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

Clean. Reliable. Nuclear.

High temperature embedded/integrated sensors (HiTEIS) for remote monitoring of reactor and fuel cycle systems

Advanced Sensors and Instrumentation Annual Webinar

October 29, 2020

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TPOC: Vivek Agarwal, INL

Project Overview

- **Goal and Objective**

  To develop and evaluate high temperature embedded/integrated sensor systems (HiTEISs) for applications in reactor and fuel cycle systems.

- **Participants (2020)**

  Xiaoning Jiang, **PI**, NC State University (NCSU) (Tasks 1, 2 & 3), **Mohamed Bourham**, Co-PI, NCSU (Tasks 2 & 3), **Mo-Yuen Chow**, Co-PI, NCSU (Tasks 2 & 3), **Leigh Winfrey**, Co-PI, Penn State University (PSU) (Task 1)

  Howuk Kim, PostDoc, NCSU (Tasks 1, 2 & 3), **Bharat Balagopal**, PostDoc, NCSU (Tasks 2 & 3), **Sean Kerrigan**, PhD student, NCSU (Tasks 2 & 3),

- **Schedule**

Year	Task	Role	Responsibility	Note
1 & 2	HiTEIS design and development	HiTEIS development	X. Jiang	NCSU
		Sensor material radiation resistance	L. Winfrey	PSU
2, 3 & 4	HiTEIS Integration and characterization	Wireless communication system	M. Y. Chow	NCSU
		HiTEIS integration & characterization	X. Jiang & M. Bourham	NCSU
2, 3 & 4	Development of embedded sensors and laser ultrasound	Laser ultrasound transducer development	X. Jiang	NCSU
		Sensor radiation/corrosion resistance	M. Bourham	NCSU
		Wireless communication for embedded sensors	M. Y. Chow	NCSU

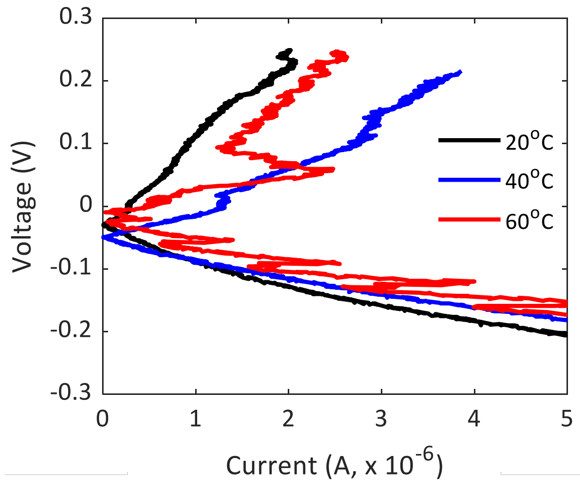
Summary of Accomplishments

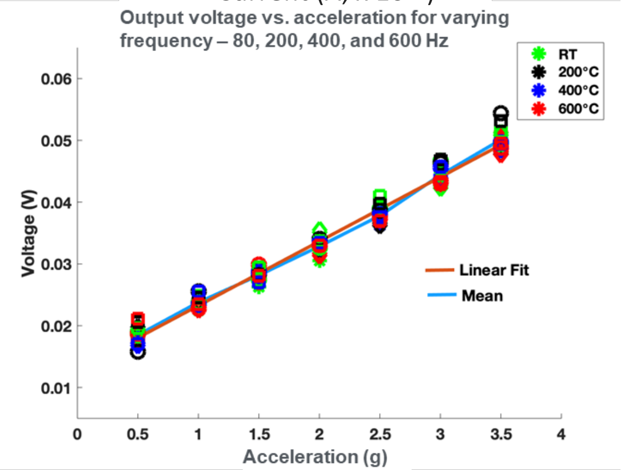
- Corrosion resistance of high-temperature (HT) sensors (Task 2)
  - Corrosion rate of sensing material is highly dependent on temperature, and reduce the potential lifetime

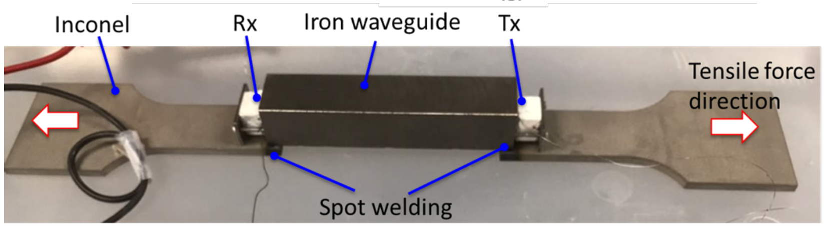
- Wireless Data Communication for HT Vibration Sensor (Task 2&3)
  - Succeeded in transferring HT vibration sensor data to a remote place* using the wireless communication system

- Nonintrusive/Embedded HT Stress Sensor (Task 2&3)
  - Demonstration of surface attached HT stress sensing

* Remote place where the sensor data is recorded is not restricted by a physical distance as long as a communication router is within 50m from the local sensing area



