Development of Radiation Endurance Ultrasonic Transducer for Nuclear Reactors

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

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Project Overview

Motivation

DOE seeks development of sensors and nondestructive evaluation technologies, capable of surviving in substantial radiation fields is necessary to advance nuclear plant control and monitoring systems, data analysis and other nuclear applications with demonstrated

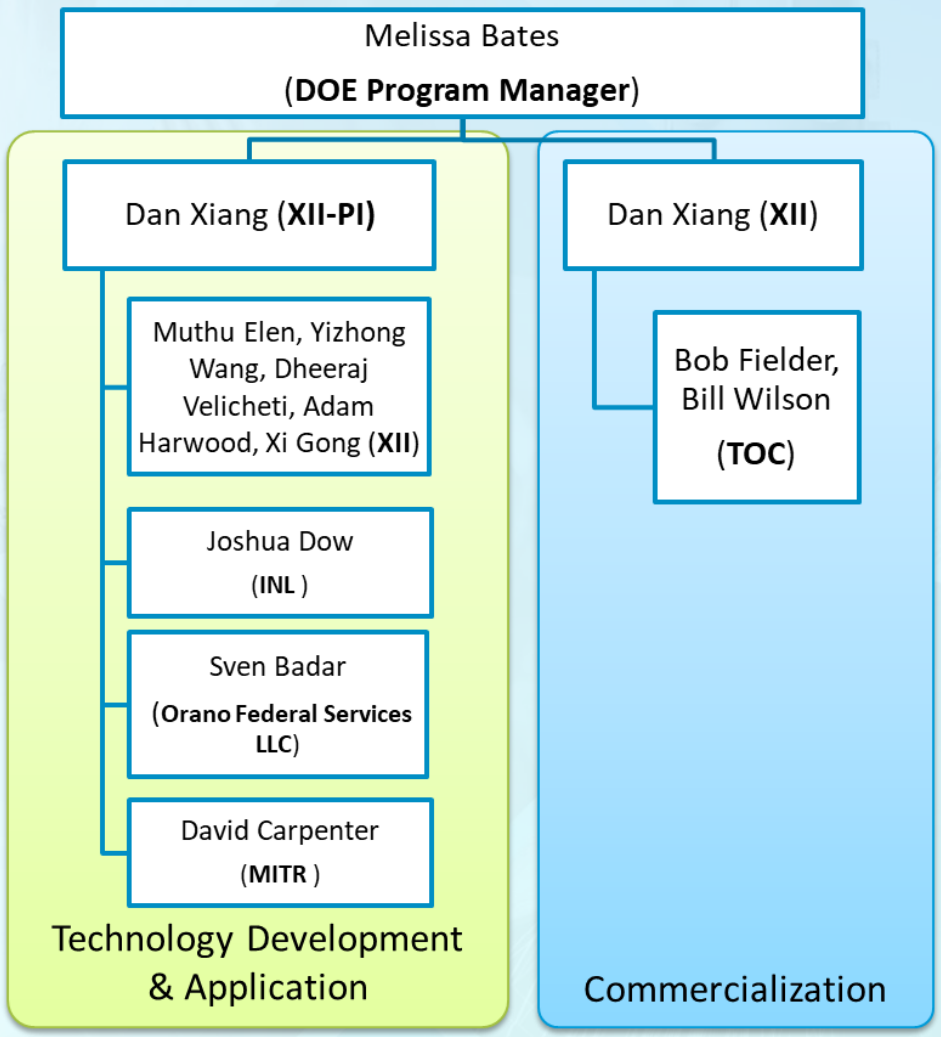
- Accuracy
- Reliability
- Resilience
- Ease of replacement and upgrade
- Directly support existing power reactors, material test reactors and other similar systems.

Our Solution

Radiation Endurance Ultrasonic Transducer (REUT) for nuclear applications. This 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.

Participants



Project Overview

REUT and sensor development target

- Improve REUT design
- Develop REUT sensor systems
  - Temperature sensor
  - Pressure sensor
  - AE sensor
  - Flow rate sensor
  - Liquid Level sensor
  - Making REUT wireless
- Testing and Validation

Tasks	2020		2021				2022				2023		Participants
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
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	X	X	X	X			XII, INL, MITR
4. Modify REUT design to support wireless interrogation					X	X	X	X					XII
5. Conduct irradiation tests and performance evaluation					X	X			X	X	X		XII, INL, MITR, Orano
6. Demonstrate prototype abilities										X	X		XII, Orano, INL, TOC
7. Transition/commercialize the technology	X	X	X	X	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 24)
Milestone 4.
Irradiation testing (month 28)
Milestone 5.
Demonstrate prototype ability and develop Phase III work plan (month 36)

Current achievements

We have

- Used improved REUT design to develop Temperature sensor, Viscosity monitoring sensor, AE and GW structural health monitoring, Flow meter, and Fluid level systems.
- Developed a 8-channel Data Acquisition System for REUT sensor systems
- Developed application software and signal processing algorithms for those sensor systems
- Developed 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.*"

