System Integration of Novel NOx Sensors for Emission Monitoring

UC Riverside PEMS 2017 International Conference & Workshop
March 30, 2017

F. Bell, M. Boettcher, J. Chee, L. Cui, J. Fitzpatrick, S. Harding, B. Henderson, D. Lippoth, O. Otero, M. Phee, L. Sorensen, V. Wang, J. Winn, and L.Y. Woo

CoorsTek
SENSORS

R. Novak and J. Visser
Ford Motor Company

Previously reported solid-state electrochemical NOx sensor using novel alternating current (AC) method

- Simple single cell design with two electrodes separated by oxygen-ion conducting ceramic yttria-stabilized zirconia (YSZ) – similar to O_2 sensor
- Applied oscillating signal with resulting wave distortion analyzed
- Potential as multigas sensor with lower cost and better performance than available amperometric (DC) sensors
- System integration for deployment in real-world applications – overview of some challenges in materials/ceramics and packaging

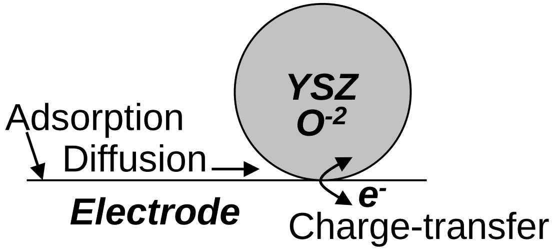
Sensing relies on electrochemical reaction rates at the electrode/electrolyte interfaces

electrolyte | ***electrode***

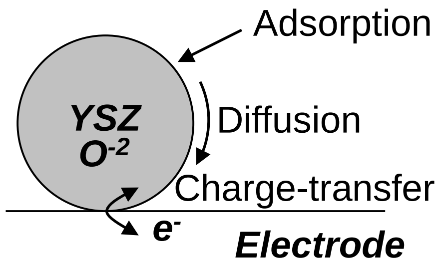
$$O^{2-} \leftrightarrow \quad \frac{1}{2}O_2 + 2e^- \leftrightarrow O^{2-}$$

$$NO_2 + 2e^- \leftrightarrow NO + O^{2-}$$

Non equilibrium reactions



Minimal NOx response when electrode surface dominates



Larger NOx response: controlling microstructure and composition is key

- Parallel reactions of O_2 and NOx: resolve ppm NOx in large 2-21% O_2 background by limiting O_2 reaction rate with porous YSZ electrolyte (conducts O^{2-} > 600°C)
- Impedancemetric (AC) sensing: requires at least one sensing electrode; symmetric or asymmetric cells with design flexibility

Ohm's Law: $V(t)=I(t)\cdot Z(\omega)$ — *Frequency-dependent complex impedance*

$$\theta = \tan^{-1}\left(\frac{Im(Z)}{Re(Z)}\right)$$

Phase angle

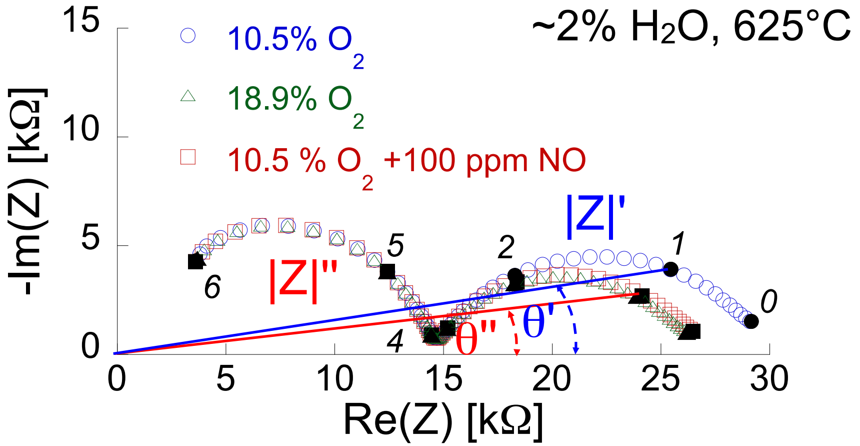
$$|Z| = \sqrt{(Re(Z))^2 + (Im(Z))^2}$$

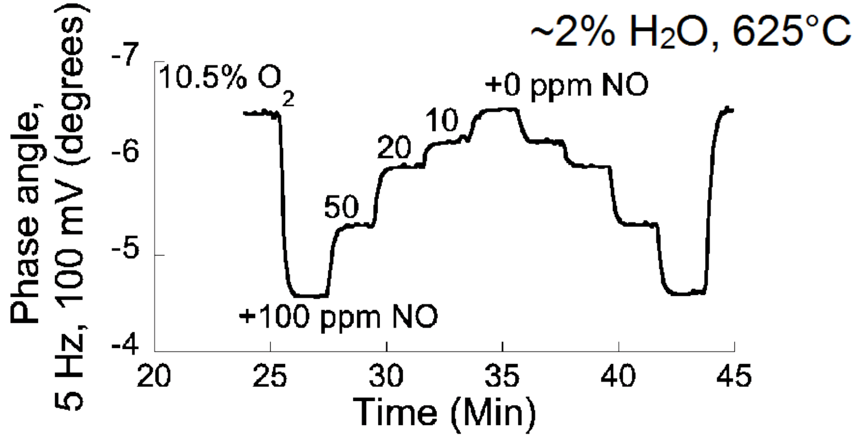
Magnitude

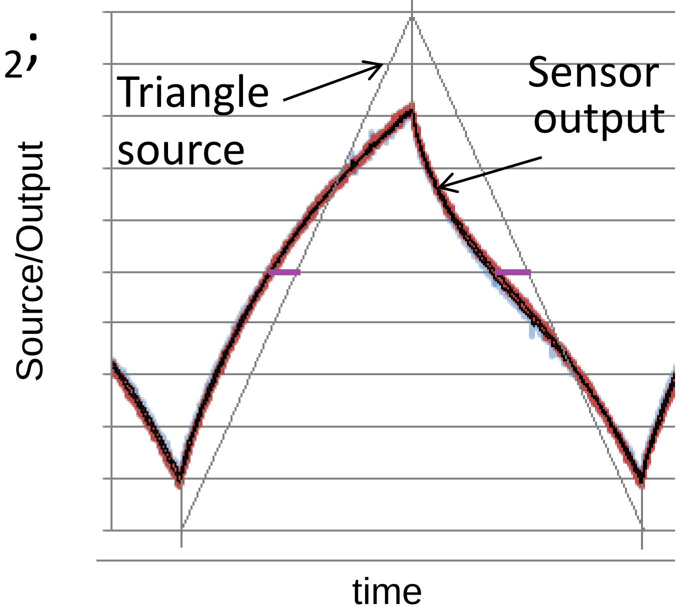
CoorsTek SENSORS

Impedancemetric sensing – phase angle (θ) signal with good stability and better sensitivity than magnitude |Z|

