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

ASI Advanced Sensors and Instrumentation

Acoustic Sensors

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Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
October 24 – 27, 2022

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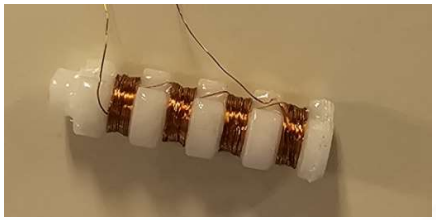
Idaho National Laboratory

Project Overview and 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)
  - In-core, multi-point temperature monitoring; Experiments in test reactors, core monitoring for high temperature advanced reactors; Structural health monitoring for reactor components

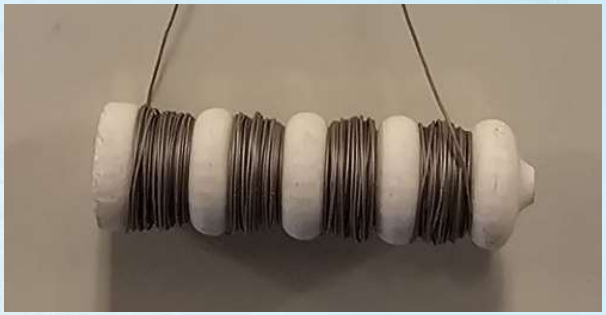
- How does the technology support the nuclear energy industry?
  - Accelerated development and acceptance of new fuels and materials through improved data density and testing in extreme conditions (Advanced Reactors and High Temperature Experiments)
  - Acoustic sensors can be used to monitor numerous parameters
  - Structural health monitoring improves safety and reliability of advanced reactors

Results and Accomplishments-Ultrasonic Thermometer (UT) High Frequency (HF)/High Temperature Transducer

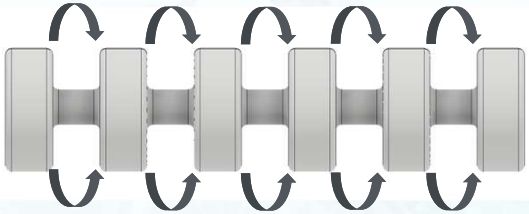


Low Temperature Coil for Bench Testing and Design Refinement

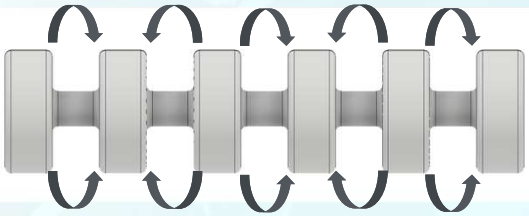
Refined High-Frequency Coil Bobbin After First Print Attempt



High Temperature Coil Printed From Aluminum Oxide-Tested to 950℃



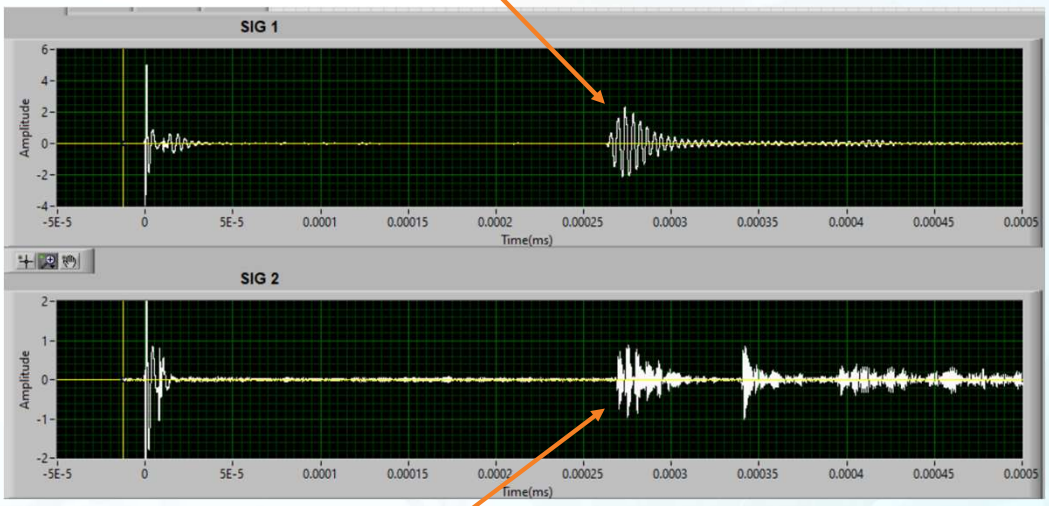
Magnetic Field Orientation When Coils Are Wound In Same Direction



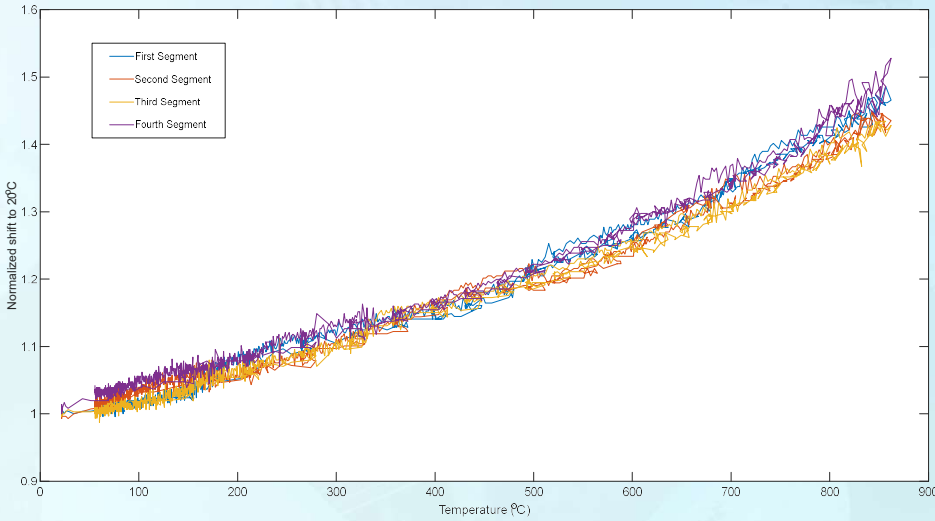
Magnetic Field Orientation When Coils Are Wound In Opposition- Creates Higher Frequency Signals

Results and Accomplishments-UT Testing With High Frequency Coils

Low Frequency (LF) Transducer: 5 Reflectors with 1 cm Spacing Cannot Be Distinguished

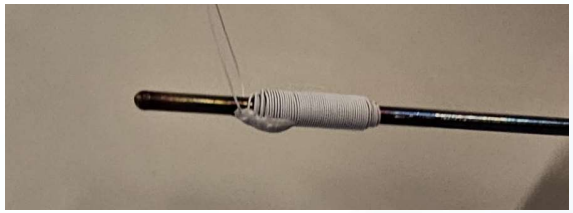


High Frequency (HF) Transducer: 5 Reflectors Clearly Separated with 1 cm Spacing

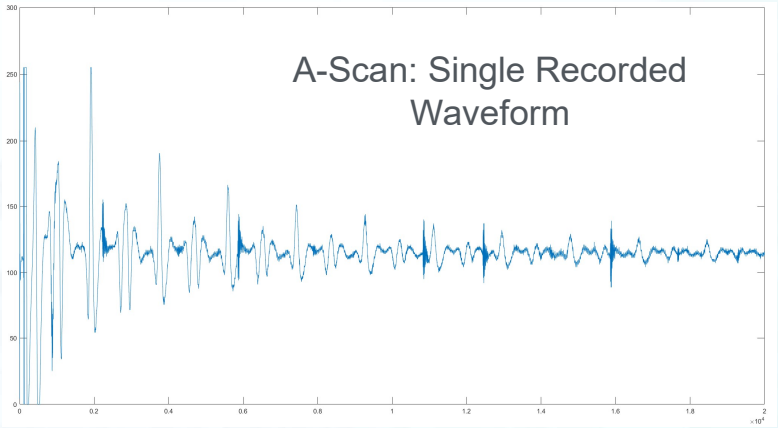


Temperature vs Delay Time for HF UT, Data for LF UT could not be Resolved

Results and Accomplishments-Magnetostrictive Heat Treat and High Temperature Coils

