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

ASI | Advanced Sensors and Instrumentation

Multimodal Sensors for Advanced Reactor Monitoring and Control

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
October 24 – 27, 2022

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Pacific Northwest National Laboratory

Project Overview (Summary)

Purpose: Design and develop a multimodal sensor for measurements of critical process parameters in advanced non-light water-cooled nuclear power plants (NPPs), for the early detection and characterization of atypical operating conditions.

Objectives:

- Develop a multimodal surface acoustic wave (SAW) measurement platform for simultaneous temperature, pressure, and gas composition sensing
- Develop algorithms to isolate the effects of temperature, pressure, and gas composition to extract three measurements from an integrated sensor
- Test and evaluate sensor for accuracy and reliability.

Research Path: A multimodal SAW sensor for temperature and pressure measurements was developed and evaluated. This information was used to design and test a SAW sensor for gas composition detection. Modeling and simulation were used to evaluate sensor designs. Sensor data was used to develop data deconvolution methods for parsing multimodal sensor data.

Project Overview (Summary)

Accomplishments:

- Temperature and pressure data matrices of SAW based multimodal sensor.
  - Temperature range [23 - 68° C]: Linear relationship and small standard deviation of arrival time with temperature across numerous runs spanning temperature range.
  - Temperature range [80 - 420° C]: Linear relationship arrival time with temp.
  - Pressure and Temperature: Pressure range [0 – 200 psig] and Temp. [60-350° C].
- Patent Pending: Provisional U.S. Patent Application 63/322,023.
- Gas concentration evaluation completed using CO_2. Enabled acquisition of data set used for application of temperature compensation techniques
  - UNT duplicated SAW responses from SAW units supplied by PNNL.
  - Deposition of SnO_2 films completed and evaluated to quantify CO_2 gas concentration of blended gas mixtures.
  - Acquired results with varied CO_2 concentrations from 0-50k ppm in 10k ppm steps
  - Successful compensation for changes in temperature to isolate changes in gas concentration

Project Overview (Schedule and Participants)

- Project Schedule
  - Project kicked off in 2019 with 3-year duration
  - Technical work concluded in September 2022, final deliverable report on schedule for delivery in December 2022

Year	Milestone/Deliverable	Description	Status
1	M3CA-19-WA-PN__-0702-014	Status Update of Multimodal Sensor Design	Completed
	M3CA-19-WA-PN__-0702-015	Status Update of Evaluation Criteria for Assessing a Multimodal Sensor Concept and Data Analytics Deconvolution of Mixed Signals	Completed
	M2CA-19-WA-PN__-0702-013	Year 1 FY20 Status Update of Smart Multimodal Sensor Design for Advanced Reactor Monitoring	Completed
2	M3CA-19-WA-PN__-0702-018	Test Plan for Evaluating Sensor Concept Sensitivity	Completed
	M3CA-19-WA-PN__-0702-019	Status update of Data Analytics Efforts for Isolating Measurement Parameters of Multimodal Sensor Data	Completed
	M2CA-19-WA-PN__-0702-017	Year 2 FY21 Status Update of Smart Multimodal Sensors for Advanced Reactor Monitoring	Completed
3	M3CA-19-WA-PN__-0702-0112	Status Update of Final Multimodal Sensor Design	Completed
	M3CA-19-WA-PN__-0702-0113	Sensor Concept Testing/Evaluation and Analytics Update	Completed
	M2CA-19-WA-PN__-0702-011	**Final Report for (Project 19-17070) Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control**	**On schedule (Dec 2022)**

- Participants (students in red)
  - **Pacific Northwest National Laboratory:** Morris Good Co-PI, Yanming Co-PI, Hardeep Mehta, Nicholas Conway, Victor Aguilera-Vazquez, Mychailo Toloczko, Ferdinan Colon, Michael Hughes
  - **University of North Texas:** Haifeng Zhang, Muhammad Aslam, Chen Zhang

Technology Impact

- Advances the state of the art for nuclear application: Work addresses technical gaps in temperature, pressure and gas composition sensing capabilities for advanced reactors.

