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

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A Self-Powered, Wireless Sensor System for Remote and Long-Term Monitoring of Internal Conditions of Spent Nuclear Fuel Dry-Storage Casks

Advanced Sensors and Instrumentation Annual Webinar

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Project Overview

- ## Goal and Objectives

The goal of this SBIR Phase IIB program is to develop a fully functional Self-Powered Wireless Sensor System (SPWSS) prototype for passive, long-term, and remote monitoring the internal conditions of nuclear waste casks.

Objective 1: Refine SPWSS prototype design and development to achieve TRL 7-8

- Refine sensor package design and prototype development to meet operation requirement, especially NUHOMS 32PTH
- Fine tune sensor sensitivity and resolution for dry-storage cask environment
- Refine microfabrication process and sensor integration technique
- Refine BAW transducer design to improve signal transfer
- Reduce overall dimension
- Refine interrogation unit and software for simultaneous measurement of temperature, pressure, relative humidity and hydrogen gas. Add fission gas sensing capabilities.
- Implement advanced signal processing algorithm to meet desired sensitivity and accuracy

Objective 2: Conduct irradiation test and performance evaluation in relevant environment .

Objective 3: Demonstrate abilities of the SPWSS system and commercialize the developed technology

Objective 4: Commercialization & Technical transitioning

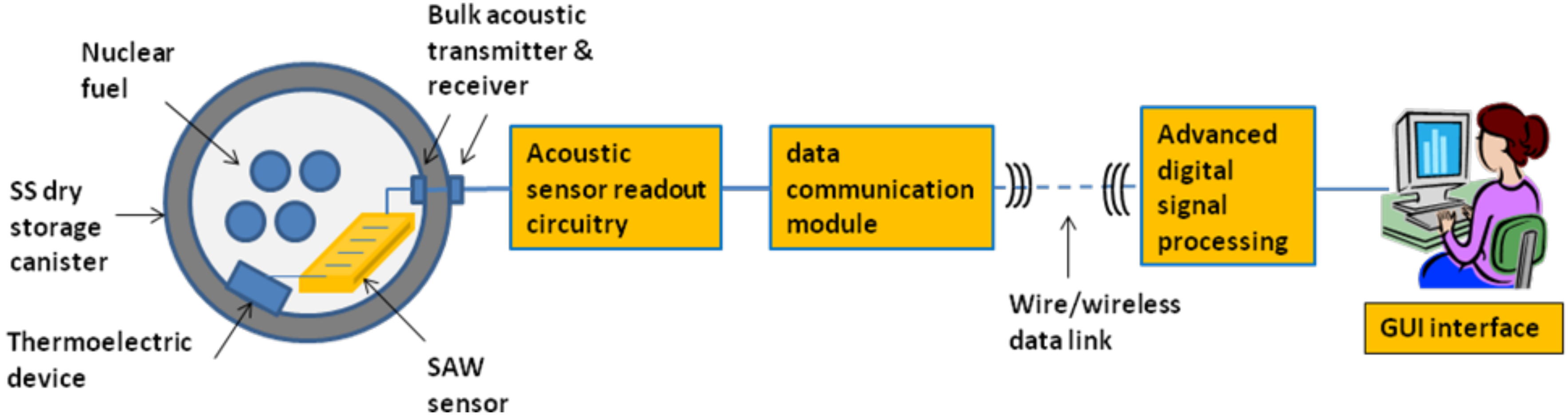
- **Participants (2020):** X-wave Innovations Inc., Orano Federal Services LLC, TechOpp Consulting, Inc.
- **Participants (scheduled):** INL, ORNL, J Kessler and Associate, EPRI, Exelon

Project Overview

- Schedule

Tasks	2019		2020				2021		Participant
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
1. Finalize project requirements	X								XII, Orano, INL, ORNL, JKA,TOC
2. SPWSS prototype design	X	X							XII, Orano
3. Key component development		X	X	X					XII
4. Implement signal processing algorithm			X	X					XII
5. Integrate and test a SPWSS prototype				X	X				XII, Orano
6. Conduct irradiation test					X	X			XII, INL, ORNL
7. Demonstrate prototype abilities							X		XII, Orano, INL, ORNL,JKA,TOC
8. Transition/Commercialize technology	X	X	X	X	X	X	X	X	XII, Orano, JKA, TOC

System architecture



Overview of the SPWSS technology for remote, long-term monitoring of internal conditions of nuclear fuel storage casks

Pending patents

1. WIRELESS SENSOR SYSTEM FOR HASRSH ENVIRONMENT #16/285,579
2. HIGH TOLERANCE ULTRASONIC TRANSDUCER #16/749,667
3. POWERLESS ACOUSTIC SENSOR SYSTEM #16/528,577

Program overview

Phase III

- Secure commercial partner
- Optimize system performance
- Comprehensive validation
- Transition technology

Phase IIB - Proposed

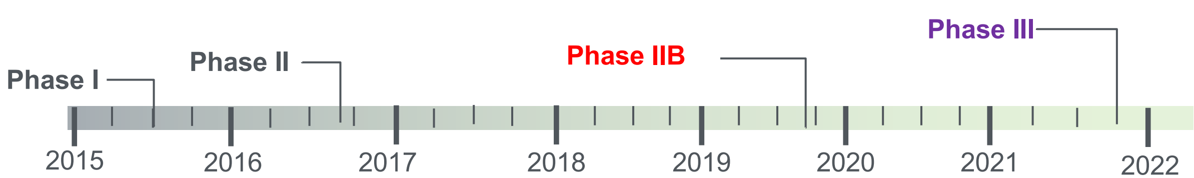
- Refine SPWSS system
- Integrate with real DSC
- Conduct irradiation testing
- Build a showcase prototype for licensing and regulation
- Commercialize technology

Phase II - Completed

- Complete SPWSS system design and development
- Test and evaluate the prototype performance
- Demonstrate abilities of the prototype system

