# R2-B.1: Orthogonal Sensors for Trace Detection

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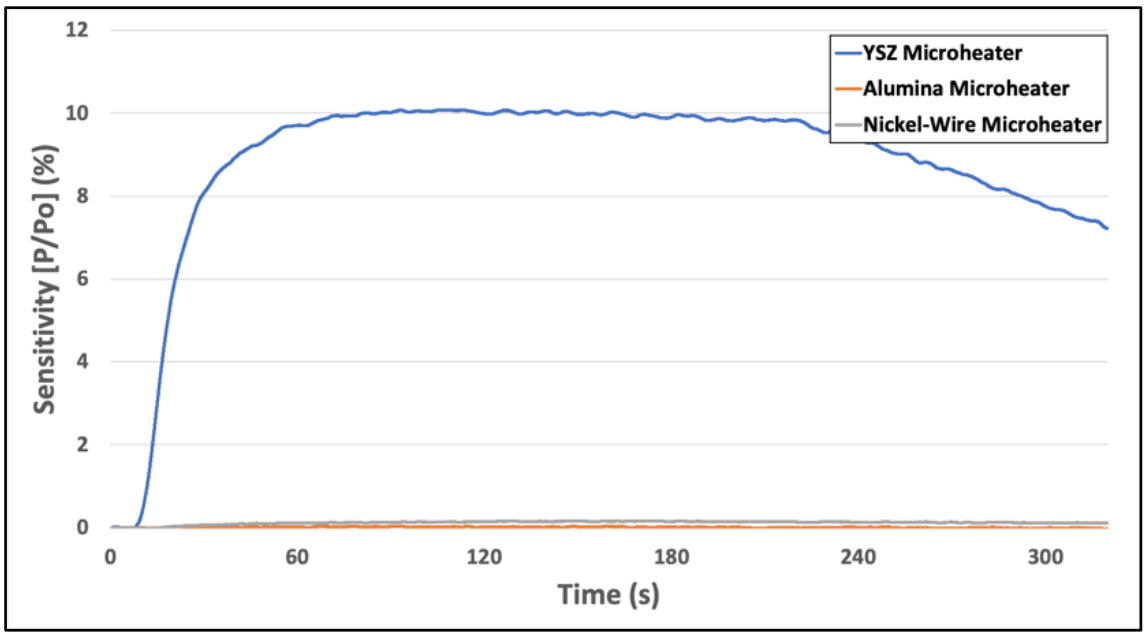
## II. PROJECT DESCRIPTION

### *A. Project Overview*

In Year 7, we have dramatically improved the sensitivity and selectivity of our orthogonal sensors for the trace detection of explosives by using ultrathin yttrium-stabilized zirconia (YSZ) as the substrate for our sensor platform (Figure 1a). Due to its highly anisotropic thermal conductivity, the lateral dissipation of heat is minimized, such that it remains in the vicinity of the catalyst (Figure 1b). As a result, the detection of peroxide-based and nitrogen-based explosives at the part-per-billion (ppb) level is now possible at very low temperatures (75°C–175°C). Prior to using these low-mass YSZ substrates, temperatures >500°C were required to get responses in the ppb range. For example, the detection limits for triacetone triperoxide (TATP) and 2,4-dinitrotoluene (DNT) using the latest sensor platform at 175°C are 78 ppb and 2 ppb, respectively. By systematically reducing the thickness of the YSZ platform from 40 μm to 8 μm, the response time was dramatically reduced and the sensitivity to TATP was dramatically increased (Figure 2). All of this was accomplished without sacrificing the catalytic surface area.

a)

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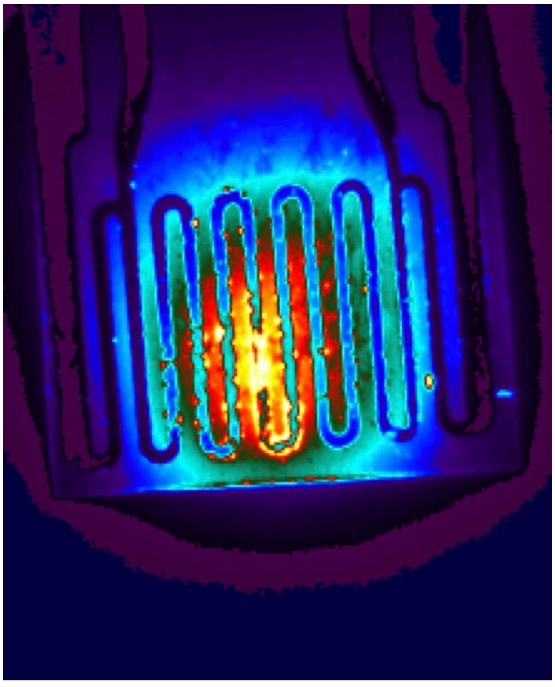

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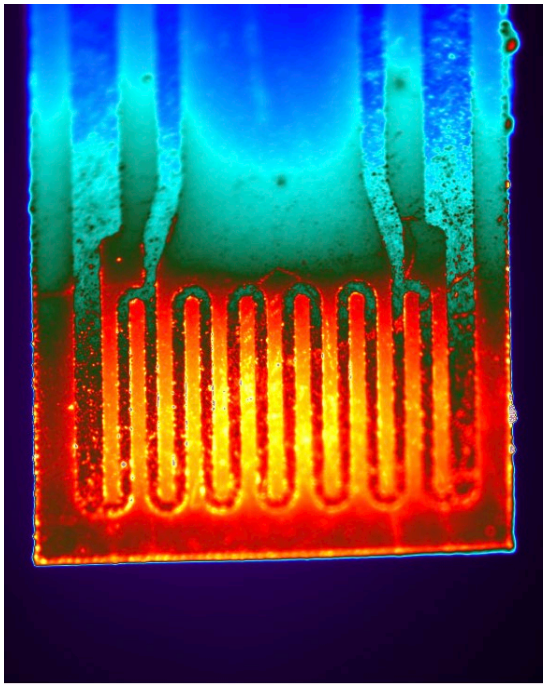


**Figure 1: Response of three different microheater platforms to 20 parts per million TATP at 175°C, employing (a) a tin oxide catalyst, (b) high-resolution infrared images of sensors fabricated on YSZ, and (c) alumina substrates. Note the localized heating in (b) relative to the heating of the entire substrate in (c).**

