High-Temperature, Radiation-Endurance Ultrasonic Sensors for Nuclear Reactor Applications

Advanced Sensors and Instrumentation (ASI) FY23
Annual Program Review meeting

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MOTIVATION

DOE seeks sensors and sensing technologies, capable of surviving in substantial radiation fields 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, test reactors, future reactors, and other similar systems.

Our Solution

Radiation Endurance Ultrasonic Transducer (REUT) related sensor systems that sustain high-temperature and irradiation environments for nuclear reactor applications. *REUT design is based on selected radiation resilient materials, material engineering and harnessing knowledge of acoustic propagation in materials.*

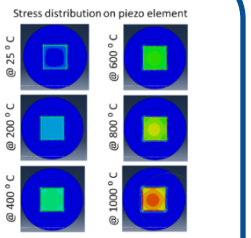
REUT SENSOR TECHNOLOGIES DEVELOPMENT

- REUT sensor design/development
- REUT sensor technologies development for nuclear reactors
  - Temperature sensor
  - Multi-point temperature sensor
  - Fluid viscosity sensor
  - Flow rate sensor
  - Liquid level sensor
  - Structural health monitoring (AE sensor & GW sensor)
  - Wireless REUT embedded sensor
- Single-channel and multi-channel data acquisition development
- Application software and signal processing algorithms development

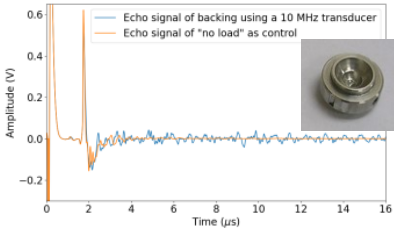
* DOE SBIR Phase II program (grant # DE-SC0020019) and Phase I program (grant # DE-SC0022826)

REUT DESIGN & DEVELOPMENT

- Designed, developed and assembled REUT-I and REUT-II prototypes made of stainless steel, ceramics and high temperature piezoelement (LiNbO3).
- Designed, fabricated and tested multiple REUT metal backing designs.
- Demonstrated REUT can generate and detect acoustic/ultrasonic signals of different frequencies.
- Simulated REUT stress distribution at higher temperatures up to 1,000 ^{o}C.
- Demonstrated REUT performance at high temperature up to 1,000 ^{o}C.
- Demonstrated REUT performance after subjecting it to seven thermal cycles off 800 ^{o}C.
- Demonstrated the use of REUT prototype for temperature measurements up to 800 ^{o}C.

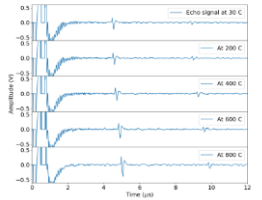


FEA simulation

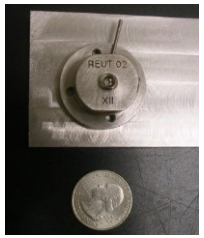


Backing development

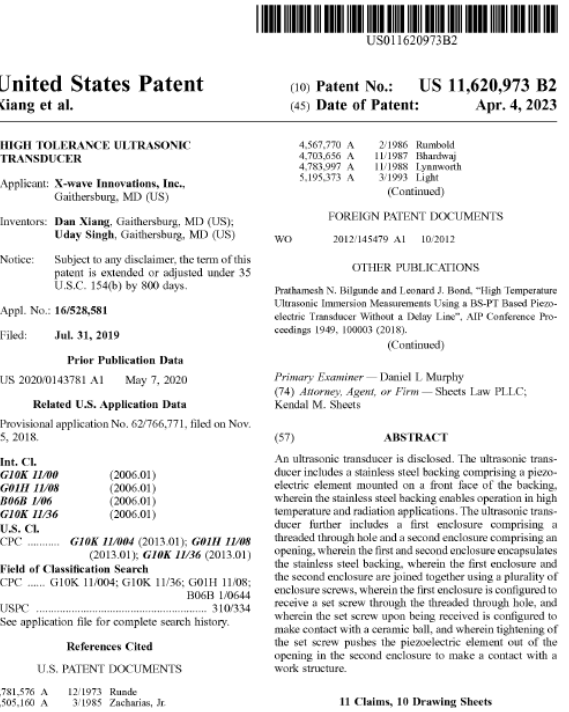
Assembly development

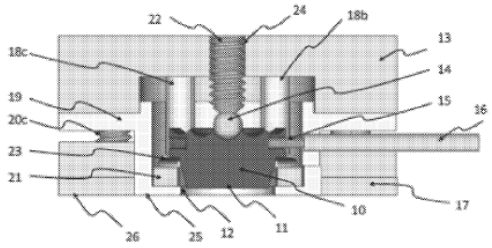


Testing



Improvement

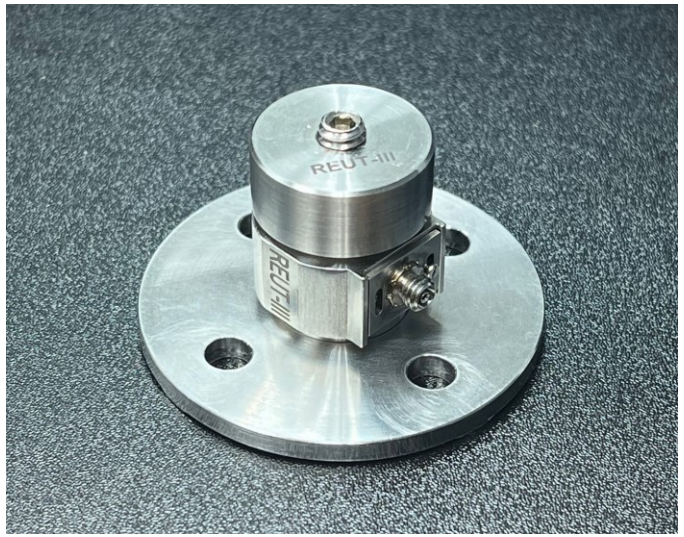


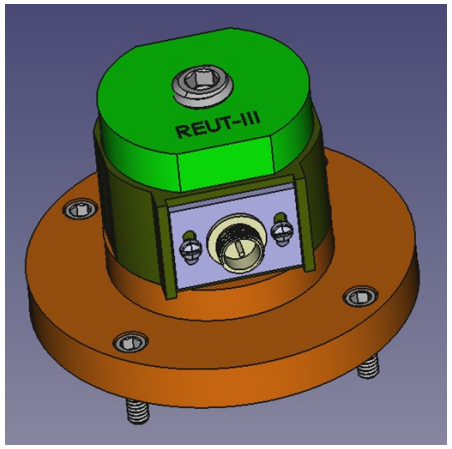


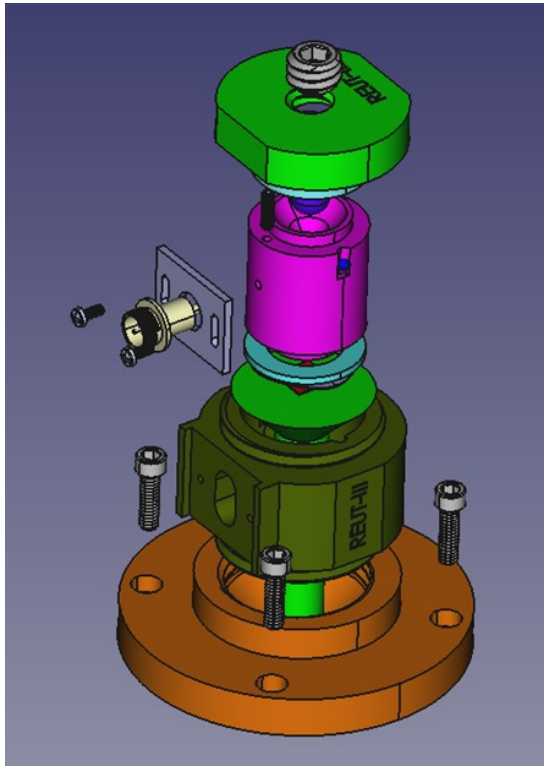
US Patent 11,620,973 "High Tolerance Ultrasonic Transducer"

Improved REUT Design – REUT III

- Improve sensor and component design to facilitate the fabrication and assembly
- Redesign the backing structure to accommodate both thin and thick piezoelectric elements to achieve higher frequency bandwidth (3.5MHz to 30MHz)
- Use a microdot connector for electrical connection based on our previous designs of REUT I and II



