

# Demonstration of Particulate Matter (PM) Sensor in post-DPF Environment

**A Presentation to:**  
**California Air Resources Board**  
**Research Division**

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By  
Honeywell Laboratories  
Plymouth, Minnesota

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***Program Objectives***

***Description of particulate matter sensor***

***Experimental design***

***Bypass Testing***

***Failed diesel particulate filter testing***

***Sensor ruggedness***

***Summary and Conclusions***

***Recommendations and Next Steps***

# Program objectives

Honeywell International intended to demonstrate a particulate matter (PM) sensor to provide on-board diagnostics for a diesel engine to monitor compliance with proposed particulate matter exhaust limits of 0.03 gm/bhp-hr as identified in California Code of Regulations, Title 13, Section 1971.1(e).

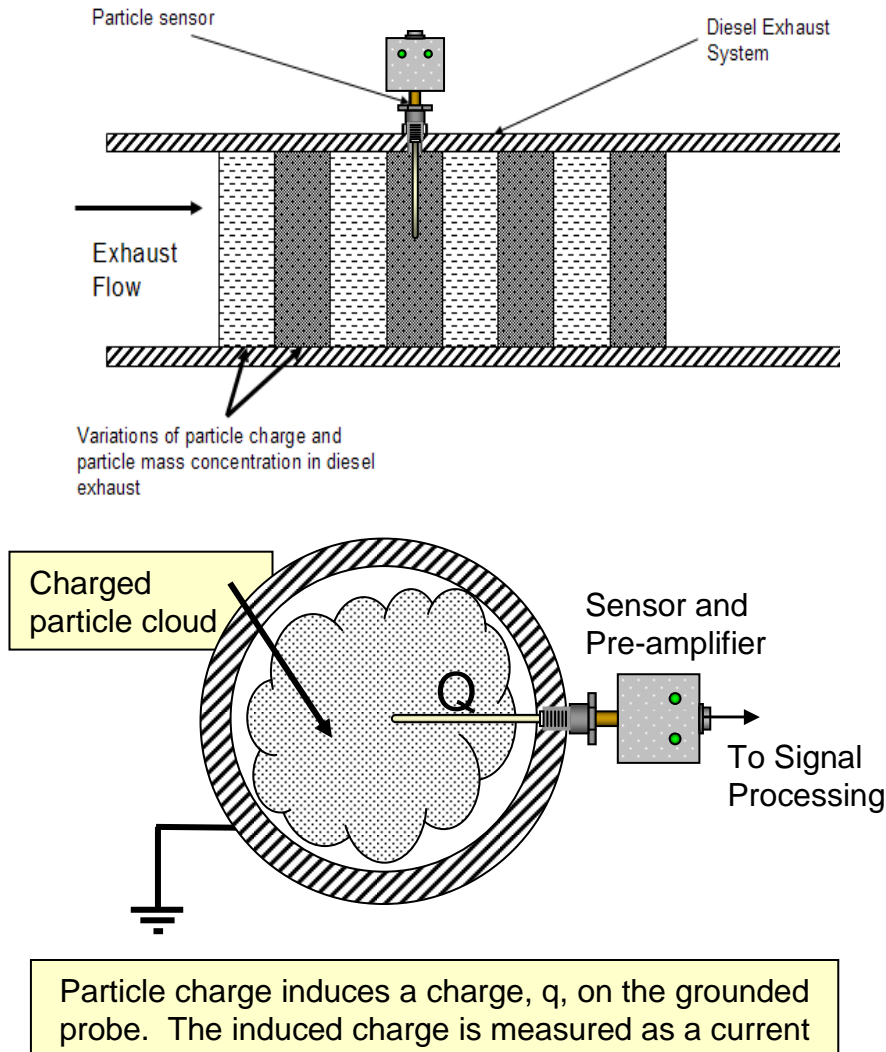
Program also intended to improve the understanding of the PM sensor response to the charge characteristics of the exhaust particles.

# Statement of Work

- Conduct on-engine testing of PM sensor within the post-DPF environment.
- Determine probe responsiveness and signal accuracy by comparing sensor with calibrated particle measuring equipment
- Measure sensor response in post-DPF environment using a functional DPF and then failing that DPF while providing the conditions approaching the 3x certification levels of 0.03 gm/bhp-hr.
- Correlate sensor output with both particle and charge distributions.

