U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Self-powered Wireless Through-wall Data Communication for Nuclear Environments

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Virginia Tech

DE-NE0008591
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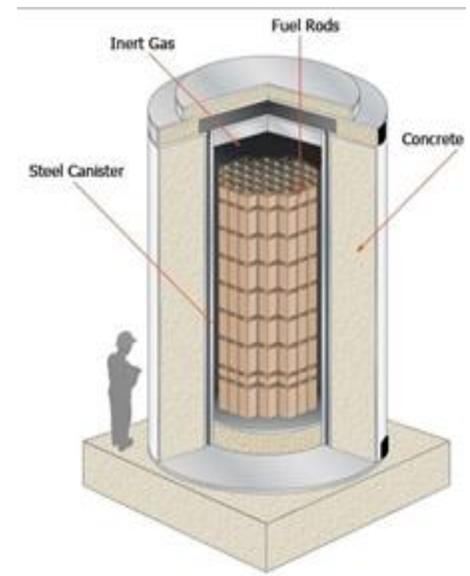
Project Overview

Background

2100 canisters for 20-50 years of spent fuel storage in the USA. 200 per year increase.



Goal, and Objectives

Develop and demonstrate an enabling technology for the data communications for enclosed metal canisters using radiation and thermal energy harvesters, through-wall ultrasound communication, and harsh environment electronics.

Participants

- Lei Zuo (PI, Virginia Tech), Dong Ha (co-PI, Virginia Tech)
- Haifeng Zhang (co-PI, U. of North Texas)
- Roger Kisner, M. Nance Ericson (co-PI, ORNL)
- Michael Heibel (collaborator, Westinghouse Electric Company)

Schedule

Tasks	Year One				Year Two				Year Three			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Kickoff meeting, review sensing environments and needs (All)	◊	◊	◊	◊								
Task 2: Designing and fabricating radiation energy harvesters (Univ. A PI)				◊	◊	◊	◊	◊				
Task 3: Designing &testing ultrasonic data transmission system (Univ. B co-PI)				◊	◊	◊	◊	◊				
Task 4: Developing high-temperature electronics (Company A co-PI)					◊	◊	◊	◊	◊	◊		
Task 5: Radiation study and shielding protection (Company B co-PI, Univ. A PI)								◊	◊	◊	◊	
Task 6: System integration, demonstration and test (All)										◊	◊	◊
Task 7: Reporting and project management (Univ. A PI)	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊

Our Solution: Self-powered Wireless Through-wall Data Communication for Nuclear Environments

Problems and solutions:

I. **Energy problem:** Independent and continuous energy source

Solution: A **radiation/thermal energy harvester** with power management;

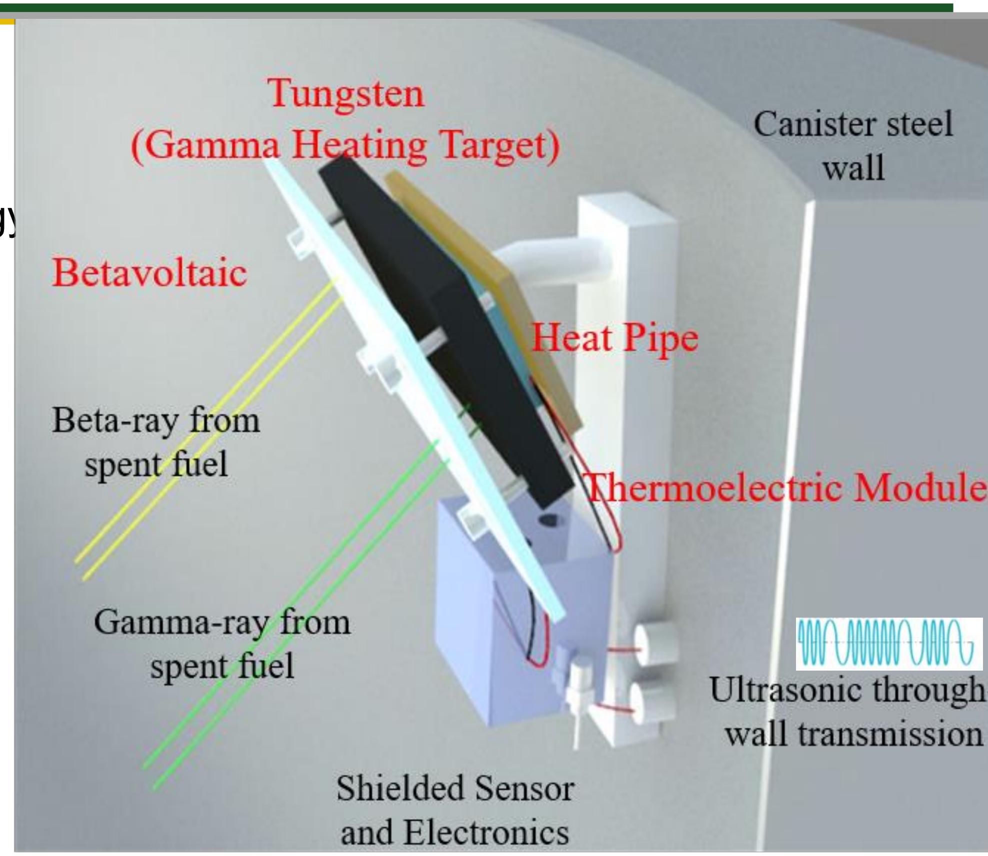
II. **Communication challenge:** Through metal wall and thick concrete wall wireless communication

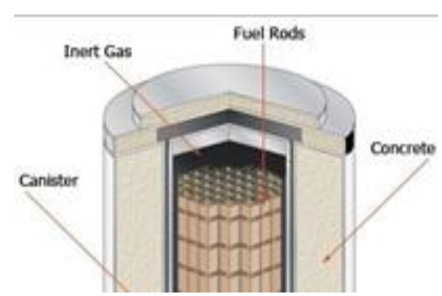
Solution: Ultrasound wireless communication using high-temperature piezoelectric transducers

III. **Harsh environment:** Electronics surviving high temperature and radiation

Solution:

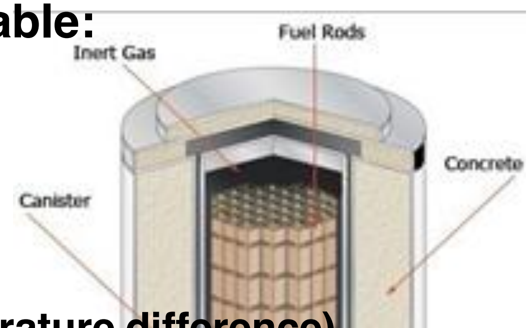
a. High-temperature radiation-hardened electronics for harvesting, sensing, and data transmission;
b. Radiation shielding for electronics and sensors





Accomplishments: Energy harvesting

Energy sources available:



1. Mechanical vibration
2. Light
3. Wind
4. Electromagnetic
5. Thermal heat (temperature difference)
6. Radiation (alpha, beta, neutron, and gamma rays)

Energy demand:

	Ultrasound	EMAT	Inductive
Mechanism	Ultrasound	Ultrasound	Magnetic
Media	Any	Any	Large skin depth
Power (Est.)	~1 watt	~2 watt	~1 watt
Bit rate (Max)	5M bps	1M bps	1000 bps

To power 1W sensing and data transmission for 3 seconds every 5 minutes, ***10mW required***.

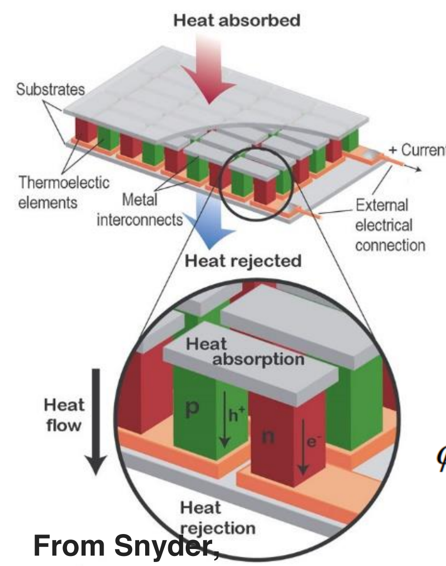
Energy harvesting strategy:

Existing temp. gradient

Gamma heating

Thermoelectric energy harvesting

Thermoelectric energy harvesting:



From Snyder, G. Jeffrey

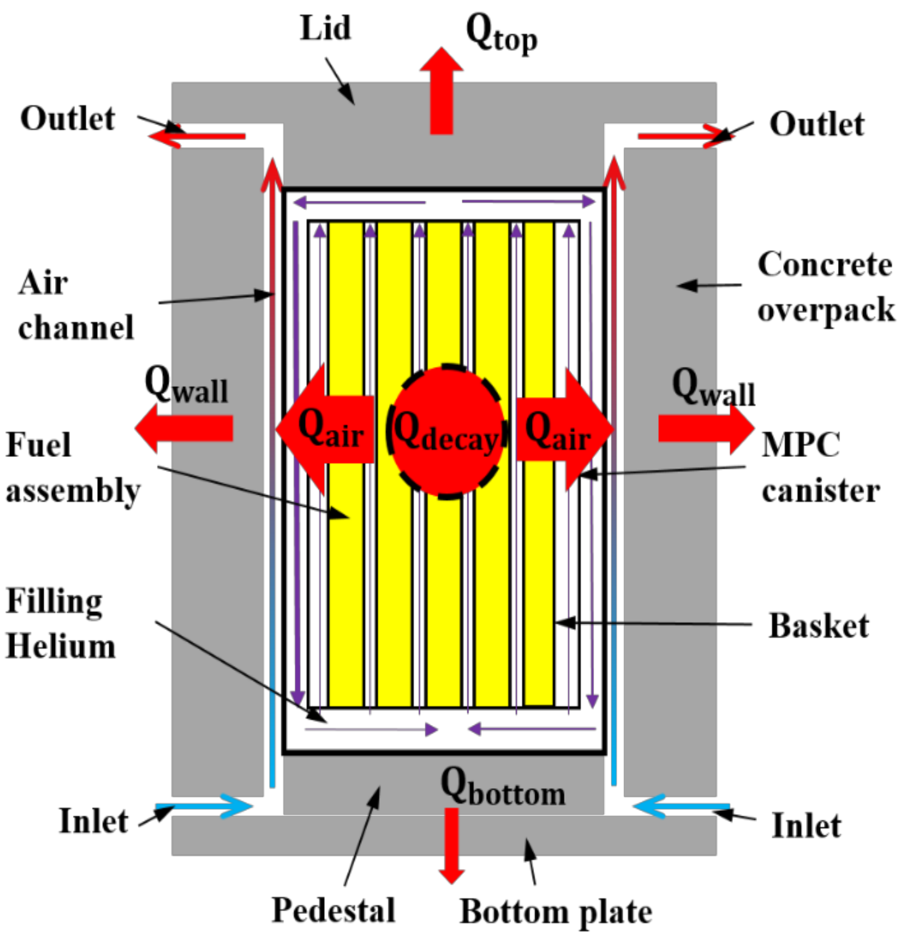
$$Z = \frac{\sigma S^2}{\kappa_e + \kappa_l},$$