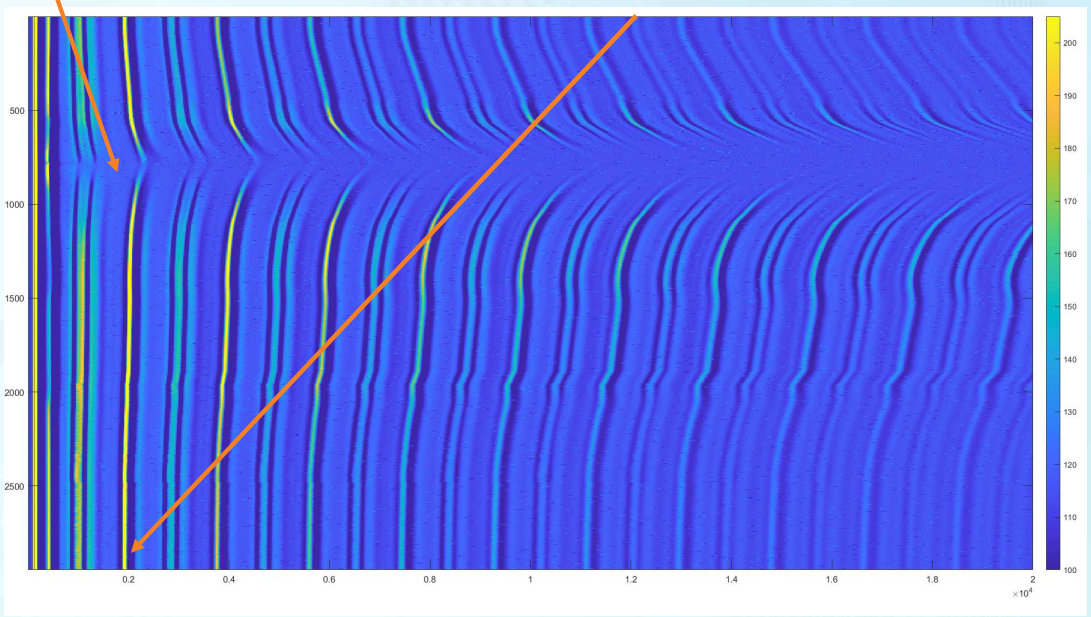


High Temperature Coil Used for Heat Treating Magnetostrictive Wire



Loss of Magnetostriction at Curie Temperature (930℃)

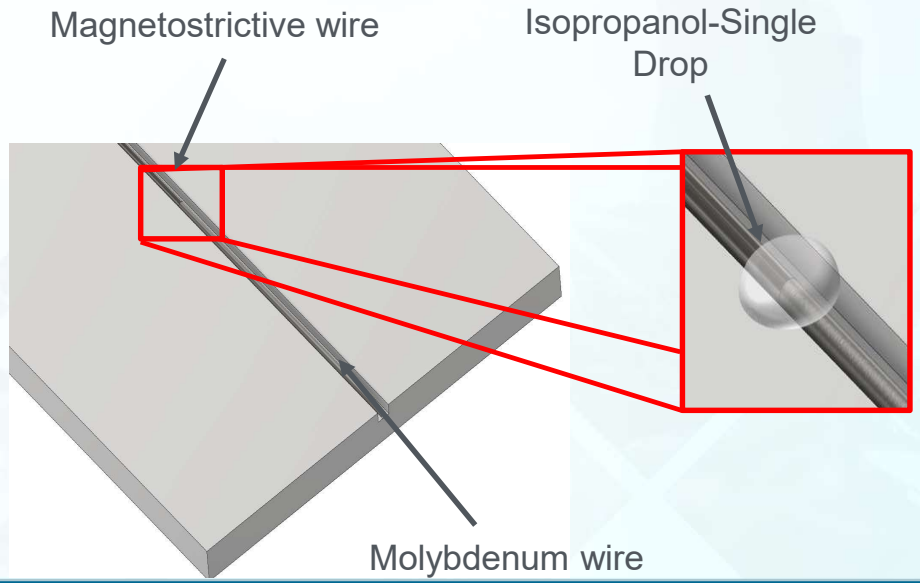
Slight Increase in Intensity After Heat Treat Indicates Completion of Annealing Process



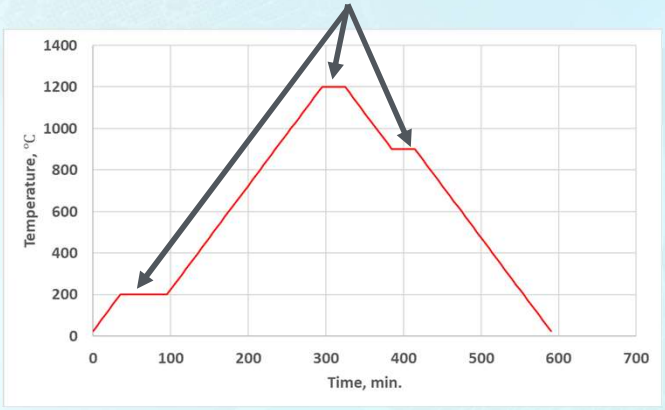
B-Scan: Trace of Recorded Waveforms Showing Amplitude as Intensity

Results and Accomplishments-UTs for BWXT Advanced Nuclear Reactor (BANR) Experiment

- Two molybdenum UTs fabricated for BANR test fit and braze development
  - Both use multiple waveguides providing four temperature measurement zones
  - New fabrication methods developed in FY-22 were used including new weld and heat treat methods
    - Single drop of isopropanol protects weld joint from oxidation, rapidly cools weld as it evaporates
  - Brazing test to be performed in early FY-23, results will inform design of UT to be included in irradiation experiment planned for the Advanced Test Reactor (ATR)



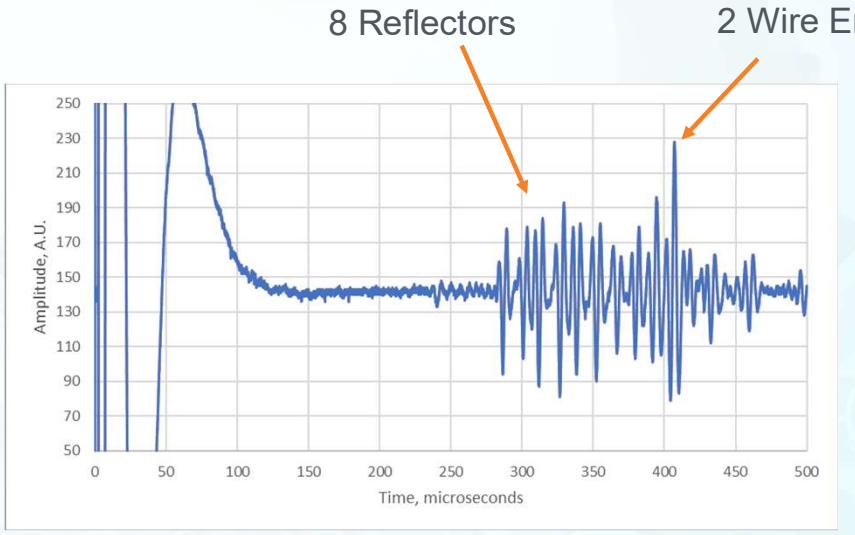
Heat treatment for molybdenum parts.
Temperature holds at 200, 1200, and 900℃.
Heating and cooling rates of 5℃/min.



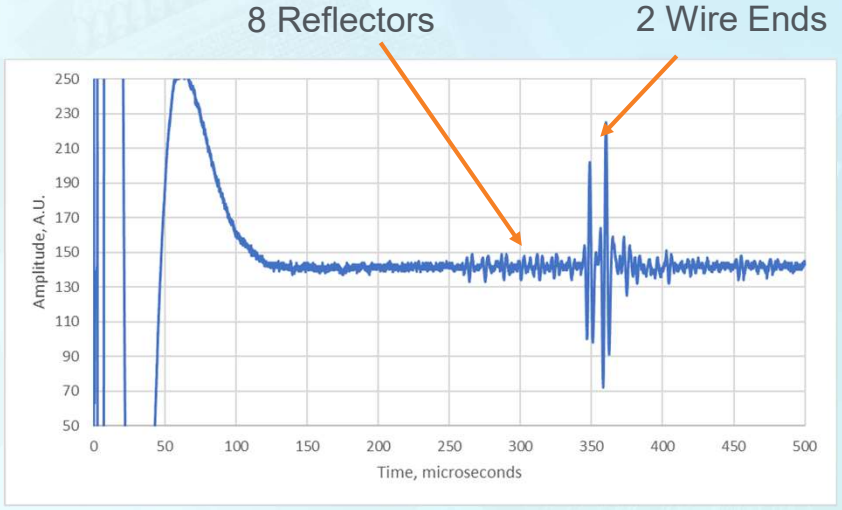
Results and Accomplishments-UTs for EVINCI Long Term Furnace Test

- Two 10 segment UTs fabricated for inclusion in Evinci related long term furnace test
- “Hybrid” design used in which each UT has two waveguides of different length with multiple reflectors on each
- Reflectors and wire ends are staggered, resulting in a cleaner signal