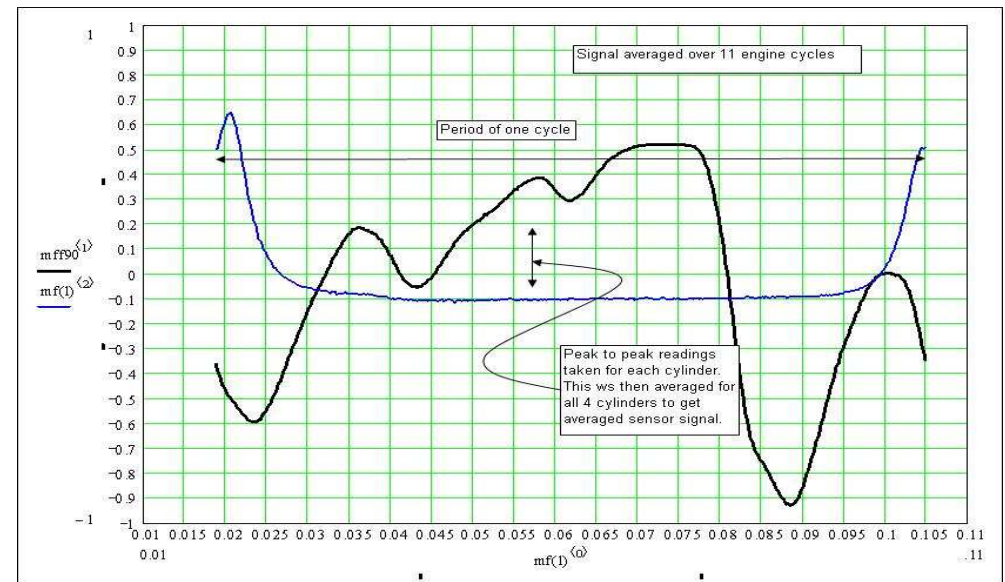
# PM Sensor - Basic Concept and Operating Principle

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## How the sensor works:

- Diesel exhaust contains charged particles.
- These charged particles induce an image charge in sensor electrode.
- Rapid sensor response allows detection of current fluctuations as individual cylinders fire.

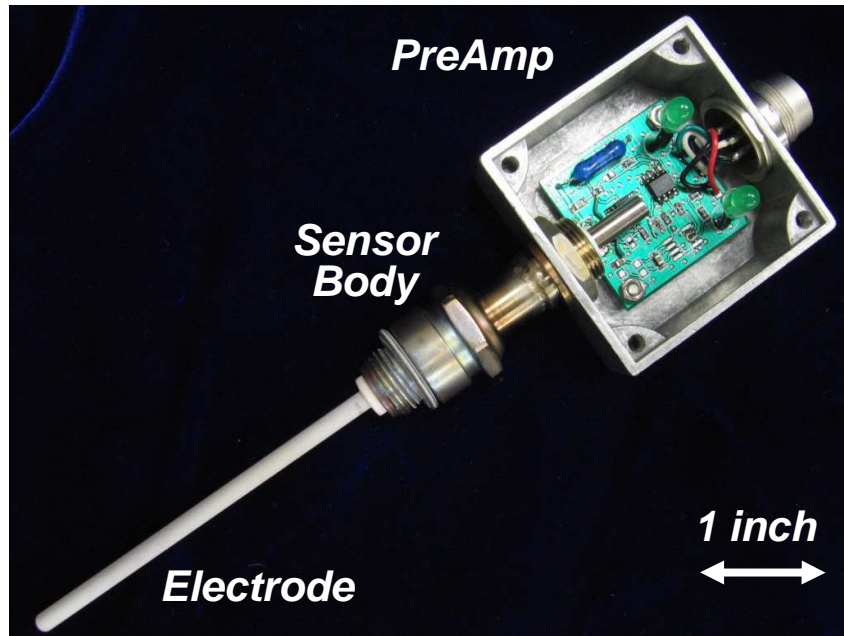


Rapid Response of PM Sensor to Cylinder Emission

Sensor capable of functioning in harsh exhaust environment.  
Possibility of detecting individual cylinder events

# Description of PM sensor and electronics

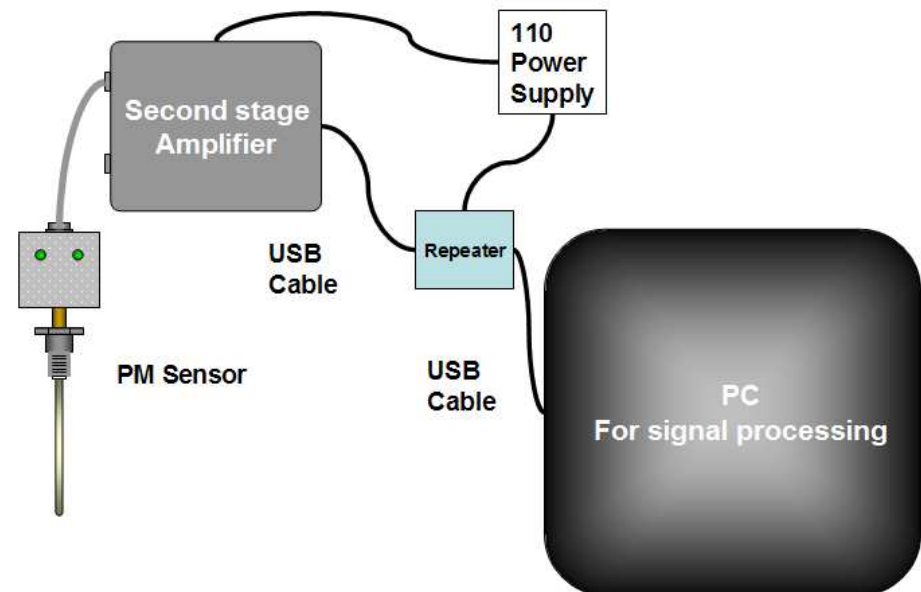
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Sensor with preamplifier attached

- Pre-Amplifier integrated with probe to minimize signal noise.
- Second stage Amplifier to ultimately be integrated with first stage.