σ Electrical conductivity
α, Seebeck coefficient
κe Electron thermal conductivity
κl Phonon thermal conductivity

$$\phi_{max} = \frac{T_1 - T_2}{T_1} \bullet \frac{(1+Z\bar{T})^{1/2} - 1}{(1+Z\bar{T})^{1/2} + T_2/T_1}$$

Accomplishments: Energy harvesting

Heat and fluid environment in the dry cask system:



The model to estimate the decay heat within the dry cask system: MPC-32 canister

Year (Since removal)	Decay Heat (kW)	Gamma Spectrum (#/s)	Neutron Spectrum (#/s)
5	38.44	2.64×10^{17}	1.02×10^{10}
10	24.52	1.47×10^{17}	8.4×10^{9}
15	21.07	1.20×10^{17}	7.0×10^{9}
20	19.00	1.04×10^{17}	5.9×10^{9}
25	17.31	9.2×10^{16}	4.9×10^{9}
30	15.85	8.2×10^{16}	4.1×10^{9}
35	14.56	7.3×10^{16}	3.4×10^{9}
40	13.42	6.5×10^{16}	2.9×10^{9}
45	12.40	5.8×10^{16}	2.4×10^{9}
50	11.49	5.1×10^{16}	2.0×10^{9}
55	10.67	4.6×10^{16}	1.7×10^{9}

Fuel: Westinghouse 17x17 assembly, with a total cask MTU of 15 spread over the 32 assemblies, an enrichment weight percentage of U-235 of 4%, a burnup of 45 GWd/MTU, 3 runs per fuel assembly, and an average power of 40 MW/MTU.

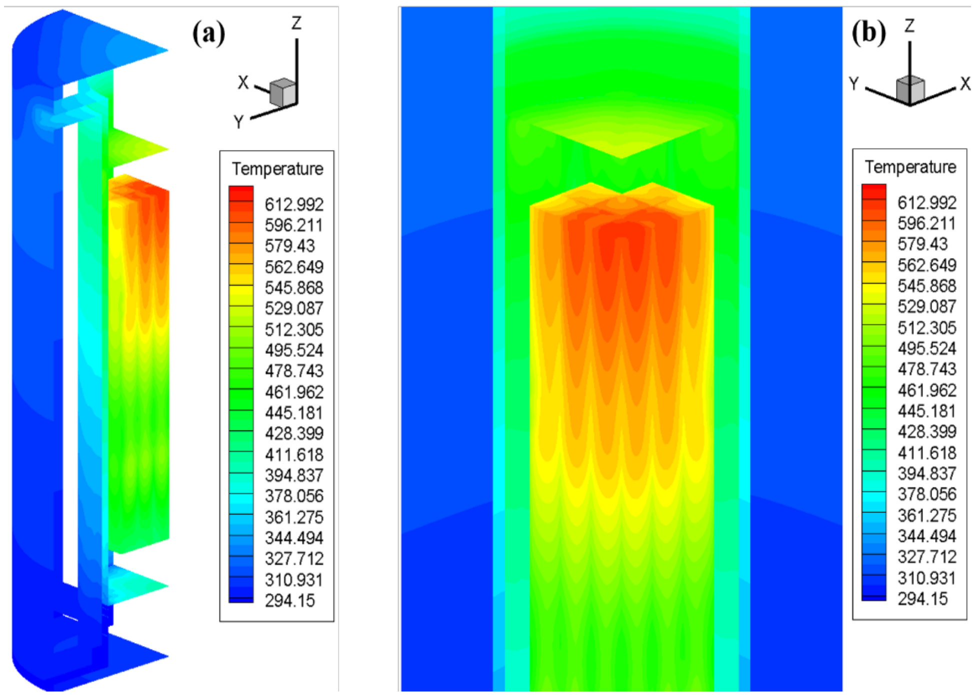
We used MCNP Package.

Accomplishments: Energy harvesting

MPC-32 canister thermal analysis

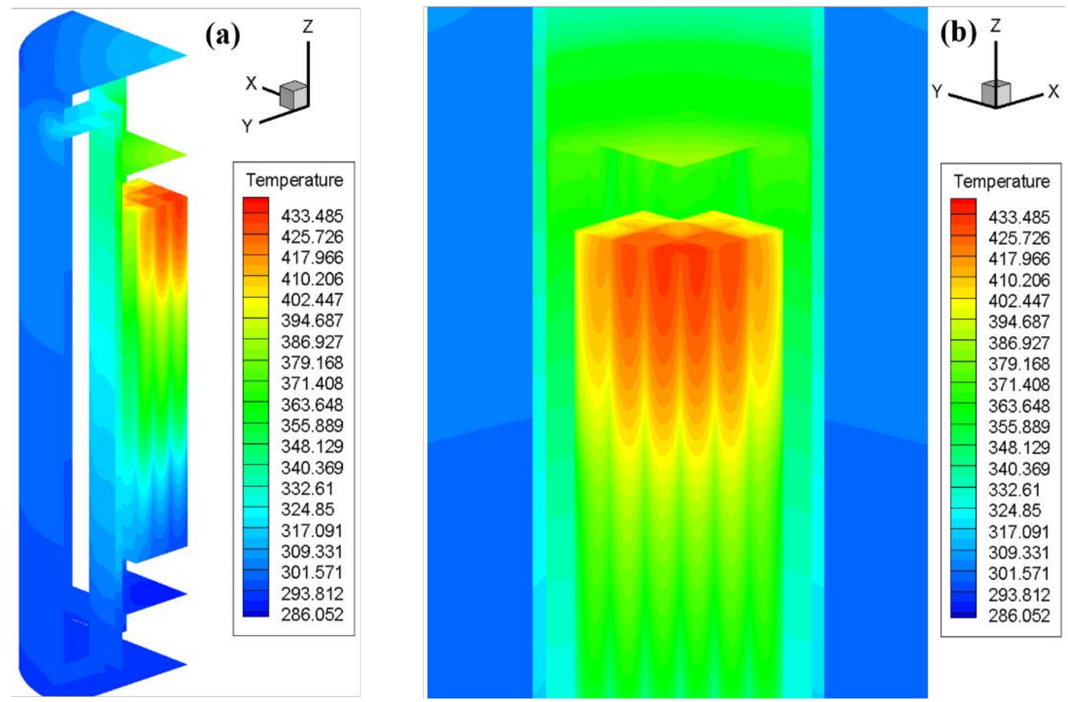
Temperature Profiles:

Years 5



Peak temperature 621.4 K (348.4C)

Years 55



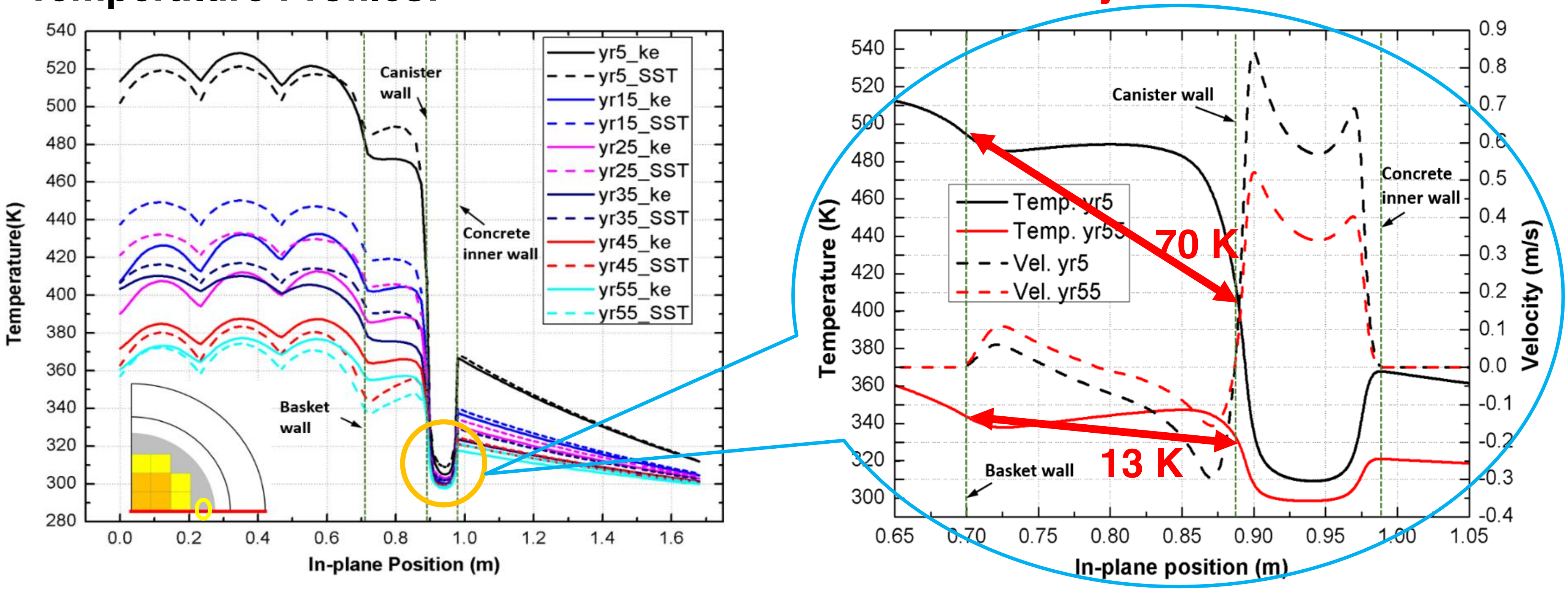
Peak temperature 436.0 K (163.0C)

- Transitional SST k-ω turbulence model and DO radiation model.
- The total decay heat was calculated using SCALE for a period of 50 years.
- **The simulation result was verified using experimental result in literature.**