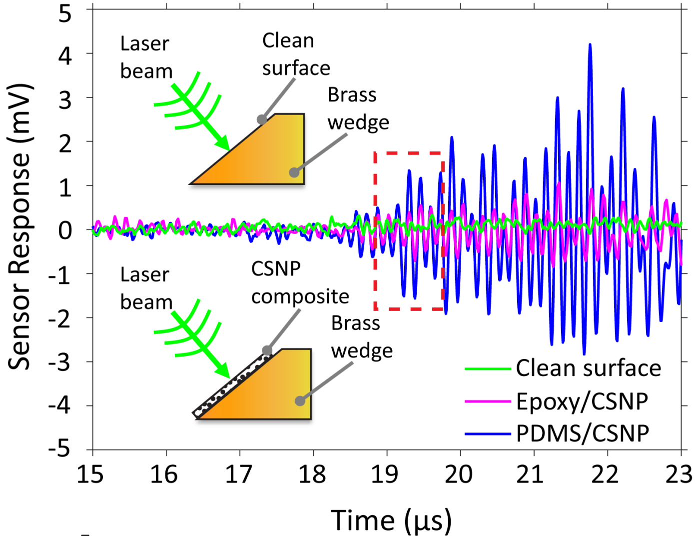


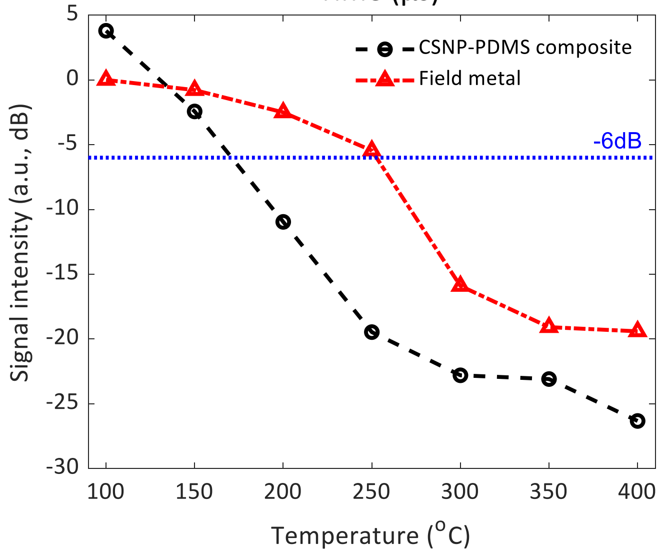


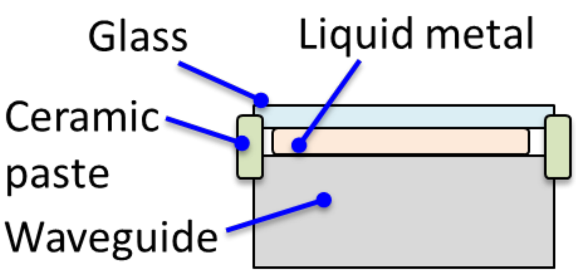
Summary of Accomplishments

- Candle Soot Nanoparticle (CSNP) Composite Based Laser Ultrasound Transducer (Task 3)
  – Polydimethylsiloxane (PDMS)/CSNP is an effective PA media applicable in a moderate temperature (<200 ^{o}C) condition

- Liquid Metal Assisted Laser Ultrasound Transducer (Task 3)
  - liquid metallic material was successfully demonstrated for HT laser ultrasound







Technology Impact

- *Advances the state of the art for nuclear application*

  Nonintrusive/embedded sensors under harsh environmental conditions utilizing innovative laser ultrasound generation techniques

- *Supports the DOE-NE research mission*
  - ✓ In-service monitoring of nuclear structures, ensuring nuclear energy supply with a reliable lifetime prediction

- *Impacts the nuclear industry*
  - ✓ Nonintrusive HiTEIS combined with wireless communication system for minimization of human influences
  - ✓ Laser ultrasound enabled remote structural health monitoring

- *Will be commercialized*
  - ✓ A liquid metallic based HT laser ultrasound generator was prototyped and the technical feasibility has been demonstrated.
  - ✓ University technology transfer office will investigate business models for commercialization with the filed invention disclosure (patent). (current TRL: 4-5)

Conclusion

- Feasibility of candle soot nanoparticle composite was demonstrated for HiTEIS applications with various interface materials (epoxy and PDMS).
- An innovative liquid metal based photoacoustic transducer was investigated and characterized at HT conditions.
- A wireless data communication system for HiTEIS was developed and validated through a compression-type HT vibration sensor.
- Nonintrusive/embeddable HT stress sensor was designed and fabricated. The HT performance will be tested after applying the HT insulation layer.
- The corrosion test results showed the necessity of the electrode insulating layer for the prolonged usage of the sensing material.
- During the extended project period, we will study HT wireless data communication for other sensing systems, sensor electrode insulating techniques for HT/radiation conditions, and laser ultrasound non-destructive testing.