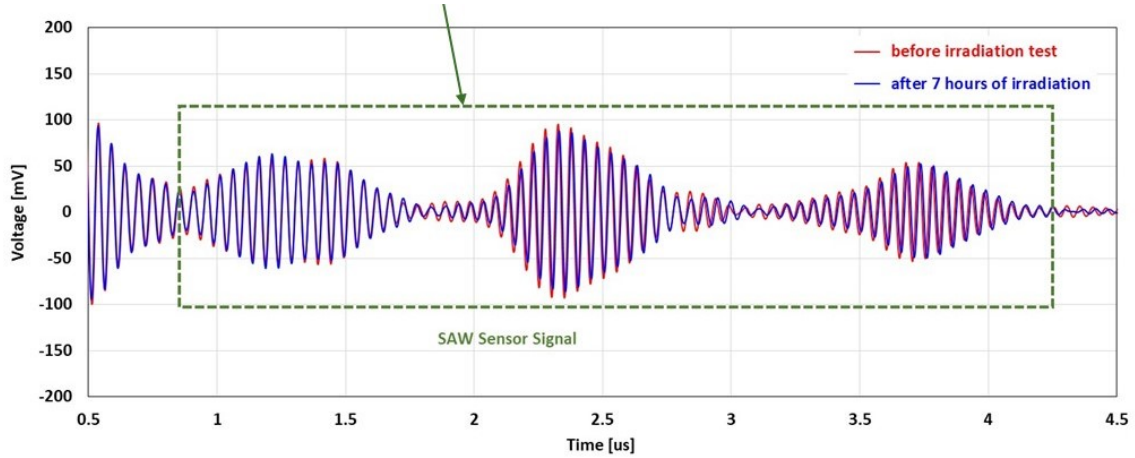


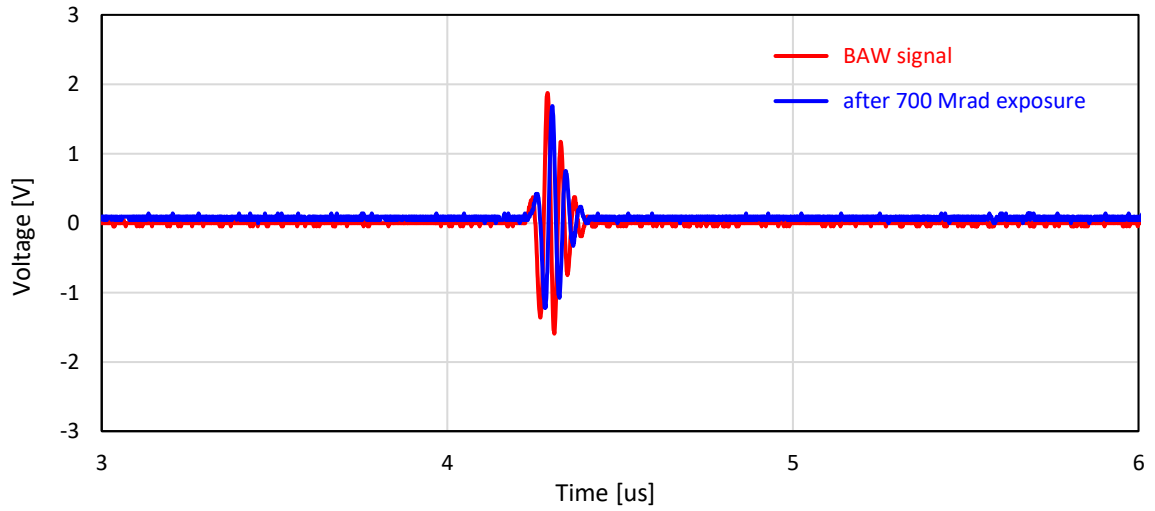


Pending US Patent 17,726,485 "Radiation and High-Temperature Tolerant Piezoelectric Ultrasonic Contact Transducer with Screw-in Assembly"

REUT NUCLEAR IRRADIATION TEST

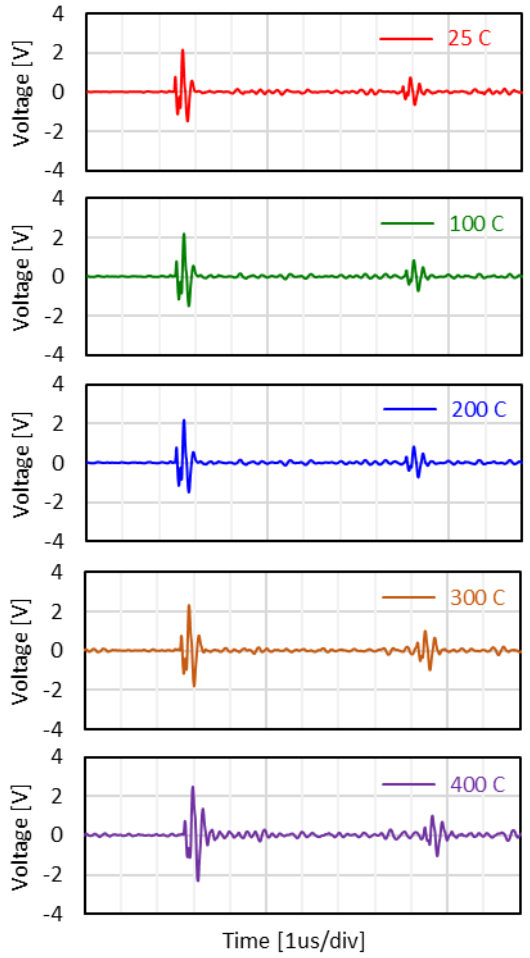
- Ohio State University Nuclear Reactor Lab (OSU/NRL)
  - Fast neutron: 10^{15} n/cm^2 for 7 hours
  - No change
- Idaho National Lab (INL)
  - Gamma: 700 Mrad
  - Small changes

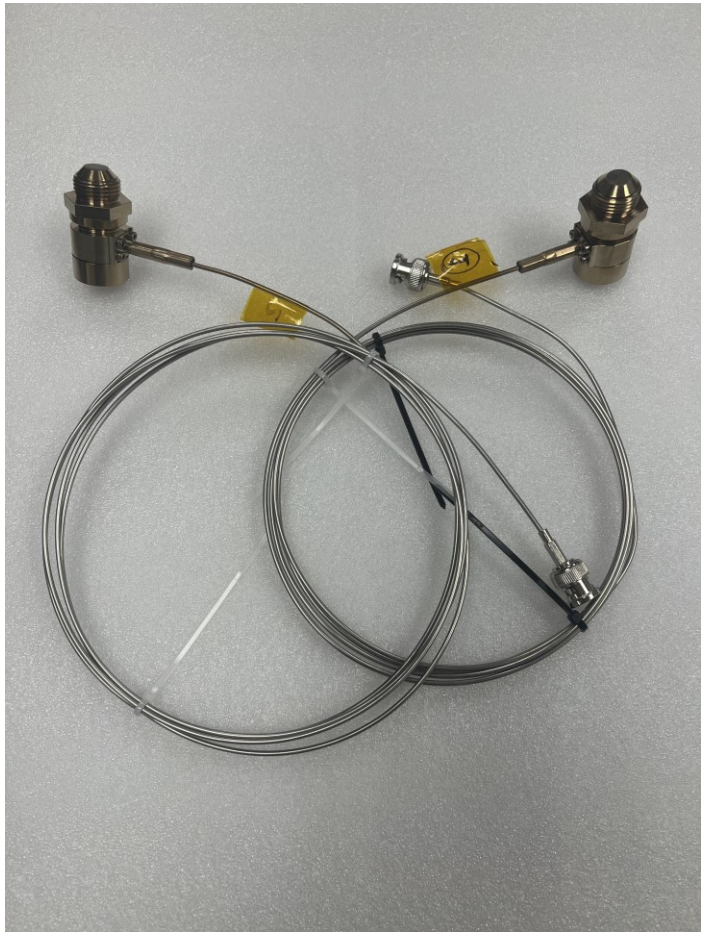




High-Temperature Durability and Robustness Test

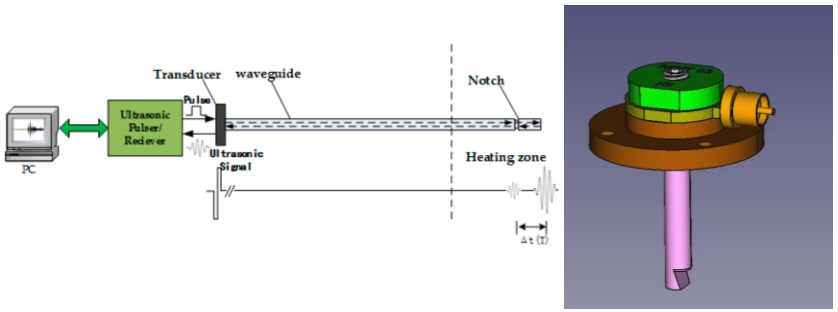
- EPRI (Electrical Power Research Institute) acquired two (2) REUT sensors for performance evaluation and robustness tests
- Both sensors have passed 500°C tests (nominal maximum temperature 800°C) at EPRI
- Durability/longevity and robustness tests with cyclical and long-standing at high temperature are underway at EPRI
- In discussion with INL and ORNL to perform qualification tests for REIT sensors (e.g., REUT temperature sensors)



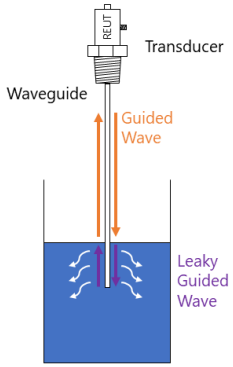


REUT SENSOR SYSTEMS/APPLICATIONS DEVELOPMENT

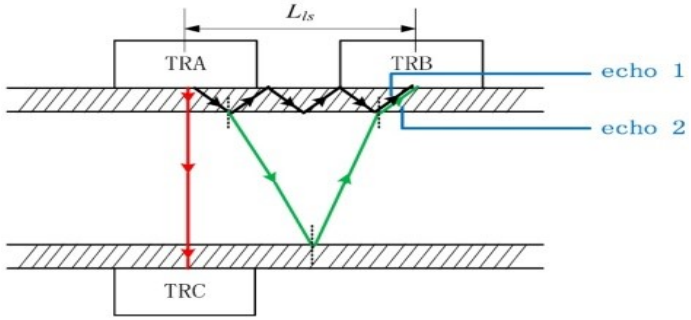
Temperature sensors



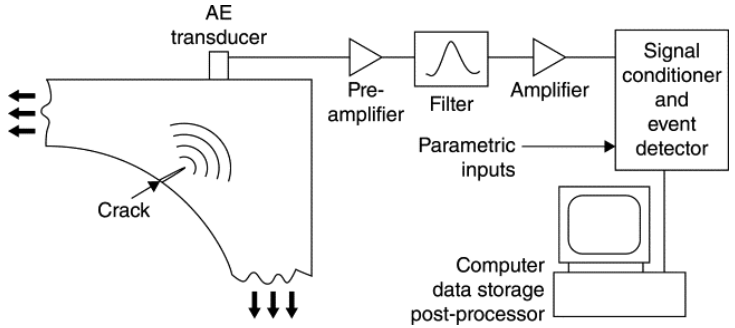
Fluid viscosity and level sensors



Fluid temperature, pressure and flow sensors



Structural health monitoring sensors



REUT TEMPERATURE SENSOR

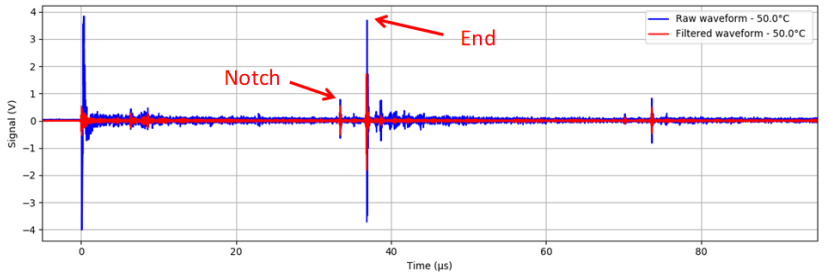
- REUT sensor head with $LiNbO_3$ can survive 800ºC
- Flange and ¾” NPT style temperature sensor with a SS316 waveguide, can support temperate measurement up to 1,000 ºC
- Waveguide length is 150mm
- Both longitudinal or shear wave were generated in the waveguide.
- Signal processing algorithm and application software were developed for temperature sensing

