Your Partner in Smart Solutions

Improved Fuel Efficiency through Adaptive Radio Frequency Controls and Diagnostics for Advanced Catalyst Systems

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DOE Merit Review, Washington DC
June 2016

Filter Sensing Technologies Inc.

ID#: ACE099

Overview

Timeline

- **Project Start: October 2015**
- **Project End: December 2017**
- **Percent Complete: 15%**

Barriers

- Emission controls are energy intensive and costly
- Lack of "ready-to-implement" sensors and controls
- Durability of 120K miles for LD and 435 K miles for HD

Need sensors and controls to exploit efficiency potential of advanced engines!

Budget

- **Total Funding: $1,378,292**
  - DoE Share: $1,101,252
  - Contractor Share: $277,040
- **Government Funding**
  - Funding in FY15: $0
  - Funding for FY16: $468,828*

* Budgeted FY2016

Partners

- **Department of Energy**
- **Corning** – *Advanced Substrates & Catalysts*
- **Oak Ridge National Lab** – *Catalyst Testing*
- **Cummins** – *HD OEM Tech. Adviser*
- **Detroit Diesel** – *HD OEM Tech. Adviser*
- **FCA** – *LD OEM Tech. Adviser*
- **DSNY (New York)** – *Fleet Testing*

Relevance – 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.

Prior Accomplishments – DPF Sensors Developed

Prior DOE Project: DPF Sensors

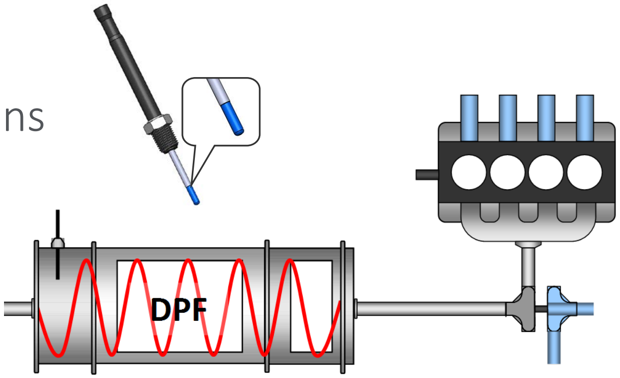
- Duration: 2012 – 2016
- Cost: $2M DOE, $0.6M Cost Share
- Industry, fleet, national lab partners

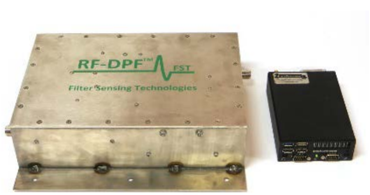
Objectives & Accomplishments

1. Developed RF sensors for DPF
2. Confirmed efficiency and performance gains
3. Technology commercialization

- Laid foundation for catalyst applications of RF sensing (this project ACE 0099)

1. **Patent Application:** US 61,897,825
2. **Publications:** 6 Technical Publications
    - SAE 2014, 2015, 2016
    - ASME 2013, 2015
3. **Presentations:** CLEERs, NBB, SV
4. **Awards:** R&D 100 Award 2014





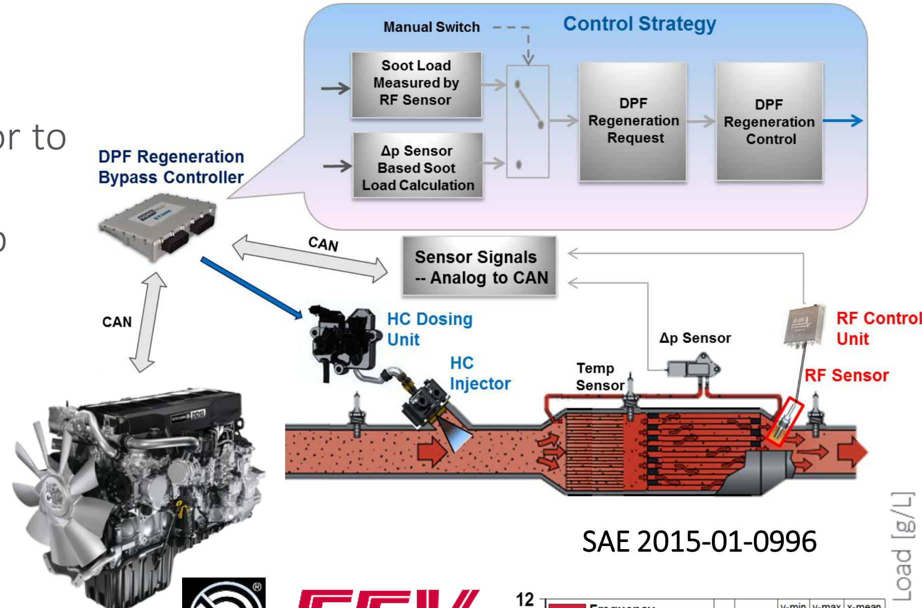
R&D 100 2014 Winner

Program Start | **Year 1** | **Year 2** | **Year 3**

Prior Accomplishments – High Performance Demonstrated

RF Filter Controls

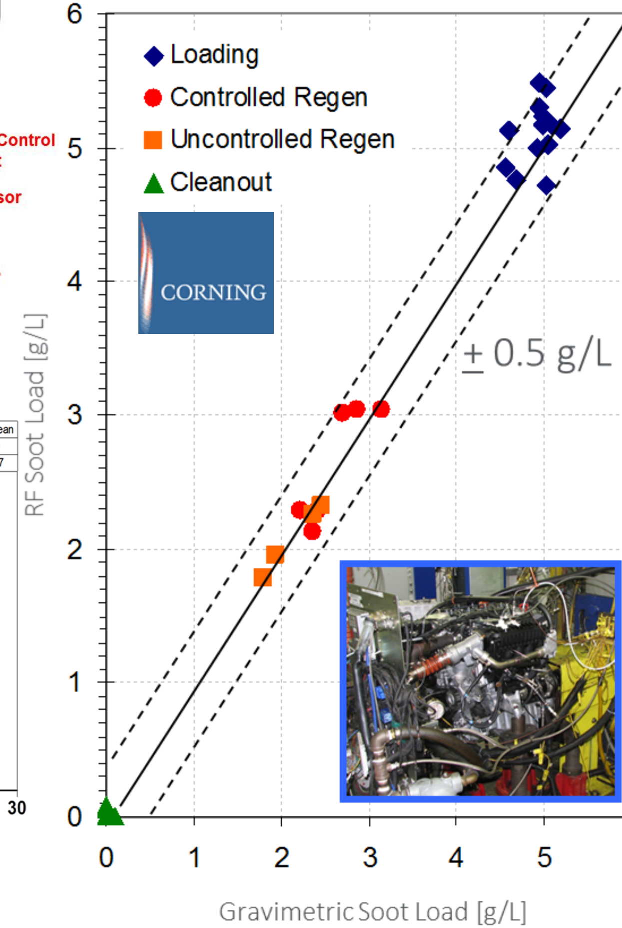
- Developed and supplied RF sensor to project team
- Direct closed loop feedback control
- DPF diagnostics
- Benchmarked vs. state-of-the-art aftertreatment controls



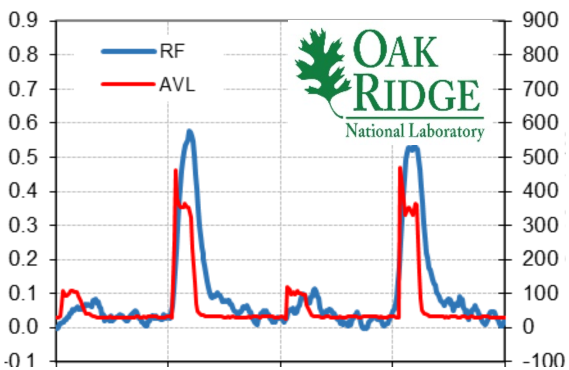
SAE 2015-01-0996

High Measurement Accuracy

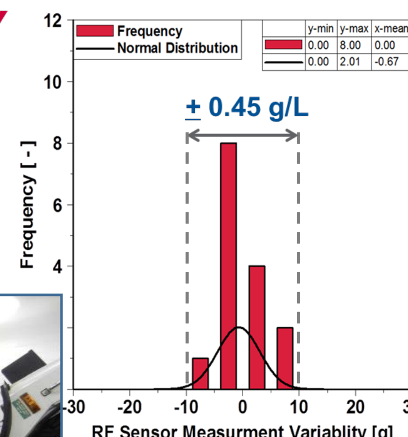
SAE 2016-01-0943



Fast Response Measurements



SAE 2016-01-0918



Light- and Heavy-Duty Applications

- Demonstrated with cordierite and AT filters

Prior Accomplishments – Advanced Filter Diagnostics

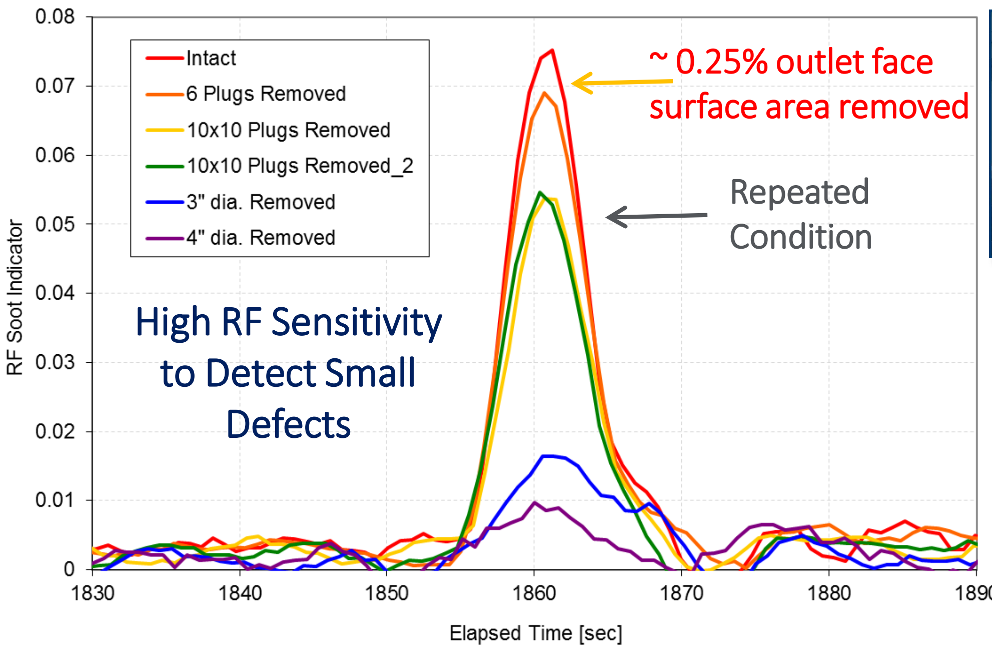
Filter Failure Detection – Possible OBD Applications

