Your Partner in Smart Solutions

Real-Time Catalyst Monitoring and Diagnostics using Radio Frequency Sensors

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Project Objectives

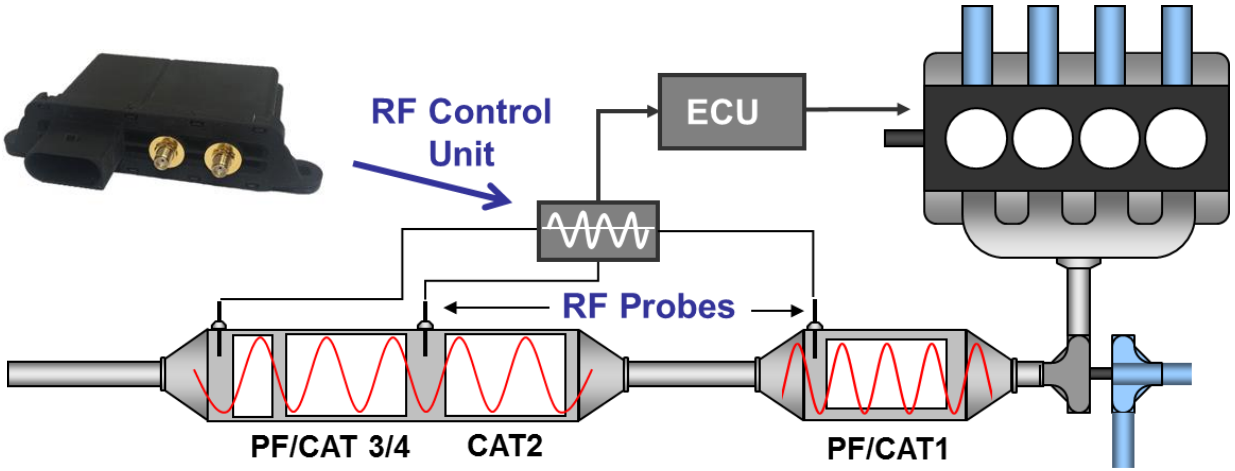
Remove Technical Barriers of aftertreatment-related fuel consumption and improve system durability, reduce system cost and complexity.

Develop RF Sensing Platform for direct measurements of catalyst state for clean diesel, lean gasoline, and low temperature combustion modes.

The Specific Objectives of this Project Include:

1. Develop RF sensors and evaluate the feasibility of RF sensing for the following catalysts and applications:
   - **Selective Catalytic Reduction (SCR):** Ammonia storage, *diesel & gasoline*
   - **Three-Way Catalyst (TWC):** Oxygen storage, *gasoline*
   - **Hydrocarbon Traps:** HC storage, *low temperature combustion*
2. Develop implementation strategies for the most promising applications to enable low-cost and robust emission controls to enable advanced combustion engines.
3. Demonstrate and quantify improvements in fuel consumption and emissions reduction through RF sensing in engine and vehicle tests with industry and national laboratory partners.

Technology Overview and Concept



- Direct measurement of multiple catalysts
- Adaptive feedback controls adjusts as system ages

CONCEPT: Multi-function ***RF sensing platform*** to enable more robust and more efficient emission controls for gasoline, clean diesel and advanced low temperature combustion modes.

Technology Assessment




Sensor Type	NOx or O2	Ammonia	Soot (PM)	RF Sensor
Applications	NOx or O_2 Only	NH_3 Only	PM Only	NH_3, O_2, NOx, HC, PM, Ash
Catalyst State	Model/Estimate	Model/Estimate	Model/Estimate	Direct Measurement
Sensing Element	Active	Active	Active	Passive

Current systems use many different types of exhaust gas sensors.

DOE Supported Test Program: Project Partners

Team Member Contributions

Performance Metric

CTS

- Develop RF sensors
- Sensor calibration
- Catalyst aging

- Production gas sensors
- Storage models
- Gravimetric (PM/Ash)

CORNING

- Advanced substrates
- Model catalysts
- HD engine dyno testing

- Production gas sensors
- Emissions bench (FTIR)
- Storage models

OAK RIDGE National Laboratory

- Catalyst bench testing
- Model validation
- Engine dyno testing

- Emissions bench (FTIR)
- Adv. Instruments Spaci-MS
- Catalyst models

THE CITY OF NEW YORK DEPARTMENT OF SANITATION

- On-road fleet test
- Volvo/Mack trucks (SCR+DPF)
- 18 Months total, 2 trucks

- Stock Volvo/Mack SCR controls
- On-road durability

Cummins **FCA** FIAT CHRYSLER AUTOMOBILES

DAIMLER Daimler Trucks North America

- OEM technical advisors
- Catalyst samples
- Design of experiments
- Parallel testing

- System requirements
- Production sensors
- In-house models

CTS

Catalyst Configurations Evaluated

Catalyst	Condition	Application	Baseline	Test Conditions	Facilities
SCR	Degreened	Cummins 8.9L ISL (2015)	N_2, Air 25 °C – 400 °C	NH_3 Storage 150, 200, 250, 300, 350, 400°C	CTS ORNL
SCRF	Degreened	Non-Production *[VW]*	N_2, Air 25 °C – 400 °C	NH_3 Storage 250°C	CTS
SCRF	Soot / Ash	Non-Production *[VW]*	N_2, Air 25 °C – 400 °C	NH_3 Storage 250°C	CTS
TWC	Degreened	GM Malibu 2L DI (2016)	N_2, Air 25 °C – 400 °C	O_2 Storage, Lean / Rich Pulses (C_3H_8)	CTS ORNL
TWC	Degreened	Chrysler V8 (2016)	N_2, Air 25 °C – 400 °C	O_2 Storage, Lean / Rich Pulses (C_3H_8)	CTS
HC Trap	TBD	Non-Production	To be completed	To be completed	ORNL