< 1 kHz: Impedance (θ and |Z|) decrease with increasing NOx and O_2; typical operation 5-50 Hz and 100 mV excitation





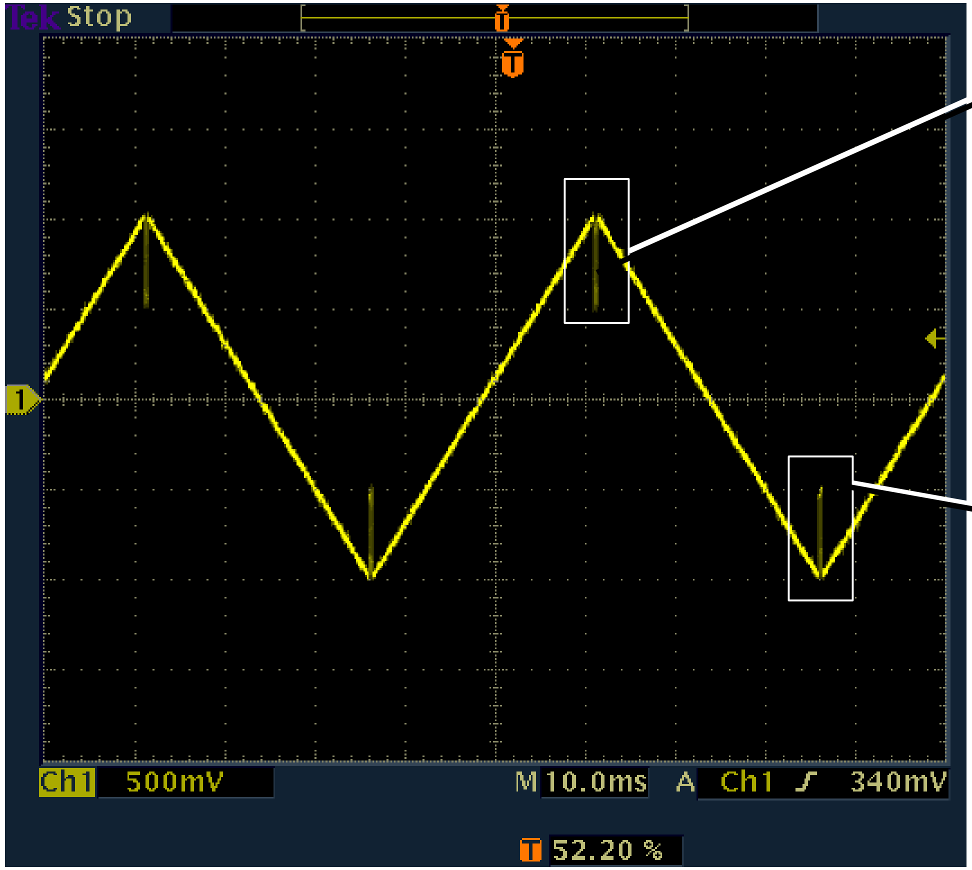


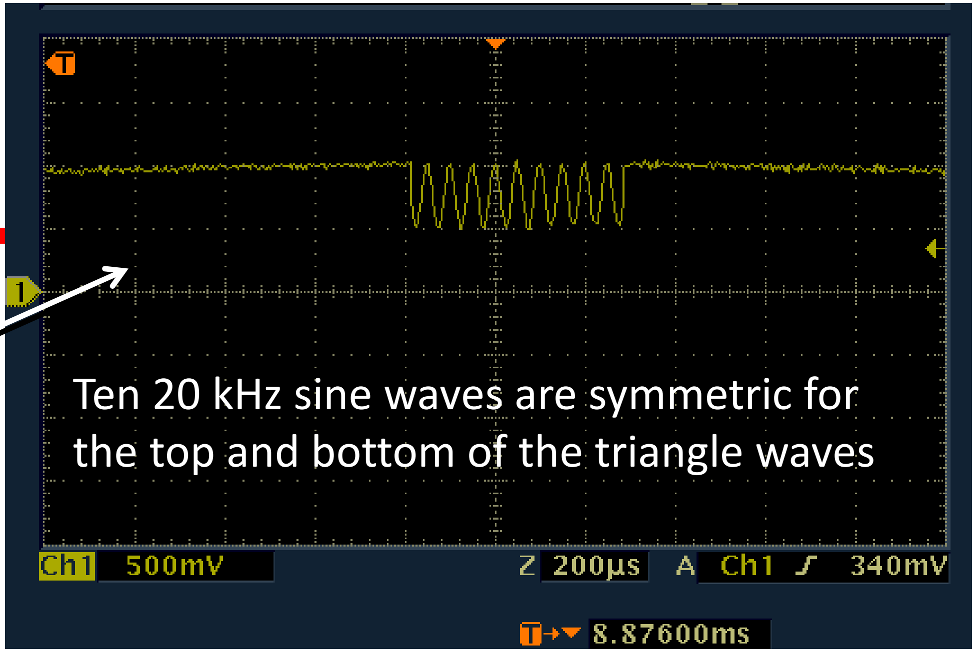
- Lab equipment (Solartron) costs ~$50k – developed portable low-cost digital electronics using triangle wave form and zero-crossing detection where complex response showed peak relatively unchanged and no real phase shift
- Digital voltage-current time differential method using complex response – different influence of NOx and O_2 allows several ways to extract oxygen

CoorsTek SENSORS

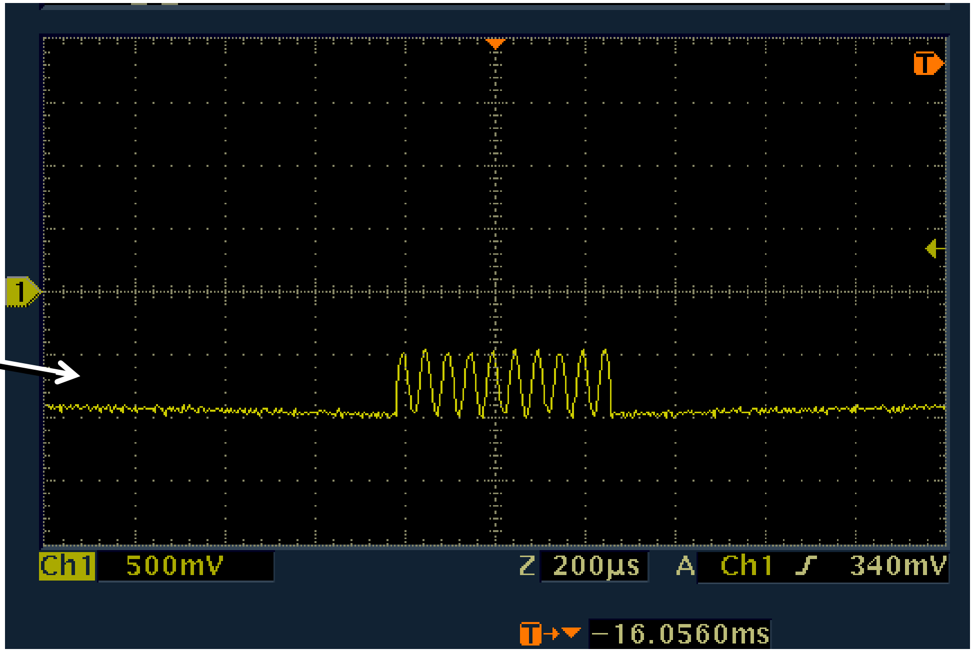
Measurement principle

Excitation with 20 Hz triangle wave with bursts of 20 kHz sine waves at top and bottom of triangle waves