Transducers



Signal for Inconel 600 sensor



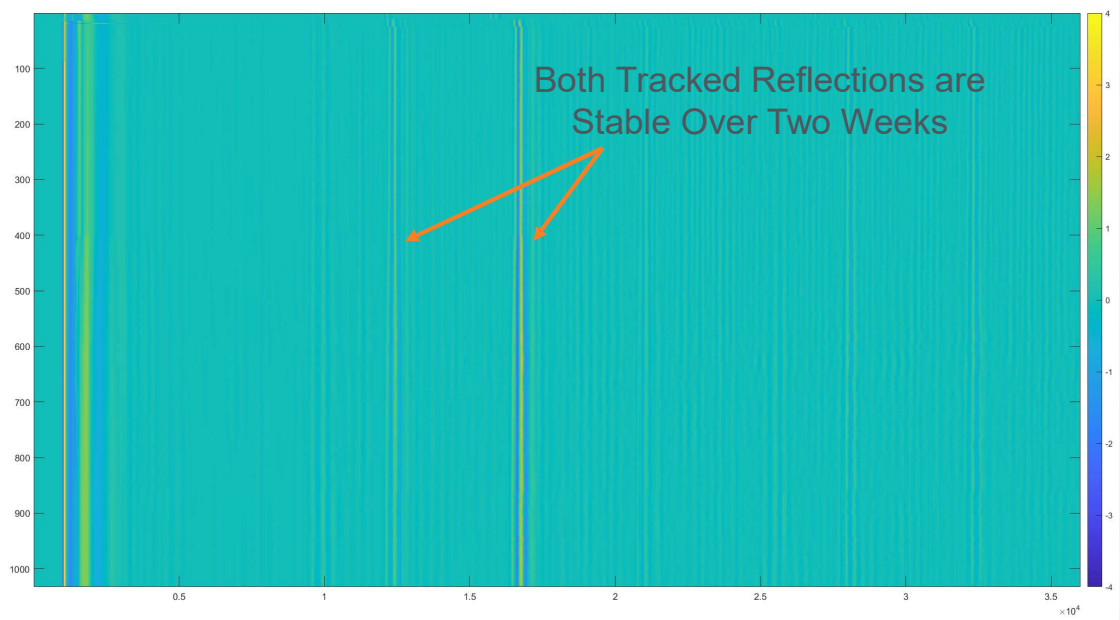
Signal for molybdenum sensor

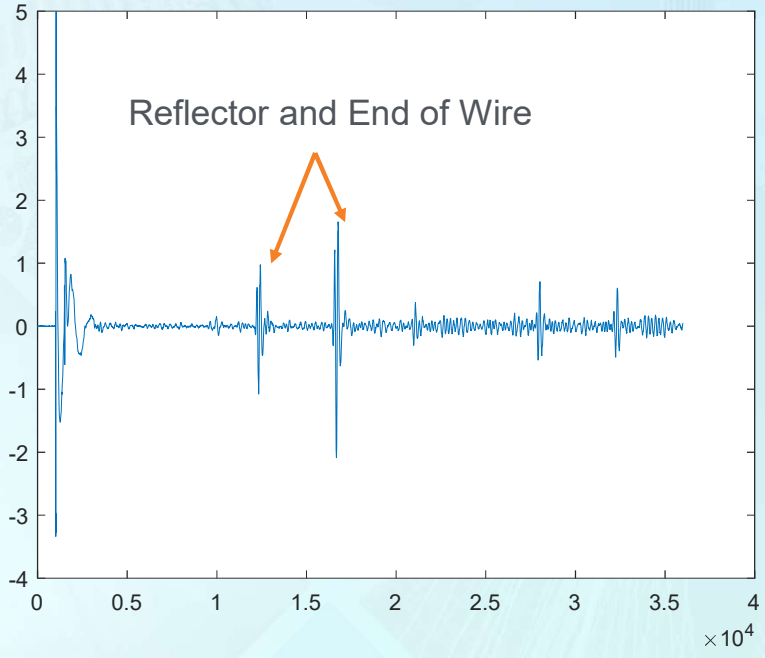
Results and Accomplishments-UTs for Planned ATR Test

- Nine UTs are being fabricated for inclusion in future ATR experiments
- Space requirements mean that the UTs must be kept very short, but multiple measurement nodes are still needed
- Six sensor materials tested to improve performance of short UT sensors
- Lower speed of sound materials are preferred, as they improve the accuracy of delay time measurements:
  - Stainless Steel
    - Standard material used for low temperature (<1000℃) measurements
  - Platinum
    - Lowest speed of sound at room temperature
  - Titanium
    - Previously used, high temperature sensitivity, low neutron interactions
  - Zirconium/Zircaloy-4
    - High temperature sensitivity, low neutron interactions
  - Silver/Palladium alloy
    - Low speed of sound at room temperature, used as high temperature magnet wire
  - Tantalum
    - Low speed of sound, very high melting temperature
- A two-week steady state test was performed at 650℃ to observe any signal changes, such as sticking or attenuation

Results and Accomplishments-UTs for Planned ATR Test: SS

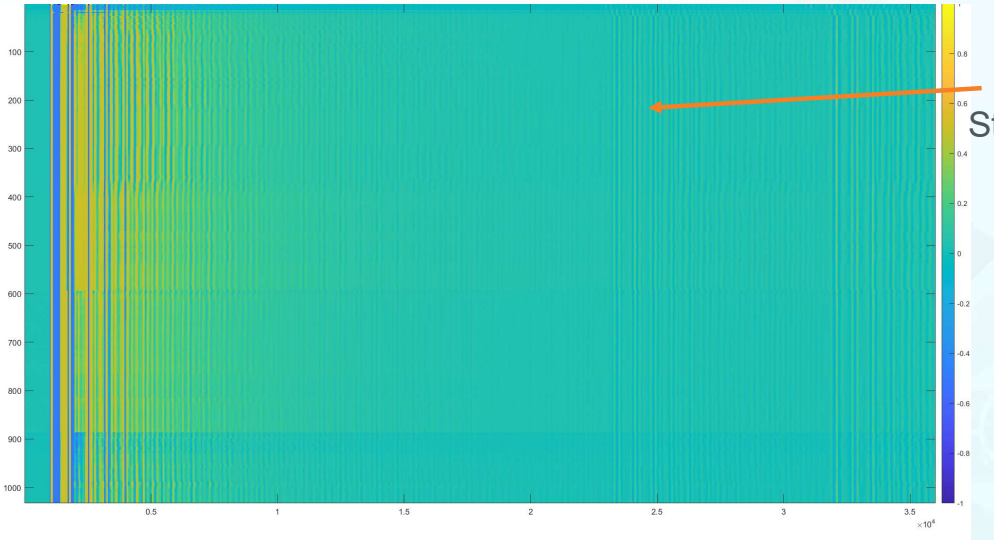
- Signal is strong, clean, consistent over course of test
- No sticking was observed