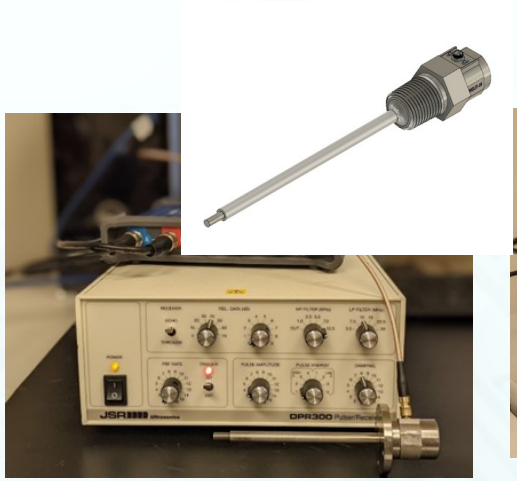
REUT is simply an ultrasonic transducer sensor which offers capability of operating at high temperatures along with potentially being radiation tolerant. Many ultrasonic sensors can be built using this REUT which can offer ultrasonic sensing capabilities at higher temperatures and other harsh conditions.

Technology Impact

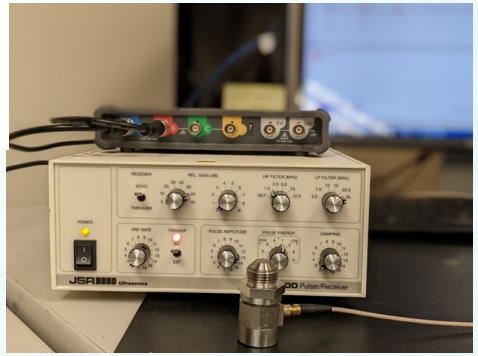
Phase II – previous work done in FY2021:

- Improved the design of REUT sensors using thread and rf connectors
- Developed a REUT temperature sensor with a waveguide
- Developed a REUT viscosity monitoring system and application suite
- Built a REUT guided wave structural health monitoring (SHM) system
- Built a REUT acoustic emission SHM system
- Developed signal processing and software with GUIs for all applications