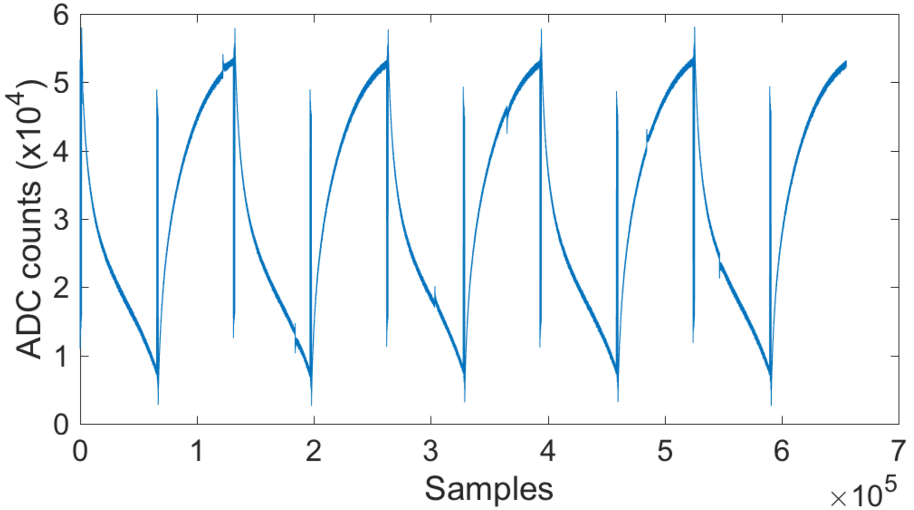


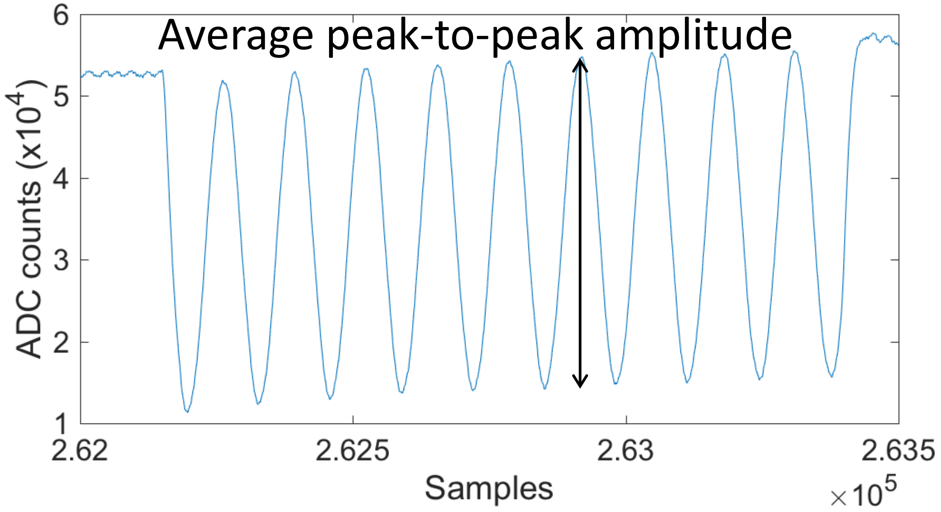


Ten 20 kHz sine waves are symmetric for the top and bottom of the triangle waves

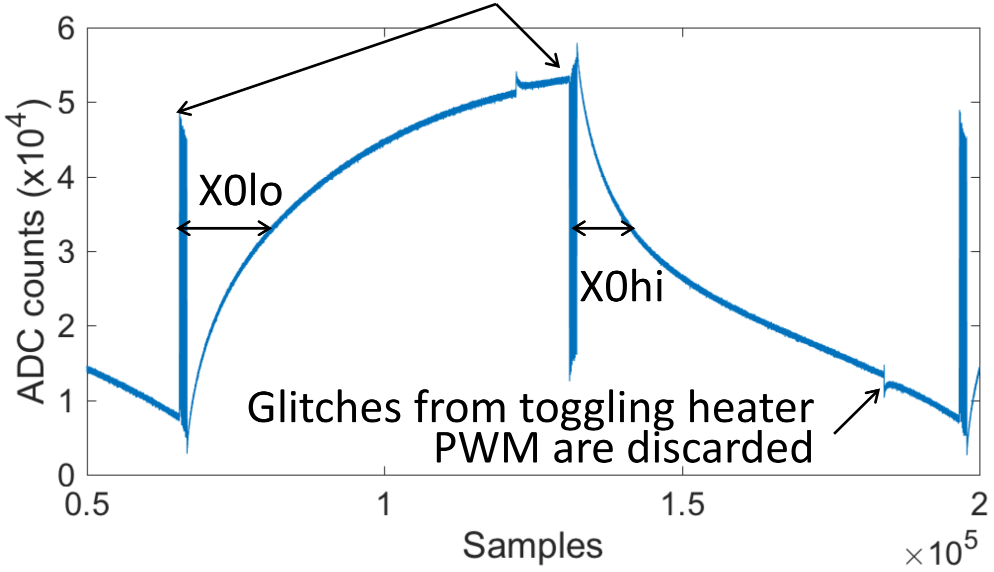


Captured current – two gas measurements at zero current condition on either side of 20 Hz wave





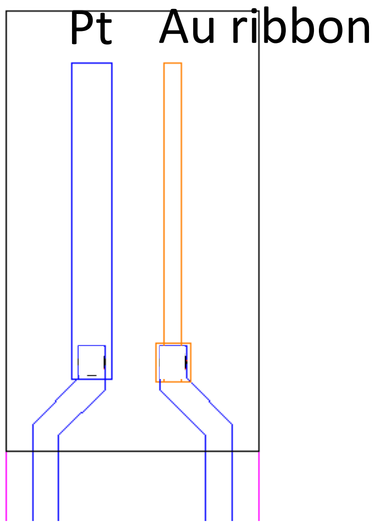
20 kHz sine waves – calculate real impedance to monitor and control temperature