"Thermal and Fluid Analysis of Dry Cask Storage Containers over Multiple Years of Service", Yongjia Wu, Jackson Klein, Hanchen Zhou, Lei Zuo, *Annals of Nuclear Energy*, Vol 112, Feb 2018, Pages 132–142

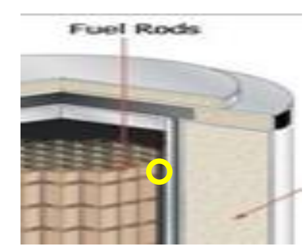
Accomplishments: Energy harvesting

Temperature Profiles: **MPC-32 canister thermal analysis**



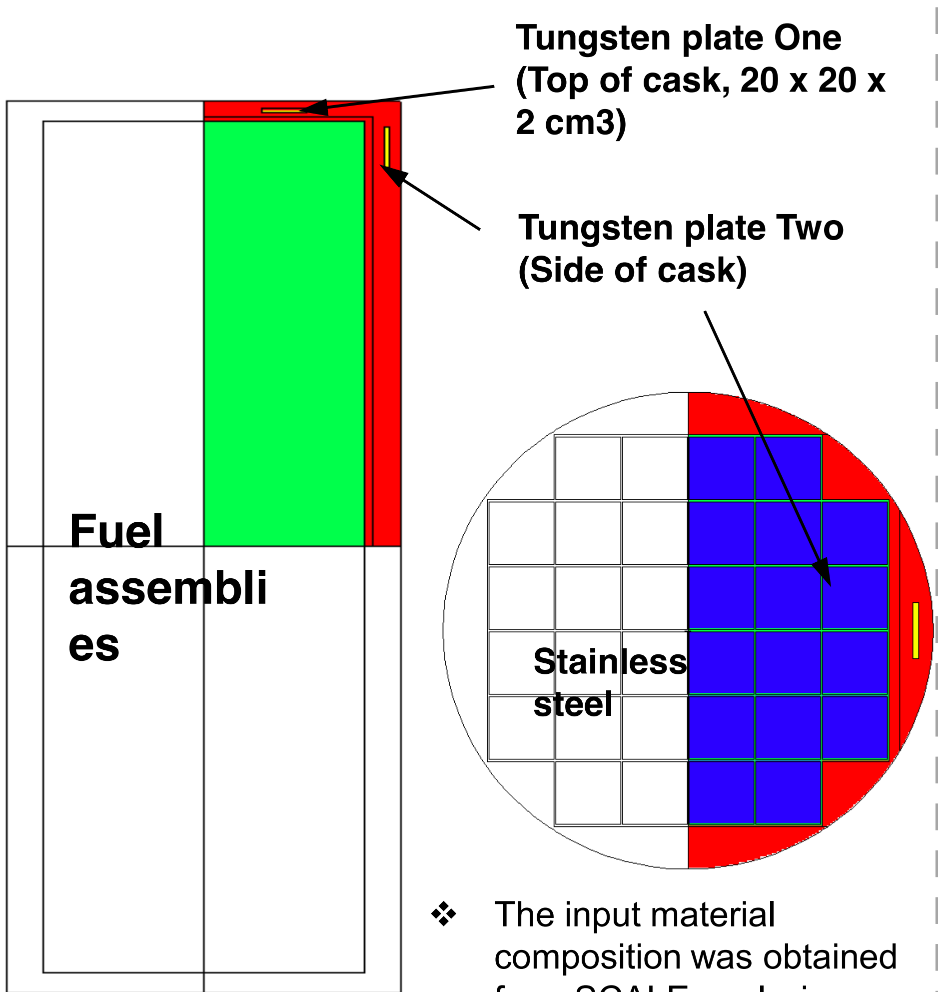
- For year 5, the temperature difference is **~70 K**.
- For year 55, the temperature difference is **~13 K**. (Two TEGs (TEG1-PB-12611-6.0) from TECTEG MFR will be enough)

$$P_{\max} = \frac{N\alpha_{PN}{}^{2}\Delta T^{2}}{4R}$$

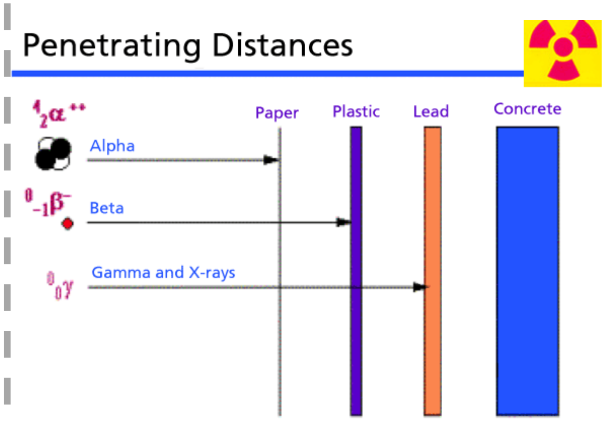


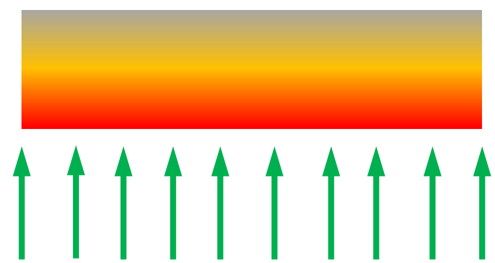
Accomplishments: Energy harvesting

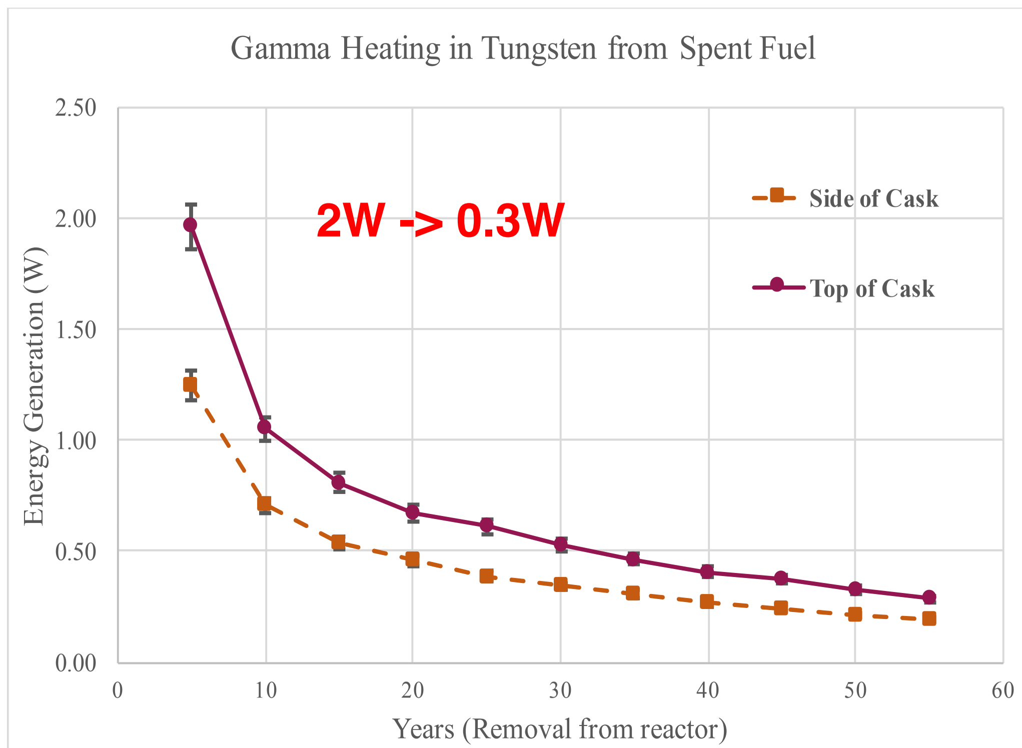
MNCP model



❖ The input material composition was obtained from SCALE analysis.