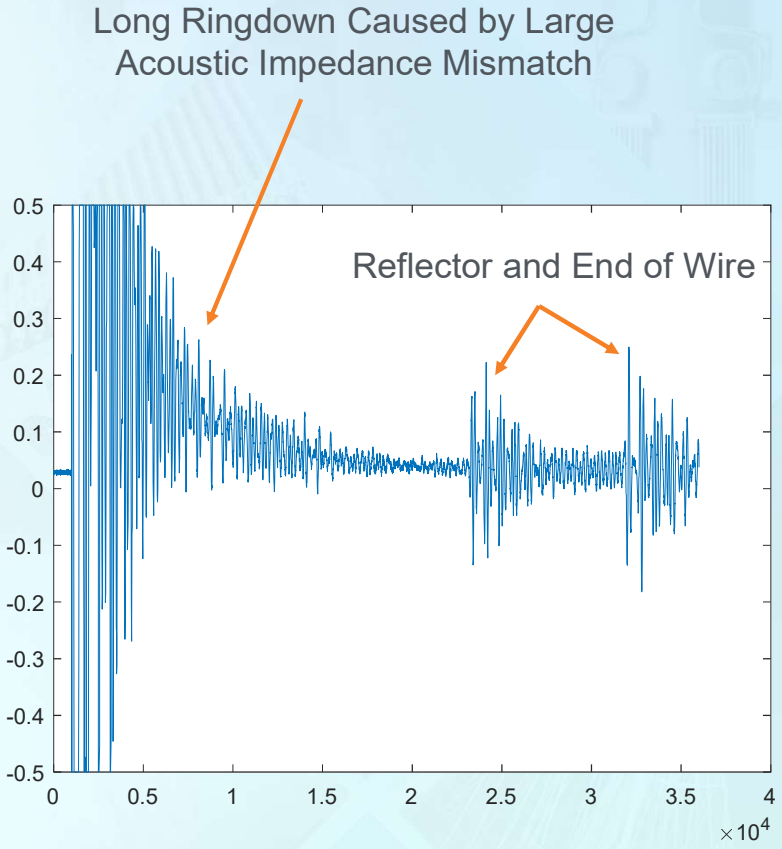




Results and Accomplishments-UTs for Planned ATR Test: Pt

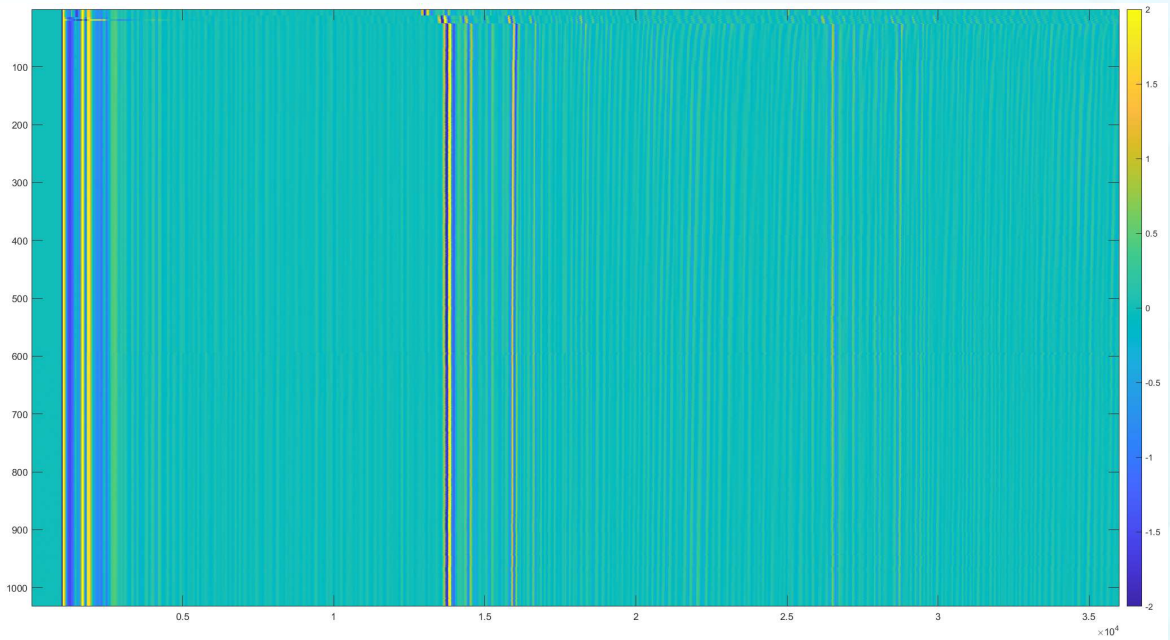
- Platinum has a very low speed of sound
- Acoustic impedance mismatch causes a long ringdown and obscures needed signal features
- The softness of the material results in plastic deformation with any applied force
- The signal shows extreme attenuation near the test temperature
- No sticking was observed

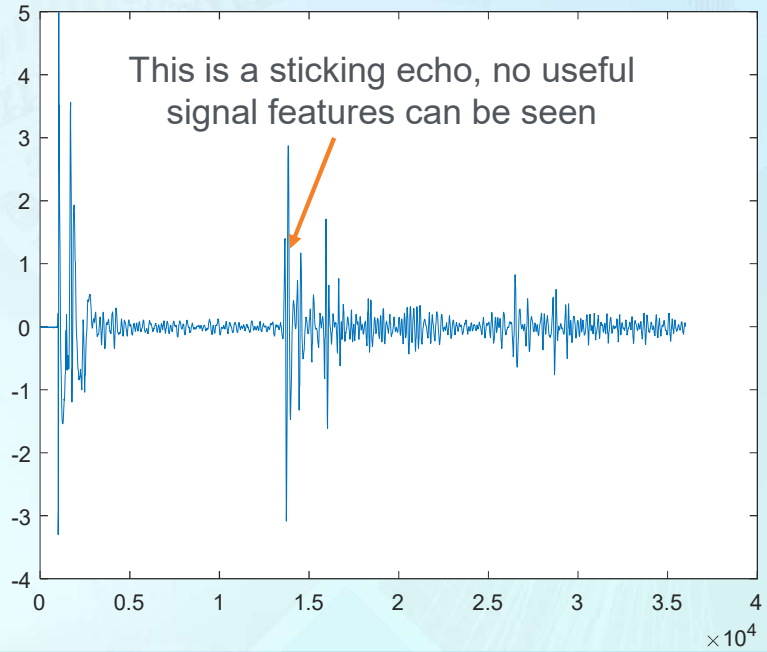




Results and Accomplishments-UTs for Planned ATR Test: Ti

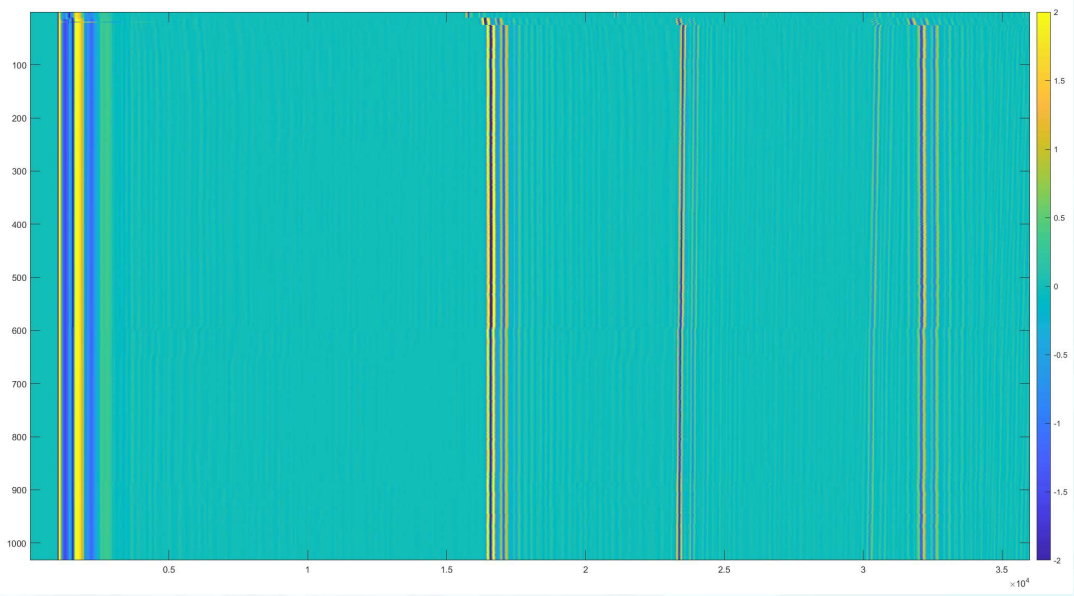
- Sticking was observed to occur during initial heat-up
- Signal was obscured during the entire two weeks of the test.

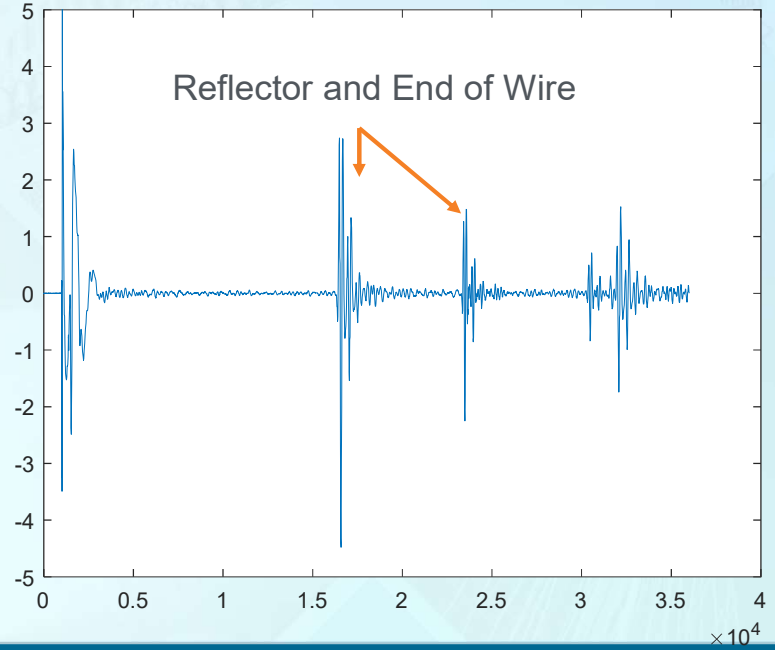




Results and Accomplishments-UTs for Planned ATR Test: Zr

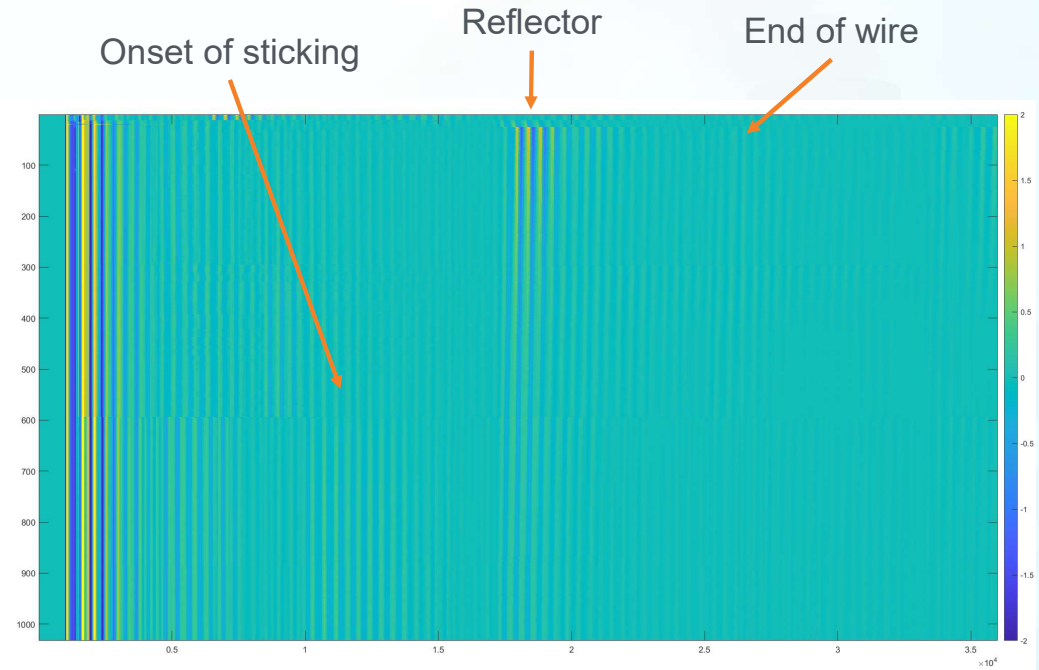
- Signal is strong, clean, consistent over course of test
- No sticking was observed