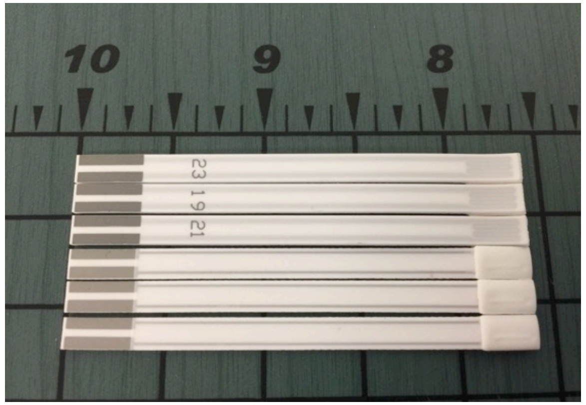
- Sampled time from start of half wave
  - X0lo: dominated by O_2 and NO
  - X0hi: dominated primarily by O_2
- 20 kHz sine wave distortions do not interfere with gas measurement

CoorsTek SENSORS

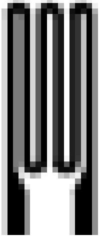
Materials/Ceramics – 1450°C cofired active sensor components and substrate with platinum (Pt) heater coil

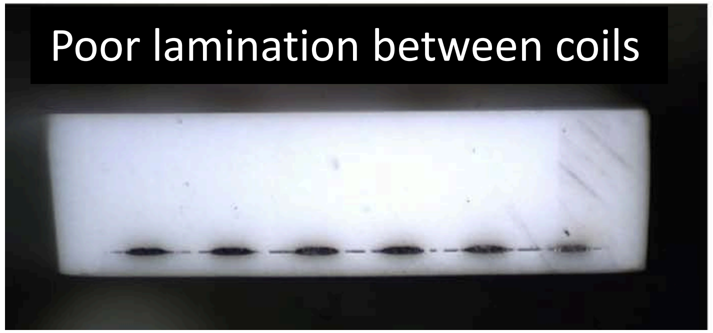


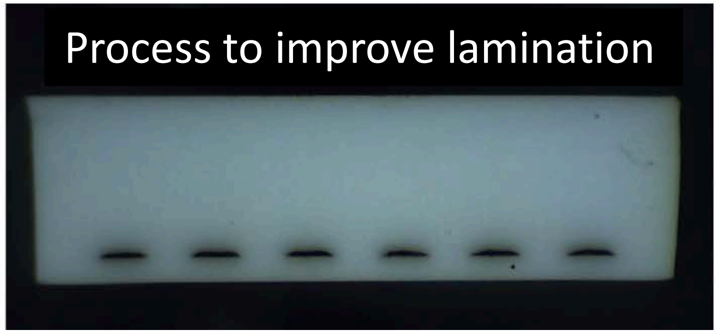
- Furnace prototypes (no heaters) with calcined porous YSZ electrolyte and gold (Au) ribbon/Pt electrodes
- Found suitable ceramic interconnect material to allow electrical connection between Au and Pt
- Advanced prototypes with active components on improved alumina substrates with embedded Pt heater coil