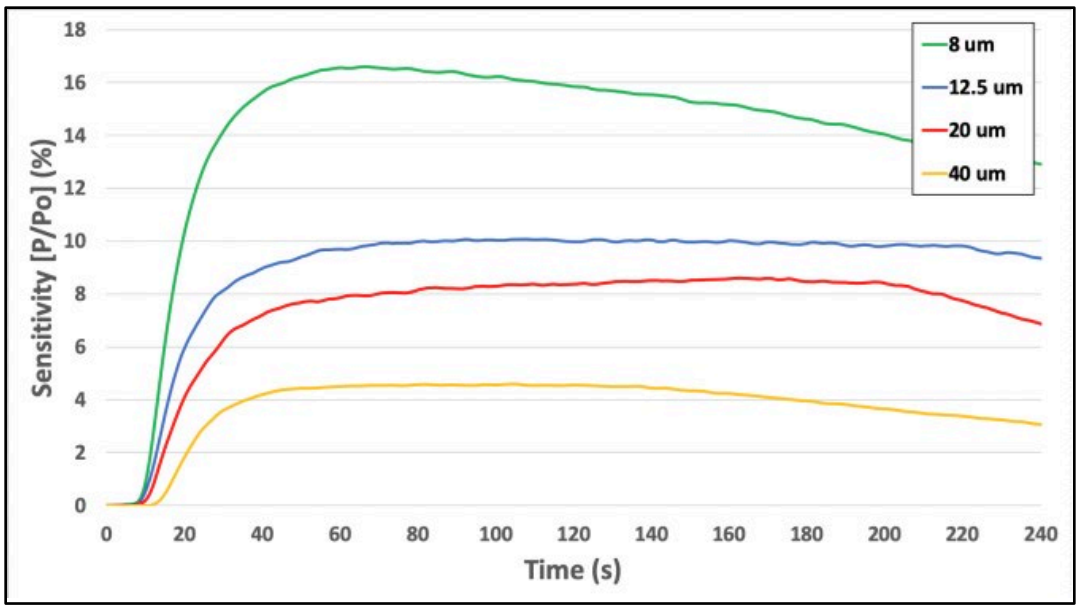



**Figure 2: Responses of four palladium-based microheaters of varying thickness of YSZ substrate to 20 parts per million TATP (T = 175°C).**

Copper and palladium-based (Pd) microheaters were recently fabricated and tested using our sensor platform. An unexpected outcome in so doing was the general catalytic effect associated with Pd microheaters. In previous studies, we showed that Pd nanoparticles dispersed into a tin oxide (SnO) matrix had a dramatic effect on sensor response [1]—by combining the specific catalytic response associated with SnO and the general catalytic effect associated with Pd, we were able to achieve unprecedented responses to a number of energetic materials relative to those responses using copper and nickel microheaters (Figure 3). With these two modifications, a stand-alone explosives trace detection (ETD) system for highly deployable detection that can be used with drones and wearables is now envisioned.

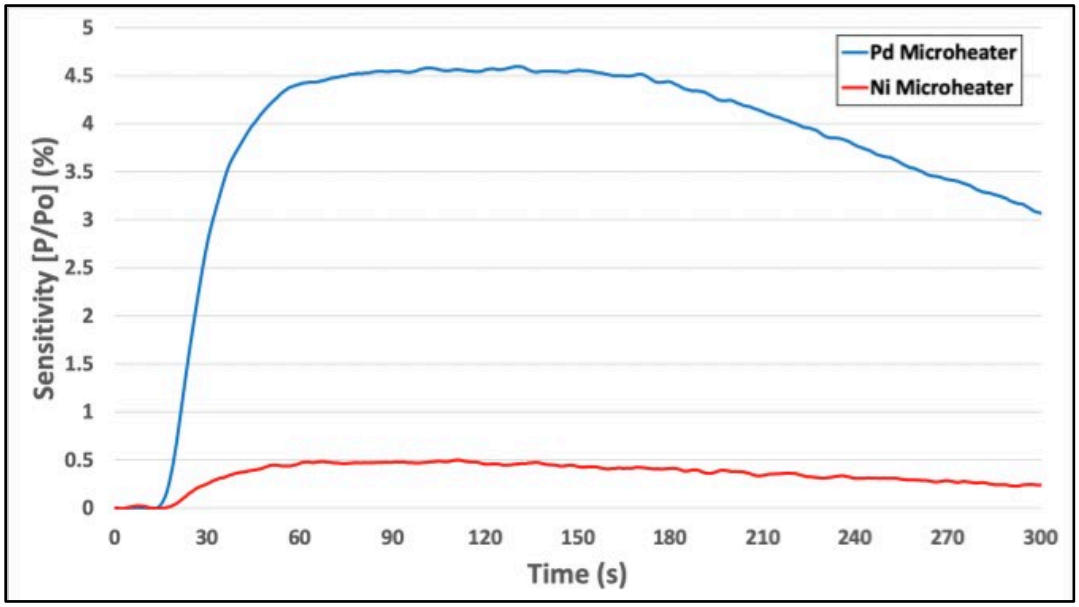



**Figure 3: Responses of two YSZ-based sensors to 20 parts per million TATP. The sensors employed two different microheater metallizations (T = 175°C).**

Due to these recent developments in sensor performance, we began to focus our efforts on sensor arrays. With an array of sensors of this type, a set of "fingerprints" unique to a specific analyte can be generated to further mitigate false positives and negatives. These "fingerprints" rely on endothermic/exothermic reactions that occur between the catalyst and the analyte. To model the functionality of the sensor arrays, Pd-based microheaters were fabricated employing four different catalysts (SnO, CuO, ZnO, and MnO) and were tested against three different analytes to generate unique "fingerprint" signatures. Overall, the SnO catalyst was found to be the most sensitive, with average sensitivity of 15%, and the MnO and CuO catalysts showed better selectivity for all three analytes. We selected hydrogen peroxide as one of the analytes to explore specificity for TATP: for example, a ZnO catalyst showed a uniquely endothermic response to 4 parts per million (ppm) $H_2O_2$, whereas the SnO and CuO catalysts showed exothermic responses (Figure 4a). In addition, an MnO catalyst was responsive to $H_2O_2$ and not TATP, even though acetone and $H_2O_2$ are well-known decomposition products of TATP (Figures 4a and 4b). Based on these results, an array of microheaters employing different catalysts will greatly improve selectivity.

