Development of a Radiation Tolerant Liquid Level Sensor

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Research Scientist: Bibo Zhong, PhD

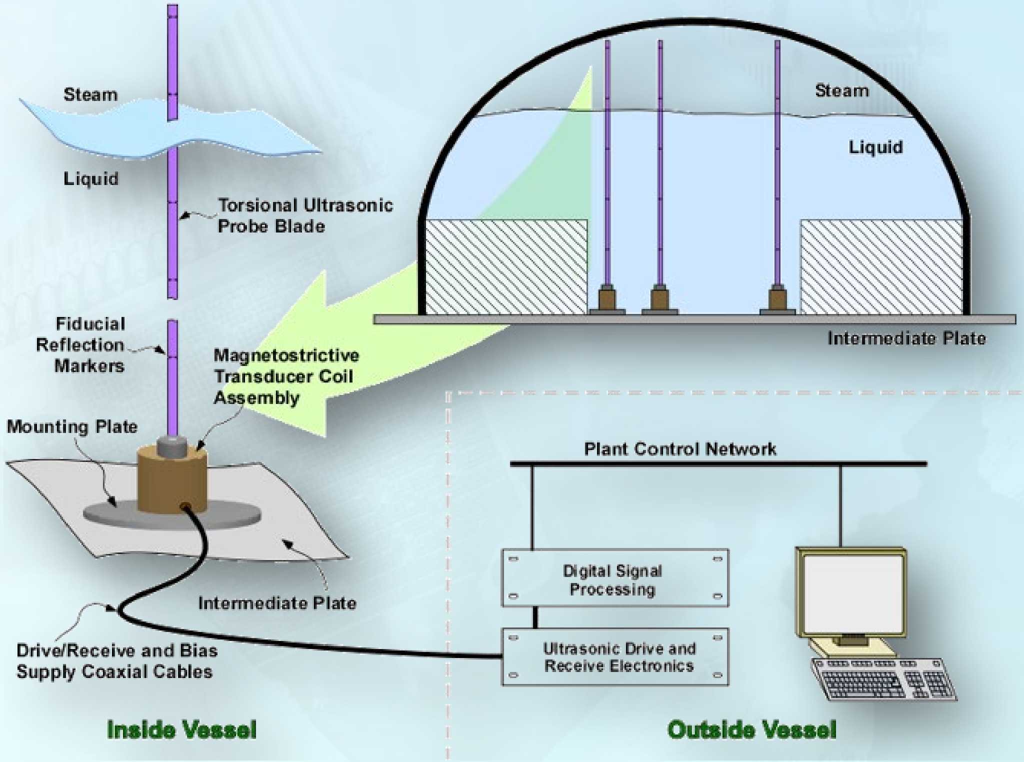
Idaho National Laboratory, Measurement Sciences

Project Overview

- Problem statement
  - Accurate and stable indication of liquid level in the boiling water reactor (BWR) feedwater systems is a known technology gap that has existed for decades.
  - Considerations associated with the harsh radiation and temperature/pressure environments limit available commercial instrumentation options.
- Goal
  - Advance the technology readiness level (TRL) of the instrument from TRL 4 to TRL 6.
    - i.e., build on the existing patent (now expired) by DOE funding.
    - rapid design iterations and rigorous testing with a large testing coverage spanning the operating conditions of target applications.
- Participants
  - PI: Sacit Cetiner
  - Team: Joshua Daw, Bibo Zhong, David Holcomb, Austin Collins (intern)
  - Industry Partners: Boiling Water Reactor Owners Group

Technology Impact

- **Enhanced Safety**: Accurate and reliable liquid level measurement is crucial for maintaining adequate water coverage over the BWRs reactor core and preventing both dry-out and overfill conditions.
- **Operational Efficiency:** Maintaining proper water levels ensures optimal heat transfer from the reactor core to the steam, which is essential for efficient power generation and can increase power output by tens of megawatts electric (MWe).
- There is potential for use in high temperature liquid cooled/fueled reactors.
  - Liquid metal, sodium, salt, etc.
  - May expand measurement to include density and viscosity.



Technology principle

Sensing principle: ***propagation delay*** of torsional waves, i.e., echo return time from the waveguide tip, when the waveguide in immerged in fluid.

- Speed of torsional waves is associated with the shape of the waveguide cross section.
- The sensitivity to the fluid level change also depends on the shape of the waveguide cross section.

Torsion, lowest-order mode, in round waveguide:

$$c_{t\bullet} = (G/\rho)^{1/2}; \qquad (3\text{-}9)$$

in elliptical waveguide of aspect ratio = 3:

$$c_{t\text{ellipse}} = 0.6\,(G/\rho)^{1/2}; \qquad (3\text{-}10)$$

in square waveguide:

$$c_{t\blacksquare} = 0.9184\,(G/\rho)^{1/2}; \qquad (3\text{-}11)$$

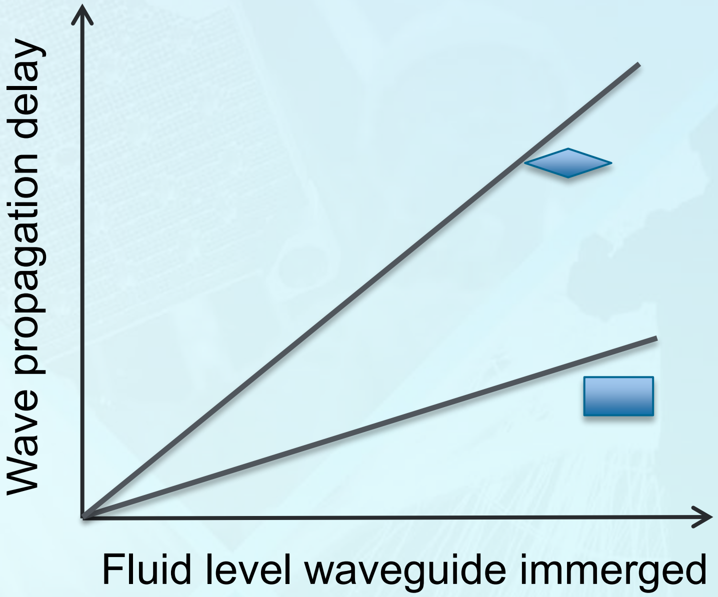
in rectangular waveguide of aspect ratio = 3:

$$c_{t\text{rect}} = 0.56\,(G/\rho)^{1/2}; \qquad (3\text{-}12)$$

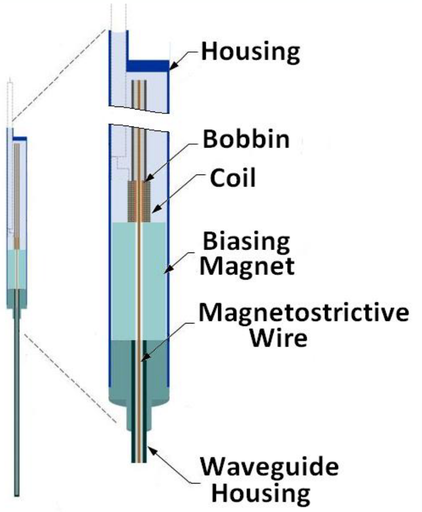
in diamond waveguide of aspect ratio = 3:

$$c_{t\blacklozenge} = 0.57\,(G/\rho)^{1/2}. \qquad (3\text{-}13)$$

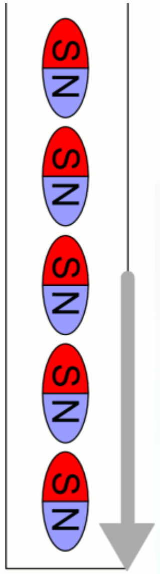
Lynnworth, Lawrence C. *Ultrasonic measurements for process control: theory, techniques, applications*. Academic press, 2013.



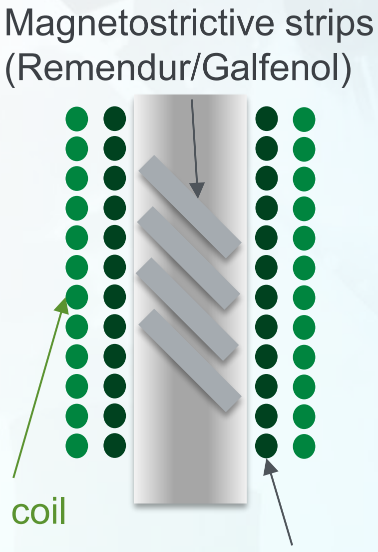
Ultrasonic Transducer (ULTRA) Irradiation at MIT

