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

Clean. Reliable. Nuclear.

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

Advanced Sensors and Instrumentation Annual Webinar

October 29, November 5, November 12 , 2020

Lei Zuo
Virginia Tech
In collaboration with
Haifeng Zhang at **Univ of North Texas**,
Nance Ericson, Kyle Reed at **Oak Ridge Nat. Lab**

Project Overview

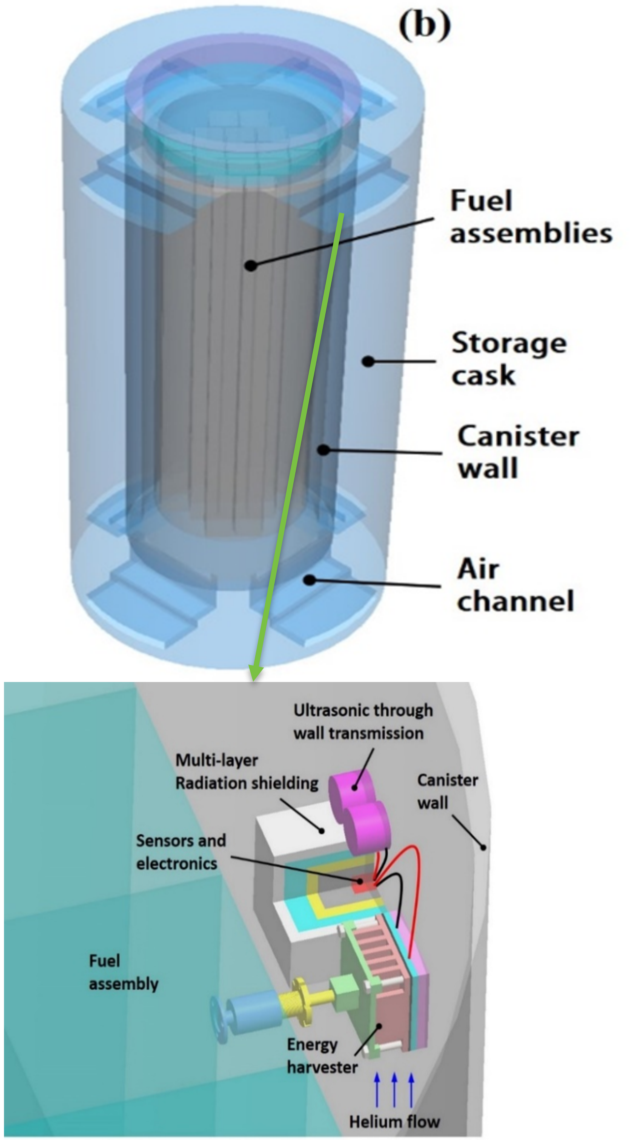
- Goal and Objective

  The goal of this proposal is to develop novel **energy harvesting and wireless through-wall communications** technology for in-situ monitoring of interior conditions in enclosed metal vessels or thick concrete walls as found in dry storage **canisters**:

  --**10mW, 1/2 SS Wall, 140C, 14.5 G Rads**

- Participants (2020)
  - Lei Zuo, **Virginia Tech**
  - Haifeng Zhang, **Univ. of North Texas**
  - Nance Ericson, Roger Kisner, Kyle Reed, **Oak Ridge National Laboratory**

- Schedule
  - 10/2016 - 09/2020



Summary of Accomplishments

- In FY20:
  - We finalized the **radiation test** and the characterization of the samples of all modules.
  - We **integrated and tested** the overall system
    - Ultrasonic data communication module,
    - **high-temperature** radiation-hardened electronics,
    - thermoelectric energy harvesting module with power management circuit.

Technology Impact

The solution has significantly benefitted data communication through enclosed metal vessels including spent fuel canisters:

(1) Cable-less and **wireless communication through a metal barrier** where RF transmission is not feasible;

(2) **Energy harvesting** from nuclear radiations and heat where no other energy sources are available;

(3) A detailed strategy for full realization of a high temperature, radiation tolerant **JFET electronics;**

(4) Multi-layer radiation and thermal **shielding** design for the electronics working in nuclear environment **;**

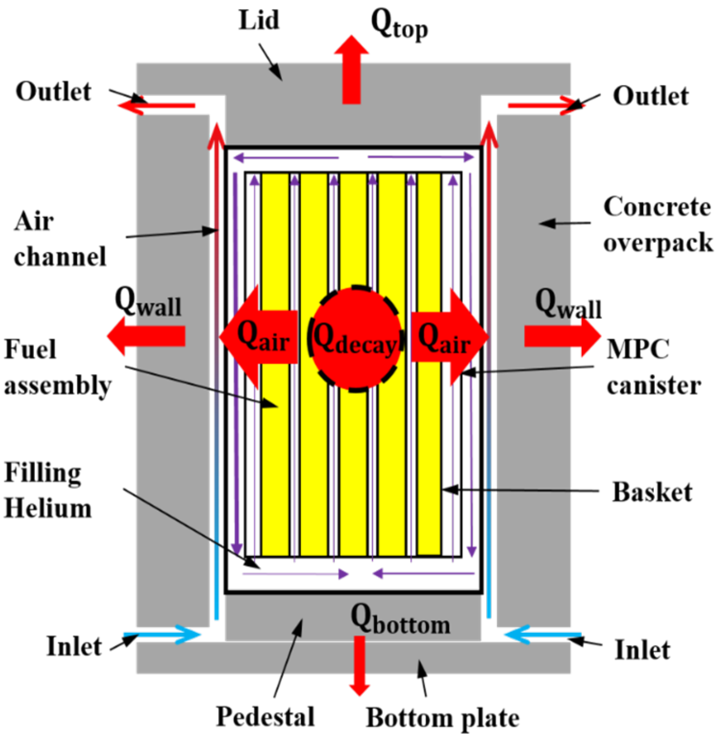
(5) Selective laser sintering **3D printing** of TE materials

(6) Lab validation of the proposed overall system for **190°C**

Accomplishments (1/14): Canister environment

- Thermal and hydrodynamic analysis of the dry cask system

Heat and fluid environment in the dry cask system:



MCNP6

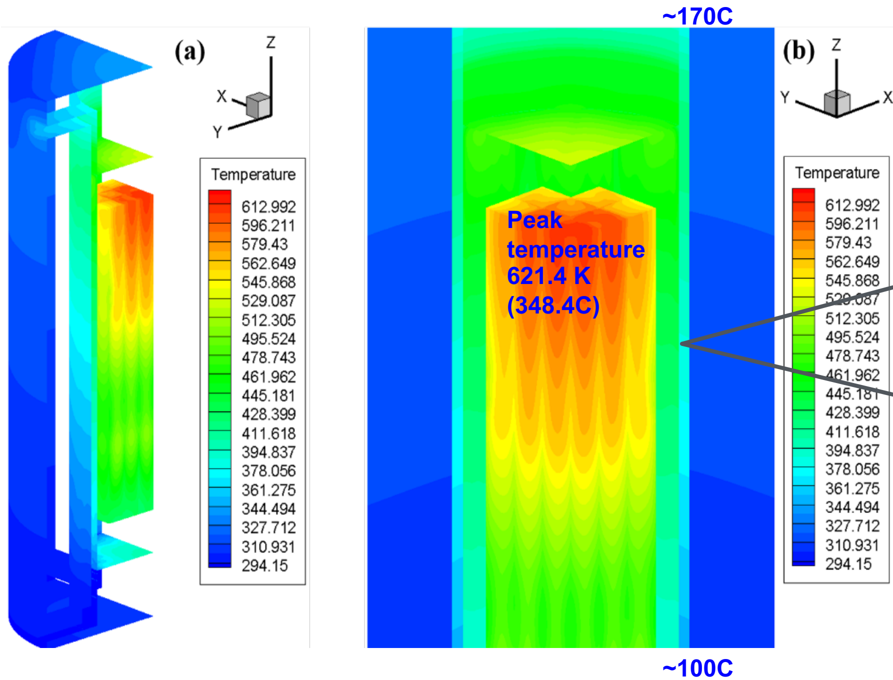
The model to estimate the decay heat within the dry cask system:

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}

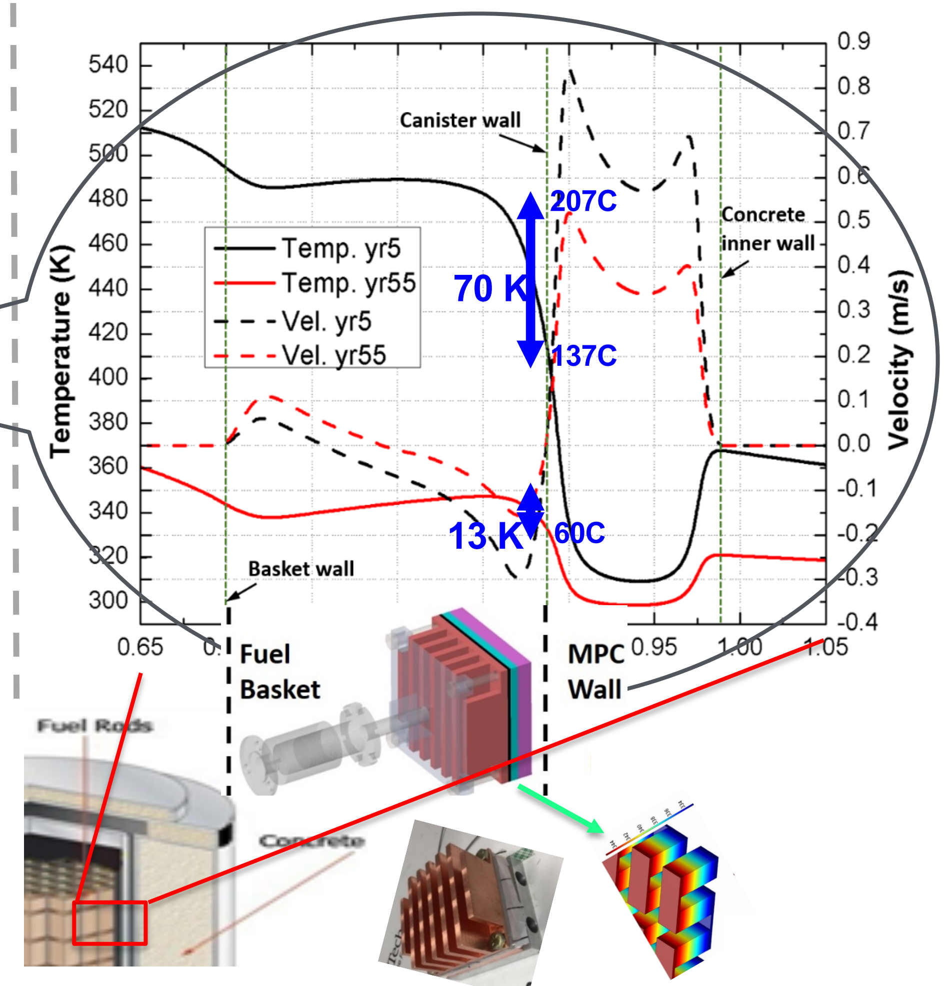
Fuel: Westinghouse 17x17 assembly, with a total cask MTU of 15 spread over the 32 assemblies, an enrichment weight percentage of U-235 of 4%, a burnup of 45 GWd/MTU, 3 runs per fuel assembly, and an average power of 40 MW/MTU.

Thermal and fluid analysis of the dry cask system

Temperature Profiles **Years 5 case**



- For year 5, the temperature difference is ~70 K.
- For year 55, the temperature difference is ~13 K.

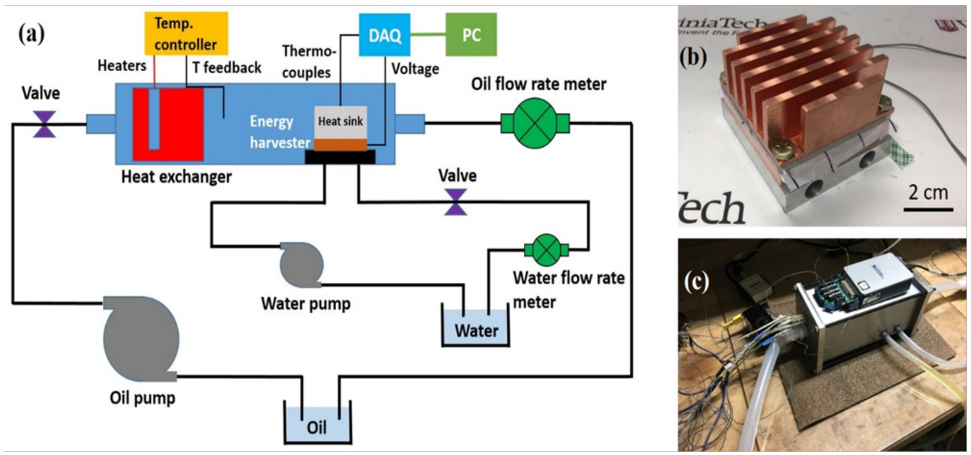


Thermoelectric energy harvesting

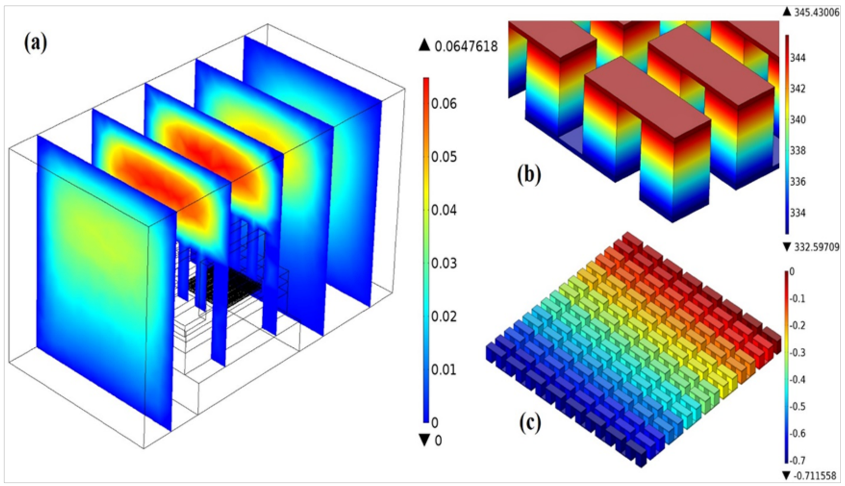
$$P_{\max} = \frac{N\alpha_{PN}^{2}\Delta T^{2}}{4R}$$

Accomplishments (3/14): Energy harvesting

- Thermoelectric energy harvesting: Experimental and simulation results



(a) The experimental setup in the lab, (b) The energy harvester, and (c) the oil channel to simulate the helium environment.