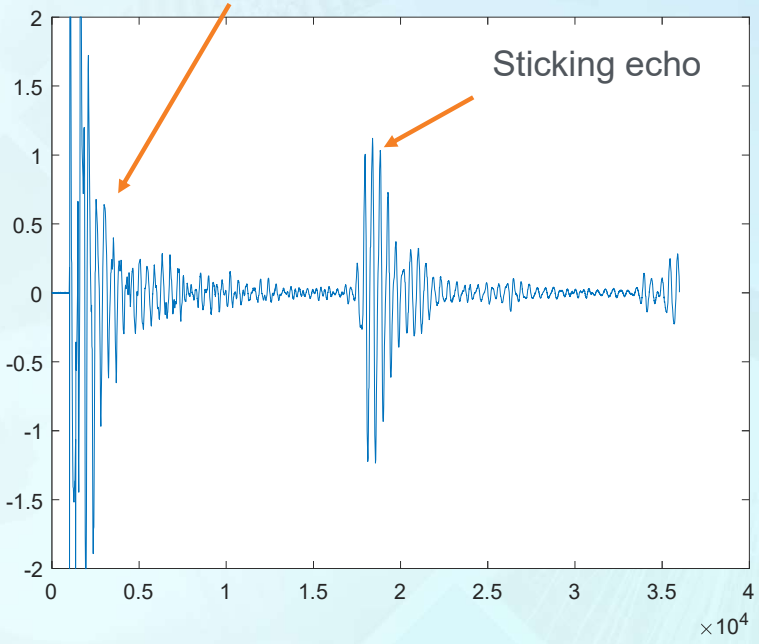


Results and Accomplishments-UTs for Planned ATR Test: Ag/Pd

- Acoustic impedance mismatch causes a long ringdown and obscures needed signal features
- The signal shows some attenuation near the test temperature
- Sticking was observed and obscured the signal

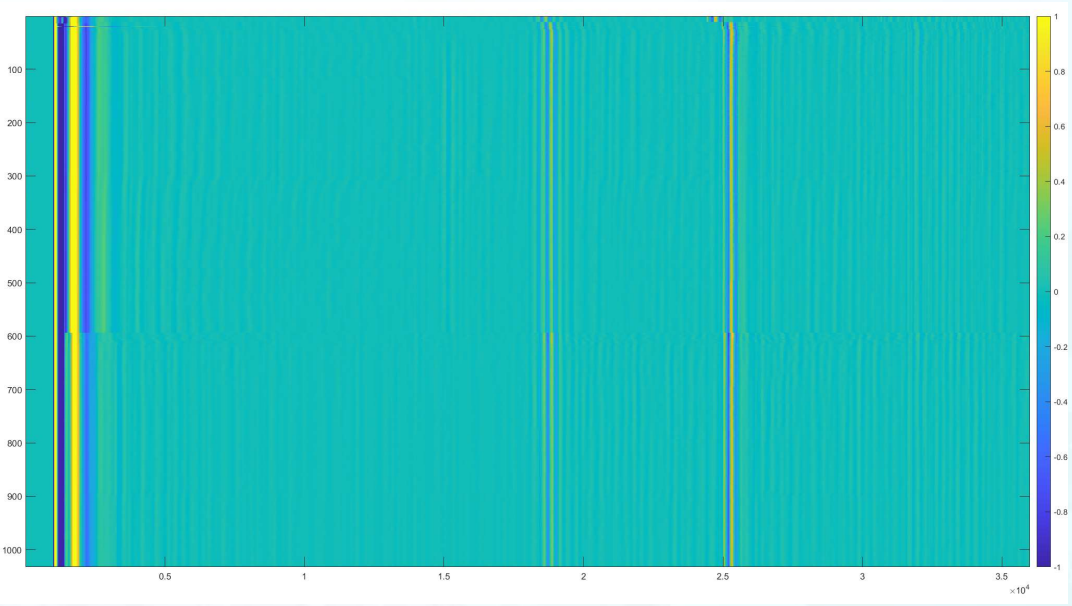


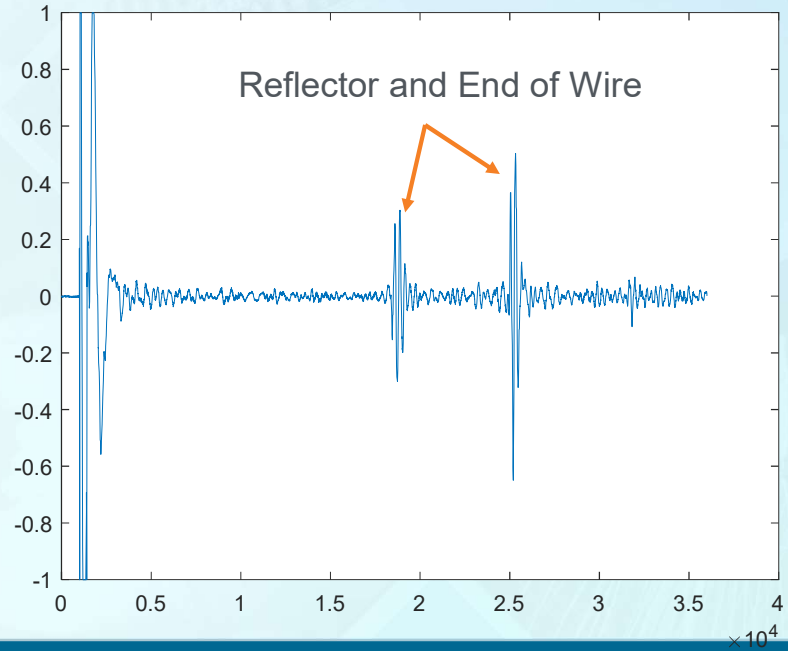
Long Ringdown Caused by Large Acoustic Impedance Mismatch



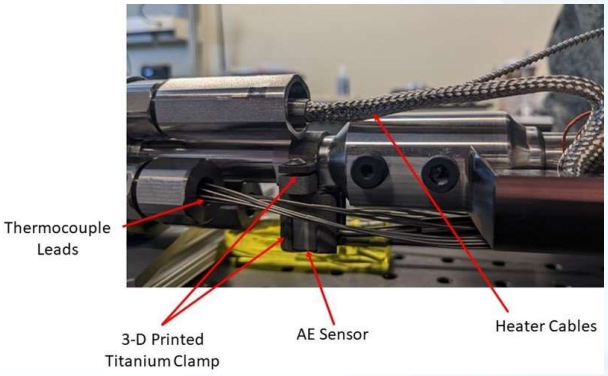
Results and Accomplishments-UTs for Planned ATR Test: Ta

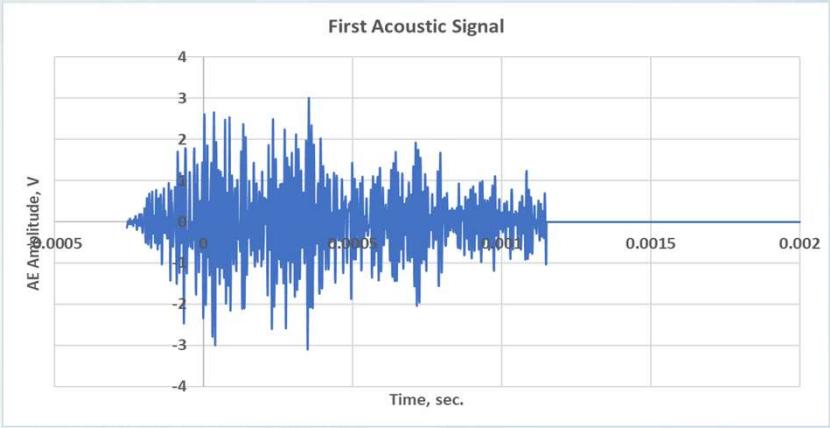
- Signal is strong, clean, consistent over course of test
- No sticking was observed