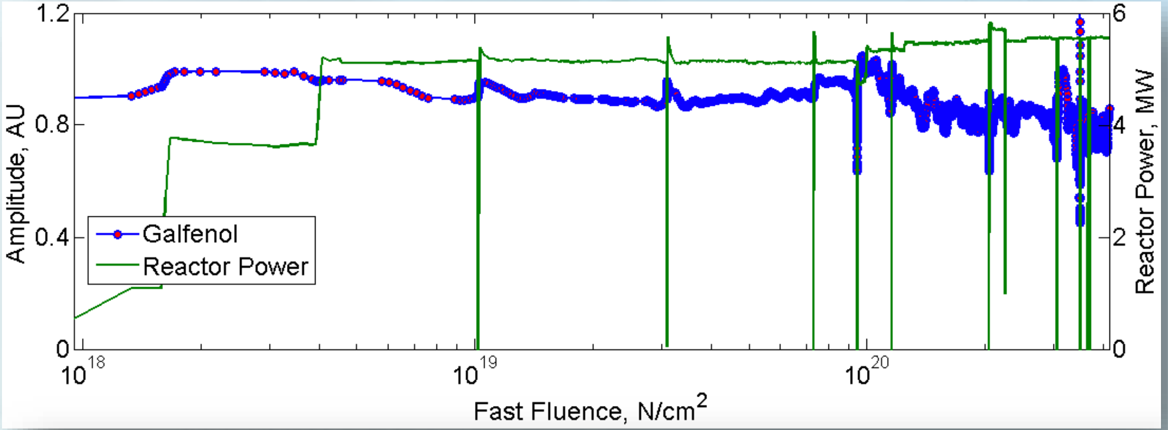


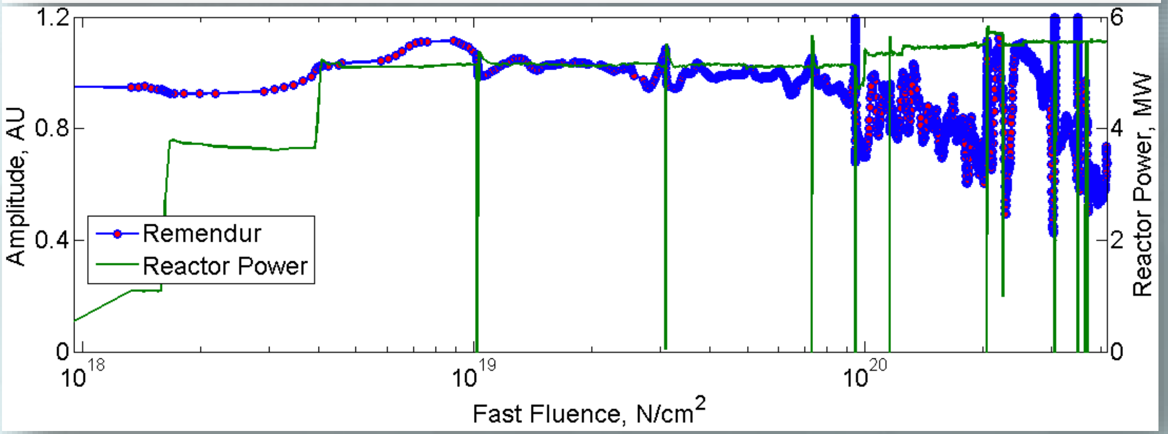
Magnetostrictive Transducers



Mechanism of Magnetostriction





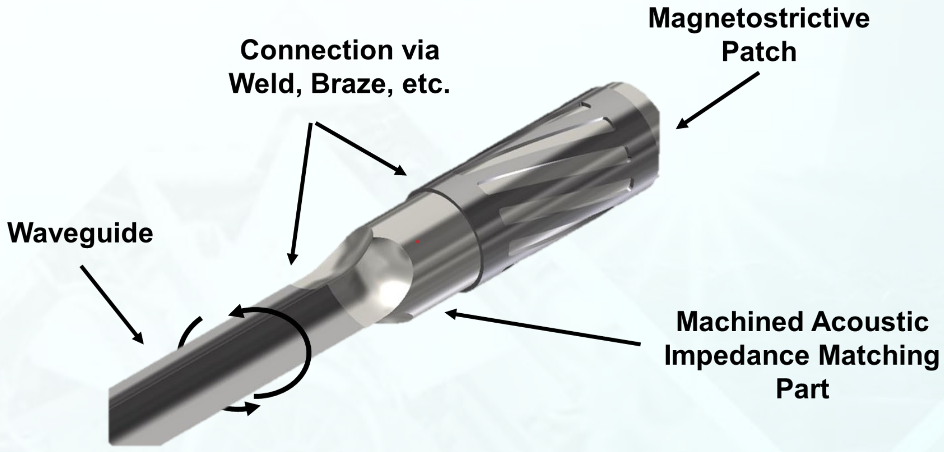


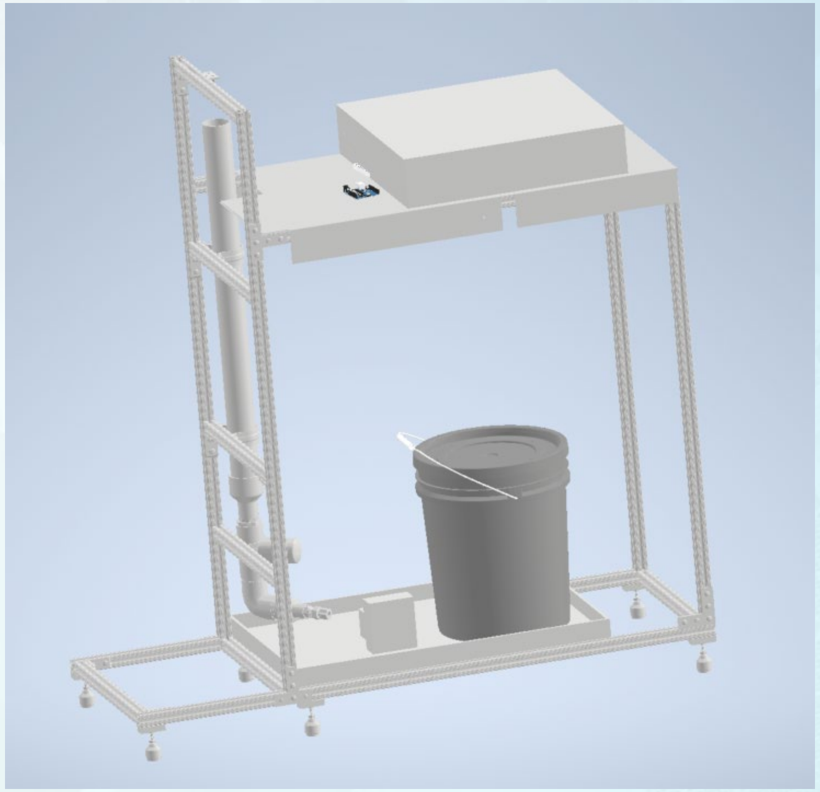
- 1.5 years in-core, ~450°C, 8.8×10^{20} n/cm^2 (Fast)
- ~1 week in Advanced Test Reactor (ATR) at full power
- **Remendur** (iron-cobalt-vanadium alloy), **Galfenol** (iron-gallium alloy) found to be highly radiation tolerant
- A separate Remendur sensor was tested in ATR for more than 7000 hours