6 Plugs Removed
0.24% Face Area

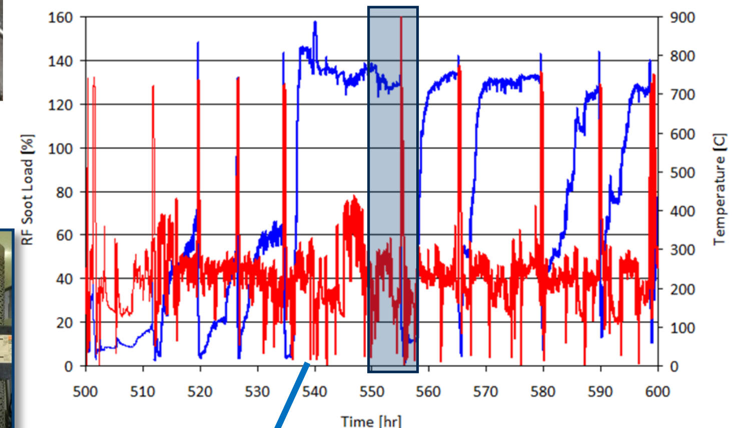
10x10 Square
4.0% Face Area

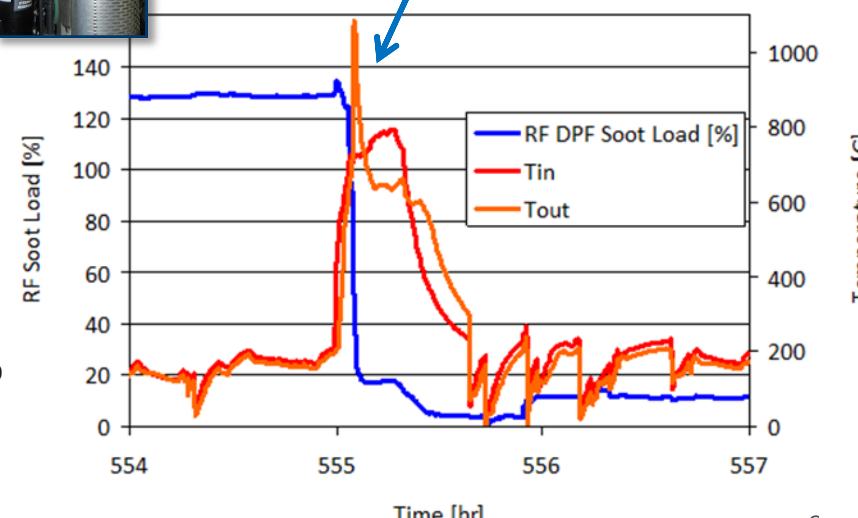
3 inch Dia.
28% Face Area

4 inch Dia.
52% Face Area



RF Detection of Malfunction Condition BEFORE DPF Failure On-Vehicle: DSNY Fleet Tests

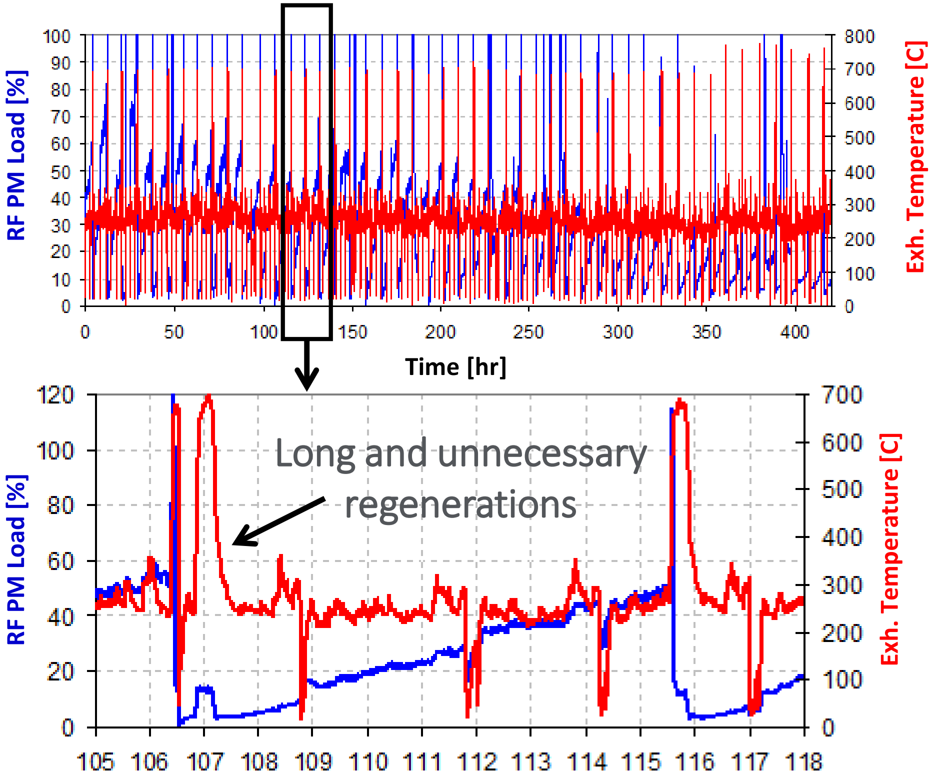




- Demonstrated applications for DPF OBD
- OBD important for practical implementation

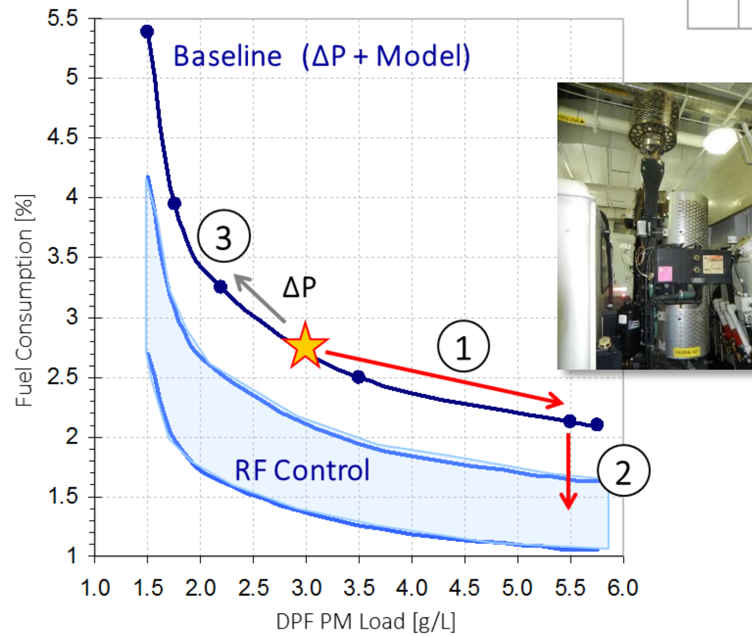
Prior Accomplishments – Efficiency Gains Evaluated

Fleet Tests Show Frequent Regenerations

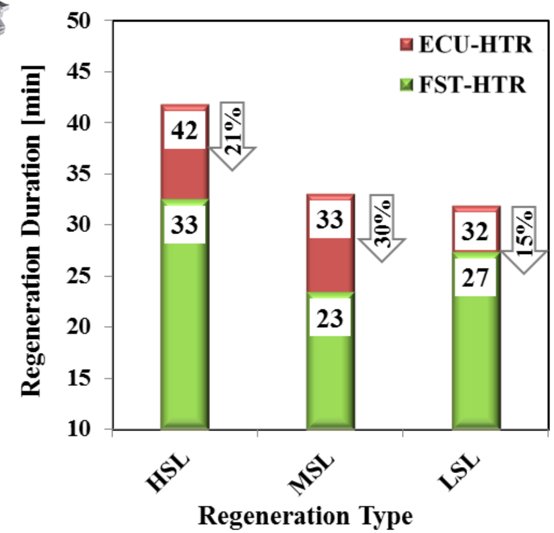


SAE 2014-01-2349

Regeneration Fuel Consumption



15% - 30% Shorter Regenerations



Efficiency Gains for RF-Based Controls

- OE control results in frequent regeneration 4%-5% of time vehicles are in operation (**NYC** urban drive cycles)
- Reduced regeneration duration (15%-30%) relative to MY 2013 HD engine and aftertreatment controls (SAE 2015-01-0996)

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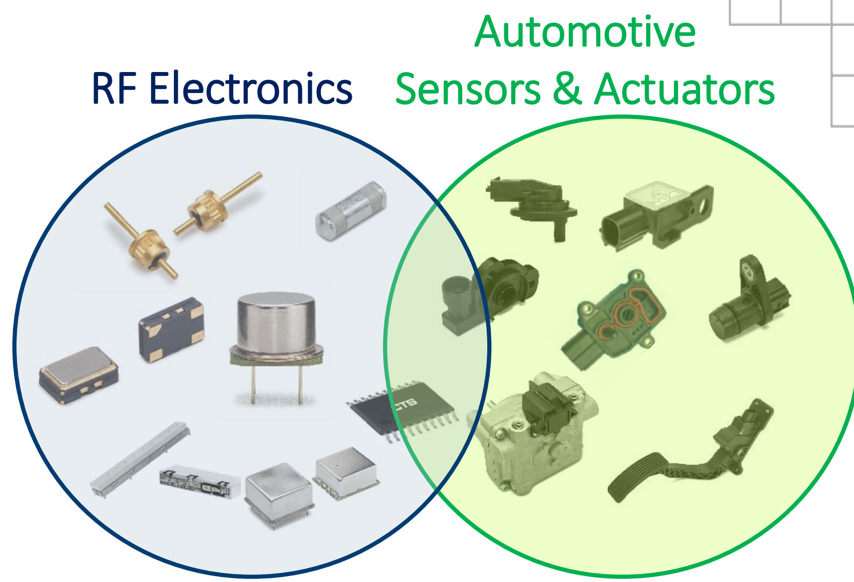
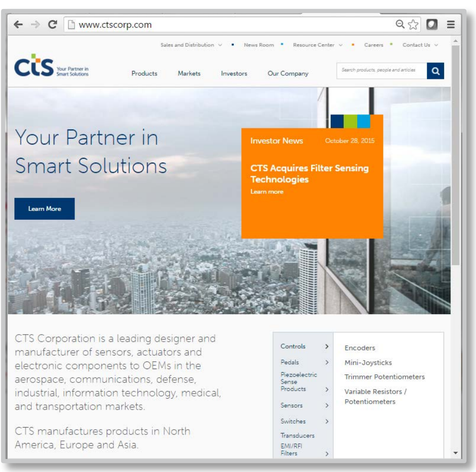
Prior Accomplishments – Commercial Objectives Achieved

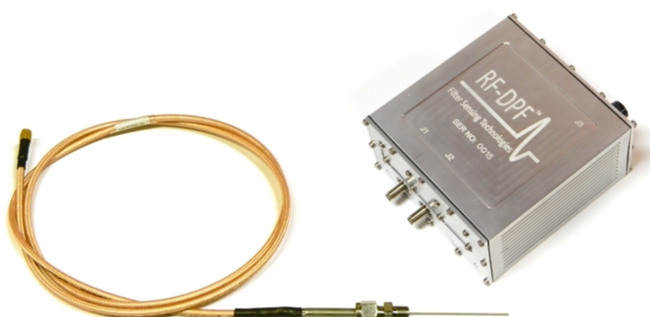
FST Acquired by CTS October 2015

- **Ticker:** CTS (NYSE)
- **Founded:** 1896, Chicago IL
- **Business:** CTS is a leading designer and manufacturer of sensors, actuators and electronic components.
- **Locations:** 11 manufacturing locations throughout North America, Asia and EU.
- **Number of Employees:** ~3,000 Globally