(a) fluid velocity contours, (b) temperature profile in TEG, and (c) electrical potential profile in TEG

Cases	ΔT	**Power Experiment (mW)**	**Power Simulation (mW)**
Year 55	12.8	**46.3**	**93.9**
Year 50	13.7	**56.1**	**106.1**
Year 45	14.5	**66.7**	**118.8**

$dP = 4.06 \sim 12.9\ mW$ Experiment uncertainty

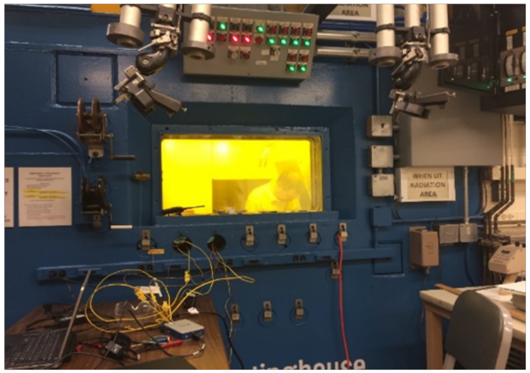
- Goal: **P>=10 mW**

Accomplishments (4/14): TEG radiation test

- Radiation Test

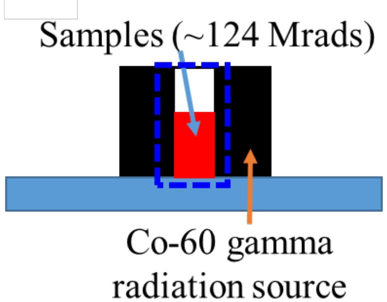
Thermoelectric Energy Harvester

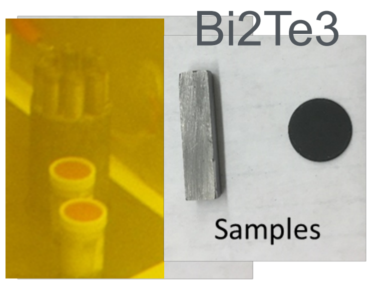
1



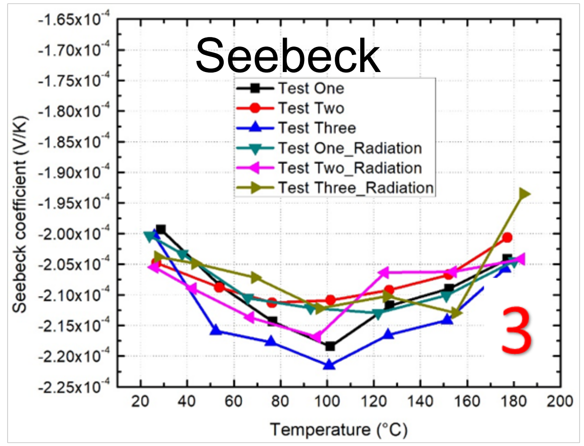
Radiation chamber at Westinghouse

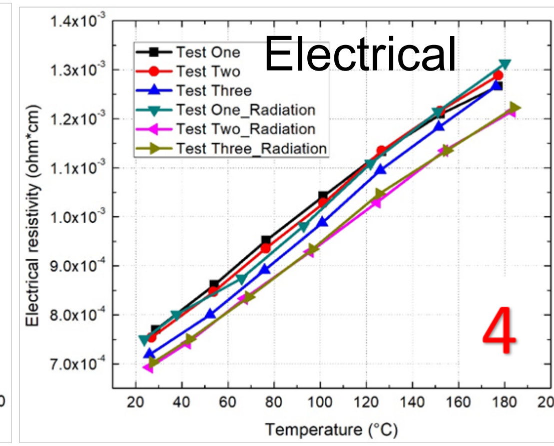
2

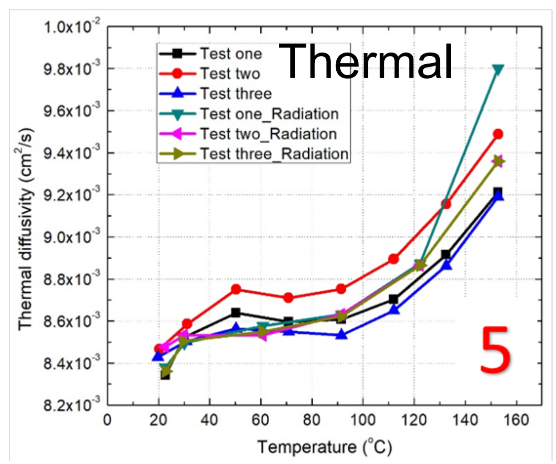




Experimental setup in the chamber







- The accumulated gamma dosage is 124 Mrads.
- No significant changes were observed after the gamma irradiation.

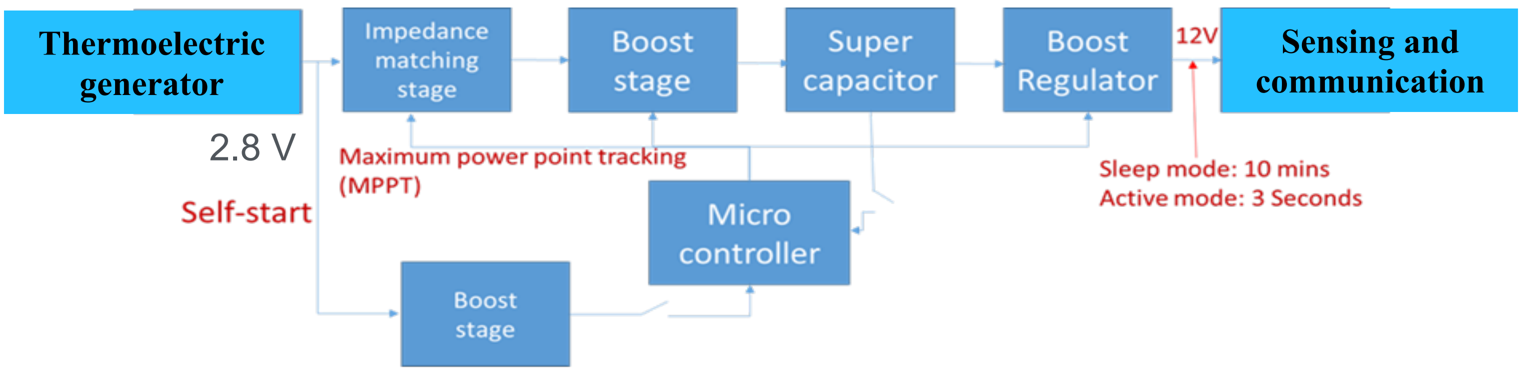
$$zT = \frac{S^2\sigma}{\kappa}T$$

Seebeck coefficient (S); Electrical conductivity (σ); Thermal conductivity (κ)

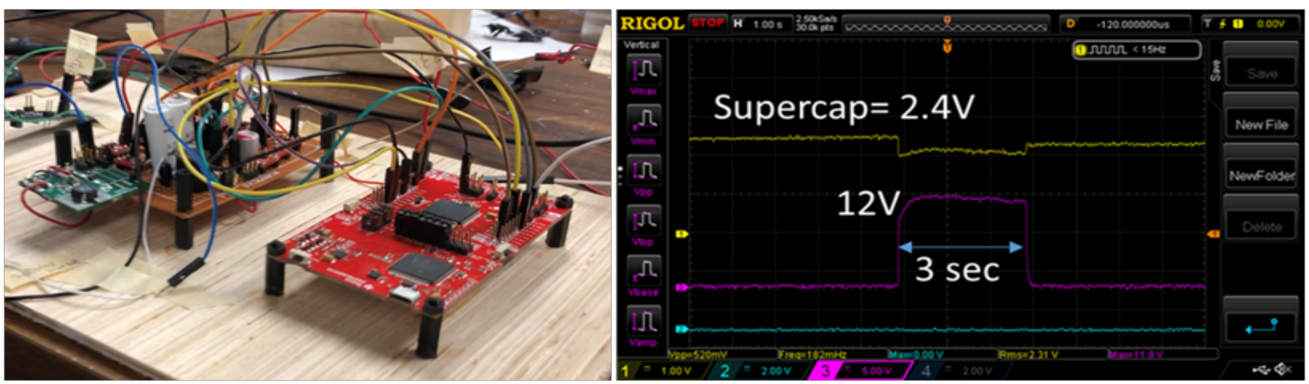
Thermoelectric materials: No obvious changes after 124 M Rads

