Development of Radio Frequency Diesel Particulate Filter Sensor and Controls for Advanced Low-Pressure Drop Systems to Reduce Engine Fuel Consumption (06B)

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ID#: ACE089

Overview

Timeline

- **Project Start: July 2012**
- **Project End: June 2015**
- **Percent Complete: 58%**

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 CIDI engines!

Budget

- **Total Funding: $2,564,850**
  - DoE Share: $1,999,884
  - Contractor Share: $564,966
- **Government Funding**
  - Funding in FY13: $385,783
  - Funding for FY14: $838,028*

* Budgeted FY2014

Partners

- **Department of Energy**
- **Corning** – *Advanced DPFs*
- **Oak Ridge National Lab** - *Testing*
- **FEV** – *Controls Development*
- **MM/SG** – *Electronics Manufacture*
- **Detroit Diesel** – *Tech. Adviser*
- **DSNY (New York)** – *Fleet Testing*

Relevance – Project Objectives

Address Technical Barriers to reduce diesel particulate filter (DPF)-related fuel consumption, improve system durability, and reduce overall system cost and complexity.

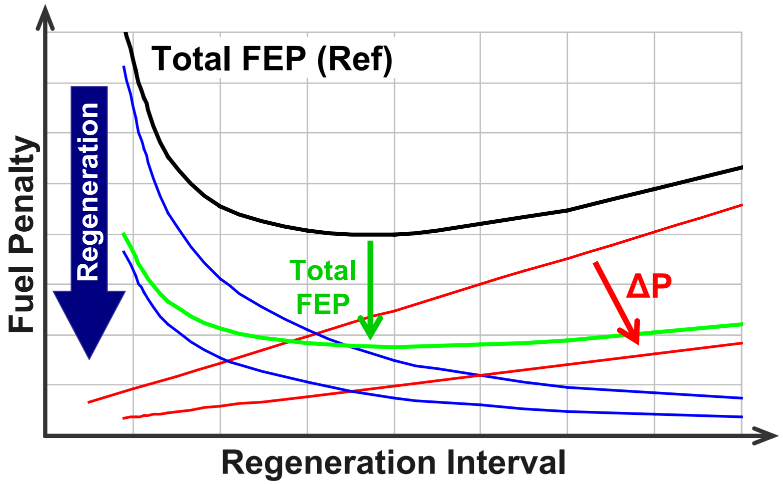
Develop RF Sensor for direct measurements of DPF soot and ash loading with advanced low ΔP systems.

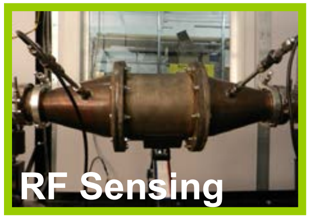
The specific project objectives include:

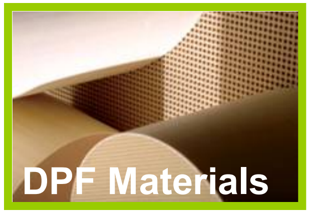
1. **Develop RF sensors** and adaptive feedback controls for direct, in-situ measurements of DPF soot and ash levels.
2. **Quantify fuel savings** with RF sensors and controls in engine dyno and on-road fleet tests in light- and heavy-duty applications.
3. **Explore additional efficiency gains** with advanced combustion modes, alternative fuels, and advanced aftertreatment via RF sensing and control.
4. **Develop production designs** and commercialization plans on the scale to significantly reduce greenhouse gas emissions and fuel consumption.

Relevance – Proposed Technology and Concept

Motivation: Enable reduced energy consumption, cost, and increased durability of particulate filter systems through improved sensing and controls.



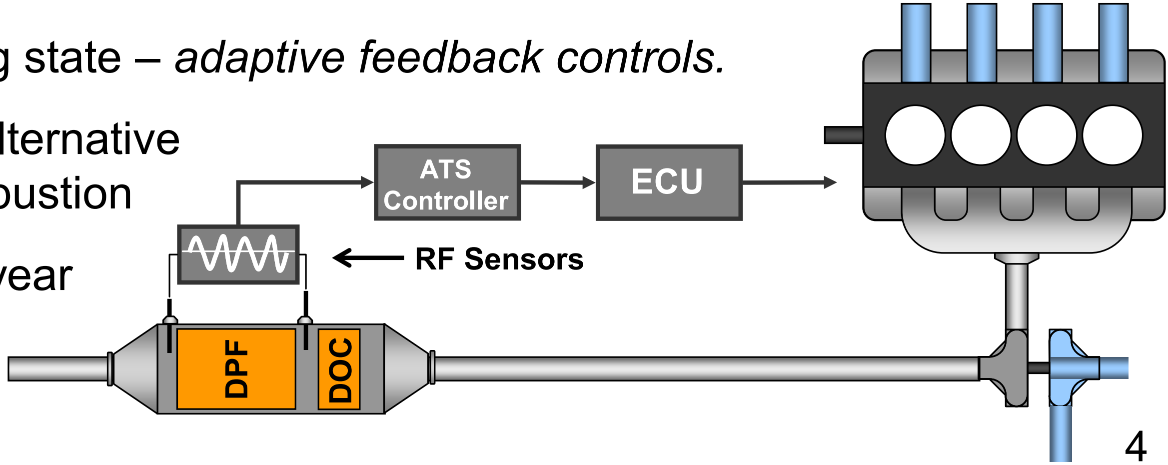




Advanced Controls

Concept: Apply inexpensive radio frequency (RF) technologies to directly monitor DPF soot **AND** ash levels and distribution with low-ΔP DPF materials.

- Direct measure of loading state – *adaptive feedback controls.*
- Additional benefits with alternative fuels and advanced combustion
- Pay-back on sensor < 1 year based on fuel savings
- Applications for OBD



Technical Approach – Overview & YEAR 2

I: Research & Development	II: Performance Evaluation	III: System Level Dev. and Testing	IV: Pre-Production Design

- **Phase I – RF Sensing Research and Development** ✓
  - Initial prototype design and development (alpha)
- **Phase II – Sensor Performance Testing and Evaluation**
  - Alpha prototype performance evaluation
- **Phase III – System Level Testing and Evaluation**
  - Beta prototype design and development
  - Control strategy design and development
  - System integration and testing
- **Phase IV – Pre-Production Designs and Commercial Plans**
  - Pre-production system designs and planning
- Results will provide over **48 months of real-world data** to quantify RF fuel savings and demonstrate on-road durability.

Approach – Project Milestones FY13 & FY14

Phase 2 - Sensor Testing		
2.1	Error Sources Identified	Complete
2.2	Correction Methods Developed	Complete
2.3	Prototype PM Measurement Accuracy Evaluation Complete	Complete
2.4	Prototype PM Instrument Benchmarking Complete	Complete
2.5	Prototype Ash Measurement Accuracy Evaluation Complete	Complete
2.6	Vehicle Integration and Demonstration Initiated	Complete
2.7	Applications with Advanced Combustion Testing Complete	Ongoing
2.8	Applications with Alternative Fuels Testing Complete	Ongoing
2.9	Phase 2 Report Complete and Submitted to DOE	Ongoing
Phase 3 - System-Level Demonstration		
3.1	Component and Systems Integration Specification Complete	Complete
3.2	Optimized Sensor Design Complete	Complete
3.3	Pre-Production Sensor Development Complete	Complete
3.4	Vehicle Integration and Demonstration 50% Complete	Complete
3.5	Optimized Controls Development Complete	Ongoing
3.6	Optimized Test Cell Evaluation Complete - Light Duty	Ongoing
3.7	Optimized Test Cell Evaluation Complete - Heavy Duty	Ongoing

Decision Point 1: Go/No-Go determination at conclusion of Phase II

Approach – Quantify Sensor Performance (FY13/14)

Team Member Contributions / Performance Metric

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- Develop RF sensors
- Sensor calibration
- PM/Ash loading

Performance Metric:
- Pressure drop (OE)
- Gravimetric PM
- Gravimetric Ash

Corning

- Advanced DPF materials
- Mercedes engine test (LD)
- Navistar engine test (HD)