Embedded Pt heater coils

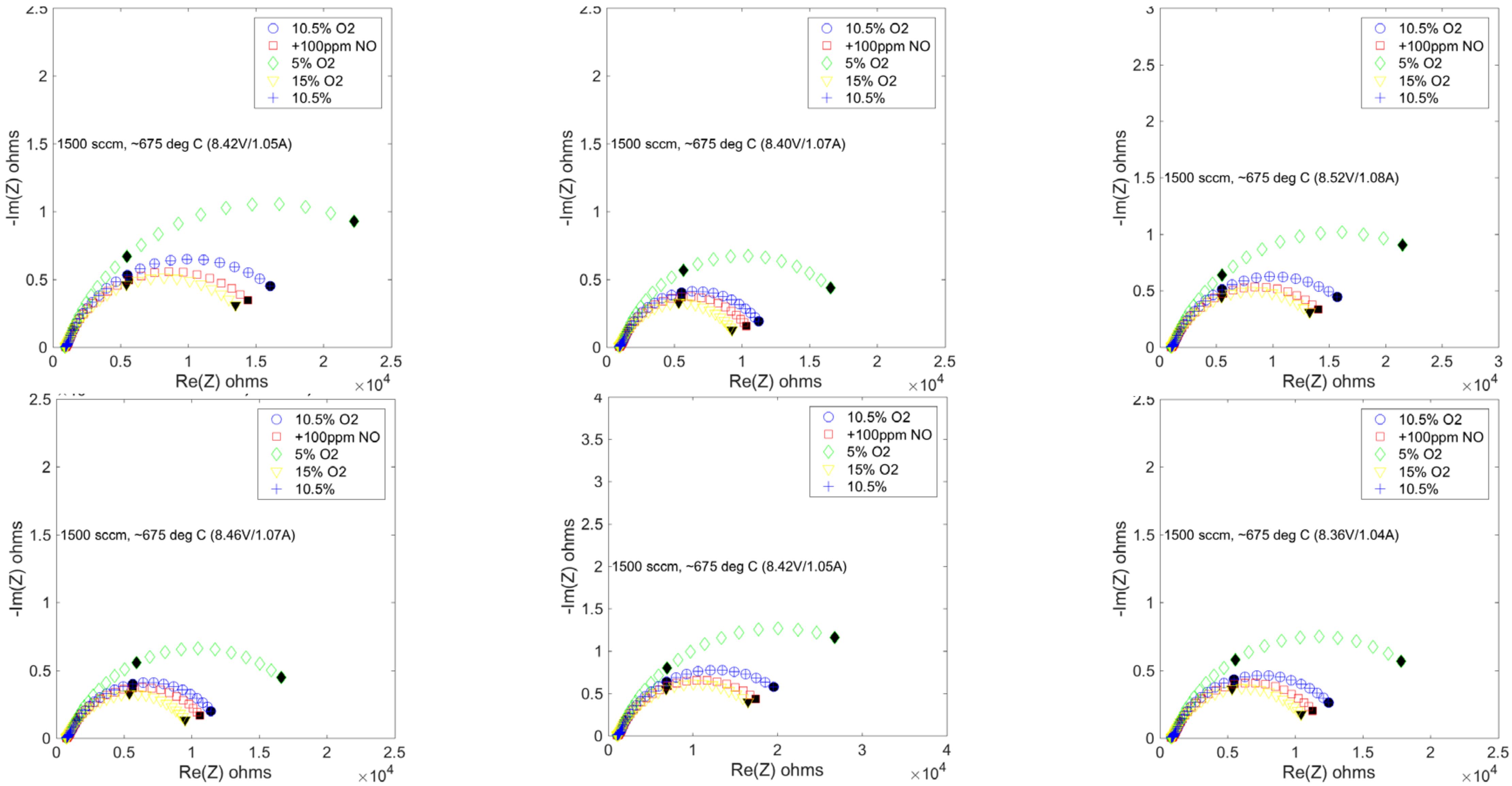






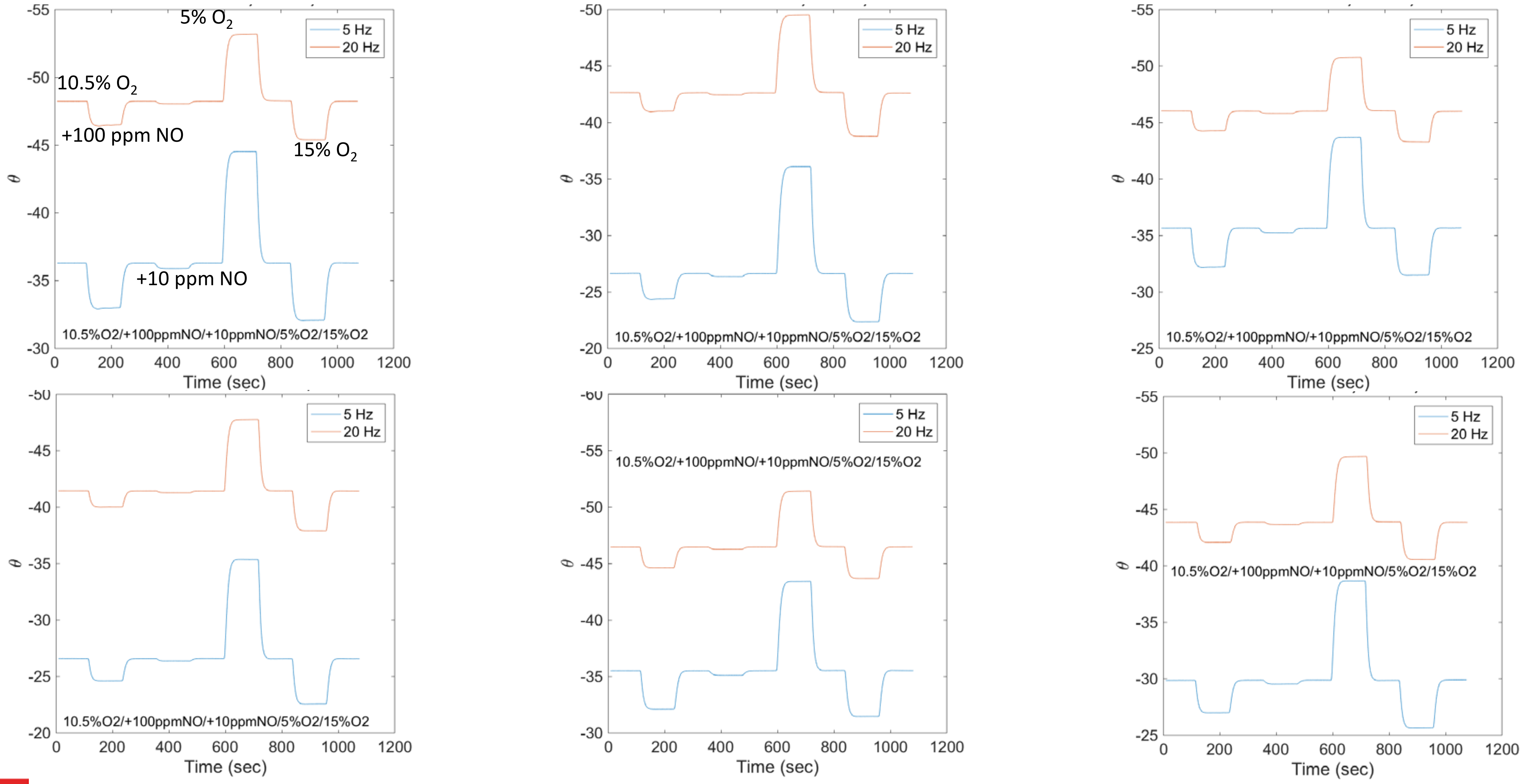
CoorsTek SENSORS

Sensors with improved sensor-to-sensor reproducibility

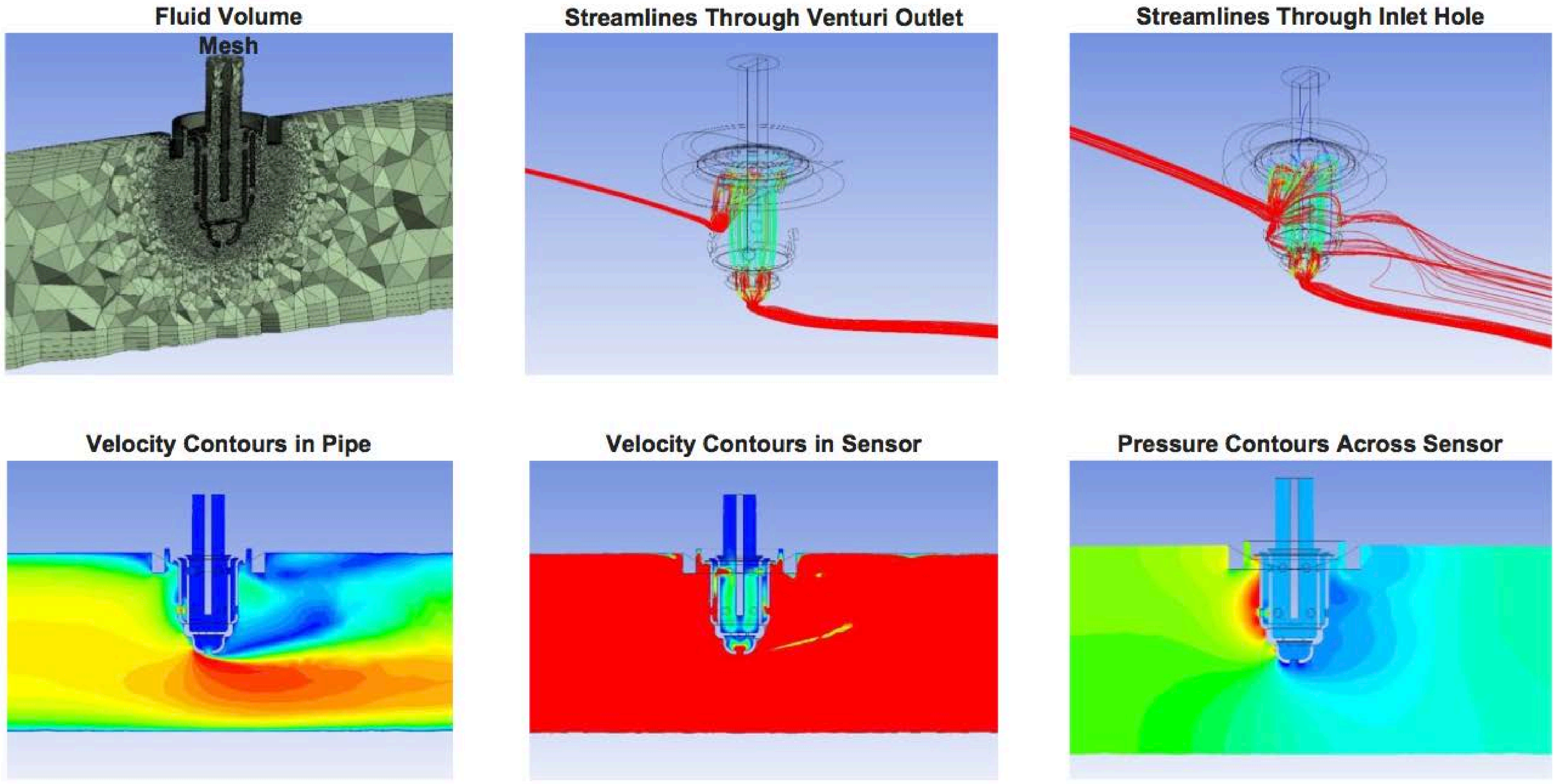


CoorsTek SENSORS

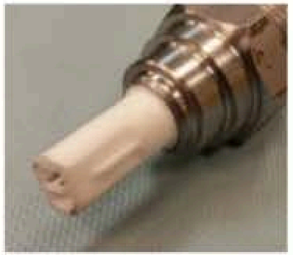
Sensors with improved sensor-to-sensor reproducibility

