Company Profile

- URL: www.multicore-photonics.com
  Industry: Industrial Sensing → Transportation → Automotive
  Employees: 6 (3 founders)
  Founded 2015
  IP: 1 Licensed | 5 Filed

Contact Information

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NSF Sponsored Research: Fiber Optic Based NOx Sensor

01. Agenda

- Who we are and what we do
- Current NOx sensor state of the art
- Background on how a different kind of chemical sensor was conceived
- One slide summary of NSF Phase 1
- Two slides covering NSF Phase 2
- Summary

02. Our Team

Darren Engle
CEO

Jody Wilson
COO

Christian Adams
SVP of Science & Technology, (Principal Investigator, NSF SBIR)

Dr. Kenneth Thompson
Director of Data Science (Principal Investigator, Air Force SBIR)

Patrick Clark
Director of Product Development

Zachary Wilson
Technician

Advisors & Investors

Dr. Axel Schulzgen
Technical Advisor

Dr. Rodrigo Correa
Technical Advisor

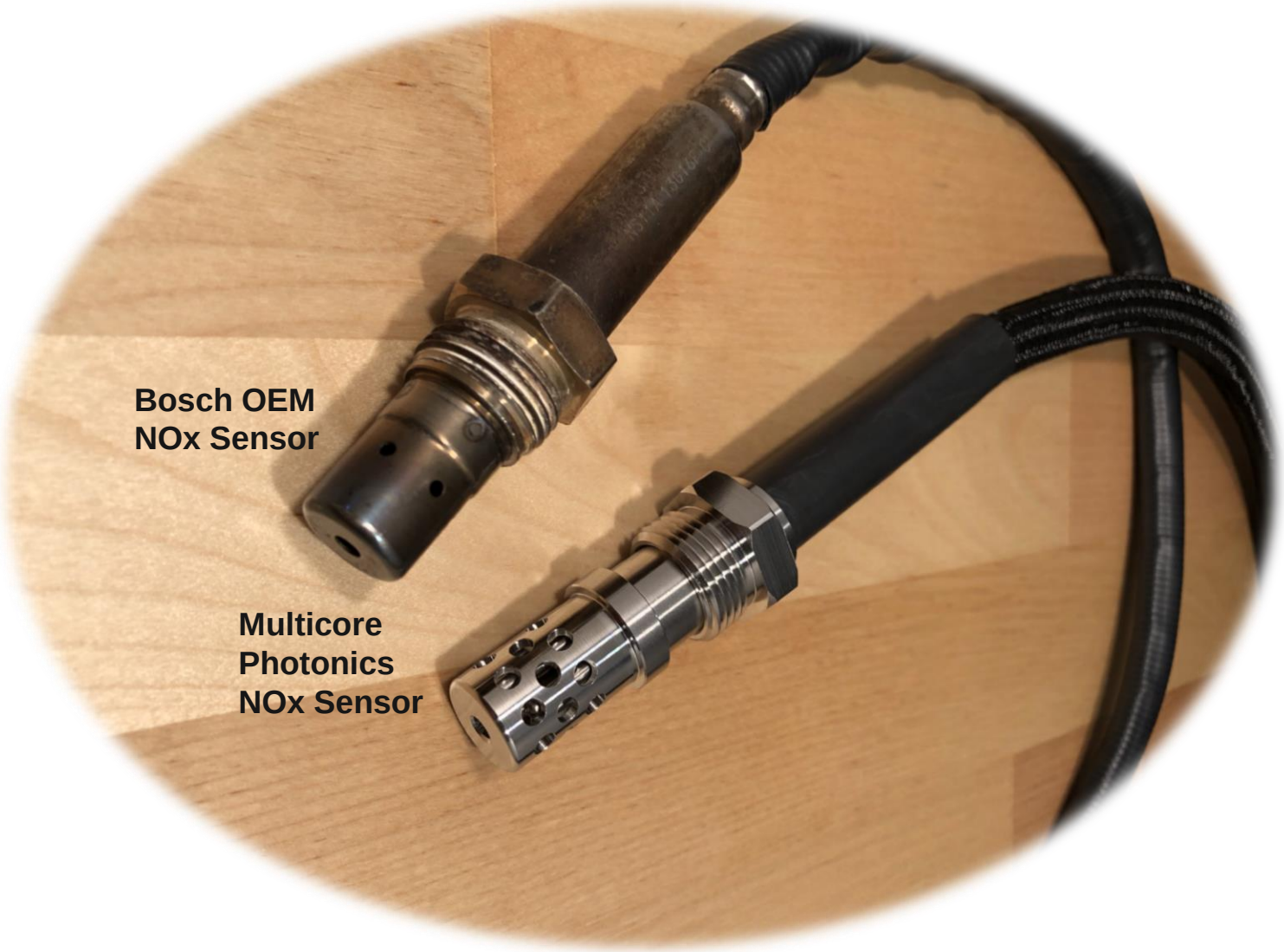
Florida Institute
Investor

Hardin Bethea
Advisor

03. Sensor Principles Review

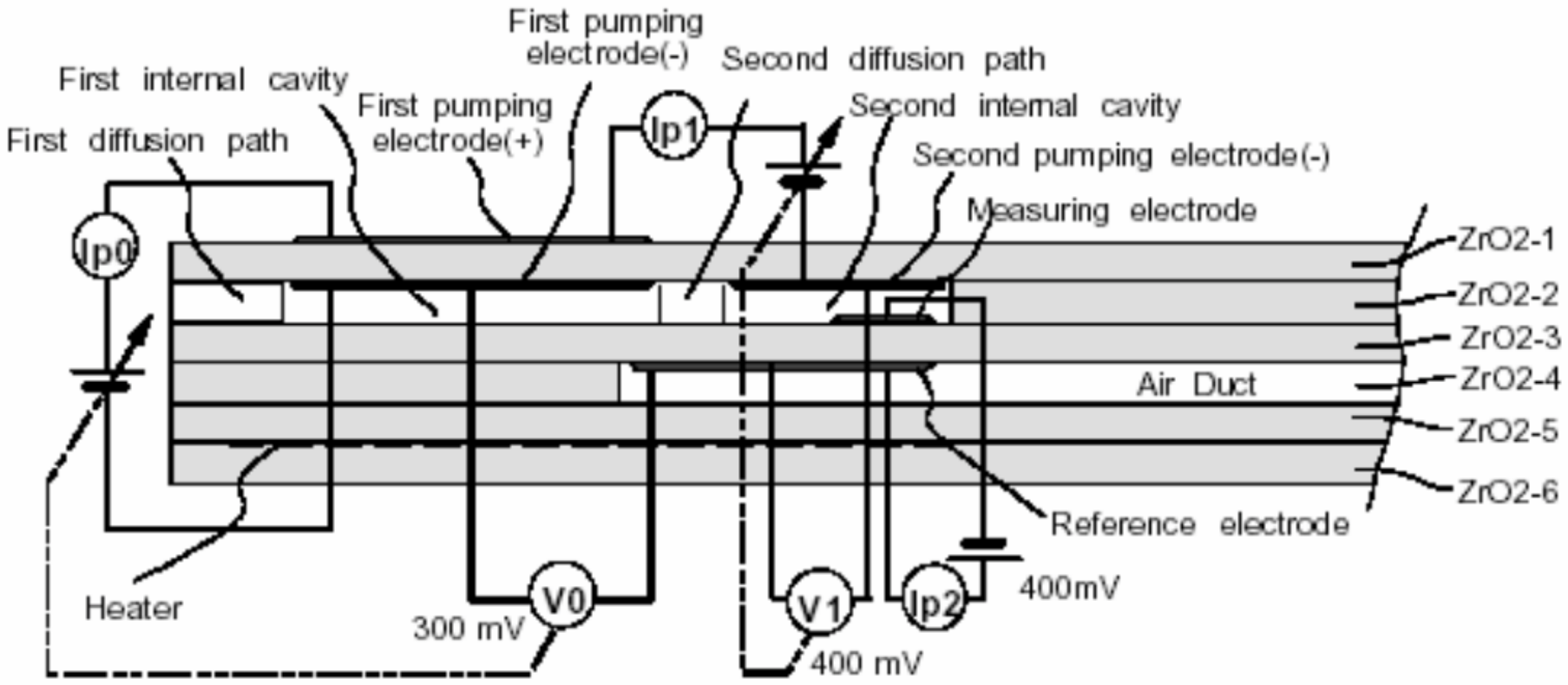
It’s critical to understand what’s involved with the oxygen sensor derivatives in detecting NOx

- **The following slides summarize what is out there now, and how we are different (<2 min)**