Performance Metric:
- ΔP + Models
- AVL micro-soot
- Gravimetric PM/Ash

Oak Ridge National Laboratory

- AVL benchmarking
- TEOMϰ benchmarking
- Fuels & adv. combustion

Performance Metric:
- AVL micro-soot, TEOM™
- Pressure drop
- Gravimetric PM

FEV

- Controls development
- DDC engine platform
- 2010+ aftertreatment

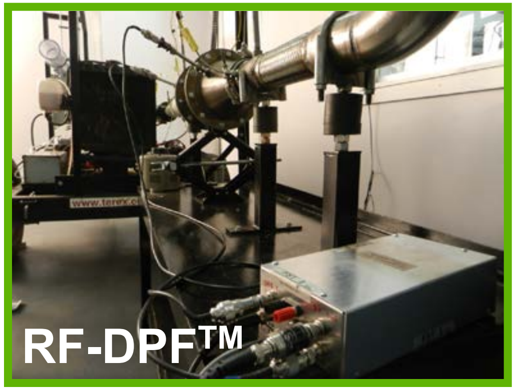
Performance Metric:
- Stock DDC controls (*ΔP + Model*)
- Gravimetric PM

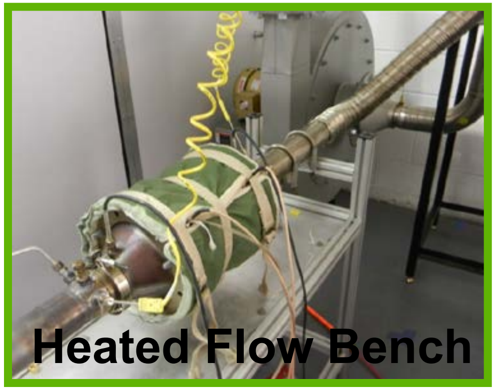
The City of New York Department of Sanitation

- On-road fleet test
- Volvo/Mack trucks ('09 & '10+)
- 24 Months total, up to 4 trucks

Performance Metric:
- Stock Volvo/Mack DPF controls
- On-road durability

Accomplishments – Phase I/II Test System Setup

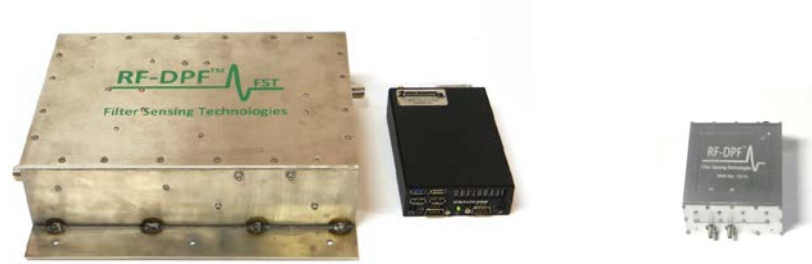




Accomplishments: Pre-Production Sensor Developed (M3.3)

Two Sensor Design Iterations Complete

- Developed second generation RF sensor and supplied to project partners for testing
- Production designs target low-cost RF chips



Program Start

- PC-controlled operation
- Analog system
- Scalar measurements
- Required two antennas
- Lab testing

Year 1 (M1.6)

- PC control required
- Vector measurements
- Required two antennas
- Self-diagnostics
- On-vehicle testing

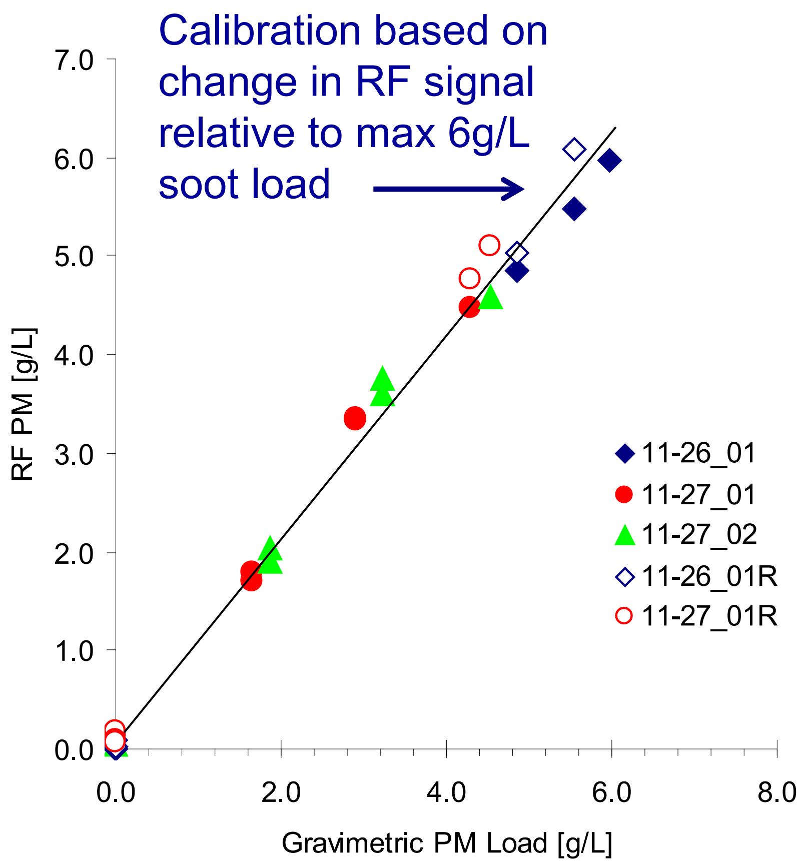
Year 2 (M3.3)

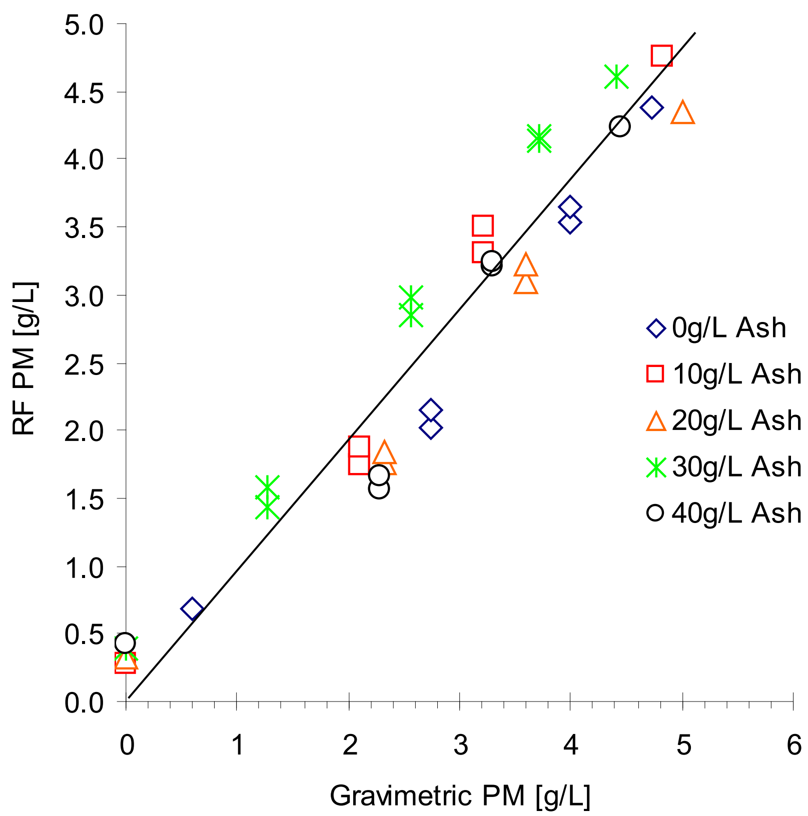
- Embedded control
- Vector measurements
- Single antenna
- Self-diagnostics
- Auto-normalization

Sensor Evolution: Reduced size and cost with increased performance

Accomplishments: PM Measurements Over DPF Life (M2.3)

Phase II performance targets achieved and include effect of ash over simulated 240,000 mile on-road ash accumulation and aging.