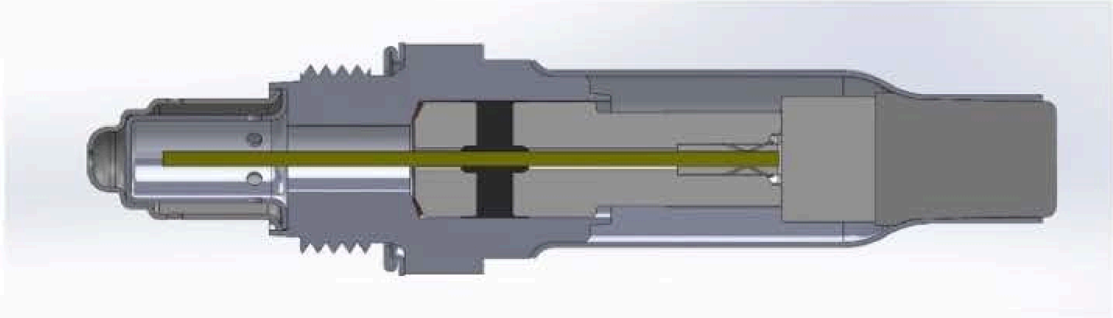


Packaging and protection tube – Venturi modeling



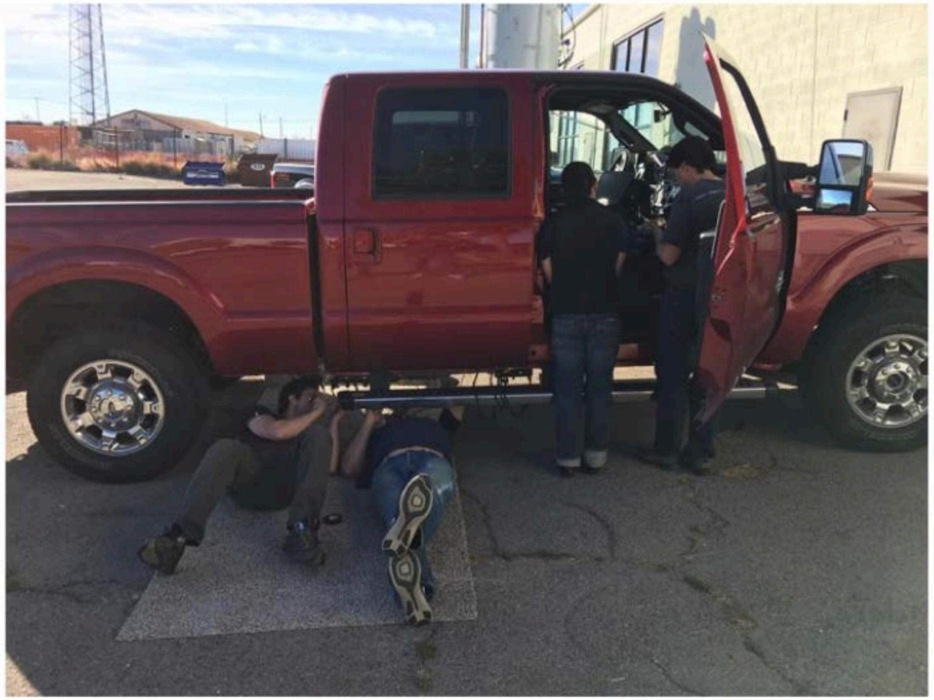
Packaging – Venturi protection tube in full assembly

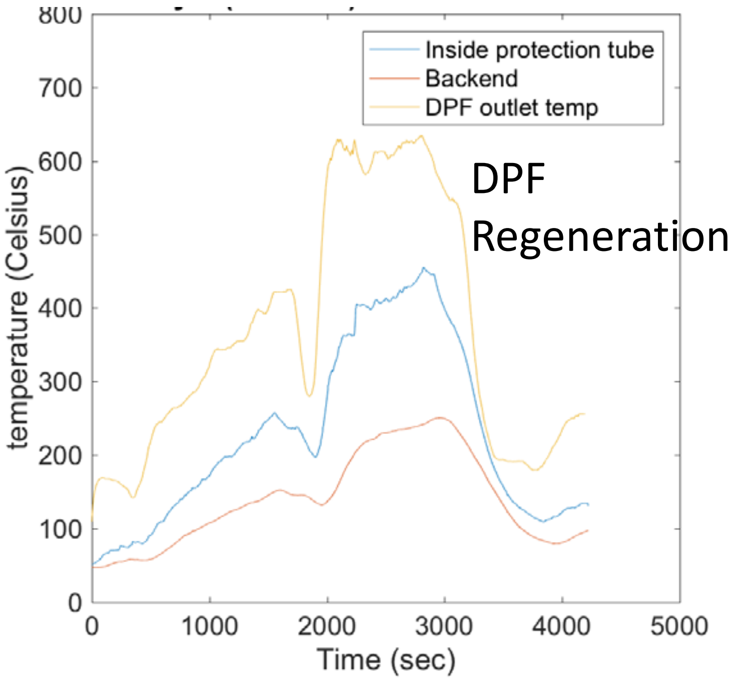




Ford (F-250 Lariat) vehicle testing at Salt Lake City (SLC) – demonstrate thermal control with heater strategy