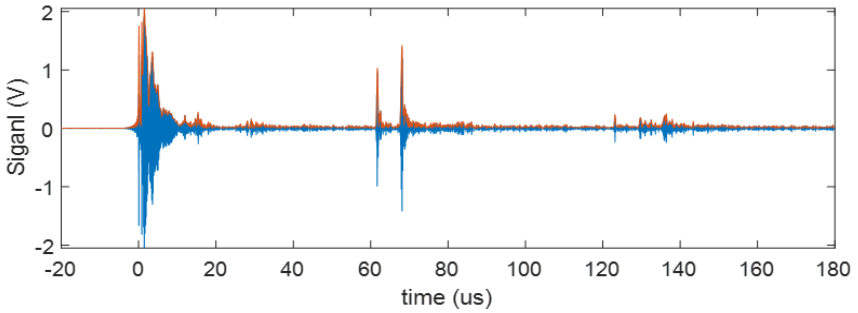
Benefits

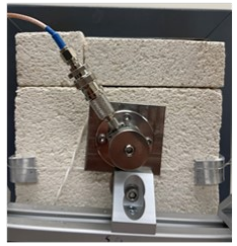
- Any piezoelectric material can be used (for best operation choose operation frequency 4 MHz or higher)
- Any ultrasonic pulser system can be used
- Application specific waveguide materials and waveguide length can be used
- Can be used in high pressure systems

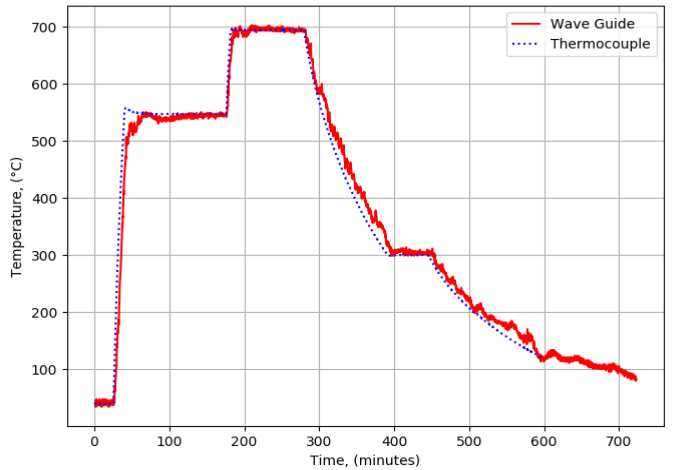
Flange style connector

¾” NPT style connector





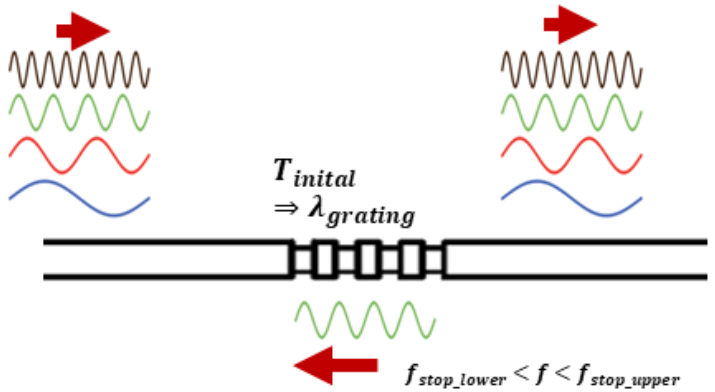


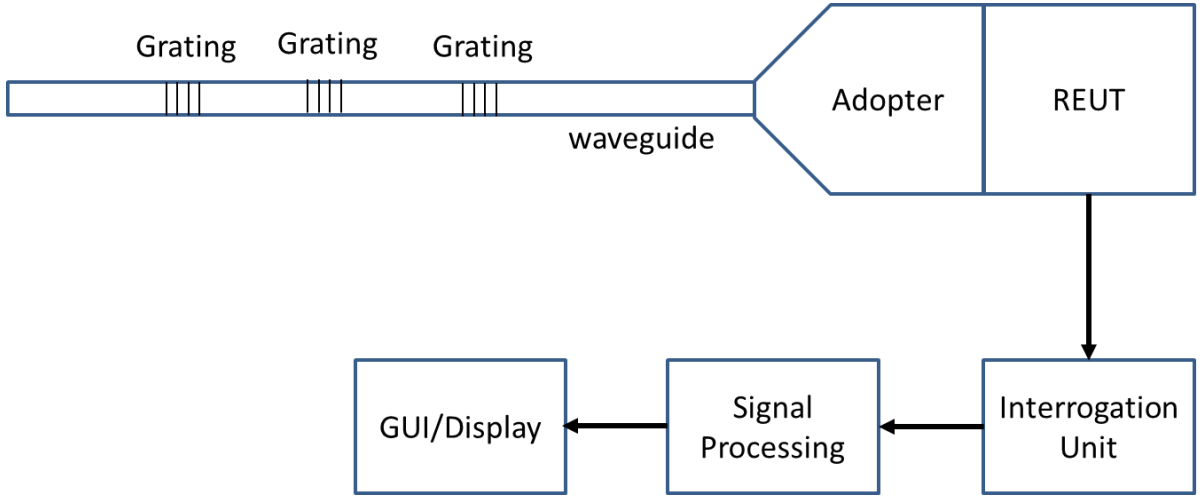


REUT MULTI-POINT TEMPERATURE SENSOR

- Gratings with periodic internal structures, will have wavelength selective reflectivity.
- The change in temperature will alter this selective reflectivity
- Analogous to Fiber-Bragg Grating (FBG) concept

$$\lambda_{wave} = 2n_e\lambda_{\text{grating}}$$



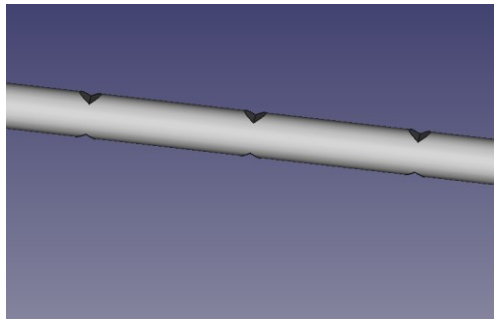


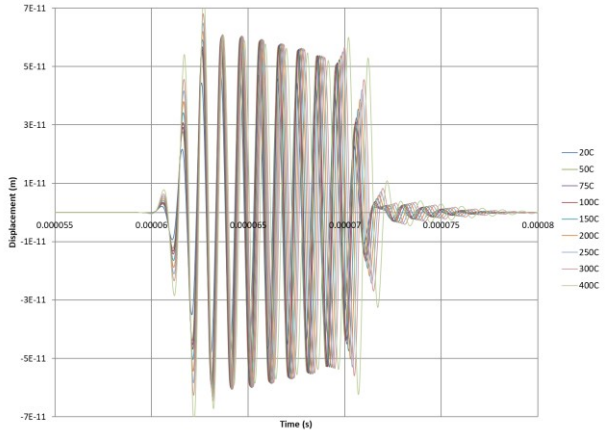
Applications

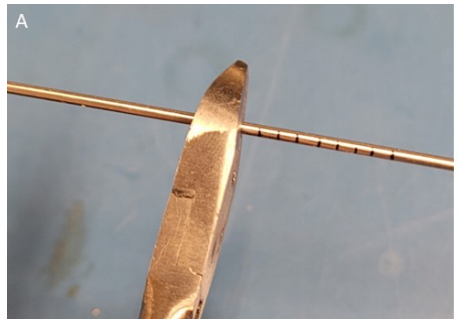
- In-pile fuel rod temperature profile measurements
- Distributed temperatures with limited access in reactors

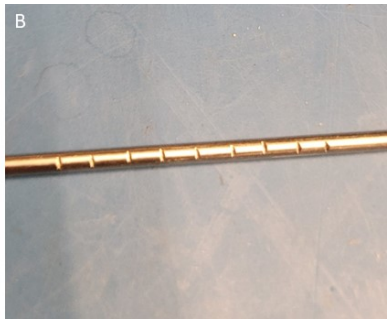
Provisional Patent #63,462,291: ULTRASONIC WAVEGUIDE SENSOR AND APPARATUS FOR DISTRIBUTED PHYSICAL PARAMETER MEASUREMENTS