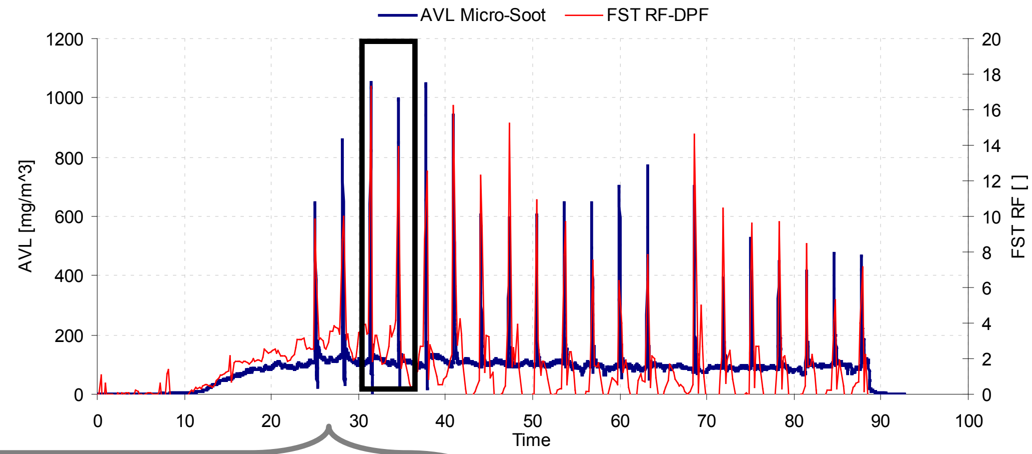
- ORNL data from 1.9L GM turbo diesel
- Semi-transient (modal) loading cycle
- Fresh DPF loading and regeneration

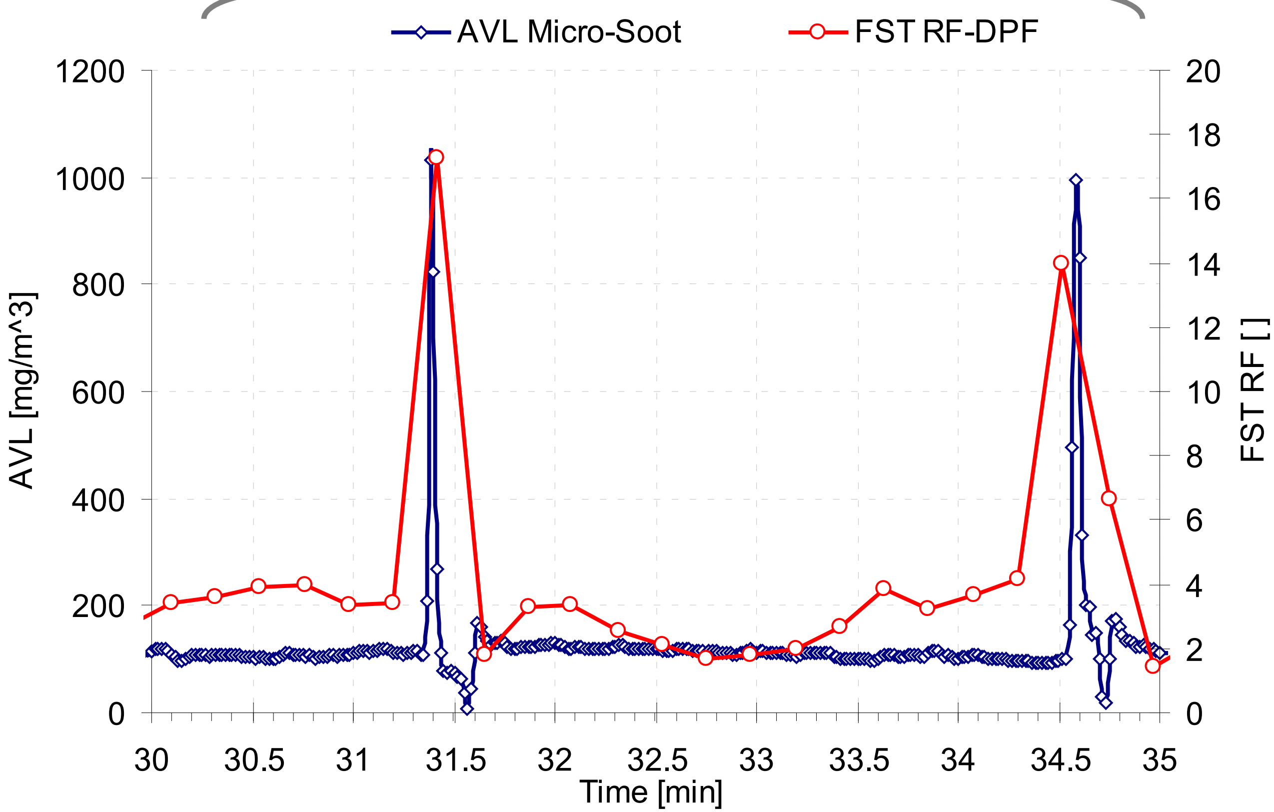
- FST Kubota D905 + Accelerated Ash
- Steady-state loading and regeneration
- PM measurements in presence of ash

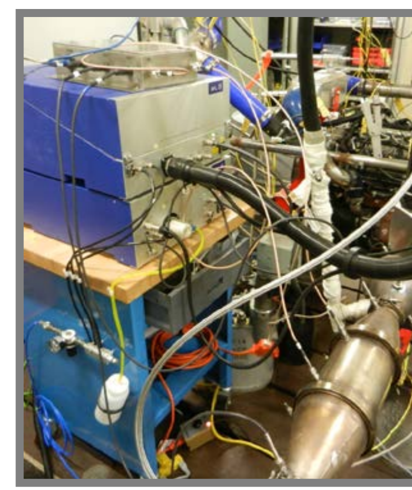
Accomplishments: AVL Instrument Benchmarking (M 2.4)

Derivative of RF Signal

- Closely correlated with AVL
- Throttle tip-in events
- RF system 12s response shows averaged signal relative to AVL 1s response







OAK RIDGE National Laboratory

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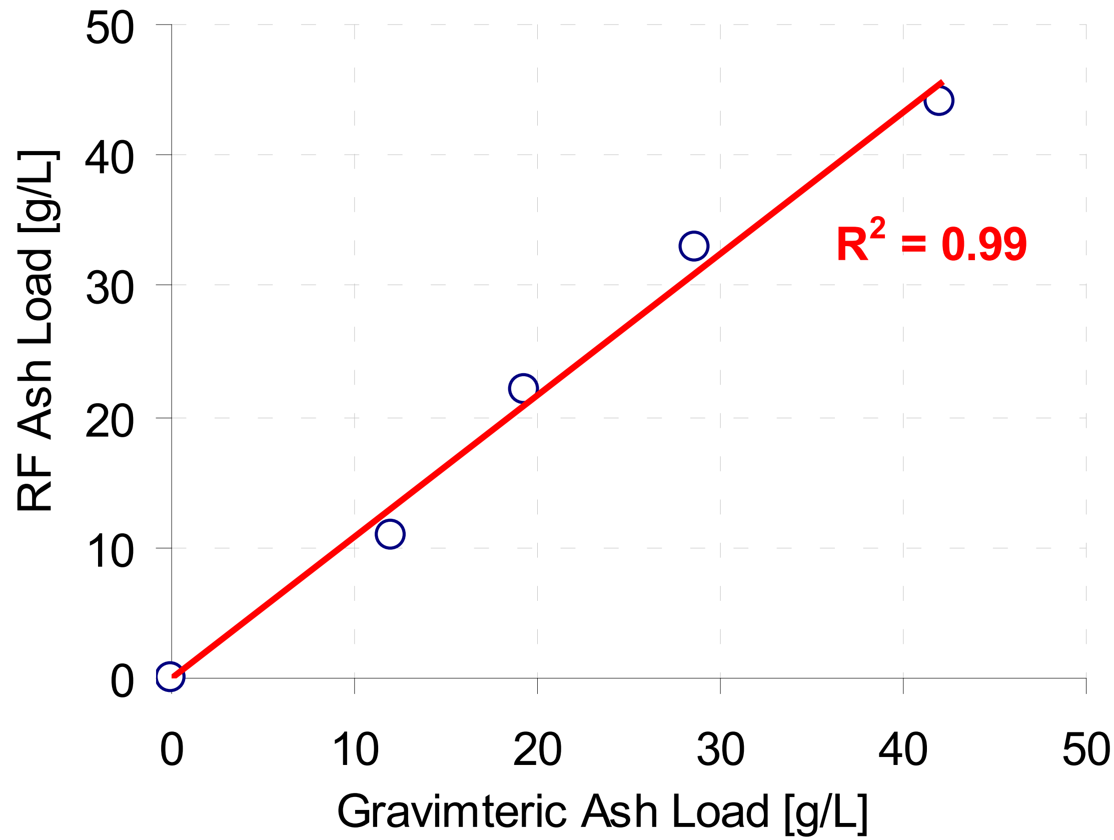
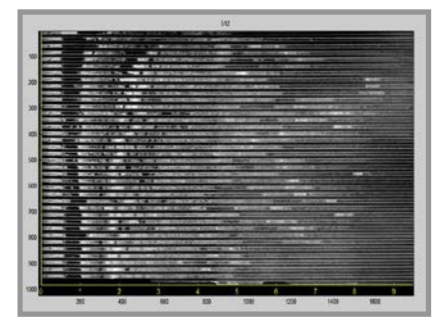
Accomplishments: Ash Measurements and DPF Aging (M2.5)

Test spans full DPF service life (before ash cleaning) and subjects RF sensors to ash and high temperature thermal aging. Additional work with large population of field DPFs ongoing.