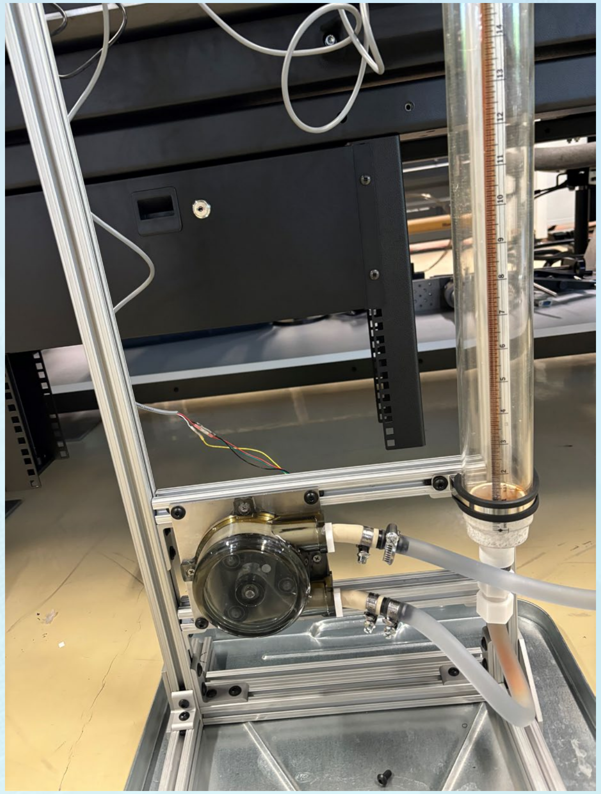
NSUF Nuclear Science User Facilities

Massachusetts Institute of Technology Nuclear Reactor Laboratory

Results and Accomplishments



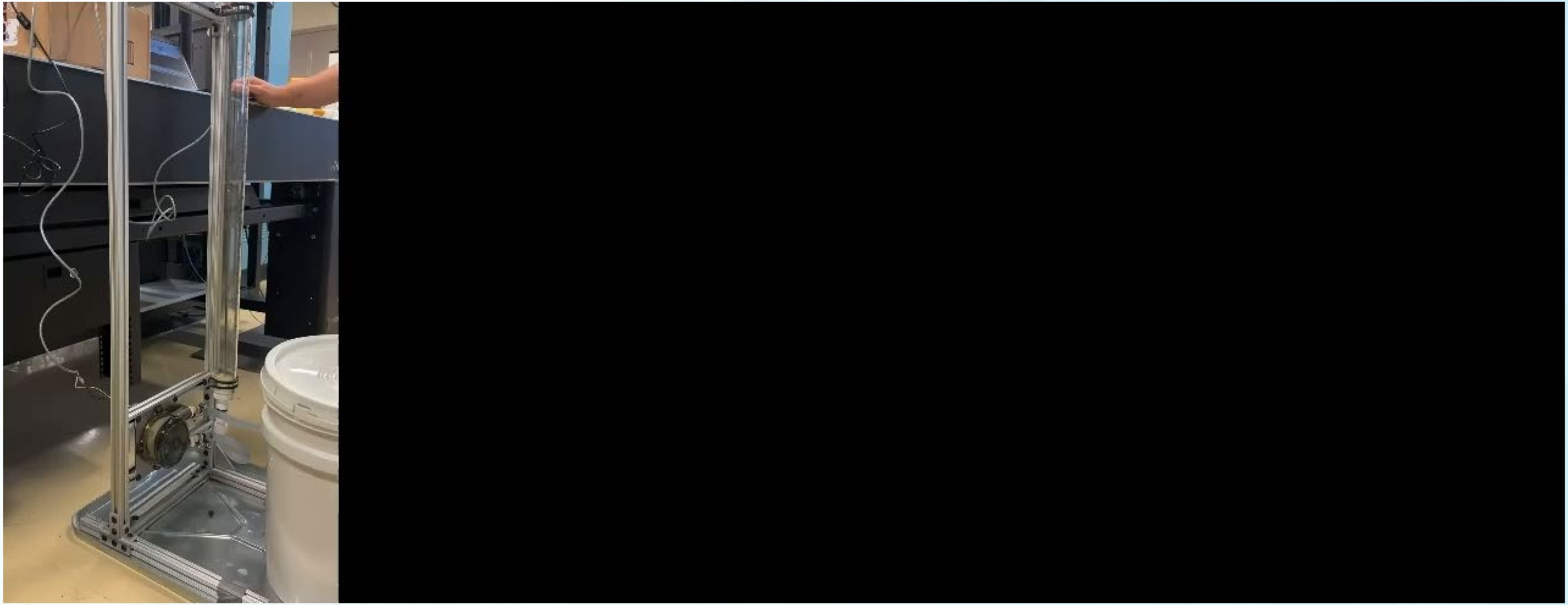




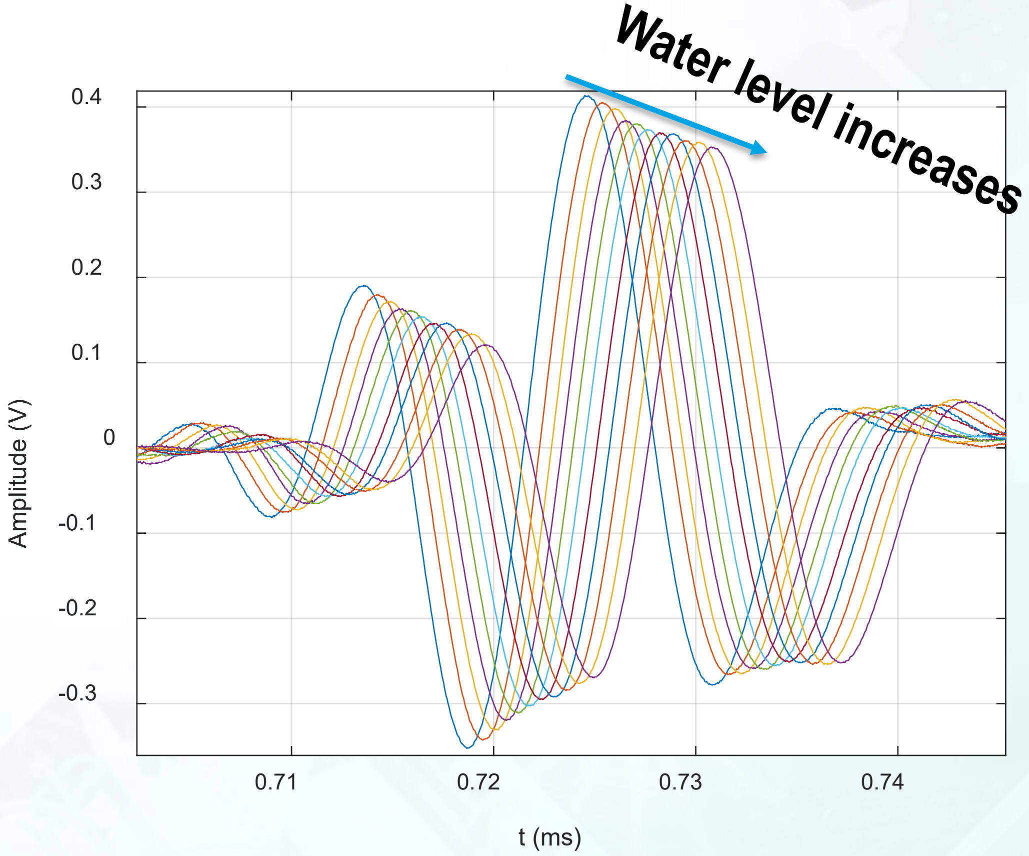
Designed and built by Austin Collins (intern)