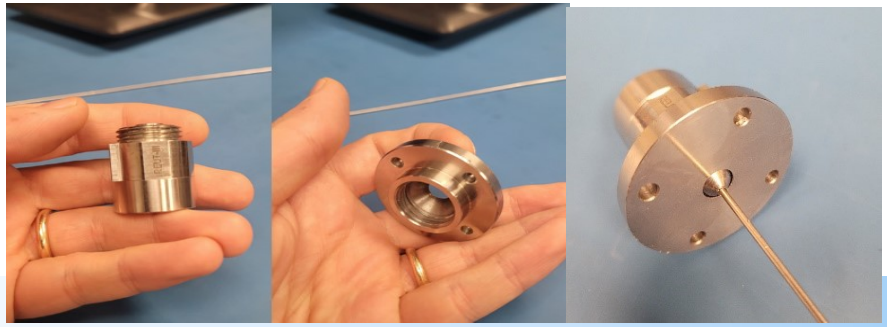
REUT MULTI-POINT TEMPERATURE SENSOR DESIGN/DEVELOPMENT

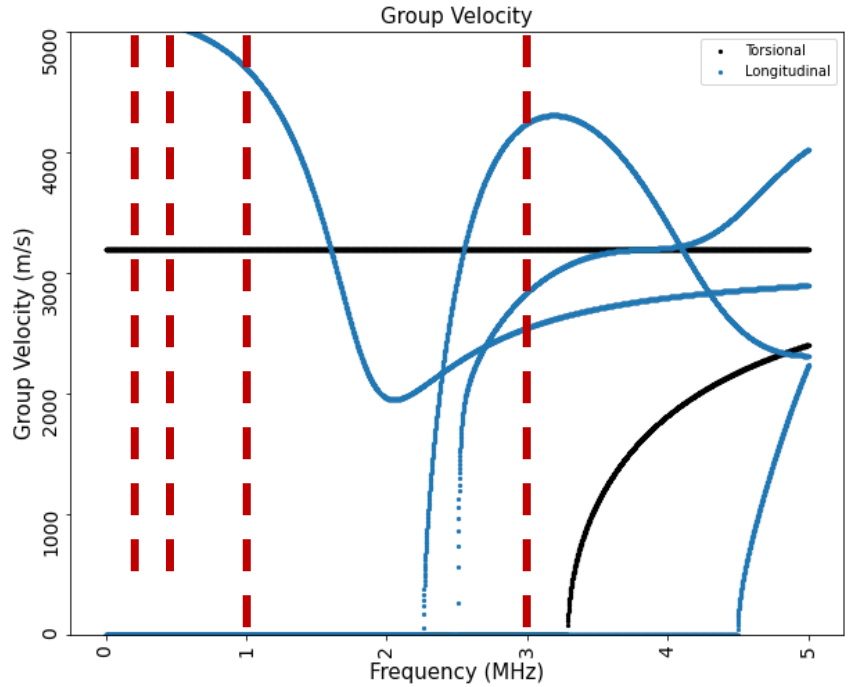






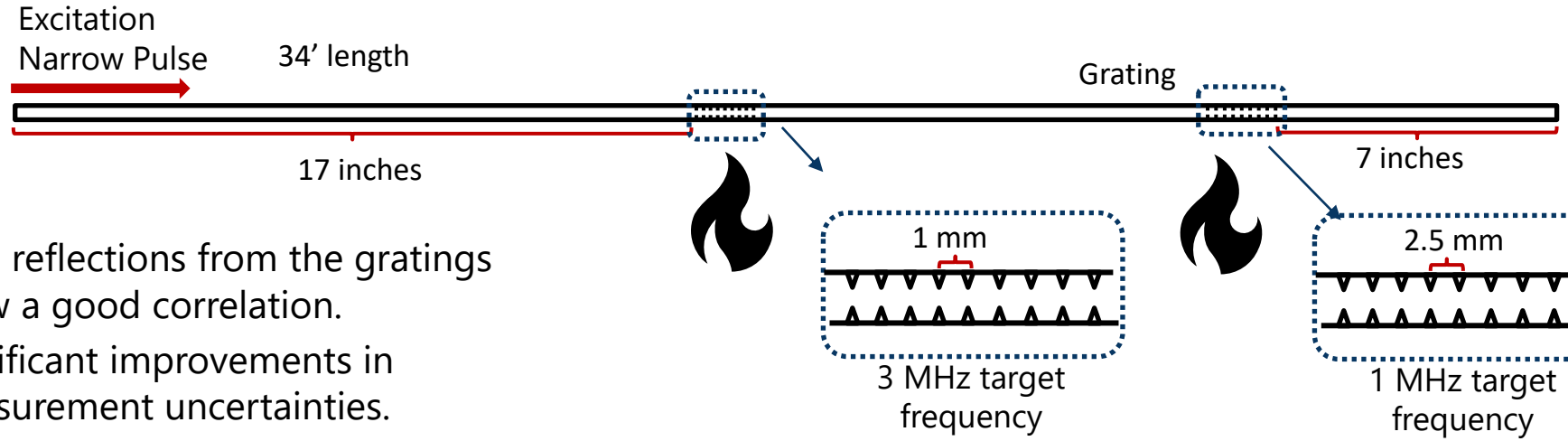






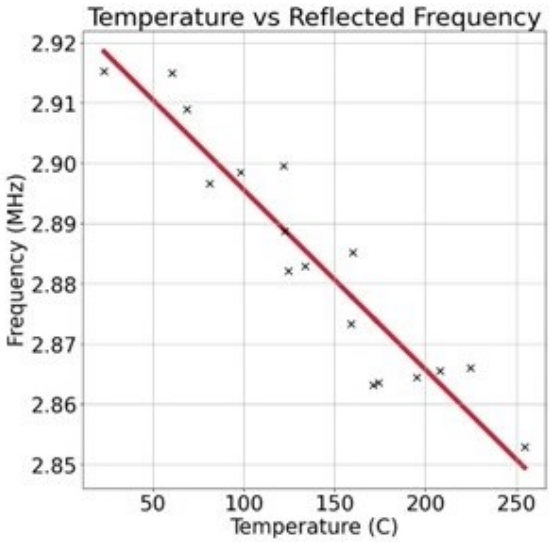
Frequency	300 kHz	500 kHz	1 MHz	3 MHz
Wavelength	18mm	12 mm	5 mm	2 mm
Half Wavelength	9 mm	6 mm	2.5 mm	1 mm

Experimentation – Temperature Tests, Waveguide #5

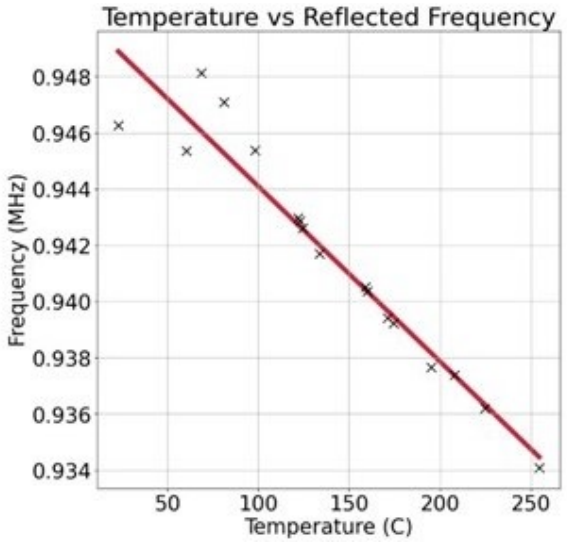


- Both reflections from the gratings show a good correlation.
- Significant improvements in measurement uncertainties.
- Cross-talk is decreased by ordering targeted frequencies high to low.