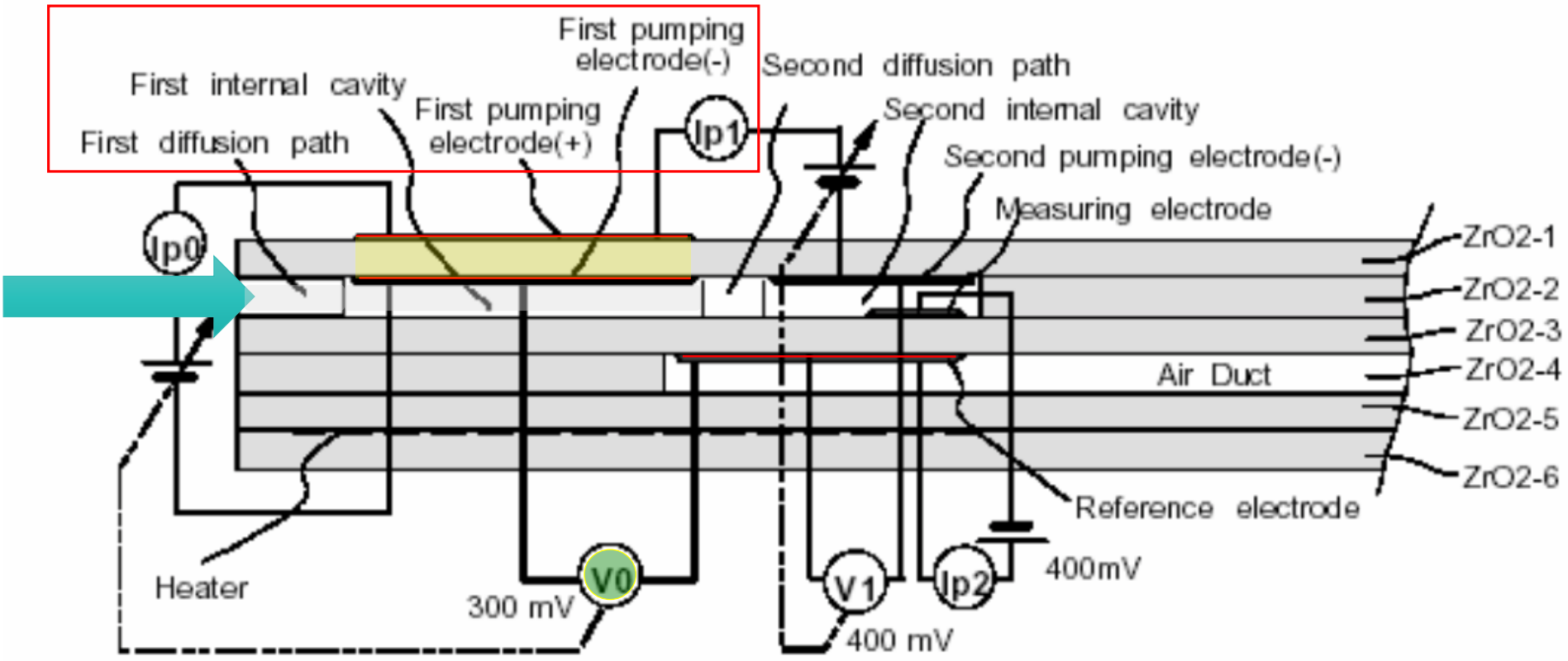
04. Sensor Principles Review

A clever way to leverage thick film processing that includes platinum, gold, rhodium, and copper metallization techniques:



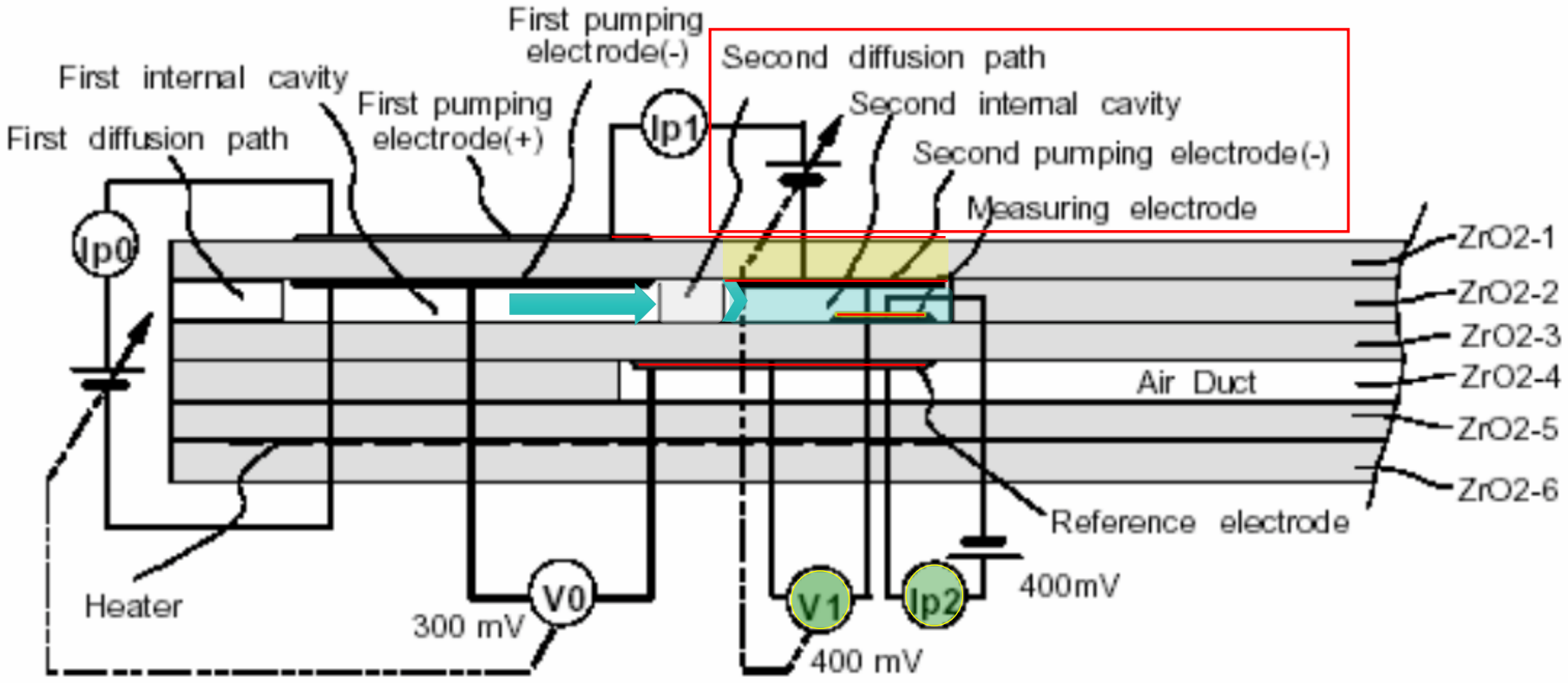
Goal of this portion of presentation is to step through the current process in detail.
Know thy competition.

Step 1: Gas Into 1st Cavity



Once the exhaust gas has entered into the first internal cavity, pumping electrodes reduce the O_2 concentration in that cavity to a given set-point.
The measured concentration in the Air Duct provides a set-point voltage reference.

Step 2: Gas Into 2nd Cavity



Since the second cavity O_2 content is **known** with the help of the reference signal in the air duct, exhaust NO_x that is reduced on the Rh measuring electrode adds additional O_2 to the 2nd cavity as O_2 is the reduction product of NO_x. So now [NO_x] can now be inferred.

07. Background & Conception of Multicore NOx Sensor

Based on the Issues with Current NOx Sensor Technology, a Solution was Generated:

Previously: Set Up a Corporate *Hardware Anti-Tamper* Laboratory Center of Excellence

- 10 years **identifying repeatable physical and electronic "fingerprints" or patterns** from platform subcomponents that could be combined to create inviolable electronic signatures, among other cryptograph generation activities
- Besides generating 12 patents, this experience resulted a unique way of looking at the world that later lead to sensor designs not based on conventional approaches, yet still utilizing existing physical principles and accepted metrology.

Multicore IP: Map Physical Phenomena "Outputs" as n-Dimensional Fingerprints

- Our patented sensor layout is comprised of **sub-sensors**, where each sub-sensor ***may*** respond in a slightly different but still repeatable manner across a set of **known** multi-dimensional inputs.
- The key (***literally***) lies in the device calibration with an n-dimensional database lookup table (LUT), a set of equations, or both; this sufficiently maps the output of sub-sensors monitoring a given environmental calibration space (i.e. exhaust).
- The calibration map must be of sufficient fidelity that it forms the outline of a "response surface" where interpolation between measured points can be done with confidence. Separate and distinct calibrations ***can*** exist on same device.
- Non-sub-sensor (i.e. external) inputs ***can*** be included in LUT as long as they are reliable, and *repeatably coincident*.