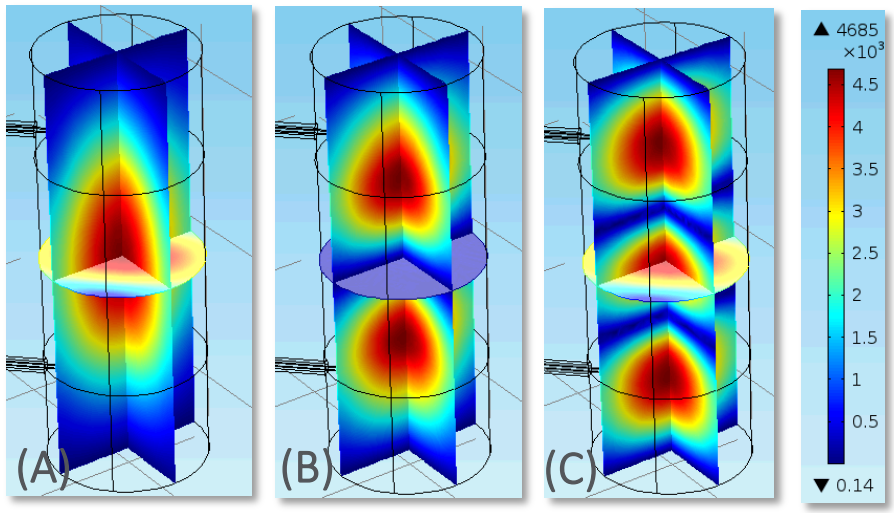
General Catalyst Test Conditions

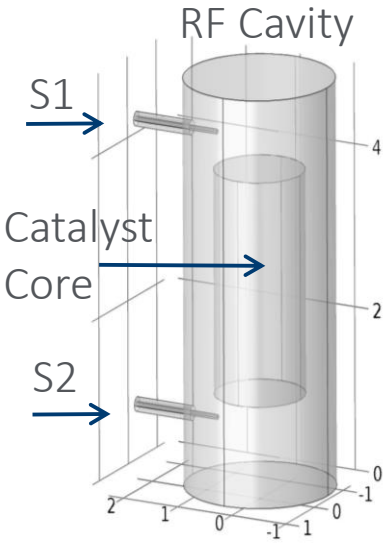
- Reference / baseline testing with air and inert conditions to characterize RF signal response to catalyst over temperature range
- SCR: 5-13% H_2O, CO_2; 0-10% O_2; 0-2% CO, H_2; 0-800 ppm HC, NH_3
- SCRF – soot/ash loading from exhaust of diesel engine and burner
- TWC: 5-13% H_2O, CO_2; 0-10% O_2; 0-2% CO, H_2; 0-800 ppm NO; 0-0.3% HC

Same catalyst core samples used with all project partners and for engine testing in Phase II.

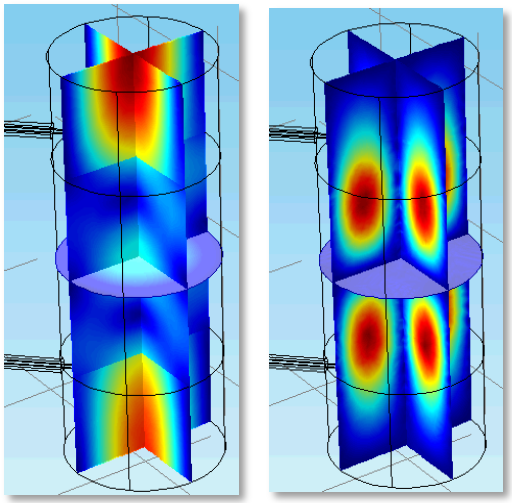
RF Cavity Simulations Developed and Validated