SHM – Guided waves

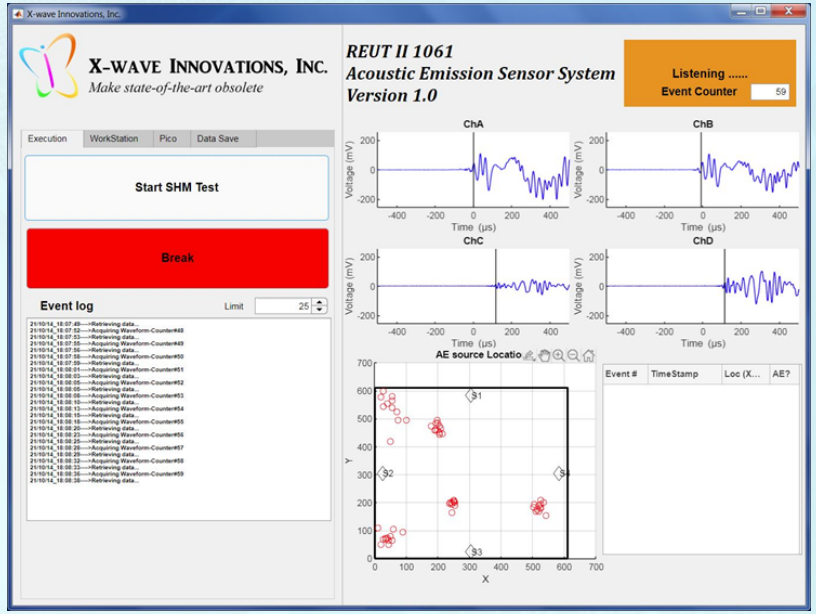


Temperature Measurement using Waveguide



Viscosity Measurement

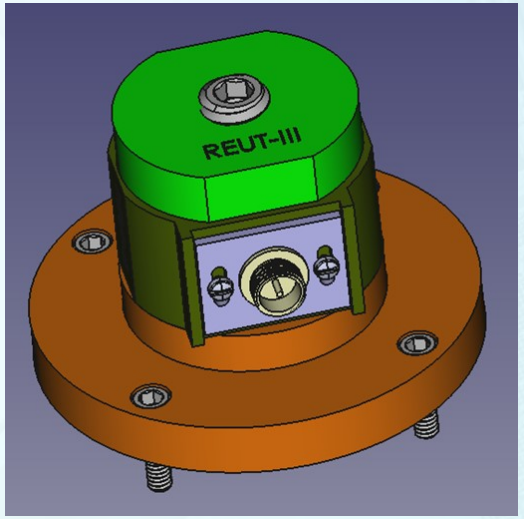
SHM – Acoustic Emission

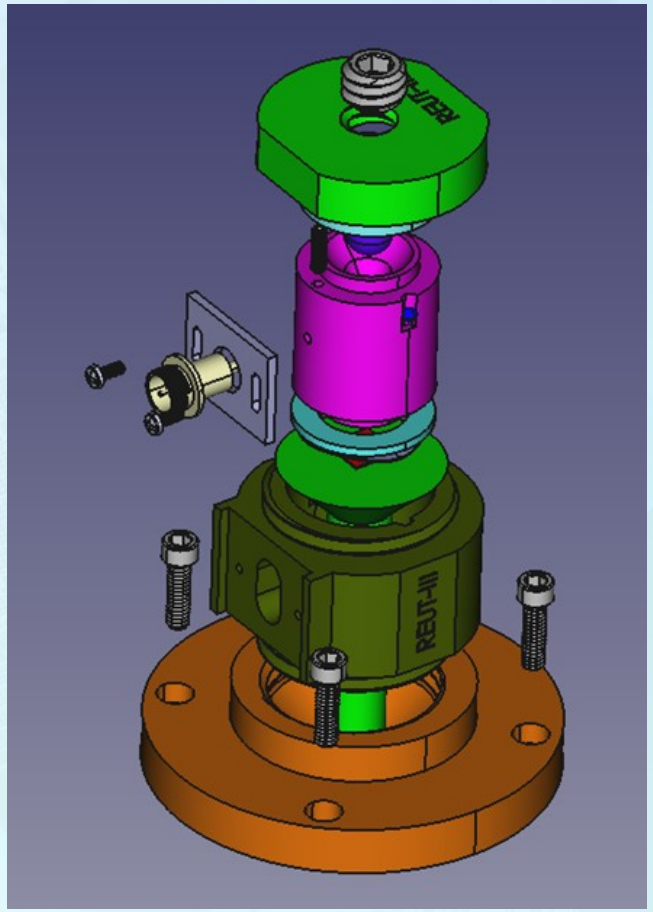


Results and Accomplishments

Improved REUT Design – REUT III

- Based on our previous designs of REUT I and REUT II, we improved the REUT-III with a microdot connector for electrical connection
- The previous backing contains 2-56 threaded hole to use threaded rod as connecting rod for excitation and reception. The newly developed backing still contains mechanism to have 10-32 micro connectors for rf connection.
- The backing length is reduced to accommodate thick piezoelectric up to 1mm in thickness. This new backing length will still accommodate thinner piezoelectric.
- Through this design, we were able to achieve higher frequencies

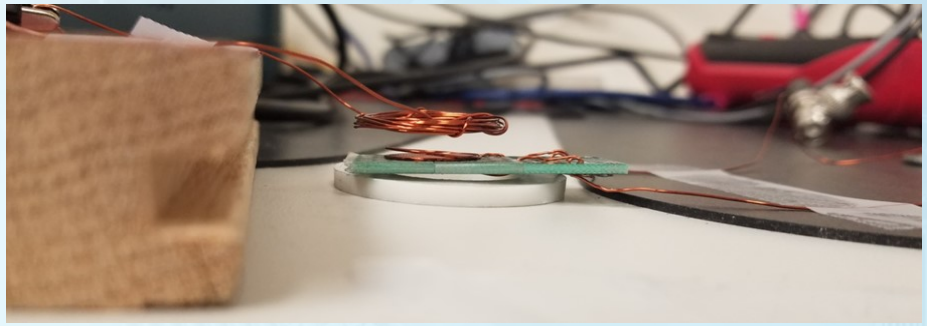


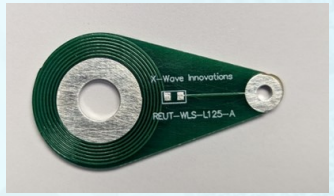


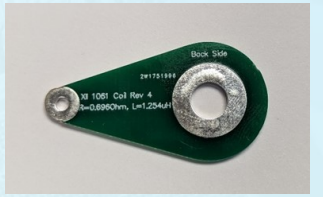
Results and Accomplishments

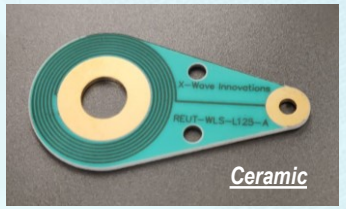
Wireless REUT:

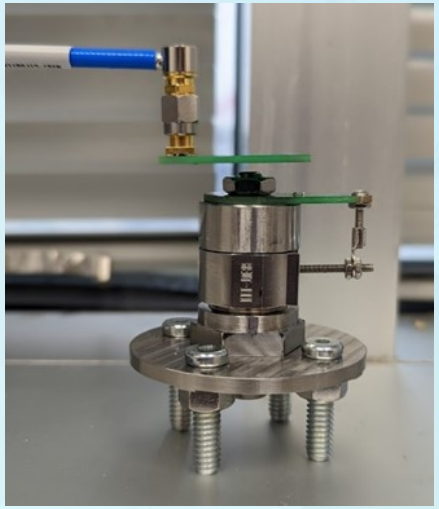
- Developed wireless REUT scheme to eliminate permanent wire connections to sensors
- Reduce sensor system maintenance, especially electrical connections failure
- Developed a wireless thickness monitoring application
- Can be adopted for the other REUT applications of temperature, viscosity and SHM applications