Accomplishments (5/14): TEG power management

- Power management circuit



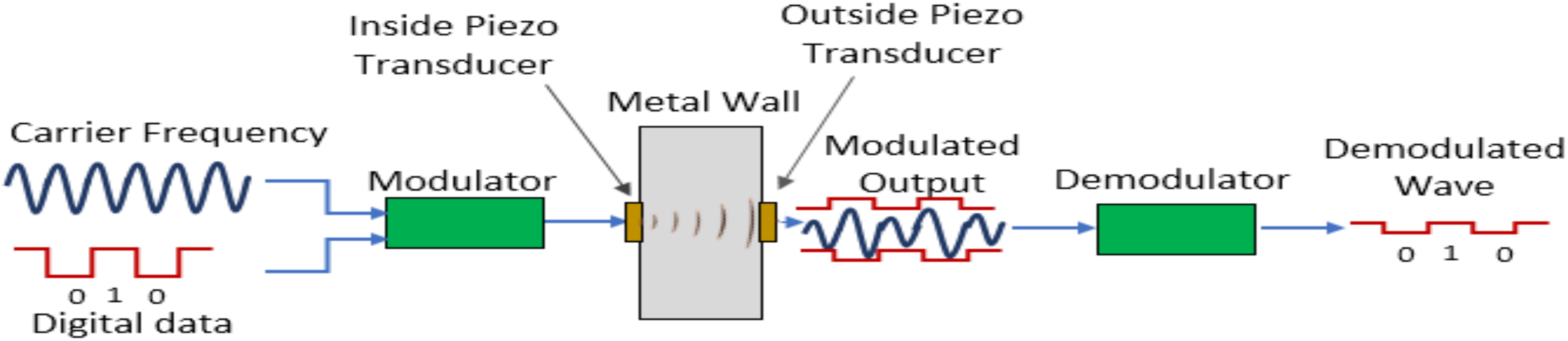
Power management circuit



Voltage profiles of the super-capacitor and the energy management circuit output

Accomplishments (6/14): Through-wall communication

TRS 200 transducer



- Test of the ultrasonic through wall transmission at elevated temperatures

Fig.2 . Through wall communication modulus in a oven.

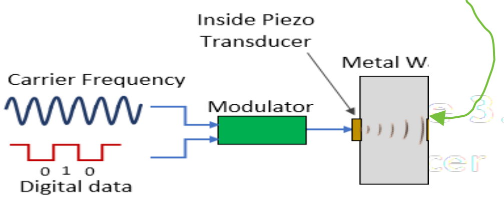
Fig. 3 . Through wall communication result (carrier wave frequency=100 kHz)

180 C

Accomplishments (7/14): Through-wall communication

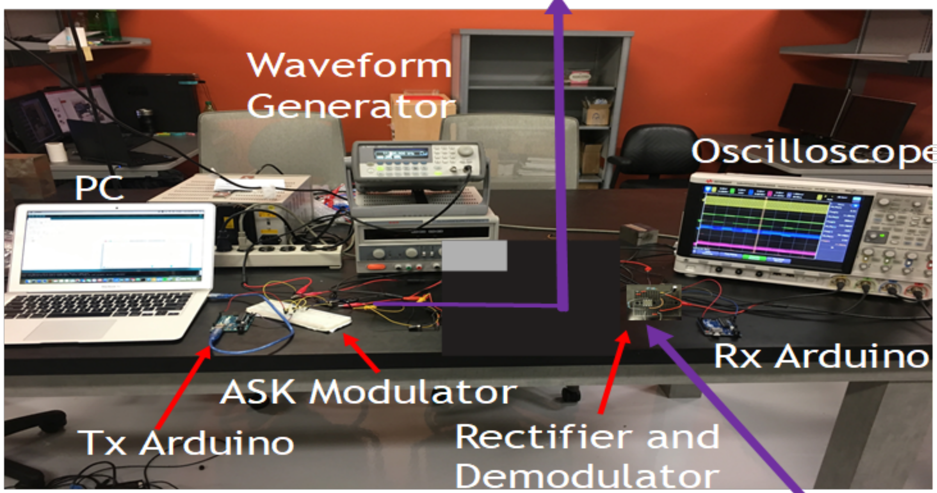
Laser Doppler Velocimetry (LDV)

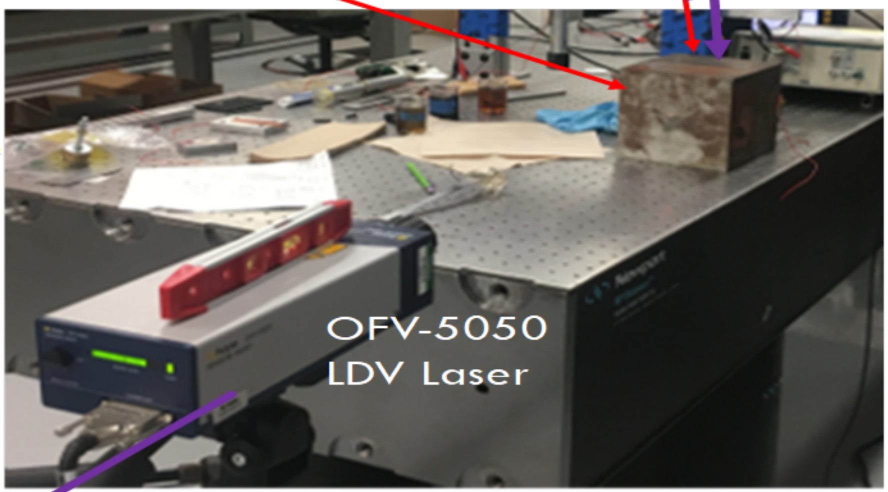
- PZT-LDV Through-Wall Communication Experiment

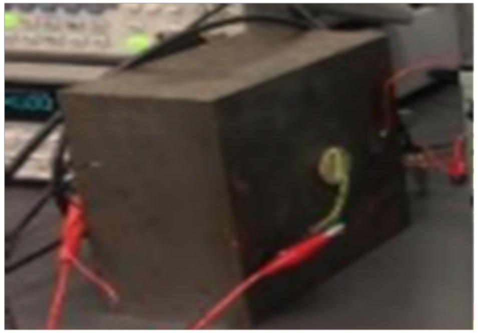


1.5in Steel Wall Setup

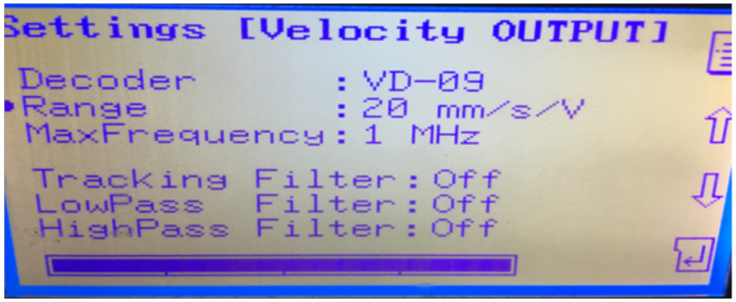
Steel wall







OFV-5000 Controller

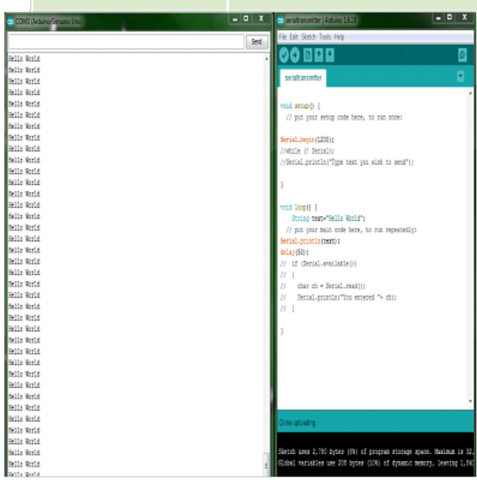


Accomplishments (8/14): Through-wall communication

- PZT-LDV Through-Wall Communication Experiment

Results of PZT-LDV Through-Wall Comm.

