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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Filter Sensing Technologies Inc.

DoE Merit Review Meeting, Washington DC

June 11, 2015

ID#: ACE089

Overview

Timeline

- **Project Start: July 2012**
- **Project End: June 2016**
- **Percent Complete: 78%**

Barriers

- **Emission controls are <u>energy intensive</u> and costly**
- **Lack of "ready-to-implement" sensors and controls**
- **<u>Durability</u> 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 FY14: $910,368
  - Funding for FY15: $703,733*

* Budgeted FY2015/16

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*

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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.

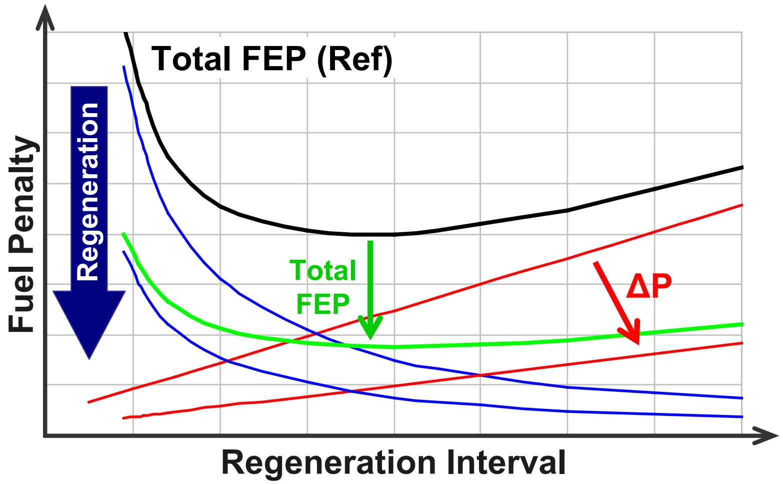
Develop RF Sensor for direct measurements of DPF soot and ash loading with advanced low ΔP systems.

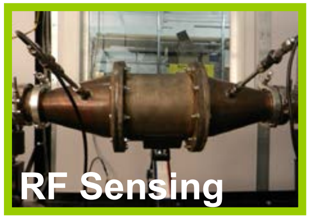
The specific project objectives include:

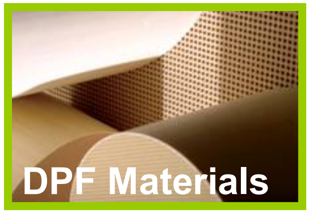
1. **Develop RF sensors** and adaptive feedback controls for direct, in-situ measurements of DPF soot and ash levels.
2. **Quantify fuel savings** with RF sensors and controls in engine dyno and on-road fleet tests in light- and heavy-duty applications.
3. **Explore additional efficiency gains** with 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.



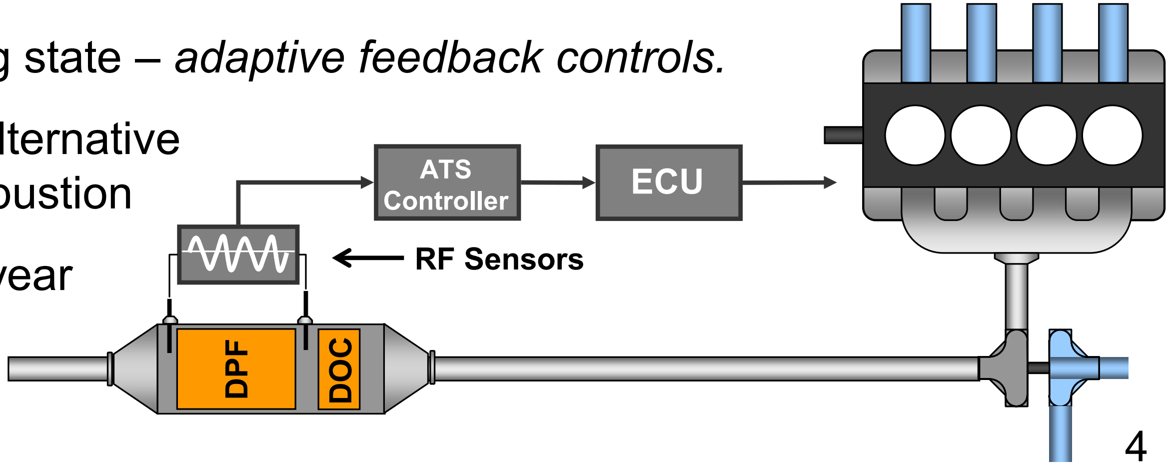




Advanced Controls

Concept: Apply inexpensive radio frequency (RF) technologies to directly monitor DPF <u>soot</u> **AND** <u>ash</u> 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 3

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.

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Approach – Project Milestones FY14 & FY15

Phase 3 - System-Level Demonstration	
3.1 Component and Systems Integration Specification Complete	**Complete**
3.2 Optimized Sensor Design Complete	**Complete**
3.3 Pre-Prodcution Sensor Development Complete	**Complete**
3.4 Vehicle Integration and Demonstration 50% Complete	**Complete**
3.5 Optimized Controls Development Complete	**Complete**
3.6 Optimized Test Cell Evaluation Complete - Light Duty	Ongoing
3.7 Optimized Test Cell Evaluation Complete - Heavy Duty	Ongoing
3.8 Optimized Vehicle Evaluation Complete - Heavy Duty	Ongoing
3.9 Vehicle Integration and Demonstration 100% Complete	**Complete**
3.10 Environment and Variability Testing Complete	Ongoing
3.11 Phase 3 Report Complete and Submitted to DOE	Ongoing

Phase 4 - Commercialization Planning	
4.1 Commercial Specifications Complete	**Complete**
4.2 Production Sensor Design Concepts Complete	**Complete**
4.3 Manufacturing Partners Identified	**Complete**
4.4 Commercialization Plans Complete	Ongoing
4.5 Phase 4 and Final Report Complete and Submitted to DOE	Ongoing

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

Approach: Quantify Performance and Fuel Savings (FY14/15)

Team Member Contributions | **Performance Metric**

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

- Pressure drop (OE)
- Gravimetric PM
- Gravimetric Ash

CORNING

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

- ΔP + Models
- AVL micro-soot
- Gravimetric PM/Ash

OAK RIDGE National Laboratory

- **AVL benchmarking**
- **TEOM benchmarking**
- **Fuels & adv. combustion**

- AVL micro-soot, TEOM
- Pressure drop
- Gravimetric PM

FEV

- **Controls development**
- **DDC engine platform**
- **2010+ aftertreatment**


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

THE CITY OF NEW YORK DEPARTMENT OF SANITATION

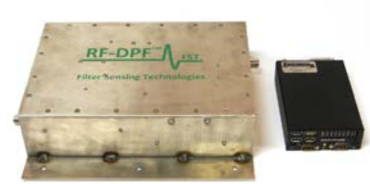
- **On-road fleet test**
- **Volvo/Mack trucks ('09 & '10+)**
- **24 Months total, up to 4 trucks**

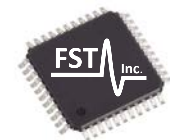
- Stock Volvo/Mack DPF controls
- On-road durability

Accomplishments: Production-Intent Sensor Developed

Production-Intent Sensor Development

- Smart sensor functions as stand-alone control unit
- Production designs targeting low-cost RF chip set





Program Start → **Year 1** → **Year 2** → **Year 3**

Multi-Function Sensor

Patent Application
US 61,897,825

R&D 100 2014 Winner

Final System Specifications

- Fast response *(< 1 second)*
- Fully-embedded control
- Vector measurements
- Single and dual antenna
- Self-diagnostics and normalization
- CAN and analog output
- Low power (12V @ 100 mA)

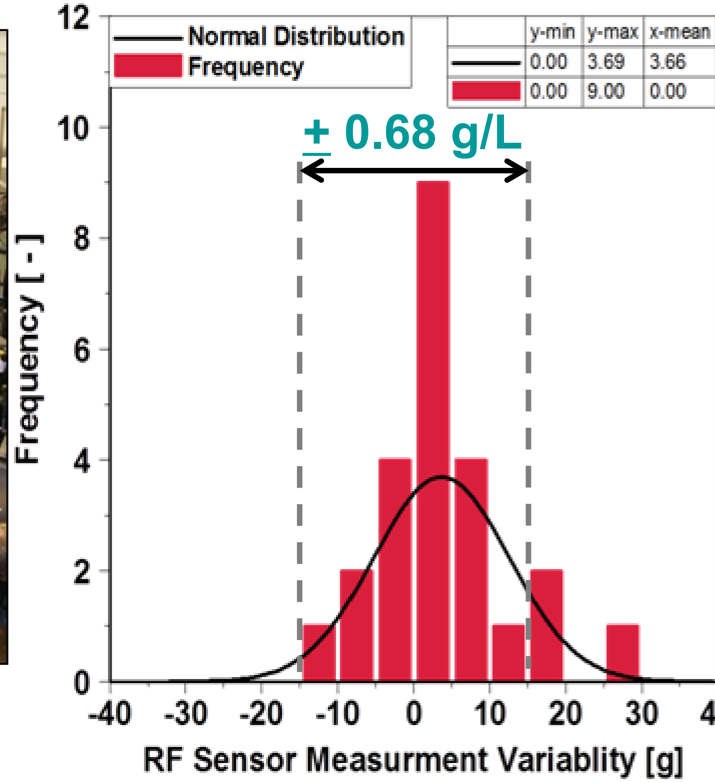
Accomplishments: RF Measurement Accuracy Evaluated

- Stock aftertreatment system with 22.03 L DPF (27.73 kg base weight)
- DOC upstream of DPF (same can) and RF antenna mounted at DPF outlet