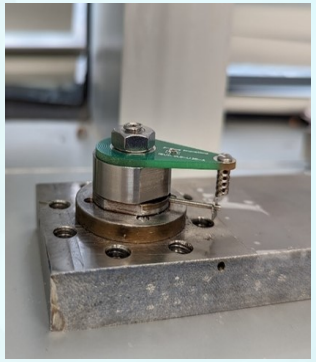








Pulse/Receiver Interrogation coil parameters			
Coil Shape	Ring	Inductance	3.976 uH
Coil Diameter	25.4	Resistance	0.145 Ohm
Number of turns	12	Impedance @ 1kHz	0.147 Ohm
Transducer pickup coil parameters			
Coil Shape	Spiral	Inductance	2.23 uH
Coil Diameter	D1=0 and D2=15.5	Resistance	0.176 Ohm
Number of turns	15	Impedance @ 1kHz	0.172 Ohm



Results and Accomplishments

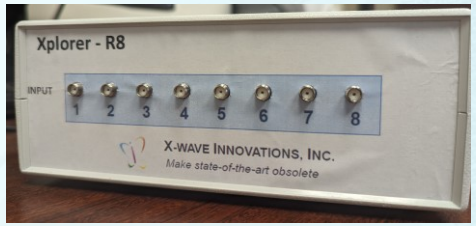
REUT Data Acquisition Hardware :

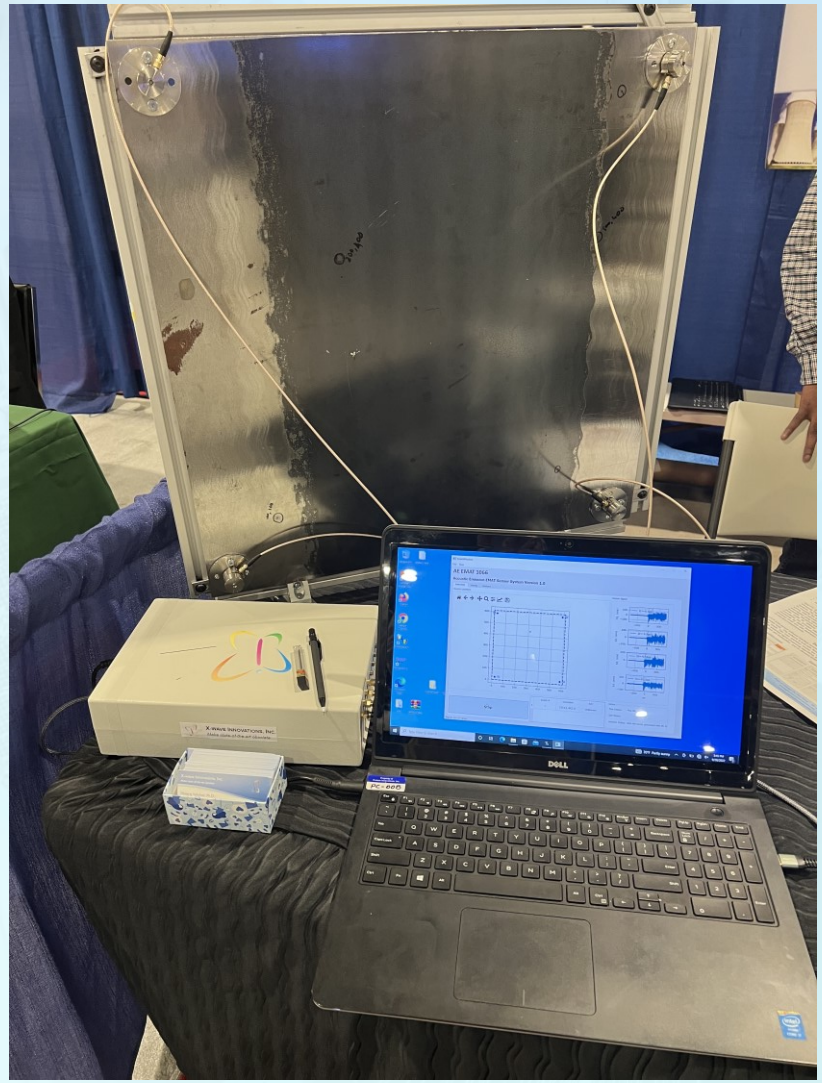
- Support up to 8 transducers
- Up to 8 transducers in transmission mode concurrently
- Up to 8 transducers in receiving mode concurrently
- Low Noise with EMI Shield and Input / Output Isolation
- Software controlled gain adjustment of receiving amplifier
- Currently configured with external High Voltage Pulse
- On-board high voltage power module and high voltage amplifier

In summary,

- 8 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 can be easily programmed by the developed application suite.