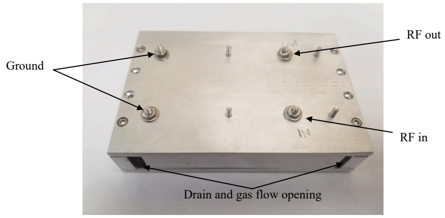
Phase I - Completed

- Design a SPWSS prototype
- Build a SPWSS prototype
- Test SPWSS prototype Performance
- Demonstrate feasibility of SPWSS approach

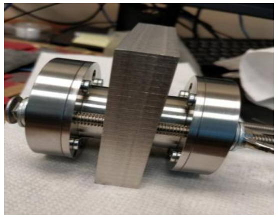


Summary of Phase IIB accomplishments

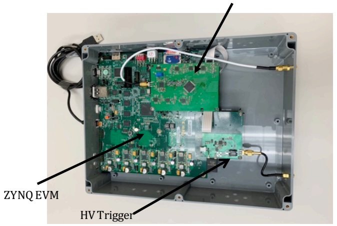
- Completed SPWSS overall system design and refinement
- Refined SAW sensor platform design, fabrication, packaging, and testing
- Refined BAW transducer design, fabrication and testing
- Designed and developed a high frequency EAMT transducer for noncontact ultrasonic detection
- Design and develop thermoelectric harvester and pulse generator for SPWSS
- Refining interrogation unit design and development



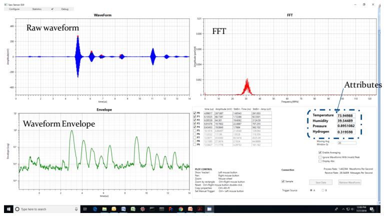
SAW


BAW


Testing



Interrogation Unit



Application Software

Technology Impact

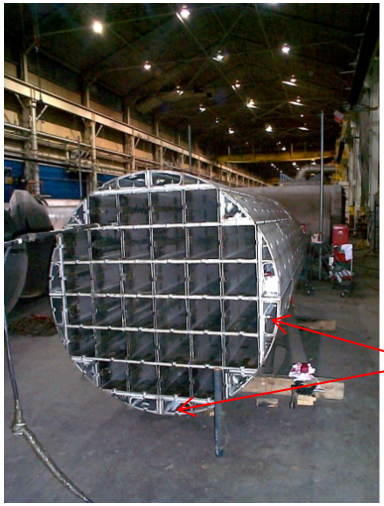
- *Develop high-temperature, radiation endurance ultrasonic BAW transducers for nuclear harsh environment applications*
- *Develop high-temperature SAW-based sensor platform for condition and gas species monitoring in nuclear environments*
- *Develop high-temperature TEG module for energy harvesting in nuclear harsh environment*
- *Support the DOE-NE research mission in nuclear waste management as well as nuclear power plants*
- *Enable smart spent nuclear fuel dry-storage canisters*
- *To be commercialized via collaboration with Orano, EPRI, etc.*

SPWSS overall system design and refinement

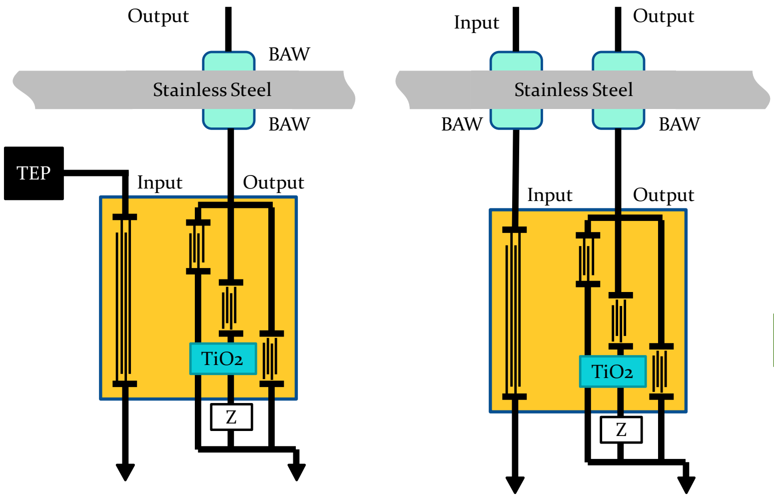
In Phase II program:

- We have developed SAW sensor and its packaging
- We have performed sensor calibration and performance evaluation
- We have developed BAW transducers for wireless communication
- We have developed electronics prototype and complementing software
- We have performed Radiation test at UWM up to 1.8kGy gamma radiation level

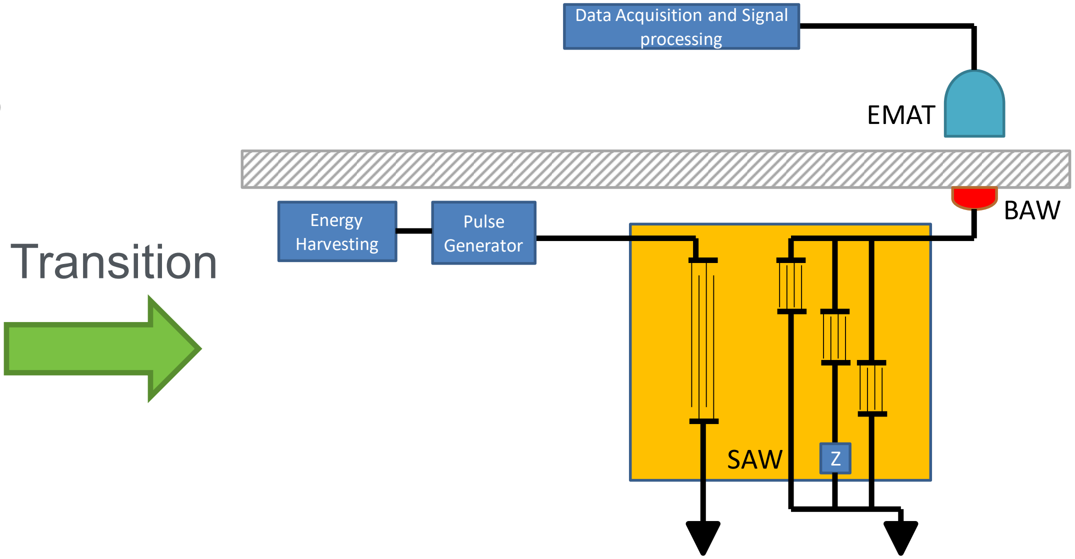
Now we are refining our design for the NUMHOS 32 PTH