Experiment #	Piezoceramic Transducer Type	Wall Type	Fundamental Resonance Frequency	Maximum Carrier Frequency	Maximum Data-rate /Baud-rate
1	TRS200HD	Aluminum 0.25 in	8.949 kHz	->8.949 kHz	10 bps
2	TRSBT200	Aluminum 0.5 in	11.3 kHz	->1.755 Mhz	155 kbps
3	TRSBT200	Steel 1.5 in	109.94 kHz	->1.25 Mhz	115 kbps

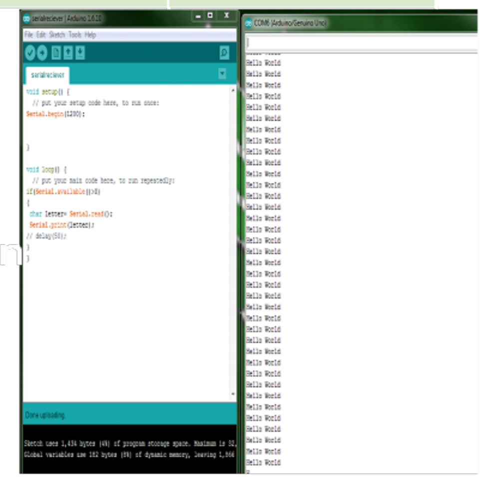


Successful Transmission of Binary Text Data Every Time

up to 115 kbps

TX Arduino Converts "Hello World" into Binary Data

RX Arduino Converts Binary Data into "Hello World"



Accomplishments (9/14): Ultrasound transducer radiation test

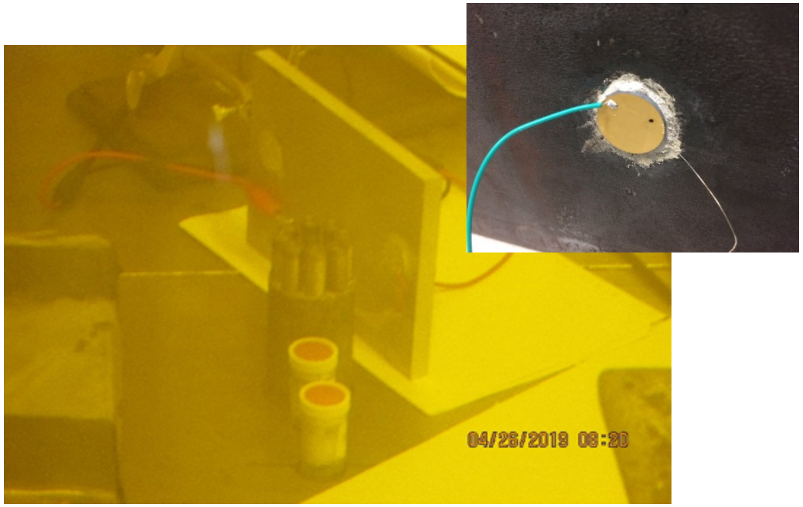
- Radiation Test (Ultrasonic Data Transmission)

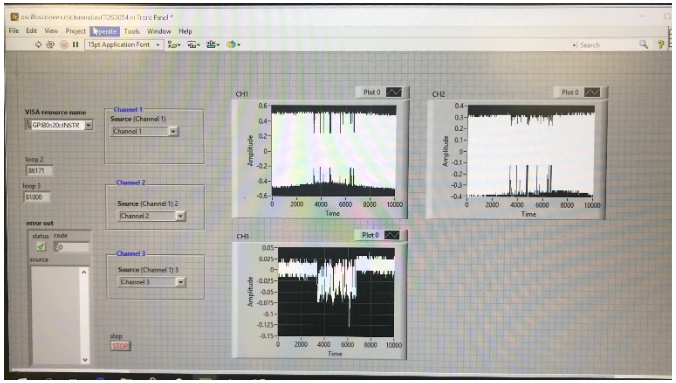
- The radiation test has been completed in Westinghouse company. The test started from Apr 23, 2019 and end on May 21, 2019.

- The total of **101 Mrad** has been applied to the **TRS 200 transducer** and receiver.

- The Labview program works well during the test period.

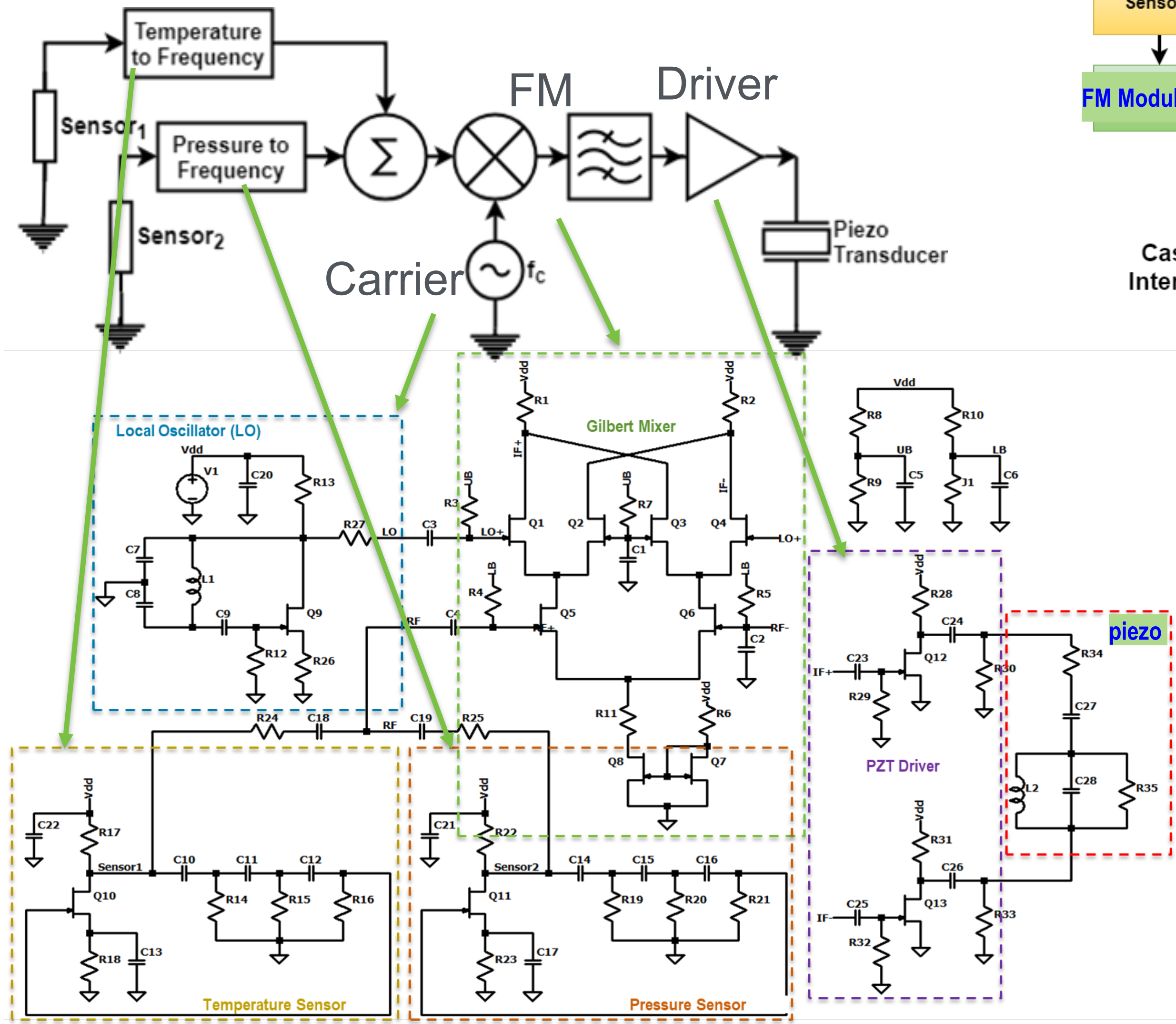
- The results show **no significant signal degradation** has been observed even when the high radiation dose is applied.