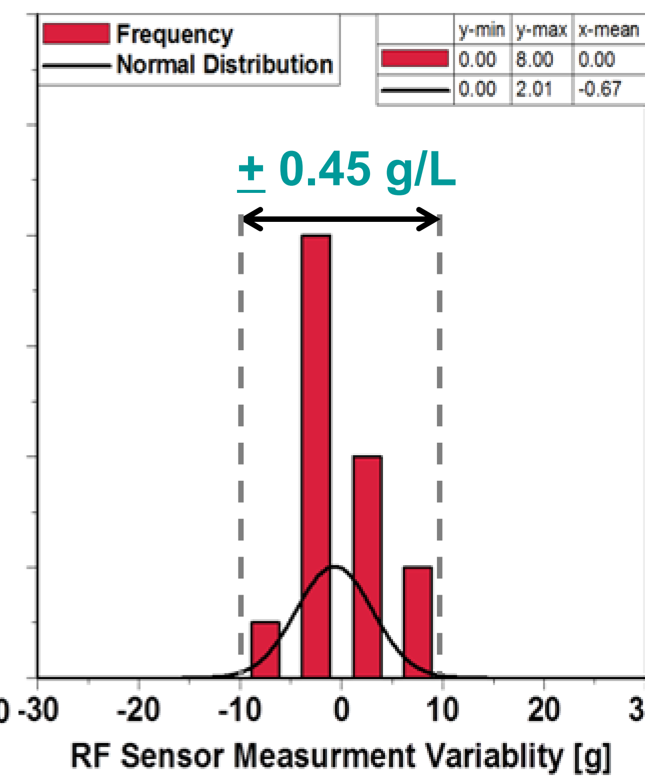
Aftertreatment

DPF and SCR

Loading Sample Set: 24 cycles
PM Load Range: 6 g – 126 g



Regen Sample Set: 15 DPF cycles
PM Load Range: 1 g – 18 g

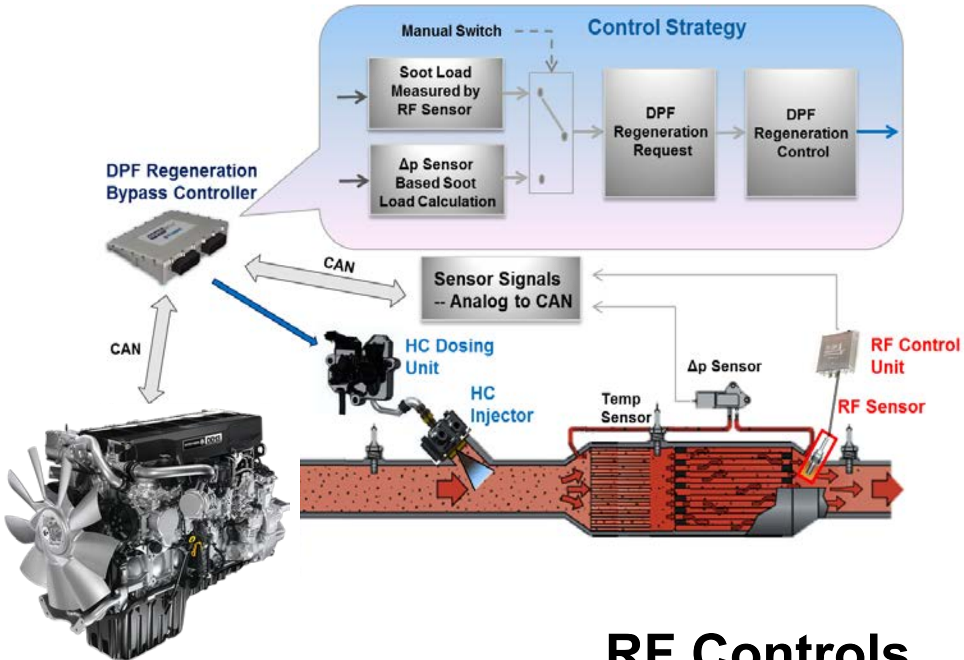


- RF sensor validation over multiple loading and regeneration cycles
- Comparison with gravimetric, AVL MSS, BG3, and smoke meter measurements

SAE 2015-01-0996

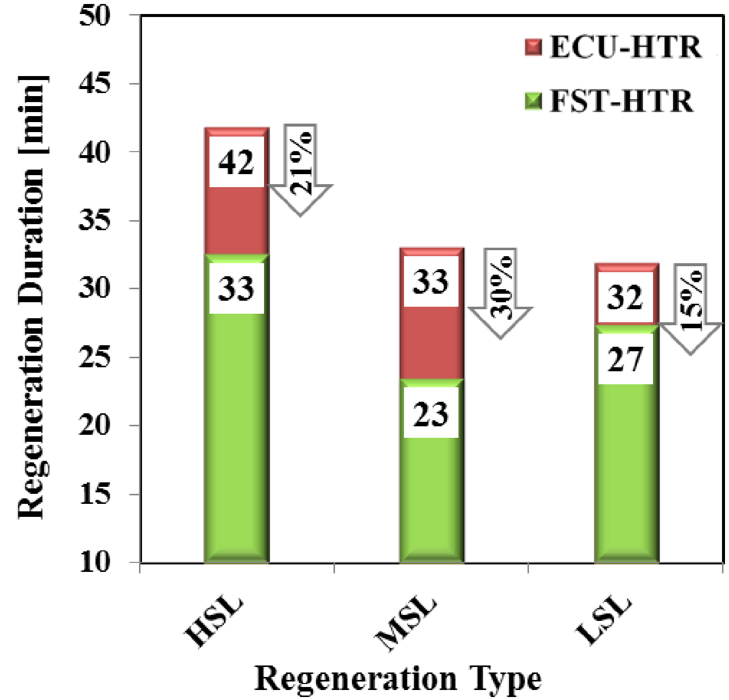
Accomplishments: RF Control Reduces Regeneration Time

RF Controller Developed for DPF Management with Industry Partners



DD13 SPECIFICATIONS	
Configuration	Inline 6 Cylinder
Displacement	781 cu. in. (12.8 L)
Compression Ratio	17.3:1
Bore	5.20 in. (132 mm)
Stroke	6.15 in. (156 mm)
Weight (Dry)	2540 lb. (1152 kg)
Electronics	DDEC®
Oil Capacity	40 qt. (38 L)
Horsepower Range	350-470

15% - 30% Reduction in Regeneration Duration



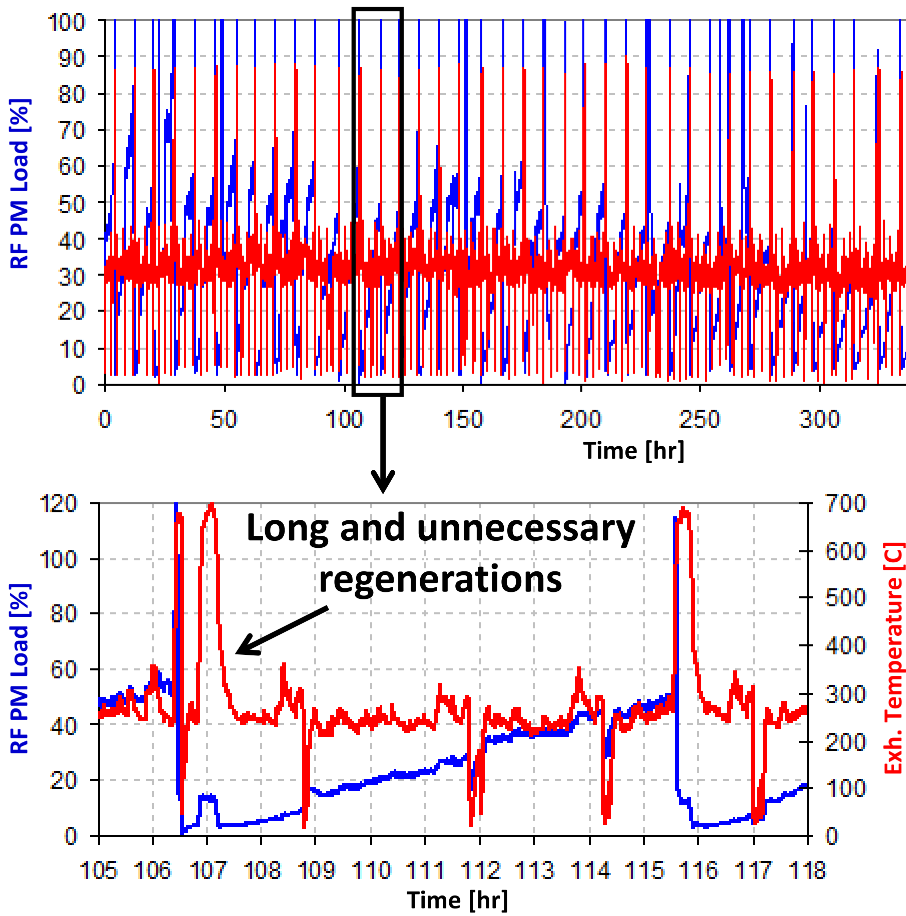
RF Controls

- **Single antenna** RF control system developed for **MY 2013** DD13 heavy-duty diesel engine
- RF system directly monitors PM levels in DPF during regeneration and terminates HC dosing once oxidation is complete
- OEM approach uses time-based regeneration