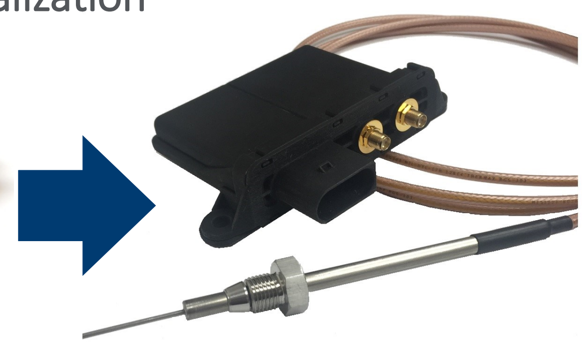




- CTS developing high-volume production RF sensor (DPF)
- Manufacturing in Elkhart, IN (USA)
- Lead OEM sales and commercialization

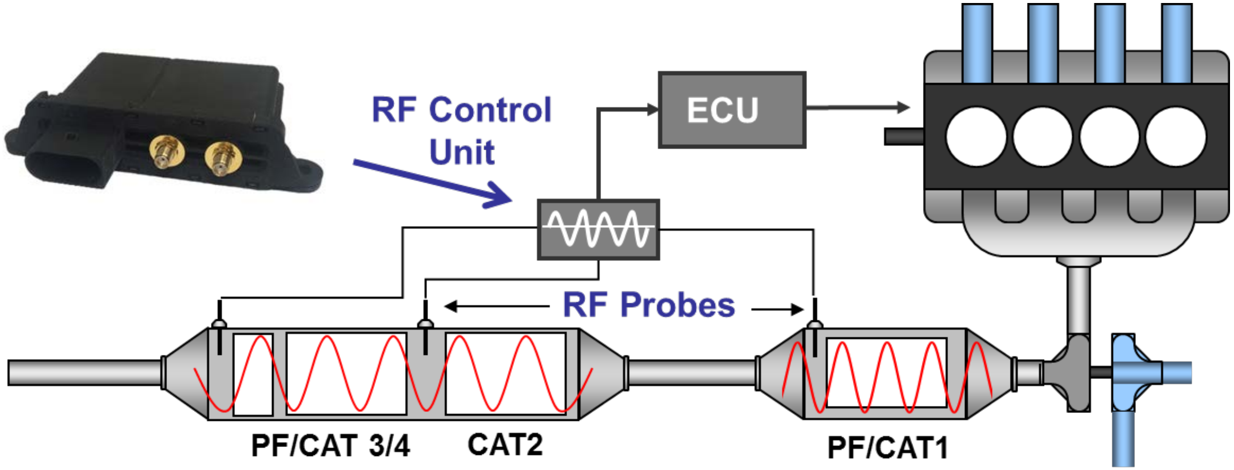


FST Prototype RF Sensor



CTS Production RF Sensor

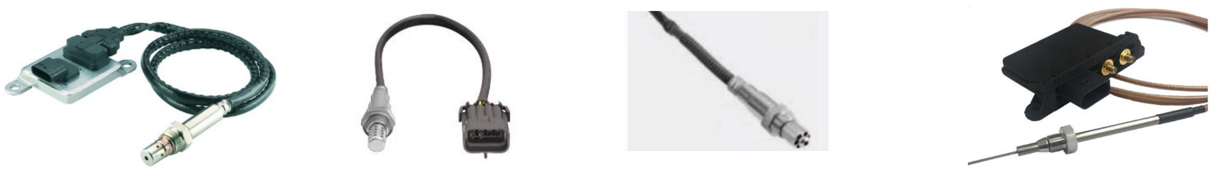
Relevance – Proposed Technology and Concept (Current Project)



- 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

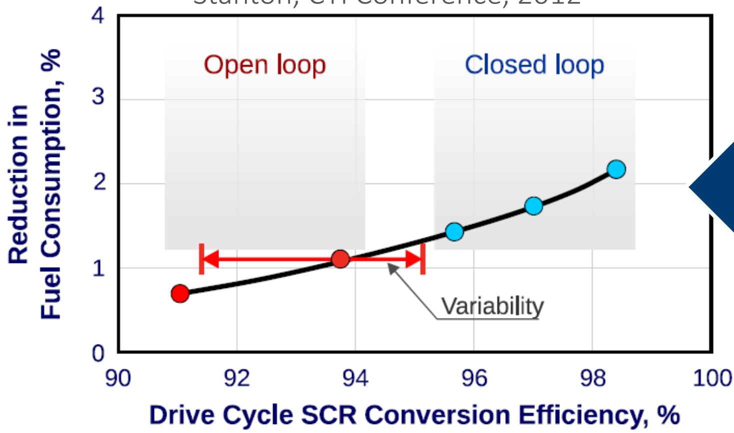
Current systems use many different types of exhaust gas sensors.

Relevance – Efficiency Gains Enabled via Smart Aftertreatment

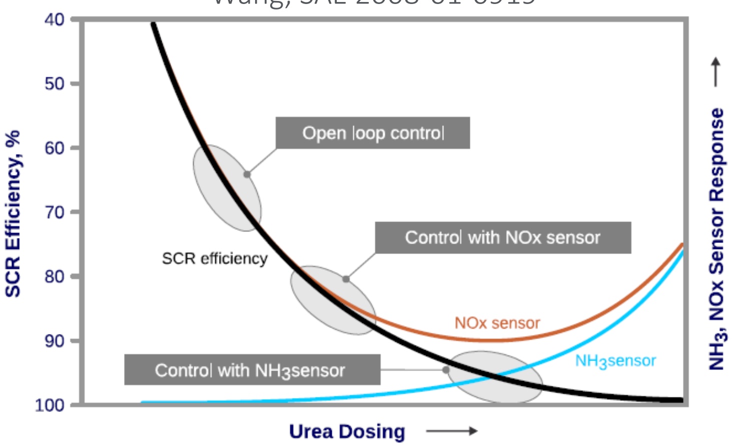
Diesel Efficiency Gains Enabled via Improved Aftertreatment   SAE 2013-0102421

Application	High Eff. NOx AT	Reduced EGR	Reduced Backpressure	Thermal Management
Line Haul	2.5%	1.0%	1.0%	0.0%
Vocational	2.5%	1.0%	1.0%	2.5%

Stanton, CTI Conference, 2012



Wang, SAE 2008-01-0919



Lean Gasoline Efficiency Gains Enabled via Lean NOx Control

Source	NOx Control	Fuel Savings vs. Stoich.	Engine Type
SAE 2011-01-0307	PASS	8.9% - 11.1%	SIDI V8 GM
SAE 2014-01-1505	PASS	1% - 7% (steady-state)	2.0L Lean BMW GDI
ACEC Roadmap 2013	LNT (MB), PASS (BMW)	12% - 20%	Mercedes, BMW

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Improved sensors and controls are key enablers for more efficient use of aftertreatment to deliver additional reductions in engine fuel consumption.

Technical Approach and Overview – YEAR 1

I. Application Feasibility

- Sensor Development
- Catalyst Screening Test & Modeling

II. Sensor Demonstration

- Sensor Optimization for Application
- Engine Dyno & Vehicle Evaluations

FST	ORNL	Corning	DSNY	OEM		Summary of Team Roles, Tasks, and Timeline	Year 1				Year 2			
							Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
						Phase I - Application Feasibility								
L					1	Project Management and Planning								
L					2	Develop RF Sensors								
	L				3	Evluate Application-Specific Feasibility								
L					4	Evaluate and Correct for Error Sources								
L					5	Develop Calibration Functions								
	L				6	Quantify Sensor Performance								
L					7	Year 1 Report								
						Phase 2 - Sensor Demonstration								
	L				8	Evaluate Optimized Sensor - Bench								
L	P	P			9	Evaluate Optimized Sensor - Test Cell								
			L		10	Evaluate Optimized Sensor - Vehicle								
L					11	Evaluate Optimized Sensor - Accuracy								
L					12	Develop Commercialization Plans								
L					13	Year 2 Report								

Work Completed   Work to be Completed   Milestone Achieved

Project Status

- Kick-Off 10/27/2015
- Q1 & Q2 focused on experimental setup and sensor development
- Technical planning meeting at ORNL with Cummins, Corning, FST/CTS February 2016
- Parallel integration activities with CTS acquisition 10/2015

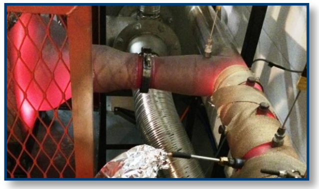
Approach – Project Milestones FY16 & FY17

Milestone Summary Table							
Recipient Name: Filter Sensing Technologies Inc.							
Project Title: Adaptive Radio Frequency Controls and Diagnostics for Advanced Catalyst Systems: Enabling Improved Fuel Efficiency and Reduced System Cost							
Task No.	**Task Title**	**Type**	**Mile-stone**	**Milestone Description**	**Milestone Verification**	**Date**	**Quarter**
1.0	Project Management and Planning	Milestone	M 1.0	Plan Updated	Team Review	Mo 3	Q1*
2.0	Develop RF Sensors	Milestone	M 2.0	Sensors Developed	Team Review	Mo 6	Q2
3.1	Ammonia Storage on SCR	Milestone	M 3.1	NH_3 Feasibility Report	Team Review	Mo 9	Q3
3.2	Oxygen Storage on TWC	Milestone	M 3.2	O_2 Feasibility Report	Team Review	Mo 14	Q5
3.3	HC Storage on Traps	Milestone	M 3.3	HC Feasibility Report	Team Review	Mo 15	Q5
3.4	Multi-Function SCR+Filter	Milestone	M 3.4	PM/NH_3 Feasibility Report	Team Review	Mo 12	Q4
4.0	Evaluate and Correct for Error Sources	Milestone	M 4.0	Errors Quantified	Team Review	Mo 15	Q5
5.0	Develop Calibration Functions	Milestone	M 5.0	Calibration Complete	Team Review	Mo 15	Q5
6.0	Quantify Sensor Performance	Milestone	M 6.0	Performance Quantified	Team Review	Mo 15	Q5
7.0	Phase 1 Report	Milestone	M 7.0	Report Submitted	Team Review	Mo 12	Q4
	Go/No-Go Decision Point	Decision	D 1.0	Targets Achieved	Team Review	Mo 12	Q4
8.0	Evaluate Optimized Sensor - Bench	Milestone	M 8.0	Bench Test Complete	Team Review	Mo 18	Q6
9.0	Evaluate Optimized Sensor - Test Cell	Milestone	M 9.0	Dyno Test Complete	Team Review	Mo 21	Q7
10.0	Evaluate Optimized Sensor - Vehicle	Milestone	M 10.0	Vehicle Test Complete	Team Review	Mo 24	Q8
11.0	Evaluate Optimized Sensor - Accuracy	Milestone	M 11.0	Accuracy Quantified	Team Review	Mo 24	Q8
12.0	Develop Commercialization Plans	Milestone	M 12.0	Plans Developed	Team Review	Mo 24	Q8
13.0	Phase 2 Report	Milestone	M 13.0	Report Submitted	Team Review	Mo 24	Q8