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Accomplishment Details

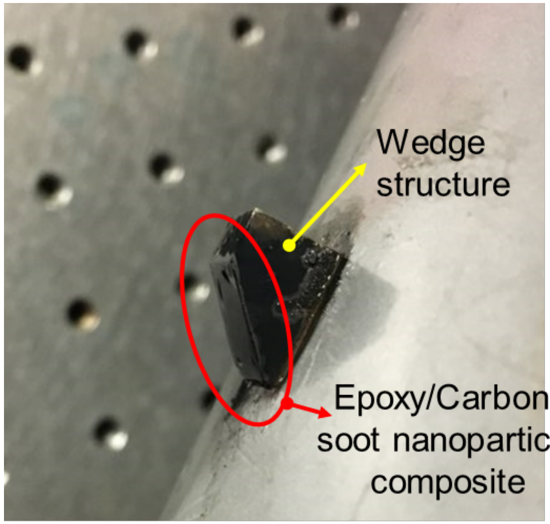
<u>Accomplishment 1:</u> Candle Soot Nanoparticle (CSNP) Composite Based Laser Ultrasound Transducer (Task 3)

<u>Purpose:</u>

- To investigate the feasibility of the CSNP composite for HiTEIS applications and to observe the influence of the interface materials (e.g., epoxy and PDMS)

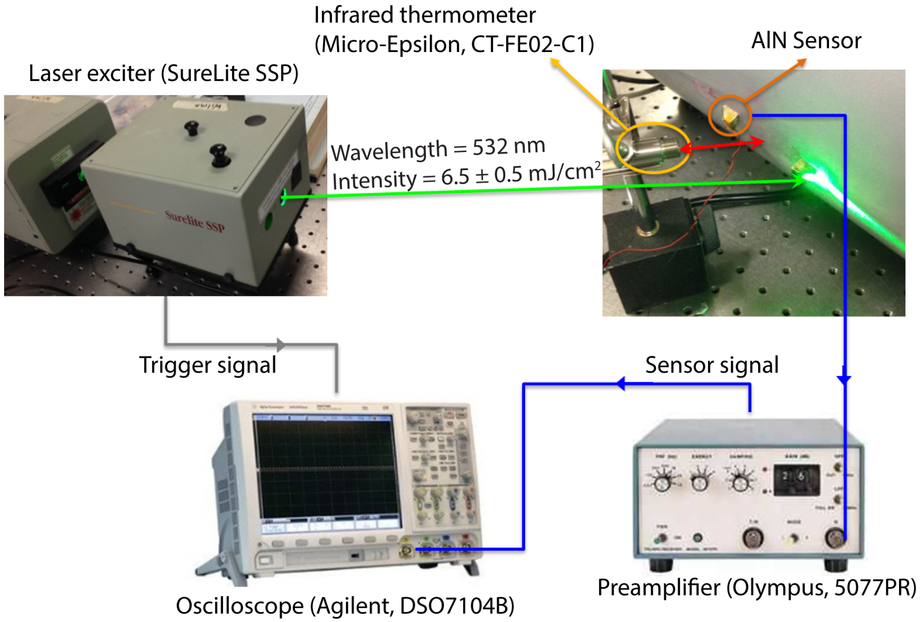
<u>Methods:</u>

A. Sensor design and fabrication



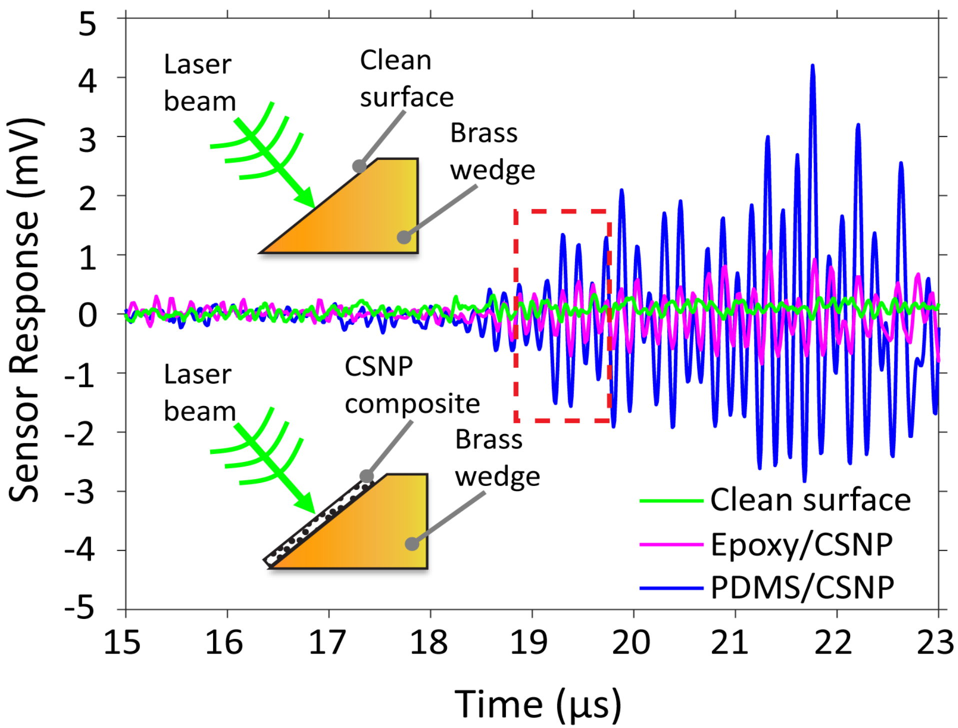
Laser-ultrasound transmitter using epoxy interface instead of PDMS.