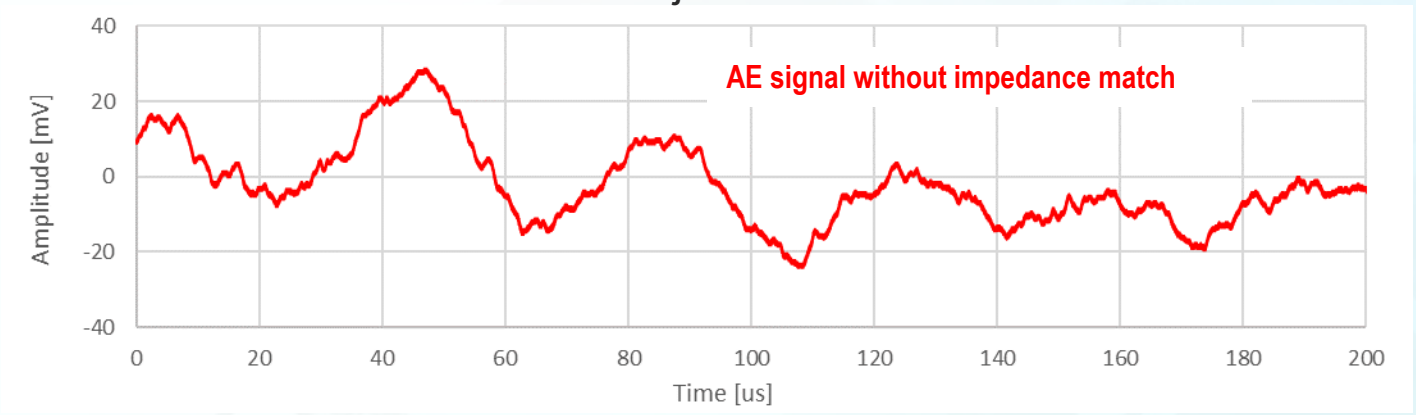


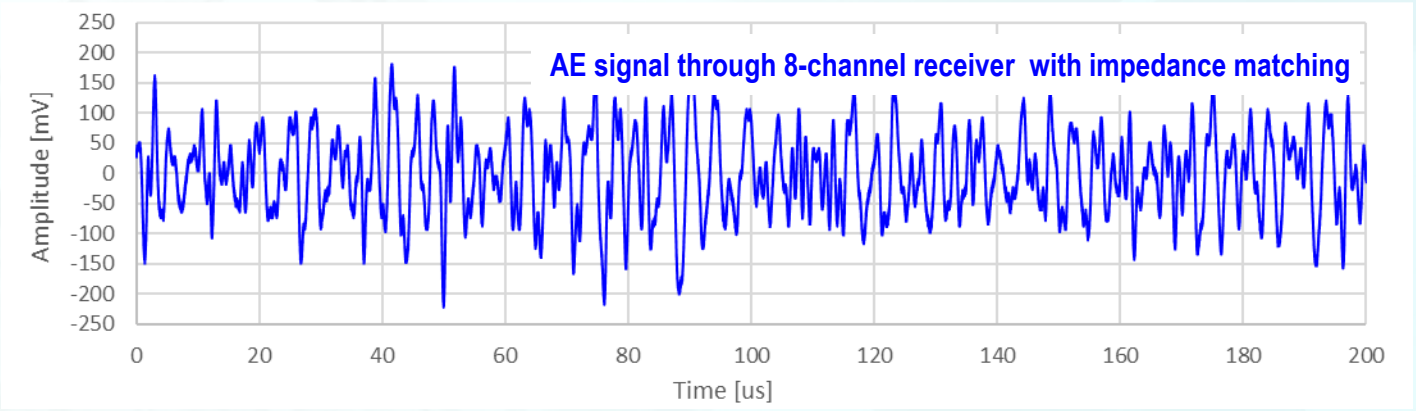


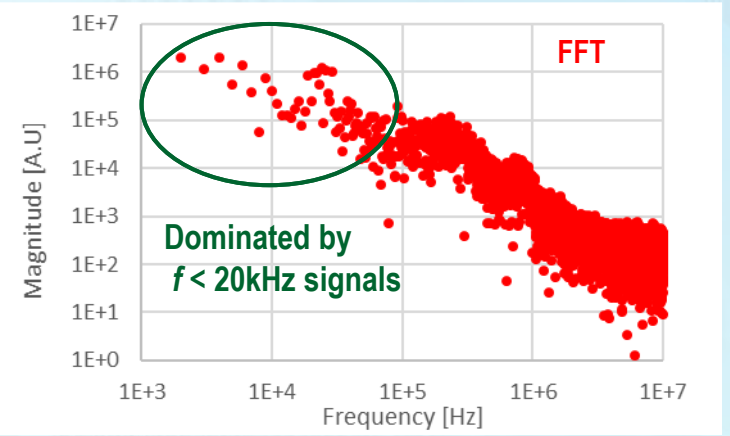
Results and Accomplishments

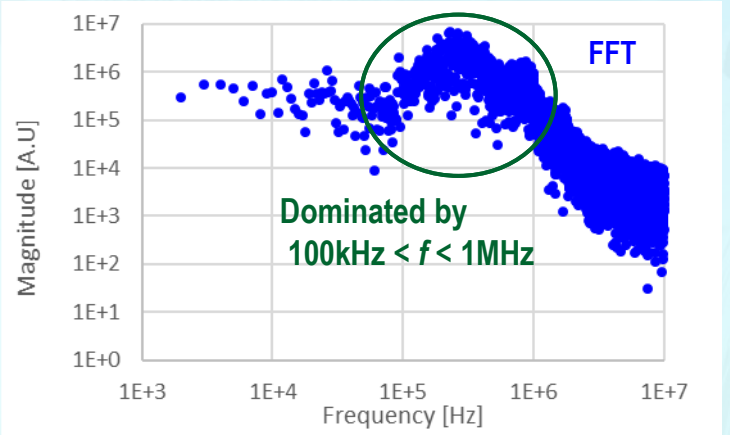
REUT AE signal with 8-channel receiver:

- 8-channel receiver has 60 dB gain on each channel.
- Input impedance matching at receiver allows us filter out both high and low frequency noise
- Gain at each channel could be adjusted via GUI