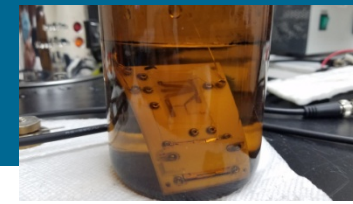
Potential location for sensor mounting



Conceptual designs of the SPWSS



SAW sensor development
- Corrosion test



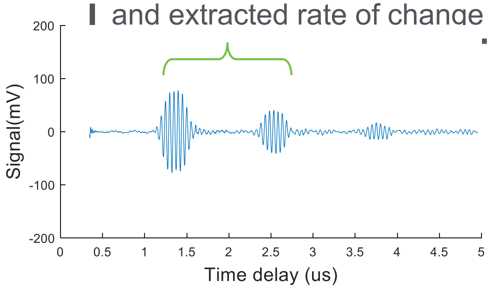
Process

We followed the protocol provided by the ORANO for corrosion test

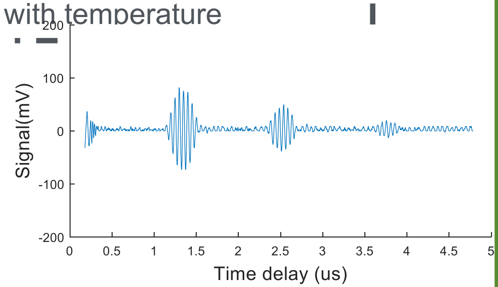
Results

Quantitative analysis suggests that there are changes in the temperature sensing capabilities

We recorded the time delay as function to temperature and extracted rate of change with temperature

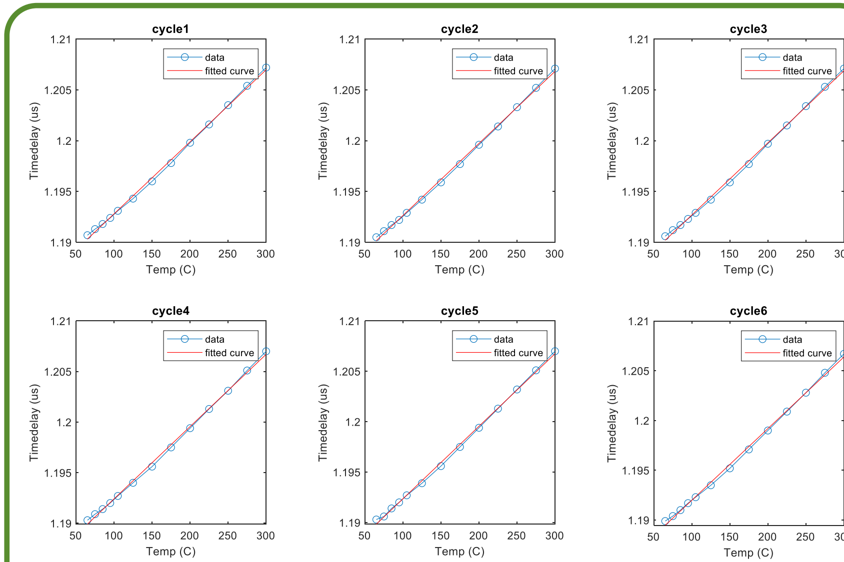


SAW response before corrosion test.

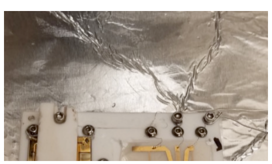


SAW response after corrosion test

Corrosion test setup



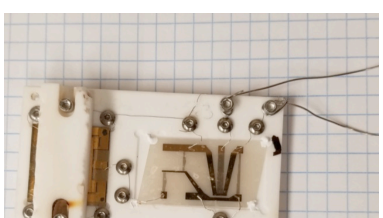
SAW sensor calibration graphs



144 hours

168 hours

Visual inspection



216 hours

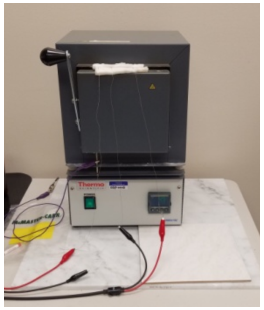
SAW sensor development
- High temperature test

Results:

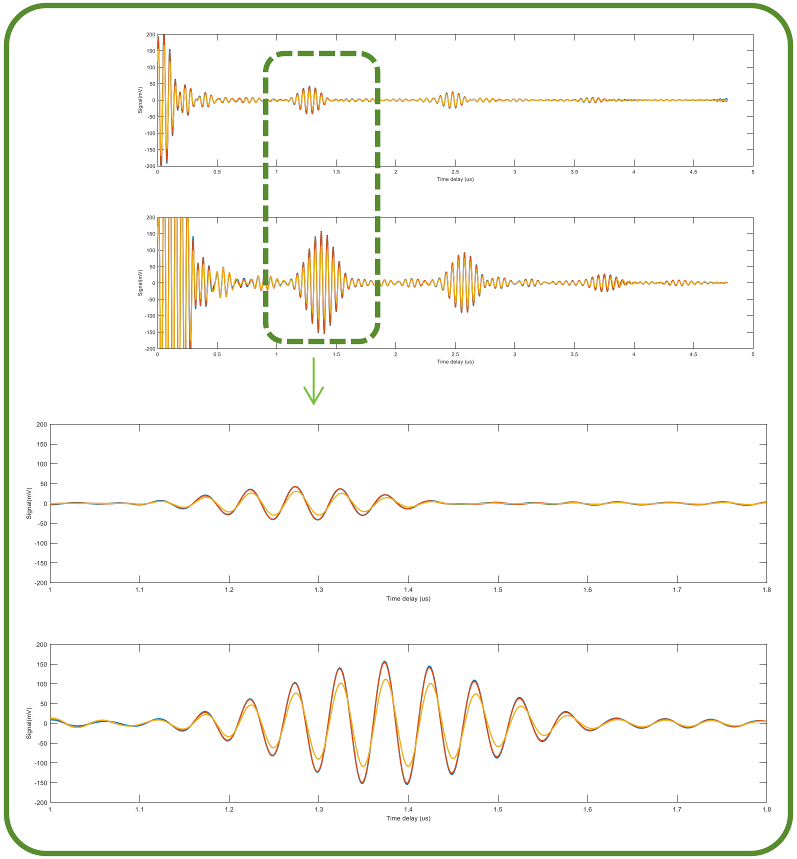
SAW sensors can survive temperature up to 300 ⁰C, but show degradation when heated up to 350 ⁰C in ambience.