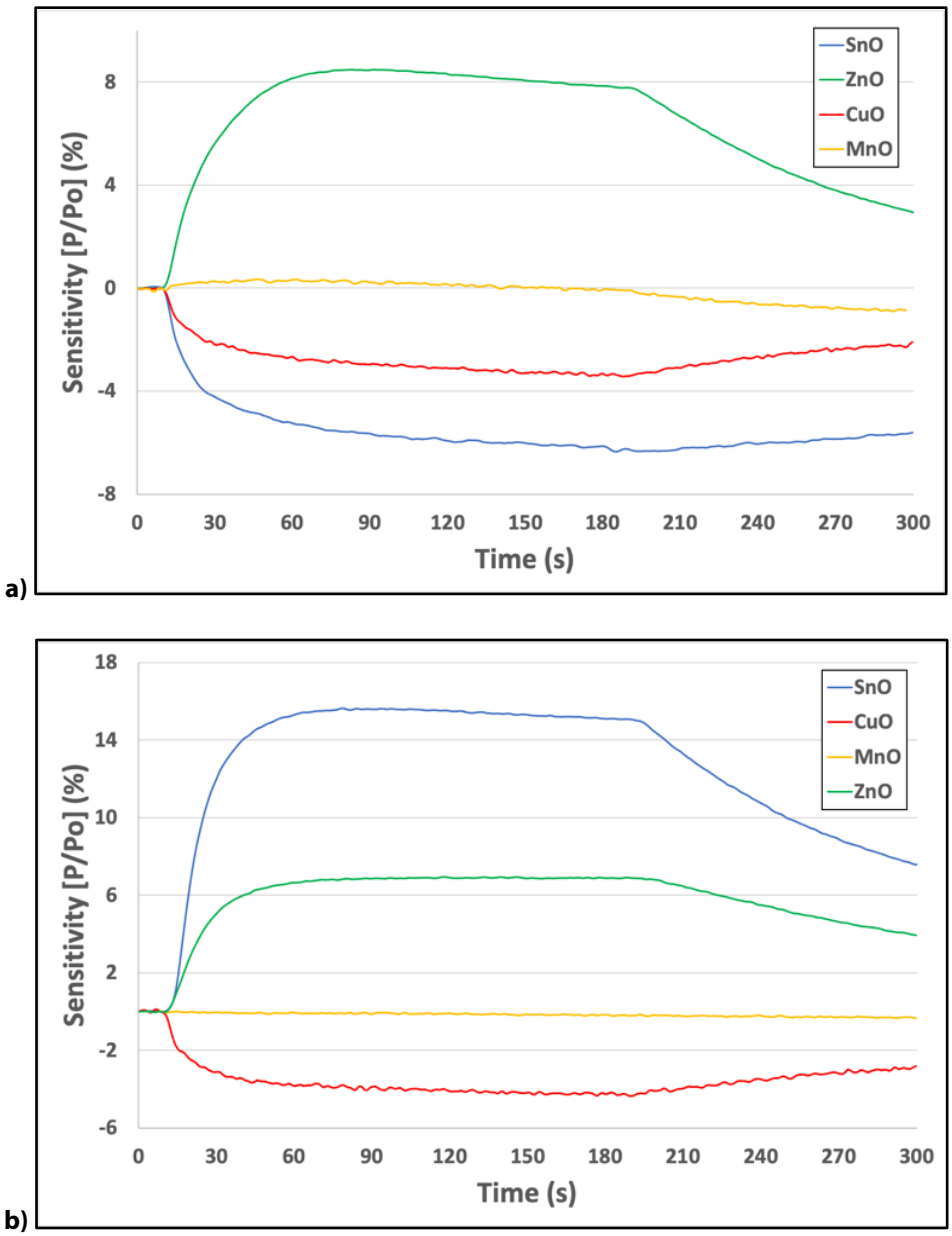
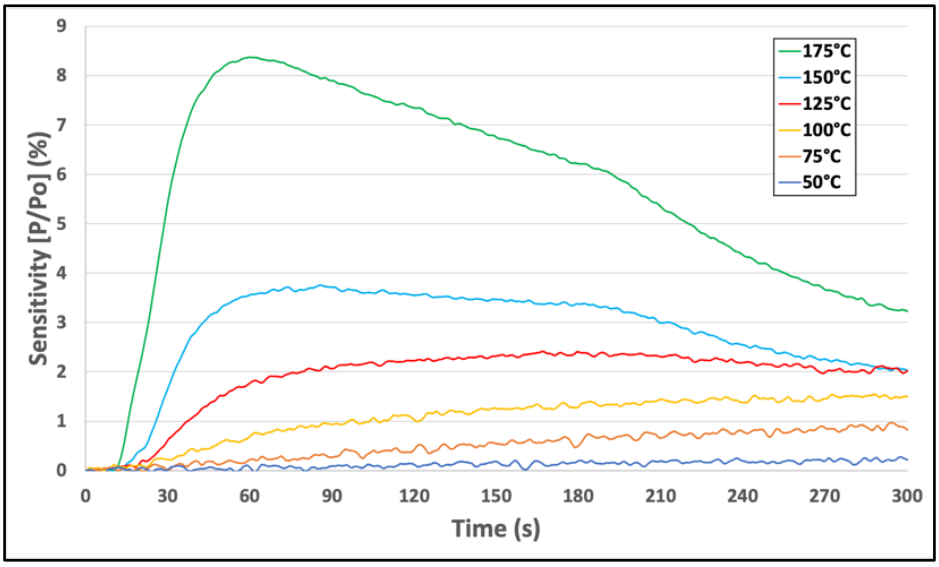



**Figure 4: Responses of four YSZ-based sensors employing different metal oxide catalysts to (a) 4 ppm $H_2O_2$ and (b) 20 ppm TATP (T = 175°C).**

In addition to explosives, we have utilized the "digital dog nose" platform for the trace detection of other compounds, most notably fentanyl. Fentanyl is a synthetic opioid pain reliever that has been shown to be 50 to 100 times more potent than morphine. This opioid is considered a highly controlled substance due to its high risk for addiction as well as severe respiratory distress and even death. Currently, fentanyl and related narcotics are being smuggled into the United States via transportation and mail distribution centers. Thus, there is a need for a portable detection system capable of continuously screening fentanyl and related narcotics in real time. Toward that end, we have focused our efforts on the detection of fentanyl and other extremely low vapor pressure compounds, which are very challenging to detect in the vapor phase. For example, fentanyl has a vapor pressure of only $3.17 \times 10^{-11}$ atm. However, due to the greatly improved sensitivity and response time of our YSZ-based sensors, we believe our digital dog nose platform is well

suited to reliably detect compounds such as fentanyl at these trace levels. Another low vapor pressure threat we have targeted is cyclotrimethylenetrinitramine (RDX), or "plastic explosive", which has a vapor pressure of only $6.16 \times 10^{-12}$ atm. This makes it a perfect simulant for the detection of very dangerous opioids like fentanyl. Figure 5 shows the response of our YSZ-based sensors to RDX (a) at a variety of temperatures and (b) at a variety of concentrations. Due to the much improved sensitivity of our platform, the detection of 6 parts per trillion (ppt) RDX has been achieved at temperatures ranging from 75°C to 175°C with sensitivities of 1%–8% respectively (Figure 5a). This YSZ platform has also allowed the detection limits to be substantially lowered. Figure 5b shows the sensor response to RDX at concentrations ranging from 0.4–6.0 ppt. Based on our ability to detect RDX at remarkably low vapor pressures, we now believe our sensor platform is capable of detecting fentanyl continuously and in real time.