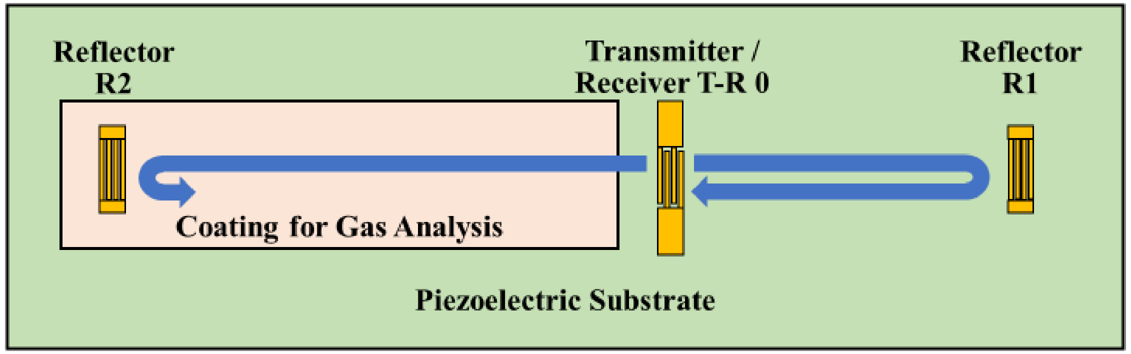
- Supports the DOE-NE research mission: Work directly contributes to the DOE mission directives by developing enabling technology capable of reliable, higher-resolution process measurements for deployment of advanced reactors.

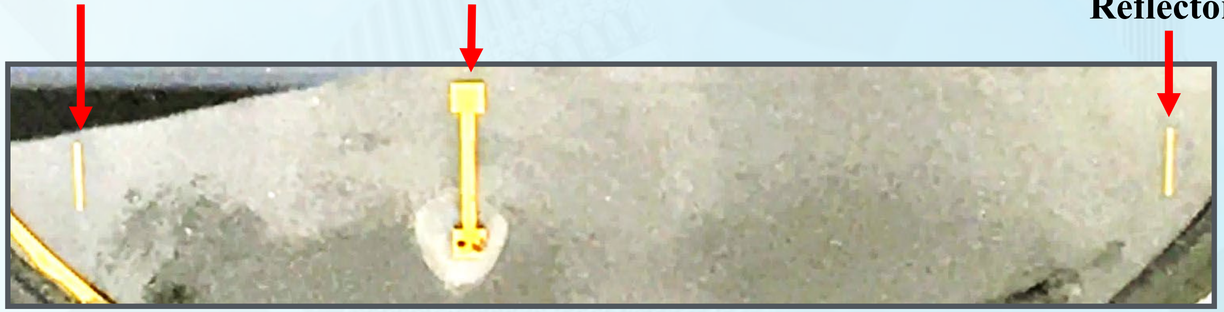
- Impacts the nuclear industry: The resulting multi-modal sensing platform will enable reduction of vessel penetrations in advanced reactors for condition monitoring sensors.

- Commercialization: Developments in simultaneous temperature and pressure sensing have produced a provision patent application. Further development of this sensing technology has commercialization opportunities relative to deconvolving measurements affected by mixed parameters to measurements of parameters of interest, multimodal sensors for a variety of harsh condition measurements across the NE space and into other harsh environment applications (advanced reactors, petrochemical, sustained high temperature operation, etc.)

Results and Accomplishments: Summary of Technology

- Piezoelectric Substrate with Interdigital Transducers and Reflectors
  - Surface Acoustic Wave (SAW) is generated and wavefronts propagate forward and backward.
  - Distance from T-R 0 and R1 and R2 are selected so responses do not interfere with each other.





Photograph of current SAW Substrate

- Four Measured Ultrasonic Parameters
  - Time-of-Flight of R1 (t_{R1})
  - Amplitude of R1 (A_{R1})
  - Time-of-Flight of R2 (t_{R2})
  - Amplitude of R2 (A_{R2})