Decision Point : Go/No-Go achieved at conclusion of Phase I

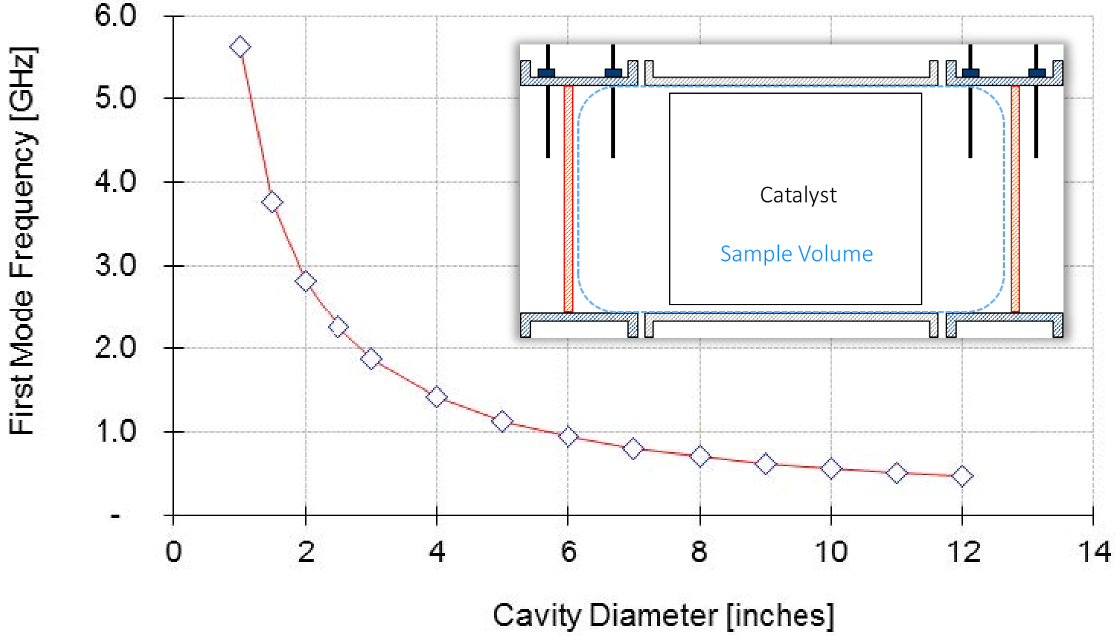
Approach – Quantify Sensor Performance and Fuel Savings

Team Member Contributions		Performance Metric
FST Inc.; 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; CTS	• OEM technical advisors • Catalyst samples • Design of experiments • Parallel testing	• System requirements • Production sensors • In-house models




Accomplishments – RF Cavity Development



Cavity Development:

- Developed small metallic cavities for core sample bench reactor measurements
- Analyzed trade-offs between cavity diameter and frequency range

Cavity Antennas

Core Sample Cavities

RF Instrumentation:

- Developed custom software for vector network analyzer
- Frequency range to 6.5 GHz for small cavity measurements
- Enables large dynamic range and high precision measurements

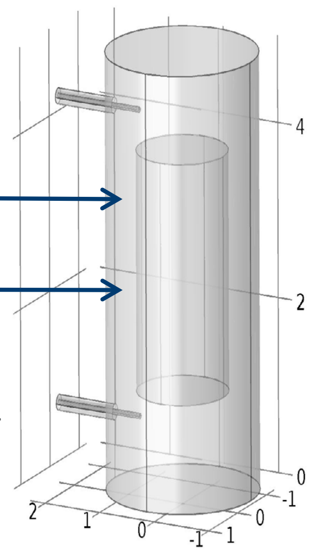
Accomplishments – RF Cavity Simulations

Antenna S1

RF Cavity

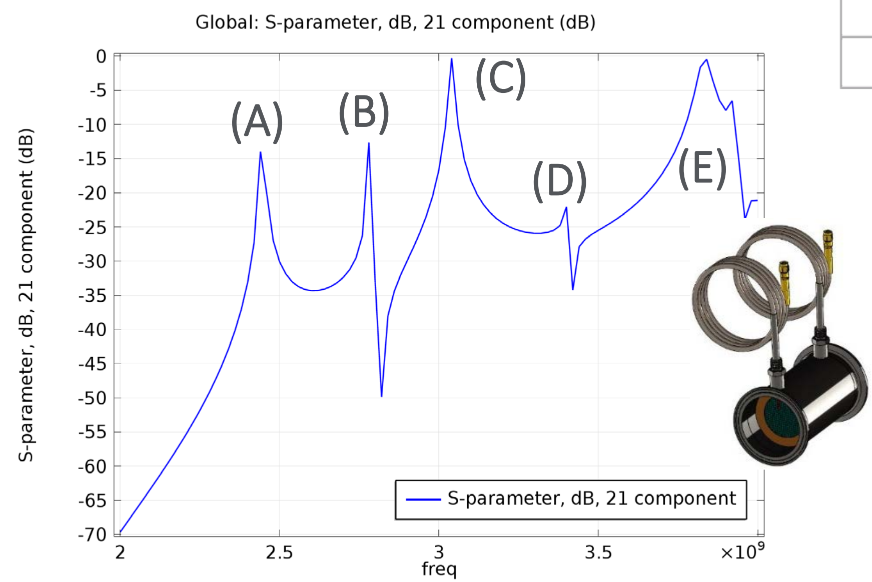
Catalyst Core

Antenna S2

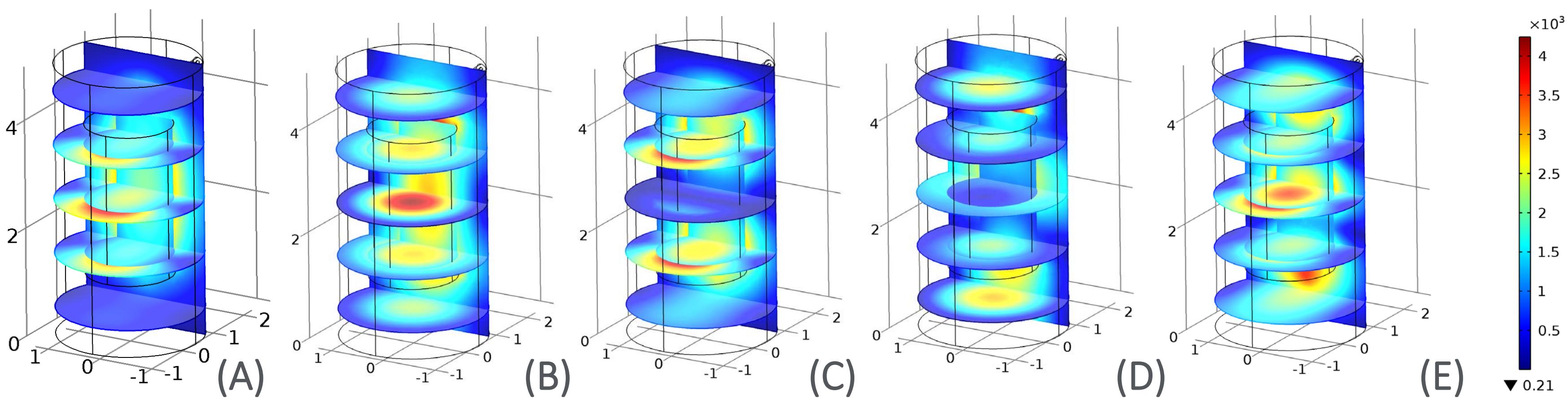


RF Simulations Developed to Guide Core Sample Cavity Designs

Simulated Cavity Resonances



Simulation Results of Cavity Electric Field Distribution



Electric field distributions provide spatial sensitivity to monitor local storage of gas species.

Accomplishments – Catalyst Selection and Preparation

Catalyst Samples Obtained (and in Process)

Catalyst Type	Application
SCR	Cummins 8.9L ISL (2015)
TWC	GM Malibu 2L DI or Chrysler V8 (2016)
HC Trap	Not in Production (Catalyst Supplier)
SCR + Filter	Not in Production (Custom Coating)

Samples harvested from Cummins SCR for bench reactor testing with core samples in Year 1

Commercial Gasoline Samples

Additional HC Traps and SCR+F samples to be obtained FY2016

Engine Testing

Second Cummins SCR system obtained for full-size engine testing at Corning in Year 2

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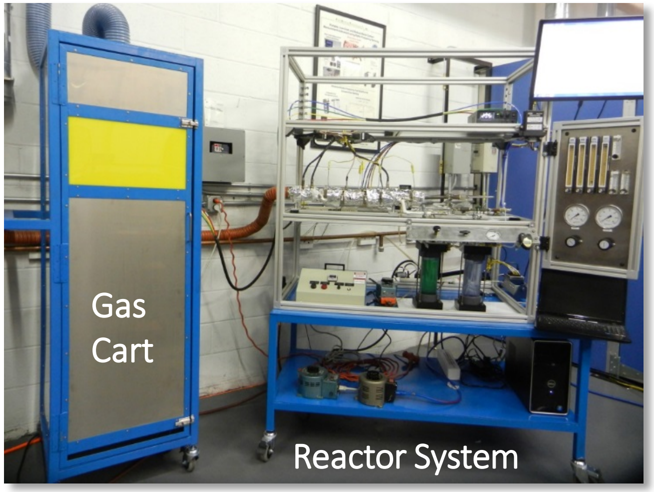
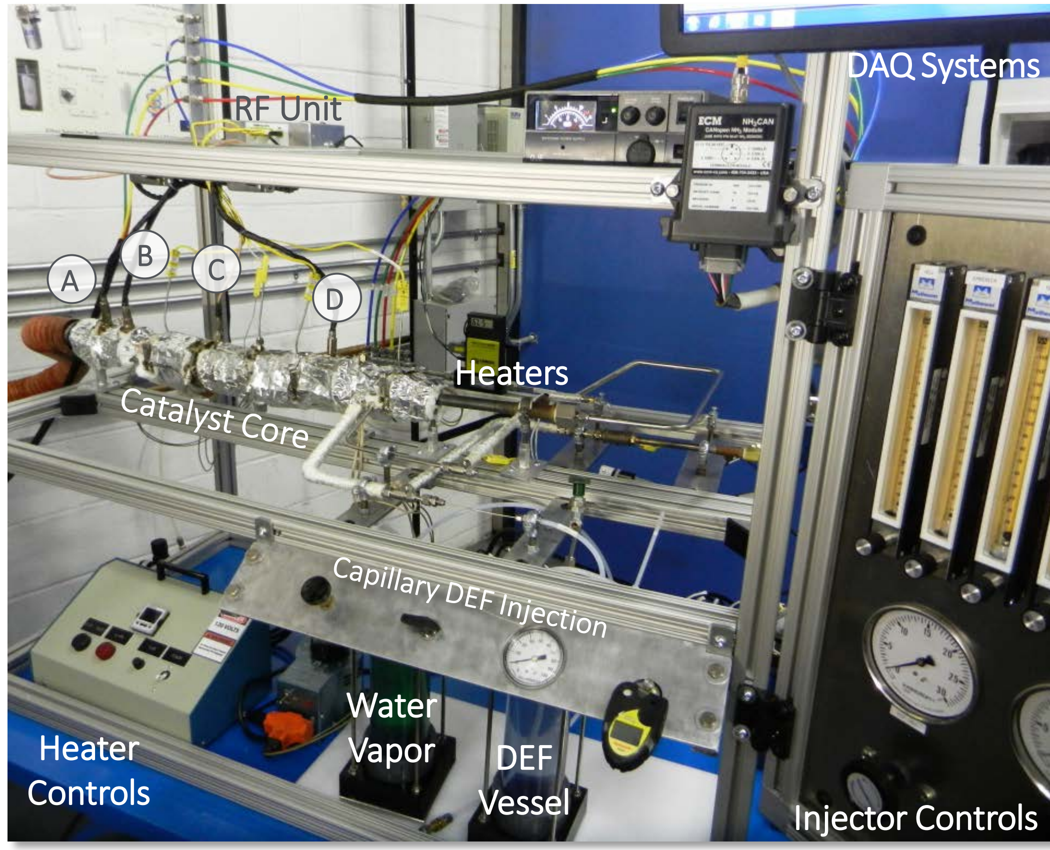
Accomplishments – Commissioned Bench Reactor System