a)

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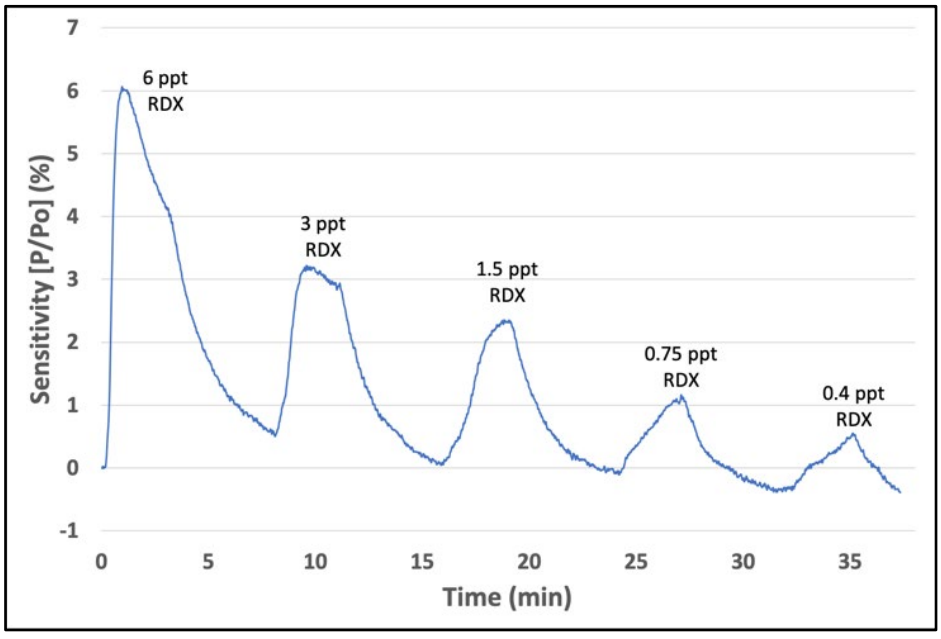


**Figure 5: (a) Response of a YSZ-based sensor to 6 ppt RDX at a variety of operating temperatures and (b) a variety of concentrations (T = 175°C).**

*B. State of the Art and Technical Approach*

The main deliverable for this research project was a portable ETD system, capable of continuously monitoring a wide variety of threat molecules in the vapor phase. Our digital dog nose is passive and noninvasive, and it operates in a manner similar to a dog's nose, where vapor is continuously drawn across sensors in a single pass, after which the vapors are expelled from the system. As the vapor is drawn across the active sensor elements, the energetic molecules are detected using a derivative of microcalorimetry where the heat effect associated with the catalytic decomposition of the energetic molecule is measured. By monitoring the electrical power difference between two microheaters (a catalyst-coated microheater and a "bare" microheater) maintained at a constant temperature, the sensor response is the heat effect associated with catalytic decomposition. In this way, the catalyst-coated microheater senses any sensible heat effects plus any heat effects associated with decomposition of the explosive molecule, whereas the "bare" microheater senses any sensible heat effects and thus is the reference. The difference between the two signals (power difference) is attributed to the energy released during catalytic decomposition.

Our sensing approach also relies on the heat effect associated with oxidation/reduction reactions that occur on the surface of the catalyst, after decomposition of the energetic molecules. This response is much more specific, and when "printed" on ultrathin ceramic substrates, it is much more sensitive and selective to different explosive molecules than other techniques [1-3]. Specifically, we monitor the heat effects associated with catalytic decomposition as well as the oxidation/reduction reactions taking place on the catalyst surface when an energetic molecule decomposes. We have shown previously [1-5] that the decomposition of TATP takes place via catalytic decomposition as opposed to ordinary thermal decomposition, as suggested by Chen and Bannister [6] and Dubnikova et al. [7, 8]. Several analytical methods have been successfully used to detect TATP at trace levels [9-12], but each has their own set of limitations. Many of these analytical techniques use large-scale equipment and require complex operational protocols. Colorimetric sensor arrays [9], for example, have been used to detect TATP at the 2 ppb level, but this method requires swabbing and thus is not amenable for continuous monitoring. One advantage of the colorimetric sensing of TATP, however, is that it is insensitive to humidity. Microeletromechanical-systems–based (MEMS-based) sensors, on the other hand, can meet the requirements for portable detection, and thus, a number of MEMS platforms have been used to detect explosives. MEMS-based sensors include metal oxide semiconductor devices [10], bulk acoustic wave resonators [11], and differential thermal analyzers [12].

*C. Major Contributions*

**Year 1**

1. Incorporated a reference microheater such that differential measurement could be made: using a reference microheater, hydrodynamic effects and sensible heat effects could be subtracted from the catalyst-coated microheater responses, such that the heat effect due to catalytic decomposition alone could be measured.
2. Implemented preconcentrator into the overall detection system to boost sensor response and thus sensitivity.
3. Detected nitrogen-based explosives (ammonium nitrate, 2,6-DNT, etc.) at the trace levels (<1 ppm).

**Year 2**

4. Used Combinatorial sputter deposition of Pd nanoparticles into a SnO catalyst matrix to improve sensor selectivity, sensitivity, and response time.

5. Detected peroxide-based explosives (TATP) and potential decomposition products ($H_2O_2$) at the low ppm level (<5 ppm).

**Year 3**

6. Developed thermally grown metal oxide nanowires as a catalyst support to increase the overall surface area of the metal oxide catalyst.
    - Increased catalyst surface area by four orders of magnitude (100 $\mu m^2$ to 4,000,000 $\mu m^2$).

**Year 4**

7. Implemented 25-μm diameter nickel wires as the microheaters in our sensor platform.
    - Lowered thermal mass of our sensor platform from 190 mg to 48 ug (5,000 times reduction).
    - Decreased overall power requirement (4 W to 1 W).
    - Improved sensor sensitivity.
8. Investigated the effects on sensor performance that humidity has (12%, 50%, 75%, and 100% RH).
9. Developed a nitrogen purge procedure to regenerate metal oxide catalyst after prolonged exposure to humid conditions.
10. Developed a portable digital dog nose sensor system that could be used for field trials.