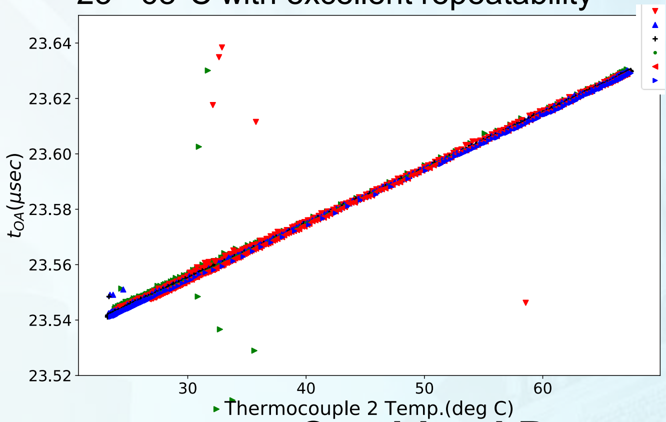
- Three Parameters of Interest
  - Temperature $T\,(t_{R1}, A_{R1}, t_{R2}, A_{R2})$
  - Pressure $P\,(t_{R1}, A_{R1}, t_{R2}, A_{R2})$
  - Fraction Gas Concentration $FGC\,(t_{R1}, A_{R1}, t_{R2}, A_{R2})$

Results and Accomplishments: Temperature/Pressure Sensing

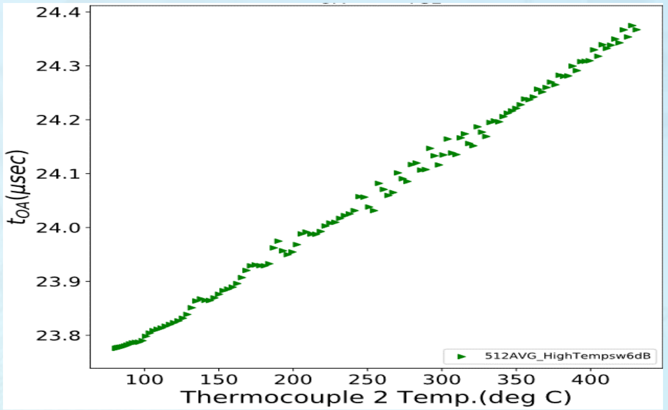
- Temperature measurements
  - Time-of-Flight of R1 response proportional to Temperature
  - Excellent Repeatability for numerous ramps up and down (23 - 68 °C)
  - A single high temperature ramp showed greater variability over 80 - 420 °C
  - Decreased amplitude prevented meaningful measurements above 420 °C
- Pressure measurements demonstrated from 0-200 psig at several temperatures from 60 to 350 °C
  - Progression of Pressure-Temperature
  - Varied pressure at a fixed temperature
  - Data runs were at fixed temperatures of 60, 100, 150, 200, 250, 300, and 350°C
  - Design suitable for testing at significantly higher pressures. Pressure testing conducted up to limit of experimental setup (regulator limit).
- Provisional patent for novel combined temperature and pressure sensing technique (63/322,023)

Temperature Measurements

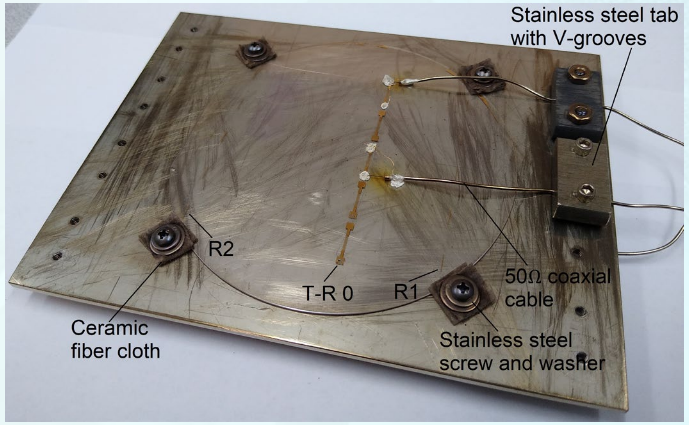
Arrival Time versus Temperature 23 - 68°C with excellent repeatability