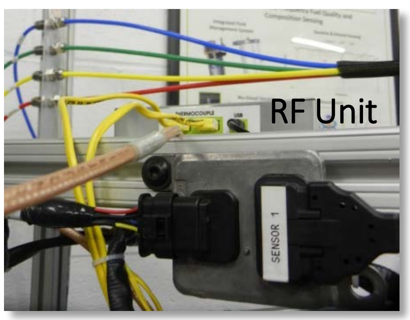
Reactor System Developed



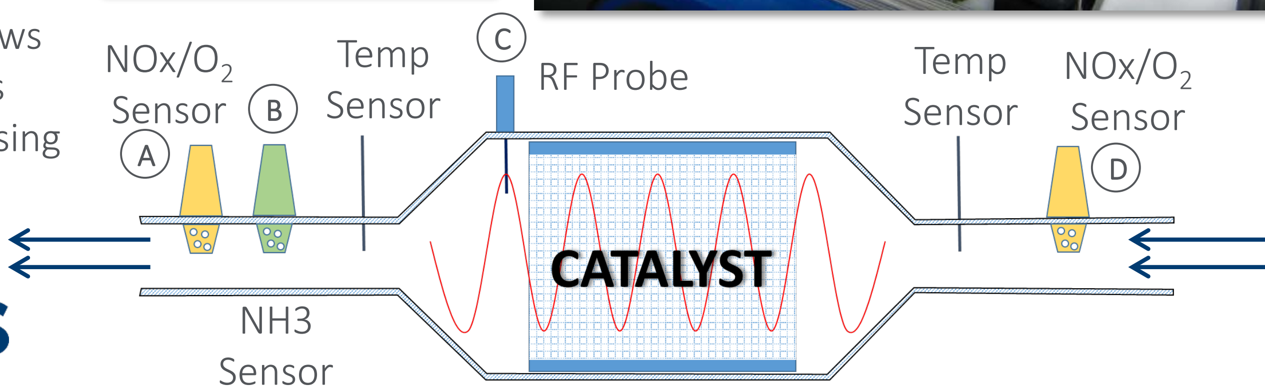
Controlled Exhaust Conditions + DEF Dosing Capable



Sensors
- RF System
- NOx/O_2
- NH_3 Sensors

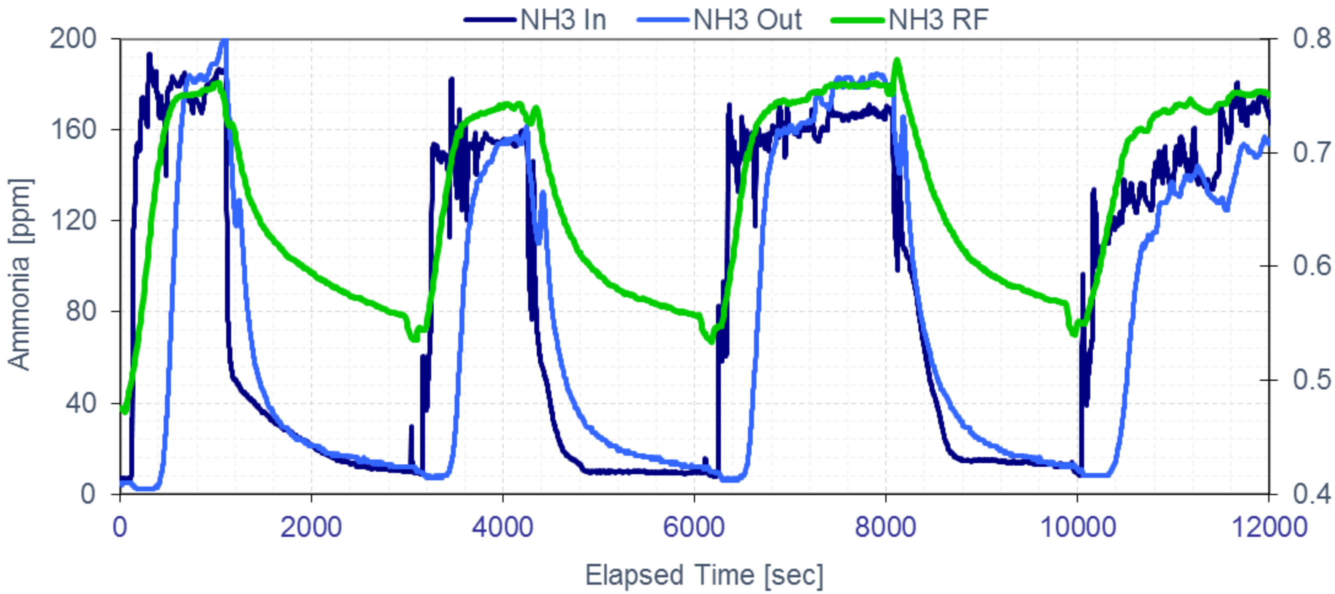


Controls
- Gas Flows
- Heaters
- DEF dosing or NH_3



Mixture Preparation
- N_2, NO, NH_3, O_2, H_2O
- Temp: 100 – 550 °C
- Flow: 0 – 100 slpm

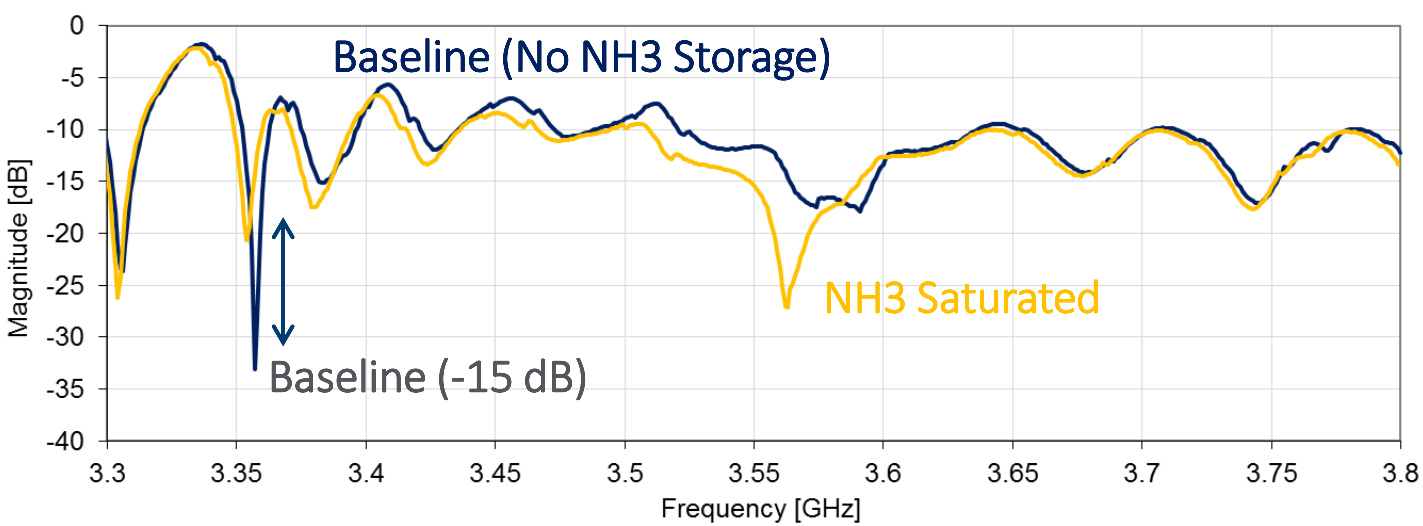
Accomplishments – Ammonia Storage on SCR