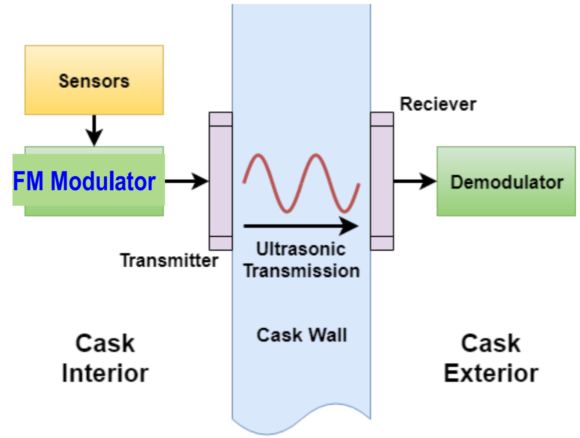


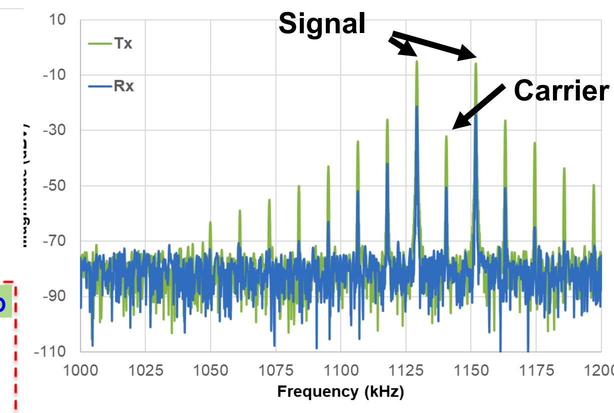


Accomplishments (10/14): Electronics for sensing & communication

- **JFET**-Based Electronics System Schematic

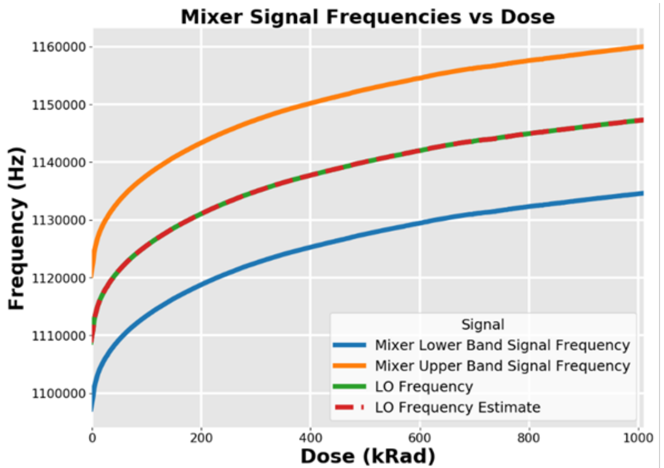




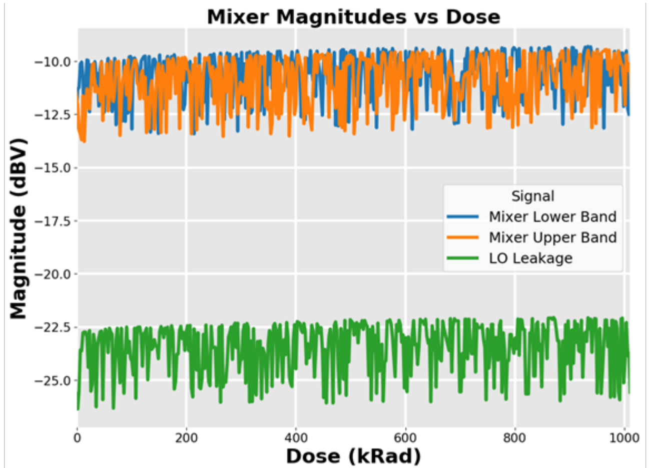


Accomplishments (11/14): Electronics radiation test

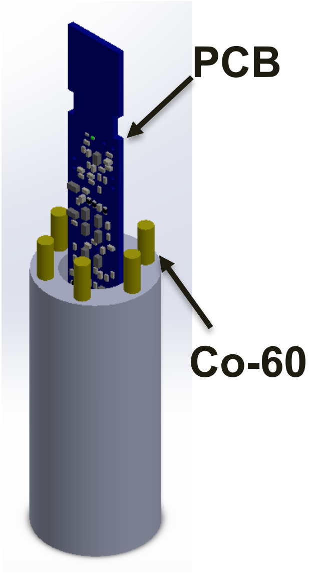
- Radiation Test (Electronics)

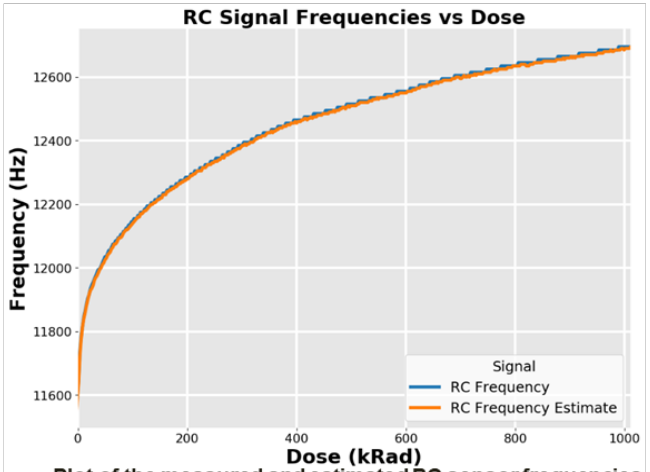


Plot of the measured and estimates of the signals in the RF frequency band of the circuit

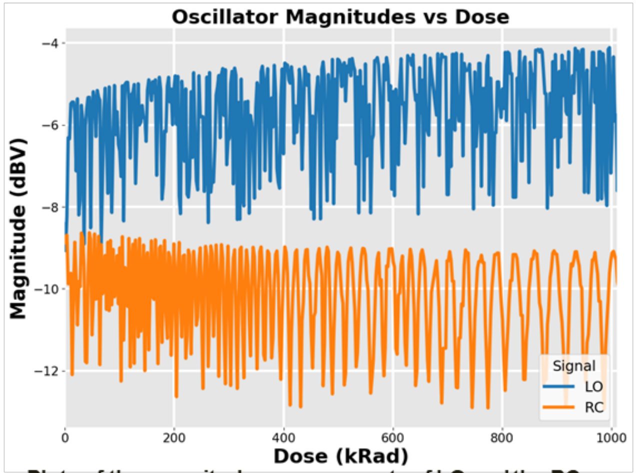


Plots of the magnitude measurements of the output of the Gilbert Mixer





Plot of the measured and estimated RC sensor frequencies



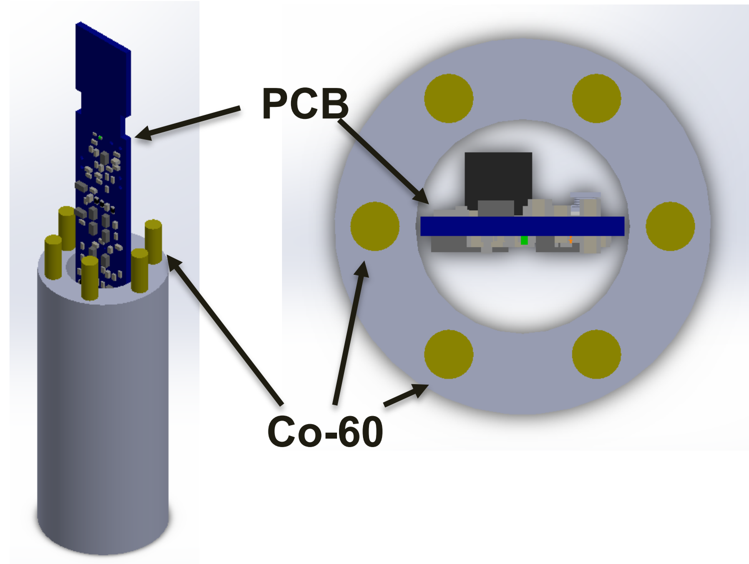
Plots of the magnitude measurements of LO and the RC sensor