SAE 2015-01-0996

Accomplishments: Two Year Fleet Durability Evaluation

Four Mack (MP-7) MY 2009 and 2010 Fleet Vehicles

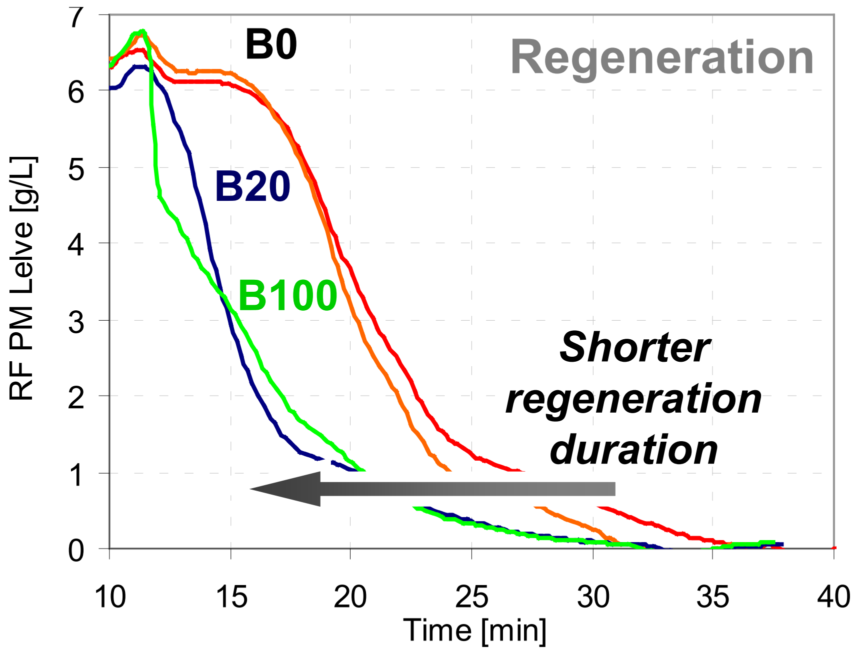


- **Raw RF signal** (not temperature corrected)
- Test trucks consume **5,000 – 8,000** gallons of diesel per year

- OE control results in regeneration 4%-5% of time vehicles are in operation (**NYC** urban drive cycles)
- RF control can reduce regeneration frequency and duration by up to 50% for these applications

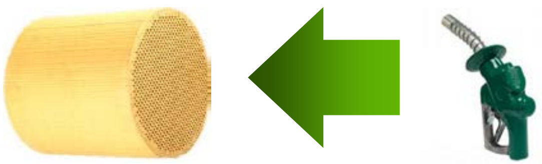
SAE 2014-01-2349

Accomplishments: RF System Optimization with Biofuels

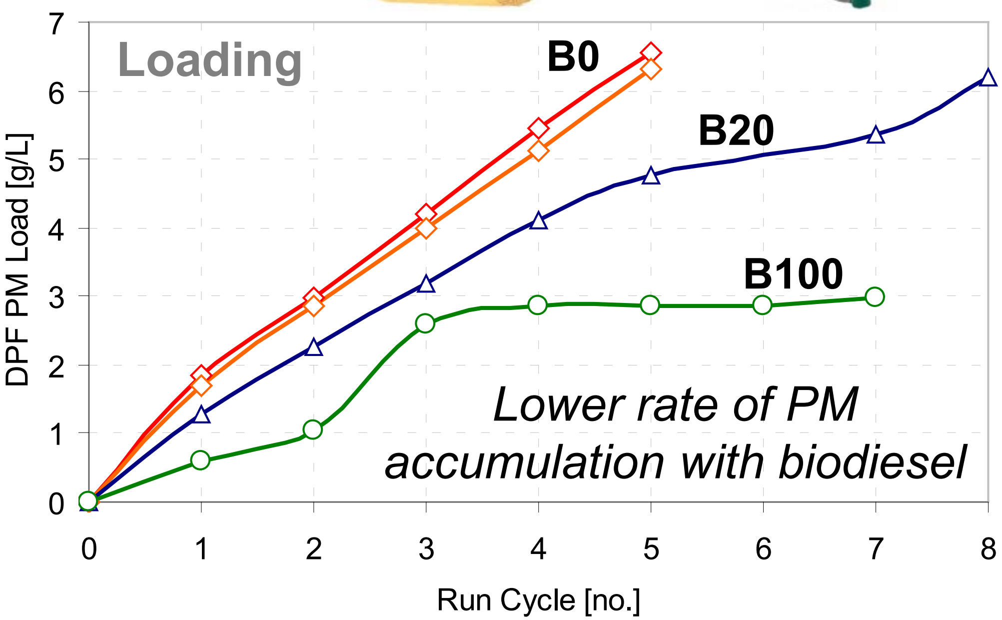


Fuel-Effects Study with ORNL

- Biodiesel blends result in lower engine-out PM and faster PM oxidation
- Conventional ΔP and models do not account for fuel effects
- RF sensing provides direct measurement of DPF load for additional optimization with cleaner fuels

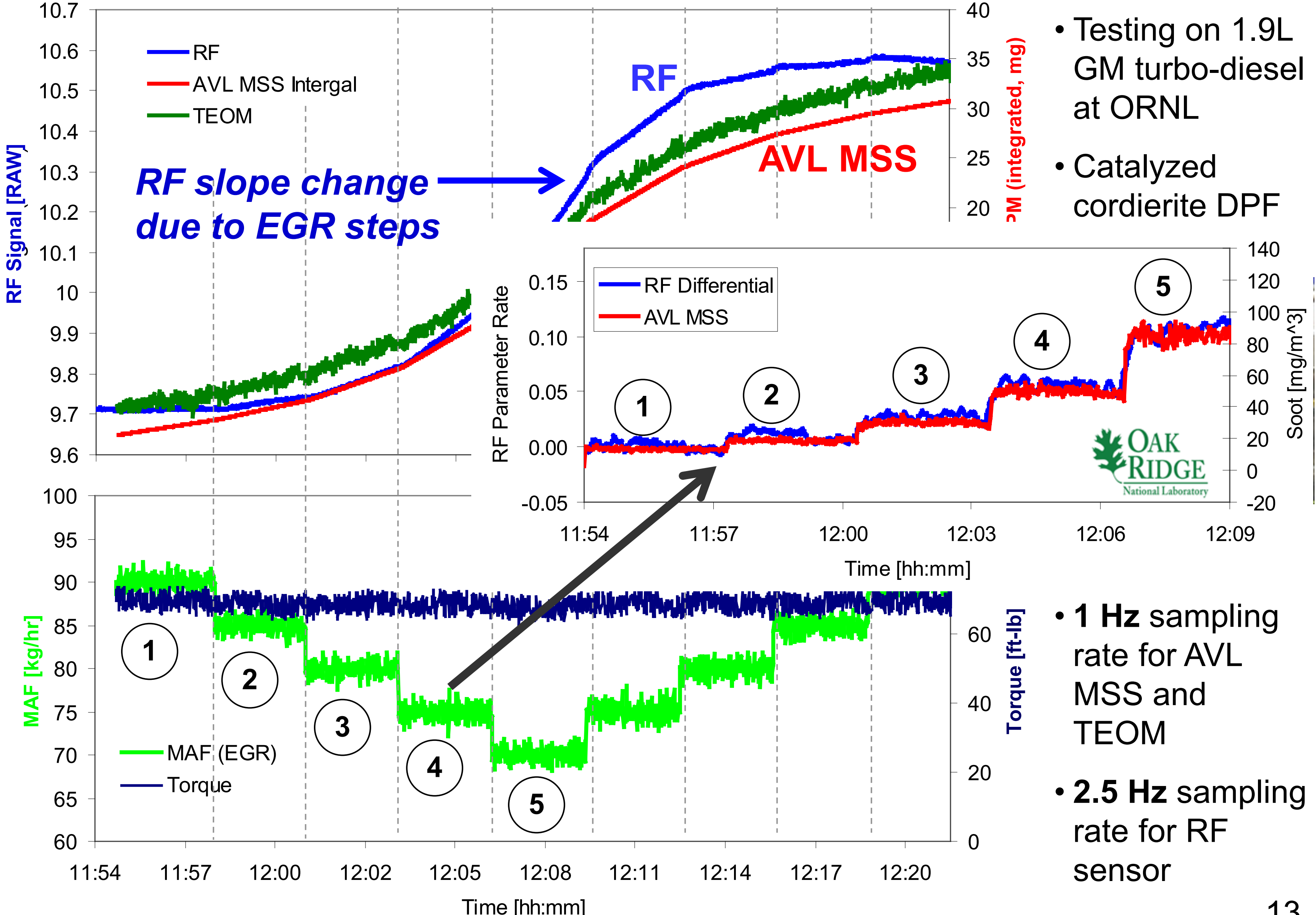


- ORNL testing with biodiesel matrix B0-B100
- Extended time between regenerations
- Demonstrated shorter regeneration duration
- Results presented at NBB conferences and workshop