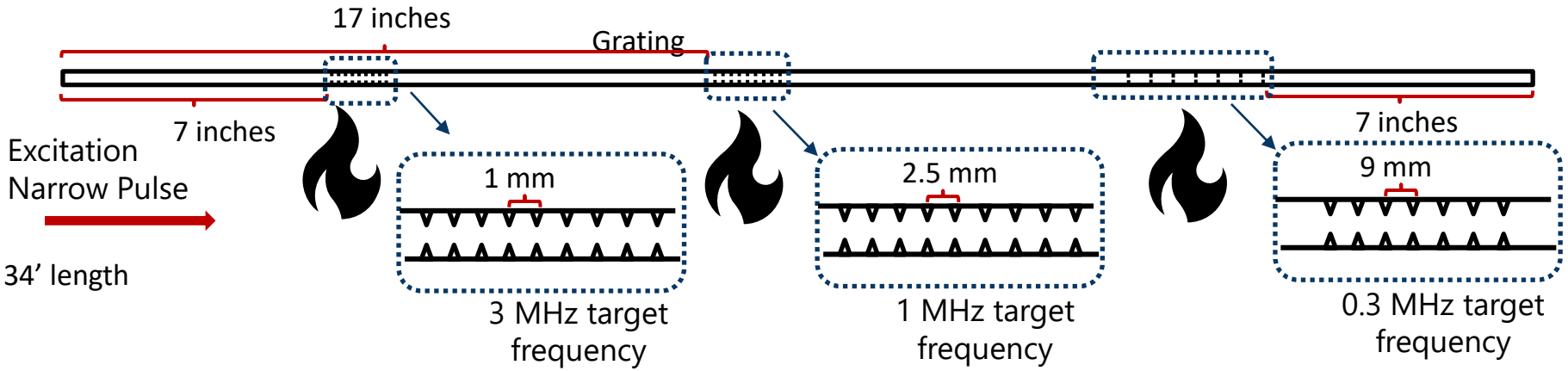
Middle Grating

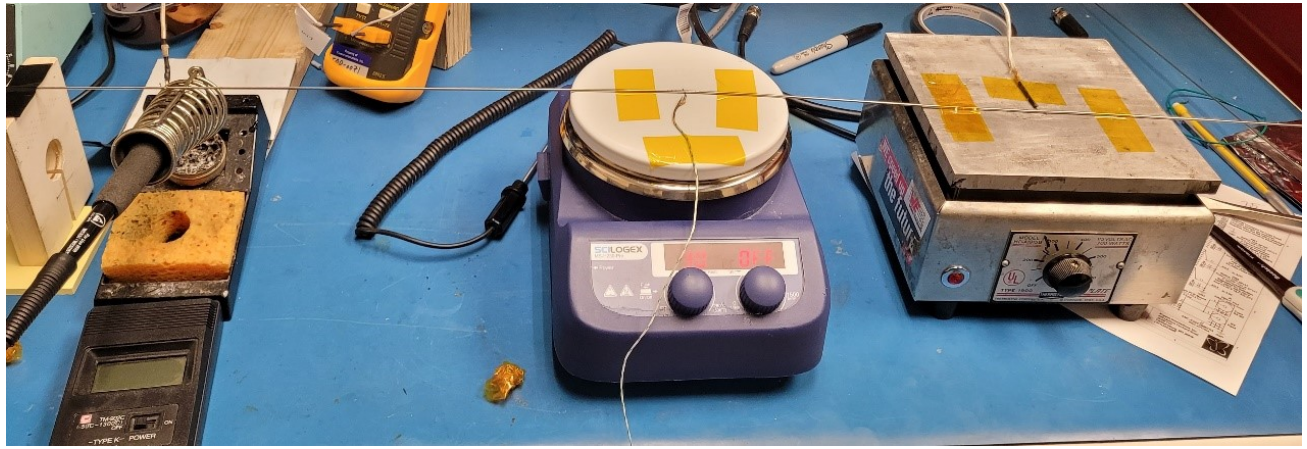


End Grating

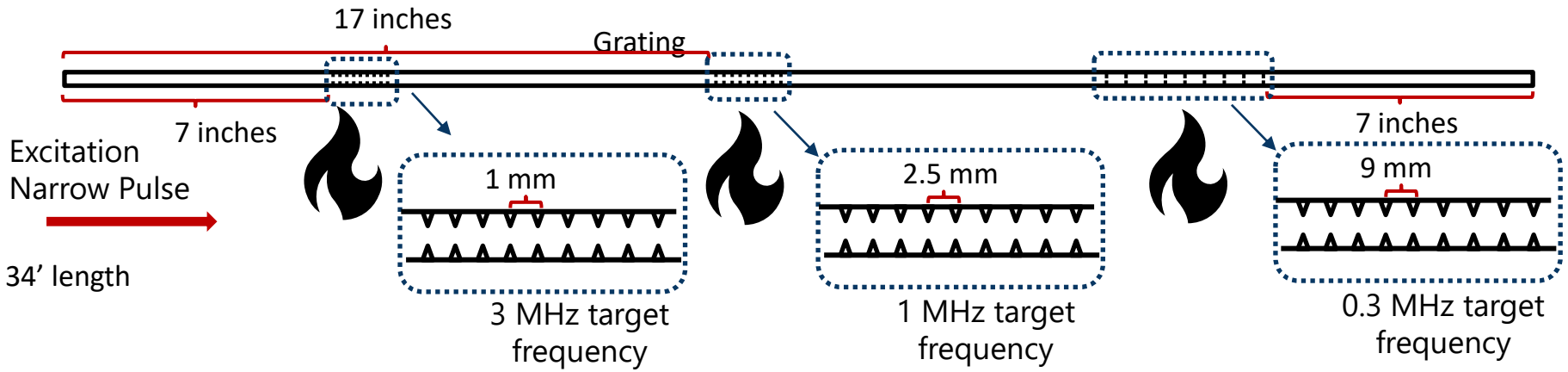


Experimentation – Temperature Tests, Waveguide #6



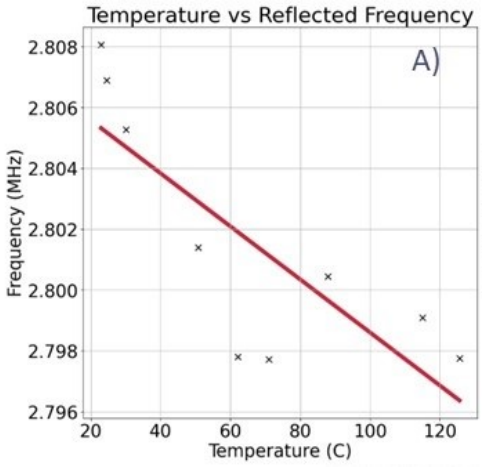


REUT MULTI-POINT TEMPERATURE SENSOR

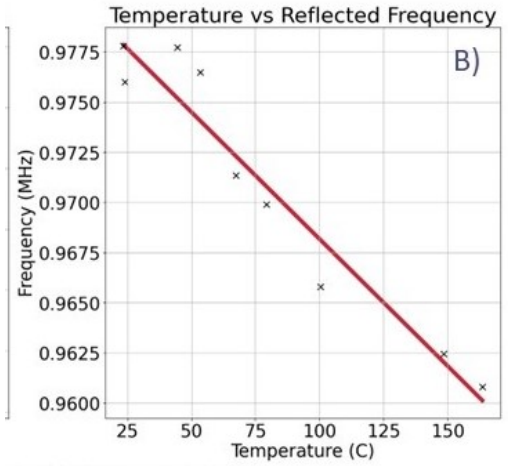


- 2nd and 3rd grating measurement results are similar to previous test without the 1st grating.
- Large variation in 1st grating measurements is resulted from the soldering iron heating source.
- Cross-talk is minimized by ordering targeted frequencies from high to low.

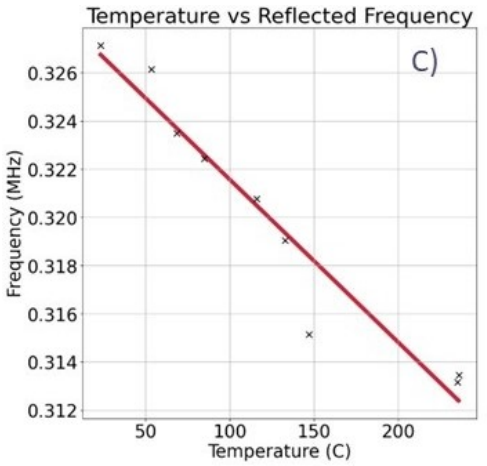
1st Grating



2nd Grating



3rd Grating

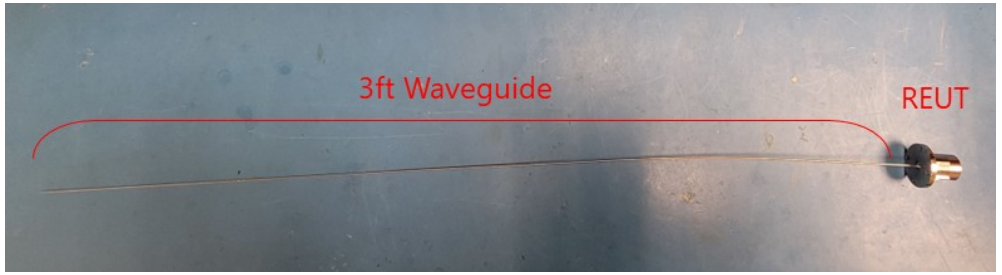


REUT FLUID LEVEL SENSOR SYSTEM

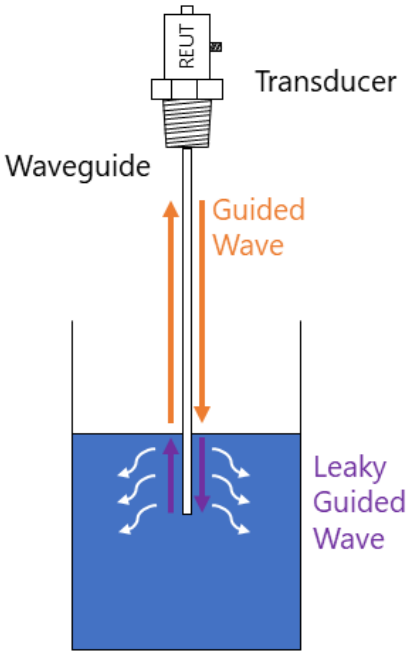
- REUT fluid level sensor with a 3’ long, 1/16” diameter SS316 waveguide
- Presently, $LiNbO_3$ is used to generate longitudinal waves
- Waveguide with gratings will be implemented to increase the fluid level measurement reliability
- Signal processing algorithms will be developed for fluid level monitoring

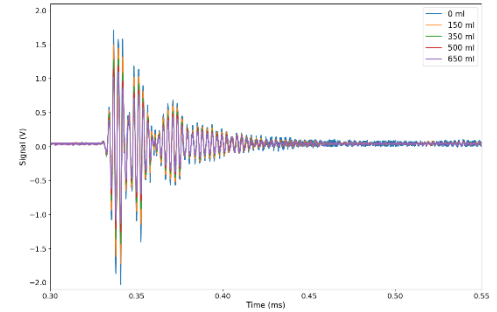
Benefits

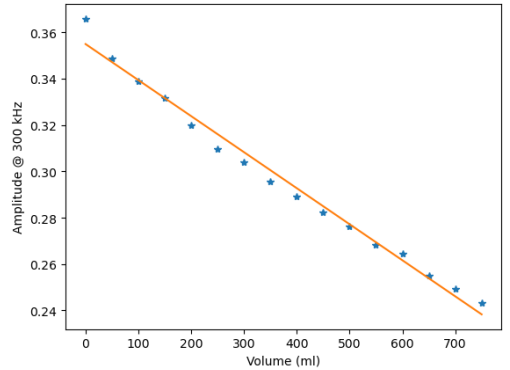
- Suitable for fluid level and temperature monitoring in nuclear reactors
- Capable of sustaining both high-temperature and high-radiation environments
- Can be used in high pressure systems



3’ x 1/16” SS316 waveguide REUT sensor for fluid level measurement







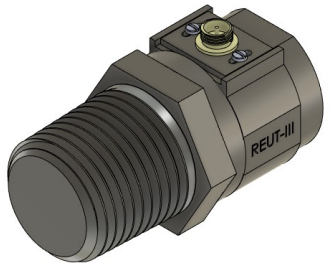
REUT VISCOSITY MONITORING SYSTEM

- ¾″-8 thread and ¾″ NPT style viscosity sensor with SS316 ¾″ delayline
- Presently, we are using X-cut $LiNbO_3$ to generate shear wave
- We have developed application suite for viscosity monitoring