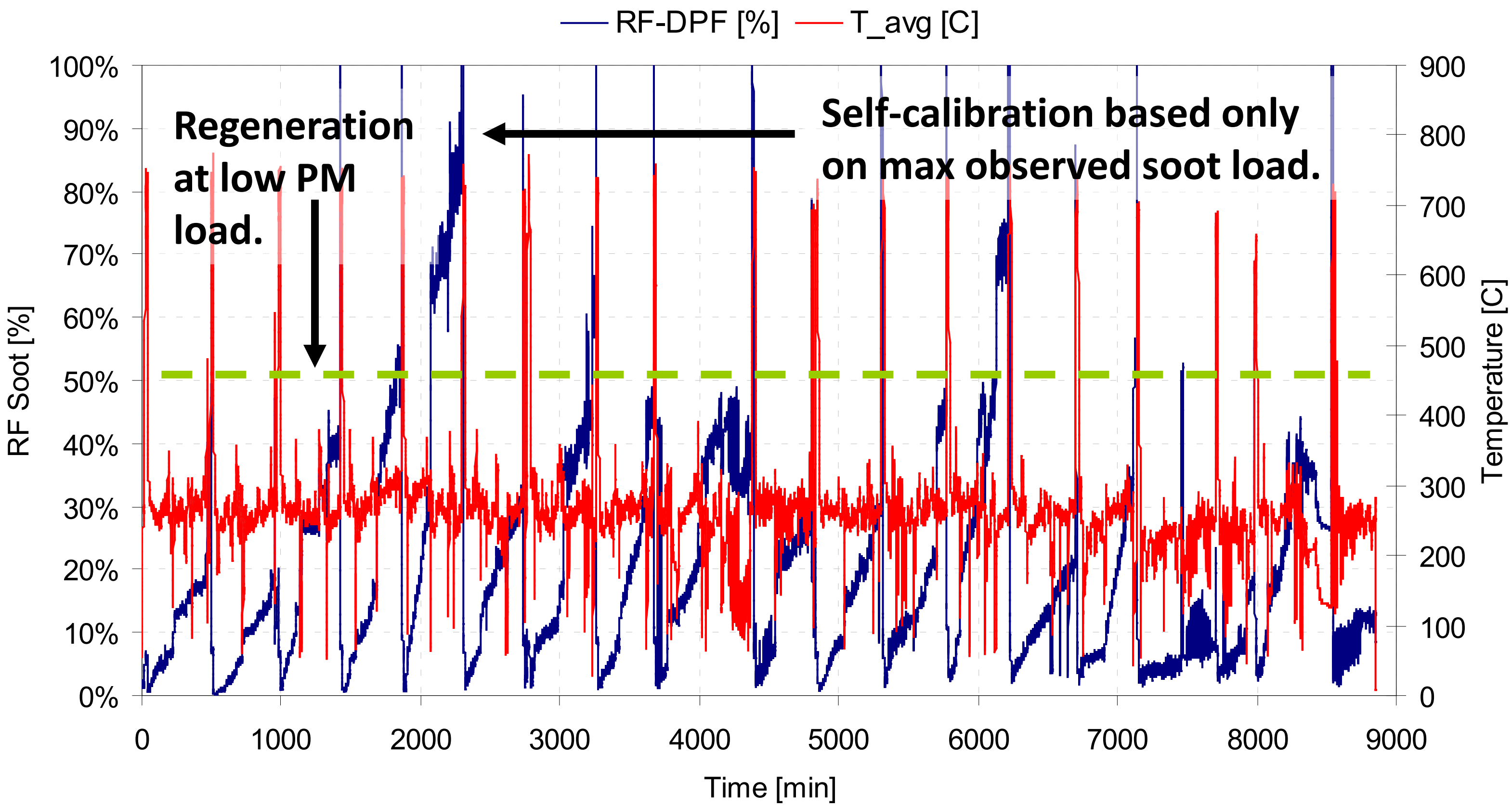


X-Ray Ash Distribution

- Ash loading estimated equivalent to **240,000 miles** of on-road operation
- Calculations based on broad frequency sweep (4.4 MHz step size)
- Expect improved resolution with smaller step size or narrower frequency range

Accomplishments: Fleet Test Fuel Savings I (M 2.6, 3.4)

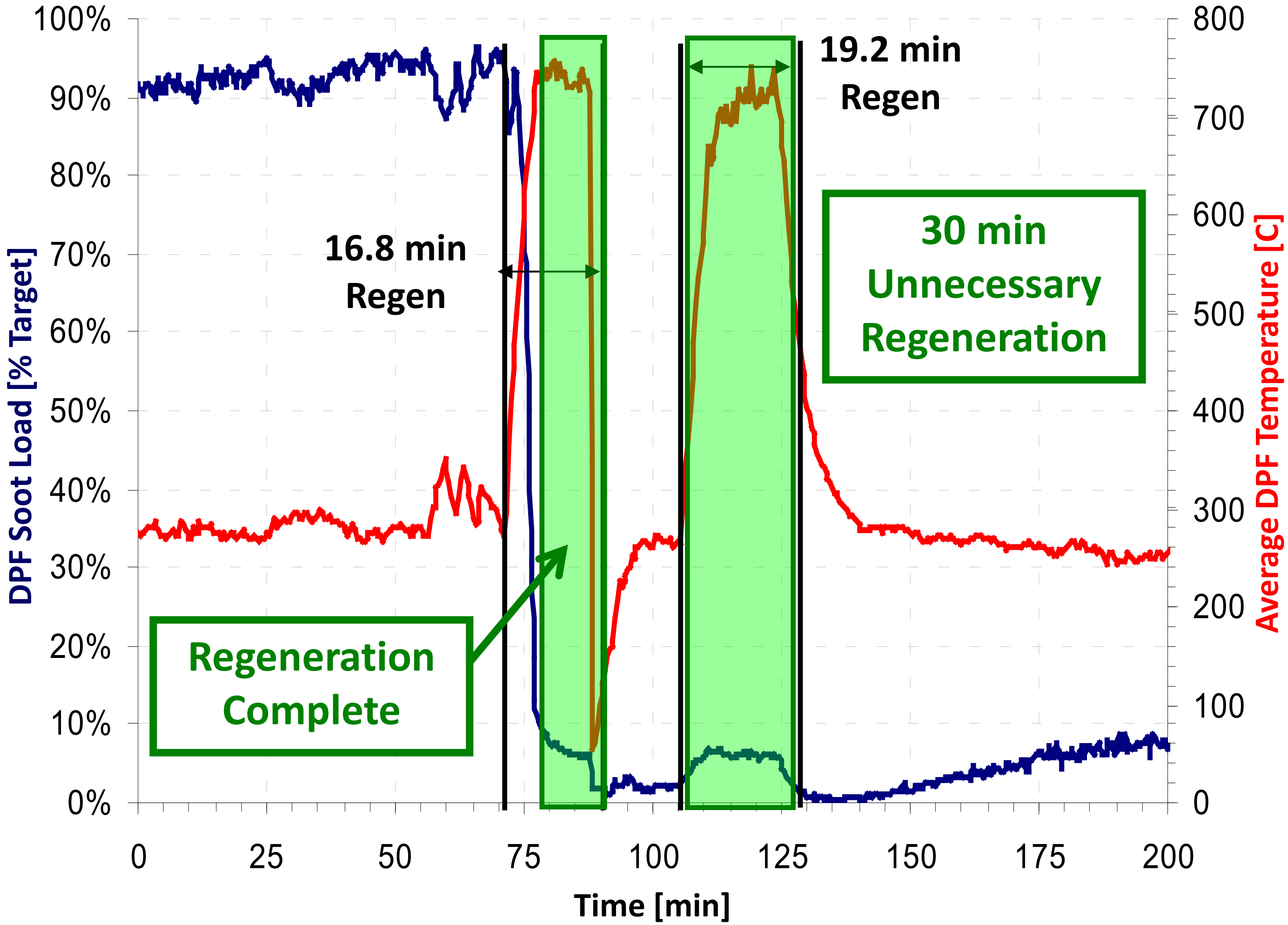
RF sensing can extend regeneration interval by 2X relative to stock 2009 Volvo/Mack DPF regeneration control system.