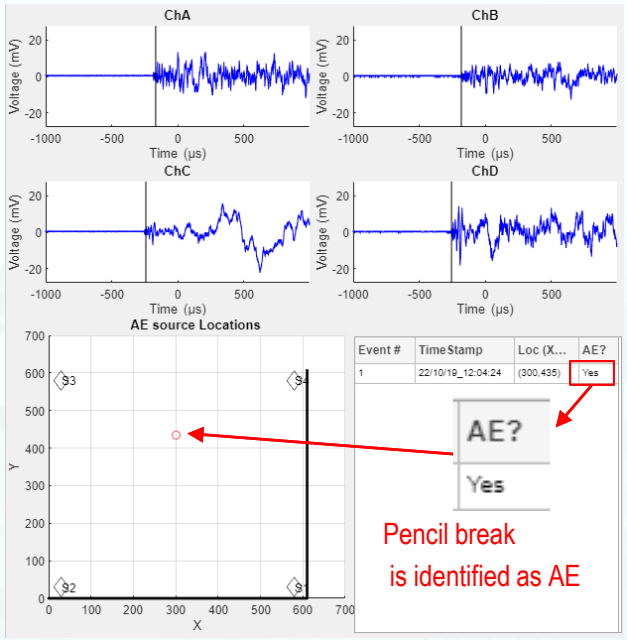


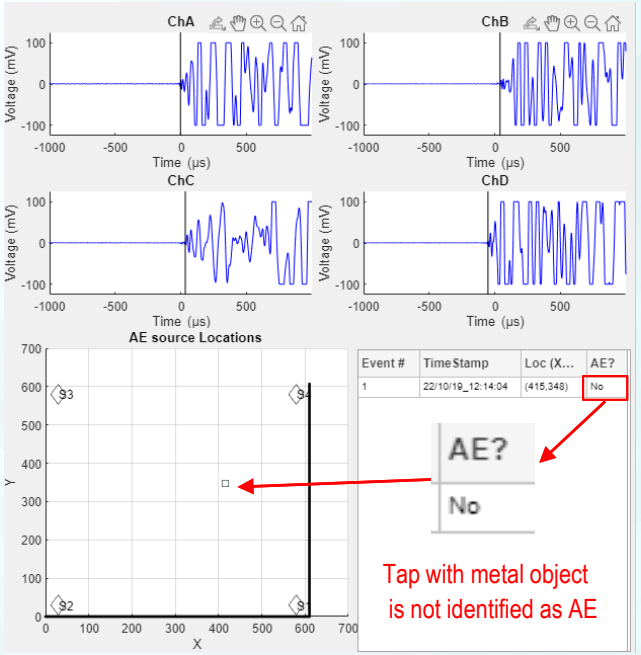


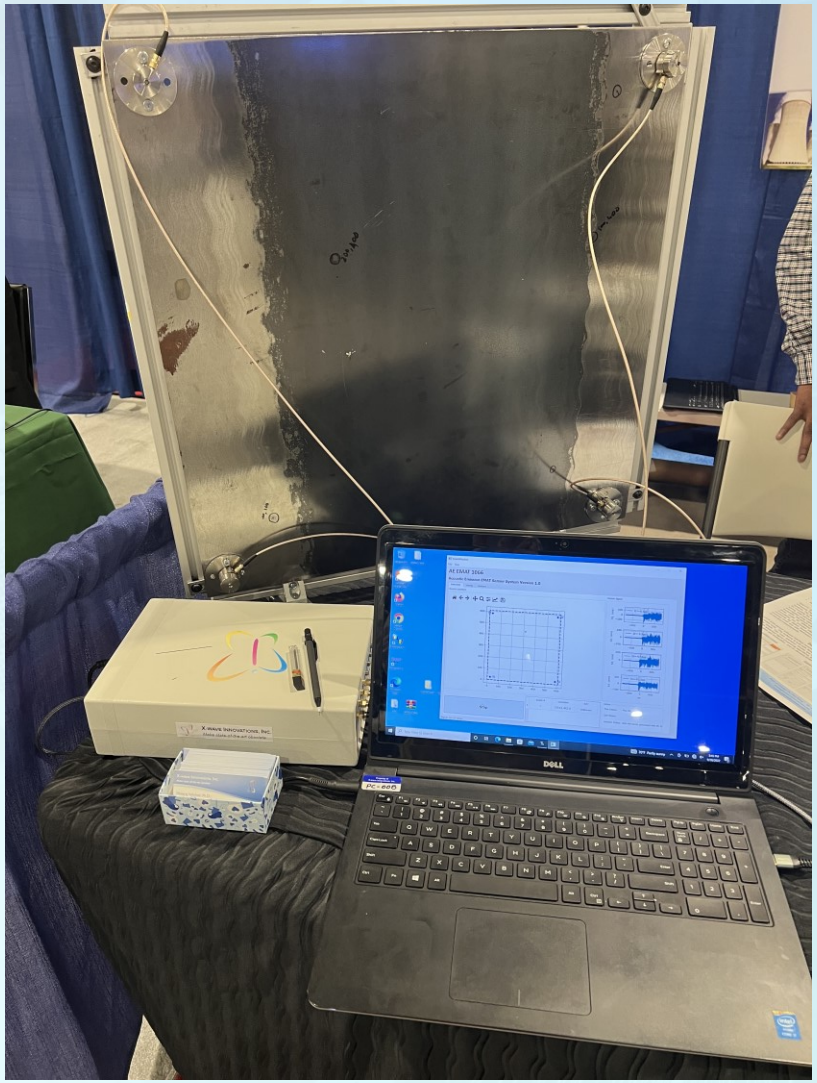
Results and Accomplishments

REUT AE signal processing and software development:

- We tested 4 (four) Z-cut 1mm thick Lithium niobate ($LiNbO_3$) crystals for receiving AE signals
- Signal processing using maximum likelihood estimation provides accurate estimation of defect location.
- The signal processing algorithm automatically estimates the ultrasonic velocity.