Experimental Demonstration #1: Laboratory Testing

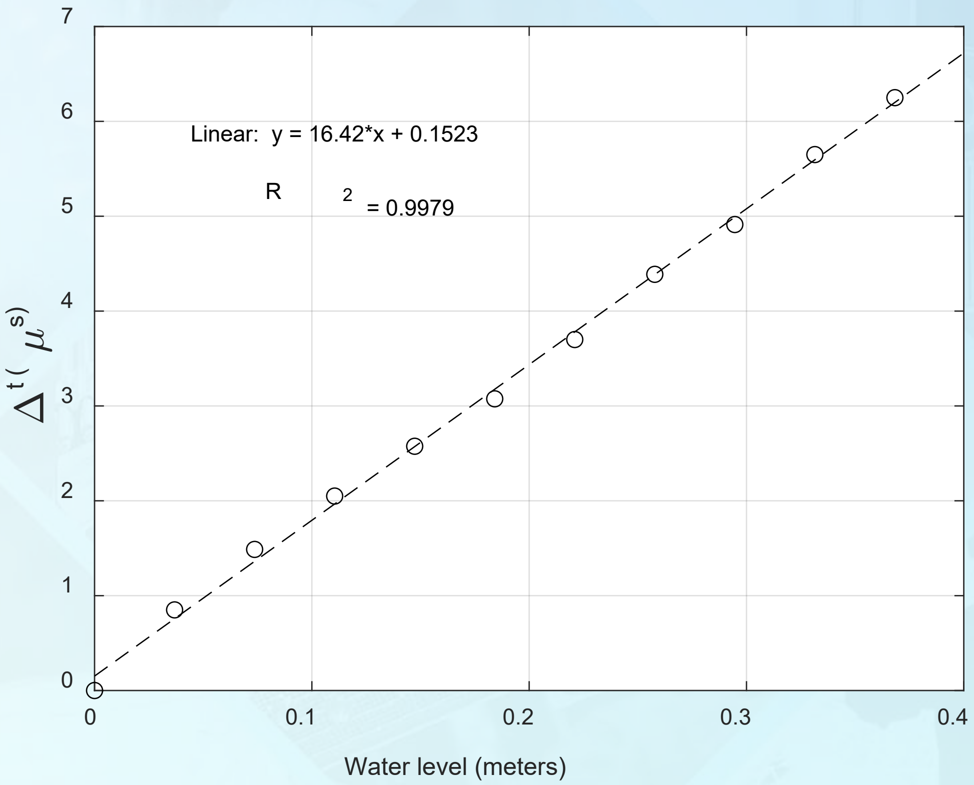
Test Bed Demonstration



Test Bed Demonstration-Results

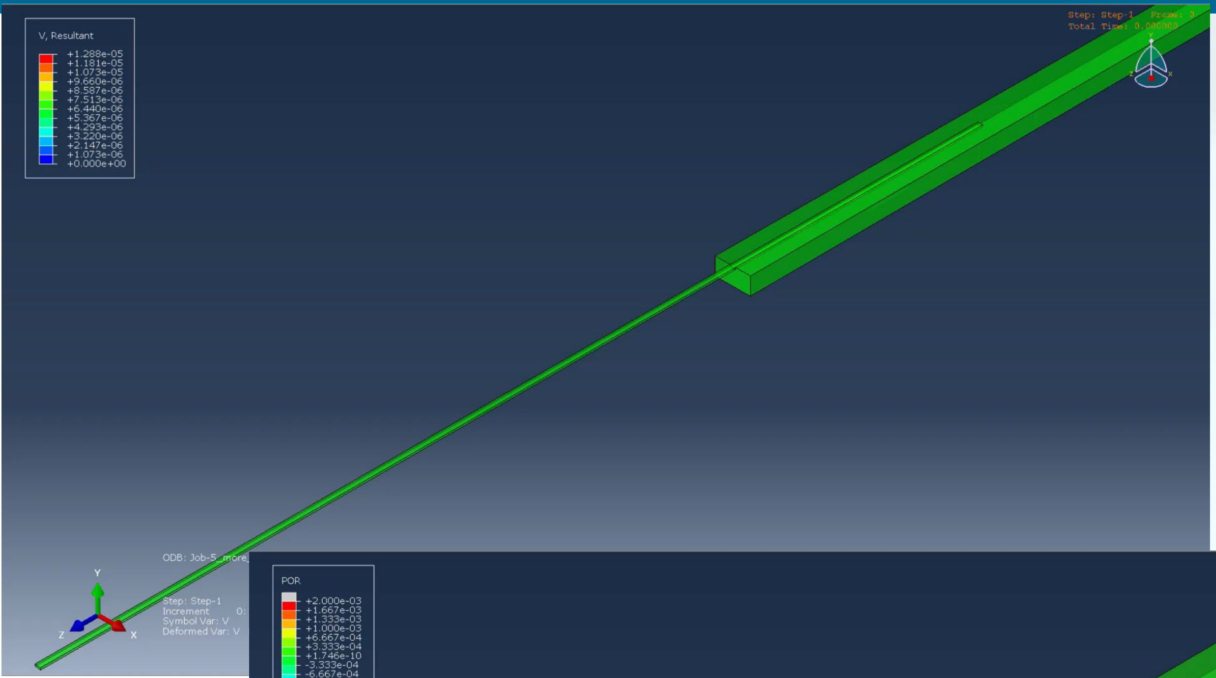


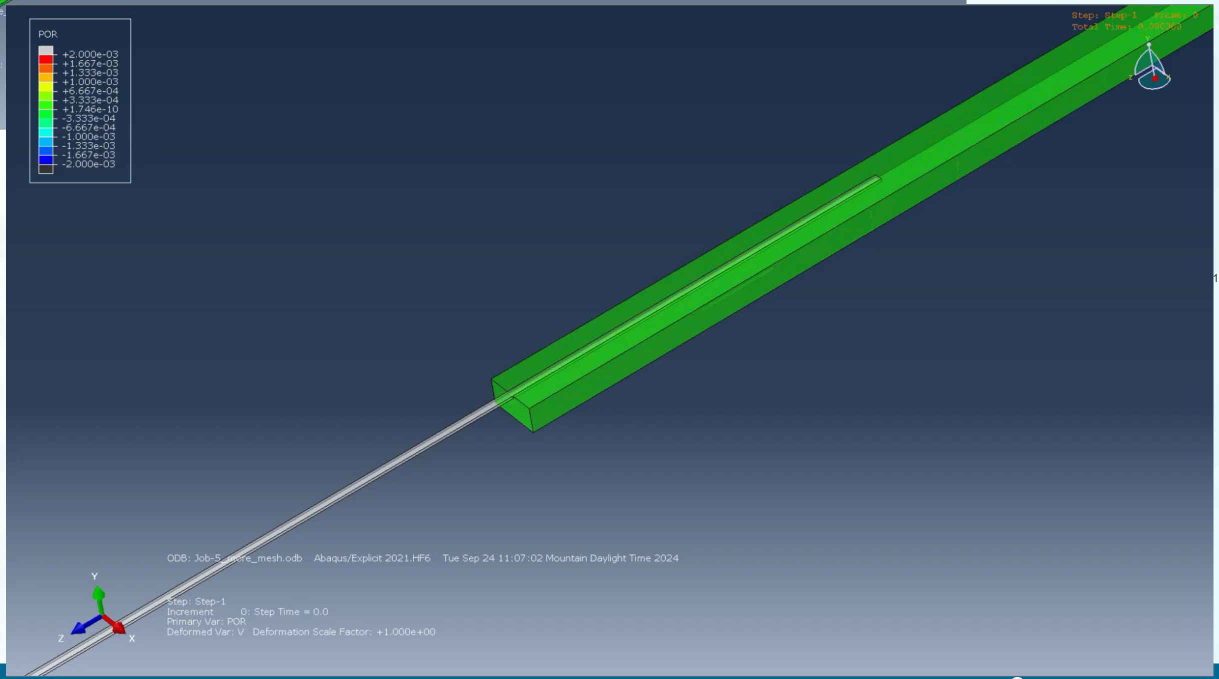
Pulse-Echo Signals for Torsional Wave Mode in Waveguide

