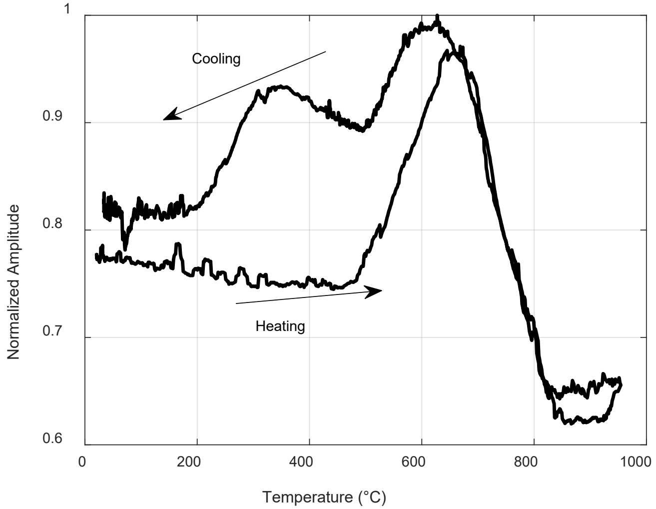
Voltage response of the magnetostrictive transducer at increasing temperatures

- Temperature effects between 500˚C and 700˚C demonstrate need for amplitude compensation
- Signals received to ~900˚C



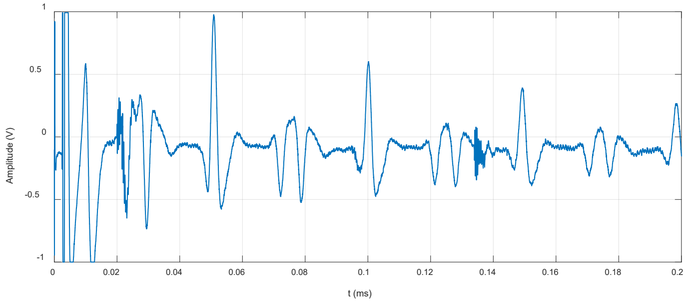
Active interrogation of Remendur wire allows better characterization of the maximum operating temperature as it allows for larger amplitude signals than those observed in the passive testing

- Similar setup to passive testing
- Magnetostrictive wire sealed in inert gas filled tube to avoid oxidation

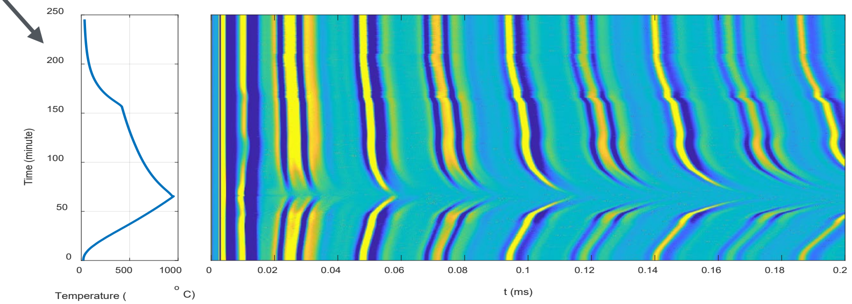


- Hysteresis implies need for annealing of Remendur for optimal performance
- Operation demonstrated to 950°C for Remendur

A-scan (time vs amplitude trace)

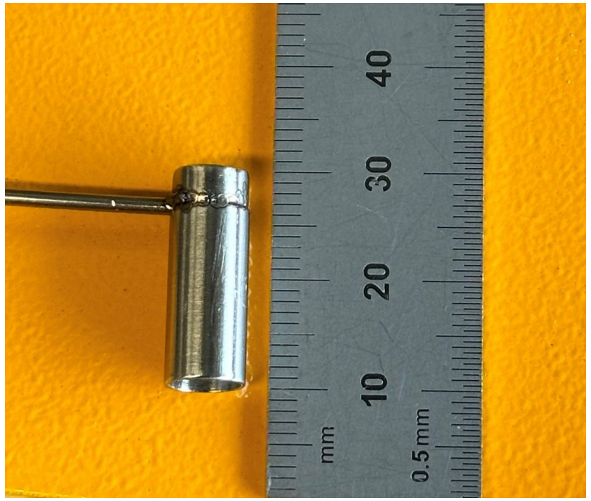


Furnace temperature vs time

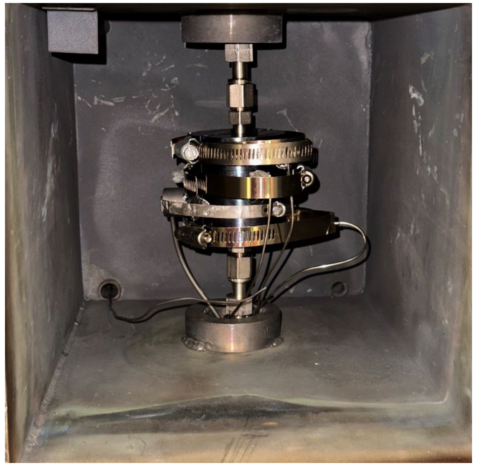


B-scan with temperatures up to 950°C

- X-axis is waveform time (A-scan)
- Y-axis is heating time (Stacked A-scans)