- Sensor constructed of inner conducting electrode surrounded by electrically isolating, thermally rugged shielding.

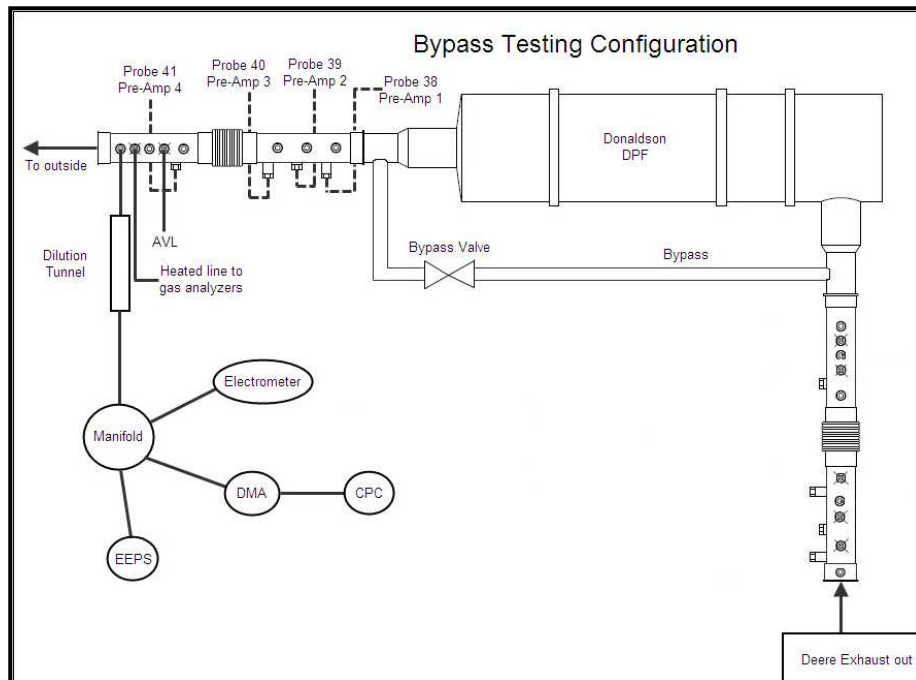


Schematic of sensor testing configuration

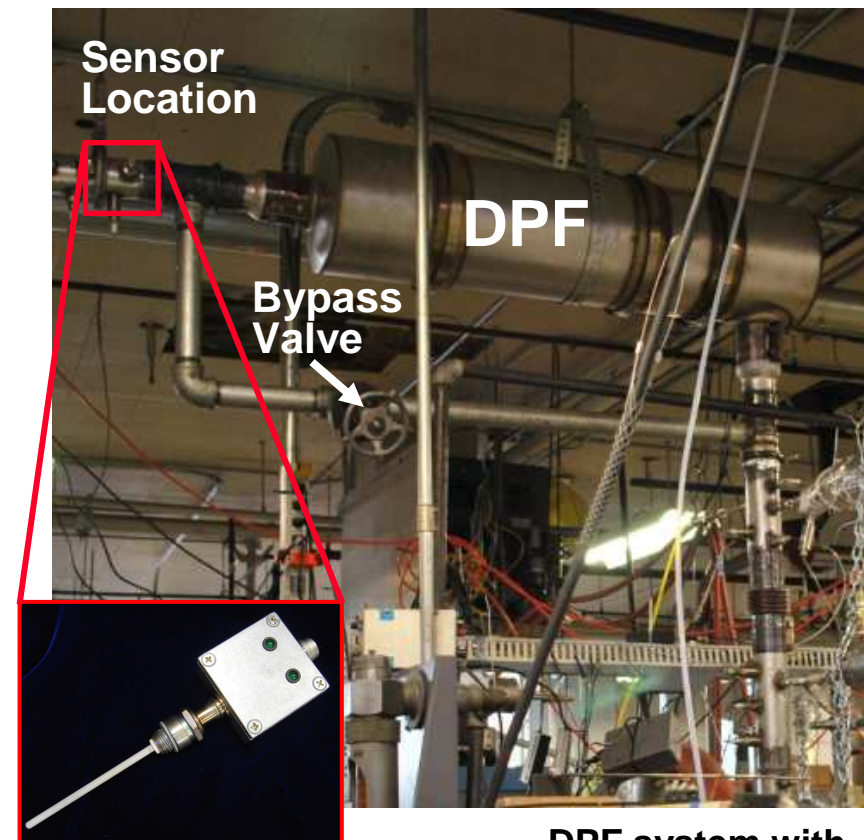
*Rugged sensor can be installed directly into Exhaust Pipe*