Benefits

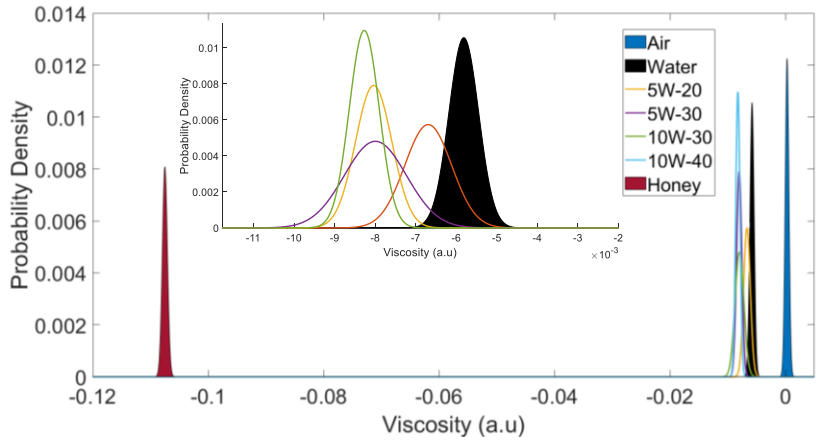
- Suitable for viscosity and temperature monitoring at high temperatures
- Current state of fluid can be used as a reference and viscosity and temperature changes with respect to reference can be monitored
- Can be used in high pressure systems

¾" NPT style connector for high pressure applications



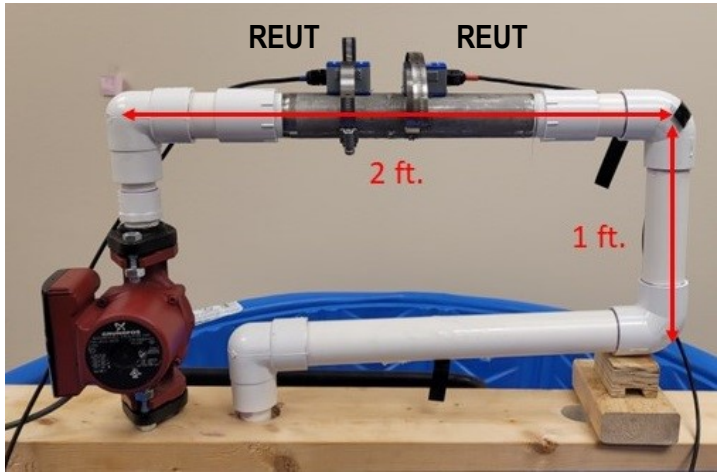
3/4 "-8 thread connector

Data Acquisition

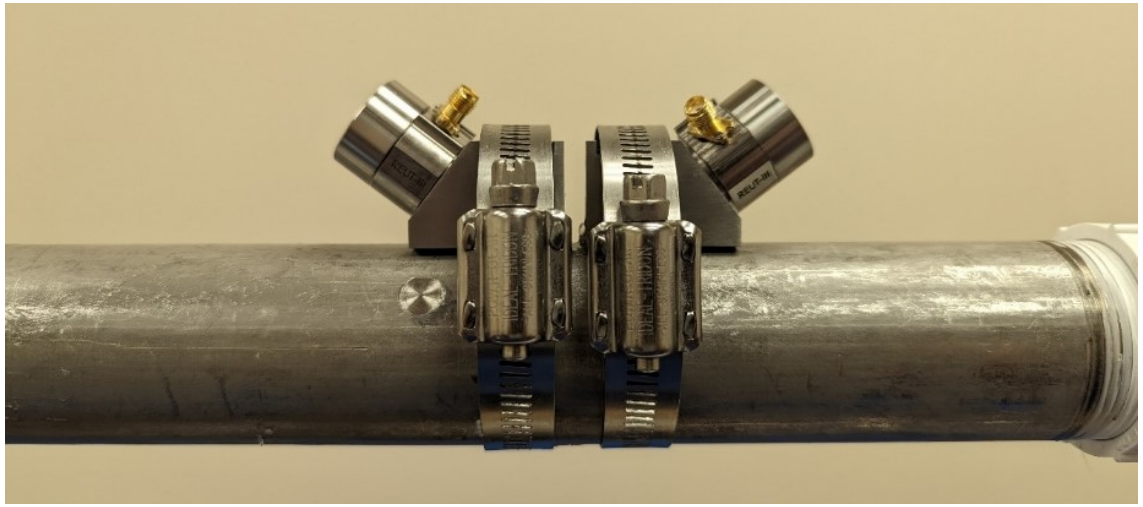


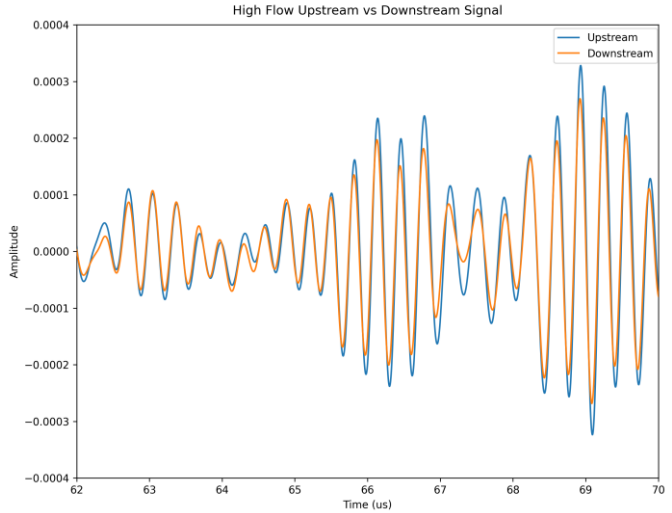
REUT FLOW RATE SENSOR

- Ultrasonic flowmeter for high- temperature and high-radiation environments
- Liquid Sodium and Molten Salt applications in advanced nuclear reactors
- Can be easily mounted and gives all advantages of the REUT sensors
- Works on the pitch catch configurations



Test loop





Downstream vs. upstream ultrasonic signals

REUT Structural Health Monitoring (SHM)

Passive AE SHM :

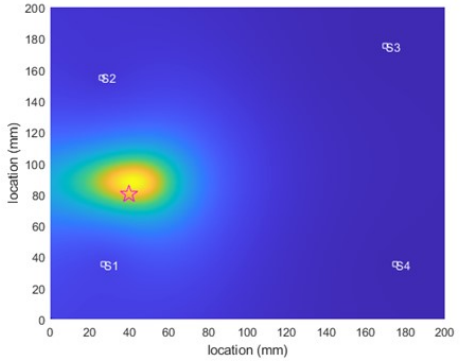
- REUT sensors with ¾″-8 thread mounting
- $LiNbO_3$ and ZnO piezo-element were used
- Signal processing technique were developed for AE monitoring and source localization
- AE sensing and localization were tested for temperatures up to 150°C

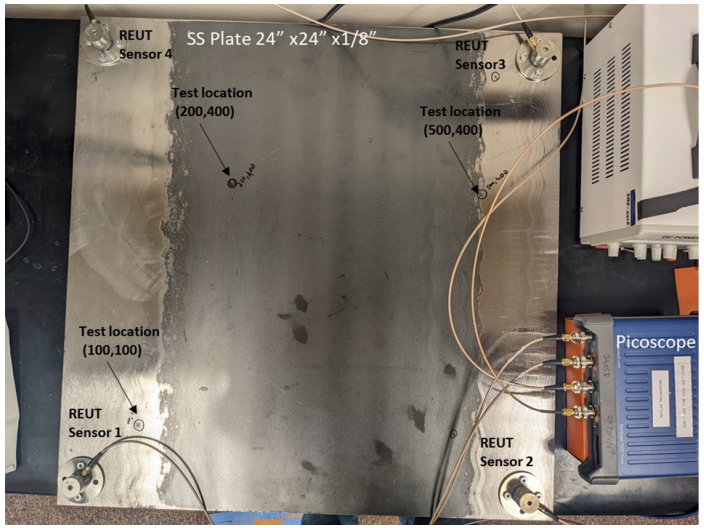
Active Guided Wave SHM :

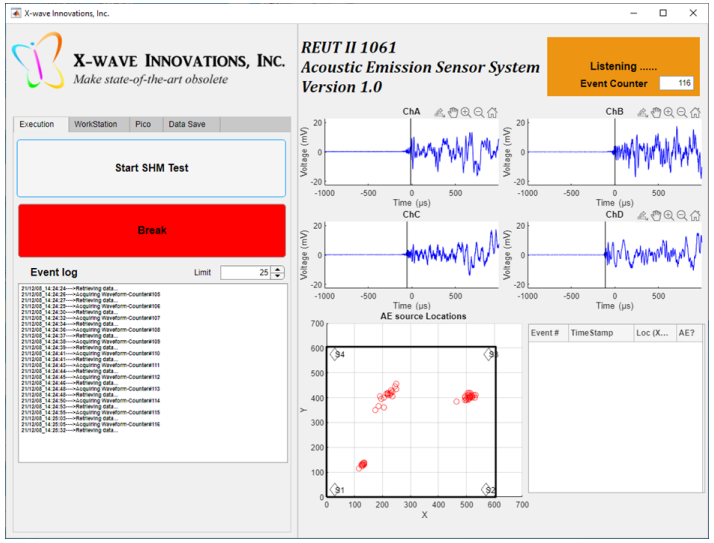
- Same AE setup for GW SHM
- Signal processing techniques were developed to detect changes in the structure and determine damage location.