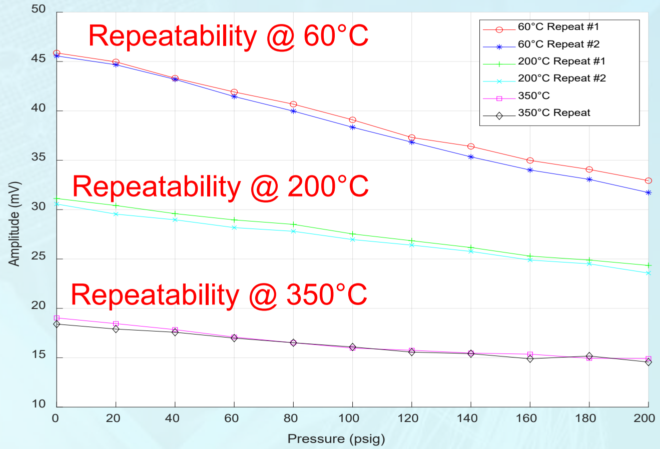
Arrival Time versus Temperature 80 - 420°C



Combined Pressure-Temperature Measurements

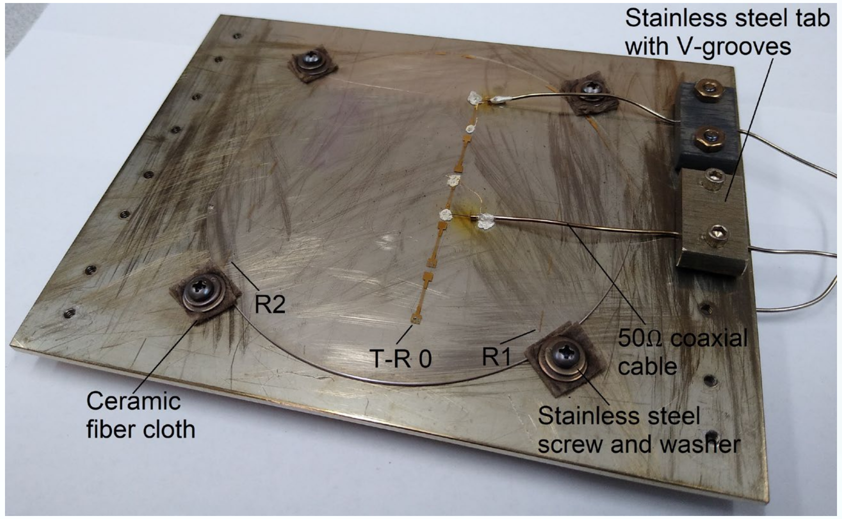


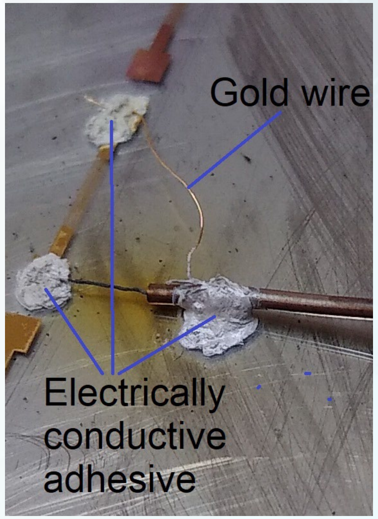
Photograph of preliminary SAW substrate wafer mounted to fixture



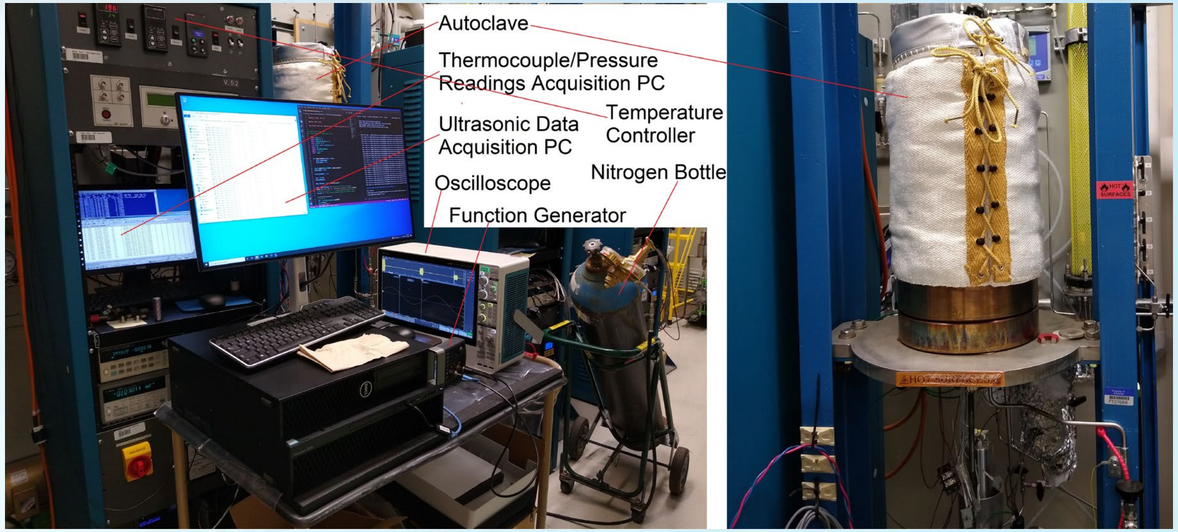
Amplitude vs Pressure for matrix of pressure (0 – 250 psig) and temperatures 60, 200, and 350°C