# Test configuration and sensor mounting

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PM sensor locations and particle instrumentation

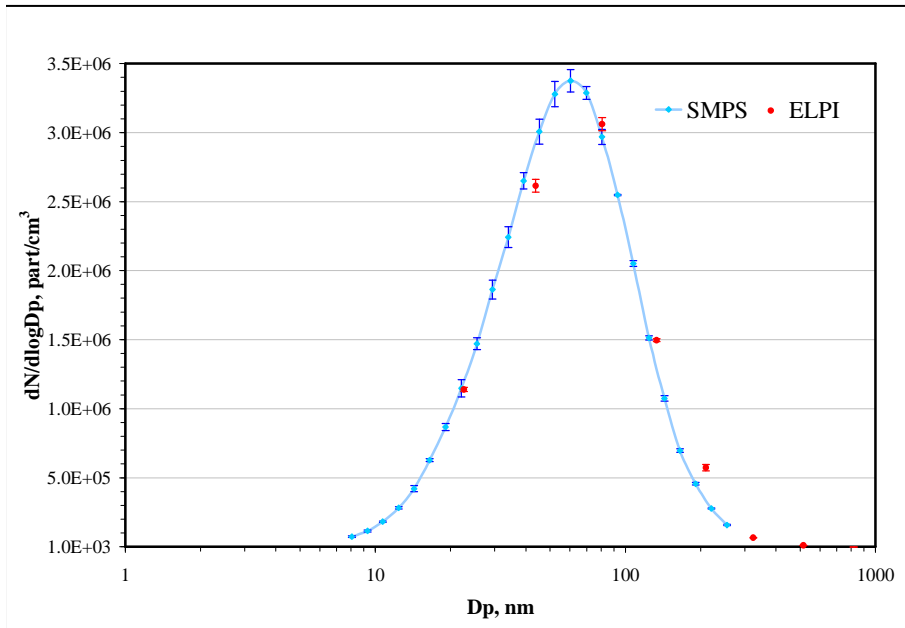


DPF system with Bypass mounted on Test Cell

- Testing done in cell at U of M Center for Diesel Research Lab
- Preliminary calibration conducted on instrumentation and engine system
- Measurements made for both particle and charge concentrations
- Bypass system used to reduce mass concentrations before failing actual DPF
- Post-DPF Particle and charge concentrations also compared to upstream levels

# Exhaust measurements - correlation of particle measurement Instrumentation

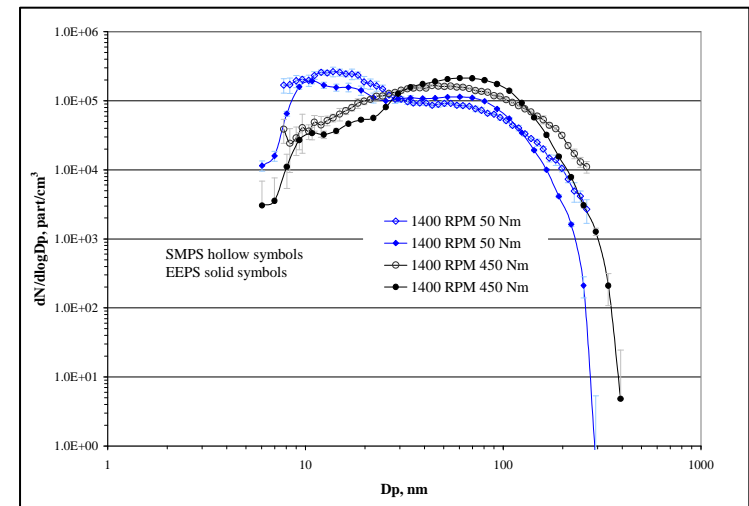
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## Correlation of Mass Concentration Equipment

- Measurements at different engine conditions shows response to accumulation mode and nuclei mode, the latter at the 50Nm loading

- Particle equipment was found to correlate extremely well both for both mass and number concentrations.