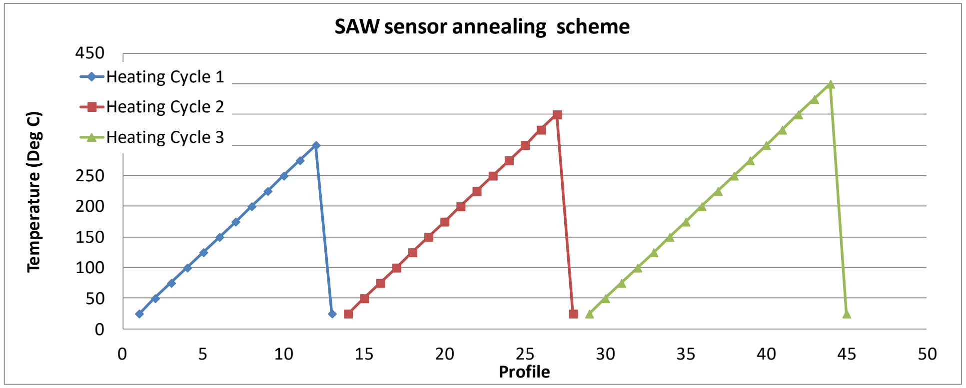
The amplitude of SAW response decreases after heating to 350 ⁰C.

For aging test sensor needs to survive ~450 ⁰C for 30 days.



SAW response acquired at 250 ⁰ C in different heating cycles



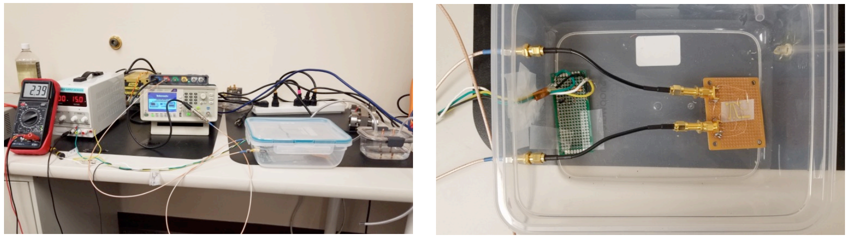


Temperature cycle for high temperature test

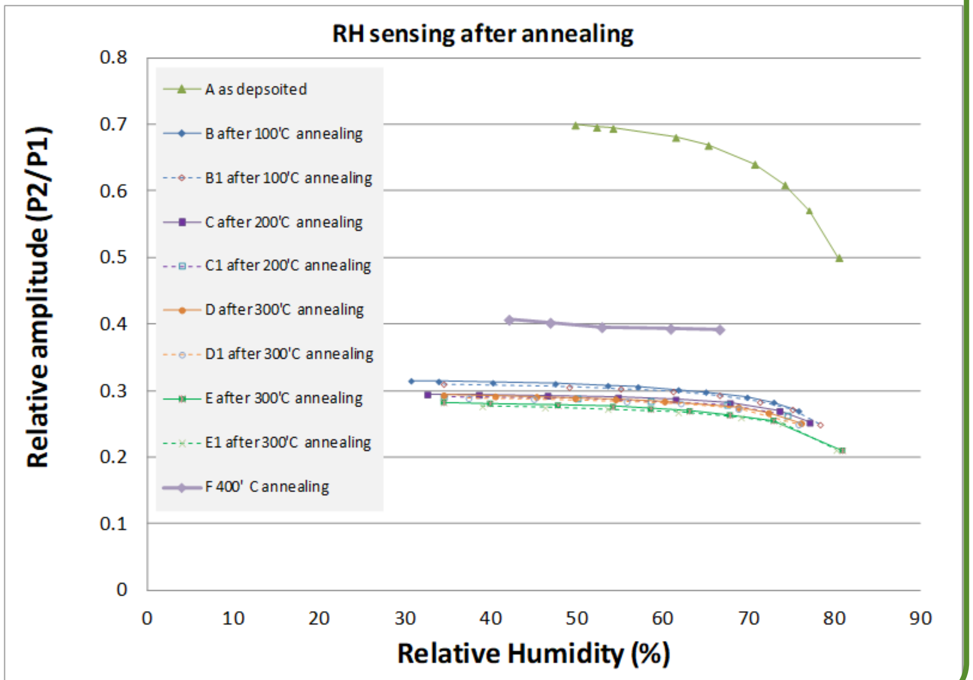
SAW sensor development
- Humidity sensing