- Data from 150 hours with 21 regenerations, avg. 18 min per regeneration
- OEM control triggers regenerations (~ every 7.1 hrs) at low soot loads
- Vehicles spends 4% - 5% of operating time in regeneration
- Average refuse truck consumes 8,600 gal. of diesel per year

Accomplishments: Fleet Test Fuel Savings II (M 2.6, 3.4)

RF sensing can reduce regeneration time 50%- 75% vs. OEM controls

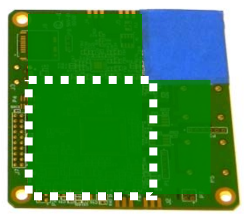


- Fleet testing demonstrates direct fuel savings via RF sensing and control
- Estimate sensor payback less than 1 year, based on fuel savings alone

Accomplishments: Sensor Design and Integration (M3.1 -3.2)

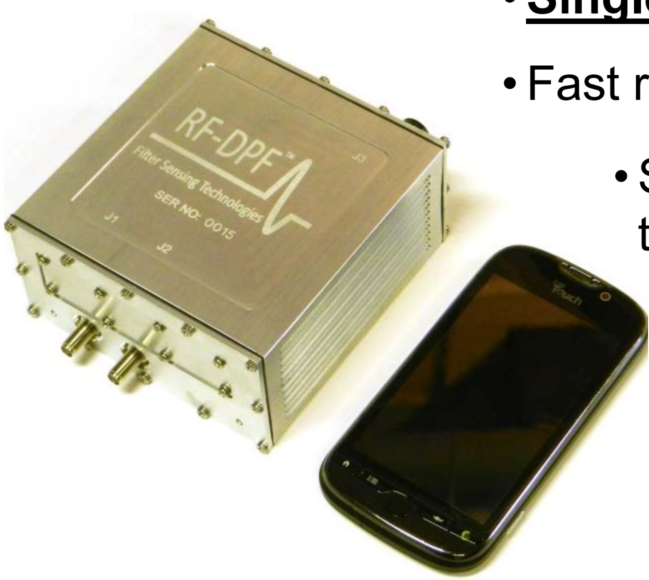
System Design Specifications Met (M3.1)

RF Board



- Board space for microcontroller and RF electronics comparable to NOx sensor.
- Additional board space includes 16 GB data storage, and features for testing and evaluation programs.

Optimized Sensor Designs Completed (3.2)

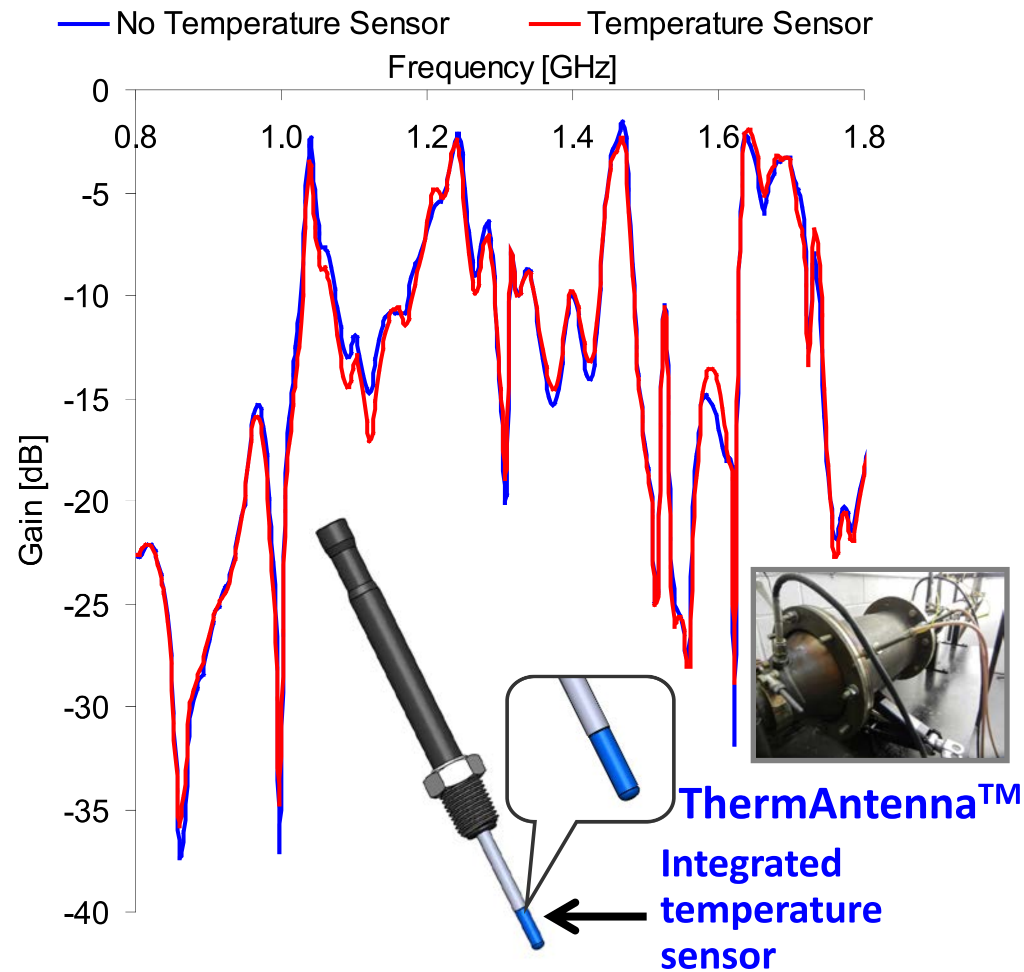


- **<u>Single</u>** and dual antenna measurement capabilities
- Fast response < 1 second for DPF measurements
- Stand-alone control unit with RTD and thermocouple inputs for temp. compensation
- CAN and (0-5V) analog output signals
- Low power 12V @ 100mA operation
- Integrated self-diagnostics and auto-calibration features

- RF system designed to function as stand-alone DPF controller

Accomplishments: Antenna Design Improvements (M 3.3)

Patent Filed – Optimized Antenna Design and Function



- Antenna re-designed to reduce part-to-part variability and production costs
- Variation less than 0.34% over 1 GHz range with ThermAntenna™
- Developed novel antenna design with integrated temperature sensor

Response to Previous Year's Reviewer Comments

Project Approach – Broad Range of Comments

Reviewers: "Excellent, well-integrated approach." Other comments - "…pressure drop is a better feedback signal and exact knowledge of DPF load is overkill". Need to define "universal calibration" and "consider changes in RF cavity cause changes in calibration."

Response: Benefits and fuel savings relative to stock pressure-based controls were demonstrated in fleet testing. Universal calibration is defined as a proportional change in RF signal relative to the clean filter which was applied across engine dyno testing and on-vehicle Volvo/Mack tests to date. Impact of cavity geometry was evaluated in models and bench testing with various different DPFs (see additional reviewer slides).

Progress, Collaboration, and Future Research

Reviewers: "Impressive progress and accomplishments," with "strongly-leveraged team of competent people and organizations." Others stated "roles of DDC and DSNY were not clear." "Solid future plans, but need clearer picture of success in a vehicle system."