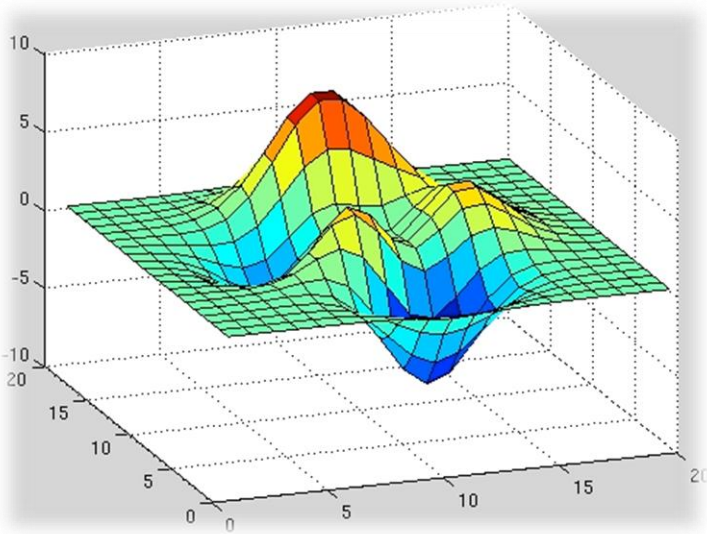
Agnostic to Sensor Type

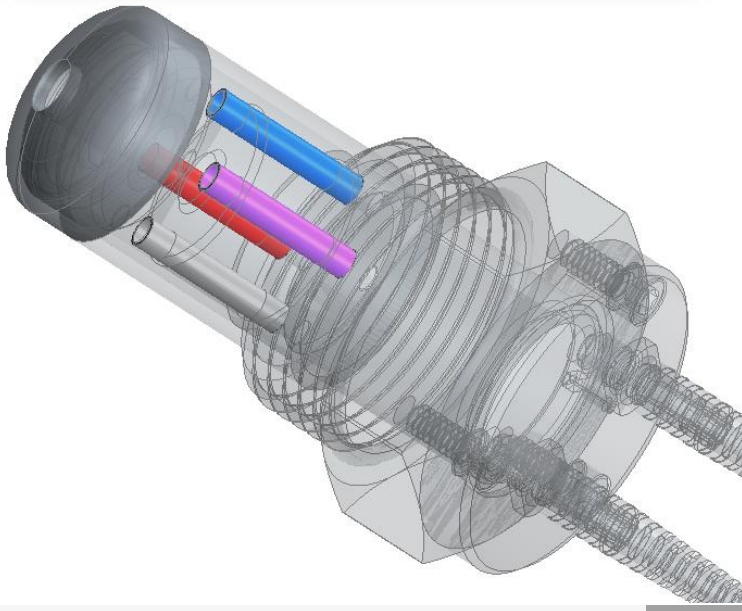
- The measurement technology employed among the sub-sensor array is ***not*** relevant. Besides thermo-catalytic activity (see following slides), spectroscopic information can be measured using multiple photo-detectors that measure the respective intensities of a matching number of slightly overlapping wavelength excitation bands; this can also generate the required "fingerprint" to identify the makeup of many fluid streams – gas or liquid. The possibilities are endless!

08. New Sensor Concept

Clean-sheet Design:

- **Multiple catalysts sensitive to multiple exhaust gas components**
  - Besides an inert reference, design has multiple and different catalyst coated sensors
  - Virtually instantaneous thermal response to CO, NOx, NH_3, & unburned HC
  - The different catalysts generate varying responses according to temperature trends and changes in gas composition
  - When individual thermocatalytic responses are mapped a very specific and repeatable calibration **hyper-surface** emerges
- **Initial design completely passive**
  - Greatly reduces complexity of design
  - Allows for fiber-optic measurement of ΔT
  - No power required





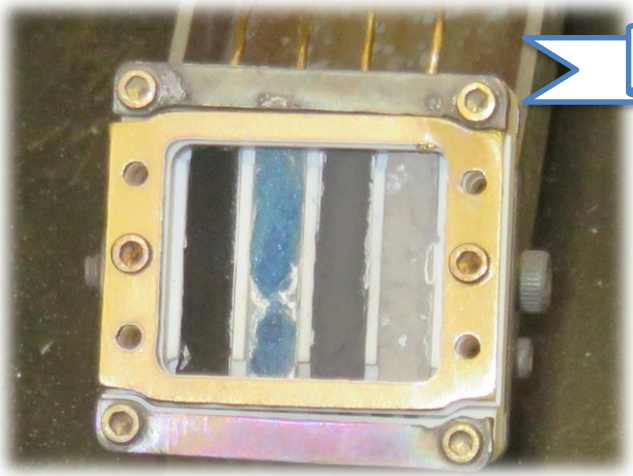
09. NSF Proposal – Fiber Optic Based NOx Sensor