Results and Accomplishments: Temperature/Pressure Sensing

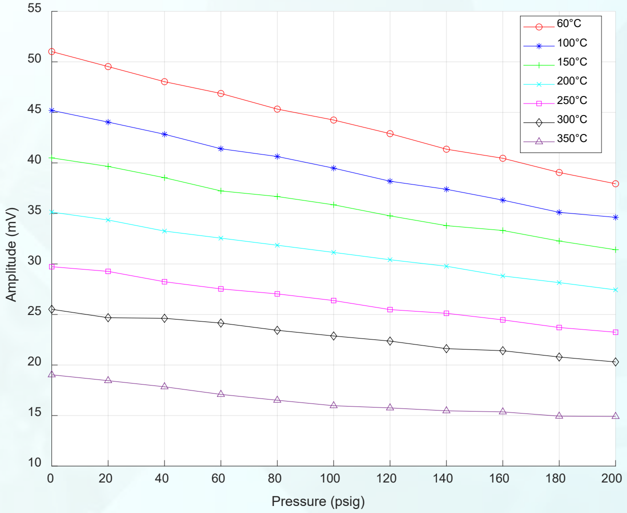




Upper left: wafer with multiple sensors mounted to SS plate
Upper right: Enlargement of T-R 0 illustrating technique for connecting SAW sensor to coaxial cable.

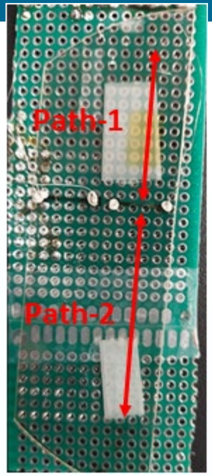


Above: Laboratory autoclave setup for evaluating temperature/pressure sensing capabilities

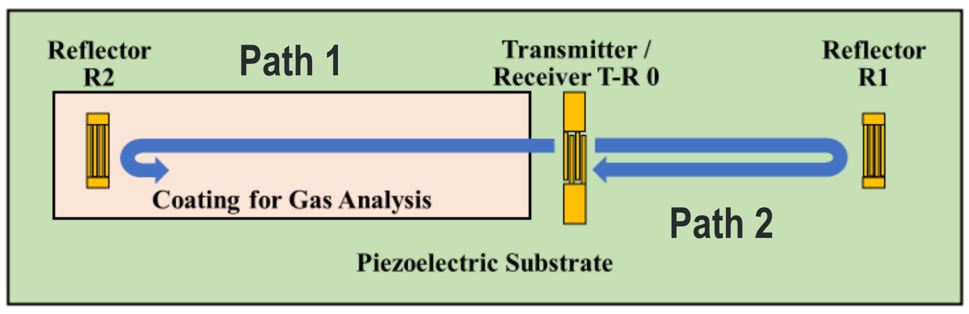


Left: Temperature and pressure test results of the 70 MHz SAW sensor. R1 amplitude versus pressure at a few fixed temperatures.