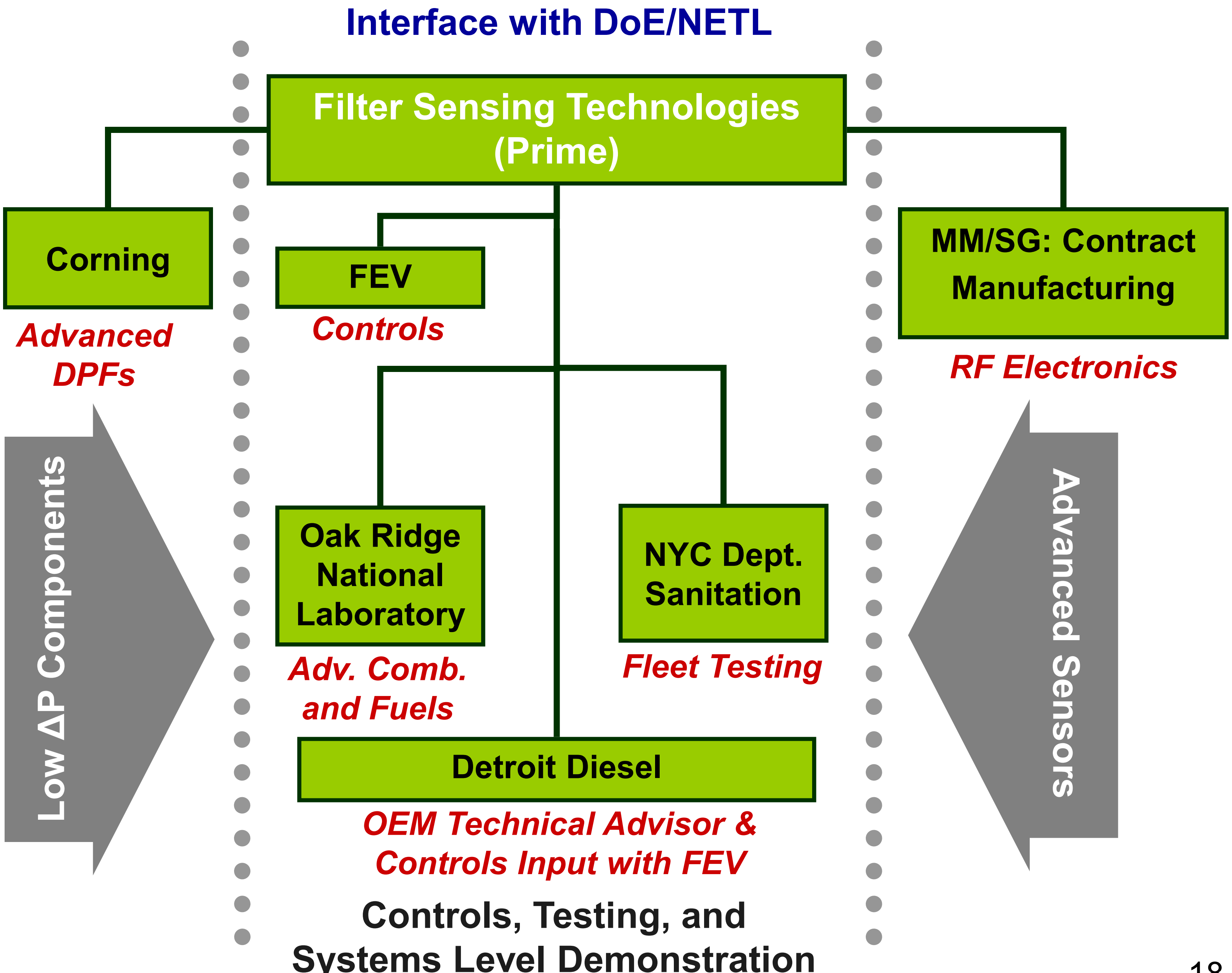
Response: Project involves parallel activities by several complimentary organizations. DDC supports FEV in controls development on DDC engine and DSNY's role in fleet testing is critical to demonstrate on-road durability and fuel savings as well as performance in vehicle system.

DOE Objectives and Resources

Reviewers: "Could possibly reduce maintenance cost," but "not clear how the technology would lead to fuel savings." "Could use value proposition for payback."

Response: Fuel savings directly demonstrated in fleet testing and will be further quantified at FEV, Corning, and ORNL in ongoing work. Estimates of payback on technology provided.

Collaboration and Project Coordination



Remaining Challenges and Proposed Future Work

Remaining tasks focus on developing optimized calibrations and controls to quantify performance relative to baseline (ΔP + Model) in a wide range of engine and vehicle applications.

Phase III – System Level Evaluation 2014 - 2015

- **M 3.5** Develop optimized RF controls on heavy-duty DDC engine with 2013+ aftertreatment **- FEV/DDC**
- **M 3.6-3.7** Quantify RF sensor performance in light- and heavy-duty engine dyno testing (***Mercedes, GM, Navistar, DDC***).
- **M 3.8-3.9** Quantify RF performance, durability, and fuel savings in on-road vehicle test (***Volvo/Mack 2009 & 2010+***)
- **M 3.10** Quantify source of error from environmental factors and part-to-part variability of optimized pre-production sensor design

Phase IV – Commercial Planning 2014 – 2015

M 4.1-4.2 Develop production specifications and designs with OEM input

M 4.3-4.4 Develop manufacturing plans and cost assessment

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Summary

Demonstrated on-vehicle fuel savings via RF sensors and controls to reduce the cost and fuel penalty of diesel aftertreatment.

Accomplishements in Second Year of Program

- Completed pre-production RF sensors and antennas (Patent filed)
- Demonstrated combined DPF **soot AND ash** measurements
- Benchmarked RF transient response with AVL micro-soot sensor
- Evaluated RF performance over **240,000 mile equivalent** DPF aging
- **Fuel savings** potential via extend regeneration interval and reduced regeneration duration ~ 50% relative to stock OEM controls in fleet test
- Fuel savings potential alone estimated to result in payback in < 1 year

Outlook and Project Impact

- Additional sensor benefits include overall system cost reduction, extended system durability and DPF life, and ash-related maintenance savings
- If successful, considerable potential to overcome barriers identified in VT Program Plan (2011-2015) through improved sensors and controls

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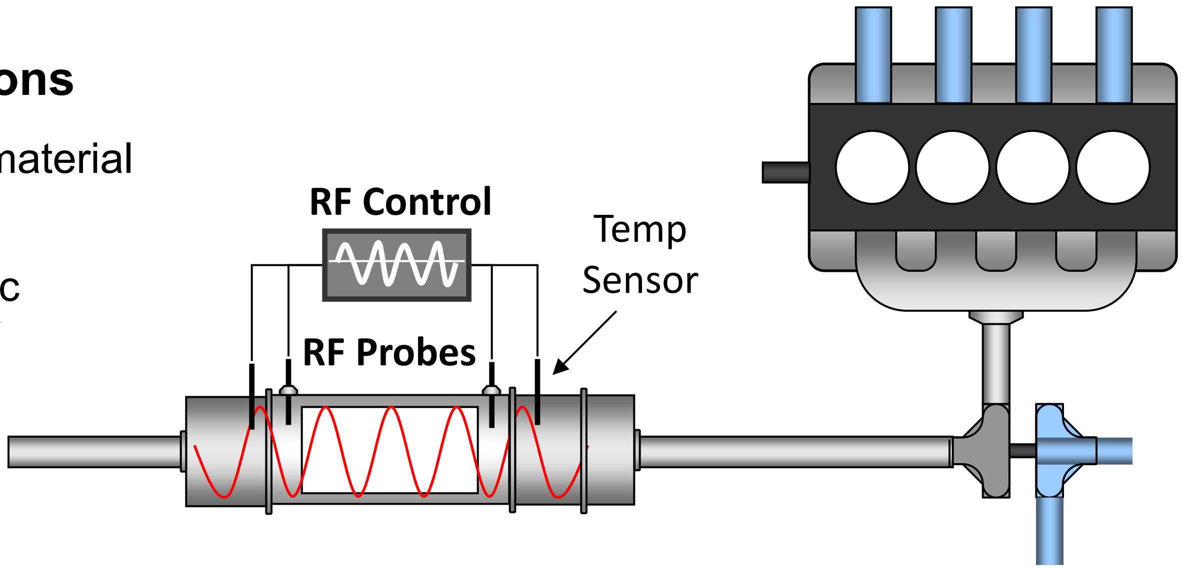
Technical Backup Slides