Phase I Proposal Submitted to the National Science Foundation in June of 2015

- **6-Month Program, Told at Git-go we Had to Dedicate 3 Months to "Customer Discovery."**

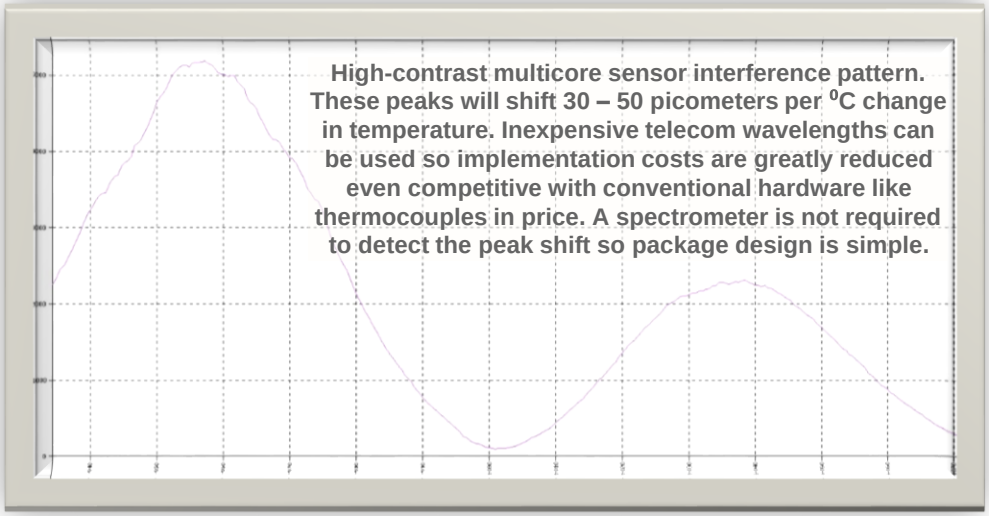
This lead to discussions with high-level employees at CARB, which in turn lead to our initial discussion with Kent and our invitation here! Unfortunately there wasn't very much time to build a multi-element high-temperature exhaust sensor, but we managed.

Tube Furnace with primitive synthetic exhaust gas flow introduced; TC-based sensors



Close-up of our "expedient" Phase I Sensor

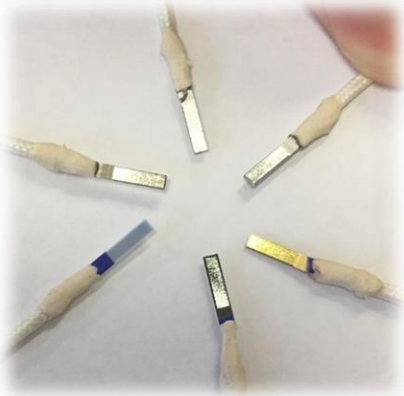
Detail showing advanced gas flow directing fixture inside



10. NSF Proposal – Fiber Optic Based NOx Sensor

Phase II Proposal Submitted to the National Science Foundation in August of 2016

- **Award notice March 2017: 2-year Technical Program with Emphasis on Product Development and Commercialization**
  - Setting up laboratory and hiring
    - Synthetic diesel exhaust (fume hood, mass flow controllers, gases and plumbing)
    - Optical bench (laser source, spectrometers, optical fiber equipment, etc.)
    - Electrical/optical engineer, software engineer, mechanical engineer, technician
  - Two parallel thrusts of the research: materials development (maximize the catalytic signals) and sensor development (maximize the measurement sensitivity)
    - Started with PVD of catalysts directly on to COTS (Omega) RTD sensor elements
    - Ended up with a custom mixture applied directly on to thermocouples
    - Continued work on multicore fiber sensor
  - Initial installation of RTD-based laboratory NOx sensor onto test truck