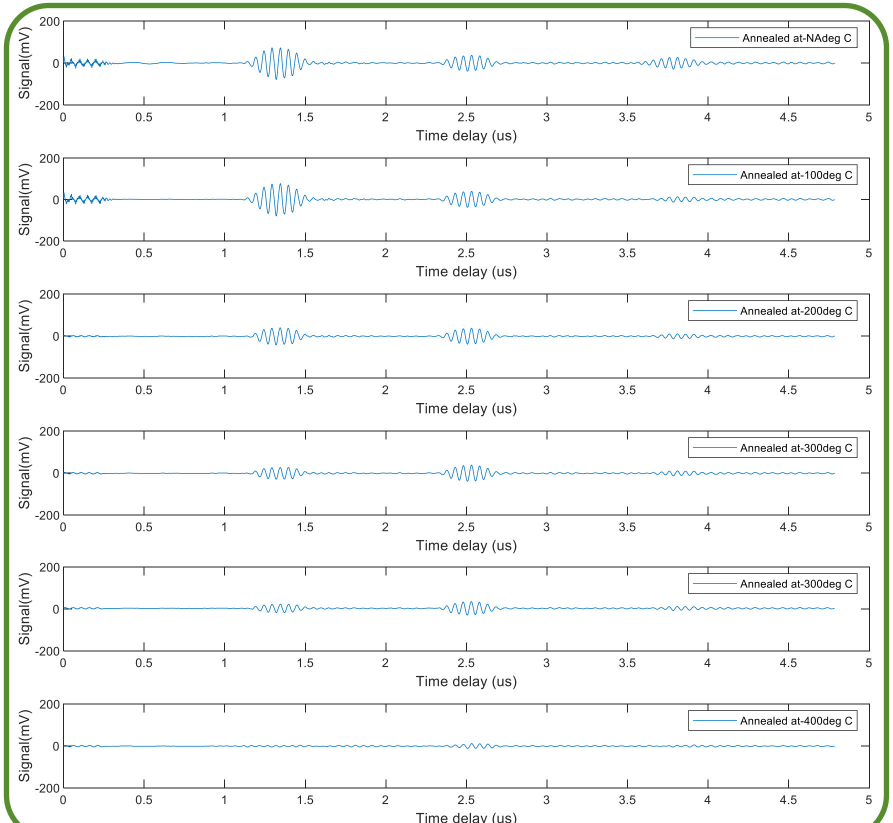
Results:

Our testing suggests that the humidity sensing degrade with heating.



Humidity sensing calibration after high temperature test

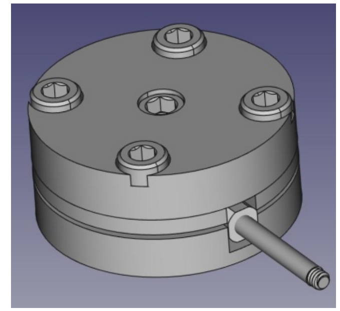




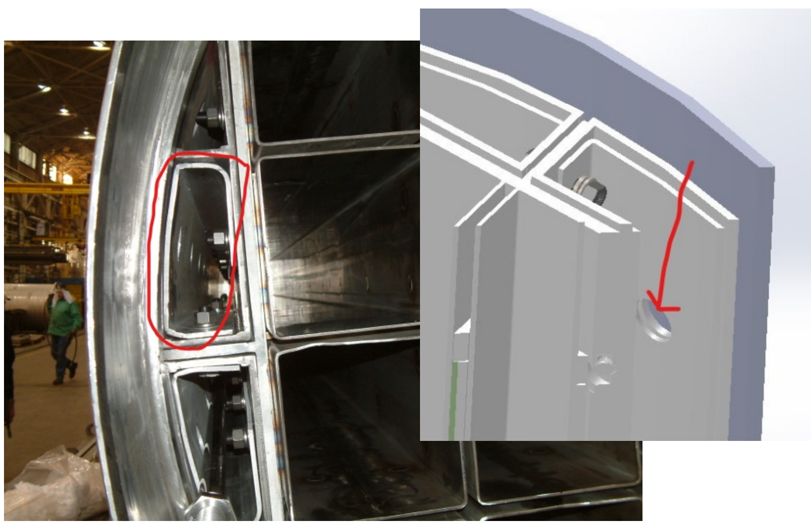
BAW for wireless data transmission

Design and development

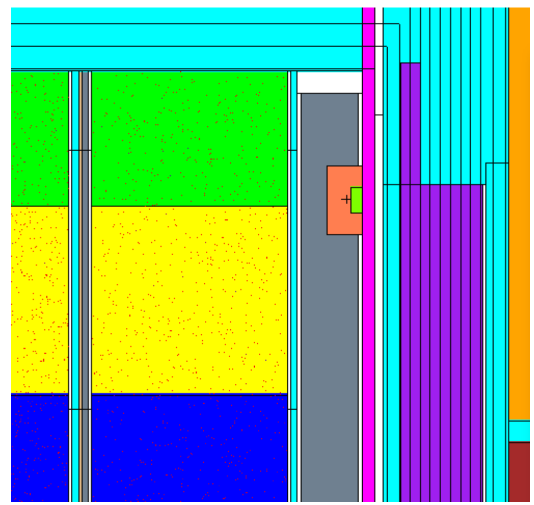
- We have developed BAW transducers for wireless acoustic communication.
- The BAW transducers is made of radiation safe materials.
- It can potentially survive for extended period of time in nuclear waste cask.



CAD image and photograph of developed transducer



Photograph of nuclear waste cask and location for BAW transducer mounting



Configuration for radiation simulation. the "dots" are the Co-60 source, 1" tungsten is orange, wafer green.

Life expectancy:

- The simulation results are provided by ORANO
- Unshielded, 4500 rad/hr, time to failure = $200.10^6/4500 = 5$ years
- 1" W shielding, 215 rad/hr, time to failure = $200.10^6/215 = 100$ years