Results of Cavity Electric Field Simulations



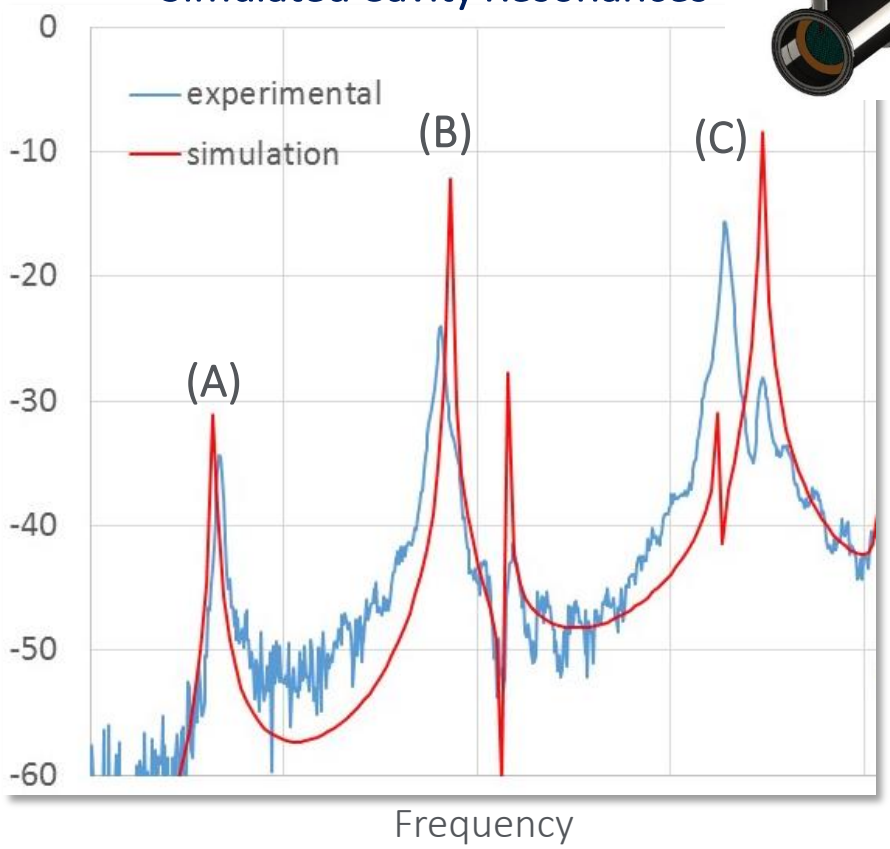


Higher Order Modes



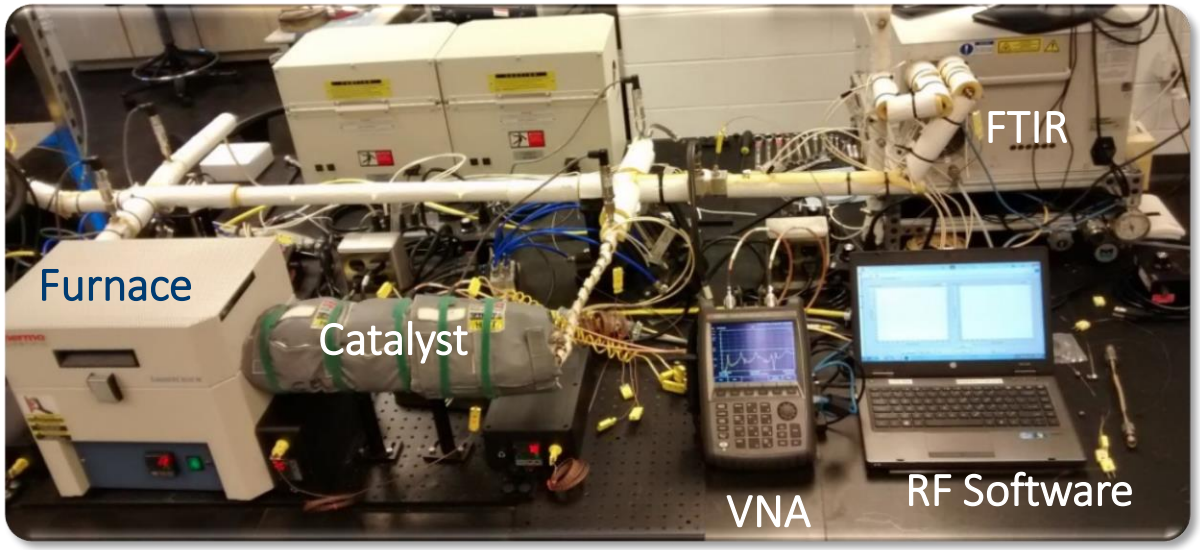
- Electric field distributions provide spatial sensitivity to monitor local storage of gas species
- Potential to monitor location of stored ammonia (front → back of SCR)

Simulated Cavity Resonances



Bench Reactor Systems for Catalyst Evaluations

ORNL Bench Reactor Setup for RF Calibration

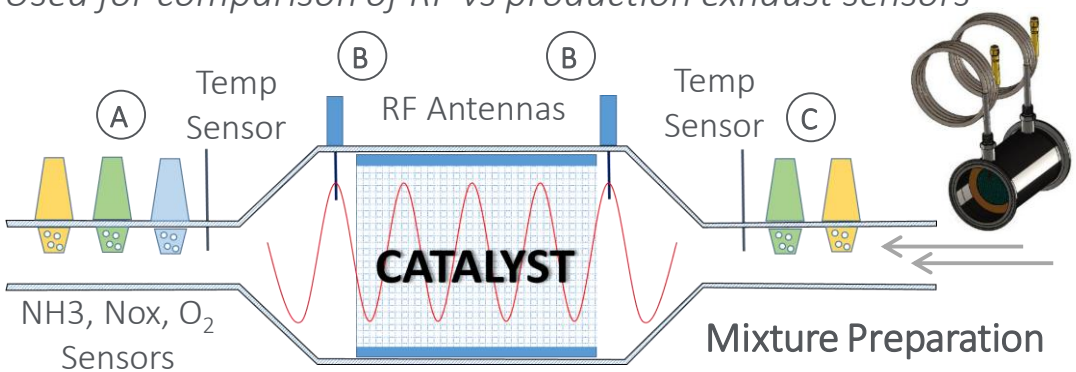


RF Sensor Calibration

- ORNL bench reactor
- Gas mixture control and FTIR measurements pre- / post- catalyst
- Standard test protocols for catalyst preconditioning, loading, and desorption tests
- Calculated NH_3, O_2 storage levels supplied as reference for RF sensor calibration of SCR and TWC
- Standard core samples used at ORNL and CTS

CTS Reactor Setup Mimics Production System Configuration for Performance Benchmarking