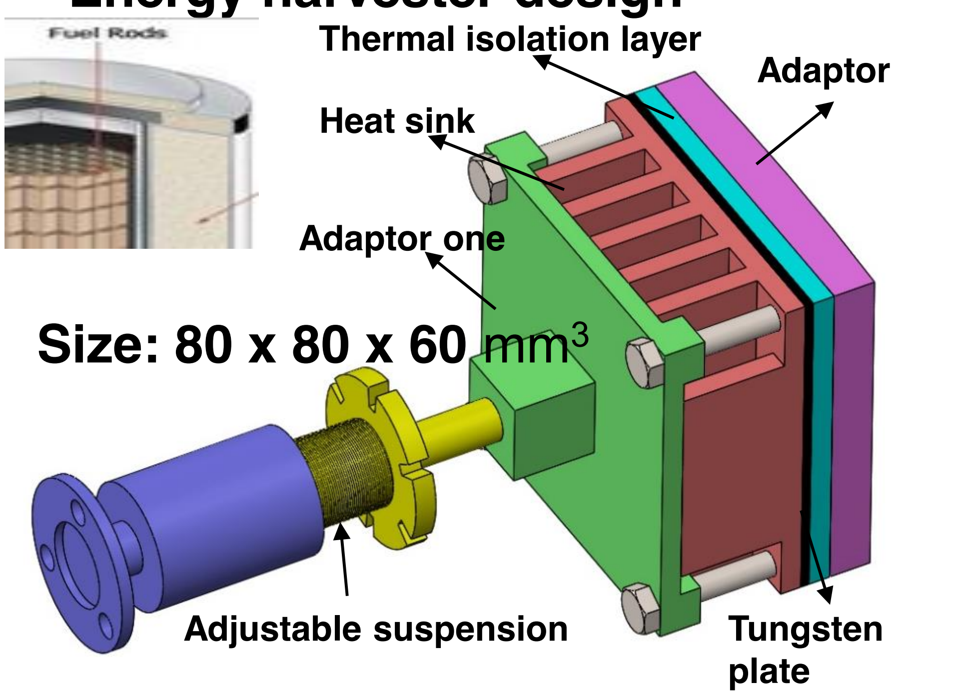






Accomplishments: Energy harvesting

Energy harvester design

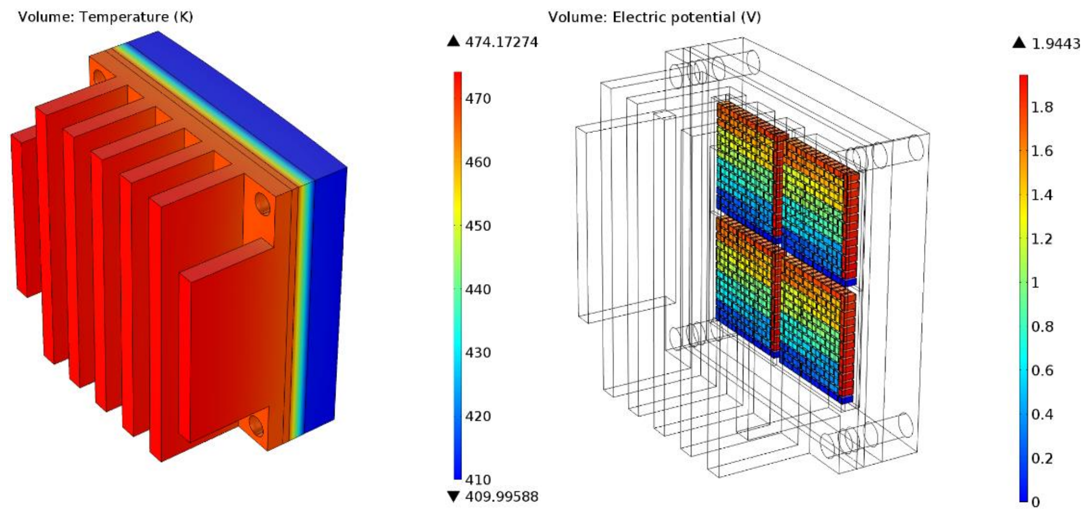


Size: 80 x 80 x 60 mm^3

❖ **Merits:** Simple, compact, low cost, reliable, and high energy output

❖ **Characteristics:** Combined gamma decay heat and convective heat

Performance estimation



Goal: P>=10 mW

Year 5

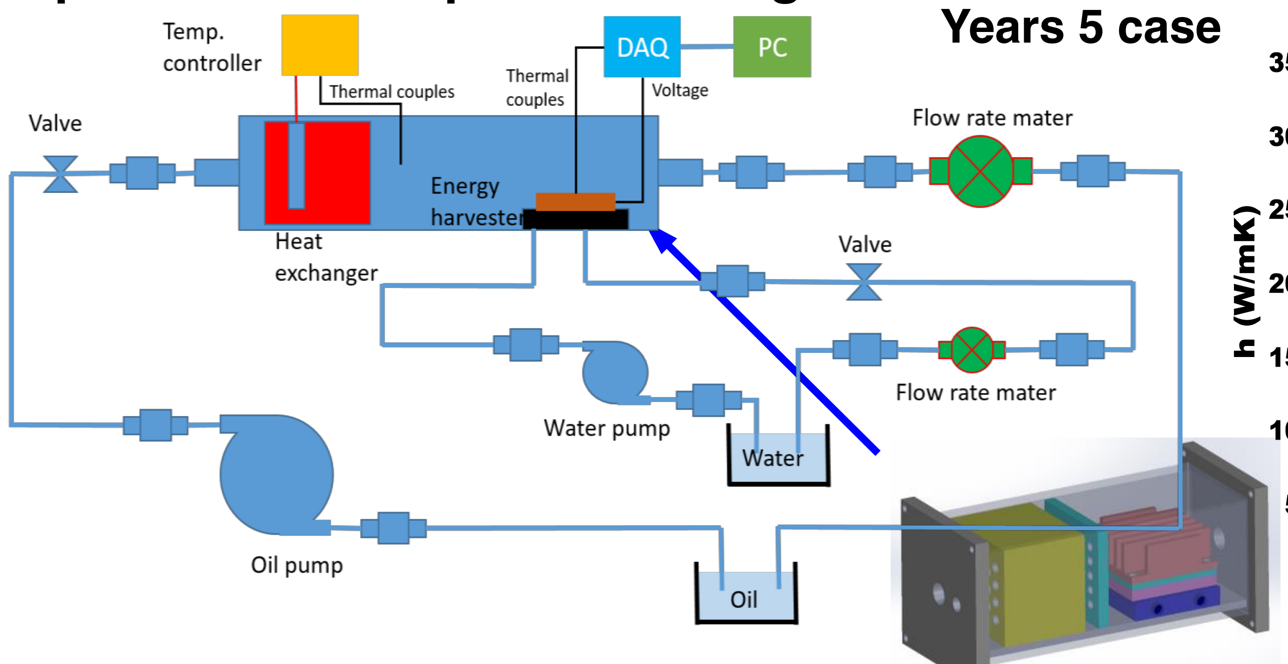
Temperature difference:
ΔT=64.2 K,
Open circuit voltage:
V=1.94 x 4 V,
Maximum power output:
P = 941 mW > 10 mW

Year 55

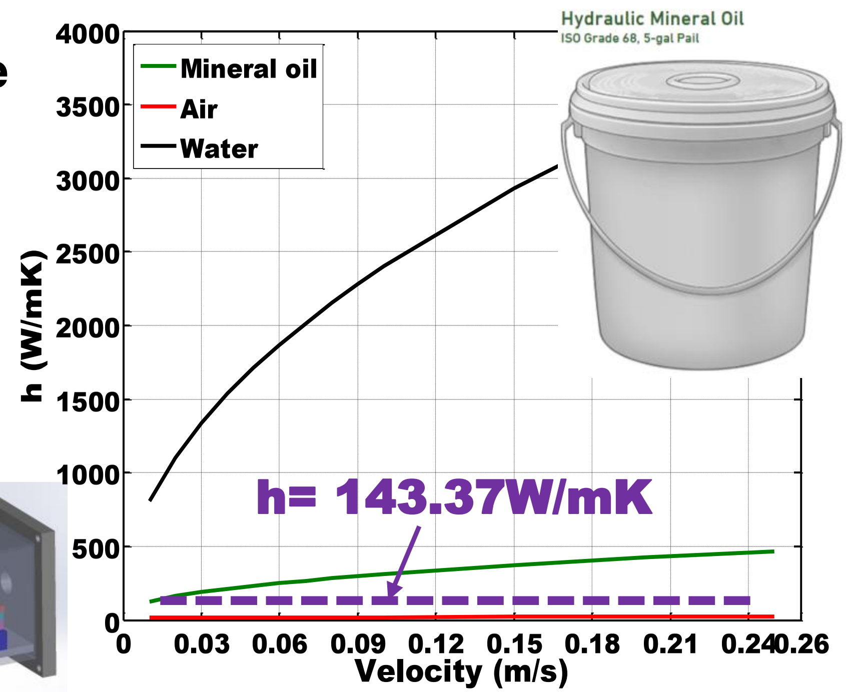
Temperature difference:
ΔT=11.7 K,
Open circuit voltage:
V=0.335 x 4 V,
Maximum power output:
P = 28 mW > 10 mW