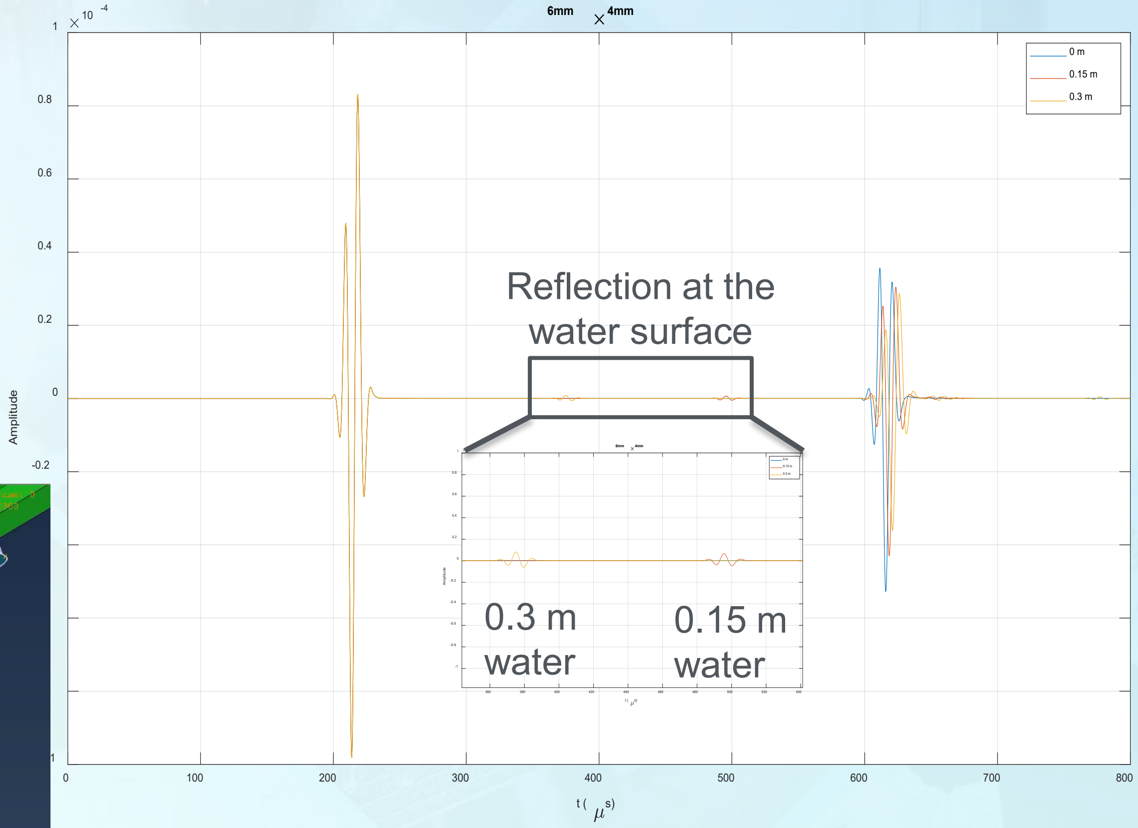


Calibration Curve Relating Time Delay to Water Level

Initial Simulation Results



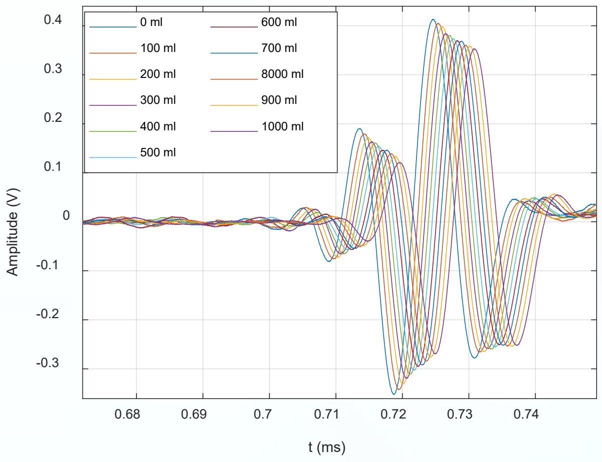


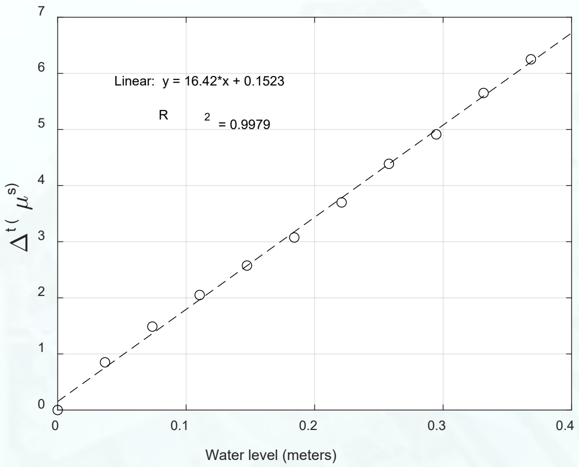


Simulation vs Experiment

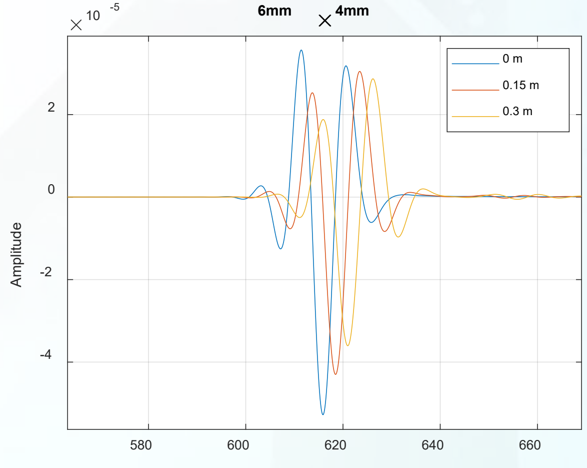
6×4 mm Rectangular Waveguide

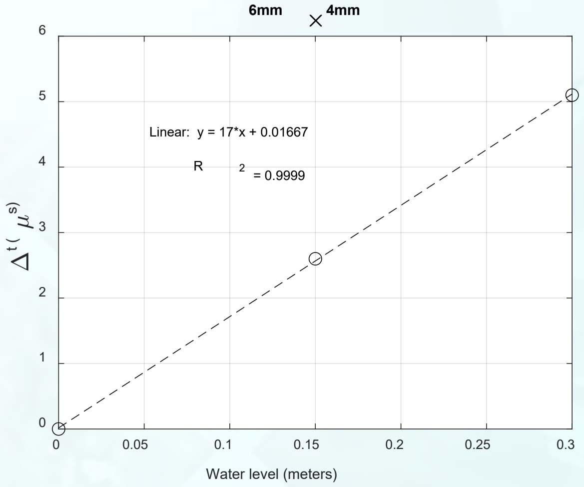
Experiment





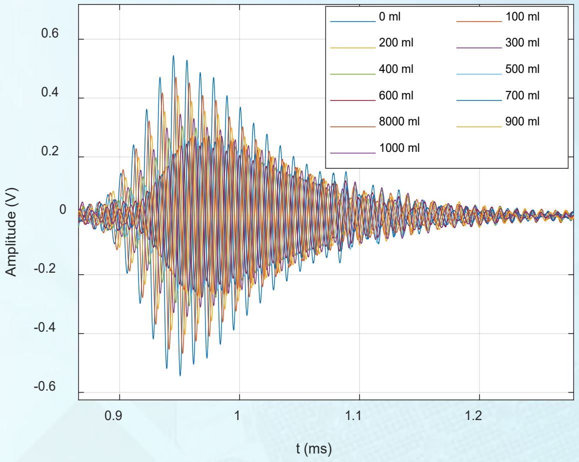
Simulation

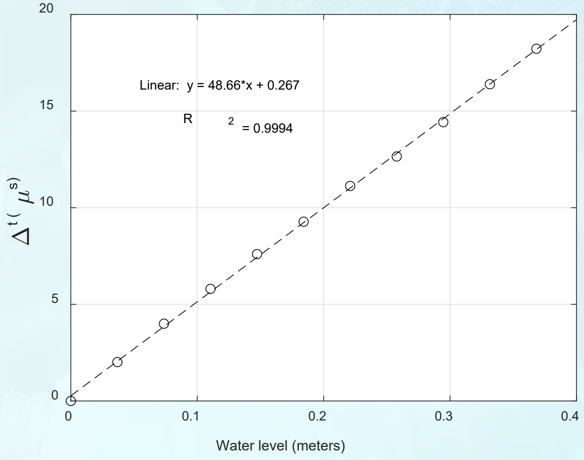




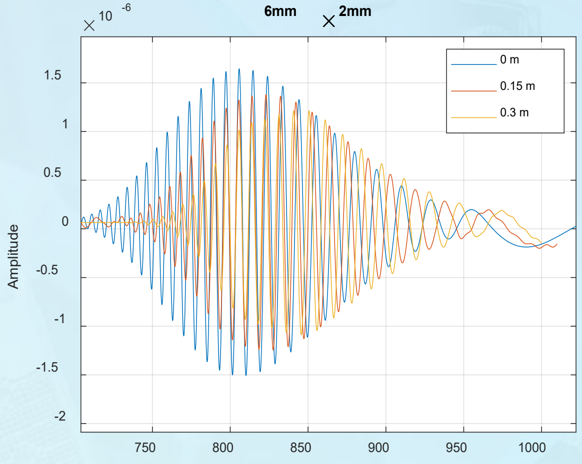
6×2 mm Rectangular Waveguide

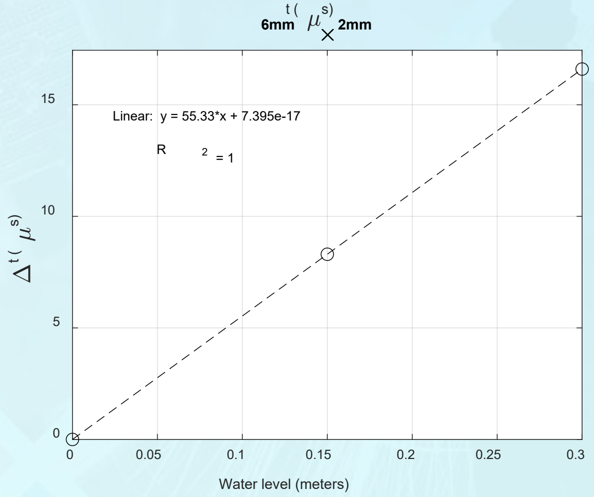
Experiment



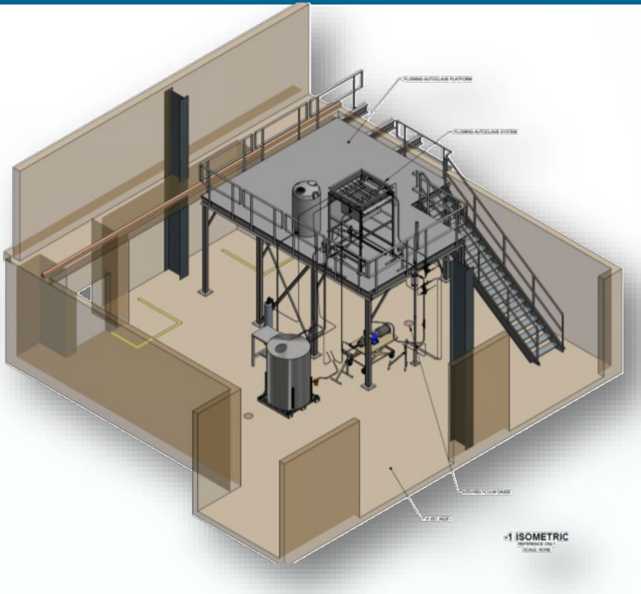


Simulation





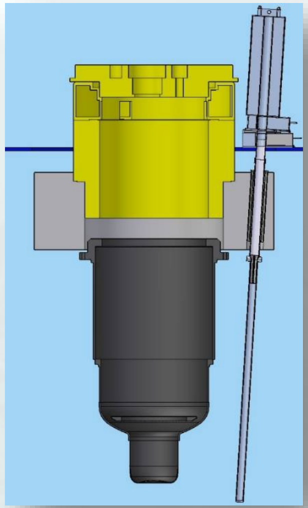