Benefits:

- Combination of GW and AE sensing for active and passive SHM
- Continuous AE monitoring and damage localization at high temperatures
- Periodic GW SHM to verify the damage and its location
- Easy to install and operate

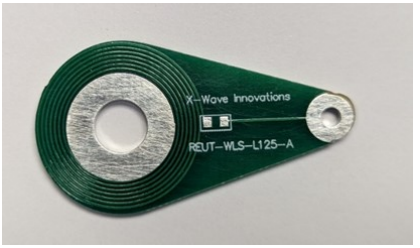




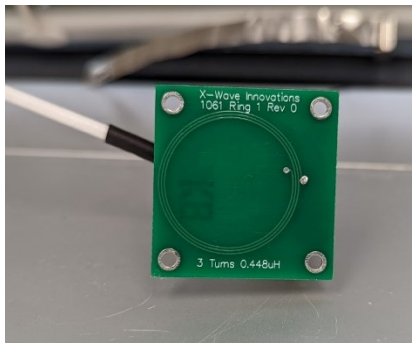


WIRELESS REUT DEVELOPMENT

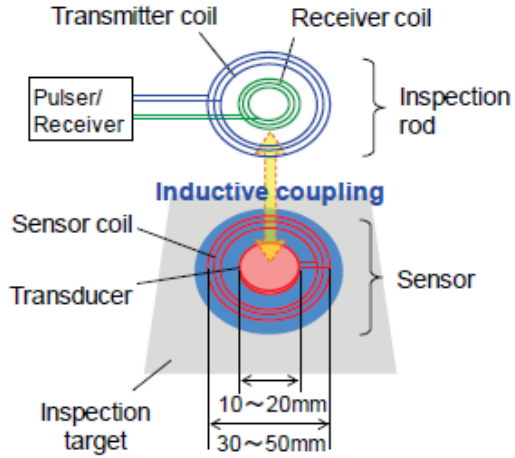
- Developed wireless REUT scheme to eliminate permanent wire connections to sensors
- Reduce sensor system maintenance, especially electrical connections failure
- Wireless wall thickness or material degradation monitoring applications
- Can be adopted for the other REUT applications of temperature,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

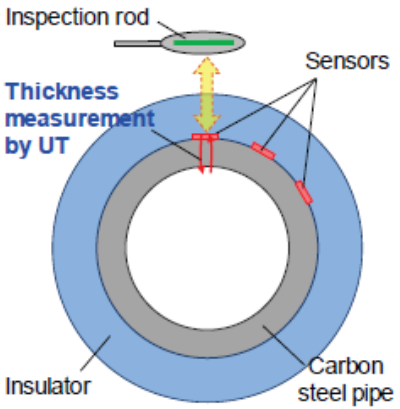


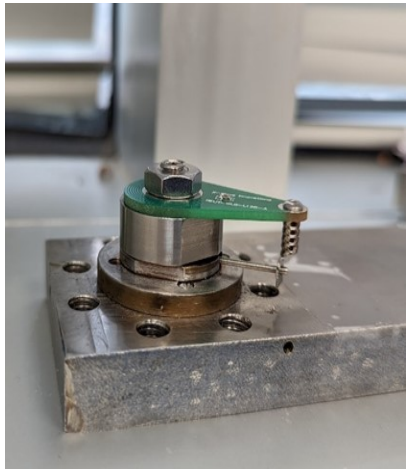
(a) Sensor coil

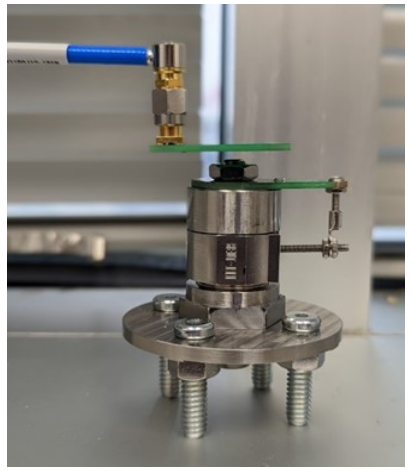


(b) Interrogator coil









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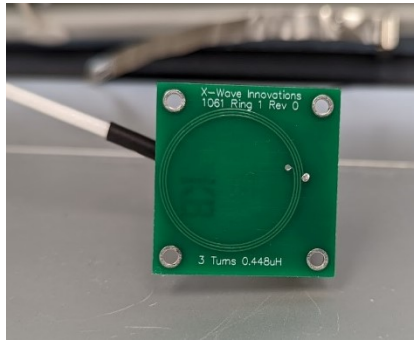
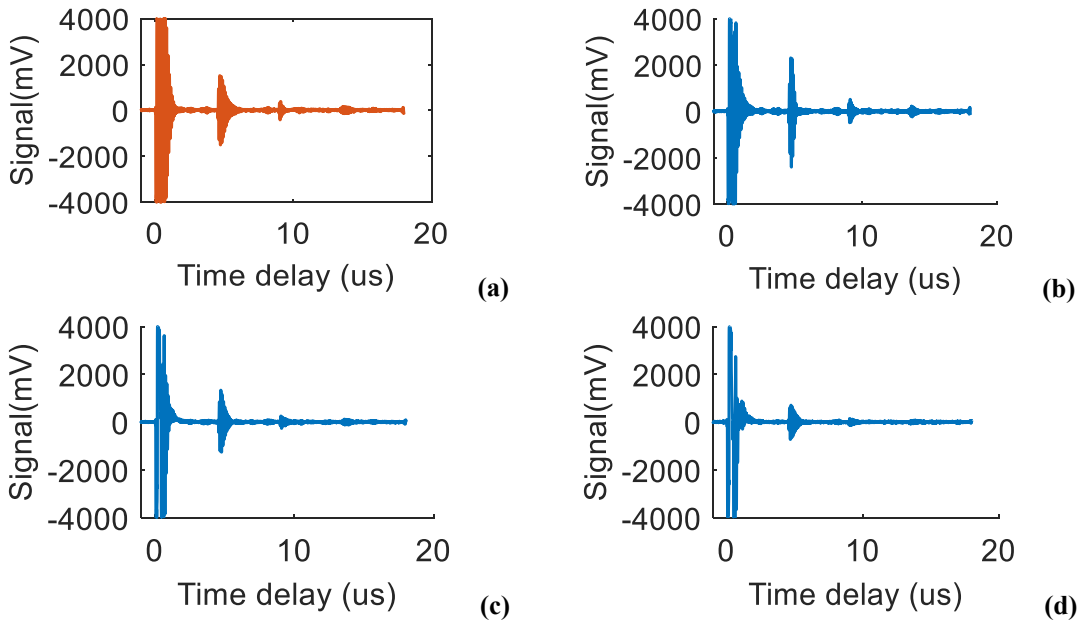
FINE TUNE PULSER/RECEIVER COIL PARAMETERS



Coil 1	Coil Shape	Ring	Inductance	0.8uH
	Coil Diameter	25.4	Resistance	0.084 Ohm
	Number of turns	3	Impedance @ 1kHz	0.084 Ohm
Coil 2	Coil Shape	Ring	Inductance	1.52 uH
	Coil Diameter	25.4	Resistance	0.091 Ohm
	Number of turns	5	Impedance @ 1kHz	0.172 Ohm
Coil 3	Coil Shape	Ring	Inductance	3.2 uH
	Coil Diameter	25.4	Resistance	0.127 Ohm
	Number of turns	8	Impedance @ 1kHz	0.128 Ohm
Coil 4	Coil Shape	Ring	Inductance	4.95 uH
	Coil Diameter	25.4	Resistance	0.145 Ohm
	Number of turns	10	Impedance @ 1kHz	0.148 Ohm



Wirelessly interrogated pulser echo signals captured with interrogation coils in the table: a) coil 1, b) coil 2, 3) coil 3 and 4) coil 4

This wireless REUT sensor system was tested to measure the thickness of two specimens, and an accuracy of 0.005 inches (0.127mm) was achieved.

Single-channel Data Acquisition Device Development

- X-1061 PR
  - Negative pulse: 400 Vp-p max
  - Low-noise amplification
  - Receiver gain: 60dB
- X-1067 PR
  - Adjustable square pulse width
  - Pulse amplitude: 100, 200, 300, 400 Vp-p
  - Operation frequency range: 100KHz – 20MHz
  - Receiver gain: 60dB

Rev. 0

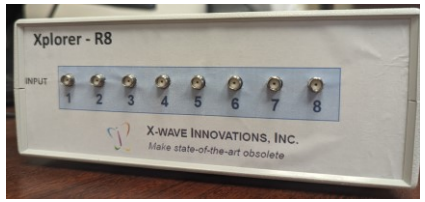
Rev. 1

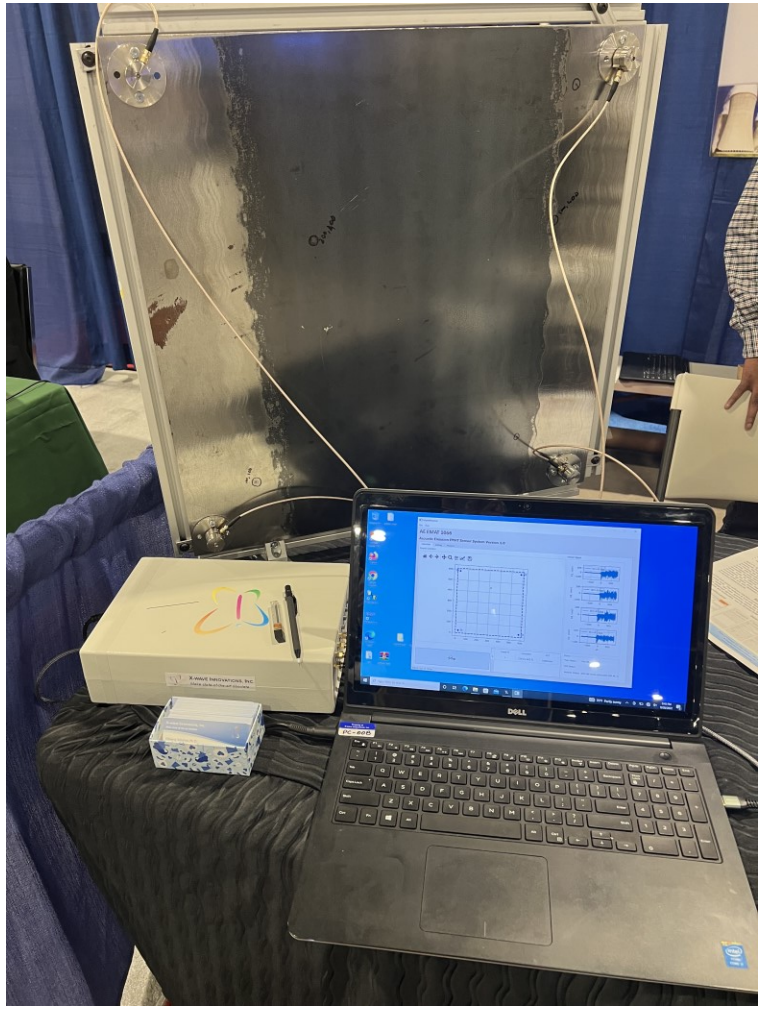
Both X-1061PR and X-1067 PR will be commercially available in a few weeks