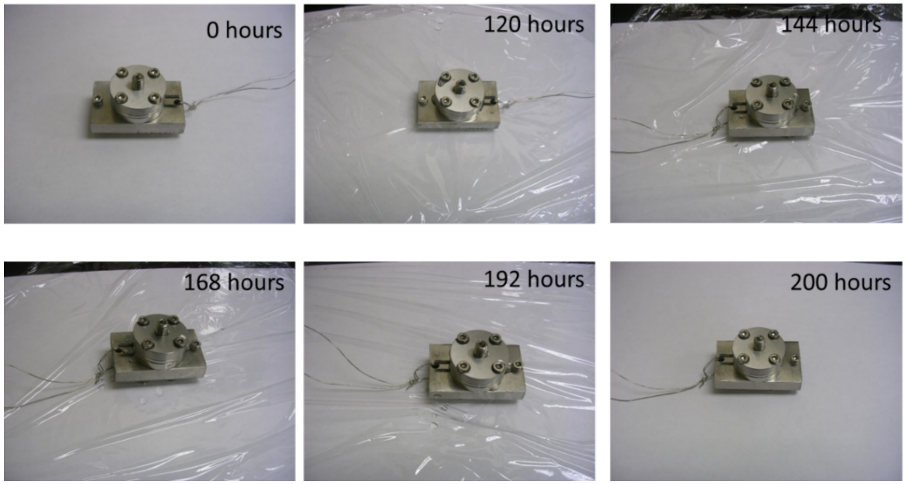
BAW for wireless data transmission

Corrosion test

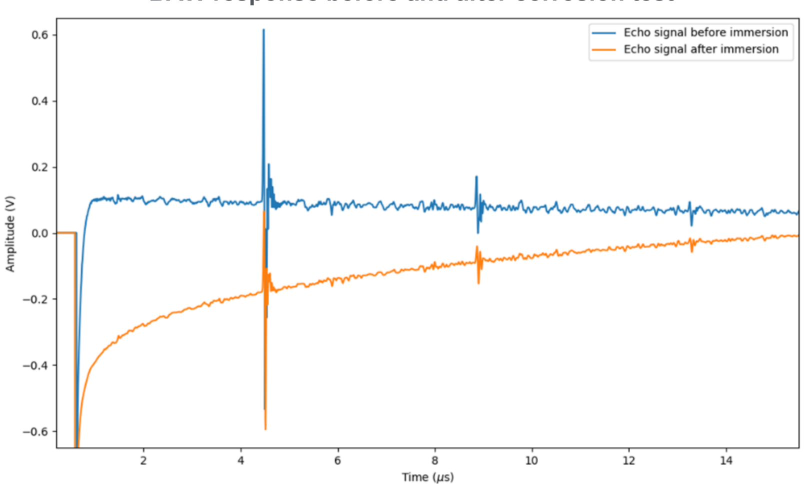
Results:
- No visible degradation was found
- No acoustic or electrical performance degradation was found.