INL prototype magnetostrictive AE sensor

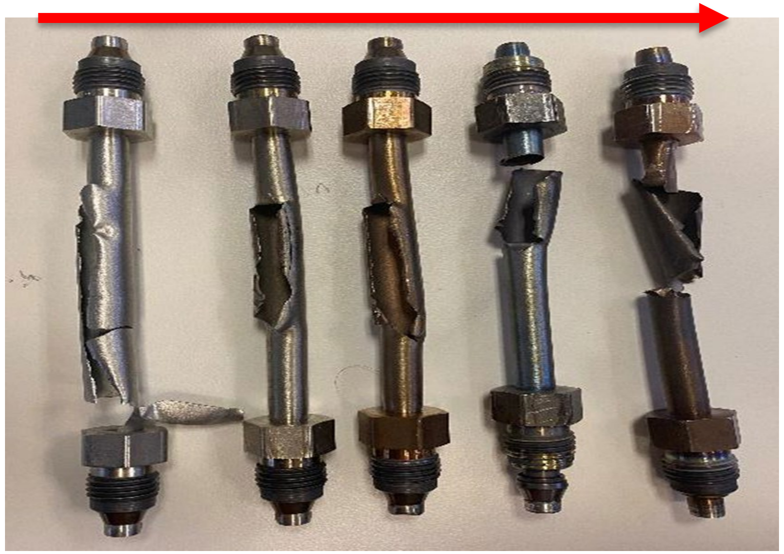


Experimental setup in furnace with hose clamps securing sensors to heat sink

- Mock-fuel pin burst testing was conducted in a heavy walled furnace capable of confining high pressure gas releases
- Stainless steel tubes were used to simulate cladding tubes and were pressurized to failure
- Two sensor types were used in the testing to detect failure:
  - Commercial piezoelectric sensor (Maximum operating temperature of 540°C)
  - INL magnetostrictive sensor
- Sensors were secured to a heat sink via clamps
- Mock pin is positioned inside heat sink, as it will be in TREAT experiment
- Tested at ambient temperature, 300, 400, 500, and 650°C

View inside high pressure capable furnace with commercial sensor and simulated fuel pin burst. No heat sink is installed for this video, this demonstration was to observe the point of pin failure.