Multi-Channel Data Acquisition Hardware

- Passive AE model (Xplore-8R) and Dual AE-GW model (Xplore-8TR)
- Support up to 8 transducers
- Up to 8 transducers in transmission mode sequentially through multiplexing
- Up to 8 transducers in receiving mode concurrently
- Low Noise with EMI Shield and Input / Output Isolation
- Software controlled gain adjustment of receiving amplifier
- Either negative pulse up to 1MHz or arbitrary waveform generator (AWG) up to 1MHz
- On-board high voltage power module and high voltage amplifier

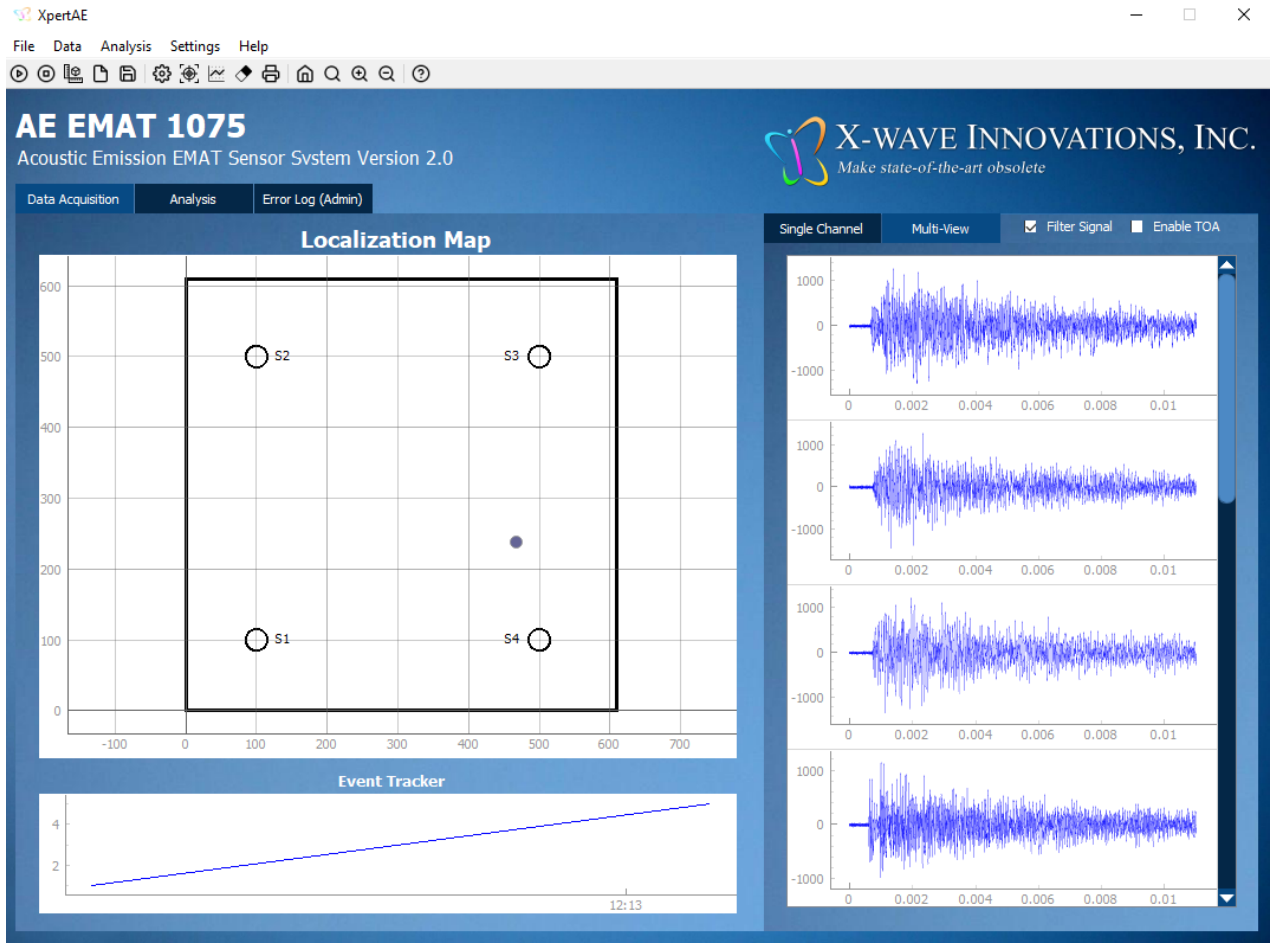
Both Xplore-8R and Xplore-8PR will be commercially available in a few months.





Application Software Development

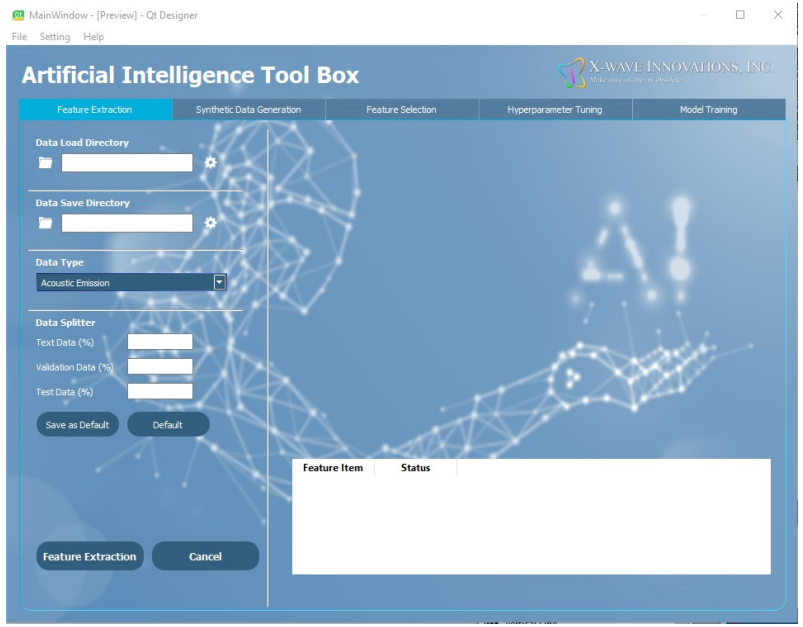
- SHM software with maximum likelihood estimation provides accurate estimation of damage/defect location.
- Signal processing algorithm automatically estimates the ultrasonic velocity.
- Artificial Intelligence/Machine Learning (AI/ML) toolbox incorporated in the software is able to distinguish true AE from other acoustic events.



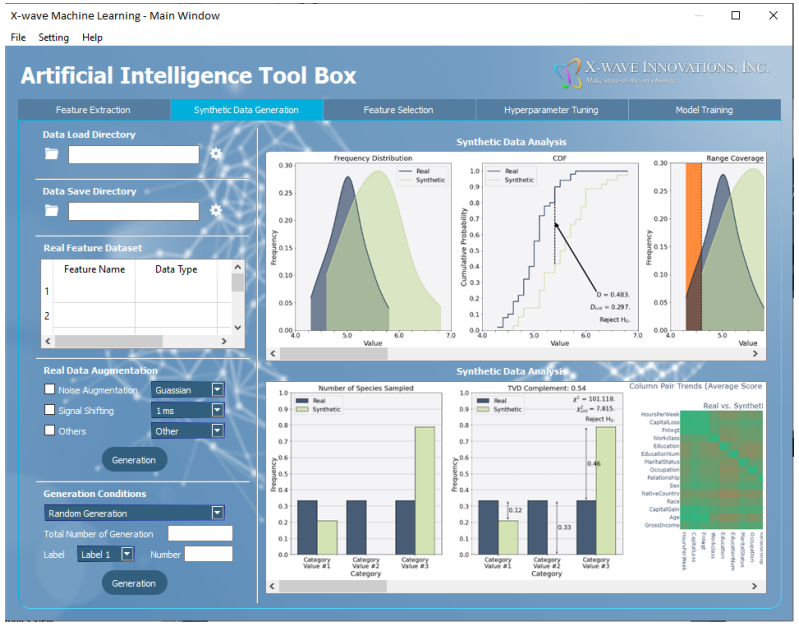
Artificial Intelligence or Machine Learning Toolbox

XII Machine Learning Toolbox:

- **Feature Extraction**
  - Waveform (AE/non-AE) signal feature analysis
- **Synthetic Data Generation**
  - Generate synthetic data for expand dataset and improve ML model performance
- **Feature Selection**
  - Increase model training efficiency and optimize the workflow for following modules
- **Hyperparameter Tuning**
  - Tuning parameters for different ML models and selecting models with better performance on a partial dataset
- **Model Training**
  - Training and validating the selected model with full dataset, provide final ML models for end users



Feature Extraction



Synthetic Data Generation

SUMMARY

- The unique REUT design allows it to continuously operate at high-temperature (e.g., 800ºC or higher, depending on selected piezoelectric element) and high radiation environments of nuclear reactors
- REUT sensor has been modified and demonstrated for
  - Temperature sensing
  - Multi-point temperature sensing
  - Liquid level sensing
  - Fluid viscosity sensing
  - Flow rate sensing
  - Structural health monitoring (AE sensor & GW sensor)
  - Wireless and embedded sensor applications
- Single-channel and multi-channel data acquisition devices are developed to accommodate REUT sensor systems
- Applications software packages with AI/ML toolbox and a variety of signal processing algorithms are developed for REUT applications

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- Dr. Susan White at Ohio State University Nuclear Reactor Lab (OSU/NRL) for the neutron irradiation test
- Dr. Luke Breon at Electrical Power Research Institute (EPRI) for durability and longevity tests