Accomplishments: Energy harvesting

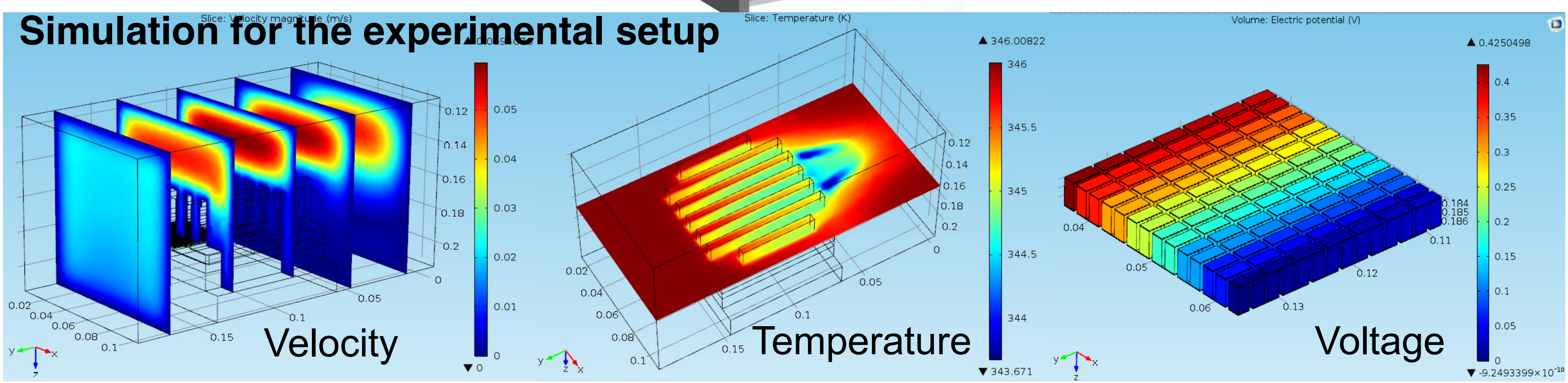
Experimental setup to test design one



Years 5 case

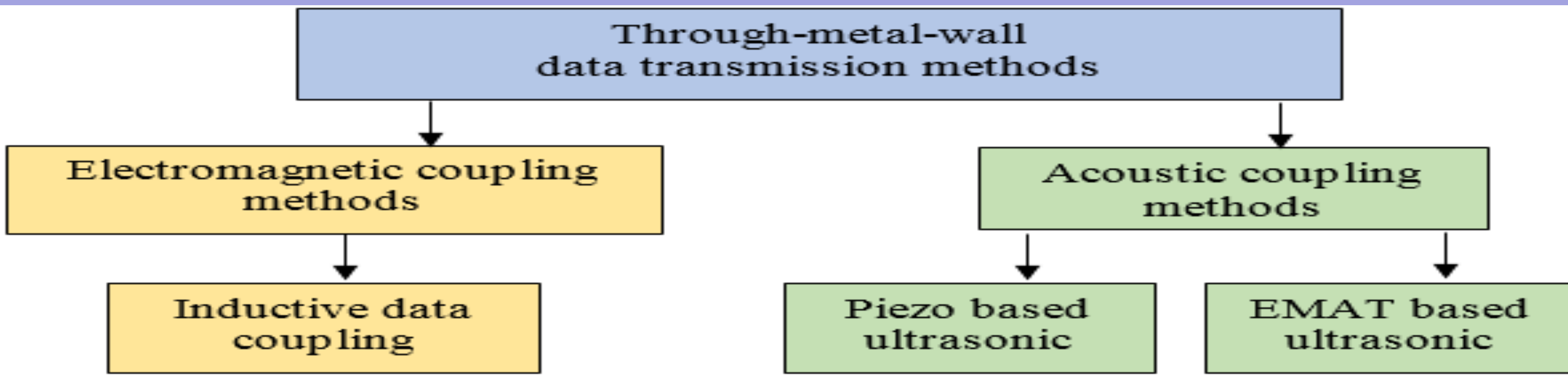


Simulation for the experimental setup



Accomplishments: Wireless communication technology

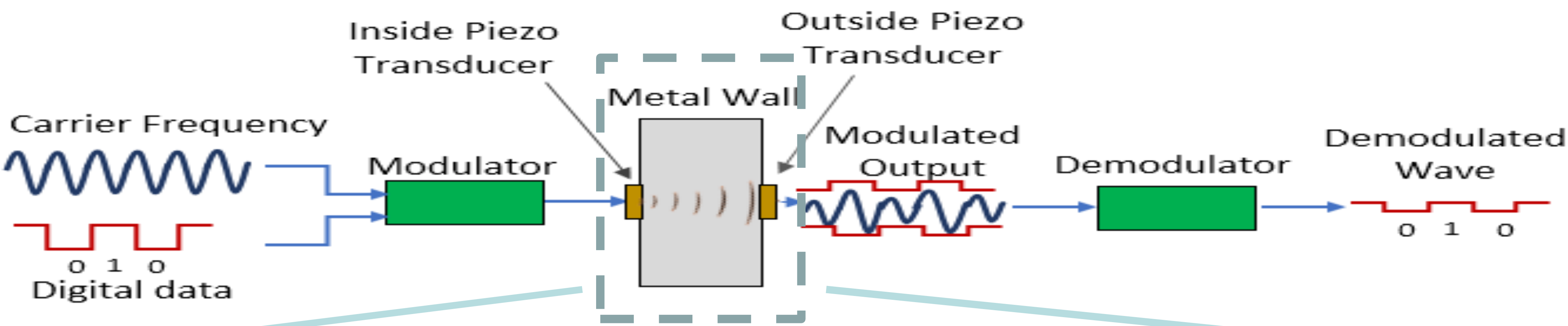
Current available through wall communication methods

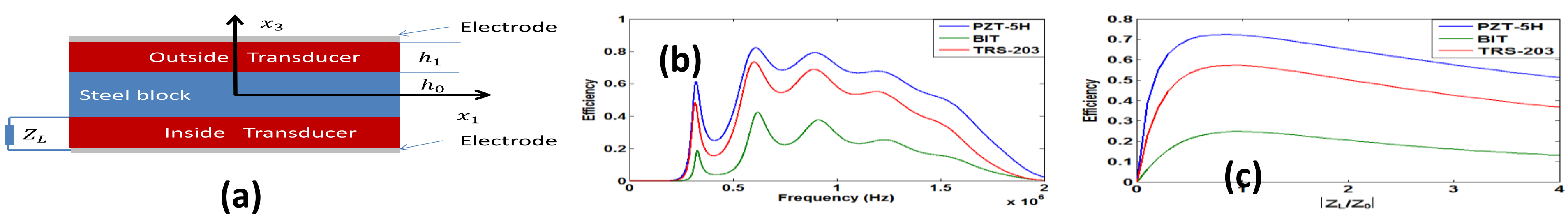


	Ultrasound	EMAT	Inductive
Mechanism	Ultrasound	Ultrasound	Magnetic
Media	Any	Any	Large skin depth
Power (Est.)	~1 watt	~2 watt	~1 watt
Bit rate (Max)	5M bps	1M bps	1000 bps

Accomplishments: Wireless communication technology

Principle of ultrasound through wall communication

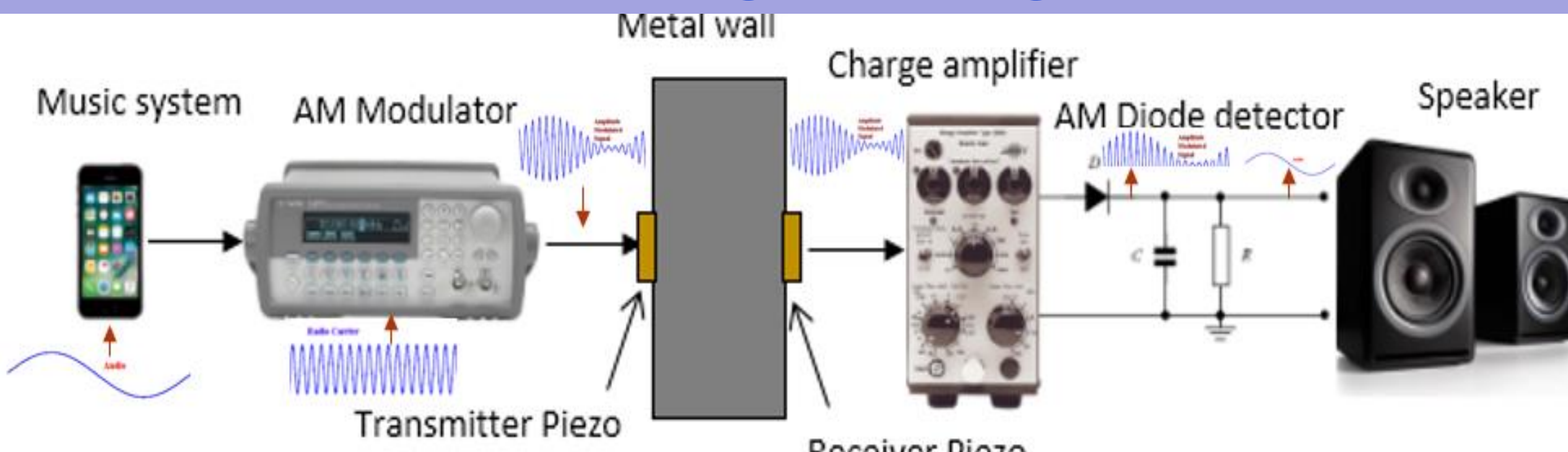


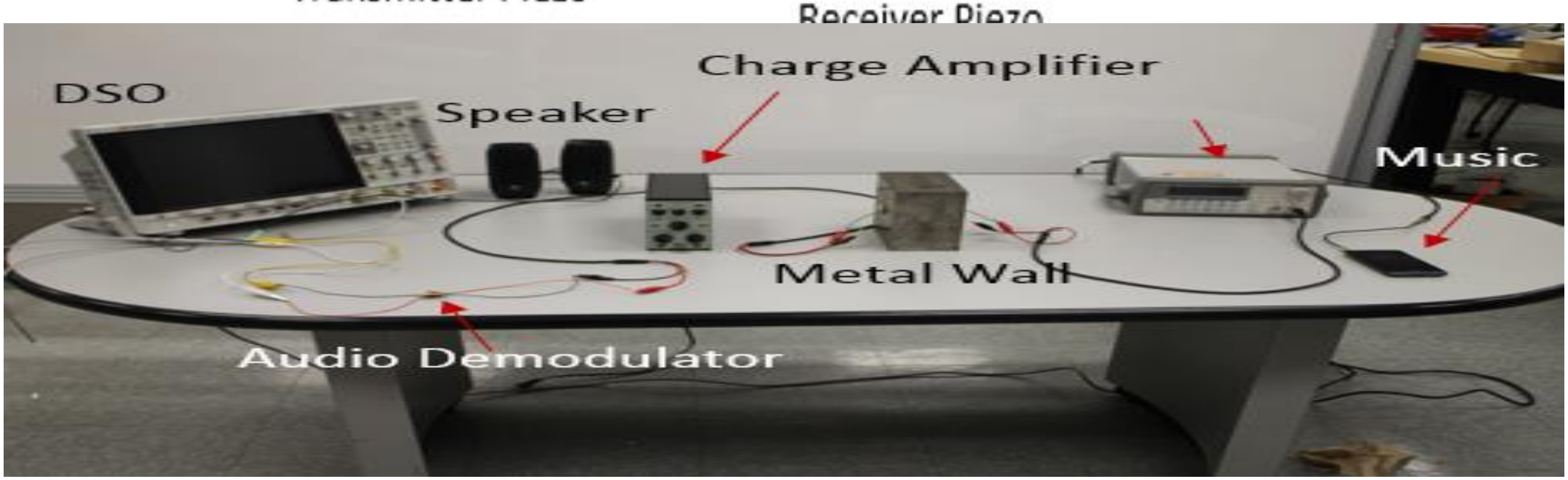


The acoustic modelling results; (a) the steel block sandwiched by two piezoelectric transducers. (b)The ultrasound transmission system efficiency versus driving frequency; (c) The system efficiency versus normalized load circuit impedance.

Accomplishments: Wireless communication technology

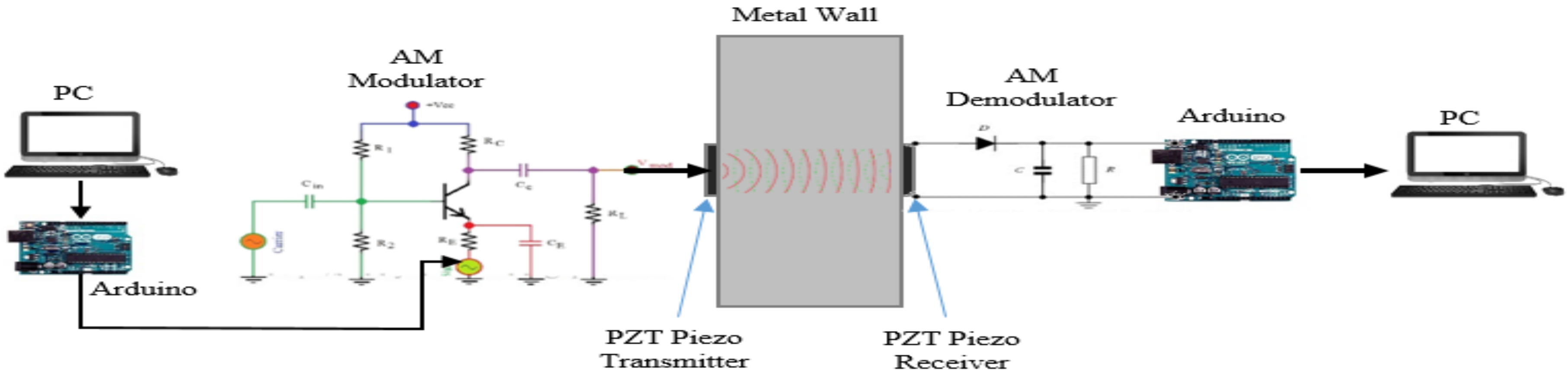
Demonstration of audio signal through-wall transmission