**Year 5**

11. Undertook a series of seminal experiments to establish the sensing mechanism of our orthogonal sensors for trace detection.
    - Verified that catalytic decomposition precedes subsequent redox reactions between the decomposition products and the metal oxide, resulting in improved sensitivity and selectivity.
12. Improved detection limits of our sensor platform to peroxide-based (TATP) and nitrogen-based (2,4-DNT) explosives.
    - Demonstrated that detection now possible in the hundred ppb level.

**Year 6**

13. Implemented 40 μm yttria-stabilized zirconia (YSZ) as the substrate for our sensor platform.
    - Perfected combination of low thermal mass without sacrificing catalyst surface area.
    - Dramatically lowered detection temperatures from 500°C to 175°C.
    - Decreased power requirements from 2 W to 500 mW.
    - Improved sensor sensitivity by 500 times.
14. Developed portable digital dog nose platform for high throughput sensing.

**Year 7**

15. Implemented yttria-stabilized zirconia (YSZ) substrates 8 μm thick for our sensor platform.
    - Detected at temperatures lower than 175°C.
    - Decreased power requirement from 500 mW to <400 mW.

- Improved sensor sensitivity (ppt detection now a reality).
- Lowered sensor response time to <10 seconds.

16. Developed Pd-based microheaters to improve sensor sensitivity (16% to 30%).
    - Pd provides a catalyst amplifying effect due to its general catalytic properties.
17. Lowered detection limits of our orthogonal sensor platform to <ppb.
18. Developed ultraselective sensor arrays with up to 9 catalyst-coated sensors for "fingerprinting."
19. Detected extremely low vapor pressure compounds such as RDX and fentanyl.

*D. Milestones*

**Milestone 1: Fabrication of Orthogonal Sensors on Ultrathin YSZ Substrates (Q1- 2019)**

- **1.1:** We fabricated thin-film microheaters on ultrathin yttrium-stabilized zirconia (YSZ) substrates with thicknesses ranging from 8 μm to 40 μm. Ultrathin yttrium-stabilized zirconia substrates were supplied by our industry partner ENrG Inc.
    - STATUS: Completed (08/2019) 100%.
- **1.2:** We fabricated Cu and Pd thin-film microheaters on our thermodynamic sensors with thicknesses varying from 0.1 μm to 0.8 μm on ultrathin yttrium-stabilized zirconia substrates supplied by our industry partner ENrG Inc.
    - STATUS: Completed (08/2019) 100%.
- **1.3:** We fabricated orthogonal sensors (conductometric and thermodynamic platforms) on ultrathin YSZ substrates.
    - **1.31:** We completed the fabrication of orthogonal sensors utilizing Cu and Pd microheaters, SnO, CuO, ZnO, and FeO metal oxide catalysts as well as other metal oxides with multiple oxidation states.
        - STATUS: Completed (09/2019) 100%.
    - **1.32:** We optimized heat treatment of catalysts (time at temperature) to maximum sensor response.
        - STATUS: Completed (09/2019) 100%.
    - **1.33:** We fabricated thin-film microheaters and metal oxide catalysts on YSZ substrates having thicknesses ranging from 8 μm to 40 μm.
        - STATUS: Completed (09/2019) 100%.
    - **1.34:** We fabricated very thin (<1 μm) Cu microheaters and electrodes for orthogonal sensors.
        - STATUS: Completed (09/2019) 100%.

**Milestone 2: Demonstration of Orthogonal Sensors Fabricated on Ultrathin YSZ Substrates (Q1-2019/Q2-2019)**

- **2.1:** We tested orthogonal sensors fabricated on ultrathin YSZ substrates against different explosives, including peroxide-based and nitrogen-based explosives (TATP, 2,4 DNT).
- **2.2:** We tested our orthogonal sensors fabricated on YSZ substrates against different opioids/narcotics.

- **2.3:** We achieved faster response times and lower power requirements for orthogonal sensors fabricated on ultrathin YSZ.
- **2.4:** We lowered the detection limits by using sensors fabricated on ultrathin YSZ. Part per trillion detection limits were demonstrated for some explosives.
- STATUS: Completed (2/2020) 100%.

**Milestone 3: Fabrication and Testing of Microheater Arrays with Detection Algorithms (Q2-2019/Q3-2020)**

- **3.1:** We made new CAD drawings of microheater patterns with line widths and line spaces ranging from 10 μm to 50 μm to minimize lateral heat dissipation and keep the catalyst at a uniform temperature.
  - STATUS: Completed (11/2019) 100%.
- **3.2**: We fabricated thin-film microheater arrays utilizing the new microheater designs.
  - STATUS: Completed (3/2020) 100%.
- **3.3:** We evaluated sensor performance utilizing thin-film microheater arrays.
  - **3.31:** We investigated cross talk (heat transfer) from one thin-film microheater to another using infrared imaging techniques: the effect of line width and line space was studied using designs with 50-μm, 25-μm, and 10-μm line width and line space.
  - **3.32:** We fabricated SnO, CuO, and FeO catalysts on the thin-film microheaters arrays.
  - **3.33:** We established sensor metrics, including response time and power, for different microheater arrays and analytes.
  - STATUS: Completed (3/2020) 100%.
- **3.4**: We patterned arrays of microheaters with different catalysts and tested them against explosives and narcotics. **(Q3-2020/Q4-2020)**
  - **3.41:** We fabricated sensor arrays on ultrathin YSZ and used them to detect explosives and narcotics.
  - **3.42:** We developed new interconnect schemes for thin-film microheater arrays to maximize the number of microheaters in a given array.
  - STATUS: Completed (3/2020) 100%.
- **3.5:** We developed algorithms to uniquely identify analytes of interest, minimizing false positives and negatives, and used them to optimize the energy budget and duty cycle.
  - STATUS: Completed (6/2020) 100%.

**Milestone 4: Field Testing Sensor Arrays on Ultrathin YSZ at the Naval Research Lab (Q3-2020)**

- **4.1:** We integrated thin-film microheater arrays into our portable trace detection system.
- **4.2:** We used our portable ETD system with integrated microheater arrays to detect a variety of explosives.
- **4.3:** We did not travel to the Naval Research Laboratory's vapor test bed for confirmation of detection limits and demonstration of sensor response in the presence of select interferents using their proprietary vapor generator; trace levels of analytes w/interferents can be delivered in a highly controlled manner traced to National Institute of Standards and Technology standards.

- STATUS: Did not complete (see below).