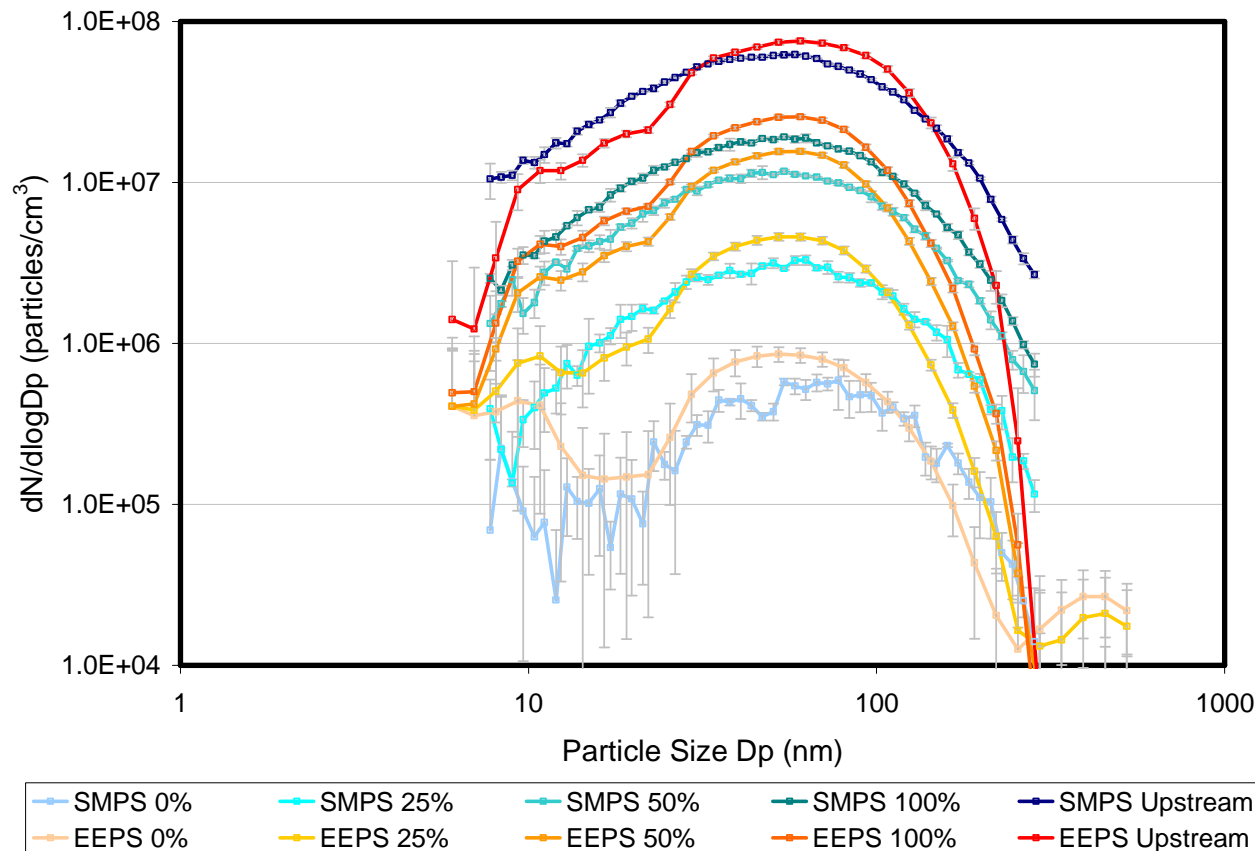


*Excellent comparison between particle measurement Instrumentation  
Exhaust particulate seen to be mainly accumulation mode*



# Effect of bypass

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- Accumulation mode for particle distribution with very little nucleation mode
- Mass and number concentrations correlate to bypass
- As bypass is changed, shape of distribution remains roughly the same.
- When bypass closed, majority of mass is coming through the trap.
- Small nucleation mode tale seen at around 10 nm

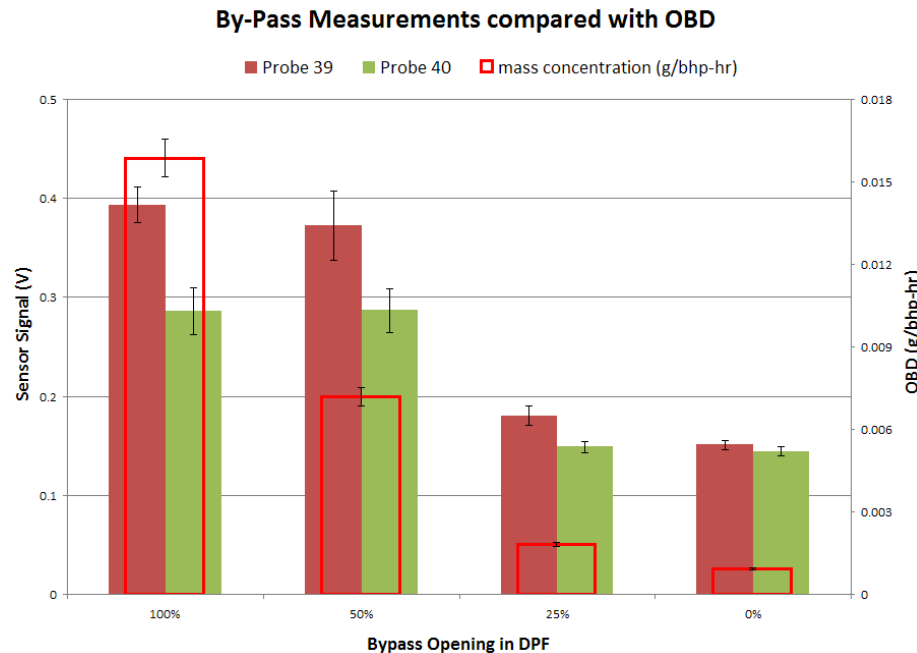
## Change in Number size distribution with Bypass Opening