Setup

Photograph of BAW taken during corrosion test

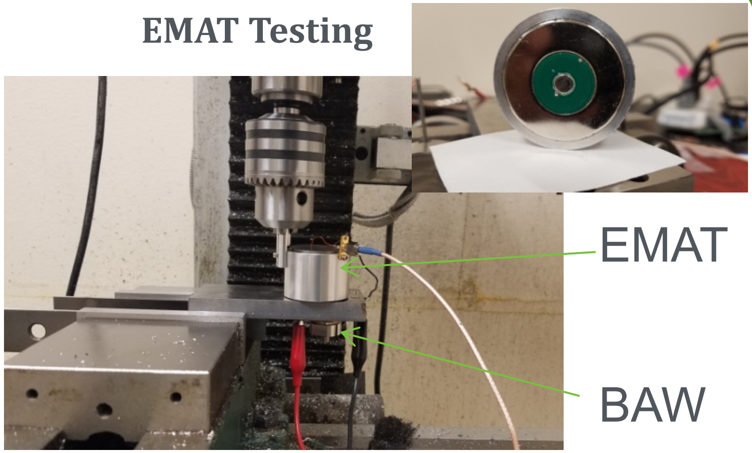


BAW response before and after corrosion test

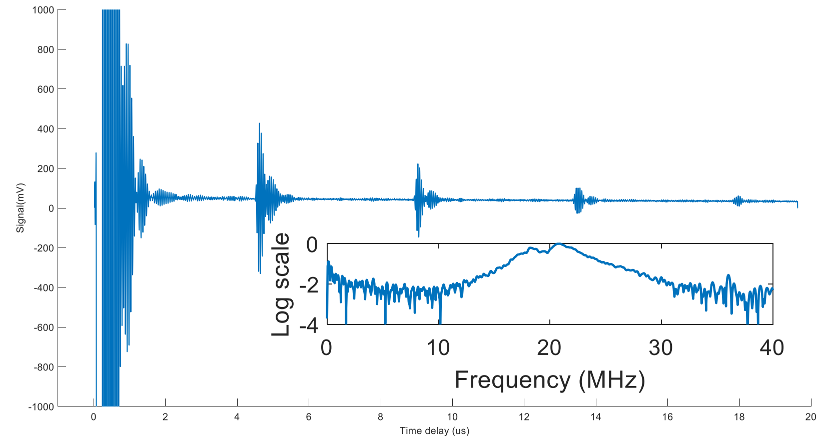


EMAT for noncontact wireless receiving

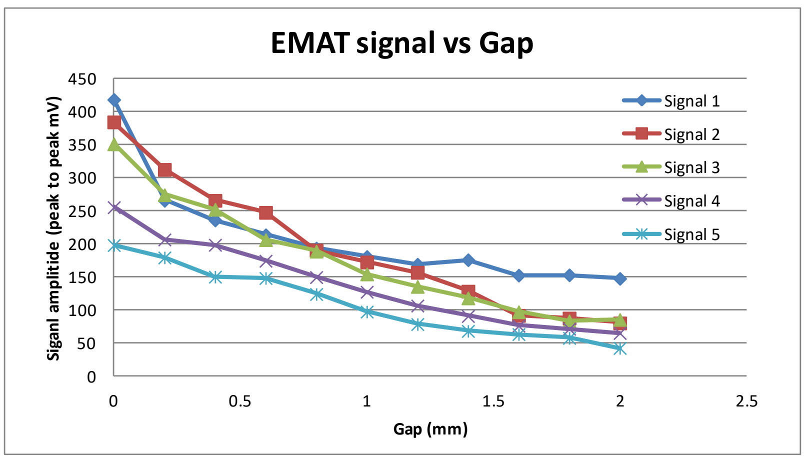
EMAT Testing



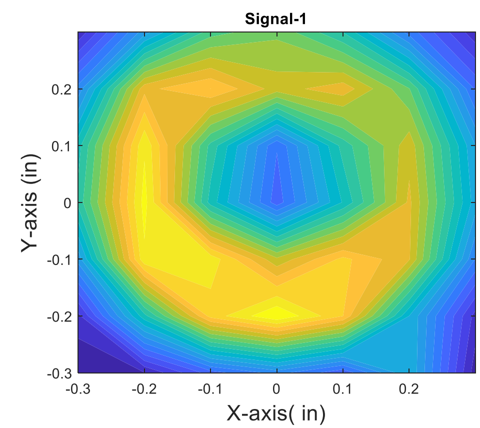
Test setup



Captured waveform



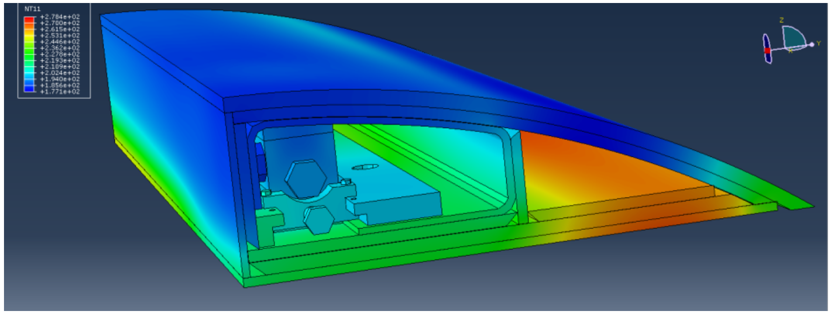
Map of EMAT signal

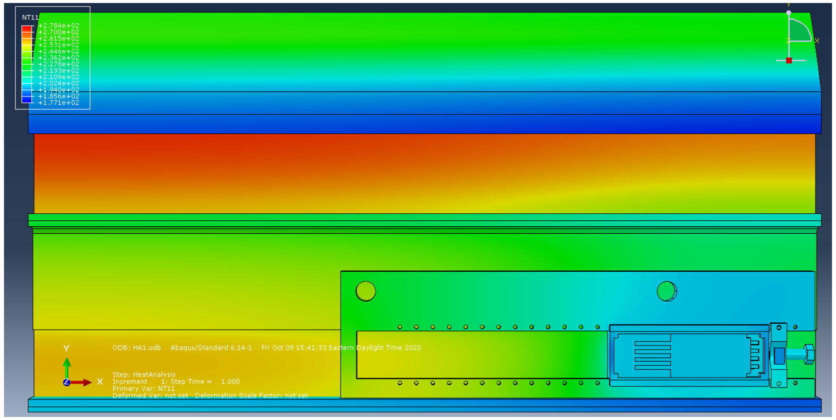


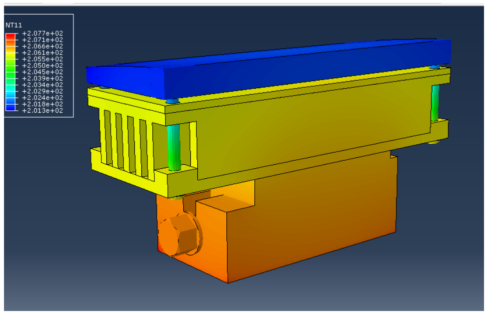
Thermoelectric Harvester development

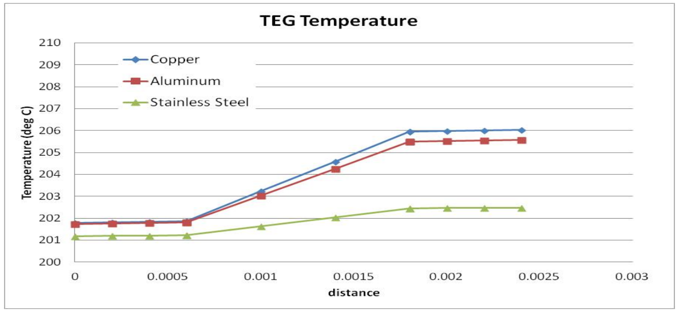
Design and development

- We have developed Thermoelectric Harvester to fit in the NUHMOS 32PTH nuclear waste cask.
- We performed heat analysis simulation to estimate temperature difference across TEG module
- Heat analysis suggest the choice of metal in harvester development is crucial.
- We have developed second harvester design to mechanically locking the module in the NUHMOS 32PTH nuclear waste cask.







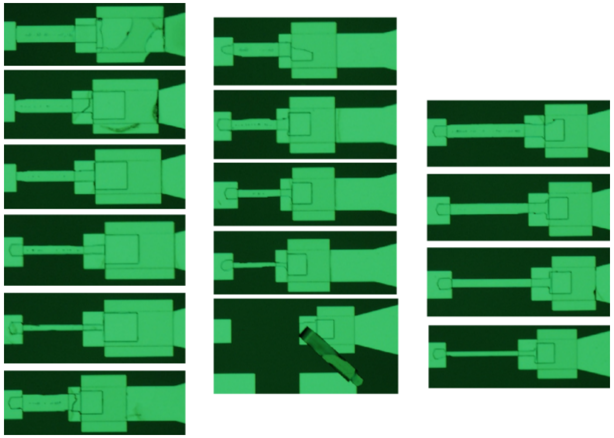


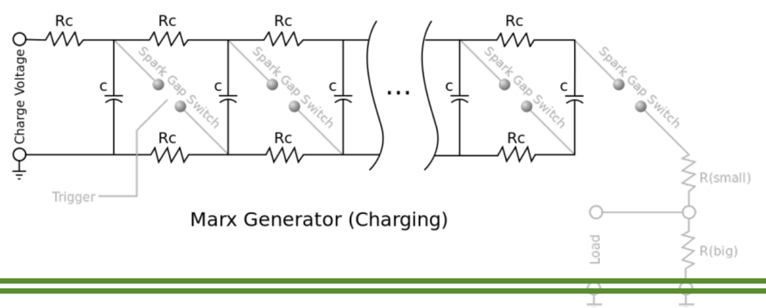
Pulser development

Design and development

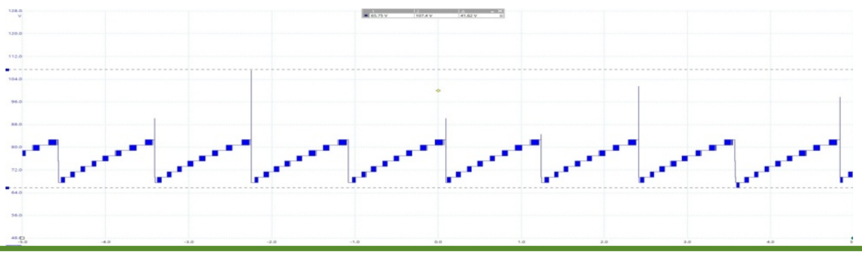
- We are developing a cantilever electrical pulse generator
- We have indentified and tested electrical circuit to amplify electric pulse amplitude to improve signal to noise ratio