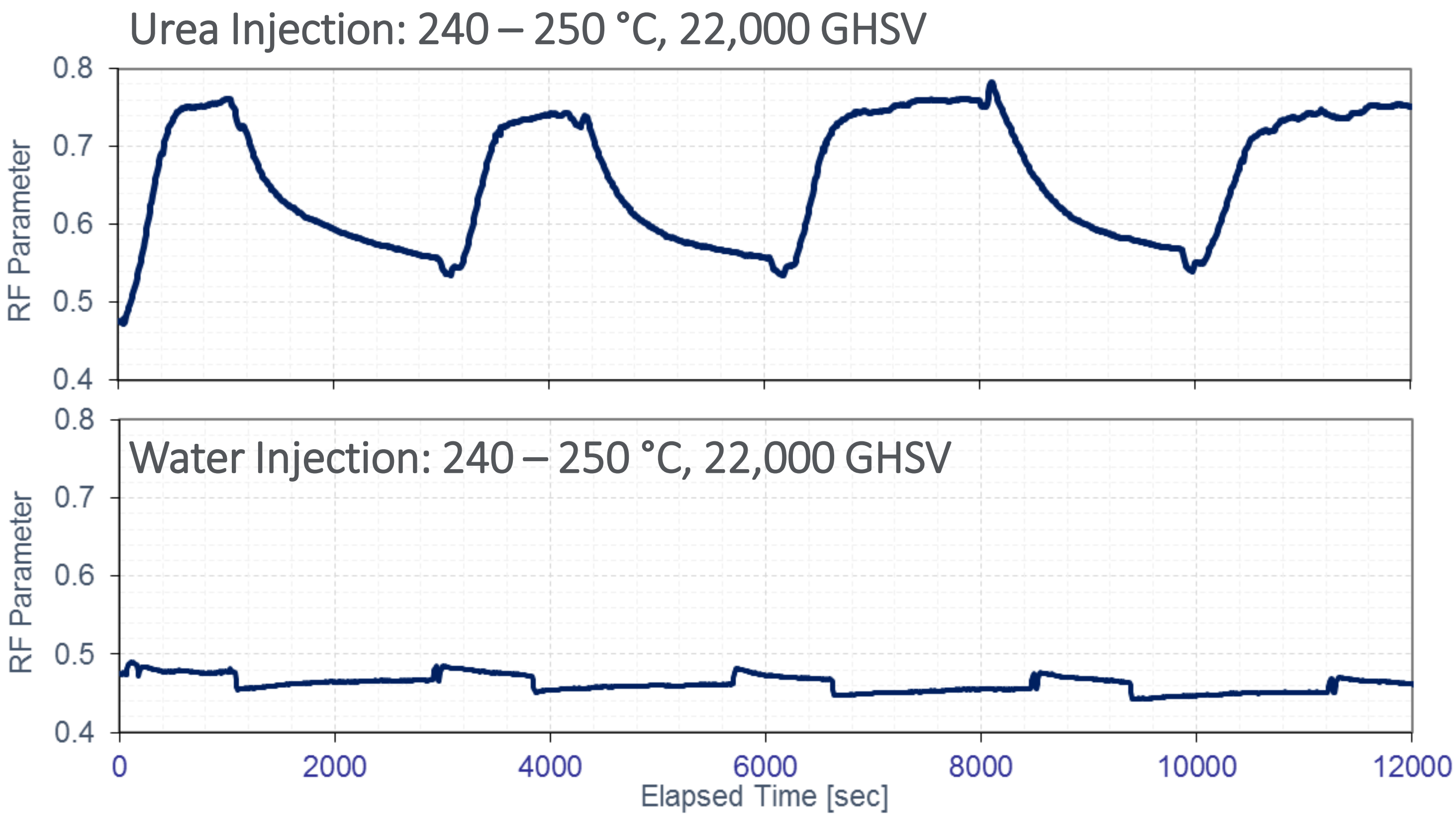
NH3 Storage

- SCR catalyst
- Measurements at 22,000 GHSV and 250 °C catalyst temp
- Urea injection on bench reactor using commercial DEF
- RF tracks NH3 stored on catalyst relative to NOx sensors (absence of NOx)

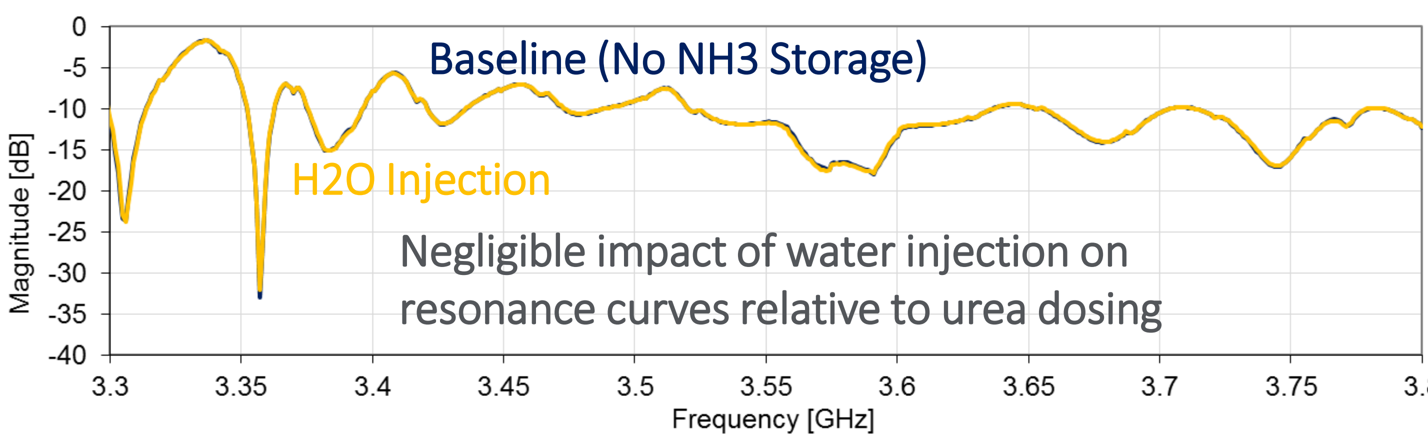
Raw RF resonance curves show impact of NH3 on single antenna (S11) measurements.



Accomplishments – Analysis of Error Sources (Water Injection)



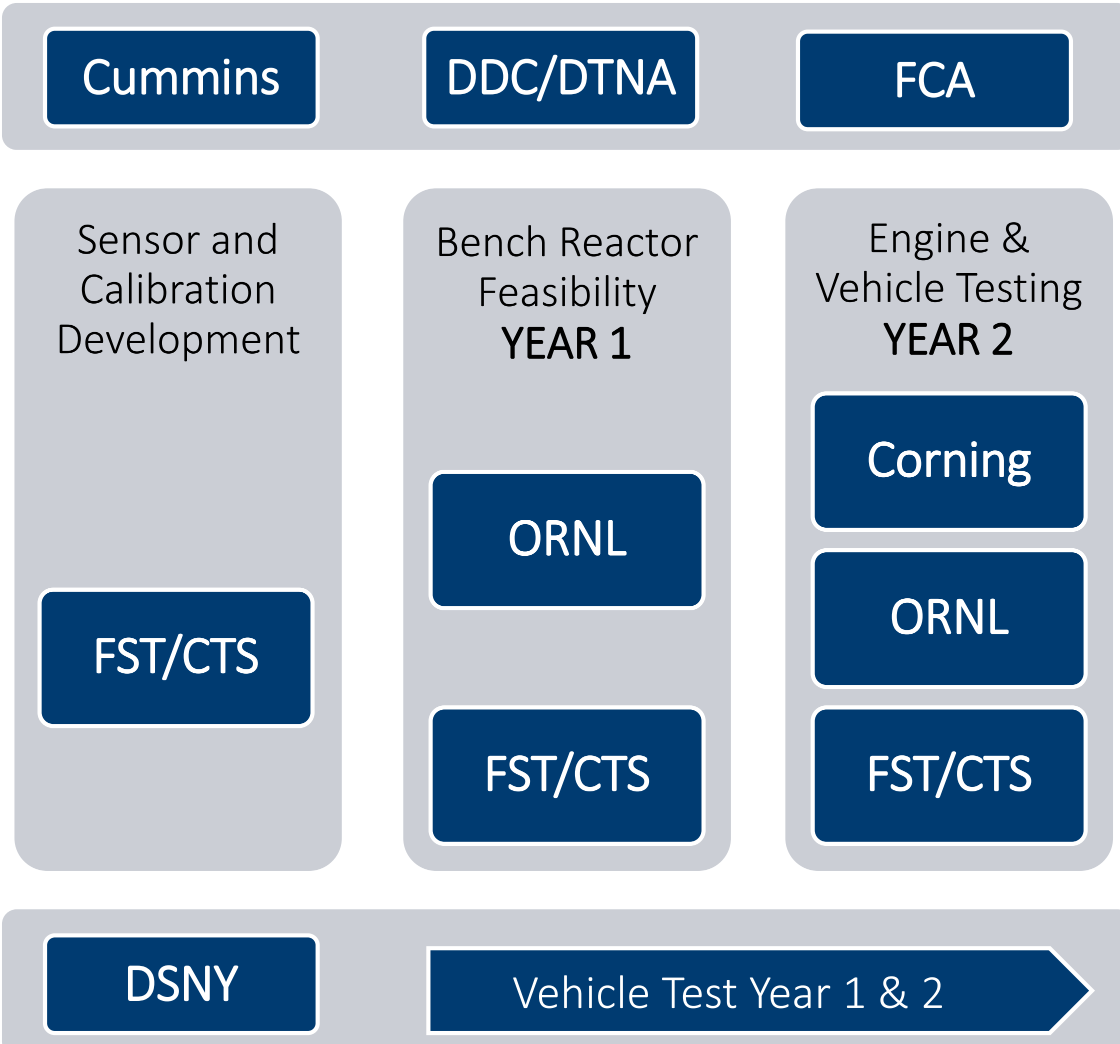
Urea and water injected at the same rates on catalyst bench reactor



Response to Previous Year Reviewer's Comments

Project was initiated Q4 2015 (FY2016).

Collaboration and Project Coordination



OEM Technical Advisors

- Input on project direction, data review, sensor specifications
- Spans LD/HD, diesel & gasoline

Core Project Team

- **FST/CTS** project lead: developing RF sensors for distribution to project team
- **ORNL** lead catalyst reactor testing in Year 1 and conduct LD engine testing in Year 2
- **Corning** provides catalyst and substrates in Year 1 and HD engine testing in Year 2 (cost share)

Vehicle Fleet Testing

- Conducted with NYC Sanitation HD vehicle fleet
- On-road durability and performance evaluations

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Remaining Challenges and Proposed Future Work

Current Status

- Project recently kicked-off and initial work focused on setup of experimental systems, modeling, and sensor development.
- Current focus is on evaluating RF sensor performance and feasibility for catalyst applications including clean diesel, lean gasoline, and LTC.

Phase I Application Feasibility (2016)

- Bench Reactor Feasibility Analysis
  - **Diesel:** Urea SCR, SCR+F
  - **Lean Gasoline:** Passive SCR / TWC
  - **LTC:** HC Traps
- Evaluate Error Sources – Noise Factors
- Develop Calibrations – Signal Analysis
- Assess Performance vs. OEM Specifications

Phase I Sensor Demonstration (2017)

- Distribute Optimized Sensor to Team for:
  - Bench Reactor Validation
  - Engine Dyno Test: HD & LD
  - Vehicle Fleet Test: HD
- Quantify Overall System Performance
- Develop Estimates of Overall system Efficiency Gains via RF Control
- Quantify System-Level Fuel Savings

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Summary

Project Initiated Q4 of 2015

- RF sensing for DPF successfully developed in prior DOE program
- Clear path to commercialization to meet the overall project objectives

Accomplishments in Q1 – Q2

- Developed and fabricated RF cavities for bench reactor evaluations in Phase I
- Applied models for RF response to guide cavity design and test setup
- Coordinated experiments with industry and national lab project team
    - Selected representative 2015/2016 catalysts for reactor core and engine tests
- Commissioned catalyst bench reactor system including integrated NH_3 and NO_x sensors as well as urea dosing to simulate real-world conditions
    - Evaluated RF sensor response to ammonia storage on SCR catalyst
    - Investigated influence of noise factors (water) on RF signal response