*Increased penetration of particles as bypass opened*  
*Similar distribution shape*

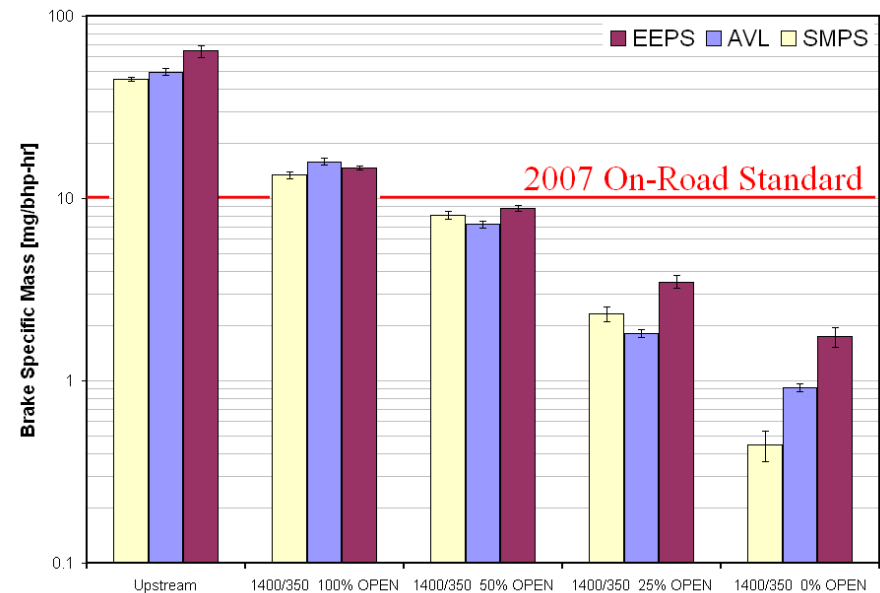
# Sensor and mass concentration with bypass

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- When bypass closed, majority of mass is penetrating DPF.



Comparison of multiple sensors with mass concentration



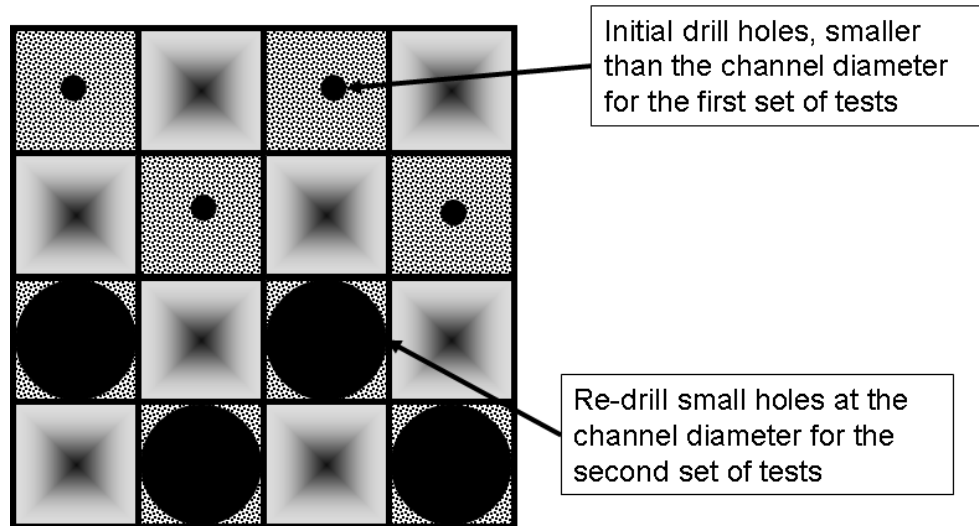
Change in Mass concentration with Bypass Opening

- PM sensor response for closed bypass. implies potential sensor response threshold
- Geometry changes in exhaust could cause sensor variation.

*Sensor data shows ability to measure small concentrations, but sensor appears to have threshold limit at lower concentrations*

# Strategies for Failing the DPF

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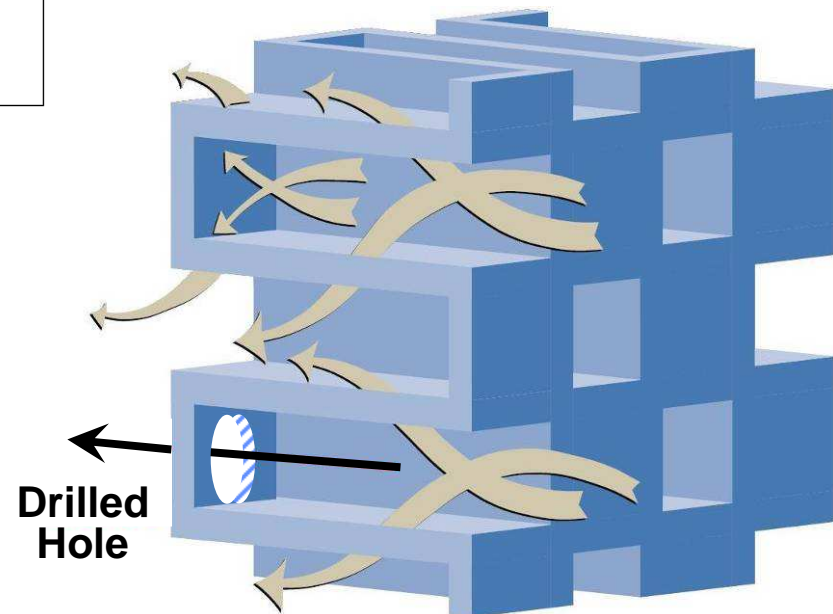