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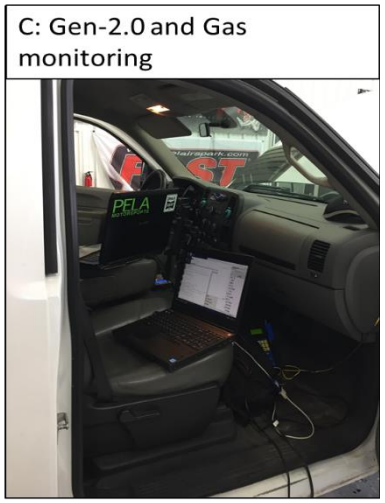
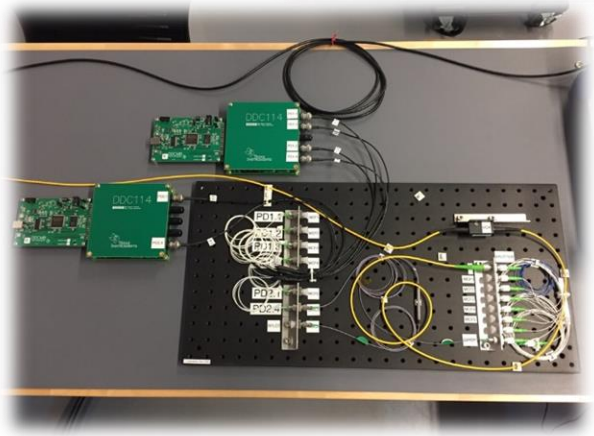