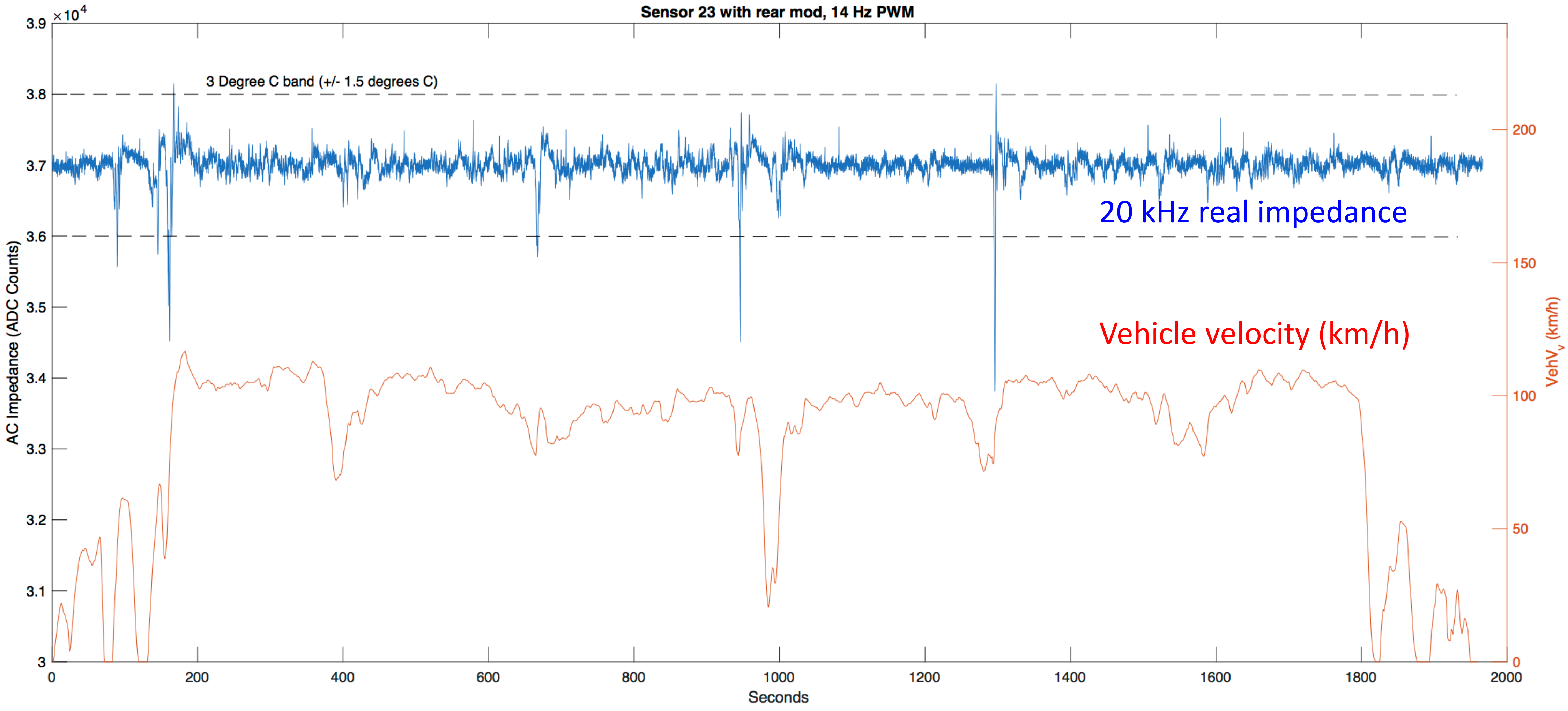
- One test position in vehicle exhaust located next to commercial NOx sensor – added a temporary bracket to hold electronics
- Characterized drive cycle (along I-80 from SLC to Park City) using instrumented thermocouple in our packaging





CoorsTek SENSORS

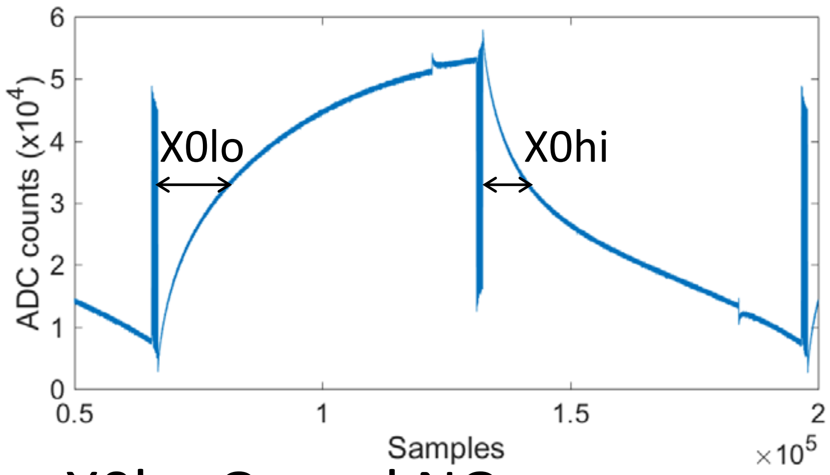
Temperature control using real impedance from 20 kHz sine waves better than ± 1.5° during drive cycle