Accomplishments: Demonstrated Fast RF Sensor Response

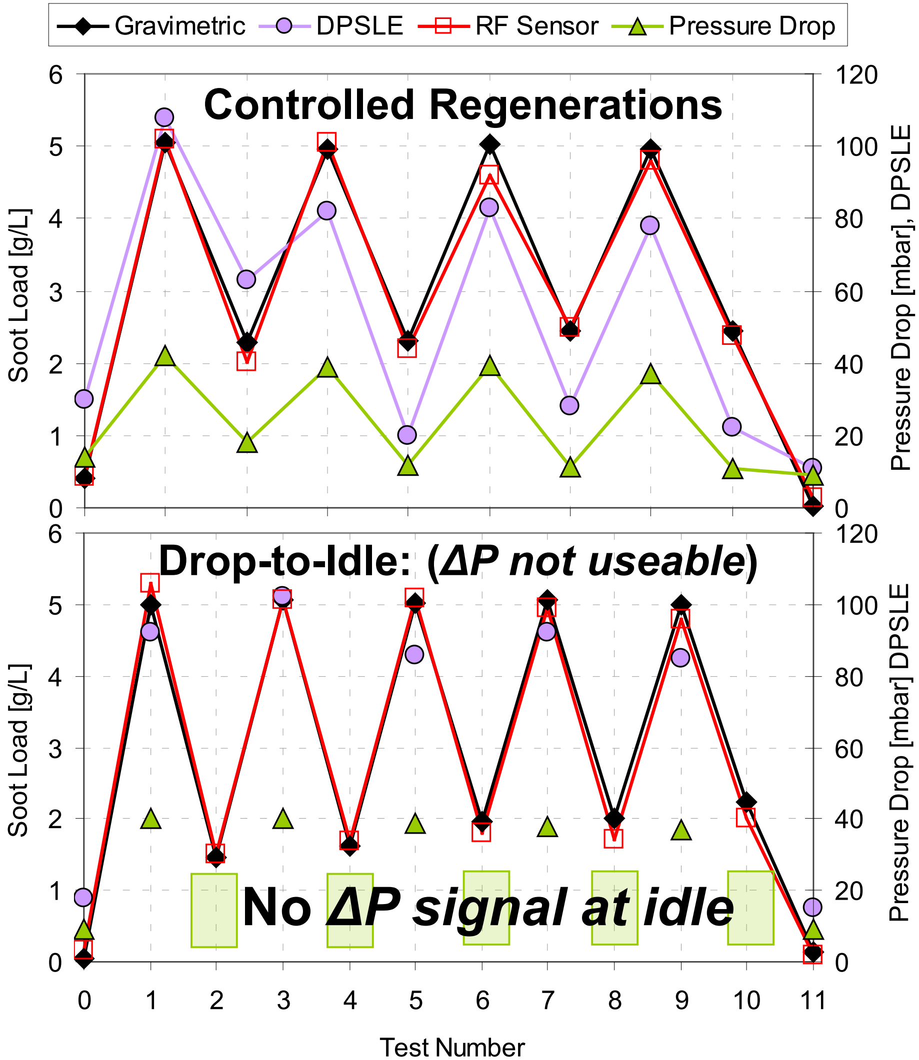
Use of DPF as engine-out soot sensor for advanced controls



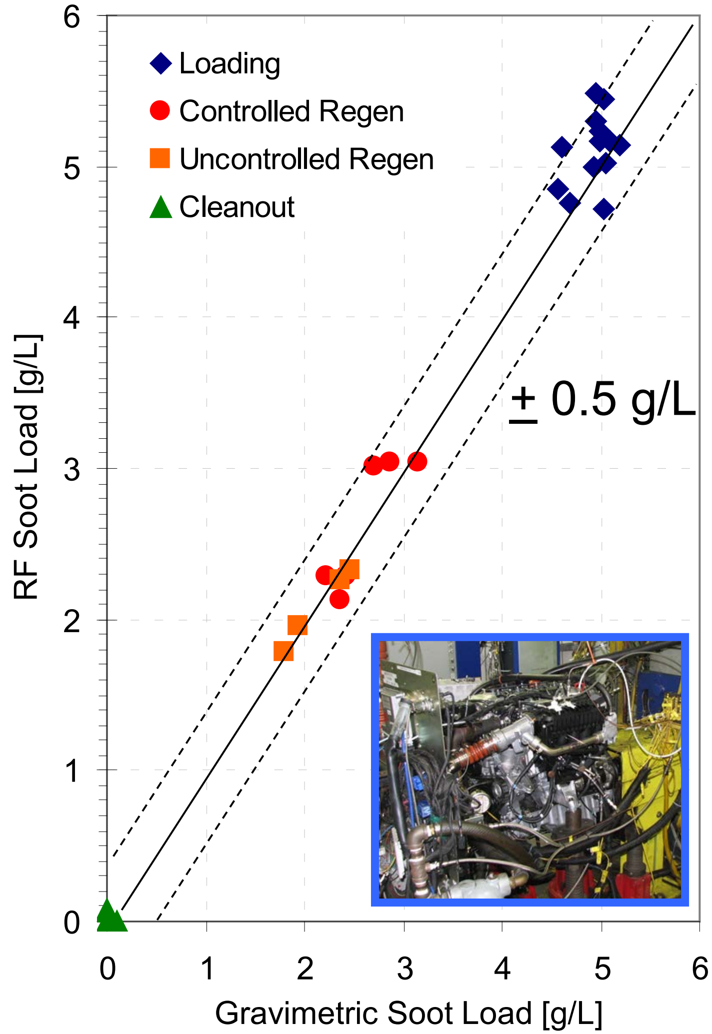
- Testing on 1.9L GM turbo-diesel at ORNL
- Catalyzed cordierite DPF
- **1 Hz** sampling rate for AVL MSS and TEOM
- **2.5 Hz** sampling rate for RF sensor

Accomplishments: RF Accuracy with Partial Regenerations

Heavy-Duty Summary

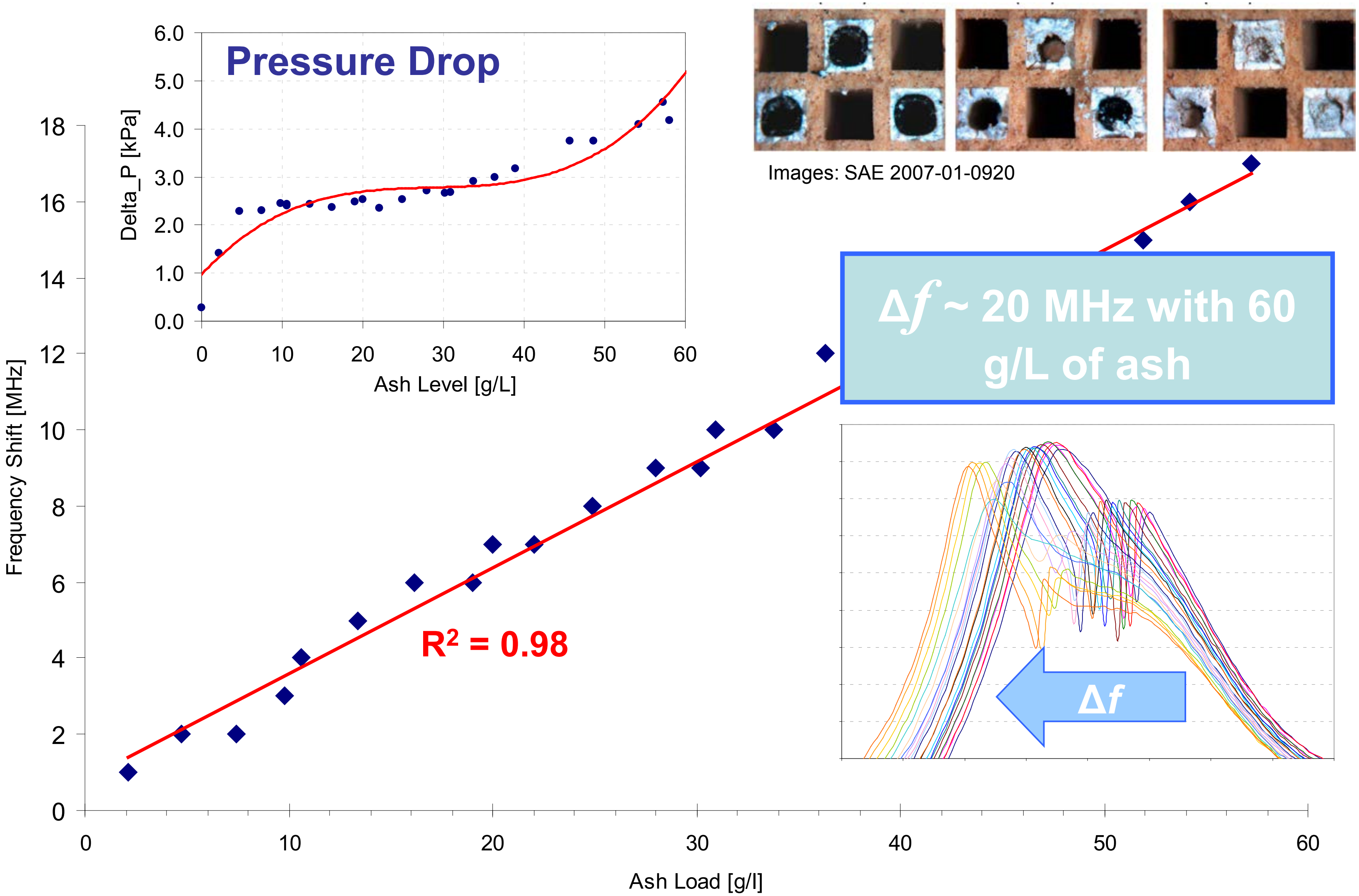


Light-Duty Summary



- **HD** tests on **Navistar** engine and **LD** tests on **Mercedes** engine at Corning
- RF accurately measures PM levels after partial regenerations