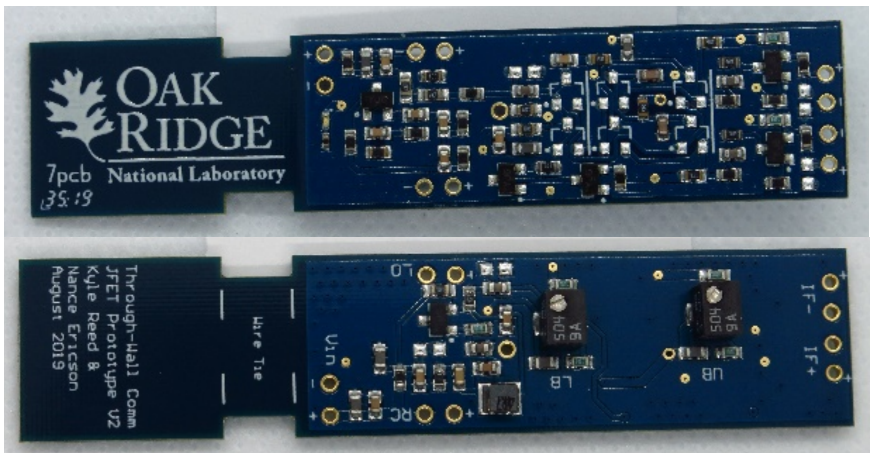
Drift due to RG147 BNC cable with TPFE insulation or ceramic capacitors

Accomplishments (12/14): Electronics radiation test

JFET Design Revision

- In FY19 (Year 3), a set of JFET boards were successfully irradiated to **2 Mrad** TID at Westinghouse with a Cobalt-60 source (Pittsburgh, PA)
- The radiation dose uniformity decreases across the board as the dose rate is increased due to the initial board and source geometries
- ~500 krad/hr can be achieved if the electronics are placed inside the source cylinder (shown on right)
- Revised JFET PCBs (shown below) were designed to fit inside the Westinghouse (Pittsburgh) Cobalt-60 source





Revised JFET circuit enabling placement inside the Co-60 source for 100 MRad dose test

- The revised JFET boards will be tested inside the source cylinder to **≥100 Mrad** or to failure
- Only a single sensor oscillator was placed on the board
- Other variability was removed from the design
- Connections are soldered directly to the board
- A tab was added on the board to better facilitate PCB placement and removal from the center of the source
- A notch was cut in the board to attach a cable tie for cable strain relief

Accomplishments (13/14): Radiation & thermal shielding

Radiation and thermal shielding for the electronics

Must survive internal γ radiation dose rate of ~33 krad/h for 50-year storage cycle (~14.5 Grad TID) → **Shielding by a factor of ~150**

Materials layers	Thermal conductivity (W/(m*K))	Thickness (mm)
Steel	50.2	2
Fiber glass	0.1	10-20
Copper	400	10
W-B4C	141.5 (Estimated by weight ratio)	25 (safe value for radiation shielding)

60mm, 210 kRads

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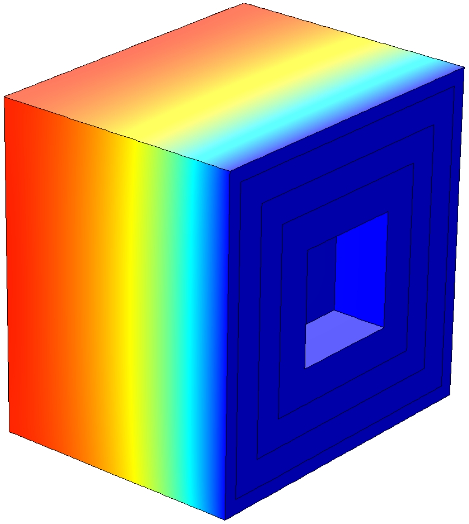
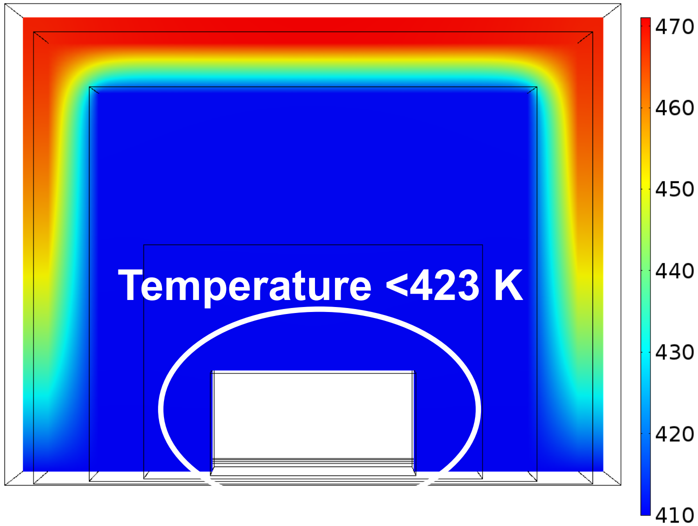
Boundary conditions (according to simulation results):
Ambient temperature: 480 K (207C)
Wall temperature: 410 K (137C)
Target: <150 °C at the internal surface (423 K)

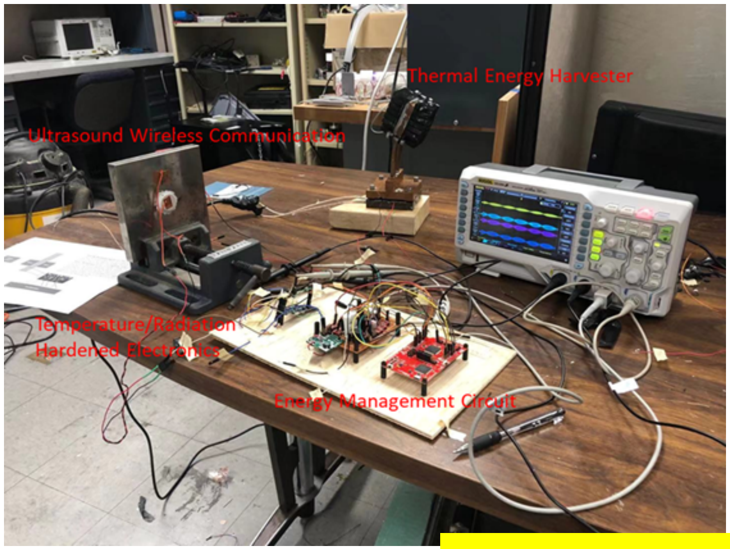




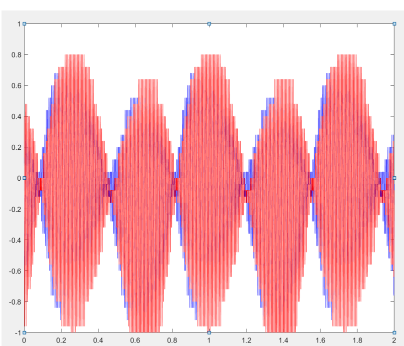
Temperature distribution in the shielding block

Accomplishments (14/14): System integration & test

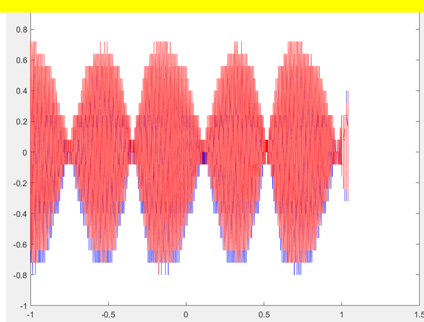
- System Integration and High-Temperature Durability Test