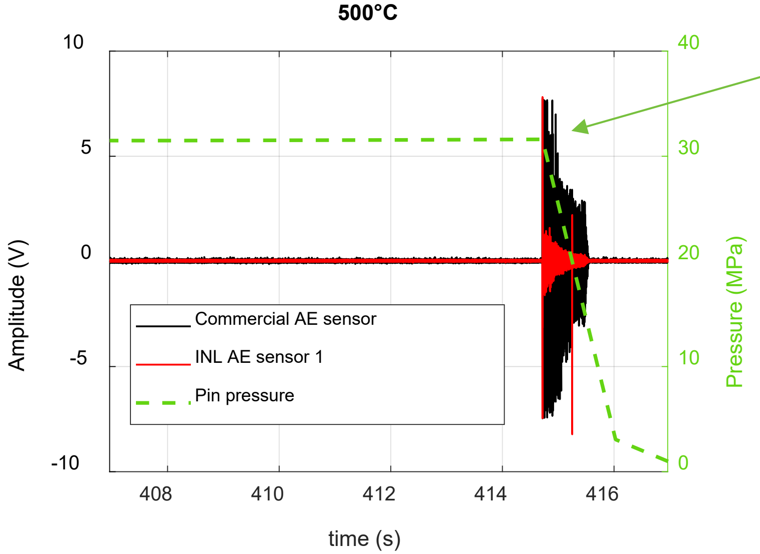
Increasing T



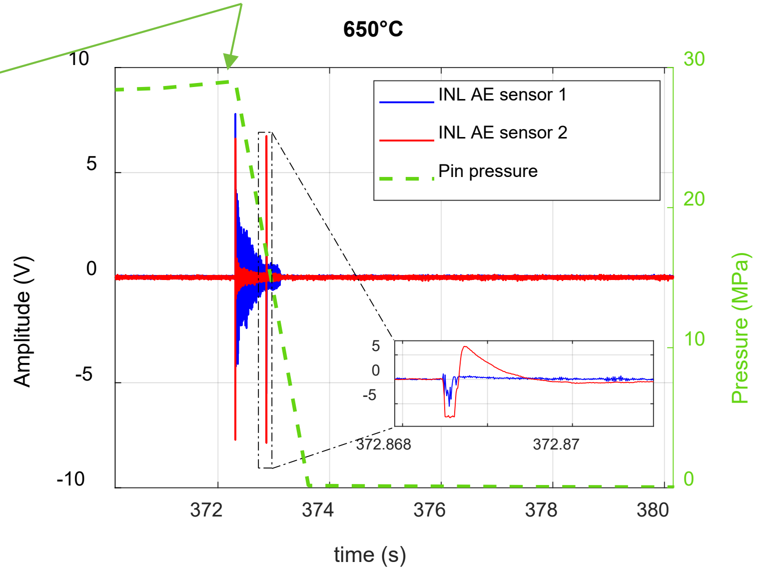
Temperature	Ambient	300°C	400°C	500°C	650°C
Burst pressure (MPa)	52.7	37.8	32.9	31.6	29

Mock fuel pins post-failure. Ruptured fuel pins fail at lower pressures as test temperature increases.

Green trace shows pressure within mock fuel pin. Burst is seen as rapid pressure drop coincident with AE signal.



Signals acquired for commercial and INL AE sensors at 500°C

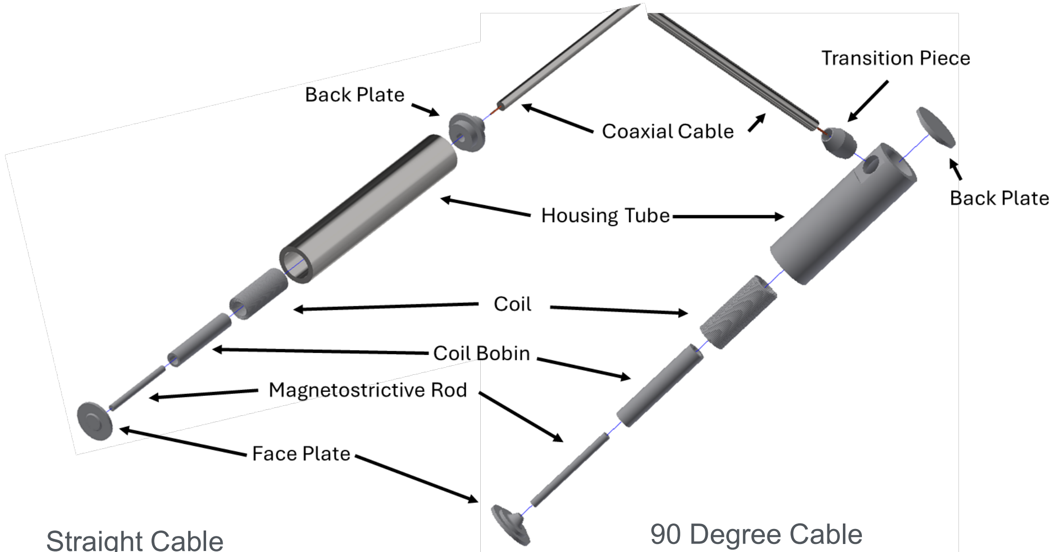


Signals acquired for two INL AE sensors at 650°C

Magnetostrictive rod based INL AE sensor performs similarly to commercial sensor but can operate at higher temperatures.

Two configurations have been developed based on results of testing and programmatic TREAT requirements

- 0.25-inch overall diameter is significantly smaller than the commercial sensor
- Lead-in cable is 0.062-inch, half that of commercial sensor
- Design allows for installation with cable in straight or 90-degree angles
- Coaxial cable has been observed to be less susceptible to EMI than twinax used in commercial sensor



Straight Cable Configuration

90 Degree Cable Configuration

Fabricated Prototype

- The goal of this work was to develop a high-temperature, radiation tolerant acoustic emission and vibration sensor. Upcoming TREAT experiment requirements were used to guide the development process.
- Several concepts were explored with a single concept chosen for development based on maximizing radiation tolerance, maximizing operating temperature, and minimizing size.
- The selected magnetostrictive rod-based AE sensor was tested for frequency response, maximum operating temperature, and ability to detect fuel pin rupture at high temperatures.
- The sensor performance was compared to an existing commercially available sensor already in use in TREAT experiments.
- A final design was developed, and prototypes fabricated.

Several areas for possible future improvement of the developed sensor have been identified:

- Increase sensitivity of MS-rod AE sensor
  - Optimize coil
  - Develop better method of DC biasing
- Develop temperature compensation methods for amplitude
- Improve low frequency performance for broader use as accelerometer
- Develop lensed fibers for in-core use of LDV
  - Purchase infrared measurement head for LDV
  - Develop method of creating lenses on end of radiation hard fiber

INL

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