Used for comparison of RF vs production exhaust sensors

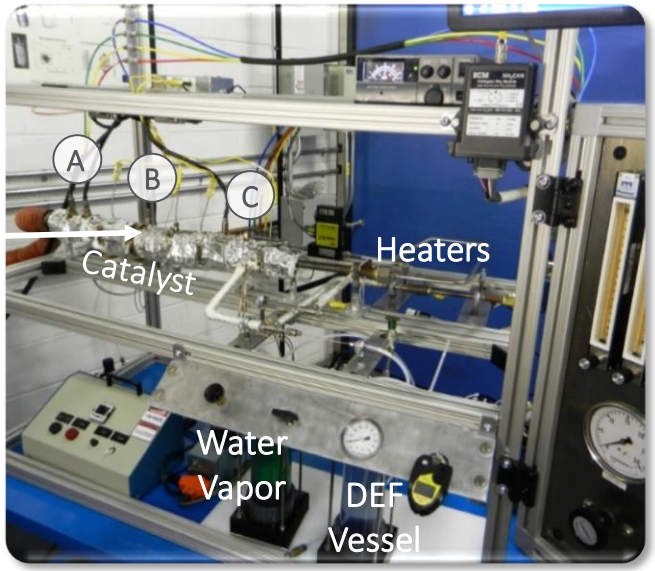


Sensors

- RF Sensor
- NOx/O_2, λ
- NH_3 Sensors

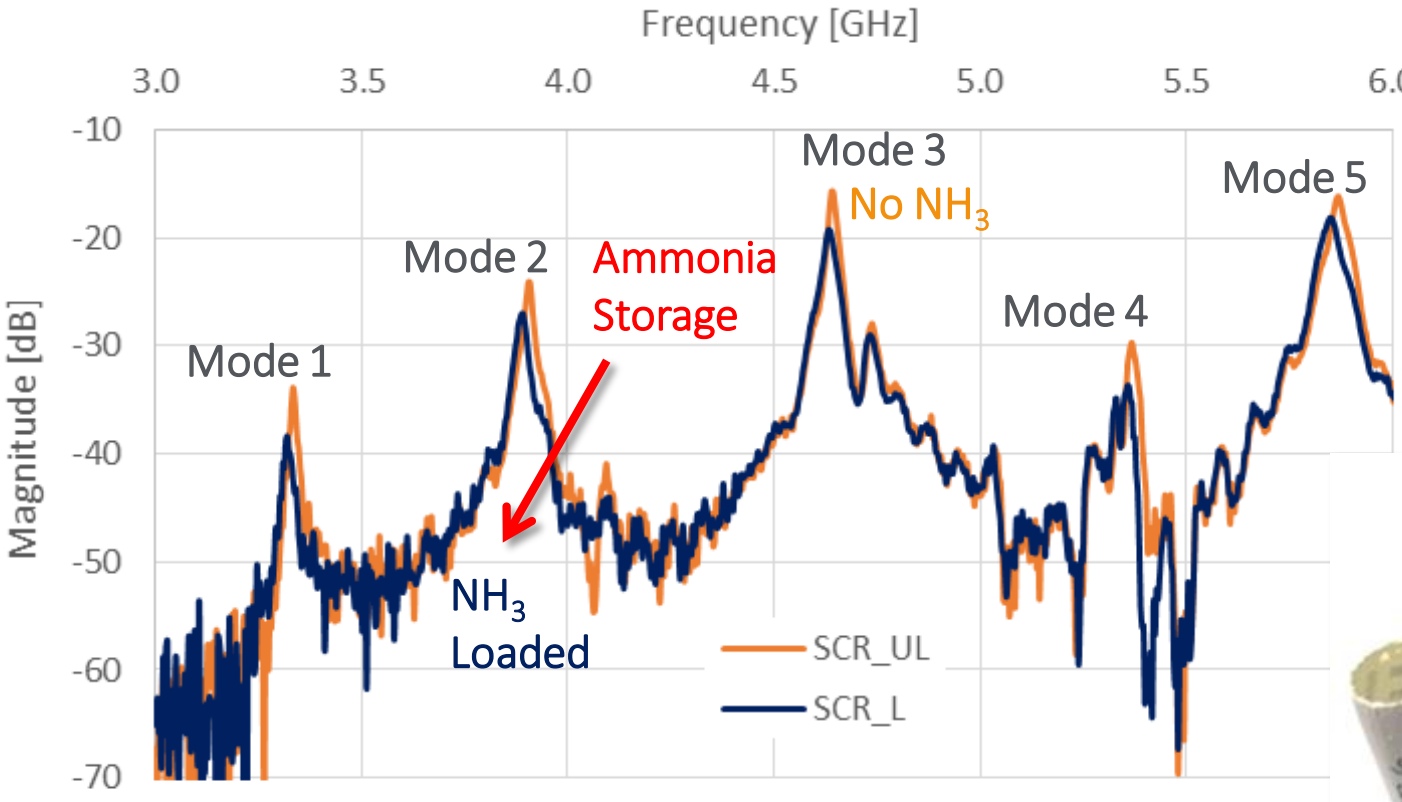
Mixture Preparation

- N_2, NO, NH_3, O_2, H_2O, CO, CO_2, HC
- Temp: 100 – 550 °C
- Flow: 0 – 100 slpm



RF Response to Ammonia Storage on SCR

Ammonia storage measurements demonstrated on laboratory bench reactor

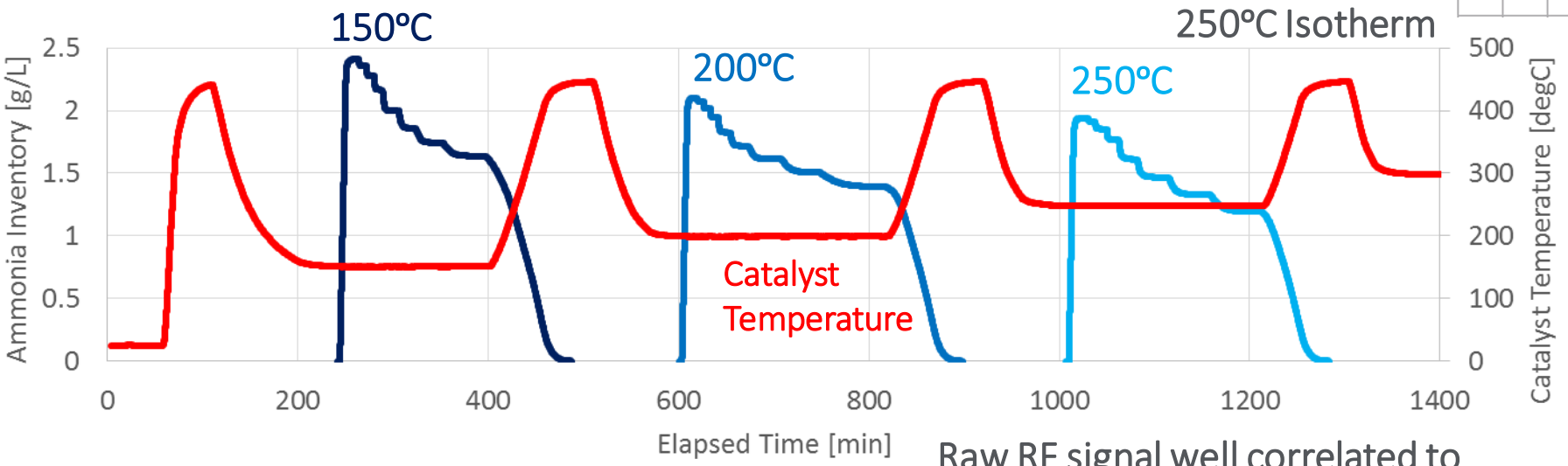


SCR core samples evaluated on bench reactor at CTS and ORNL

Catalyst Bench Reactor Testing Confirmed NH_3 Impact on RF Signal

- Maximum 5 dB reduction in signal amplitude with NH_3 storage
- Fully-desorbed state (sharp resonant modes) – No ammonia storage
- Reduction in amplitude and shift in frequency with ammonia storage