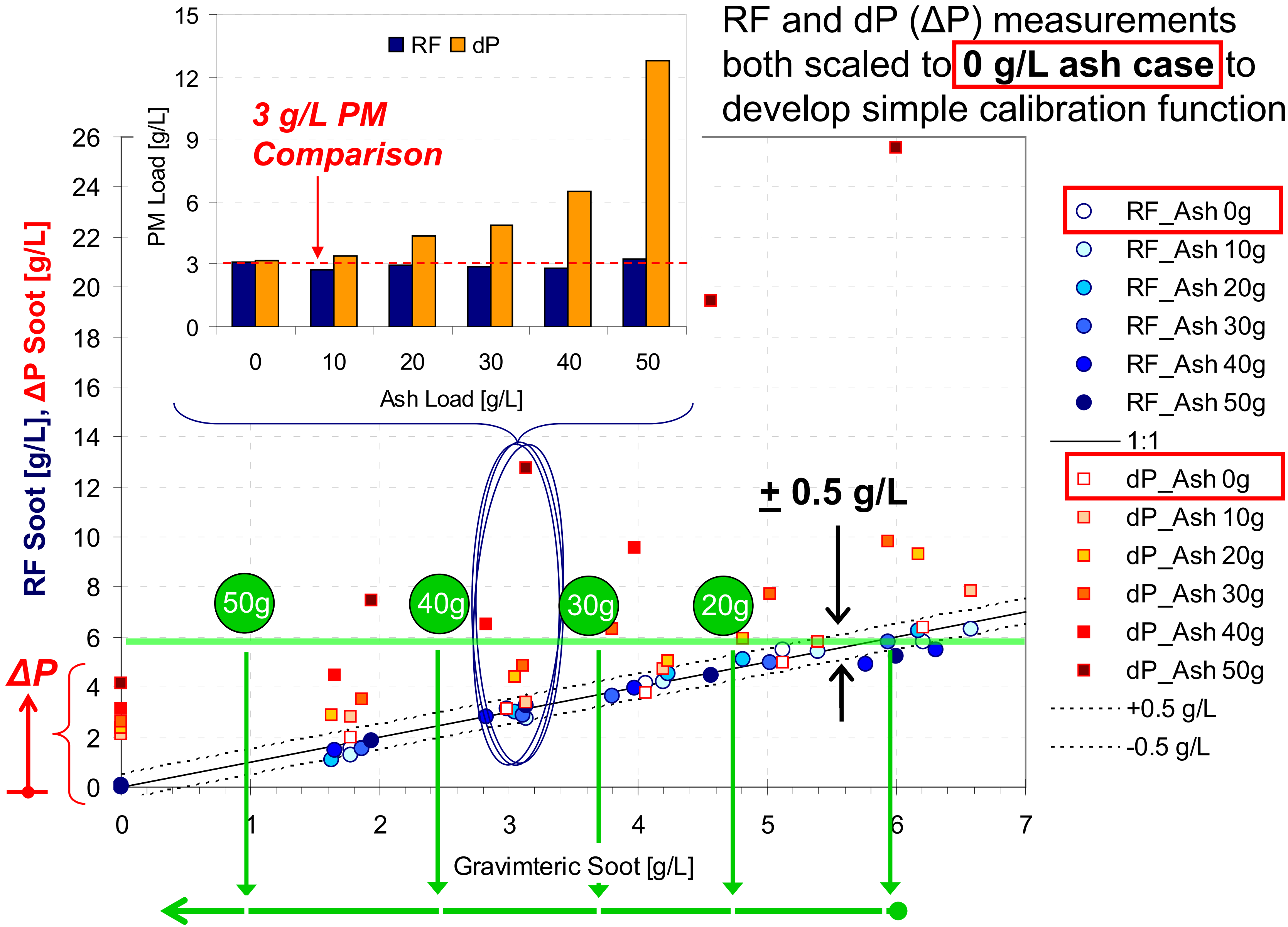
Accomplishments: Direct Measurement of DPF Ash with RF



- Ash loading level equivalent to **~ 380,000** miles of on-road accumulation
- Frequency shift at resonance well-correlated to ash level in DPF

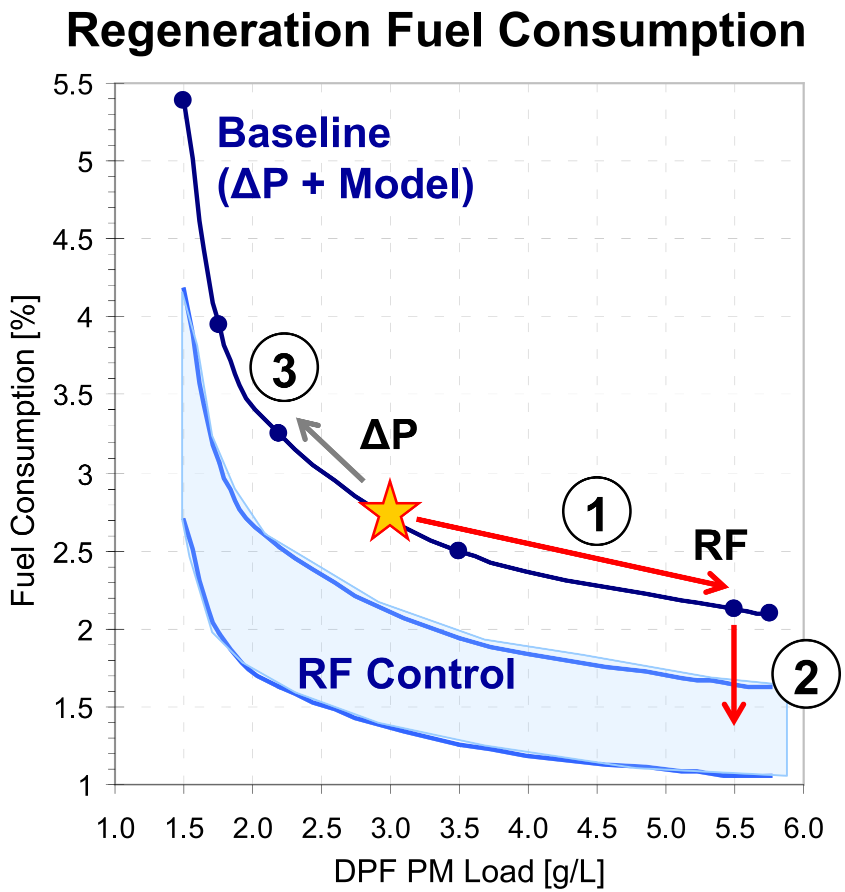
Accomplishments: RF Sensor Accuracy Unaffected by Ash

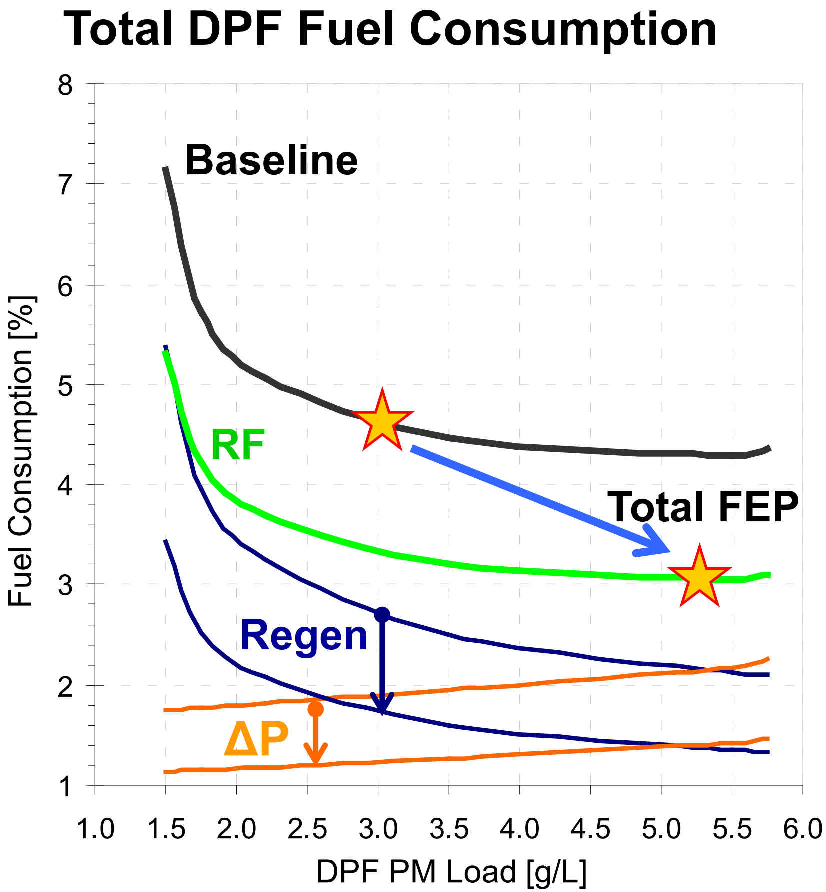
RF and dP (ΔP) measurements both scaled to **0 g/L ash case** to develop simple calibration function



ΔP regeneration frequency increases with ash (over-estimate PM load)

Accomplishments: Fuel Savings with RF Sensing 1.5% - 3%





1. Increase regeneration interval to utilize full DPF storage capacity
2. Shorten regeneration duration by ending regeneration when DPF is clean
3. Mitigate ash effects through direct soot AND ash measurements

Baseline data in charts adapted from: SAE 2009-01-1275, SAE 2010-01-0535, SAE 2010-01-0811

Response to Previous Year's Reviewer Comments

AMR 14 general questions grouped into three broad categories:

I. Clarify advantages over ΔP/models

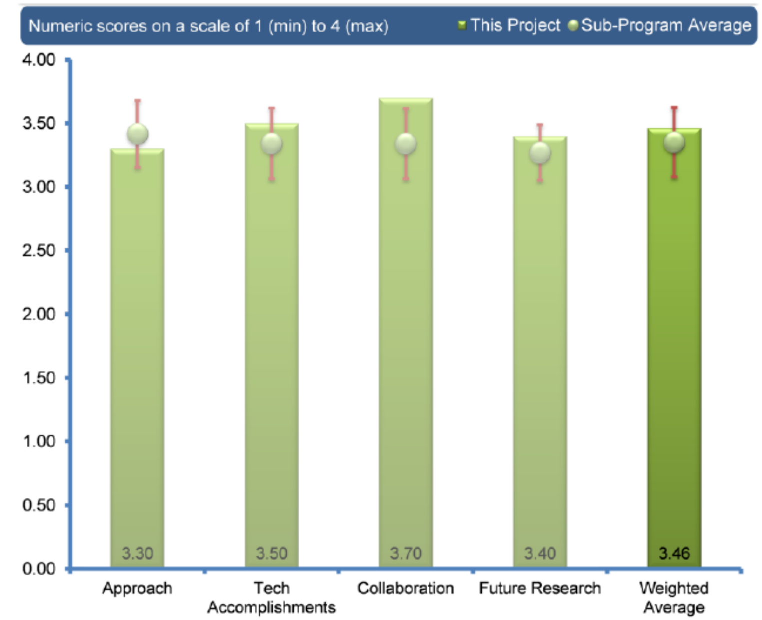
Response: FY2014/15 has focused on direct comparison with ΔP and models (dPSLE), see slides 10, 14, and 17. Technical backup slide 27 provides additional examples, as do the SAE publications resulting from this work. There are many conditions (idle, regeneration, non-uniform loading, and ash) which introduce errors in ΔP or where the measurement is too unreliable to be used.