Showing strategy for simulating end cap failure

- Most effective, reproducible failure method was end cap failure
- Small holes in end cap simulate artificial “crack” in DPF
- Ability to manage flow through the DPF drove selection of failure method

## Potential DPF failure mechanisms considered

- Thermal Separation
- Ring Crack Failure
- End Cap failure

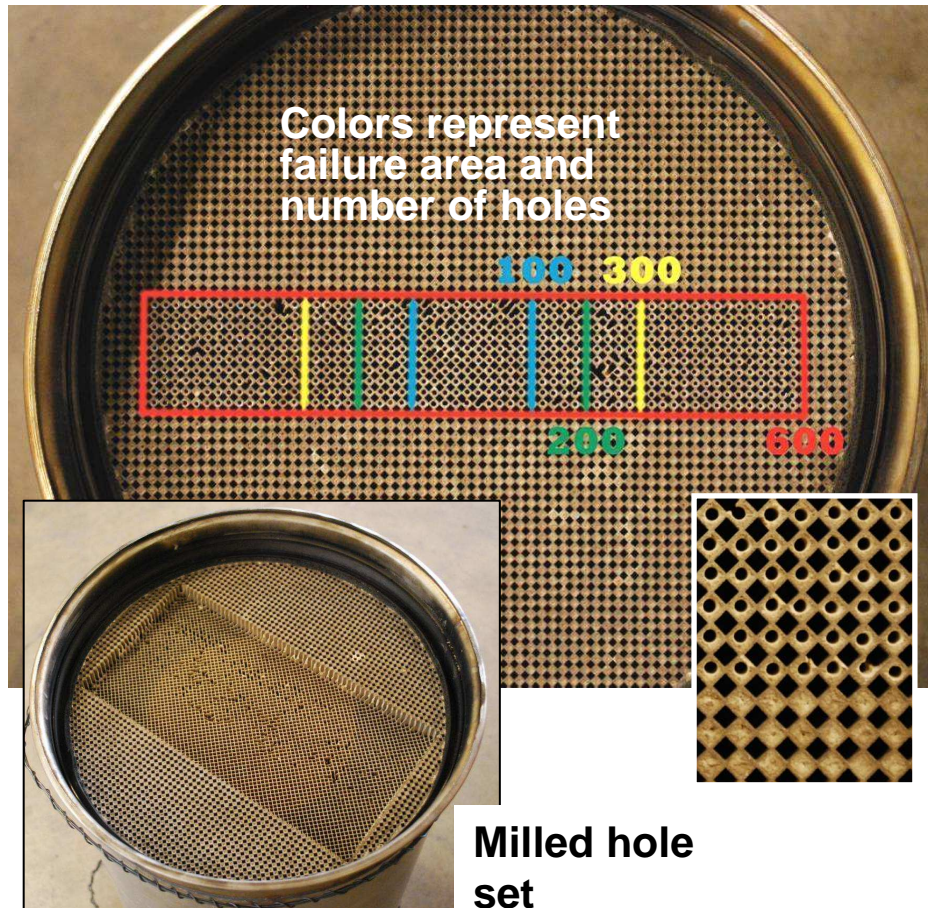


Visualization of Flow penetration through DPF

*Simulated failure based on real world failure mechanisms*

# Failing the DPF

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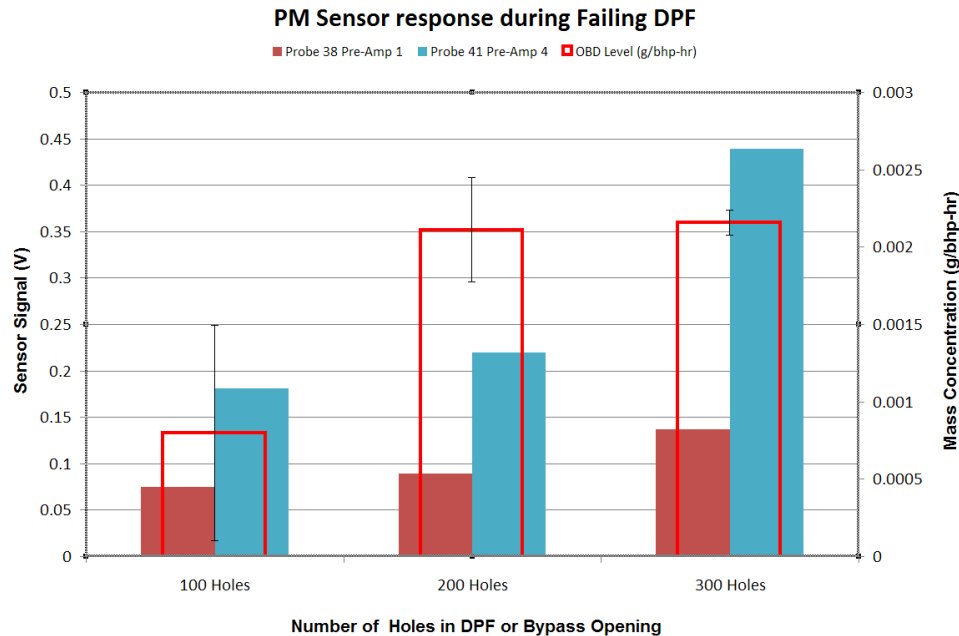
- Attempts were made to maintain channel walls while holes drilled in end cap