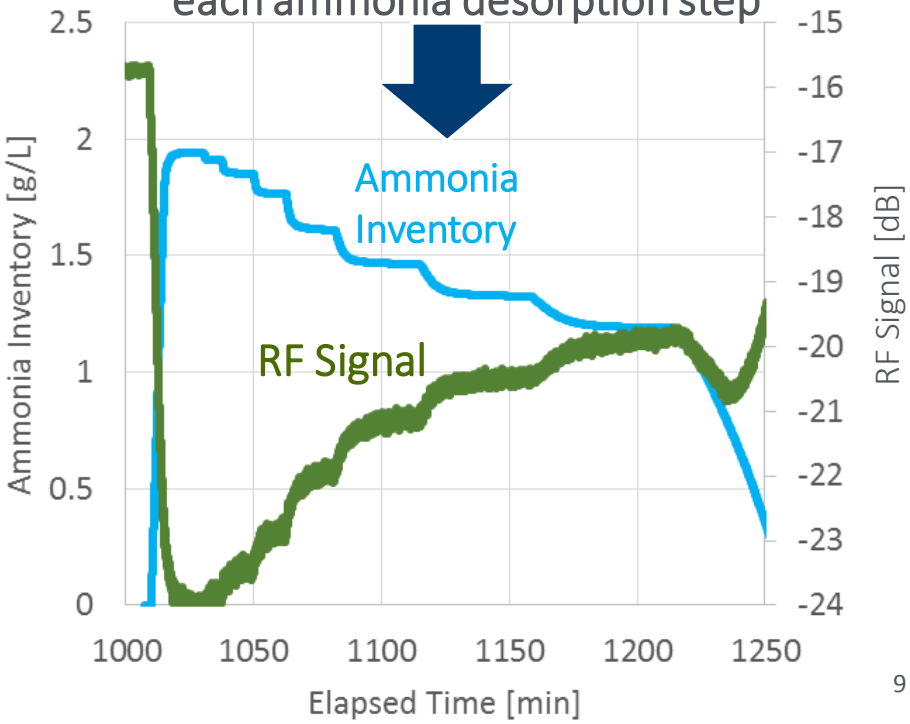
Temperature Compensation of SCR: System Calibration



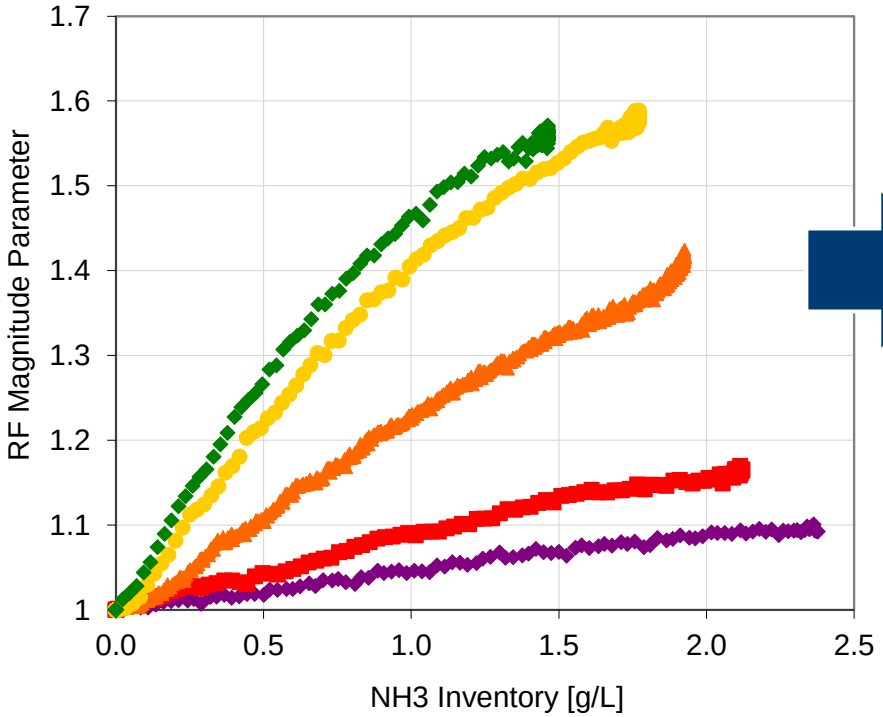
RF sensor calibrated for SCR performance using a series of desorption isotherm tests

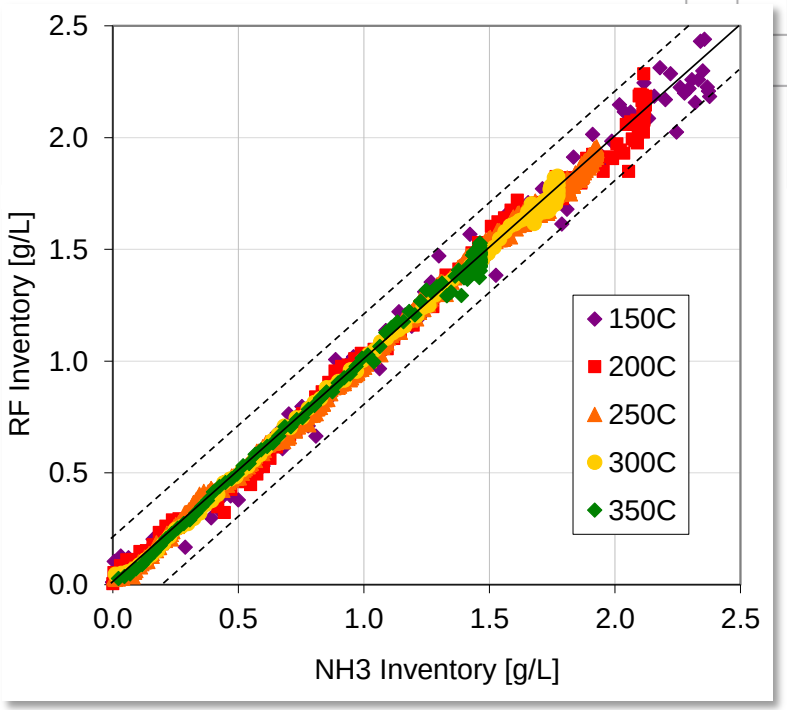
- Catalyst loaded to saturation, then ammonia injection is reduced to allow for desorption
- High-temperature SCR regeneration performed between desorption isotherms
- RF response measured at each temperature to allow for incorporation of temperature compensation