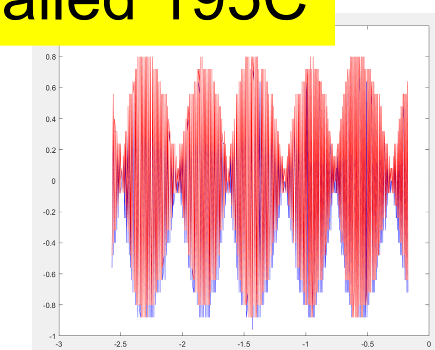
Survived 190 C, failed 195C



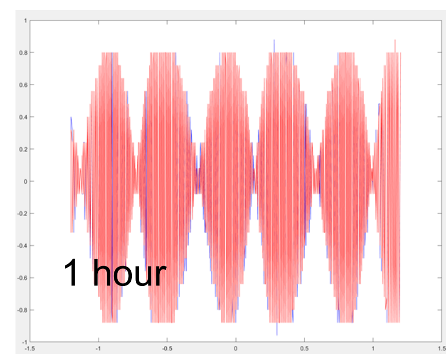
Room temperature



20 min



40 min



signal input
signal output

Conclusion: Self-Powered Wireless Through-wall Data Communication for Nuclear Environments

Goal: 10mW, 1/2 SS Wall, 140C, 14.5 G Rads

- **A thermoelectric energy harvester:** existing temperature gradient in the canister. **Compact** (8 × 8 × 6 cm), thus can be easily installed. **94 mW** even after 50-years of canister storage, Bi2Te3 **124 M Rads** radiation dose
- **Ultrasonic data communication**: **1.5 inches** metal wall, Operation up to **180 C** with TRS BT 200, **101 M rads**. A novel **laser-ultrasonic data** communication system with good data transmission rate **115 kbps**
- **Multi-sensor and communication electronics** system has been developed for in-cask monitoring based on **Si JFETs,** successfully tested to a radiation dose of **2 M Rads** total dosing. The electronics survived at **190C**
- A system **integration test and high-temperature** durability test were done.
- **Radiation tests** were done in Westinghouse hot cells: 124M, 101M,
- The **W-B4C** was identified as the **radiation shielding** material for both gamma and neutron shielding, 1 inch is enough.

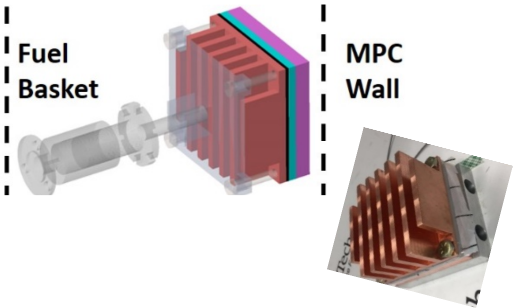
Accomplishments (13/13)

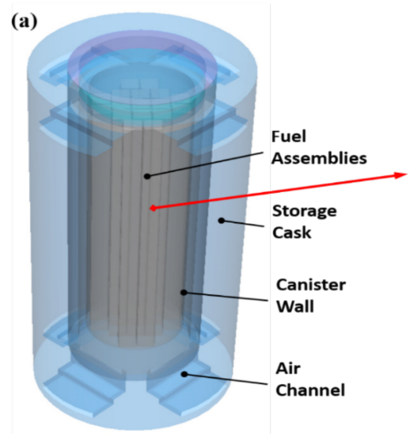
- Publications

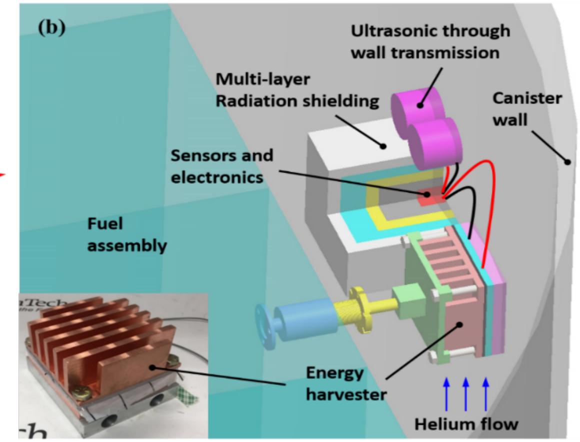
1. **Self-powered Wireless Through-wall Data Communication for Nuclear Environments**. Yongjia Wu, Lei Zuo, Suresh Kaluvan, Haifeng Zhang, Milton Nance Ericson, Kyle Reed, Roger A Kisner. the 11th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT), Feb 2019, Orlando FL
2. **Modeling the Selective Laser Melting-Based Additive Manufacturing of Thermoelectric Powders**, Y Wu, K Sun, S Yu, L Zuo, *Additive Manufacturing*, 2020
3. **Energy harvesting for wireless communications in nuclear environment**. Yongjia Wu, Jackson Klein, Hanchen Zhou, Haifeng Zhang, Lei Zuo*Annals of Nuclear Energy* 126 (2019)
4. **Thermal and fluid analysis of dry cask storage containers over multiple years of service**. Y Wu, J Klein, H Zhou, L Zuo. *Annals of Nuclear energy* 112 (2018): 132-142.
5. **Direct Energy Deposition 3D Printing of Thermoelectric Materials: Simulation and Experiments**, K Sun, Y Wu, H Qi, Z Wu, L Zuo, ASME *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2019*
6. **Energy Harvesting for Nuclear Waste Sensing and Monitoring**. Y Wu, J Klein, H Zhou, L Zuo. ASME *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Vol. 51722. American Society of Mechanical Engineers, 2018. (**Best Paper Award**)

Q&A: Self-Powered Wireless Through-wall Data Communication for Nuclear Environments

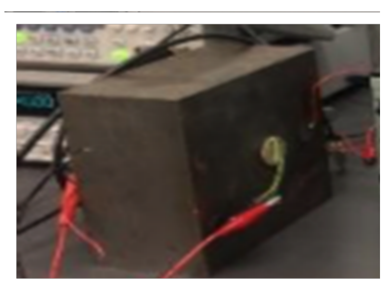
Energy harvester: 100mW, 124 MRads

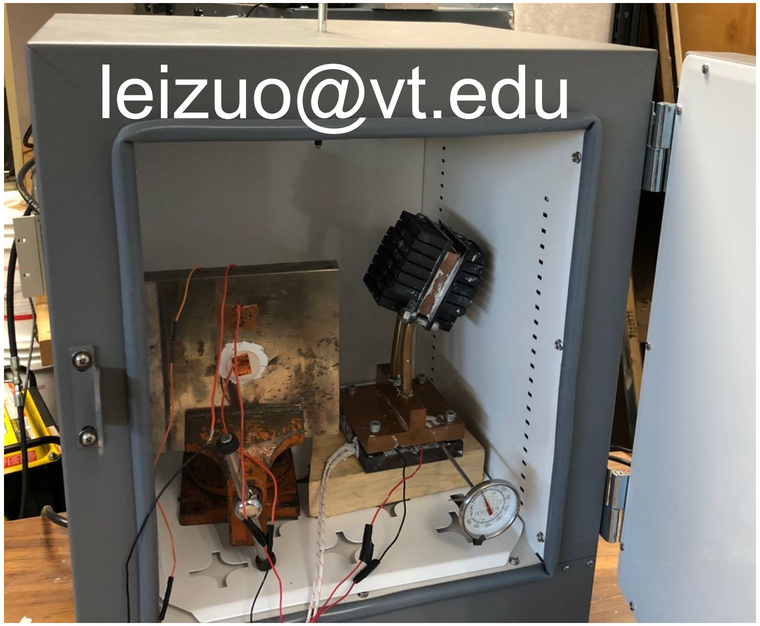






Ultrasound communication: 100kbps, 180C, 101 Mrads





Electronics: FM, 190C, 2 Mrads