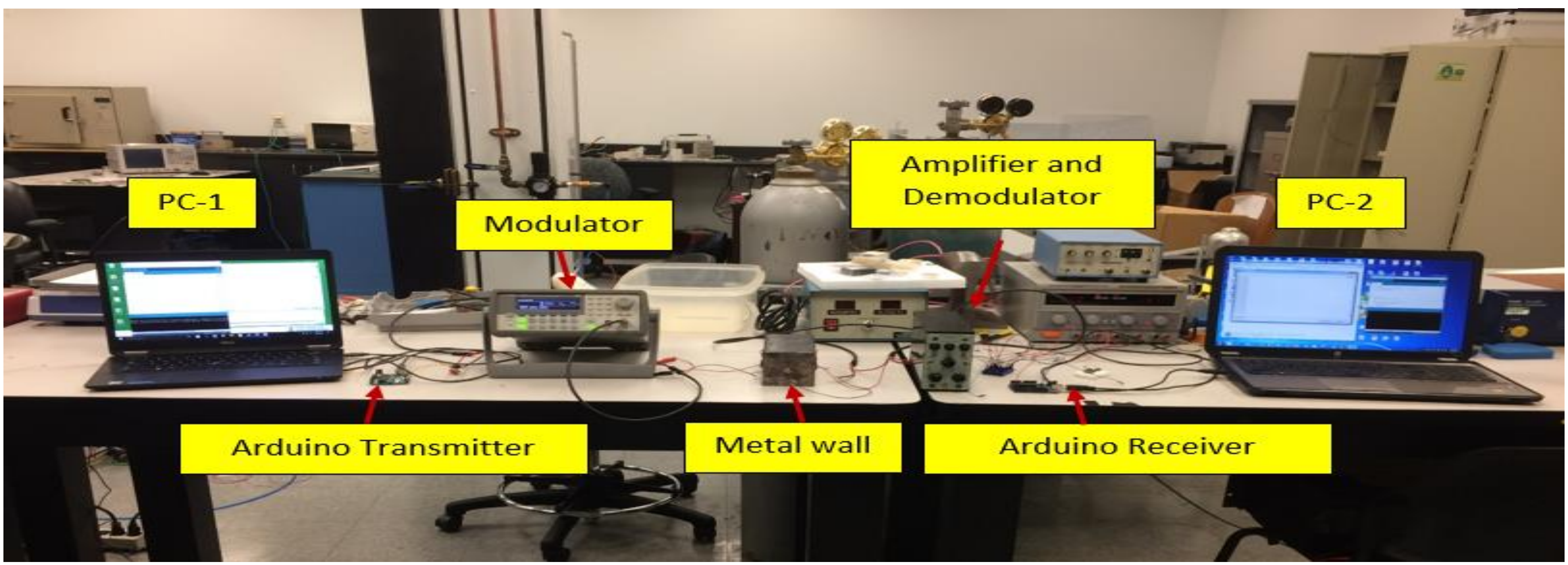




Accomplishments: Wireless communication technology

Ultrasonic TEXT transmission system at room temperature

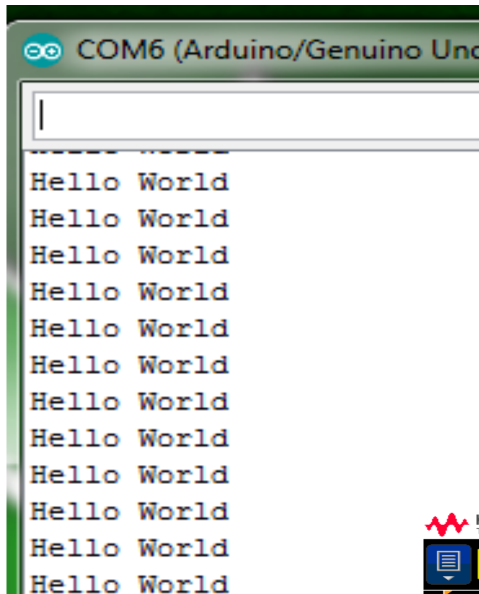


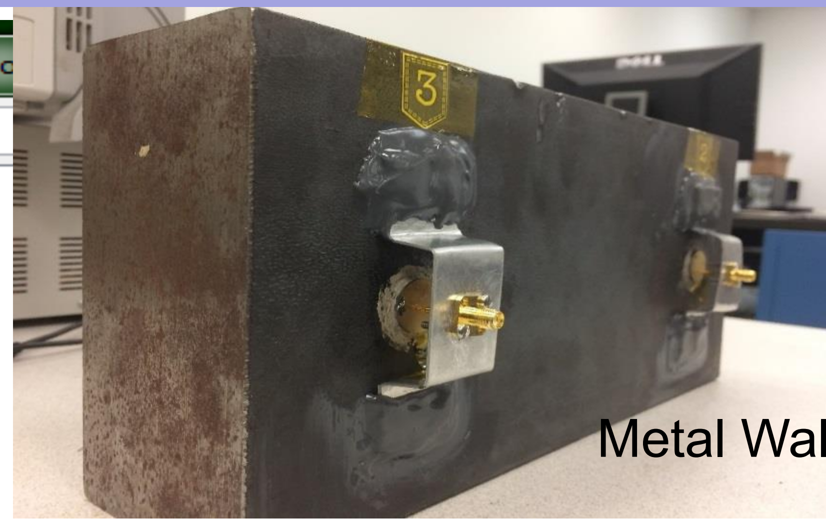


Accomplishments: Wireless communication technology

Demonstration of High Temperature TEXT Transmission

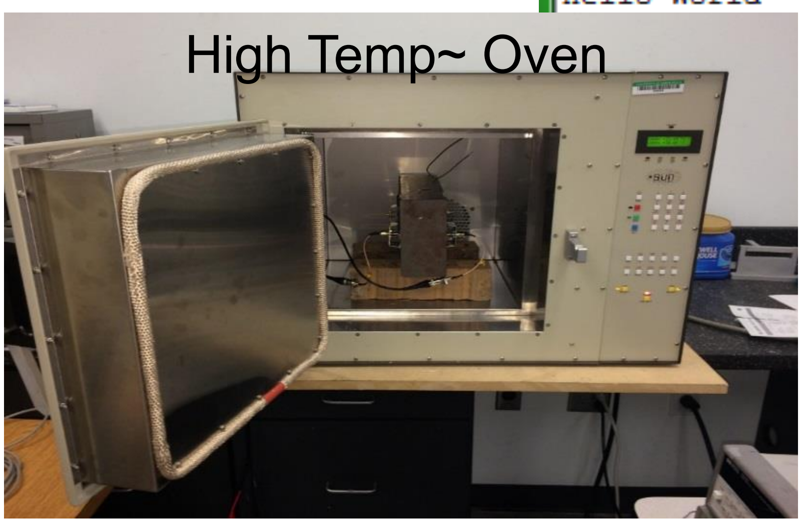
Results

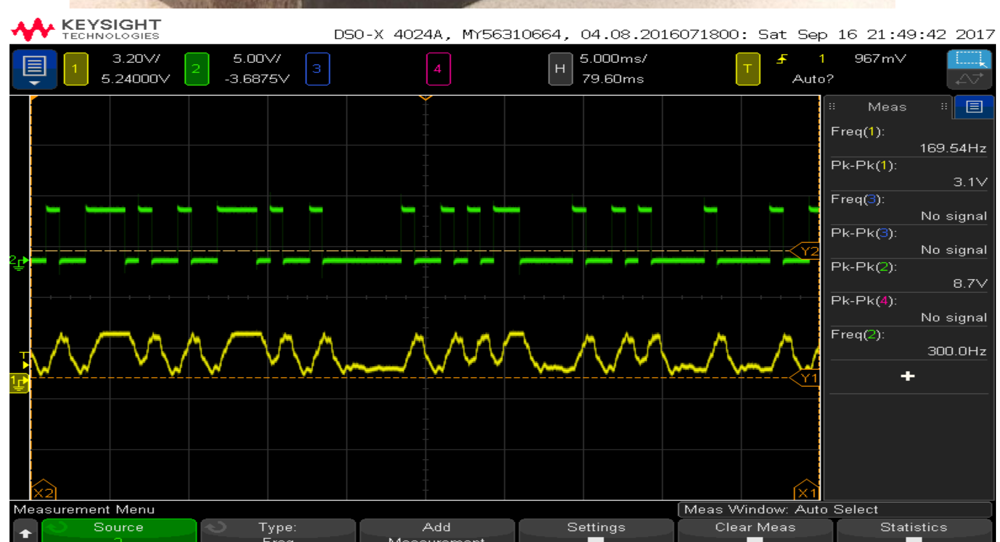




Metal Wall

High Temp~ Oven



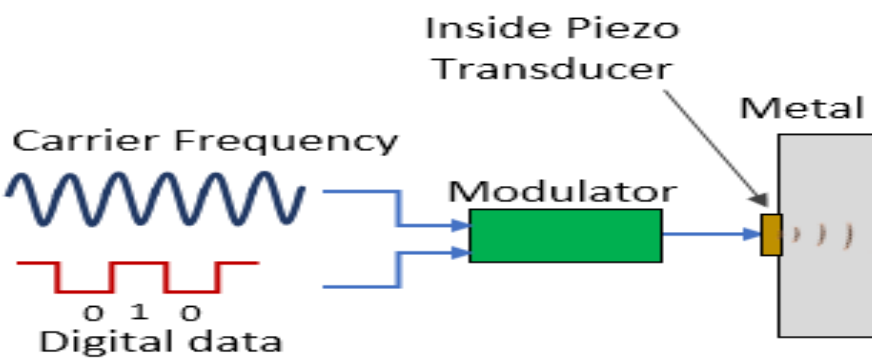


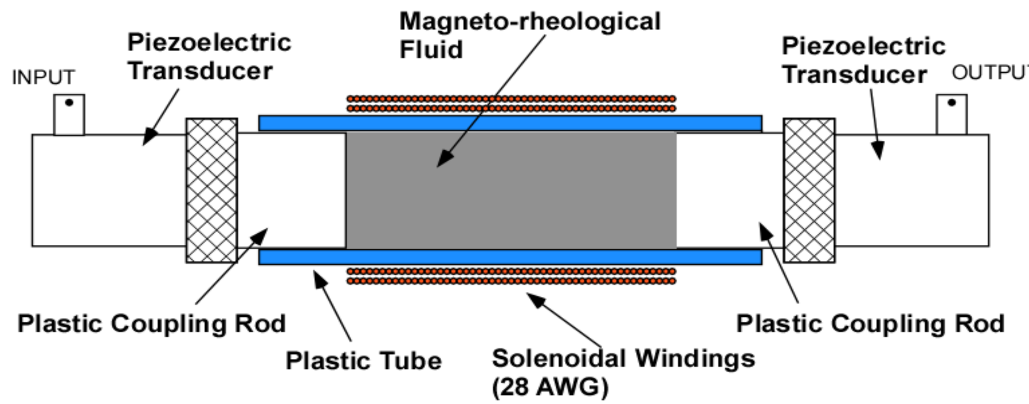
Binary Data Transmission

Accomplishments: Method for Low-Power Ultrasonic Communications Across Barriers

Alternative Modulation Method

- **Focused instead on developing a modulation method**
  - Three transducer method described by Murphy
  - Modulating transducer
  - Used compressional waves