Future Experimental Demonstrations

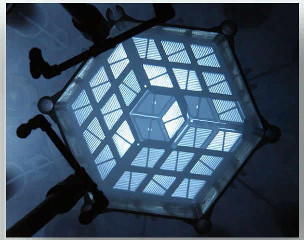


Parameter		Measurement
Flow Rate		0 - 20 gal/min
Temperature		20 - 320 °C
Pressure		Up to 2500 psig
Water Chemistry		Yes, Controlled
Test Sections Available*	Length	Up to 12 ft
	Diameter	1 in & 1.5 in

#2: INL Flowing Autoclave System

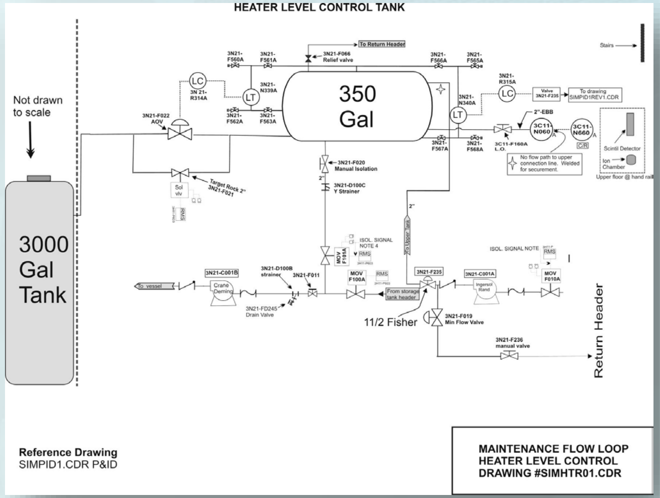
#3: INL Gamma Tube





#4: MIT 3GV Facility

- Thermal neutron flux ~1×10^{13} n/cm^{2}s
- Fast neutron flux ~1×10^{10} n/cm^{2}s
- Normally operated air- or helium-filled with water-cooled jacket
- Access manually or via cask/crane



#5: Plant Hatch Instrument Testing Facility

Concluding Remarks

Accomplishments to date

- Test bed developed and demonstrated
- First prototype successfully demonstrated
- 2 IDRs and 1 patent filed

Near term tasks

- Optimize waveguide and transducer through multi-physics modelling
  - Shape (inertia)
  - Cross-section (inertia)
  - Material (acoustic speed, compatibility, etc.)
- Develop multi-property measurement
  - Level
  - Temperature
  - Density
  - Viscosity
- Develop temperature compensation method
- Irradiation Testing
  - Gamma (INL)
  - Neutron (MITR)
- Demonstrate
  - Flowing autoclave
  - Hatch nuclear power plant

Bibo Zhong
Research Scientist (INL)
Bibo.Zhong@inl.gov
W 208-526-0462 | C 402-706-5008
ORCiD: 0000-0001-8720-3481
https://scholar.google.com/citations?user=HjYWopMAAAAJ&hl=en&

Thank You