B. Characterization



Accomplishment Details

Results:



a. 1.4-folds greater signal intensity when using PDMS/CNSP than the acoustic signal (pink solid line) produced by the epoxy/CSNP

b. High thermal expansion of PDMS (i.e., β_{PDMS} ~ 9 $\times 10^{-4}$ K^{-1} and β_{epoxy} ~ 8 $\times 10^{-5}$ K^{-1}) results in more effective PA energy conversion

c. High acoustic mismatch between PDMS and brass (i.e., Z_{PDMS} ~ 1.5, Z_{epoxy} ~ 2.9, and Z_{brass} ~ 34 MRalys) was less dominant in PA effect.

Conclusions:

- PDMS/CSNP is an effective PA media applicable in a moderate temperature (<200°C) condition
- The HT (>200°C) feasibility of PDMS/CSNP material needs to be investigated.
- Needs to study a new photoacoustic (PA) material instead of polymer-based composites for HT applications.

Accomplishment Details

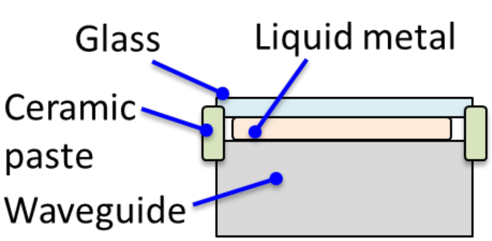
Accomplishment 2: Liquid Metal Assisted Laser Ultrasound Transducer (Task 3)

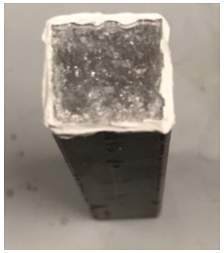
Purpose:

- To present a new PA transducer utilizing a liquid metallic material and to demonstrate the performance for the laser ultrasound generation

Methods:

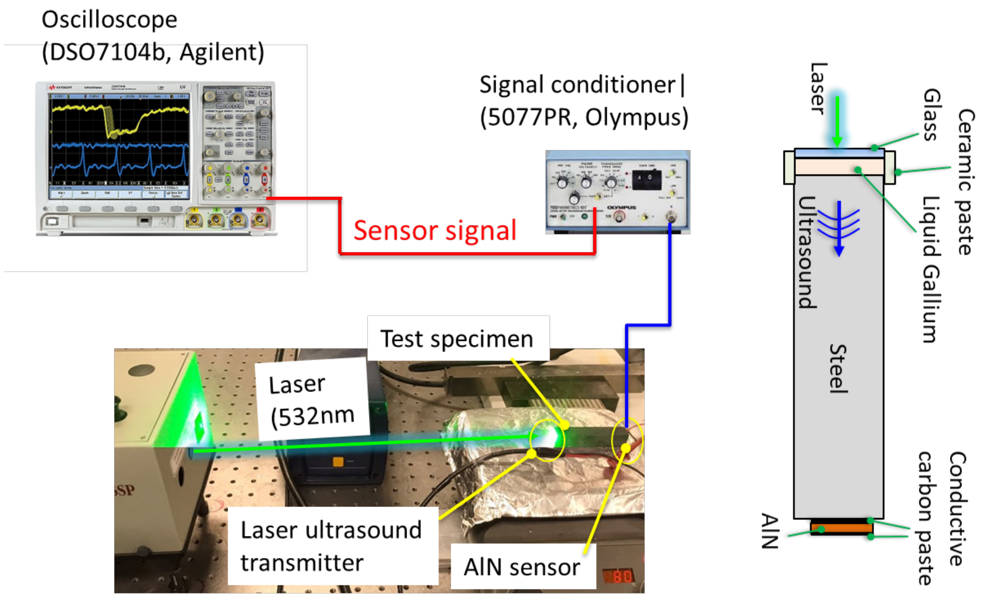
A. Sensor design and fabrication





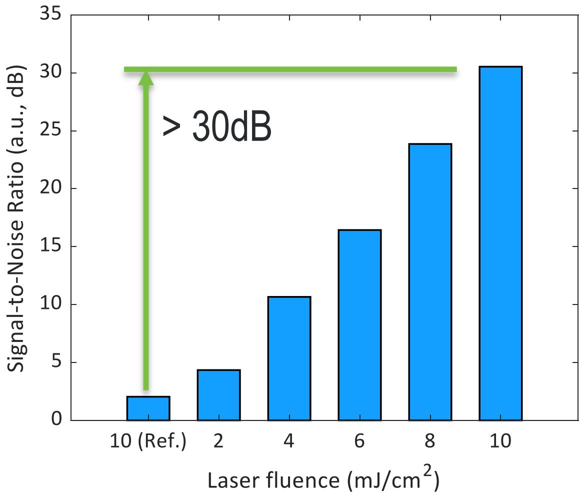
Hypothesis:
Liquid status of metals produces the relatively high photoacoustic energy conversion owing to the excellent thermal expansion rate (>800 ppm K-1) even though the optical absorption rate of liquid metals (10~15%) is lower than typical metals (i.e., steel, 40-50%).

B. Characterization

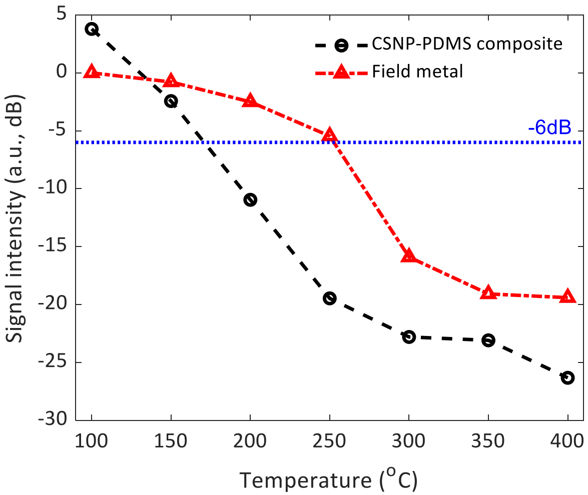


Accomplishment Details

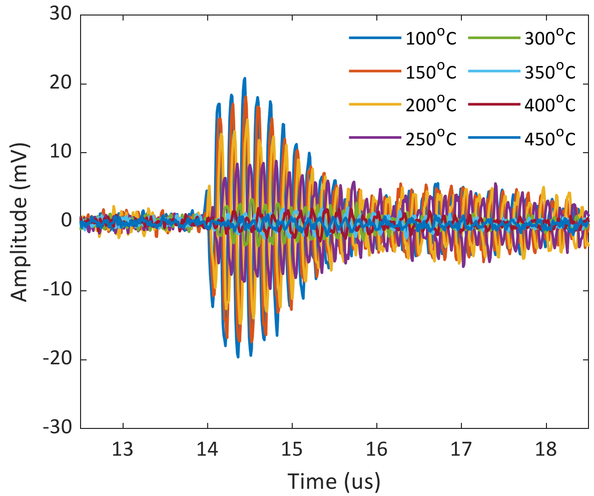
Results:



Over 30 dB gain using the liquid metallic PA transducer



More stable HT performance than CSNP composite



Clear wave packets detected at HT conditions

Conclusions:

- A new modality utilizing liquid metallic material was investigated.
- Over 30 dB gain using the liquid metal PA transducer
- Ensured the temperature stability of the liquid metallic materials in PA energy conversion

Accomplishment Details

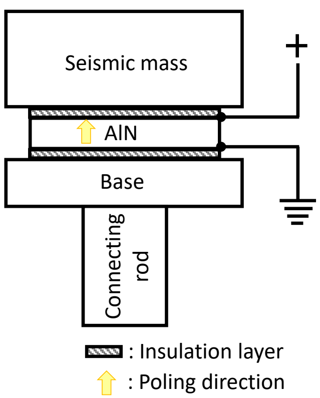
Accomplishment 3: Wireless Data Communication for HT Vibration Sensor (Task 2 & 3)

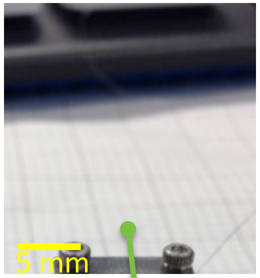
Purpose:

- To investigate the feasibility of wireless data communication for HT sensors

Methods:

A. Sensor design and fabrication

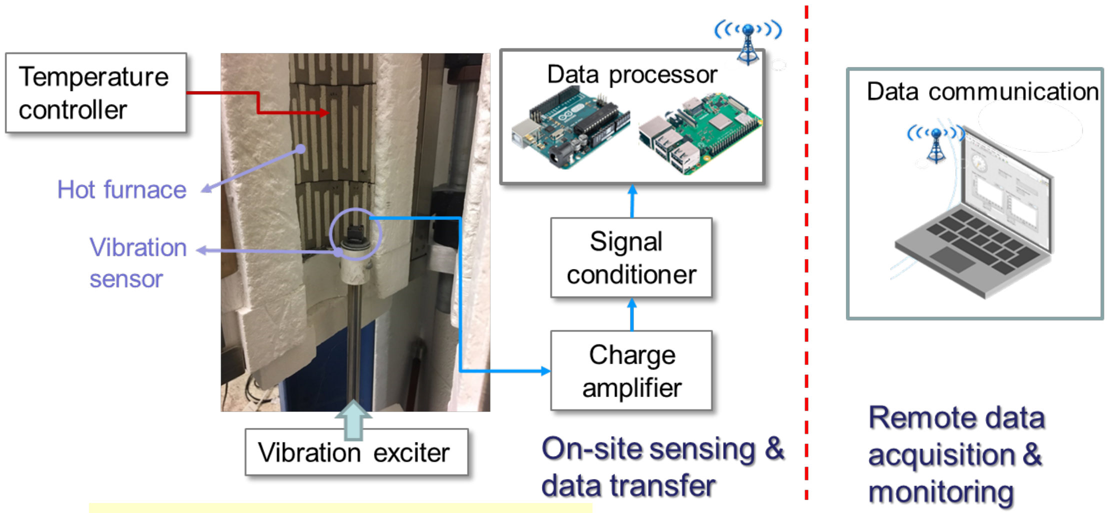




Connector
for the embedment

a. Compression type AlN
b. Connecting rod for the sensor embedment to a counter part structure

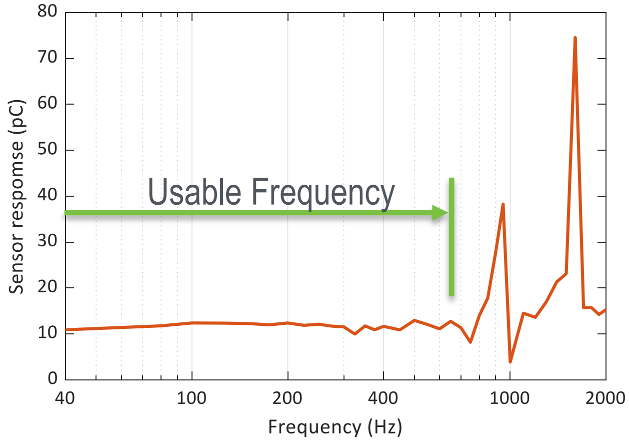
B. Validation



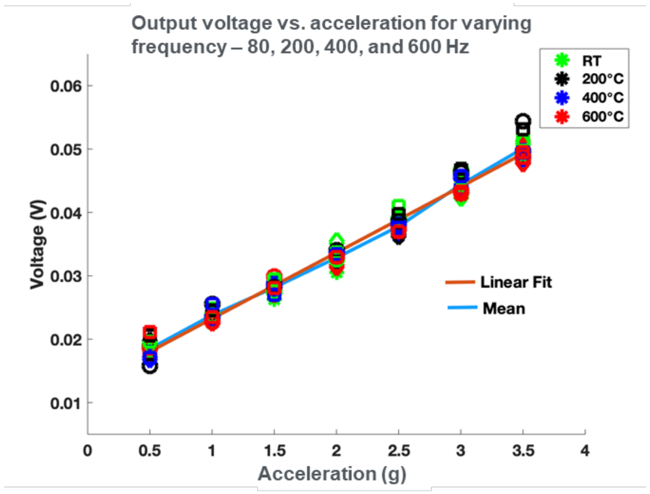
Vibration level: 0.5 – 3.5 g
Frequency: 80 to 600 Hz
Temperature: RT to 600 ^{o}C

Accomplishment Details

Results:



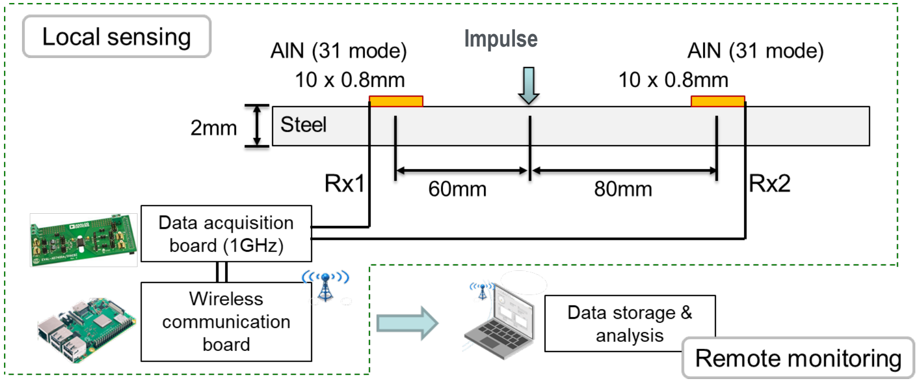
a. Sensor sensitivity ~ 10 pC/g
b. Usable frequency ~600 Hz



a. Low temperature dependency
b. Data (wireless) sensitivity about 7.9 mV/g

Conclusions:

- Succeeded in transferring HT vibration sensor data to a remote place using the wireless communication system
- Developed a low temperature/frequency dependent vibration sensor
- Expand the data communication method to an HT acoustic emission sensor (in progress)