Basic RF Sensor Operation and Background

RF Sensing Applications

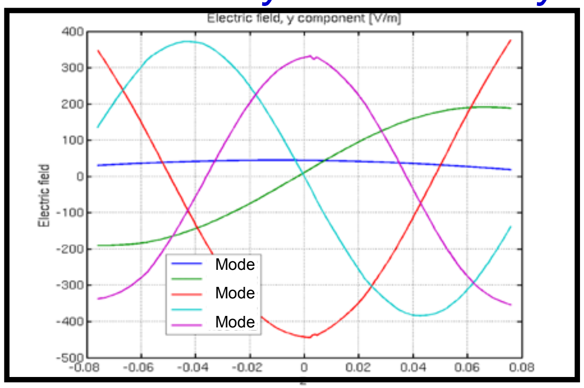
- Direct measurement of material accumulated on DPF
- Prior work by GM, Atomic Energy Canada, Univ. of Bayreuth



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

Modes in Cylindrical Cavity

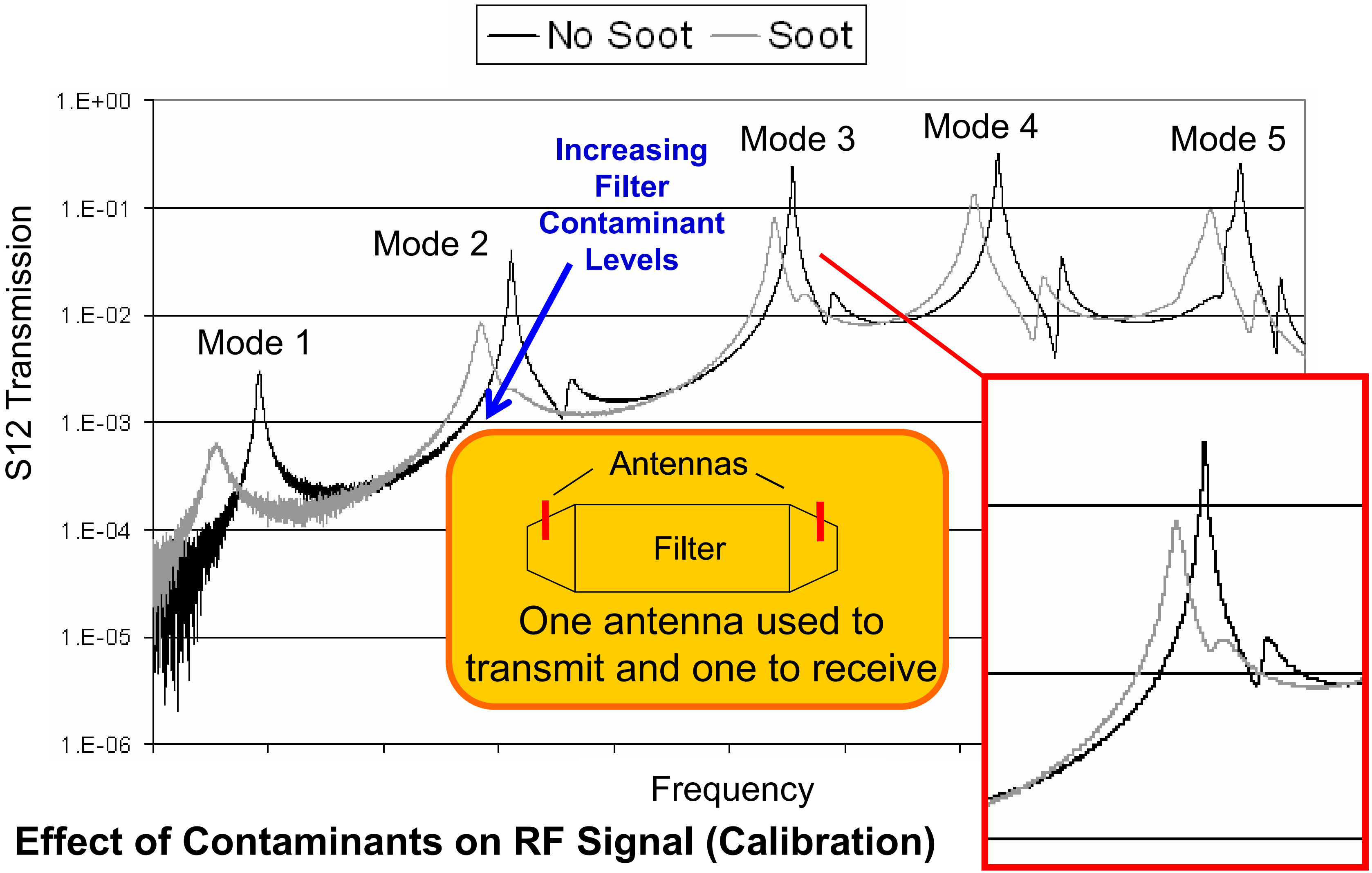


Signal Affected by Dielectric Properties of Contaminants

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

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$$

Example of Raw RF Signal and Correlation to PM Load

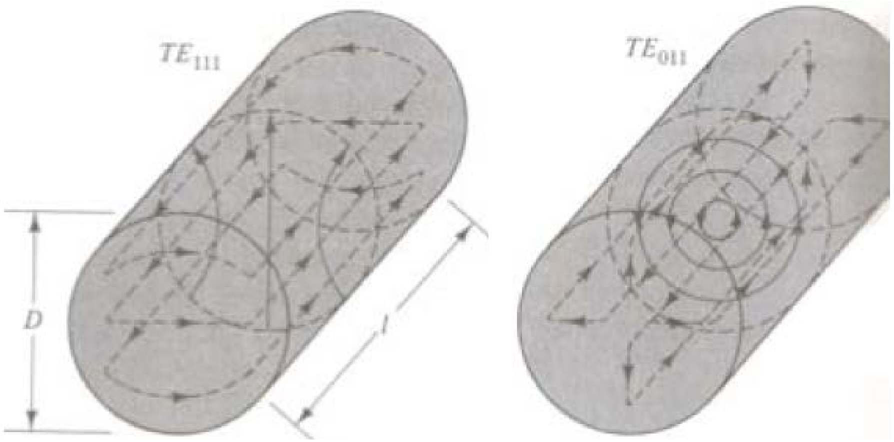


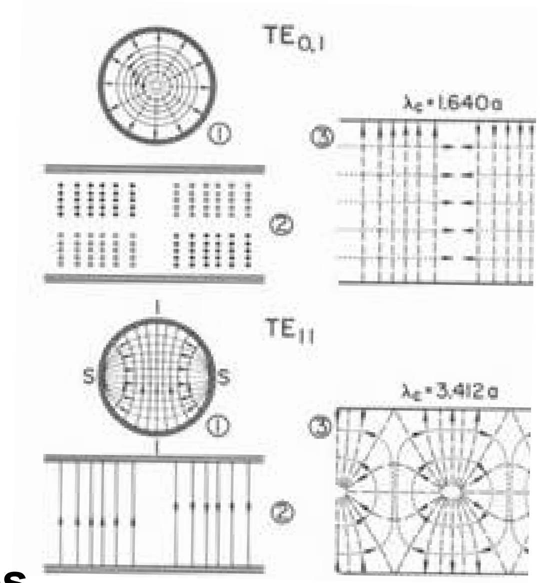
Effect of Contaminants on RF Signal (Calibration)

- Filter resonant modes (peaks) occur at specific frequencies
- Standardized metric for soot loading is the measured change in each resonant mode relative to the clean filter and can be universally applied