II. Clarify fuel savings and objectives

Response: Key barriers identified by DOE for this project include fuel savings and aftertreatment durability. Slide 17 summarizes fuel savings from fleet and engine dyno testing, including state-of-the art comparison with MY 2013 engines (slide 10) . Reduced regenerations and measurements of ash (slide 15) directly enable improved DPF system durability in the field.

III. Need more engine manufacturers

Response: The team includes broad representation (national lab, DPF supplier, an engine/truck manufacturer, and heavy-duty fleet). Testing included LD and HD engines from other manufacturers not directly involved (Mack, MB, GM, Navistar, Kubota). Since FY2014 several commercial sensor development programs have been launched with OEMs further demonstrating commercial interest and additional OE involvement.



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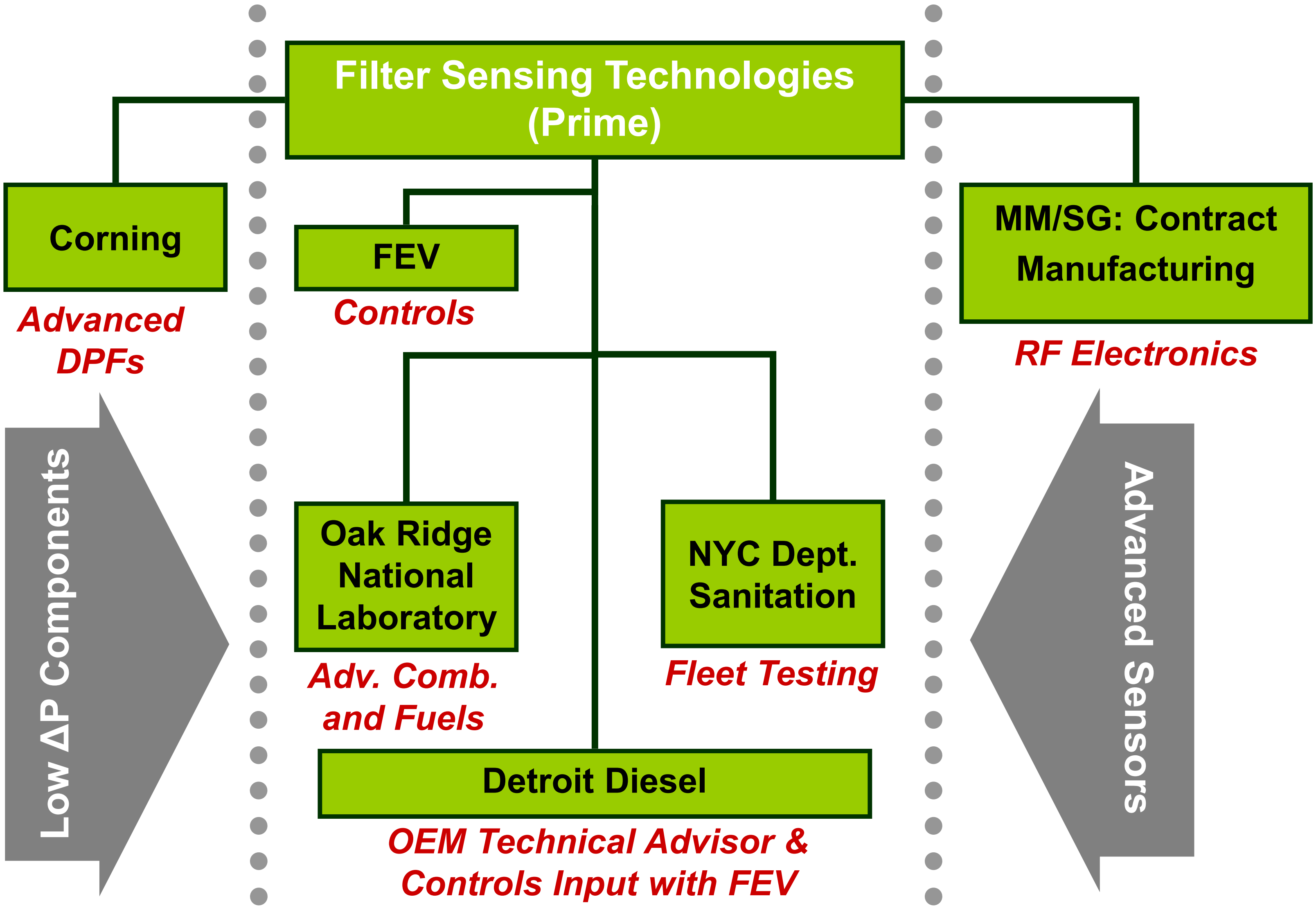
Collaboration and Project Coordination

Interface with DoE/NETL



Controls, Testing, and Systems Level Demonstration

Remaining Challenges and Proposed Future Work

Remaining tasks focus on evaluation of 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 2015 - 2016

- **M 3.6-3.7** Quantify RF sensor performance in light- and heavy-duty engine dyno testing (***Mercedes, GM, Navistar, DDC***).
- **M 3.8** 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 2015 – 2016

M 4.4 Develop commercial/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 Third Year of Program

- Completed production-intent sensor designs (patents pending)
- Demonstrated high accuracy for DPF **soot AND ash** measurements showing clear advantages over current ΔP and models (dPSLE)
- Fast response (< 1sec.) and good correlation with lab instruments
- Evaluated RF sensor over **380,000 mile equivalent** DPF aging and two year fleet durability test with four test vehicles
- Demonstrated additional system optimization with biofuels
- Developed and benchmarked RF controls on MY2013 HD engine
- **Fuel savings** via extend regeneration interval and reduced regeneration time estimated from 1.5% to 3% depending on application over DPF life

Outlook and Project Impact

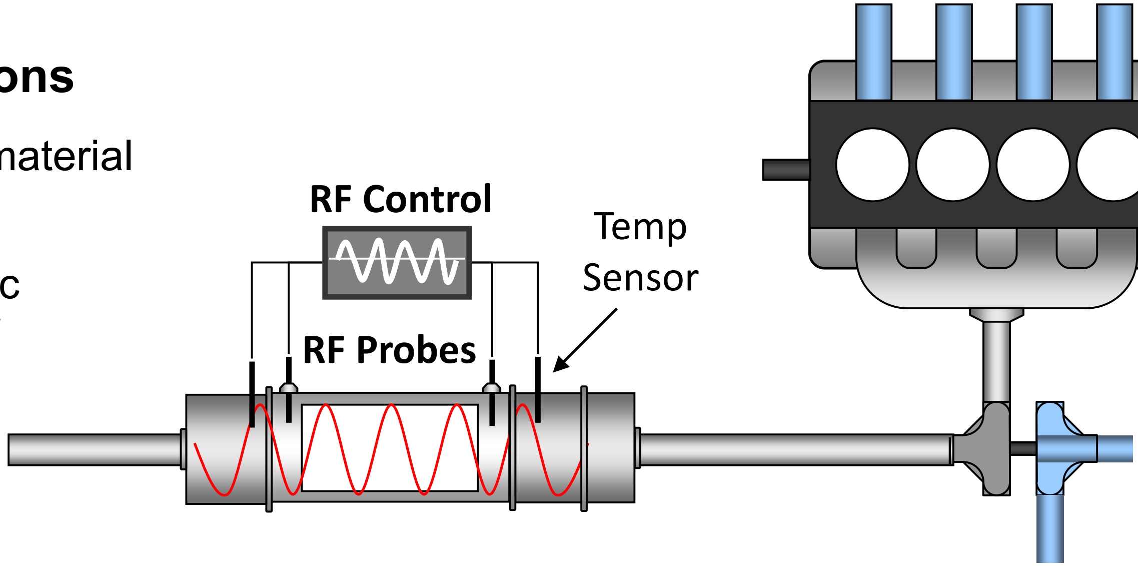
- Additional sensor benefits include overall system cost reduction, extended system durability and DPF life, and ash-related maintenance savings
- Considerable potential to overcome efficiency and durability barriers identified in VT Program Plan through improved sensors and controls

Technical Backup Slides

Basic RF Sensor Operation and Background

RF Sensing Applications

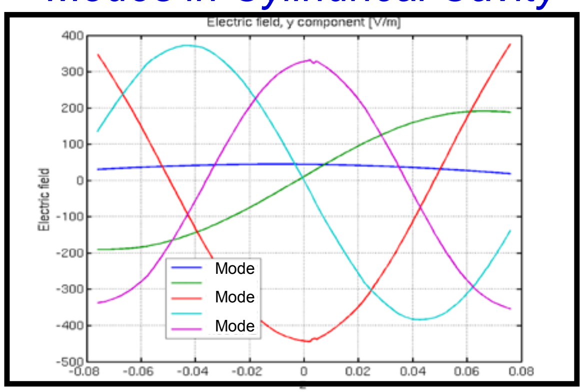
- Direct measurement of material accumulated on DPF
- Prior work by GM, Atomic Energy Canada, Univ. of Bayreuth