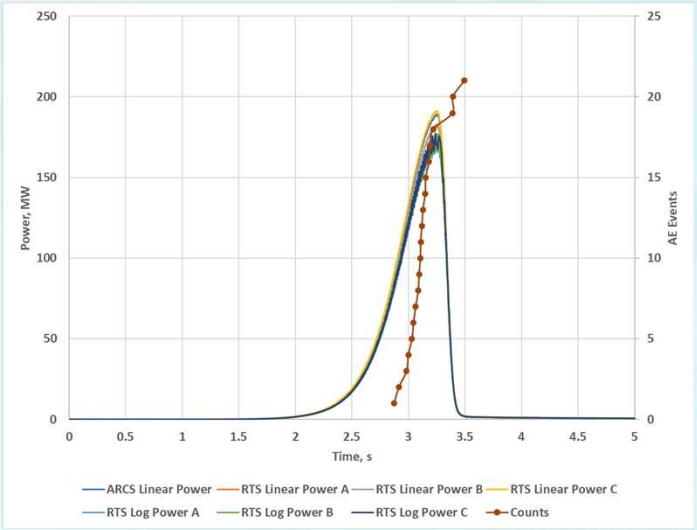




Results and Accomplishments-AE Sensor Testing





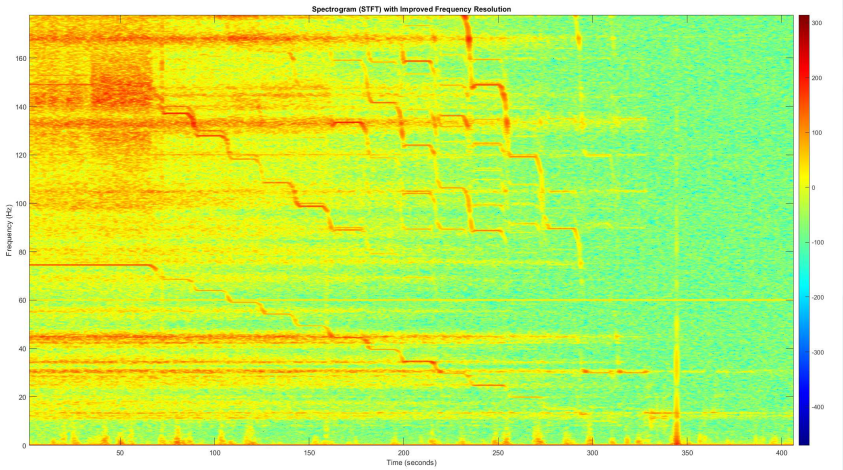


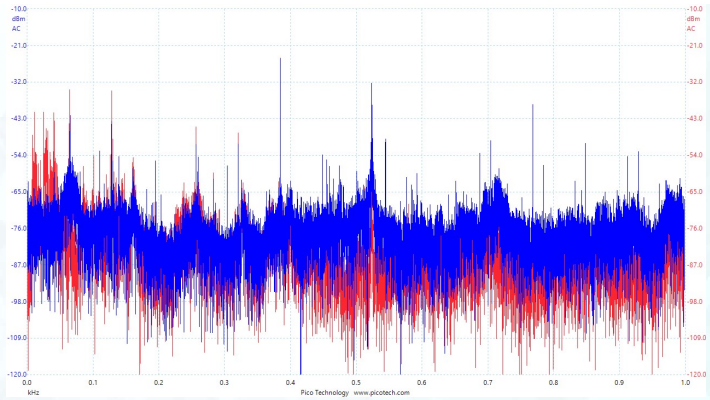
Commercial AE sensor:

- Tested on benchtop and in furnace using “pencil break” method
  - Good performance to ~550 C.
- Included in several test irradiations
  - Survived low power transients
  - Some noise issues/crosstalk
- Detected possible cladding breach/boiling
  - Waiting on PIE to verify

Results and Accomplishments-Vibration Sensor Testing

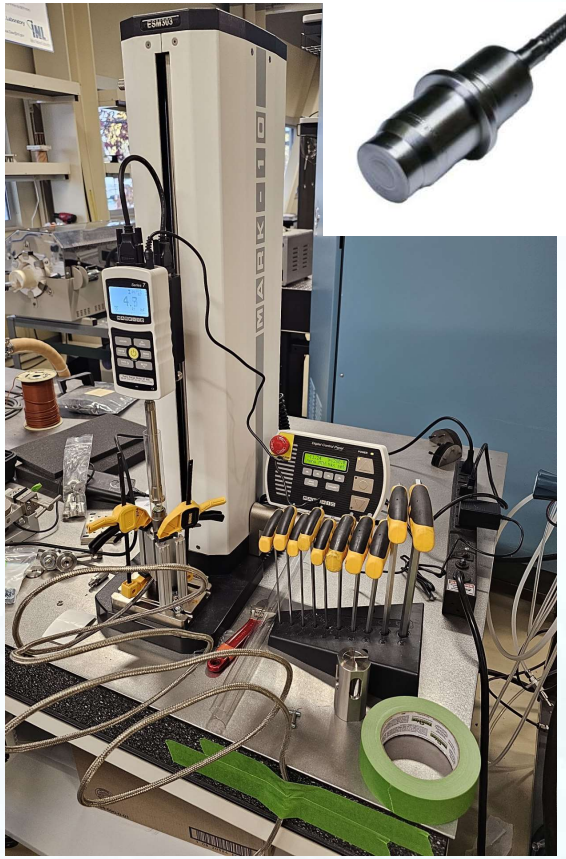
System measurements with varying pump speed

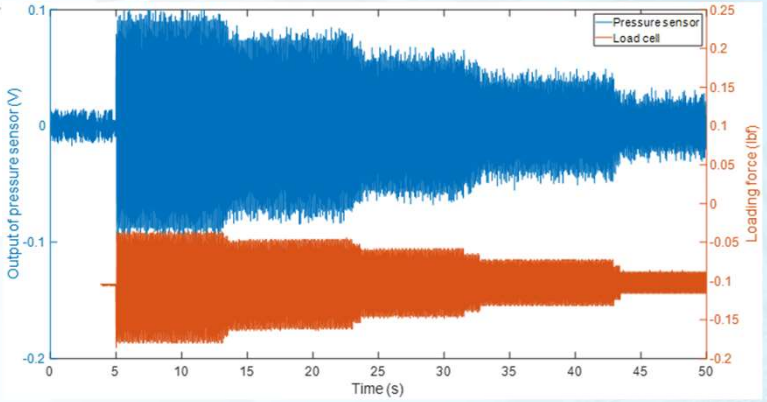


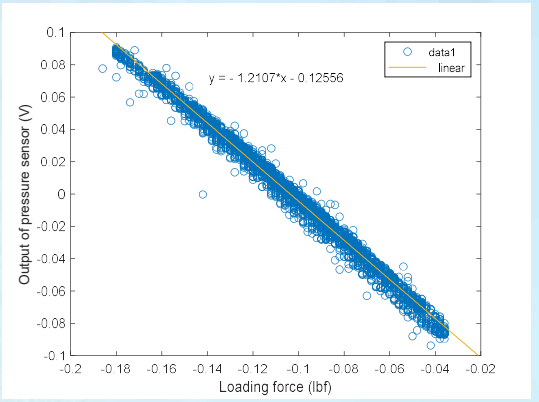


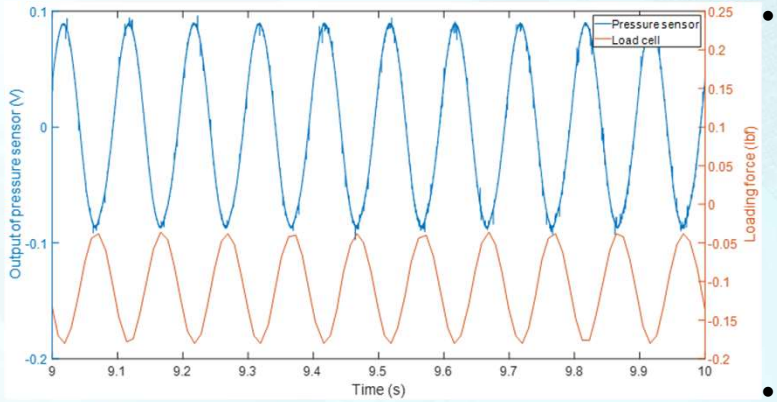
- Accelerometer and LDV show close agreement
- Notable changes to frequency spectrum with changing components and pump speeds
- FAS is ideal facility for testing vibration sensors

Results and Accomplishments-Pressure Sensor Testing









- Dynamic pressure sensors tested using tensile/compression testing system and acoustic drivers
  - High frequency performance is excellent, but current leakage limits low frequency use: cannot be used for static pressures
- Testing in autoclaves planned