Raw RF signal well correlated to each ammonia desorption step



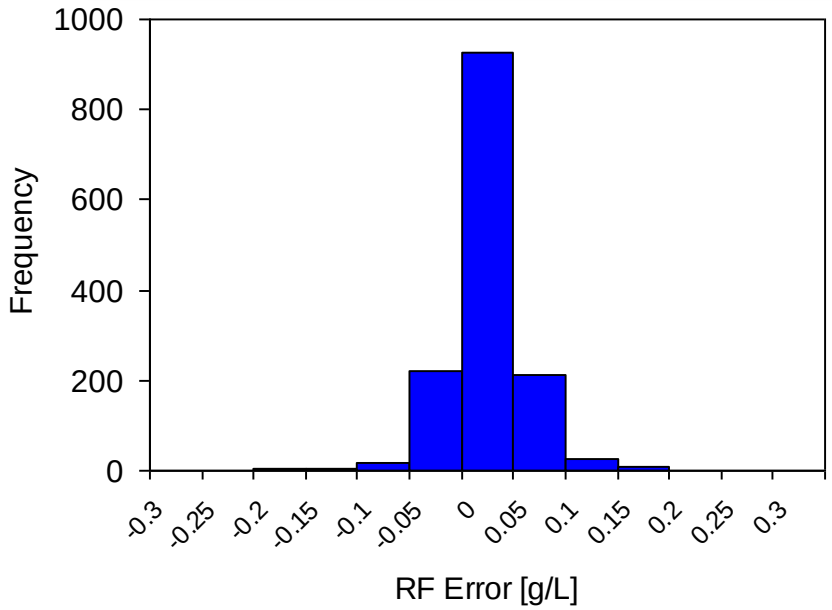
Ammonia Inventory Measurement with RF





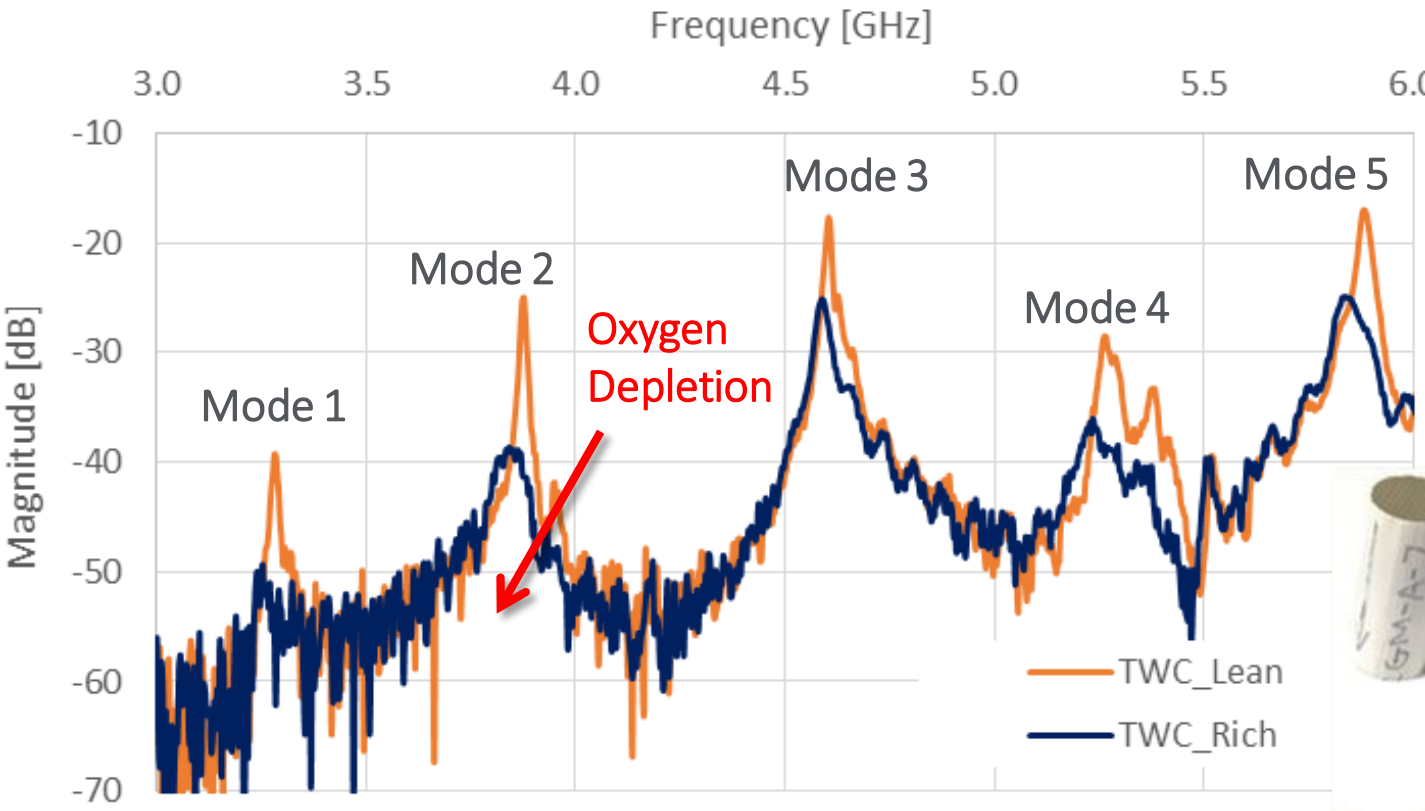
Go / No-Go Decision Criteria Achieved:

- Developed RF calibration for ammonia storage measurements including temperature compensation within 10% of full-scale
- Calibrated RF sensor for the SCR has a mean measurement error of **0.000 g/L** and a standard deviation of **0.036 g/L**



Oxygen Storage Readily Detected on TWC

Oxygen storage measurements confirmed on laboratory bench reactor

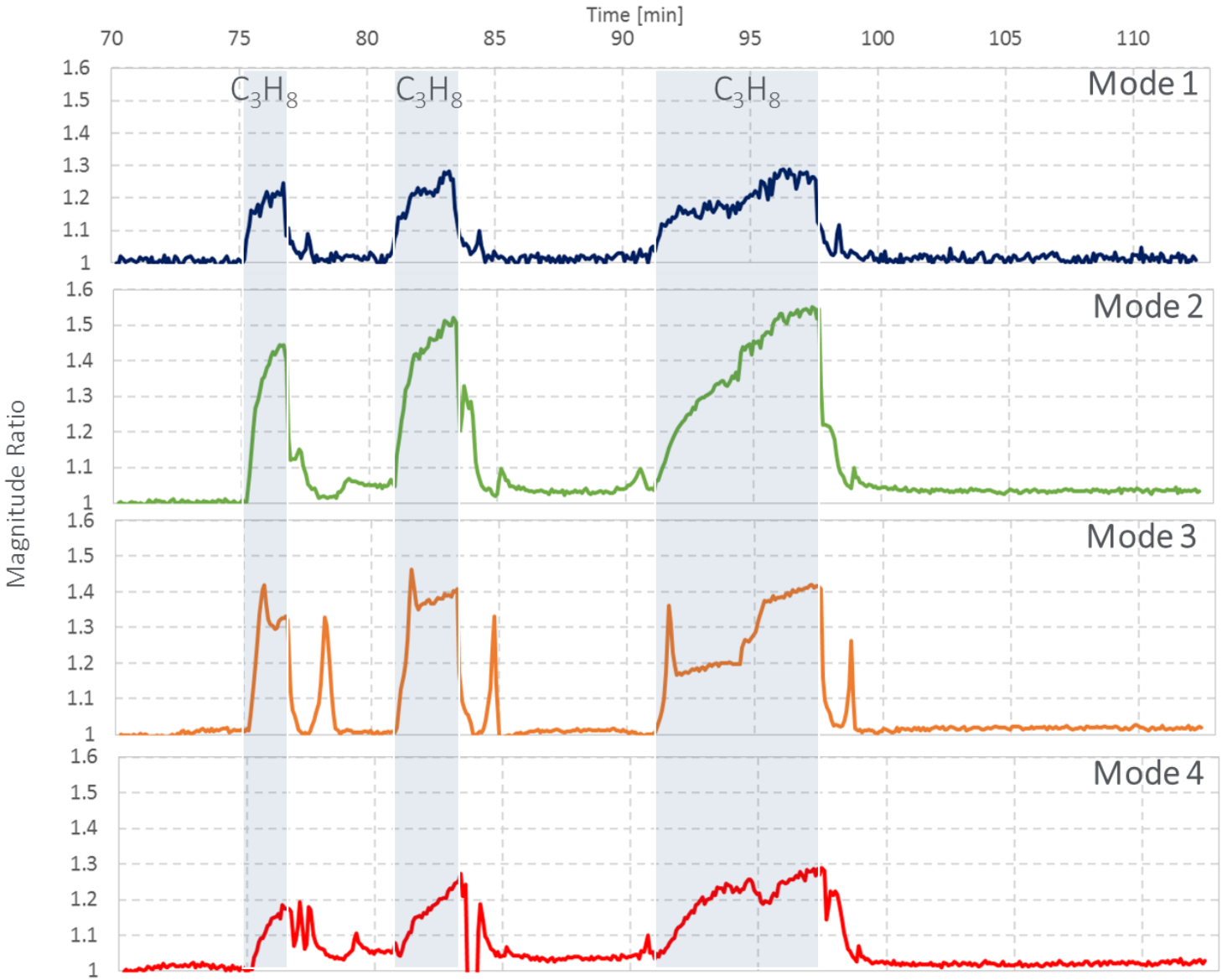


TWC core samples evaluated on bench reactor at CTS and ORNL

Large RF Response to Change in TWC Oxidation State

- Lean Conditions: Oxygen storage inhibits Ce conductivity (sharp resonances)
- Rich Conditions: Oxygen depleted state results in large dielectric loss
- Impact on specific resonances function of local electric fields