**Milestone 5: Integration of Sensor Arrays for Drone and CT Applications Using High Throughput Design (Q4-2020)**

- **5.1**: We finalized the design for high throughput sensing using sensor arrays formed on ultrathin YSZ substrates.
  - STATUS: Completed (12/2019) 100%.
- **5.2:** We fabricated sensors with a modified "pitot tube" design for high throughput sensing.
  - **5.21:** We optimized the size and pattern of vias and microchannels within the ultrathin YSZ substrates for effective sampling of high flow-rate streams.
  - **5.22:** We fabricated micromachined channels and vias within the ultrathin YSZ substrates having thicknesses ranging from 8 μm to 40 μm.
  - STATUS: Completed (1/2020) 100%.
- **5.3:** We demonstrated sensor arrays with modified "pitot tube" design using micromachined channels and vias within the ultrathin YSZ substrates for high throughput sensing.
  - **5.31:** We demonstrated high flow-rate sensing at flow rates up to 100 cubic feet per minute.
  - **5.32:** We evaluated detection limits, response times, false alarm rates, etc. for our high throughput sensor in a CT tunnel environment.
  - STATUS: Completed (5/2020) 100%.
- **5.4**: We packaged sensor arrays using micromachined channels and vias within the ultrathin YSZ substrates used for high throughput sensing.
  - STATUS: Completed (5/2020) 100%.
- **5.5**: We finalized the interconnect schemes for sensor arrays used for high throughput sensing.
  - **5.51:** We demonstrated the ability to detect explosives in the head space of a CT tunnel in real time.
    - STATUS: Completed (4/2020) 100%.
  - Due to the COVID-19 pandemic and the restrictions placed on travel and gathering, testing at the Naval Research Laboratory in Washington, DC planned in Year 7 did not happen. In short, we were not able to field test our ultrathin, low thermal mass sensor arrays at the Naval Research Lab's vapor test bed (Milestone 4). As soon as things are relaxed and we can travel there, we plan to complete the testing of our low thermal mass sensor arrays.

*E. Final Results at Project Completion (Year 7)*

There were many successful results over the life of the project, but those with the biggest impact on DHS and its stakeholders were realized in Year 7. Perhaps the result with the single greatest impact on transition was lowering thermal mass (i.e., moving to extremely low thermal mass substrates for our sensor platform). At the starts of our project we were using relatively thick (1 mm) aluminum oxide substrates for our thermodynamic sensor platform. Over the course of the project we systematically reduced the thermal mass by a factor of 5,000, eventually using YSZ substrates 10 μm thick. This not only improved the sensitivity and response times (30 s to less than 1 s) of our thermodynamic sensor but also greatly improved the selectivity of our sensor.

Other benefits were realized along the way as well. The power requirements were dramatically lowered as the thermal mass was lowered, resulting in more efficient thermal cycling of our sensor, which made truly portable detection systems possible. The ultrathin YSZ substrates with their highly anisotropic thermal properties minimized the lateral dissipation of heat, which in turn enabled us to dramatically lower the operating temperature of the catalyst. As a result, the operating temperature of our sensor was lowered from 500°C to <175°C. Lastly the resolution of the sensor was improved as the thermal mass was reduced, which enabled us to not only identify the threat but also determine quantitatively how much of the threat was present in the vapor.

Another related successful result was lowering the detection limits for all the explosives of interest. Using the ultrathin, low thermal mass YSZ sensors with Pd microheaters, detection limits in the part per trillion range are now possible. At the start of this project, detection limits in the part per million range were not even possible. This means that the resolution for detection was improved by more than four orders of magnitude over the life of the project.

And finally, the third successful result was that very low vapor pressure analytes, such as RDX and fentanyl, could be detected using our orthogonal trace detection system. Simply put, this means that threats that don't really have a vapor pressure can be detected, including threats that are packaged or concealed, which could provide a complementary tool for those screening at airports and postal distribution centers.

## III. RELEVANCE AND TRANSITION

### *A. Relevance of Research to the DHS Enterprise*

- One of the operational homeland security challenges that our orthogonal sensor technology addresses is the detection of explosives in the CT tunnel environment. Our technology can provide inexpensive add-on capability to TSA and others to achieve a redundant or additional screening system to augment some of the shortcomings associated with CT.
- Another operational homeland security challenge that our ETD system addresses is the ability to detect opioids as well as explosives. We have demonstrated that our ETD system can detect fentanyl, which is extremely difficult to detect by other methods. One of the issues mentioned by several DHS stakeholders is that commercial trace detection systems should be able to detect narcotics as well as explosives.

### *B. Status of Transition at Project End*

We have been working with several commercialization partners, funded through the FlexTech Alliance for the past eighteen months, to develop and commercialize a new class of ultrathin, flexible circuits. This will enable high-performance silicon electronics to be directly packaged with a solid-state lithium battery technology on thin-film MEMs-like sensor platform from University of Rhode Island (URI). In short, the team received a $2.8 million award in September 2018 to develop a sensor platform for drone applications whereby monolithic sensors are integrated with thin-film batteries to produce a sensor system with integrated processing. This will enable the integration of a power module, sensor, signal processing, and telemetry electronics into a package with total thickness <250 μm. Such packaging will enable our sensors to be used in small drones, wearables, and other volume/weight-sensitive detection platforms. Furthermore, with only small changes to the catalyst, we will be able to detect a number of analytes, including toxics and narcotics, and provide an enabling technology to the military and first responders.

By using ultrathin YSZ as the substrate for our sensor platform, unparalleled sensitivity and selectivity for the detection of energetic materials was achieved. In addition, a significant reduction in the power required

to operate the sensor was achieved, which makes onboard portable applications such as drones or wearables possible. Table 1 shows a comparison of sensor microheaters utilizing different YSZ substrate thicknesses. Microheaters fabricated on 8 µm YSZ required the least power (215 mW) while Pd microheaters on 8 µm YSZ required the lowest overall energy (0.78 J). Due to the similar power requirements for the Cu (215 mW) and Pd (260 mW) microheaters, the Pd microheaters were chosen for packaging due to the catalyst amplification effect associated with Pd (16.2% versus 5.2%).

| | Power Requirement (mW) | Sensitivity‡ (%) | Response Time* (s) | Energy (J) |
|---|---|---|---|---|
| **Cu (40 µm YSZ) †** | 320 | **0.5** | **10** | 3.2 |
| **Cu (20 µm YSZ) †** | 300 | 2.75 | 9 | 2.7 |
| **Cu (12.5 µm YSZ) †** | 245 | 3.2 | 8.5 | 2.08 |
| **Cu (8 µm YSZ) †** | **215** | 5.2 | 6 | 1.29 |
| **Pd (40 µm YSZ) †** | **370** | 4.5 | 8.75 | **3.24** |
| **Pd (20 µm YSZ) †** | 330 | 8.5 | 5 | 1.65 |
| **Pd (12.5 µm YSZ) †** | 280 | 10 | 4.5 | 1.26 |
| **Pd (8 µm YSZ) †** | 260 | **16.2** | **3** | **0.78** |