Results and Accomplishments-Sensor Development Planning


PRS/RPT-23-03913
Revision 0

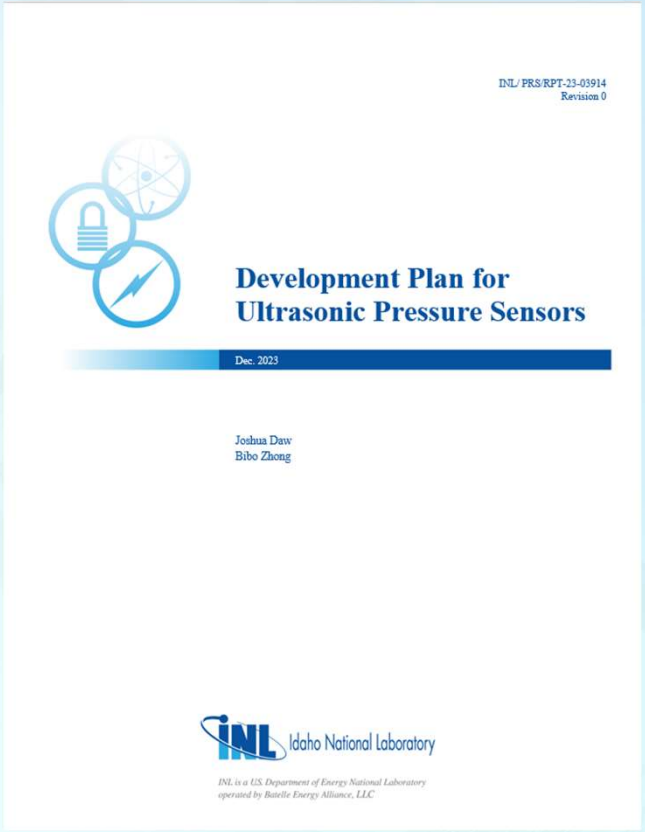
Development Plan for Acoustic Emission and Vibration Sensors

Nov. 2023

Joshua Daw
Bibo Zhong

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC


INL/ PRS/RPT-23-03914
Revision 0

Development Plan for Ultrasonic Pressure Sensors

Dec. 2023

Joshua Daw
Bibo Zhong

Idaho National Laboratory

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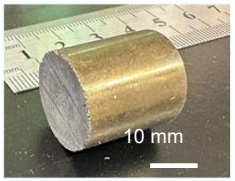
Results and Accomplishments-BSU

Nanosynthesis of Magnetostrictive Materials

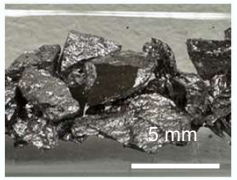
- Synthesized Terfenol-D nanoparticles at room temperature
- Synthesized Galfenol nanoflakes at -190 ℃

Terfenol-D (Room-temperature Ball Milling)

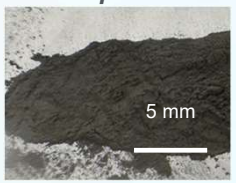
Bulk



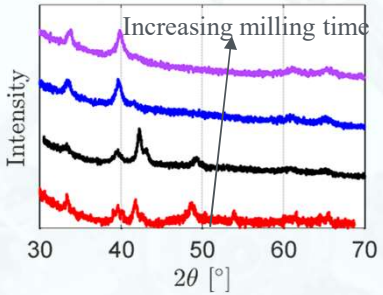
Pellets



Nanoparticles

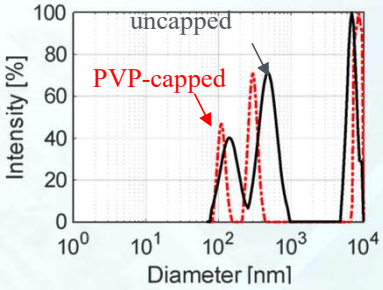


XRD Results

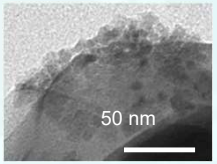


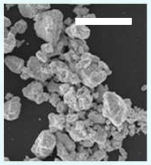
No oxidation peaks

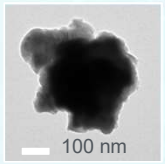
DLS Results



Particle Morphology

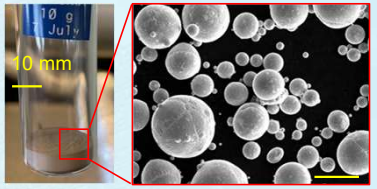




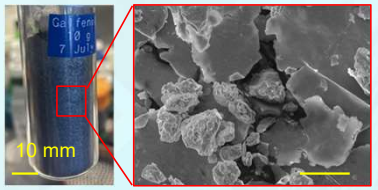


Galfenol (Cryogenic Ball Milling)

Microparticles from LLNL



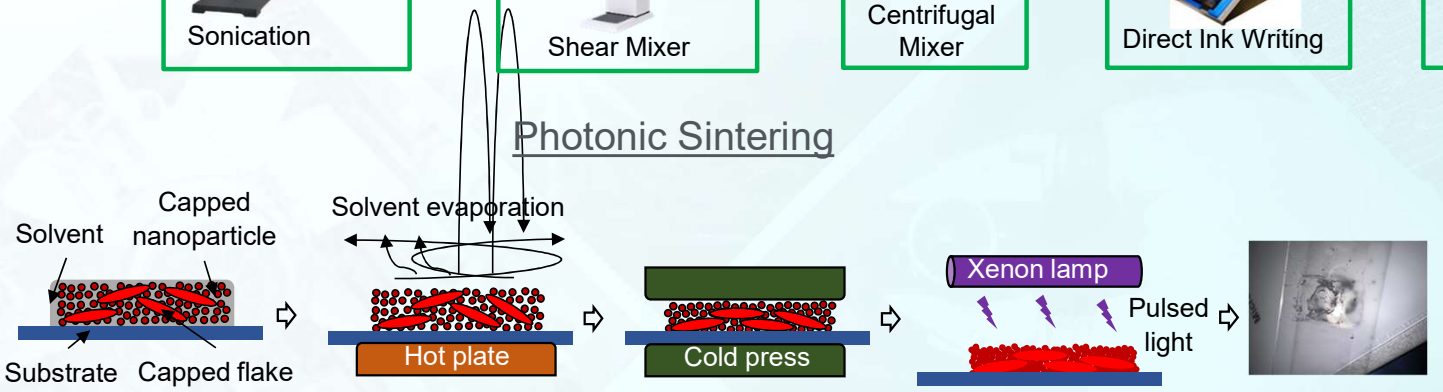
Nanoflakes



Results and Accomplishments-BSU

Terfenol-D Printing

- Printed monolithic Terfenol-D films using direct ink writing
- Conducted thermal and photonic sintering of Terfenol-D films

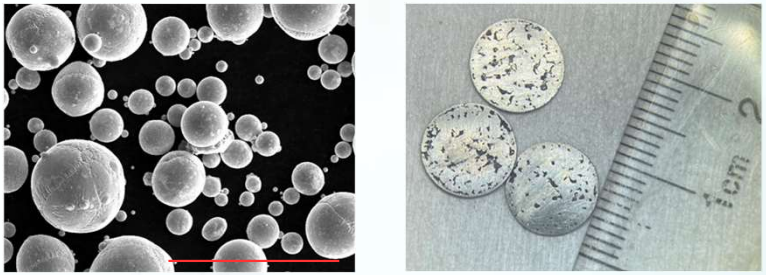


Results and Accomplishments-BSU

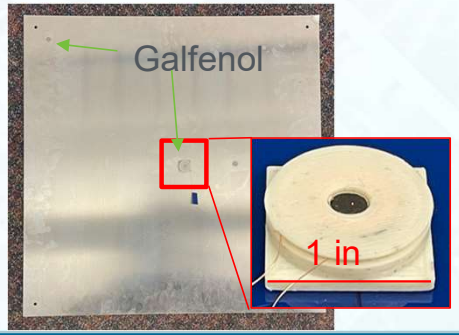
Galfenol-based Lamb Wave Transducer

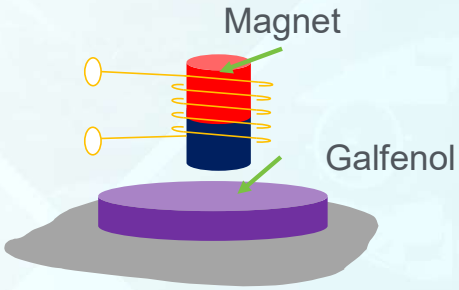
- Tested Galfenol discs provided by LLNL (printed by laser powder bed fusion)
- Demonstrated the capability of Galfenol discs in generating and detecting Lamb Waves

Printed Galfenol Discs (Provided by LLNL)