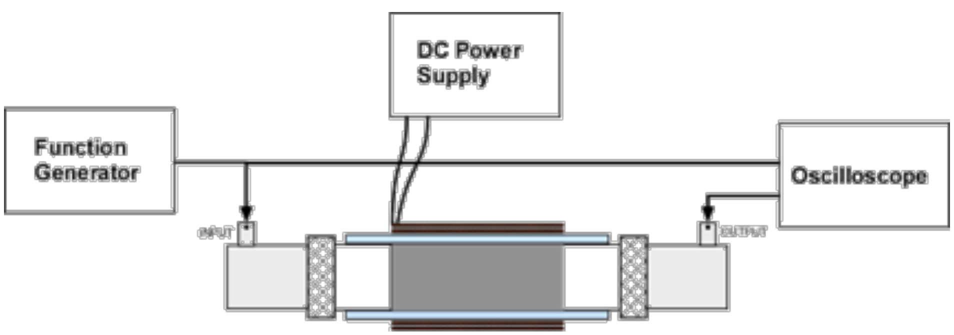


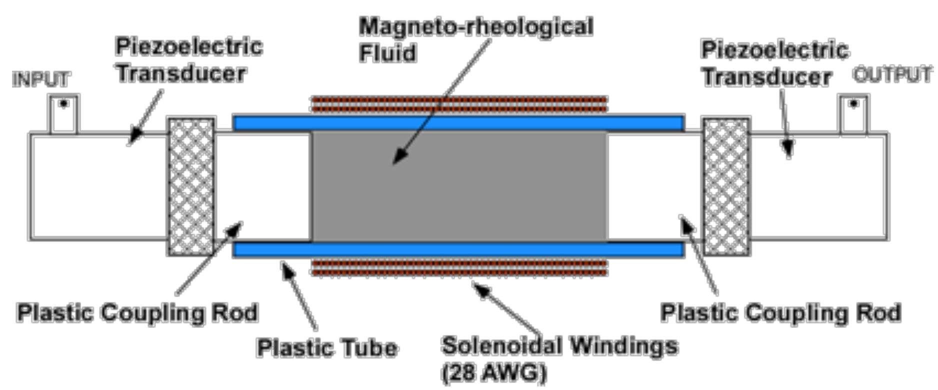


Accomplishments: Method for Low-Power Ultrasonic Communications Across Barriers

First Task Was Build an Experimental Apparatus for Studying Modulation

- **In-line propagation (not reflecting)**
- **First apparatus operated at 100 kHz then switched to 2.25 MHz**
- **Used magnetic fluid to change acoustic propagation**
  - Magnetorheological fluid—we observed attenuation with magnetic field but it was inconsistent
    - MR fluid easily precipitates (5-50 μm)—results are inconsistent and depend on when you agitated the apparatus
    - Attenuation of transmitted waves from 3 to 16 % with up to 10 amps of coil current
  - Ferrofluid—we observed repeatable attenuation
    - Particles stay in suspension (10-50 nm)
    - Range of attenuations up to 47 dB at 2.28 MHz

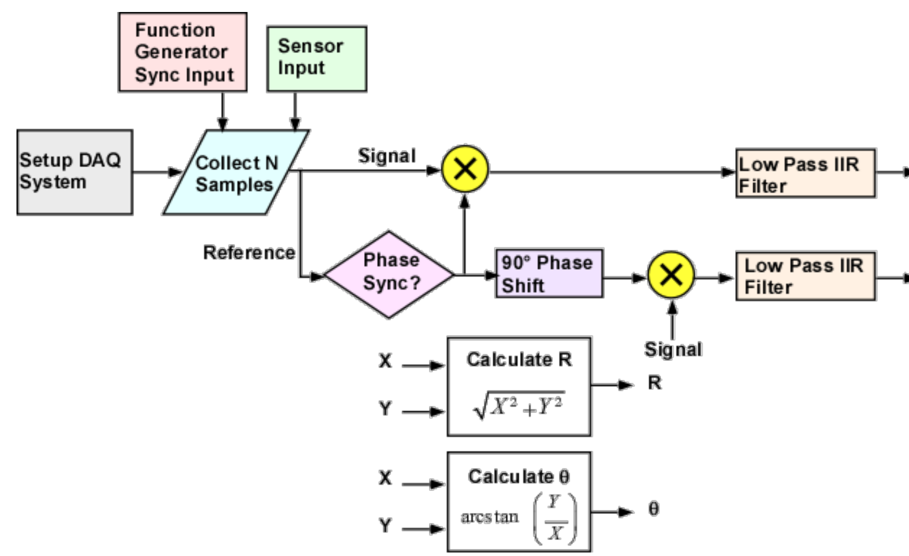


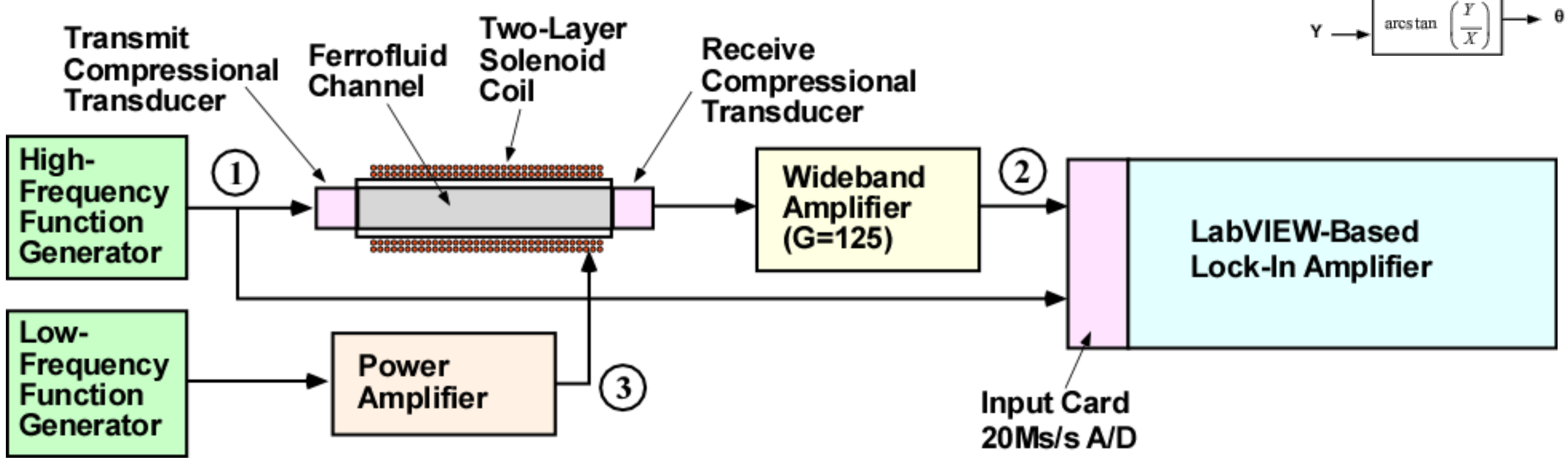


Accomplishments: Method for Low-Power Ultrasonic Communications Across Barriers

Using LabVIEW Lock-In Amplifier to Improve Signal-to-Noise Ratio for Low-Energy Signal

- 2.23 MHz continuous Sine wave driving transmitting transducer at 10Vpp
- Ferrofluid filled acrylic tube
- Permanent magnet suspended approximately 8 mm above coil section as a bias magnet
- Modulation coil driven with a 3Vpp 1Hz continuous sine wave
- 20 Ms 4-channel A/D card