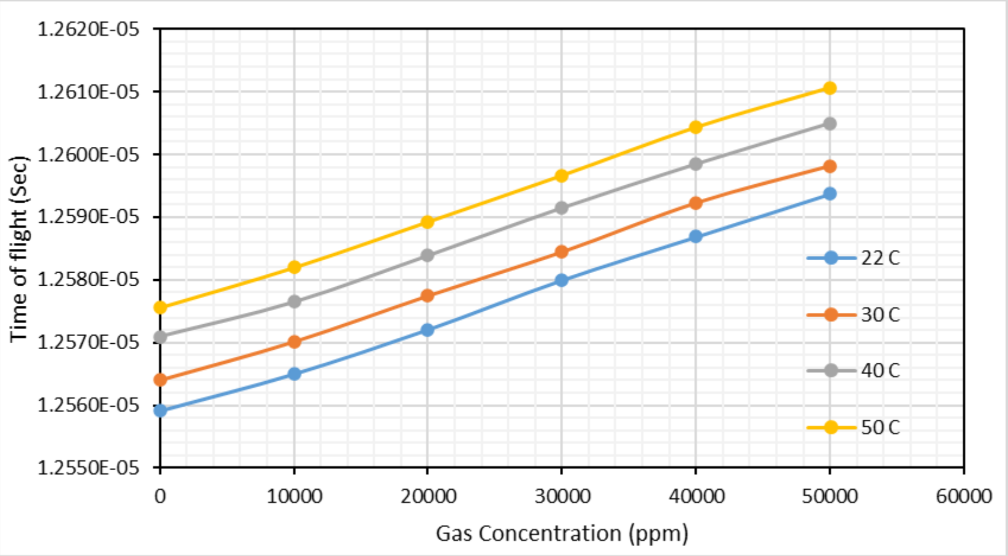
Results and Accomplishments: Gas Concentration Sensing



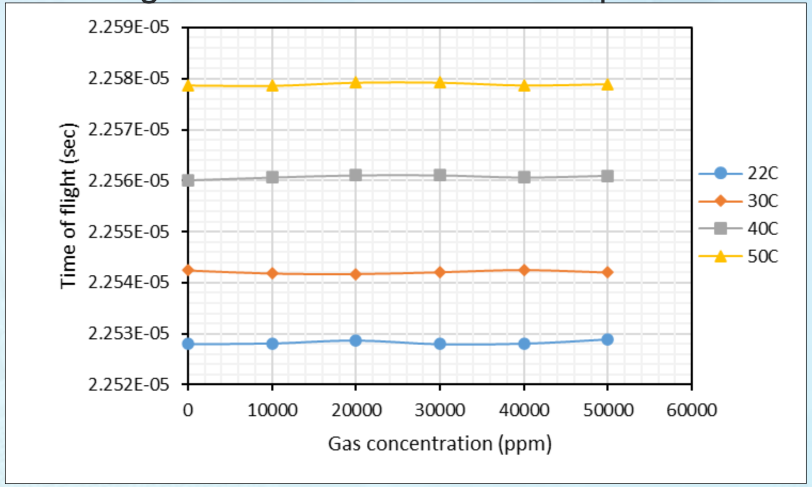
Left: SAW sensor on PCB for gas sensing evaluation
Right: Diagram of sensor layout with coating applied to path-1



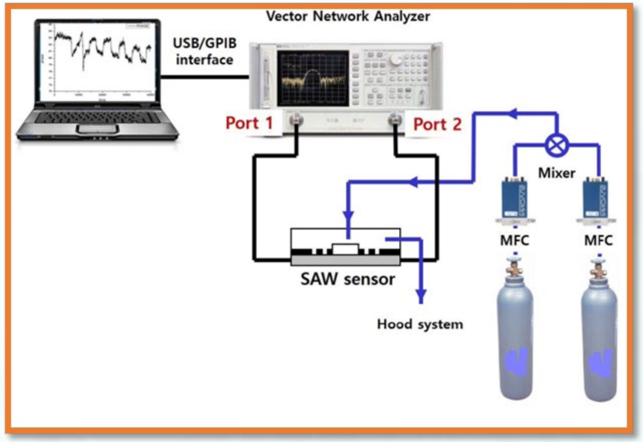
Coated Path-1: The effect of gas concentration and temperature on the TOF