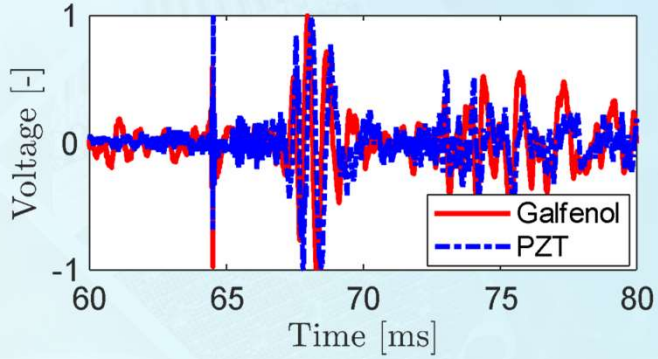


Galfenol Lamb Wave Transducer

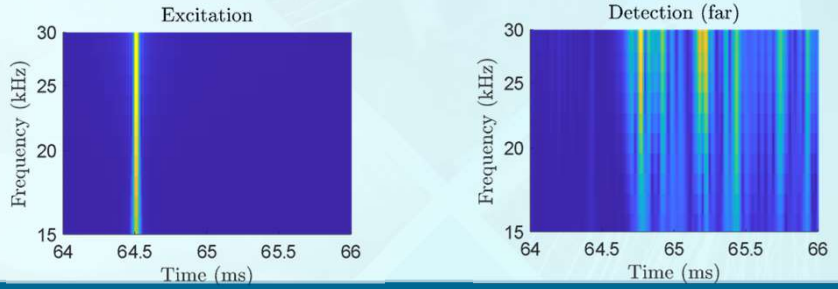




Galfenol vs. PZT discs (Time-Domain Signal)



Galfenol discs (Frequency Domain Signal)

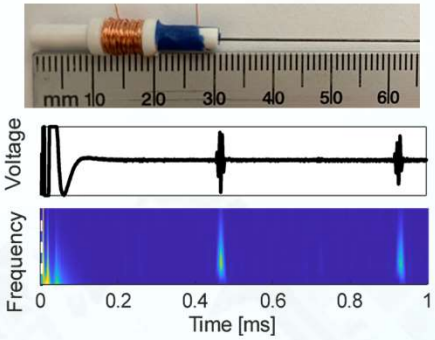


Results and Accomplishments-BSU

Galfenol-based Waveguide Transducer

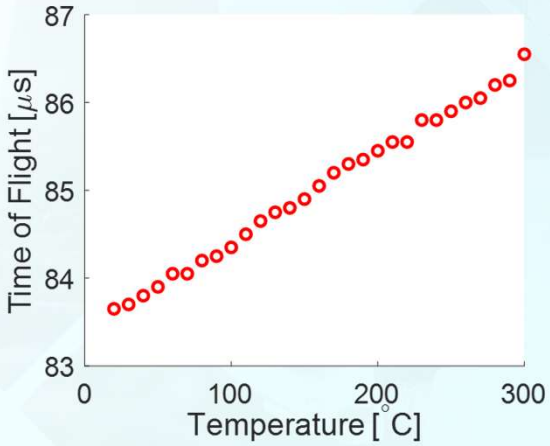
- Tested Galfenol waveguides with different diameters (0.5, 0.8, and 1.0 mm)
- Tested Galfenol waveguides up to 300 ℃
- Visualized wave propagation in the 1.0 mm diameter waveguide using a laser vibrometer

Galfenol Waveguide

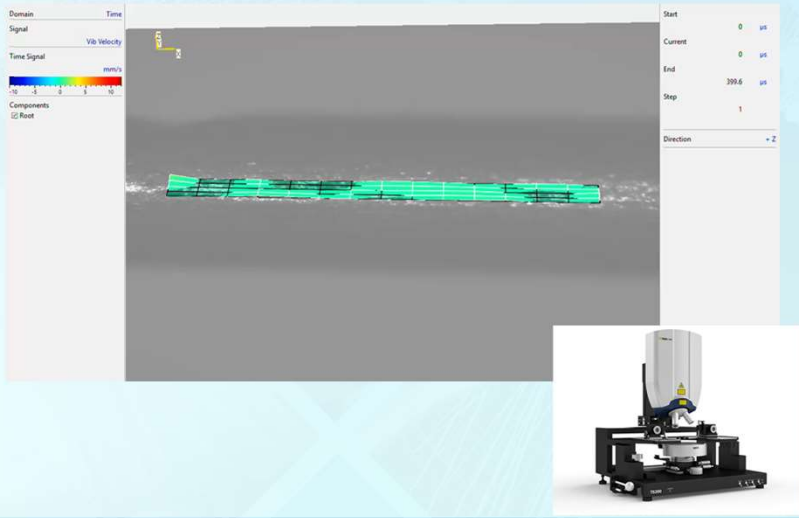


High Temperature Test (Joule Heating)

Time-of-Flight vs. Temp



Wave Visualization (Polytec MSA-600)

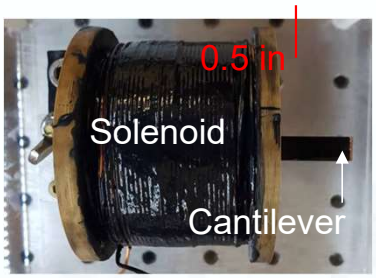


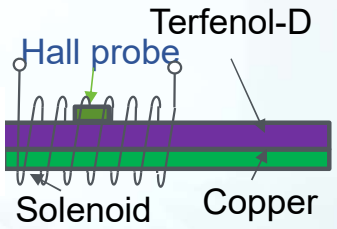
Results and Accomplishments-BSU

Magnetostrictive Material Modeling

- Collected Terfenol-D unimorph beam data for model validation
- Developed a finite element model that accounts for both major and minor loop responses
- Developed a finite element model that can handle both time- and frequency-domain analyses

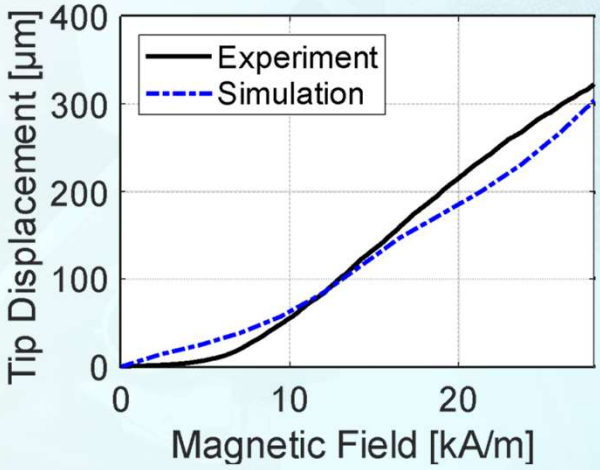
Terfenol-D Unimorph Cantilever



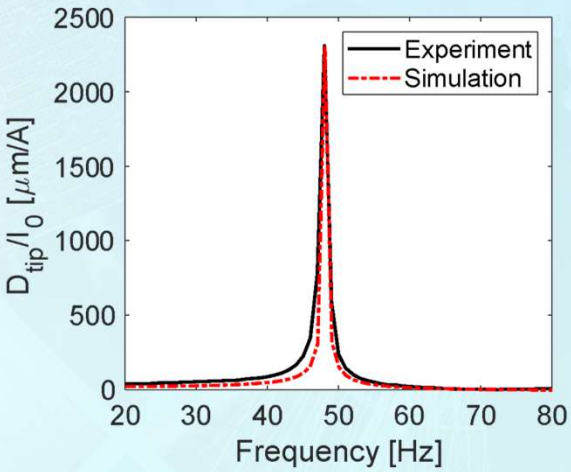


The tip deflection (measured by laser displacement sensor) is measured as a function of the solenoid current (I_0) or the longitudinal magnetic field (measured by a Hall probe)

Time-domain Simulation



Frequency-domain Simulation



Results and Accomplishments-BSU

- This project supported 2 undergraduates, 1 MS student, and 1 PhD student in FY23.
- Joy Morin, the PhD student working on this project, received the INL Graduate Fellowship and will start at INL in January 2024.
- Joy Morin gave a presentation entitled " Nanosynthesis of Terfenol-D Enabled by High Energy Ball Milling" on September 13 at the ASME SMASIS conference (Austin TX, September 11-14, 2023)
- Three papers have been published in FY23:
  1) Joy Morin and Zhangxian Deng. " Nanosynthesis of Terfenol-D Enabled by High Energy Ball Milling" *in proceedings of SMASIS* 111048 (2023).
  2) Draper, Alejandro, et al. "Multiphysics modeling of printed surface acoustic wave thermometers." *Sensors and Actuators A: Physical* 359 (2023): 114491.
  3) McKibben, Nicholas, et al. "Aerosol jet printing of piezoelectric surface acoustic wave thermometer." *Microsystems & Nanoengineering* 9.1 (2023): 51.

Concluding Remarks

- Improved UT design tested
  - High temperature, high frequency coils show marked improvement over prior design for closely spaced reflectors
  - Optimization of magnetostrictive properties requires tailored heat treatment, process developed with real time monitoring
  - UTs fabricated using new techniques for several AR applications and future ATR irradiations
- Commercial AE, vibration, and pressure sensors tested using INL infrastructure
  - Benchmarks sensors and testing facilities for near term sensor development
  - Some testing is ongoing
- BSU has made significant progress in modelling, testing, and printing of magnetostrictive materials and sensors

International Instrumentation and Measurement Technology Conference Special Session: Sensors and Measurements for Small Modular and Micro-Reactors

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Thank You