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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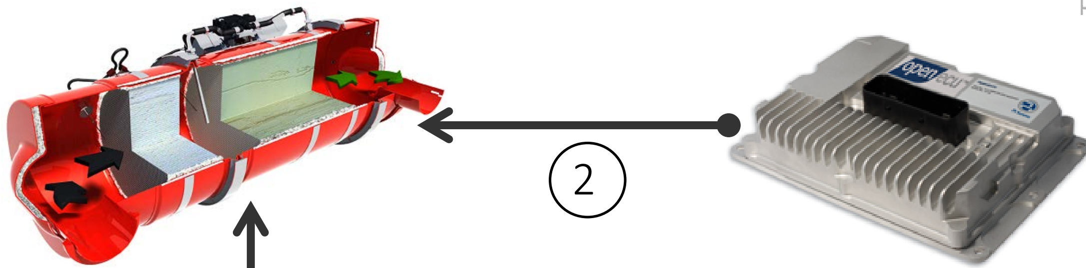
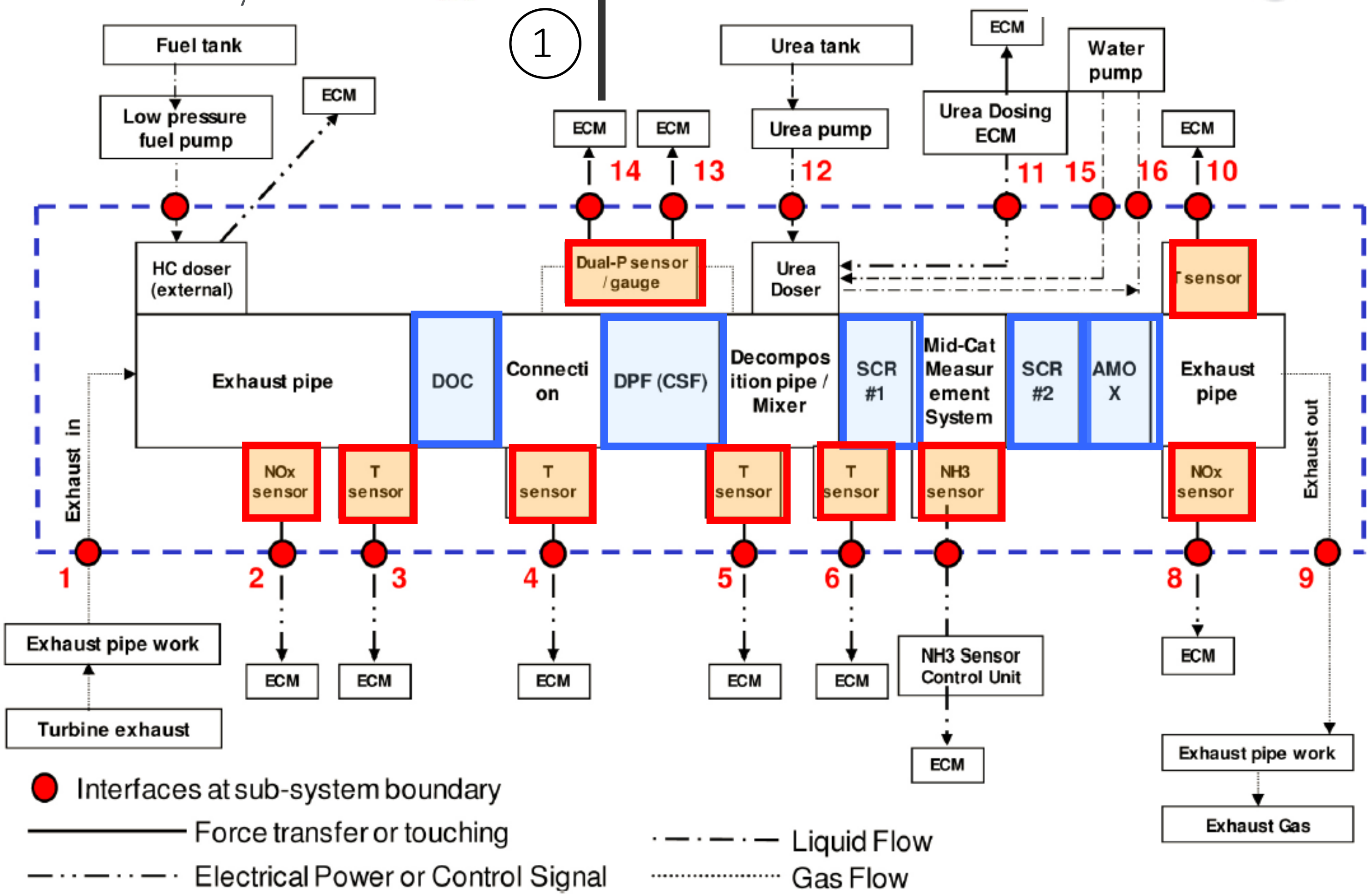
ACE099 AMR 2016

Technical Backup Slides

Challenge: Determination of Catalyst State

- Current systems rely on (1) gas sensor measurements and (2) models (indirect)
- RF-based approach provides <u>direct</u> measure of catalyst state

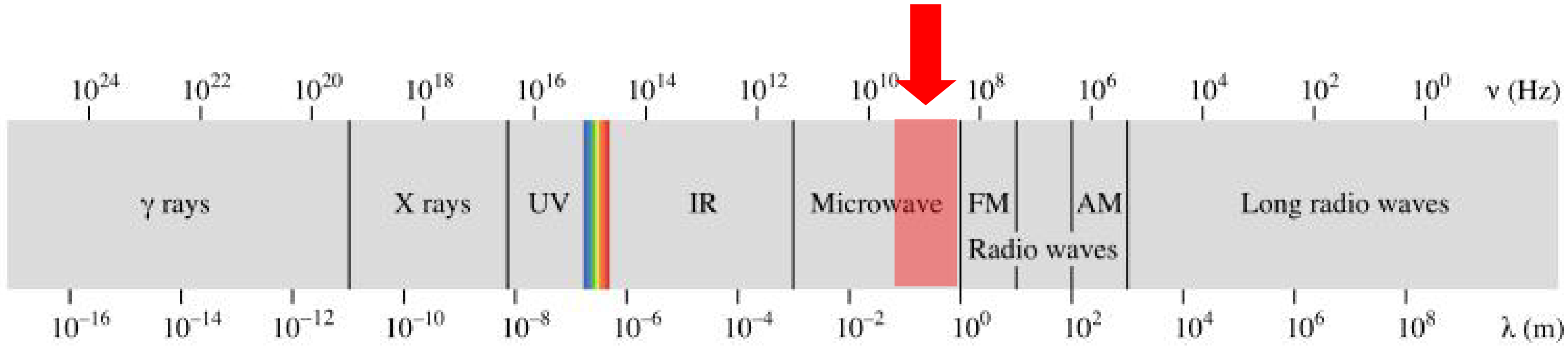




Stanton, D., "Systematic Development of Highly Efficient and Clean Engines to Meet Future Commercial Vehicle Greenhouse Gas Regulations," SAE Int. J. Engines 6(3):1395-1480, 2013

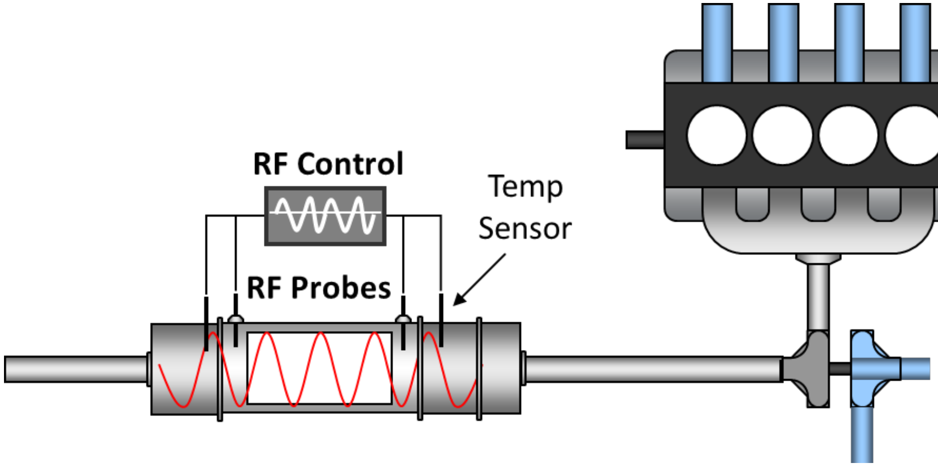
RF Measurements and Material Dielectric Properties

Microwave Frequency Range



Microwave Cavity Resonance

- Utilize filter housing as resonant cavity
- Resonant modes established in conducting cavities at specific frequencies
- Signal characteristics of modes affected by material through which the wave travels

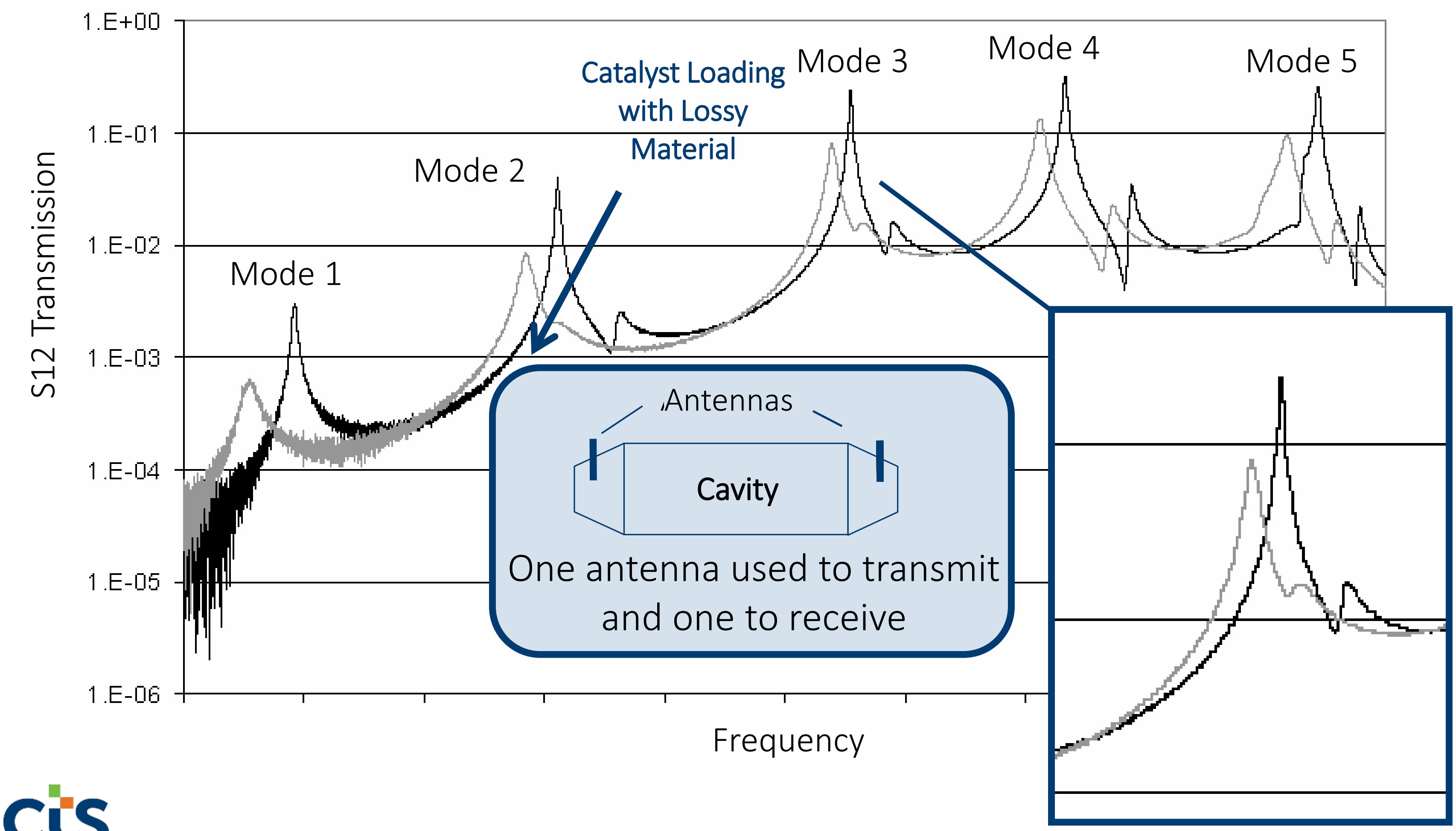


Signal Affected by Dielectric Properties of Exhaust Species

$$\kappa = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \qquad \tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$$