- Machine learning module included in the software is able to distinguish AE from other events.



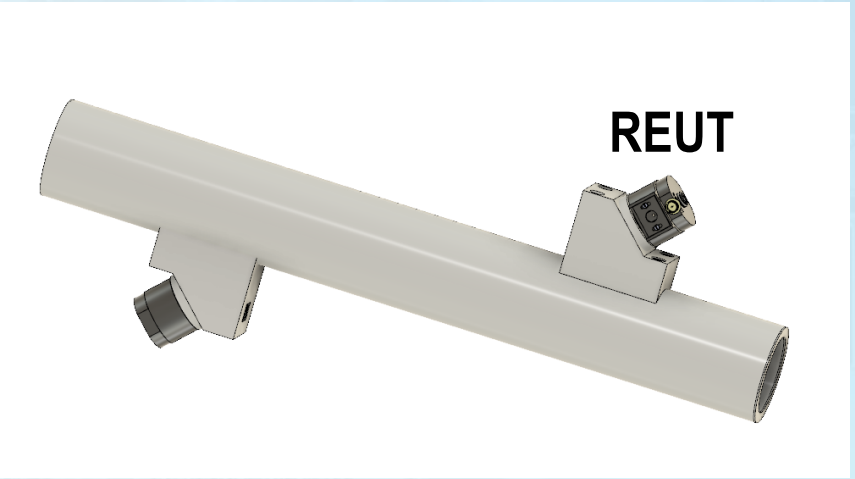




Results and Accomplishments

Flow Rate Measurement with REUT

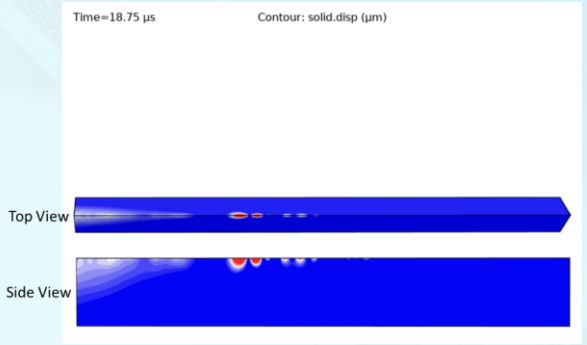
- To measure flow rate in radiation environments and at high temperatures
- Used for Liquid Sodium, Molten Salt applications in nuclear reactors
- Works on the pitch catch principle
- Can be easily mounted and gives all advantages of the REUT transducer