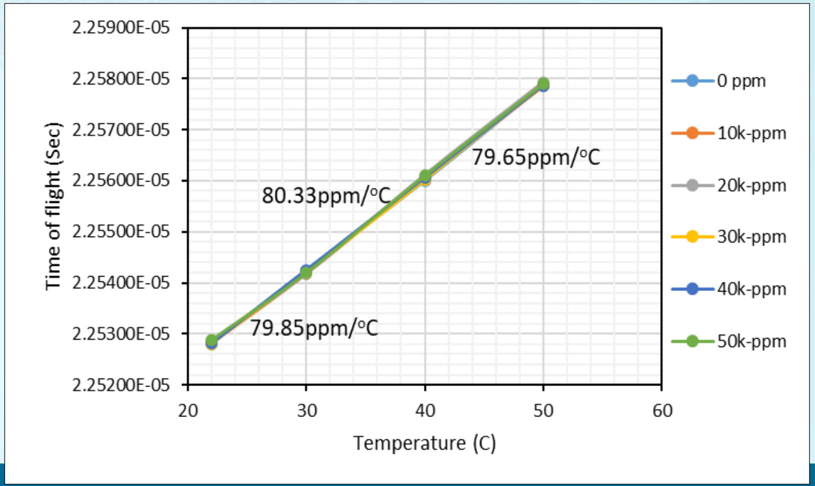
Uncoated Path-2: No effect from gas concentration changes on the TOF at fixed temperatures



Experimental setup for CO2 gas sensing evaluations (VNA used for resonance, oscilloscope for TOF measurements)



Uncoated Path-2: Significant effect on TOF from changes in temperature at fixed gas concentrations

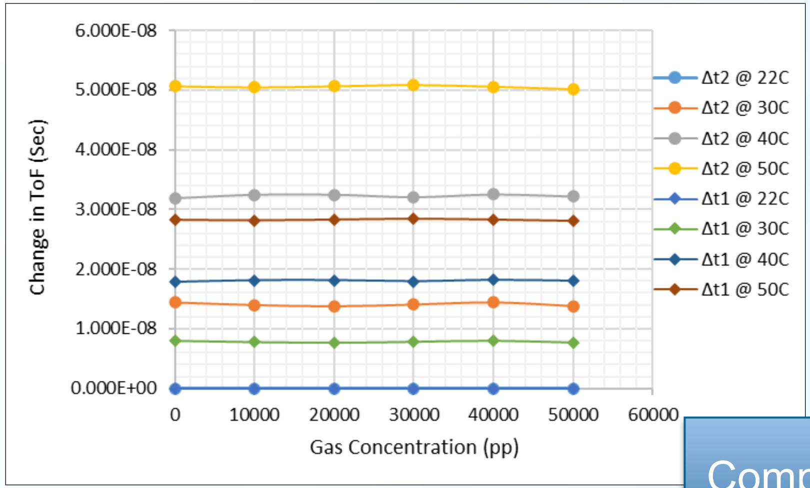


Responses from uncoated Path-2 (affected by temperature) can be used to compensate for temperature effects in Path-1 to isolate gas concentration changes

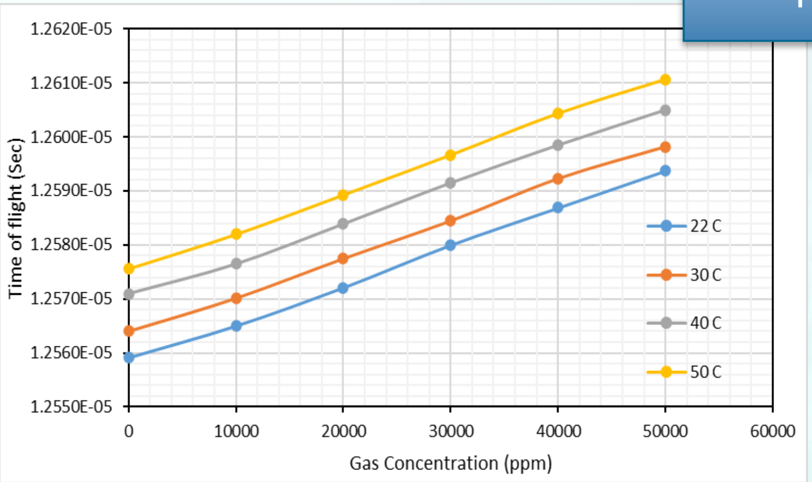
Results and Accomplishments: Gas Concentration Sensing