Schematic of wireless acoustic emission sensor

Accomplishment Details

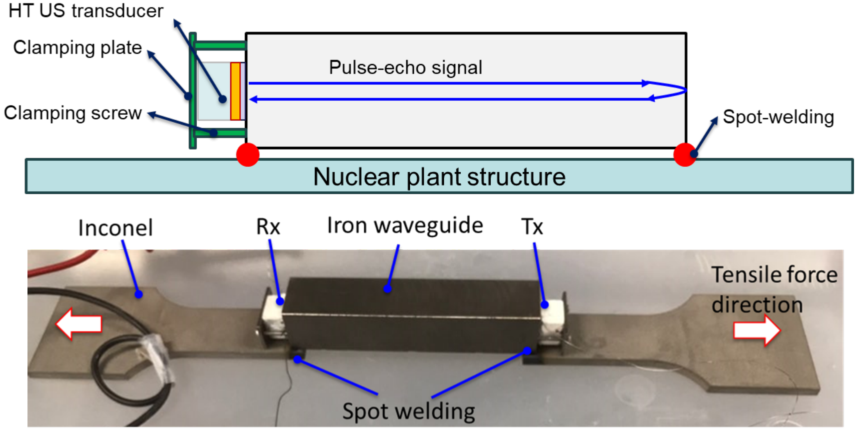
Accomplishment 4: **Nonintrusive/Embedded HT Stress Sensor (Task 2 & 3)**

Purpose:

- To investigate the feasibility of embedded HT sensing

Methods:

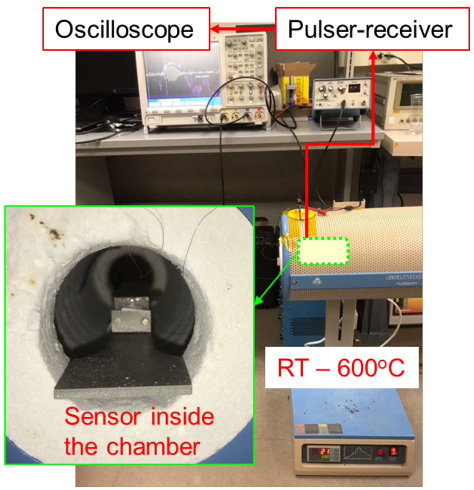
A. Sensor design and fabrication



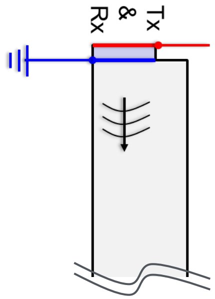
Tx is optional; Rx only is needed for the pulse-echo signal

Time-of-flight change due to mechanical stress is used for the stress estimation (i.e., acoustoelastic effect).

B. HT validation



C. FEA simulation



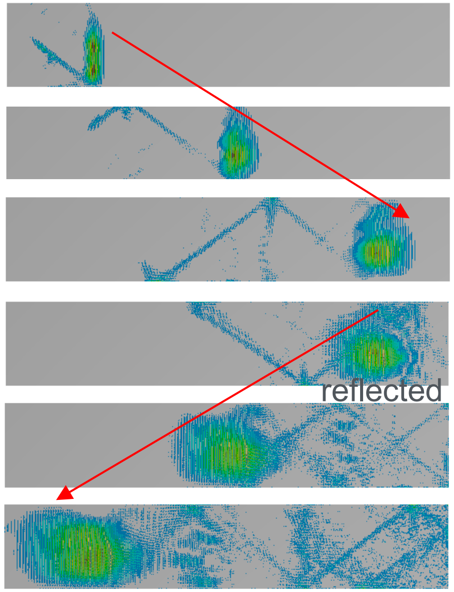
a. ANSYS Workbench rel. 17.1 (Cannonsburg, PA)

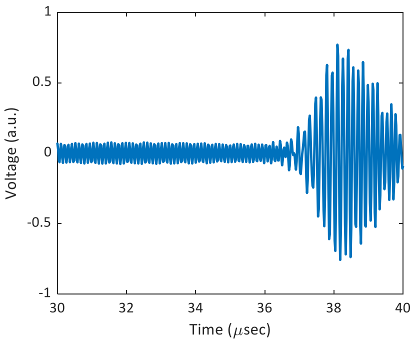
b. Tone burst voltage excitation

Accomplishment Details

Results:

Simulation results

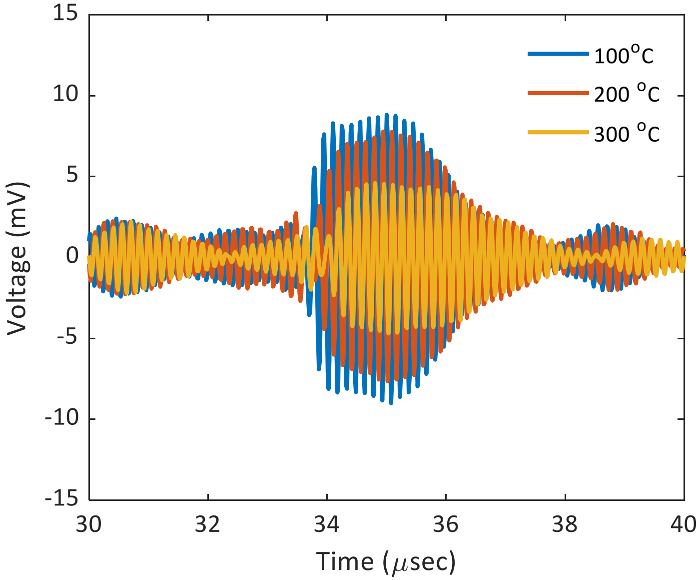




a. Simulation of the pulse-echo signal using AlN transducer

b. Longitudinal wave with the single wave packet

HT pulse-echo test results



a. Measurable for the pulse-echo signal up to 300 ^{o}C
b. Damage of electrodes at HT over 400 ^{o}C

Conclusions:

- Studying the HT insulating technique of electrode surfaces on the sensing material
- Ensuring the HT stability of the electrode, the HT stress sensor will be tested using a tensile machine.

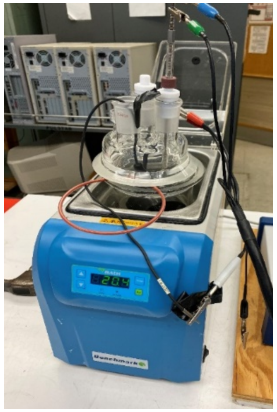
Accomplishment Details

Accomplishment 5: Corrosion resistance of HT sensors (Task 2)

Purpose:

- To investigate the corrosion resistance performance of HT sensors

Methods:

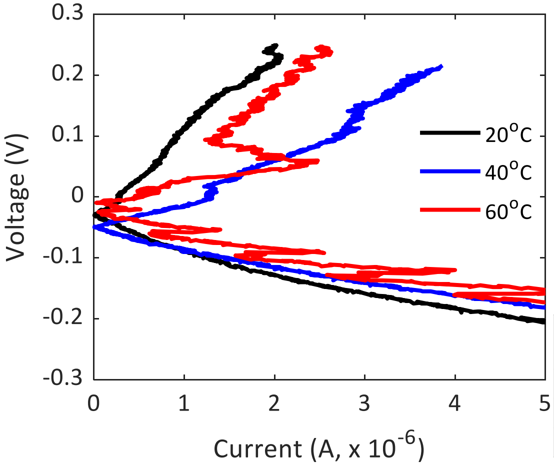


a. Corrosion effect on AlN using Cyclic Polarization Testing

b. Acidic solution of KNO_3 with a pH of 6.09

c. The corrosion response at various temperatures

Results:



a. Corrosion analysis provided estimation of corrosion rate

b. Heavily influenced by temperature

Temperature	Corrosion Rate (mmpy)	Lifetime (yr)
20 °C	0.1221	10.24
40 °C	0.2596	4.83
60 °C	0.2725	4.61

Conclusions:

- Corrosion rate of sensing material is highly dependent on temperature, and reduce the potential lifetime
- Needs to conduct the corrosion analysis after depositing an insulation layer (e.g., ZrO_2 or ZnO) over the sensor

Accomplishment Details

Publications:

A. Journal papers (2)

[1] H. Kim, S. Kerrigan, M. Bourham, and X. Jiang, "AlN Single Crystal Accelerometer for Nuclear Power Plants," *IEEE Transactions on Industrial Electronics*, In Press, 2020.

[2] H. Kim, W. Y. Chang, T. Kim, and X. Jiang, "Stress Sensing Method via Laser-Generated Ultrasound Wave Using Candle Soot Nanoparticle Composite," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 67, No. 9, pp. 1867-1876, 2020.

B. Conference papers and presentations (1)

[1] H. Kim, B. Balagopal, S. Kerrigan, M. Y. Chow, M. Bourham, and X. Jiang, "Noninvasive liquid level sensing technique using laser generated ultrasound," *Proceedings of SPIE*, Online presentation, Vol. 11380, 1138003, 2020.

C. Newsletter (1)

[1] H. Kim, S. Kerrigan, B. Balagopal, M. Y. Chow, M. Bourham, and X. Jiang, "Noninvasive High Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Nuclear Power Plants," *Update on NEET ASI Advanced Instrumentation Development Activities*, U.S. Department of Energy, No. 12, pp. 21-23, 2020.

D. Invention Disclosure (1)

[1] H. Kim and X. Jiang, "Liquid Metal Assisted Photoacoustic Transducer," 15 Oct 2020.

Awards:

A. Student competition

At the American Nuclear Society (ANS) 2nd annual Pitch your PhD Competition, Sean Kerrigan placed 2nd. Kerrigan's work is on "Development, Fabrication and Testing of Wireless Non-Intrusive AlN-based Piezoelectric Sensors".