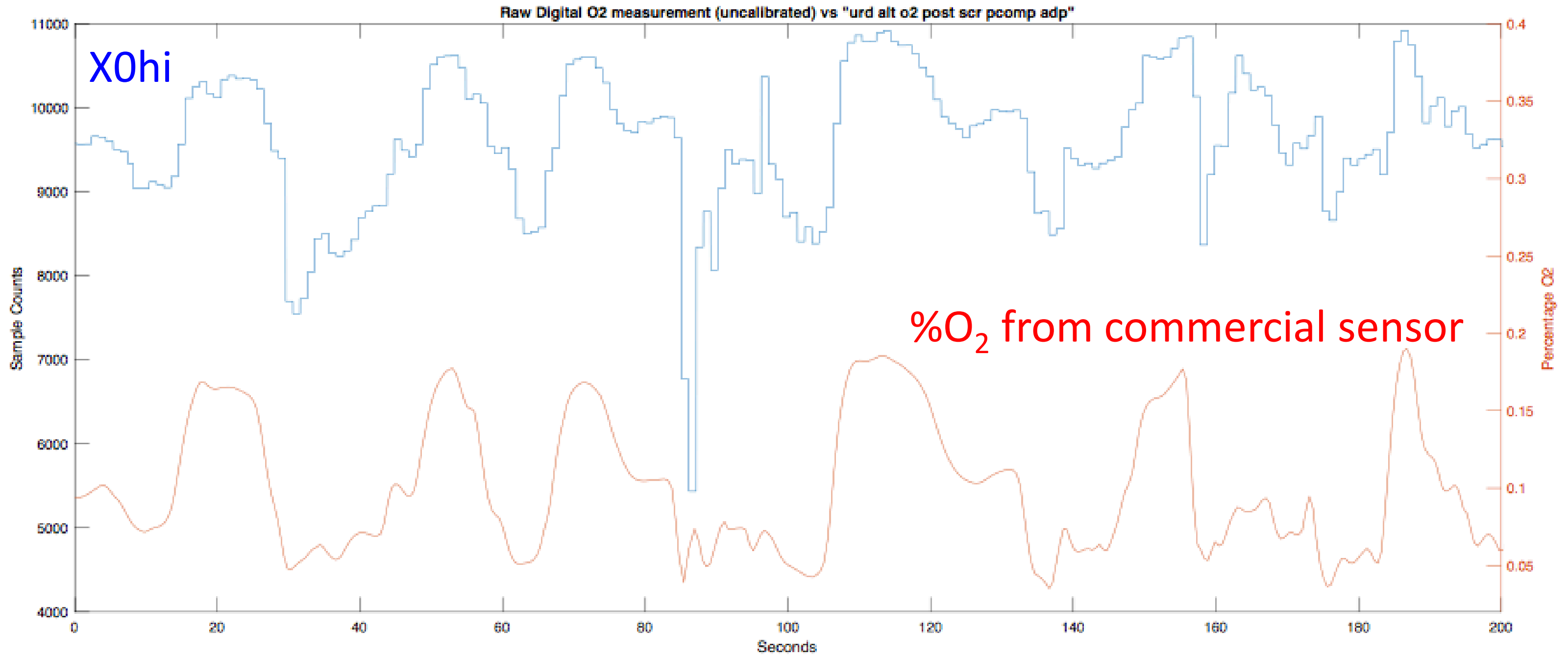
CoorsTek SENSORS

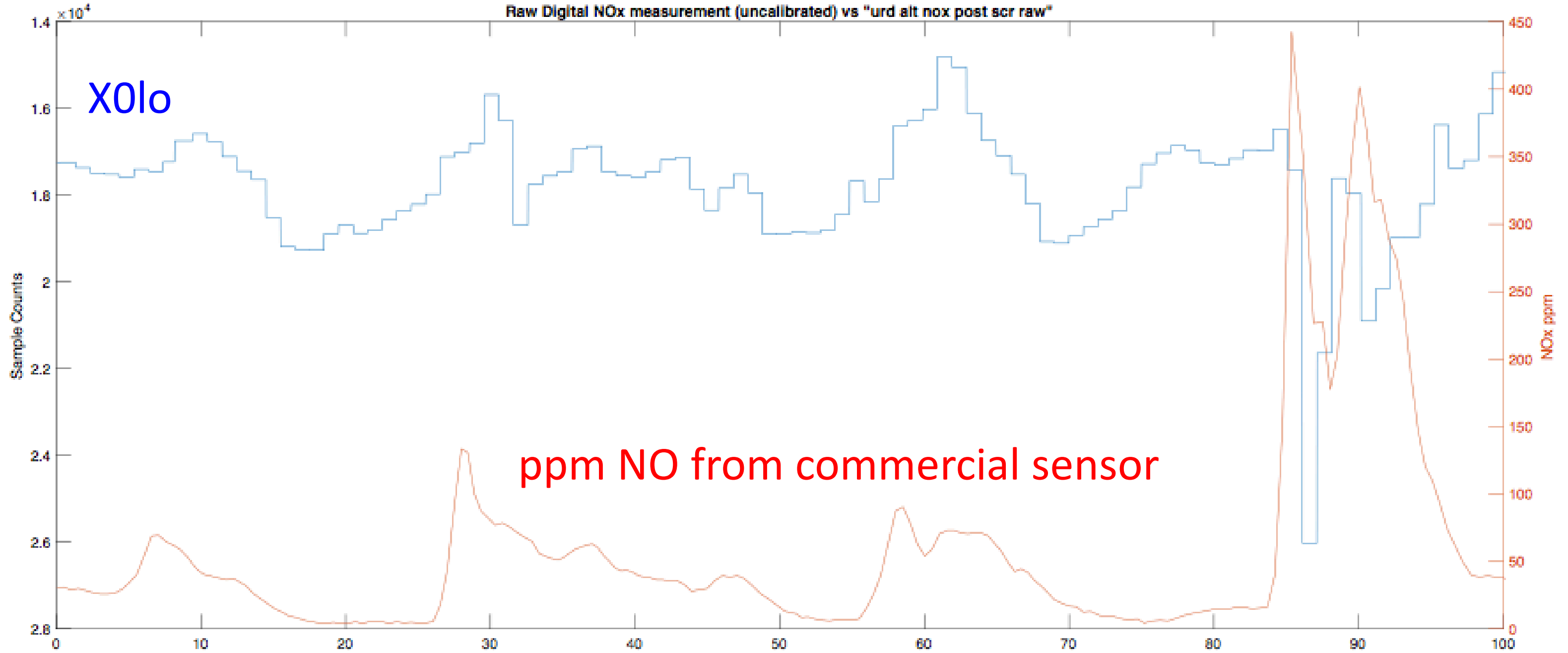
Vehicle testing

- Gas measurements on either side of 20 Hz wave correlated with readings from commercial NOx sensor



- X0lo: O_2 and NO
- X0hi: mostly O_2





Ongoing activities in system integration

- Multiple strategies for O_2 measurement including DC values from 20 kHz sine wave excitation – measurements to mitigate interference and cross-sensitivity to other components including H_2O and NO_2
- Improving stability of 20 kHz thermal measurement – better stability of furnace prototypes compared to advanced prototypes
- Demonstrating panelization and materials selection for mass fabrication – better understanding Au/Pt electrical connection and work on alternative interconnection strategies
- Packaging – components with improved electrical connection (vibration and thermal cycling) and water bath testing of water resistant treatments
- Planned vehicle testing at Ford scheduled in April

Summary

- Measurement principle of impedancemetric multigas/NOx sensor – digital voltage-current time differential method using complex response of YSZ-based electrochemical cell
- Materials/ceramics work for more advanced prototypes with better sensor-to-sensor reproducibility and packaging improvements demonstrated in vehicle testing – temperature control to ± 1.5°
- Ongoing system integration activities include multiple strategies for detecting O_2 and other components, improving stability of thermal measurement, and demonstrating mass fabrication and robust packaging
- Planned vehicle testing at Ford scheduled in April

CoorsTek SENSORS

Questions? Thank you for you attention! lw@emisense.com