Temperature compensation using scaling method: Responses from uncoated Path-2 (affected by temperature) were used to extract temperature effects from coated Path-1 in order to isolate gas concentration changes

Temperature effects on TOF for both Path-1 (Δt1) and uncoated Path-2 (Δt2)

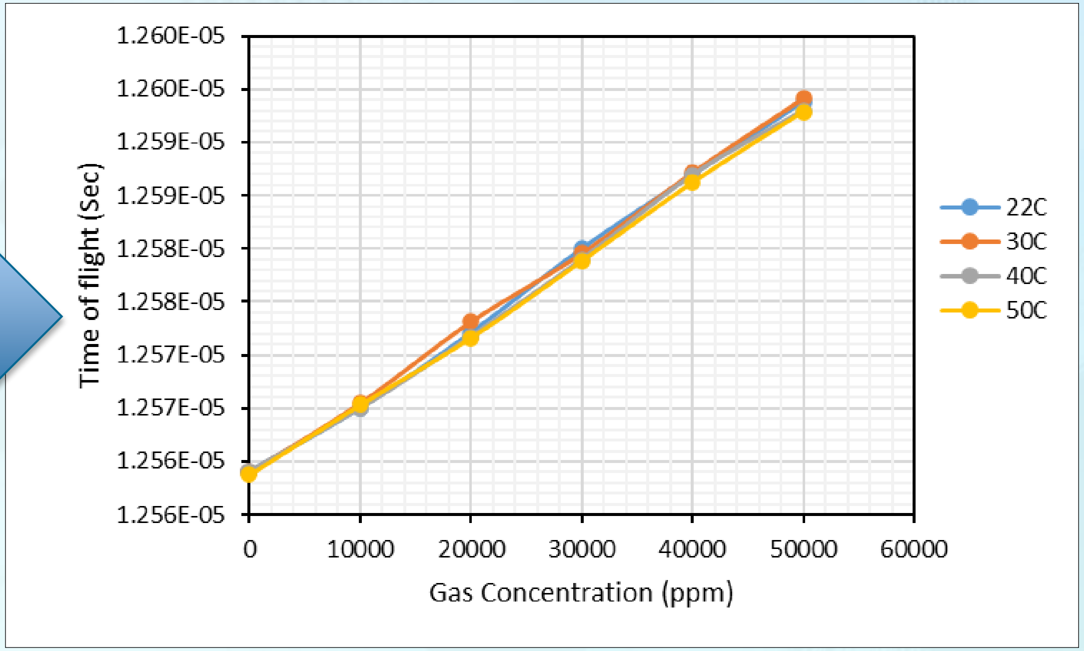


Coated Path-1: The effect of gas concentration and temperature on the TOF



Compensation

Gas concentration vs. TOF using temperature compensation to isolate CO_2 response from temperature effects



Results: Multimodal sensor can measure gas concentration by using temperature compensation

Concluding Remarks

- Technical work has concluded for the scope of this 3-year effort to develop multimodal measurement platform to address sensing gaps for advanced reactor implementation
  - Significant progress has been made toward developing a single-port multimodal sensor for temperature, pressure and gas composition sensing in advanced reactors.
  - Temperature measurements were demonstrated in excess of 400C
  - Simultaneous temperature and pressure measurements were demonstrated up to 350C and 200 PSIG
  - Simultaneous temperature and gas composition measurements with parameter isolation were demonstrated with CO_2 concentrations up to 50k ppm
- One remaining deliverable will be submitted in December in support of last milestone (M2CA-19-WA-PN__-0702-011)
- Provisional U.S. Patent Application 63/322,023 for novel SAW approach for combined temperature and pressure measurements
- Future efforts could focus on further development of this technology and preparing it for field deployment
  - Continued testing to evaluate simultaneous changes in all three parameters of interest
    - Algorithm development for parameter isolation
    - Expand testing to other gasses of interest
  - Prepare for field evaluation/deployment in test reactor environment
    - Higher operating frequency (down-size and repackage sensor)
    - Transition to AIN for radiation tolerance
    - Higher temperature capable interface or wireless

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Thank You