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

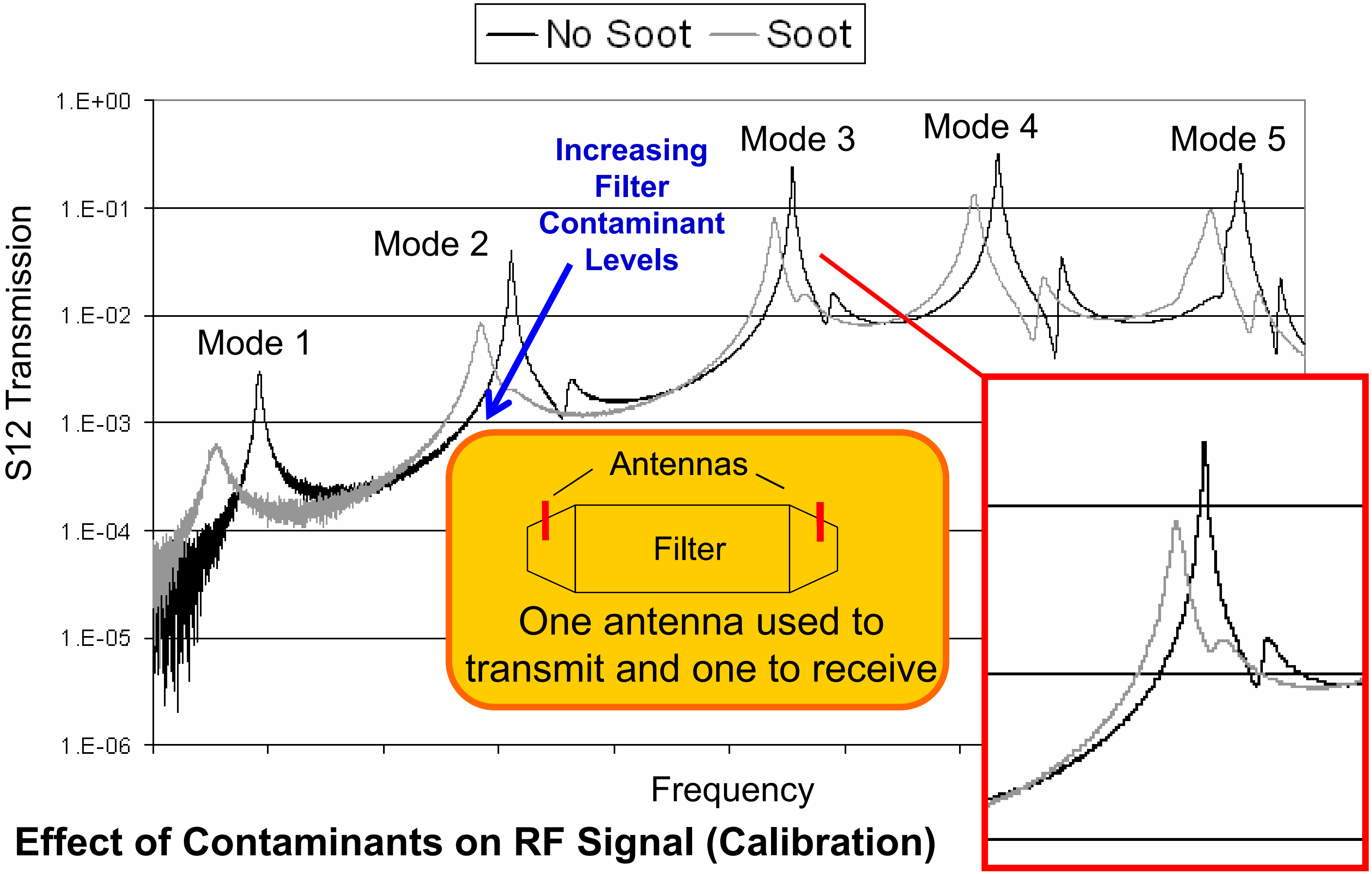


Signal Affected by Dielectric Properties of Contaminants

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

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

Example of Raw RF Signal and Correlation to PM Load

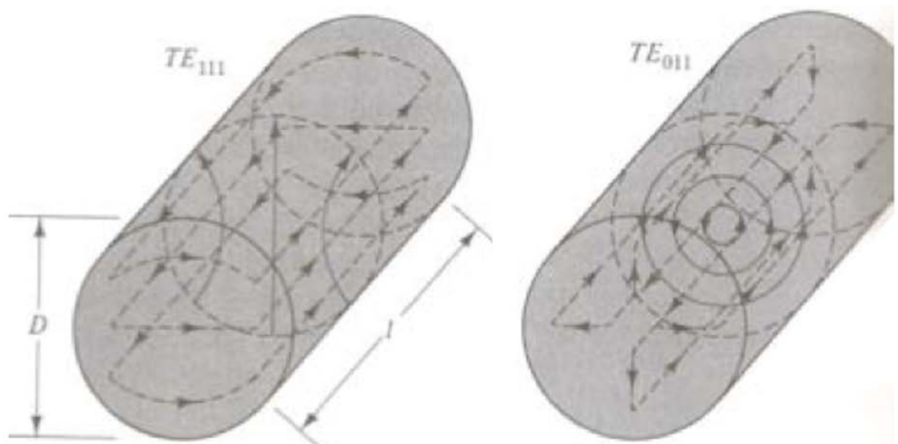


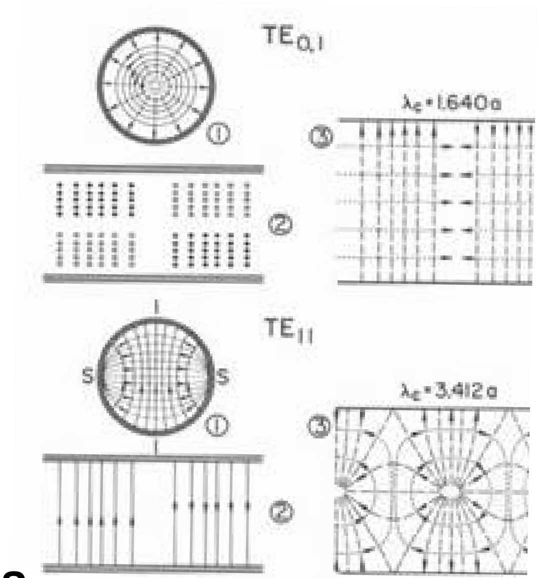
Effect of Contaminants on RF Signal (Calibration)

- 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

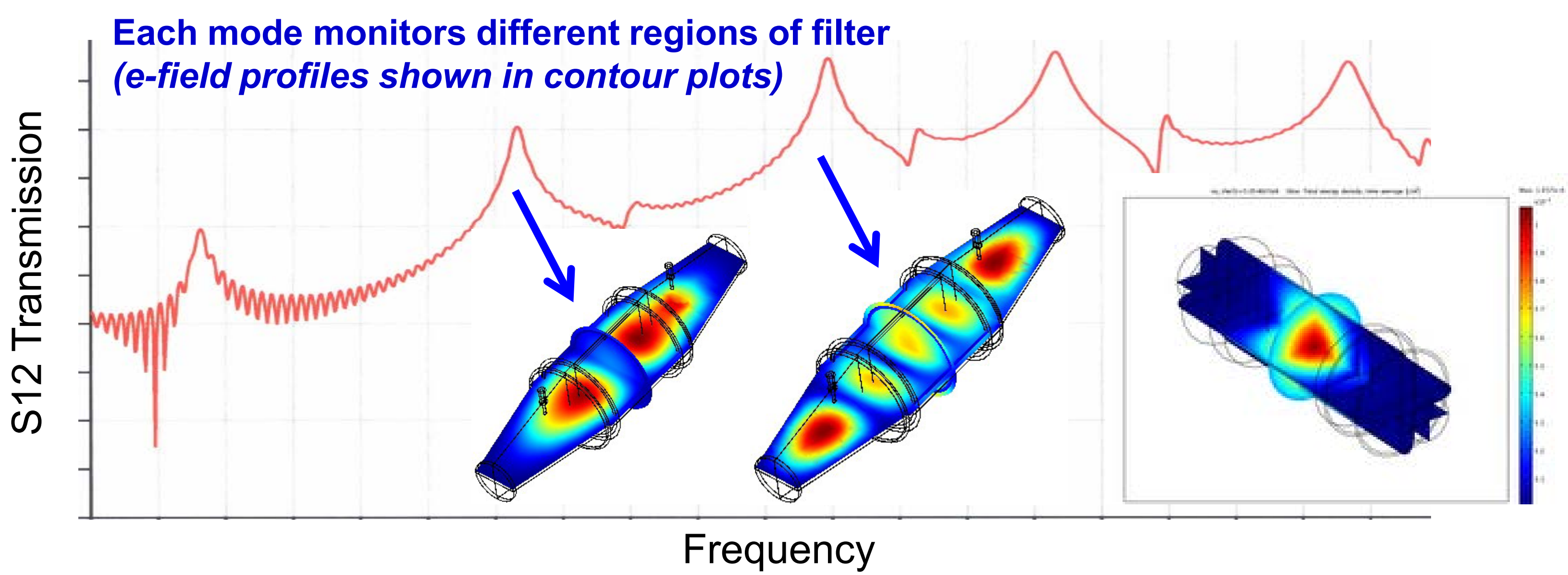
Resonant Modes Also Monitor Spatial Distribution