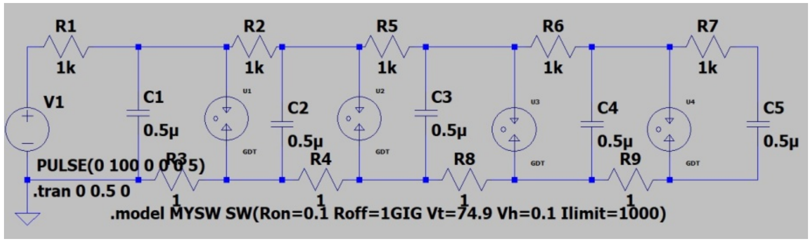
Photograph of developed cantilever



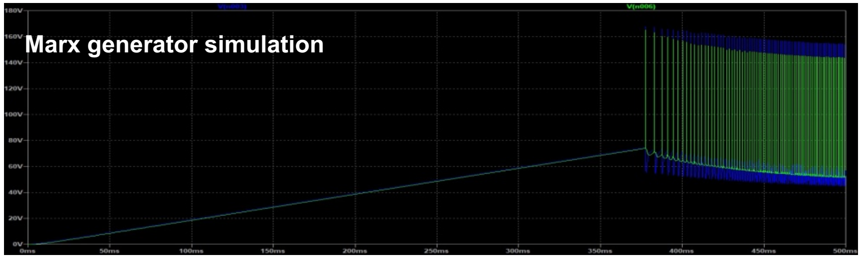


Marx generator testing





Marx generator simulation



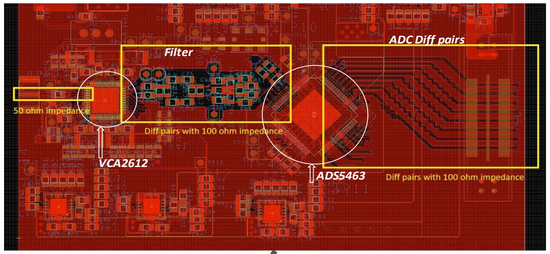
Interrogation unit

Development

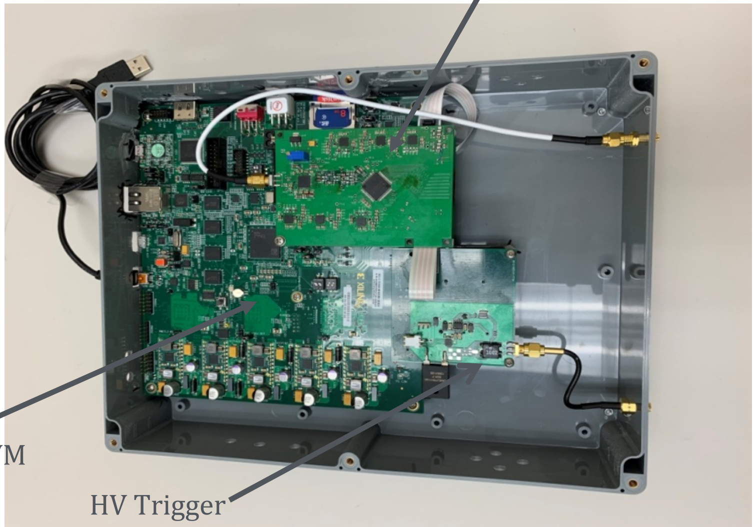
Hardware system Refinement Rev 3

- Rev 2: ZYNG 7Z020 ZC702 EVM based 12″ x9″ x 3″
- Rev 3: ZYNG 7Z010 MicroZed based 6.3″ x 4.25″ x 1.75″

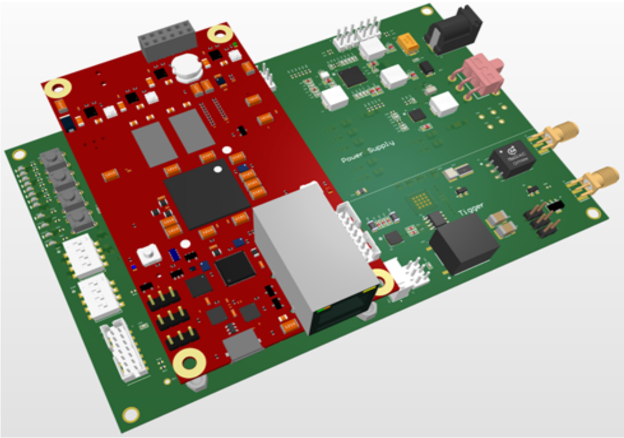
ADC & Amp

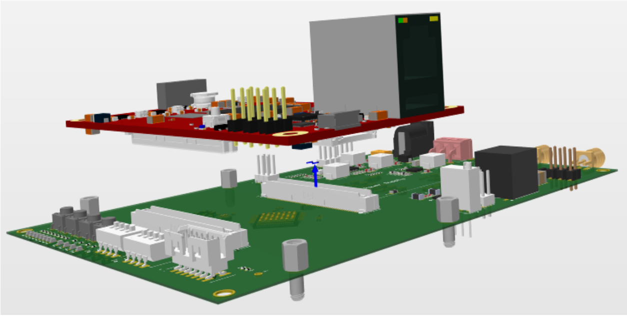


Rev 2



ZYNQ EVM





Future development

- Refinement of SAW sensor and its calibration
- Fabrication and testing of thermoelectric harvester
- Refinement of pulser design
- Refinement in EMAT design
- Refinement electronic and software
- Sensor system testing
- Irradiation testing
- Commercialization/Transition

Questions and contact info

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