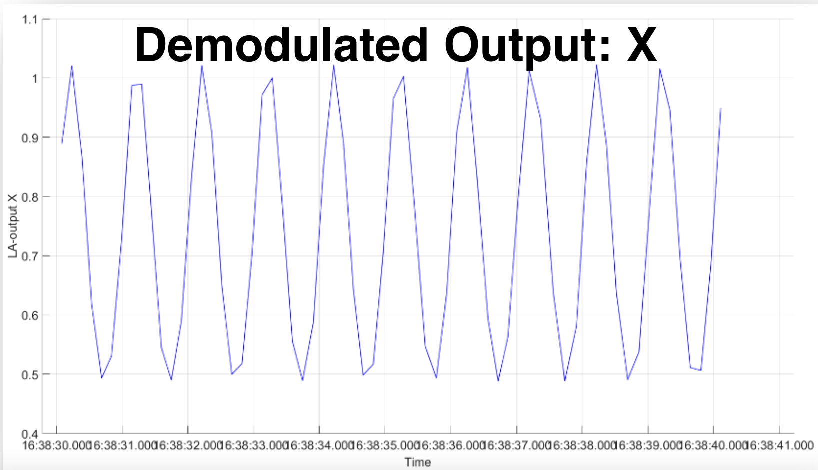


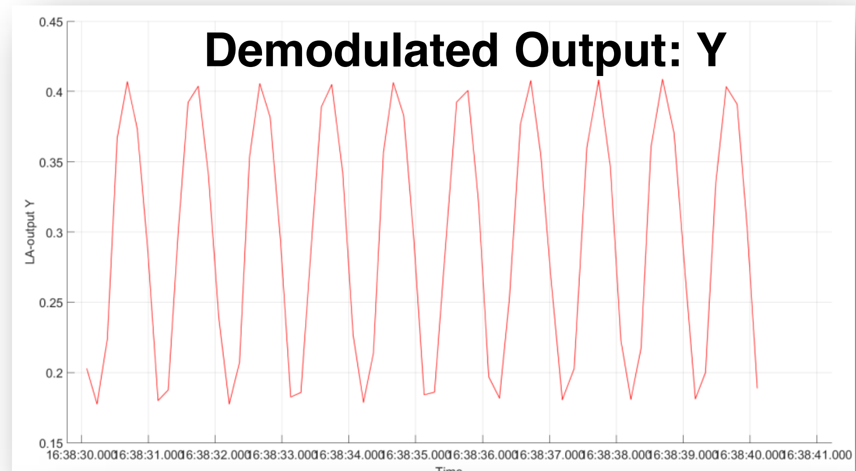


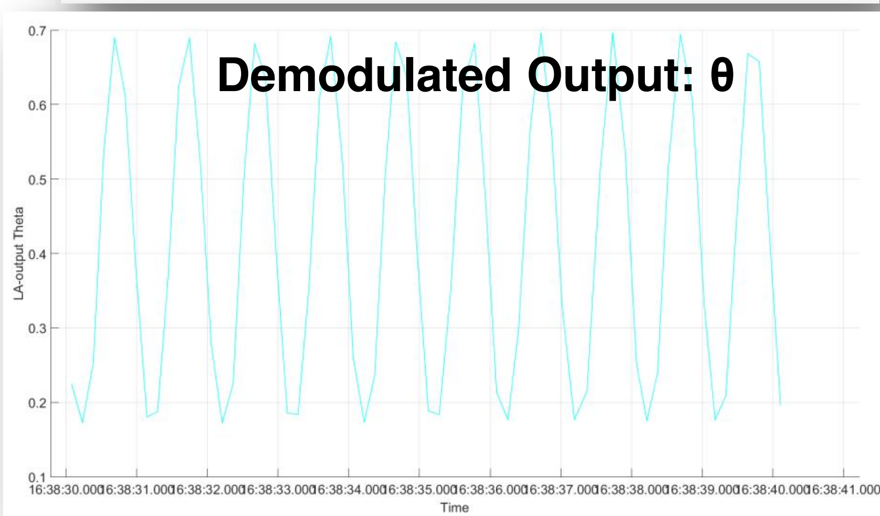
Accomplishments: Method for Low-Power Ultrasonic Communications Across Barriers

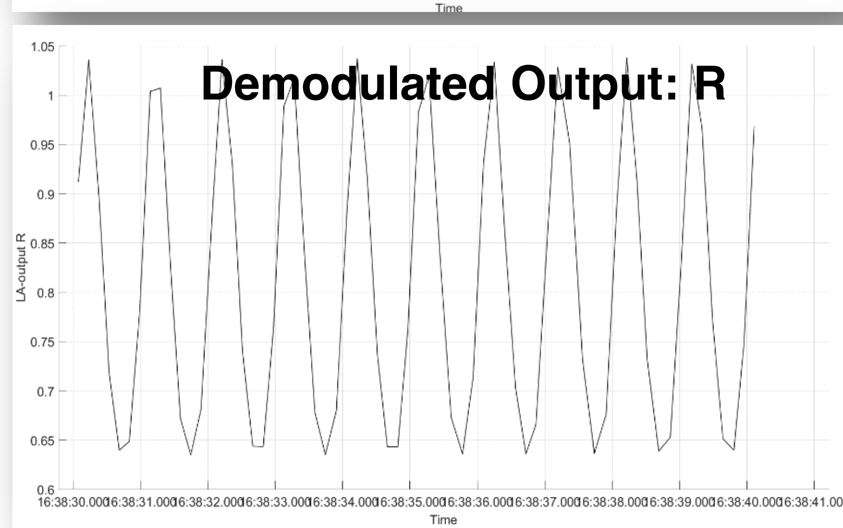
Result of Synchronous Detection by LabVIEW System Look Good but Slow

- Results below show successful modulation of ferrofluid
- Permanent magnet experimentation confirms that pre-biasing fluid is necessary









Accomplishments: Method for Low-Power Ultrasonic Communications Across Barriers

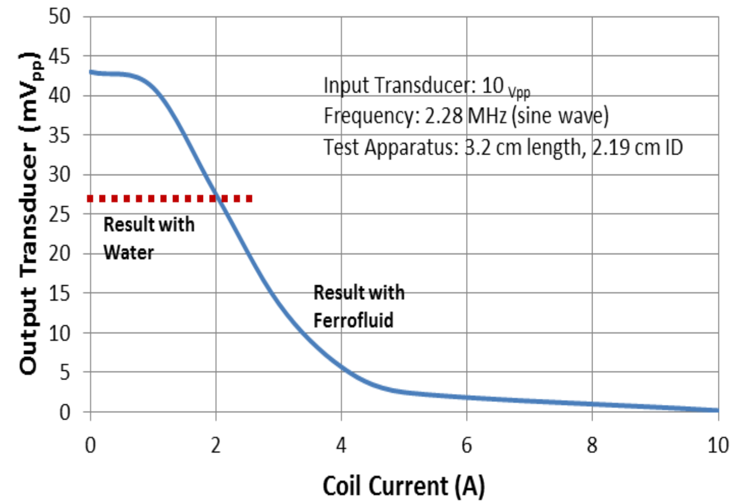
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

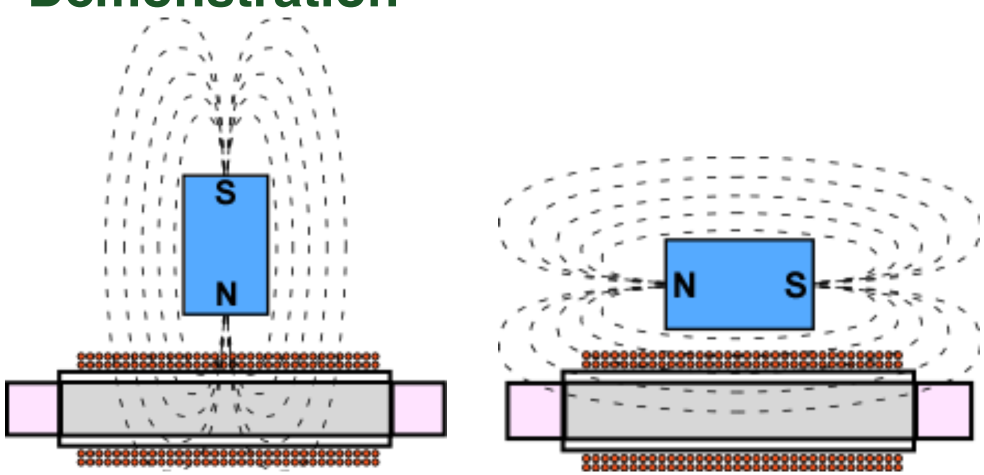
OAK RIDGE National Laboratory

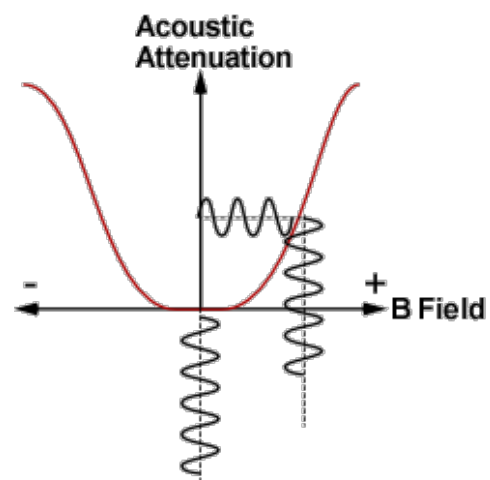
Conducting a Study of Bias Magnet Effects

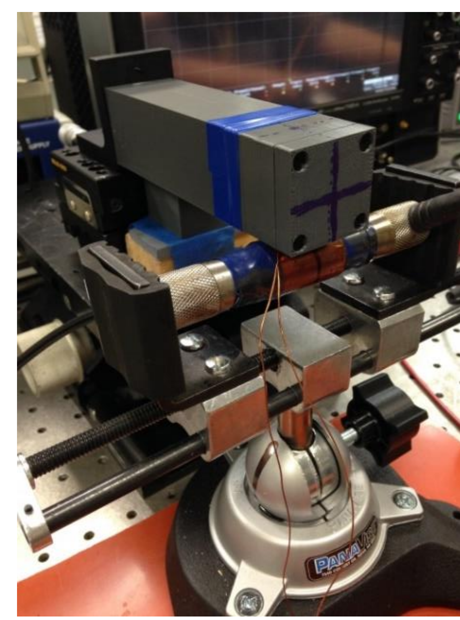
- Nano particles are randomly distributed
- Application of magnetic field causes alignment and clumping
- As particles clump their combined mass affects loading and changes the spring-mass transfer function
- A dead zone exists as field is first applied
- Ferrofluid is field polarity insensitive
- The question is where to put the magnet



- Next Steps Are to Conduct a Reflective Demonstration







Technology Impact

- **VT:** We analyzed the thermal and radiation environment in the dry cask. We have shown energy harvesting from thermal and gamma radiation the using thermoelectrics. The proposed self-sustainable package can be integrated into enclosed nuclear vessels. We have shown its application to the spent fuel canisters of dry cask storage. Similar technology can be applied to reactor vessels or reactor containment building communications.
- **UNT:** The capability to communicate through thick metal walls without physical penetration has great potential applications in hazard environments, especially enclosed nuclear reactors. In this project, amplitude modulation (AM) of ultrasonic waves was used to exchange data via metal wall at high temperature. Compare to other data communication methods, the ultrasonic technique has the advantages like, high speed (over 5M bps) data transfer, high temperature (over 300 C), and Less Power consumption (Less than 1Watt). The impact of such a solution is that it's highly useful in hazards, harmful nuclear environment.
- **ORNL:** Using a Ferrofluid Has Potential Benefits for Enhanced Modulation. We found that its excitation by magnetic field is simple to accomplish. It works at ultrasonic frequencies. It is radiation insensitive and can be made to use little power at modulation side.

Conclusions

- **VT:** TEG using the temperature difference existing in the canister combined with gamma heating effect can provide enough power for the wireless sensing and communication system working in the nuclear canister. The energy harvester can harvester enough energy even after 50years operation.

- **UNT:** The AM modulation based through wall Audio communication principle is verified with PZT piezo transduce at room temperature. After the concept verification at room, similar technique used for binary/TEXT data communication has been successfully demonstrated 20 – 100 C. We new step is designed for temperature up to 300C with TRS200HD high temperature transducer.

- **ORNL:** We developed a Unique Method of Ultrasonic Communication using ferrofluid. This technology permits transmission of data across barrier with low energy requirement. And are going to demonstrate the modulation-demodulation scheme.