* Response time was arbitrarily determined to be the t10 time or time required to reach 10% of the overall response
† All microheaters fabricated with 0.5µm metallization thickness
‡ All microheaters employed a 0.9µm thick SnO catalyst

**Table 1: Copper- and palladium-based sensors fabricated on YSZ substrates of varying thickness.**

Our sensor platform employs a proprietary Anderson Loop circuit to maintain the desired operating temperature as well as measure the resulting heat effects due to catalytic decomposition. Unfortunately, the Anderson Loop circuit requires significantly higher power levels than those required for drones and wearables, and thus an alternative circuit (ALA) was designed. A breadboard design for the ALA was completed and coupled with a microheater that was directly bonded to the surface of a battery made by ITN Energy Systems, as shown in Figure 6. Continued development efforts led to a new ALA circuit, based on a printed circuit board (PCB), with lower noise and power requirements (Figure 7). The new ALA circuit showed ~20 mW of noise compared to the ~80 mW observed from the previous iterations.

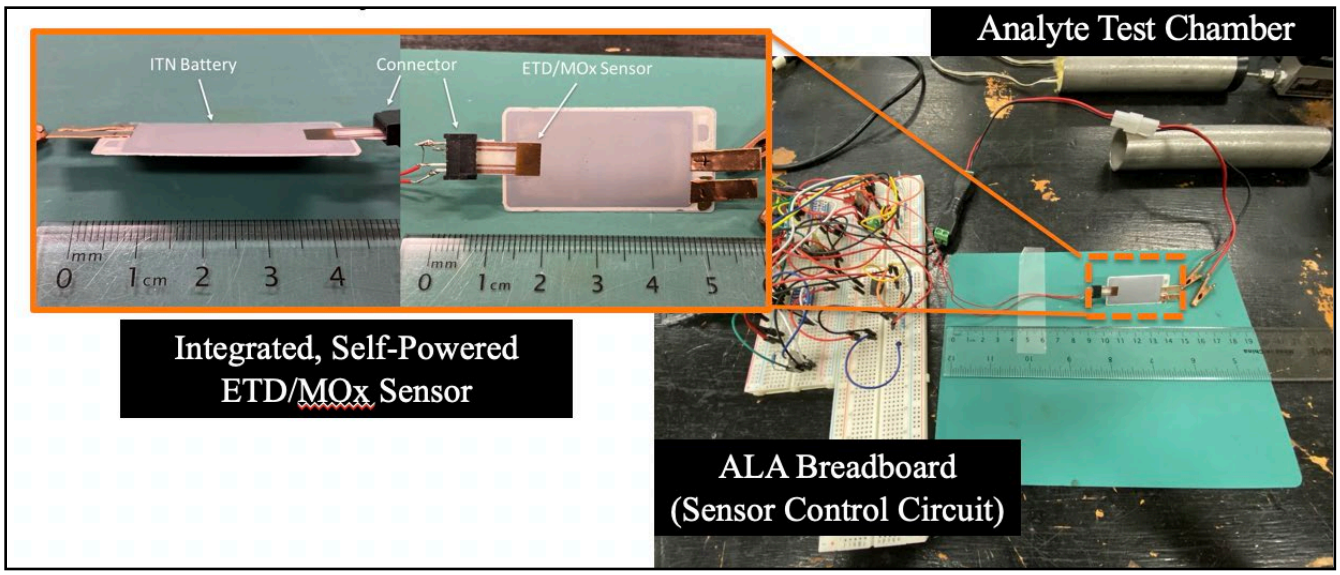


**Figure 6: Self-powered sensor, where the URI's ETD was directly bonded to the surface of the ITN battery.**

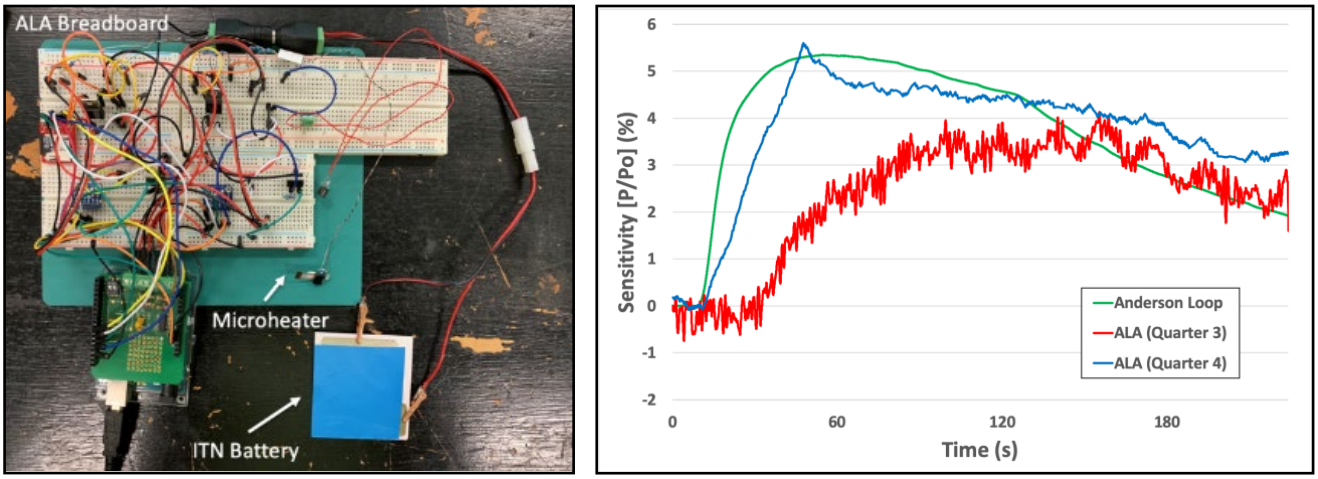


**Figure 7: (left) ALA breadboard circuit powered by an ITN battery and (right) comparison of ALA circuit response and noise floor with the power-hungry Anderson Loop (SnO catalyst).**

Given the improvements in sensitivity and response time when using Pd microheaters, a comparison between the performance of YSZ-based sensors using the original power-hungry Anderson Loop and the new ALA circuit was assessed. Figure 8 shows the ALA circuit has similar performance and lower power compared to the Anderson Loop.