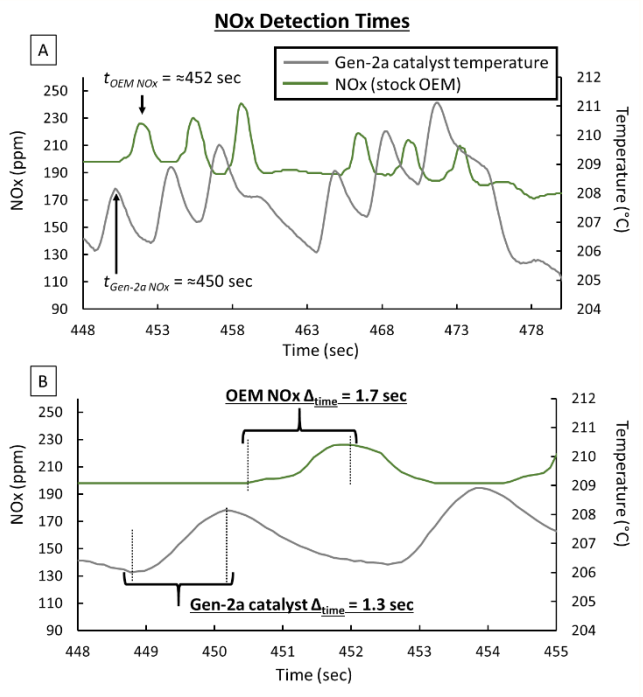


11. NSF Proposal – Fiber Optic Based NOx Sensor

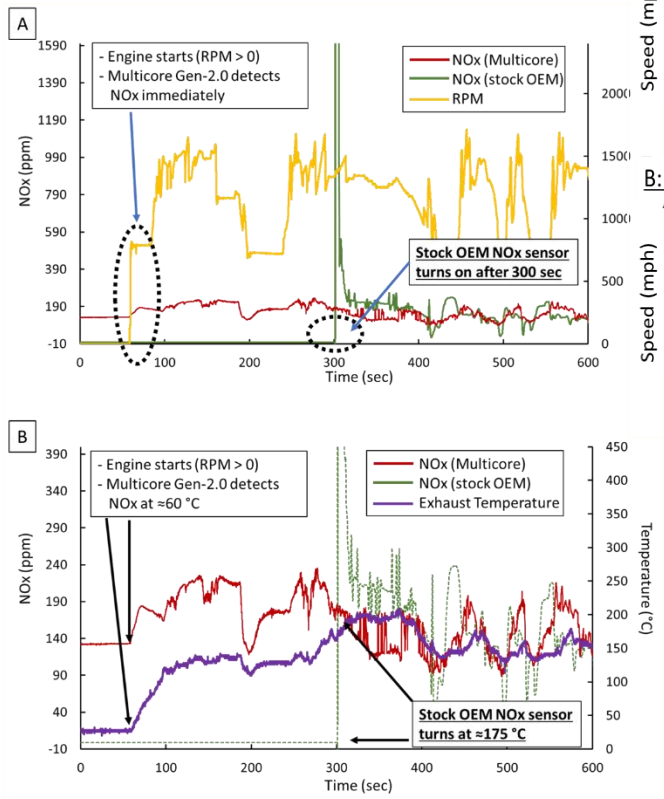
Important Data Points

Noteworthy tests conducted so far include

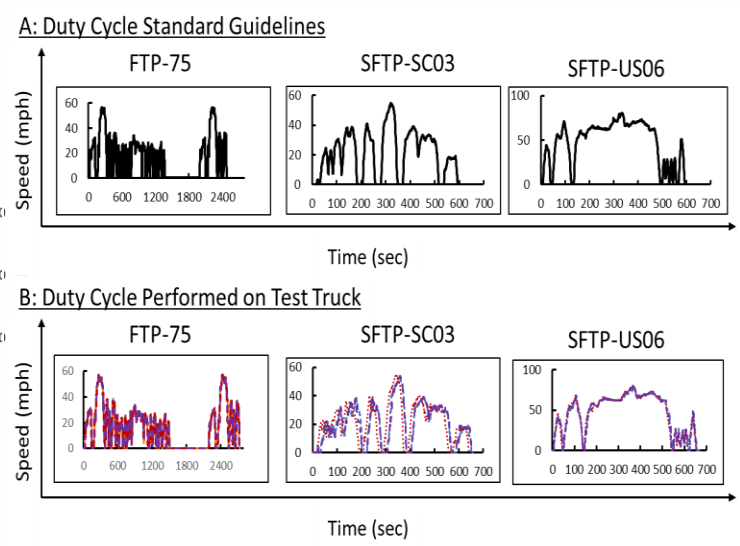
- DOT test parameters where the light off & response times were recorded.



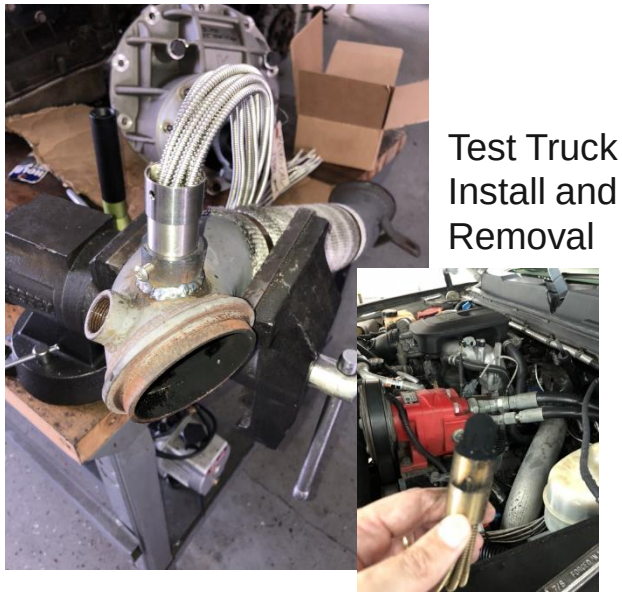
Detection time of Multicore Gen-2a sense is faster than the OEM NOx sensor.
A: Shows six NOx peaks (OEM NOx sensor) vs. six temperature peaks (Gen-2a). The six temperature peaks precede the six peaks of the OEM sensor. B: Gen-2a sensor measures the increase in time in ≈1.3 seconds vs. ≈1.7 seconds for the slower OEM NOx sensor. Next NOx event is captured before OEM finishes the first.



Light-off time of Multicore Gen-2a sense is faster than the OEM NOx sensor.
A: Light-off times. Multicore NOx sensors detects emissions as soon as the engine starts, as indicated by the RPM going from zero to non-zero once the system starts. The OEM stock NOx sensor does not have a NOx reading until >250 seconds from the start of the engine. B: Light-off times are also related to temperatures. Multicore NOx sensors detects NOx at ~60°C, while OEM stock NOx sensor detects NOx at ~175°C



A: Three EPA duty cycles. B: Data from test truck, each test was performed in triplicate.



Test Truck Install and Removal

12. Conclusion & Summary

Multicore's Gen-2a NOx sensor:

- Has a faster light-off time (nearly instantaneous) than both the stock OEM NOx sensor (≈300 seconds) and a commercial 5-gas exhaust gas analyzer (≈120 sec)
- Has a detection speed greater than both Multicore's Gen-1 NOx sensor variant and the stock OEM NOx sensor. (Gen-2a > Gen-1 > stock OEM).
- NOx accuracy is commensurate with a commercial 5-gas exhaust gas analyzer in two of the three tested duty cycles.
- Is ready for pre-commercial sales.

Next Steps

1. Improve Software Detection Algorithm
   - Deploy 20 pre-commercial Multicore Gen-2b NOx sensors to gather additional field data.
   - Conduct additional laboratory synthetic exhaust tests
2. Third-Party Verification
   - General Motors
   - Cummins
   - Universities/Agencies
3. Commercial Sales

   Manufacture, assemble and qualify the first run of 1,000-units (Gen-2c NOx sensor)
4. Continued Development of the Optical Sensor Variant (Gen-3a NOx sensor)