Typical Resonant Mode Electric Field Profiles*



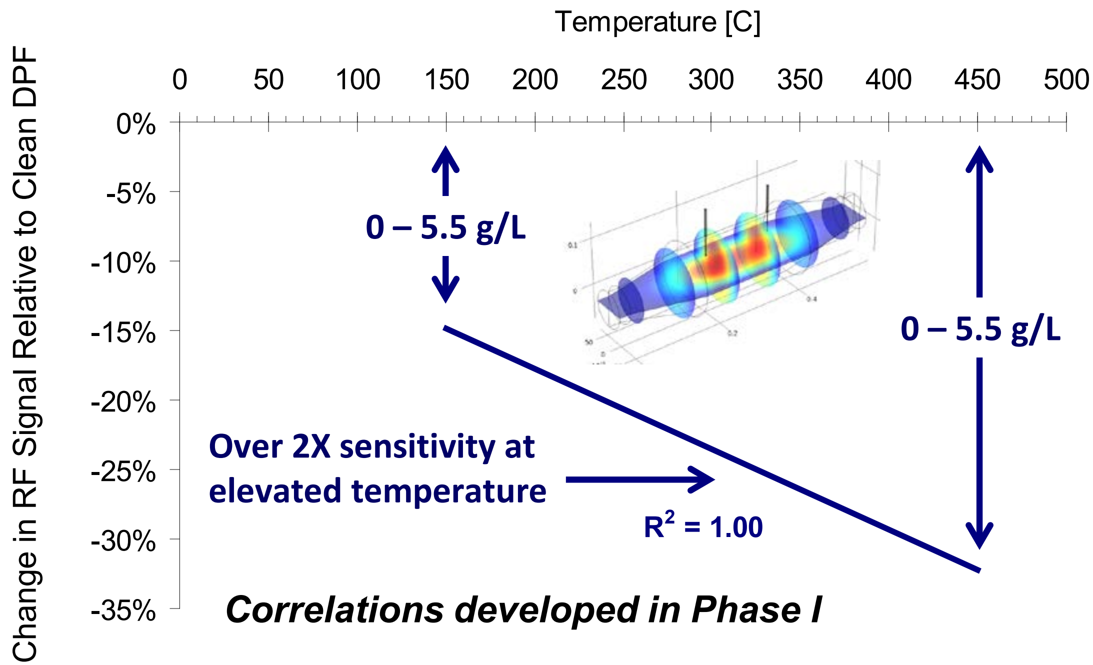


RF System Models for Filter-Specific Geometries

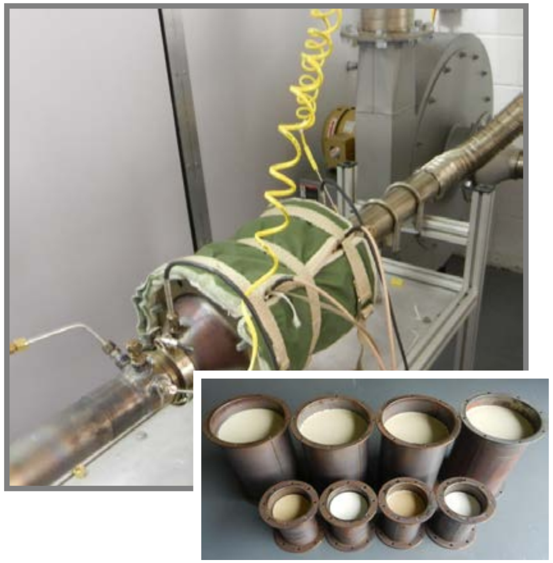


* Adam, Stephen, F., Microwave Theory and Applications, Prentice Hall, Inc., Engelwood Cliffs, New Jersey, 1969.

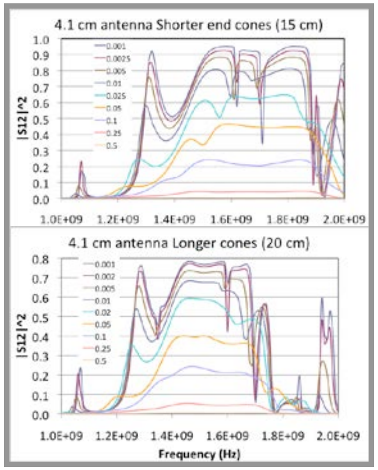
Universal RF System Calibration and Part-to-Part Variability



Test Bench for Temperature Characterization



Universal System Calibration Methodology (M2.1-2.2)



1. Approach based on engine/bench experiments and models.
2. FST RF control unit automatically generates and saves reference scan for clean DPF (auto-zero function).
3. Reference scan accounts for variations in DPF geometry, materials, catalyst coating, canning, or antenna variations.
4. 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).

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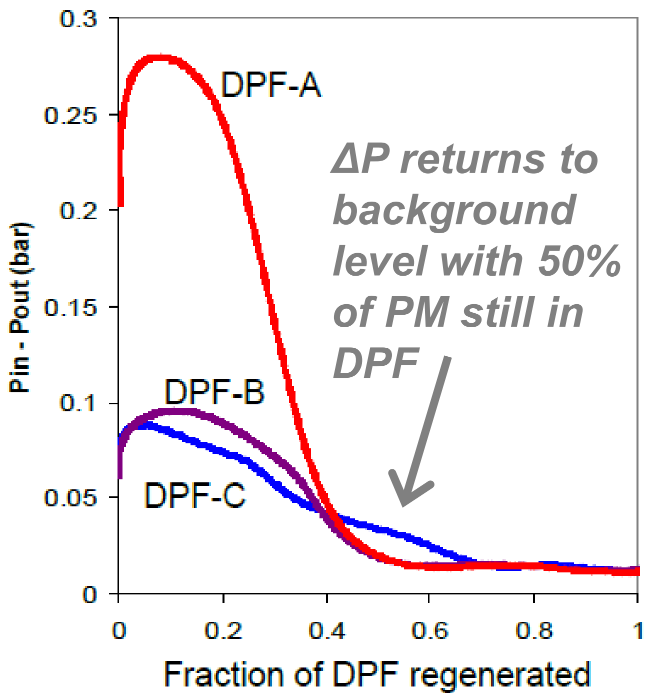
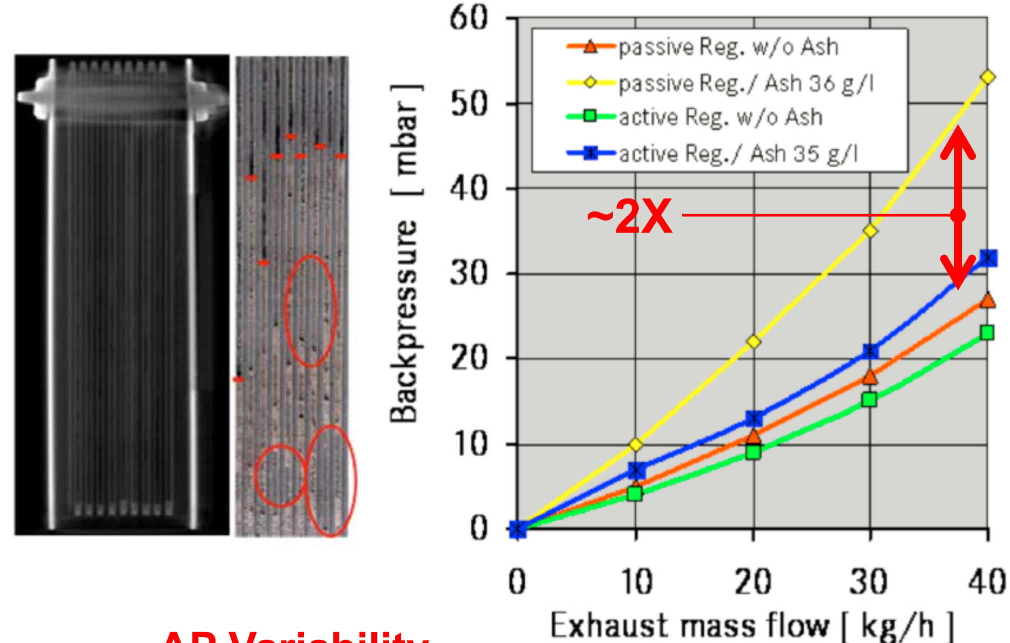
Challenges for Pressure Drop Measurements

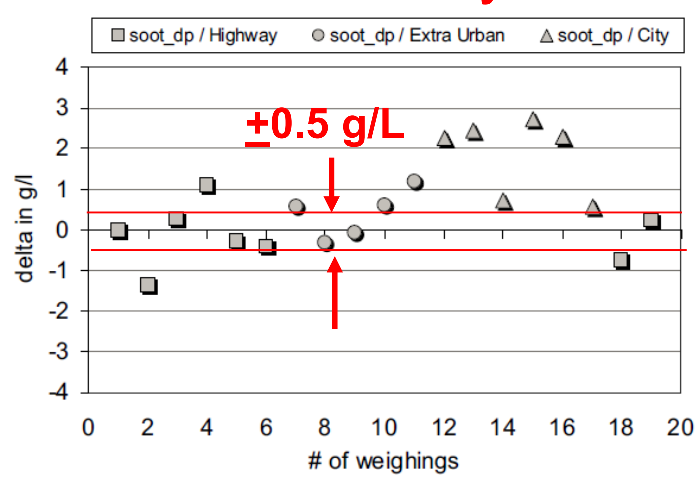
Pressure drop unreliable during regeneration[1]



Ash impacts DPF durability and soot load estimate with ΔP (~2X for same ash load)[2]



ΔP Variability



Error in ΔP measurement with new DPF (no ash)[3]

References:

1. Toops, T., Finney, C., Nafziger, E., and Pihl, J., "Neutron Imaging of Advanced Transportation Technologies," DOE AMR 2013.

2. SAE 2012-01-1732

3. SAE 2009-01-1262

Thank You!