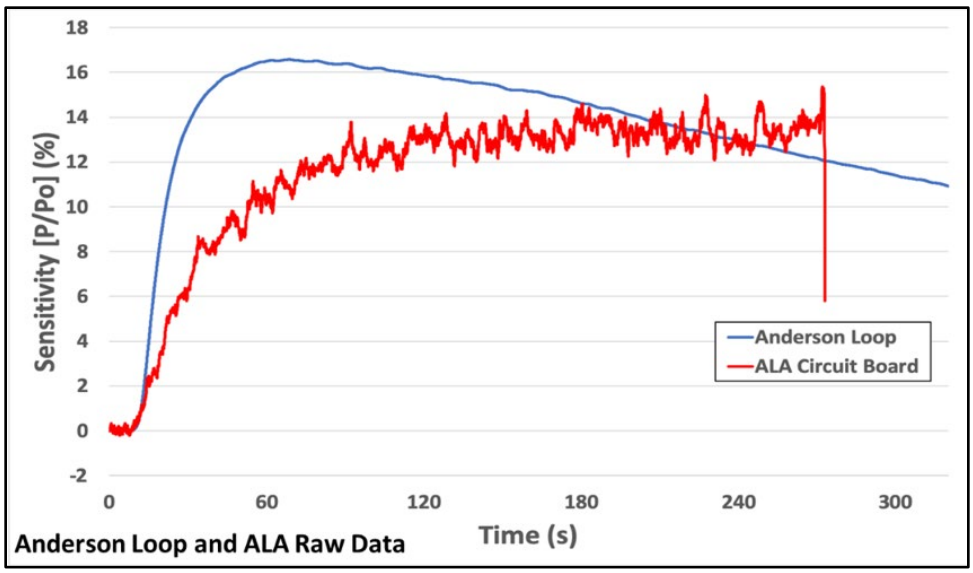


**Figure 8: Comparison of the responses of a Pd microheater with a SnO catalyst fabricated on a YSZ substrate to 20 ppm TATP powered by the Anderson Loop (blue) and an ALA circuit (red).**

### *C. Transition Pathway and Future Opportunities*

There is considerable potential for transition using our orthogonal sensors for the trace detection of explosives (and narcotics) in future screening systems. This includes mounting our sensors onto the surface of an unmanned aerial vehicle wing with a low vertical profile (low drag) or wearable sensors for firefighters and first responders. The detection of explosives, toxics, and narcotics are the targets for these applications. In other applications, such as the CT tunnel environment, screening the head space around baggage for explosives and narcotics in the time it takes to X-ray baggage is now possible with the high flow-rate version of our sensor. We have been working with several commercialization partners, funded through the FlexTech Alliance, to develop and commercialize a thin-film, MEMs-like version of our orthogonal sensor. Our partners are helping us develop thin-film arrays of chemical sensors that can detect a broad spectrum of compounds in real time as part of an early detection warning system. This "smart skin" sensing platform will employ multiple thin-film microheaters fabricated on ultrathin YSZ substrates. Each microheater will be coated with a different catalyst to form "active" sensor elements, and one will remain uncoated and serve as a reference. In this way, a broad spectrum of threat molecules can be detected in real time.

### *D. Customer Connections*

| Name | Title | Institution | Email | Phone |
|---|---|---|---|---|
| Mark Fischer | Senior Scientist (Explosives) | FLIR | Mark.Fischer@FLIR.com | 401-372-9535 x 11615 |
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| Brian Berland | Chief Science Officer | ITN Energy Systems | Bberland@itnes.com | 303-285-5107 |
| Alan Davis | Research Professor | NUWC/University of Rhode Island | davis@ele.uri.edu | 401-874-5482 |

## IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

### A. *Peer Reviewed Journal Articles*

1. Ricci, P.P., Rossi, A.S., & Gregory, O.J. "Orthogonal Sensors for the Trace Detection of Explosives." *IEEE Sensors Letters, 3*(10), October 2019, pp. 1–4. https://doi.org/10.1109/LSENS.2019.2944587.
2. Ricci, P.P., & Gregory, O.J. "Continuous Monitoring of Vapor Phase Threats Using Ultrasensitive, Low-Power Sensors." *IEEE Sensors Journal*, in press.

### B. *Peer Reviewed Conference Proceedings*

1. Ricci, P.P., & Gregory, O.J. "Trace Detection of Explosives Using Metal Oxide Nanostructured Catalysts." *TechConnect 2019*, Boston, MA, June 2019.
2. Gregory, O.J., Olenick, J., & Olenick, K. "Ribbon Ceramic: Novel Form Factor Enabling Thermal Product Applications." *NATAS 2019*, Newport, RI, August 2019.
3. Ricci, P.P., & Gregory, O.J. "Ultrasensitive, Thin-Film Sensors for the Trace Detection of Explosives." *NATAS 2019*, Newport, RI, August 2019.
4. Ricci, P.P., & Gregory, O.J. "Low-Power Sensors for the Trace Detection of Threats in the Vapor Phase." *FLEX 2020*, San Jose, CA, February 2020.
5. Ricci, P.P., & Gregory, O.J. "Ultrasensitive, Orthogonal Sensors for the Trace Detection of Explosives." *ISADE 2020*, Charlotte, NC, April 2020.

### C. *Other Presentations*

1. Interviews and/or News Articles:
   a. Hampton, M. "Wanted: A Bomb Detector as Sensitive as a Dog's Nose." *IEEE Spectrum*, 11 October 2019. https://spectrum.ieee.org/tech-talk/semiconductors/devices/using-a-twopronged-approach-to-detect-explosive-substances-from-bombs.
   b. CBS News. "'Innovation Checkpoint' and 'Digital Dog Nose': TSA Tests New Security Technology." 25 November 2019. https://www.cbsnews.com/news/tsa-testing-advanced-airport-security-technology-digital-dog-nose-innovation-checkpoint/.
   c. CBS Boston. "URI Researchers Test New TSA Tech 'Digital Dog Nose,' Gel to Flash-Freeze Explosives." 25 November 2019. https://boston.cbslocal.com/2019/11/25/university-of-rhode-island-uri-tsa-tech-digital-dog-nose/.
   d. Larson, B. "High Tech: TSA Testing A 'Digital Dog Nose.'" Fox News, 27 November 2019. https://video.foxnews.com/v/6109645048001#sp=show-clips.
   e. Liberatore, S. "TSA Is Testing New 3D Rotating Scanning Technology to See Through Your Baggage and 'Digital Dog Noses' to Detect Explosives at Airport Security in an Effort to Speed Up Lines." *Daily Mail*, 25 November 2019. https://www.dailymail.co.uk/sciencetech/article-7724599/TSA-testing-new-technology-cut-wait-time-check-in.html.

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