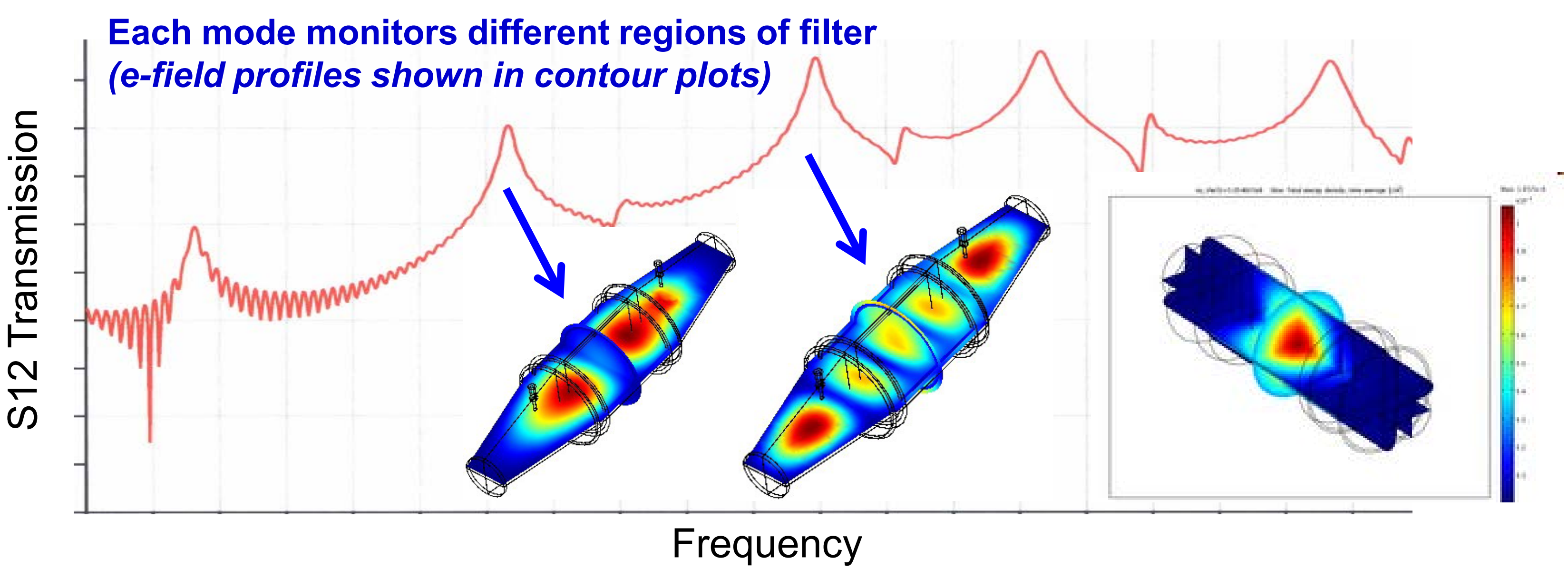
Resonant Modes Also Monitor Spatial Distribution

Typical Resonant Mode Electric Field Profiles*



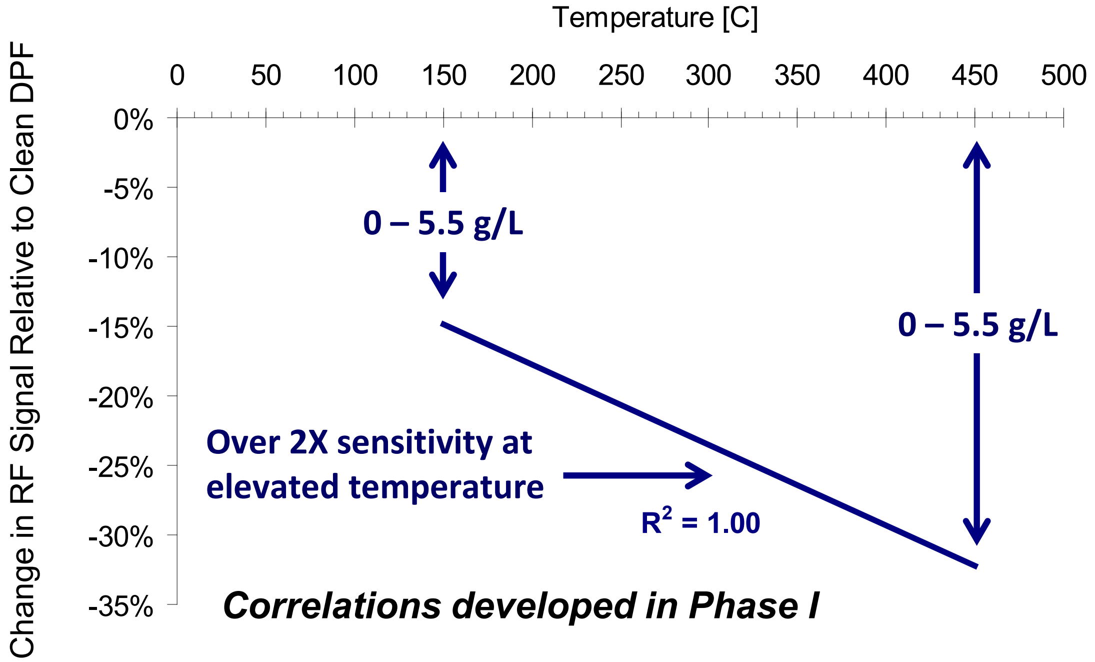


RF System Models for Filter-Specific Geometries

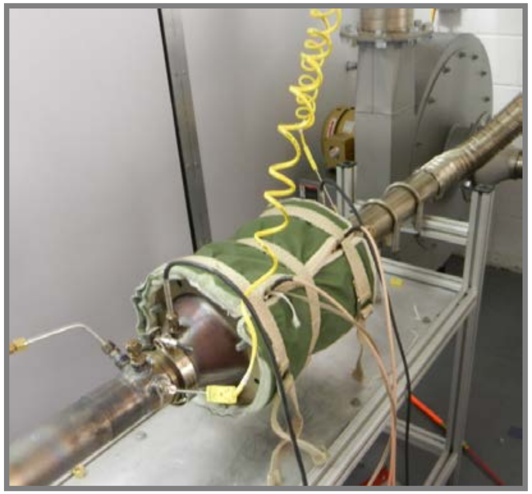


* Adam, Stephen, F., Microwave Theory and Applications, Prentice Hall, Inc., Engelwood Cliffs, New Jersey, 1969.

Universal RF System Calibration and Part-to-Part Variability



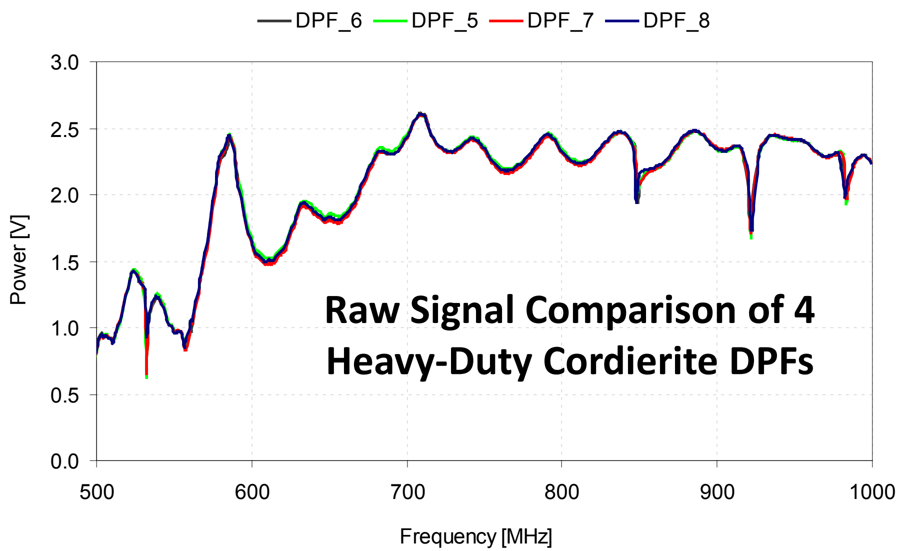
Test Bench for Temperature Characterization



Universal System Calibration Methodology (M2.1-2.2)

1. FST RF control unit automatically generates and saves reference scan for clean DPF (auto-zero function).
2. Reference scan accounts for variations in DPF geometry, materials, catalyst coating, canning, or antenna variations.
3. Universal calibration stored in RF controller relates relative change in reference (clean) signal to soot load as function of temperature enabling direct temperature compensation (as in chart above).

Canning Geometry and Variation on RF Signal (M 2.1)



Evaluation of DPF Canning Variability

- Models and bench tests applied to quantify impact of geometry and material variations on RF signal
- Impact of geometry not significant for typical design tolerances and can be accounted for in auto-normalization (see slide 25)