Design of flow rate sensor

Fluid Level Measurement

- Use a wedge to propagate ultrasonic wave
- Fluid level measured by detecting position of interface using time-delay measurement
- Can be used in high temperature fluids



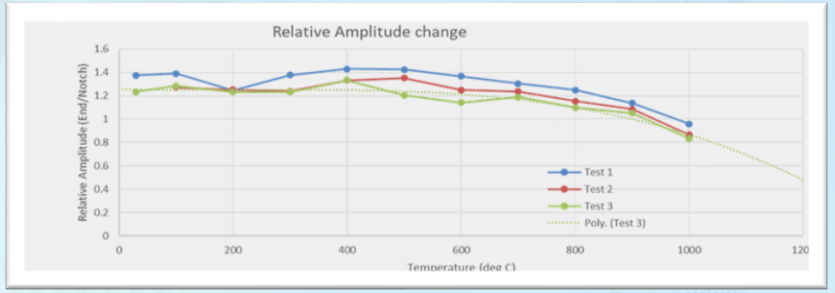
ultrasonic wave propagating on wedge

Technology Impact

Benefits of REUT

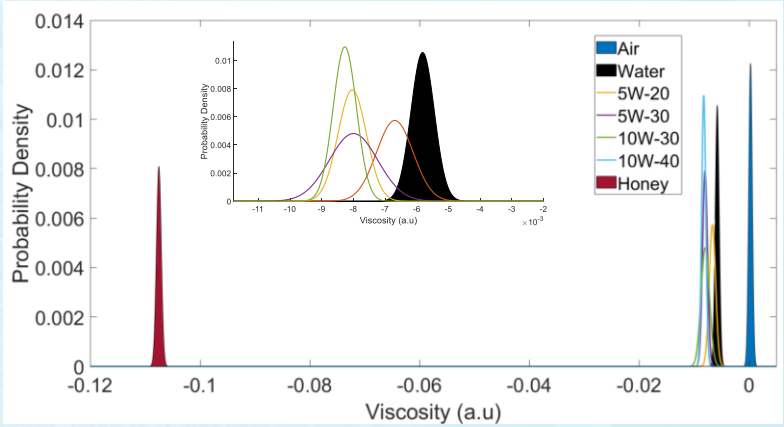
Temperature Measurement

- 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 waveguide length can be used for temperature measurements
- Can be used in high pressure systems



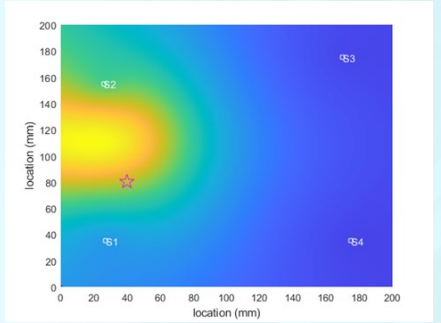
Viscosity Measurement

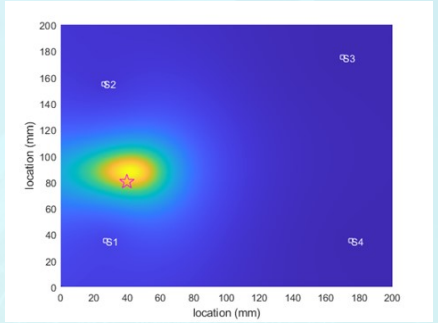
- Suitable for viscosity and temperature monitoring at high temperatures
- Current state of fluid can be used as a reference and viscosity and temperature changes with respect to reference can be monitored



SHM with Acoustic Emission and Guided Ultrasonic Waves

- Suitable for AE monitoring and localization at high temperatures
- Easy to install and operate
- GW SHM can be combined with AE sensing for both active and passive SHM





Flow meter & Fluid level

- Can be used in radiation environments, nuclear reactors
- Can be used to measure high temperature fluids, molten salts and liquid sodium

Concluding Remarks

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:

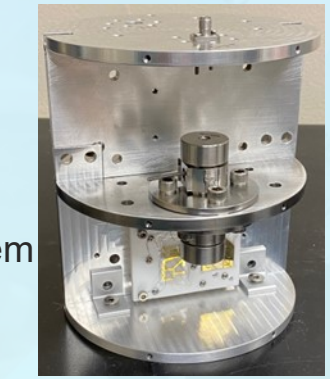
- Completed DOE I-corps for market research and commercialization
- Showcased REUT technology at Defense TechConnect Summit 2022 Fall Conference
- Approached Nuclear and O&G to get insight about sensor needs

Summary:

- We modified REUT design with improved performance
  - Wireless REUT
- We modified and tested REUT systems for potential applications:
  - Temperature measurement
  - Viscosity monitoring
  - SHM monitoring
- We developed a 8-Channel DAQ system (HW/SW) for REUT field implementation

Future work:

- Development of flow rate meter, and fluid level measurement sensor systems
- Complete pulser/receiver in 8-Channel DAQ system
- Performance evaluation of REUT in radiation environment



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Thank You