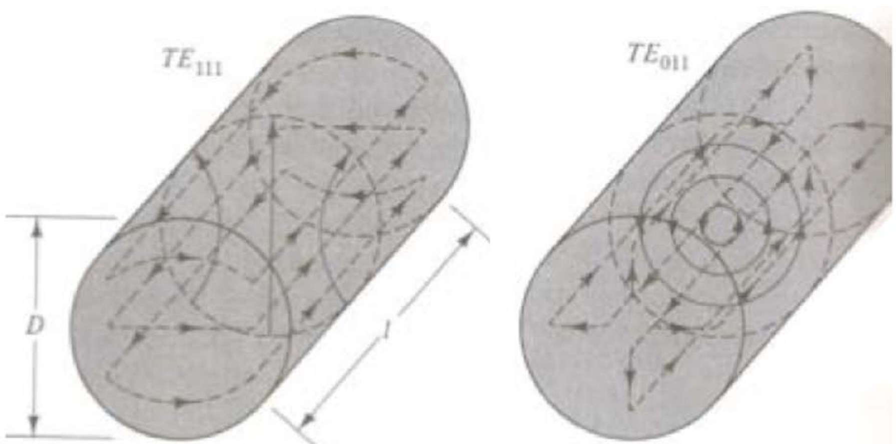
Example of RF System Operation: Transmission

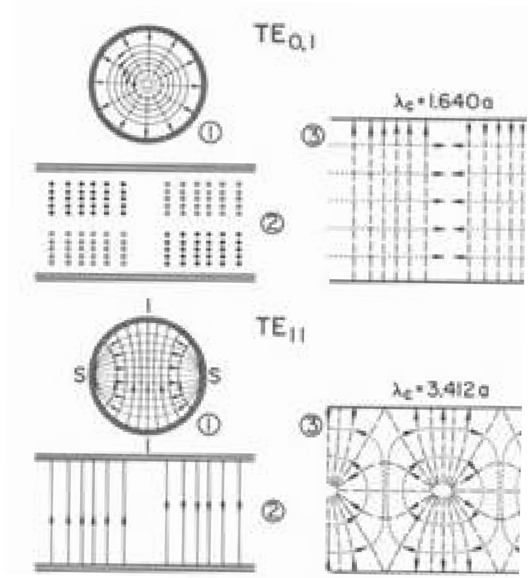
- Multiple modes exist in the cavity depending on frequency of operation
- Mode structure (field profiles, direction) depend on the geometry and the frequency



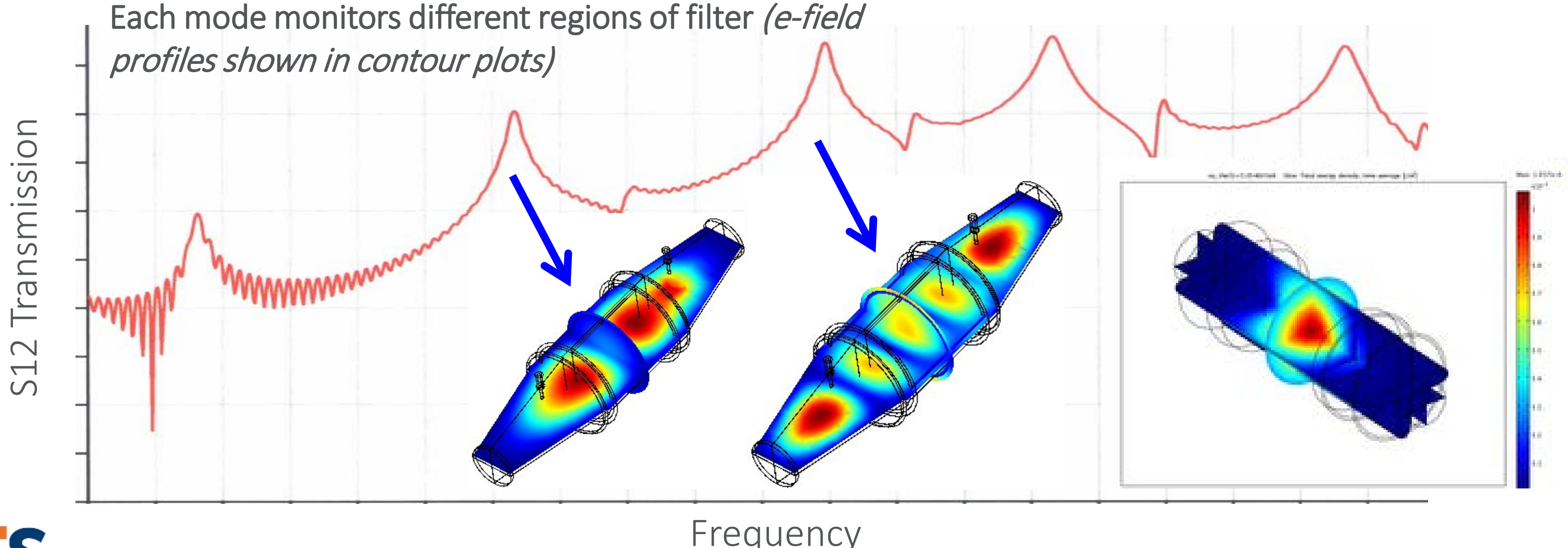
Resonant Modes Provide Spatial Information

Typical Resonant Mode Electric Field Profiles*





RF System Models for Filter-Specific Geometries

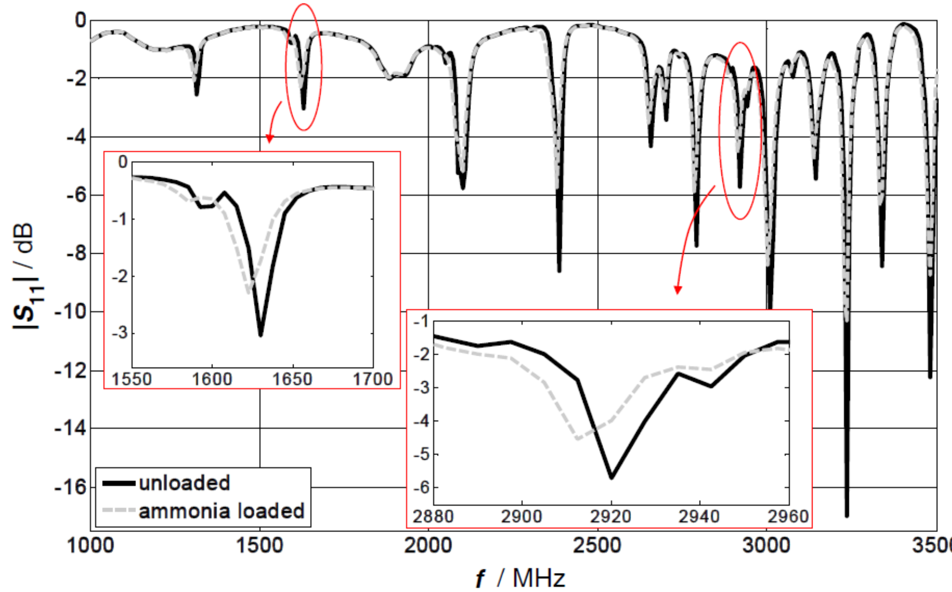


* Adam, Stephen, F., Microwave Theory and Applications, Prentice Hall, Inc., Engelwood Cliffs, New Jersey, 1969.

Literature Review – Relevant Prior Work

SCR:

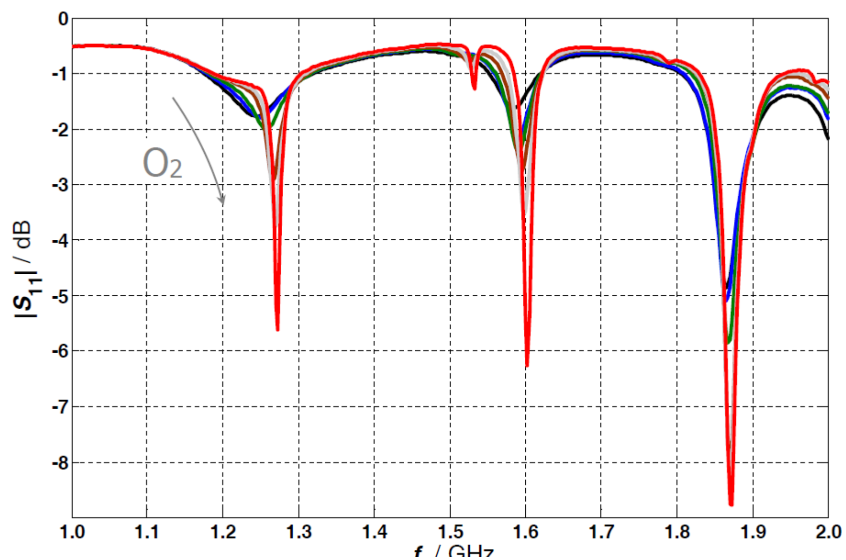
Reflection (1 antenna) for unloaded and ammonia-loaded conditions at 300 °C



S. Reiß, D. Schönauer, G. Hagen, G. Fischerauer, R. Moos, Monitoring the ammonia loading of zeolite-based ammonia SCR catalysts by a microwave method, Chem. Eng. Techn., 34, 791-796 (2011)

TWC:

Reflection (1 antenna) for oxygen storage on three-way catalyst at 400 °C



total flow:
20 l/min N_2

stepwise oxygen loaded by adding 3000 ppm O_2 for 1 min each

$T \approx 400$ °C

S. Reiß, M. Spörl, G. Fischerauer, R. Moos,
Realabgastauglichkeit einer HF-gestützten Automobilabgasdiagnose, G. Gerlach, P. Hauptmann (Hrsg.), 9. Dresdner Sensor-Symposium, 7.-9. Dezember 2009, Dresden, p. 263-266

Thank You