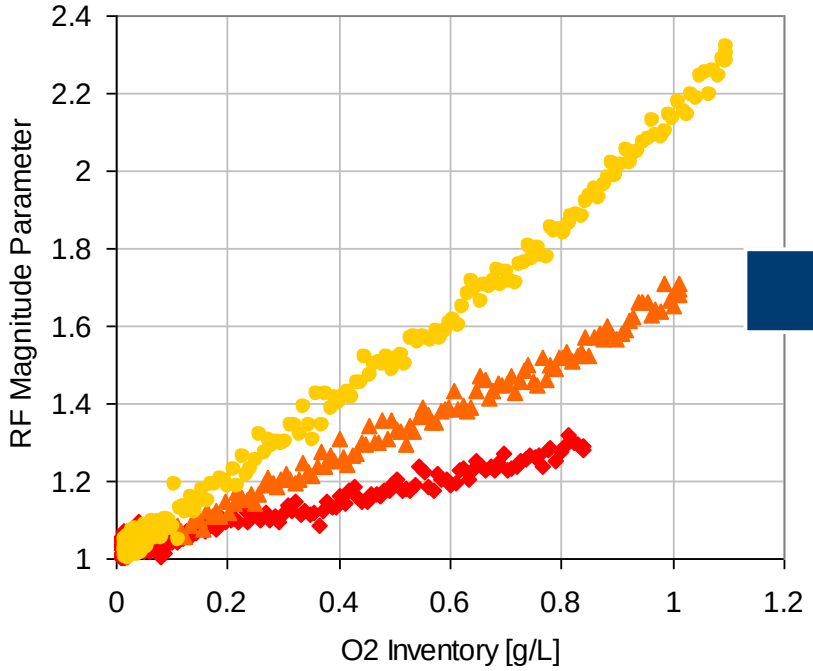
Response to TWC O_2 Storage / Depletion

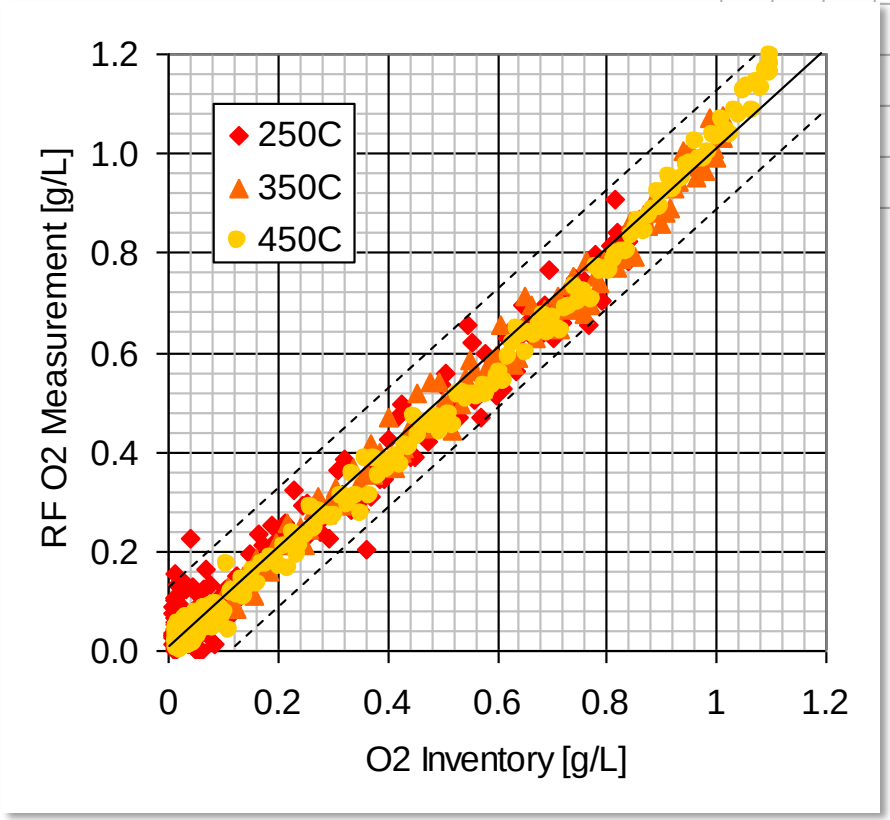


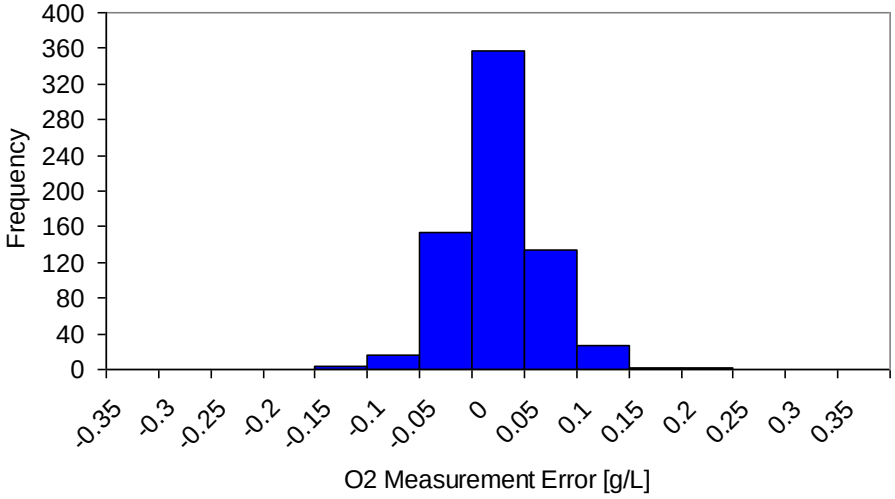
RF Resonances

- RF resonance response to O_2 depletion
- Modes respond quickly when HC added to system and stored O_2 on catalyst is consumed
- Characteristics of each mode vary, possibly indicating spatial sensitivity of signal to O_2 consumption

Oxygen Inventory Measurement on TWC







TWC Calibration Developed

- Developed RF calibration for oxygen storage measurements including temperature compensation within 10% of full-scale
- Calibrated RF sensor for the TWC has a mean measurement error of **0.000 g/L** and a standard deviation of **0.040 g/L**

Summary

RF Sensor Catalyst Application Feasibility Study

- Developed production-intent RF sensors
- Applied models for RF cavity response to guide experimental design and data analysis
- Coordinated experiments with industry and national lab project team
- Confirmed feasibility to directly measure stored ammonia on SCR and oxygen on TWC
- Developed initial SCR and TWC RF sensor calibrations to meet project accuracy targets
  - Demonstrated NH_3 storage measurements from 0 to 2.5 g/L with $2\sigma = 0.072$ g/L [lab]
- Started vehicle fleet testing on heavy-duty and medium-duty vehicles
- Conducted systematic analysis of noise factors for RF measurements

Outlook and Project Impact

- RF sensing may provide a paradigm shift for emissions control by providing a direct measurement of catalyst state – optimize control and system diagnostics
  - Robust and low cost emission controls are needed to overcome key barriers limiting the widespread use of advanced combustion engines

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  - New York City Dept. of Sanitation (Fleet Testing)