- Failure area progressed from center of DPF to outer perimeter
- For larger failure areas channel ends were milled off and then DPF channels cleared



- Number of openings to be drilled for each subsequent test was selected based upon previous measurements.

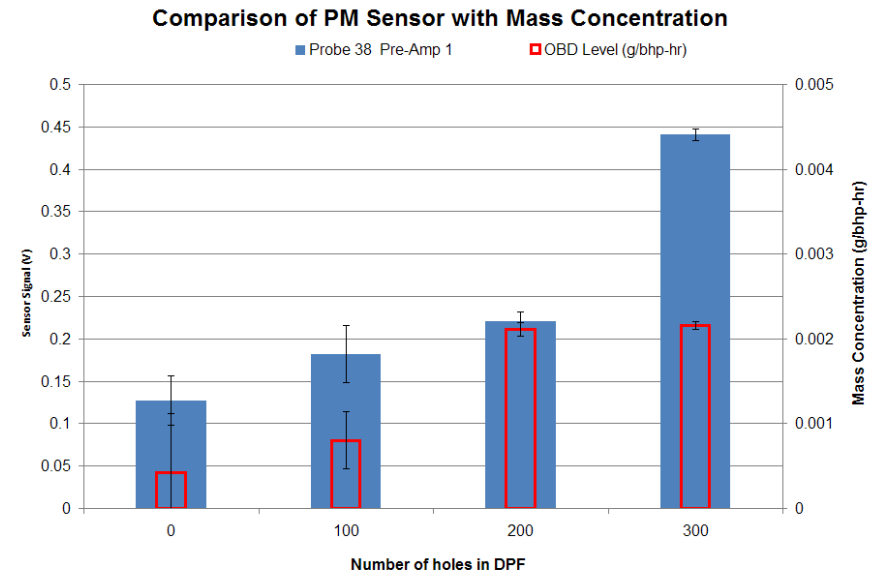


# Sensor response during initial DPF failing



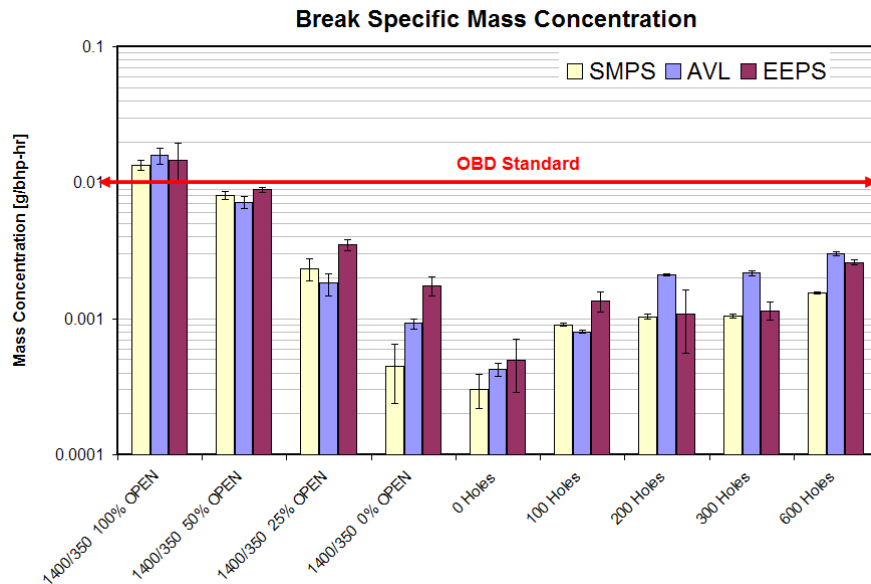
- Testing conducted for initial DPF failure modes on first engine indicated rough correlation between PM sensor and mass concentration.
- Between 200 and 300 holes sensor signal increased at greater rate than mass concentration.

- Variation in sensor response to similar mass concentrations indicate possibility of sensor response to location.



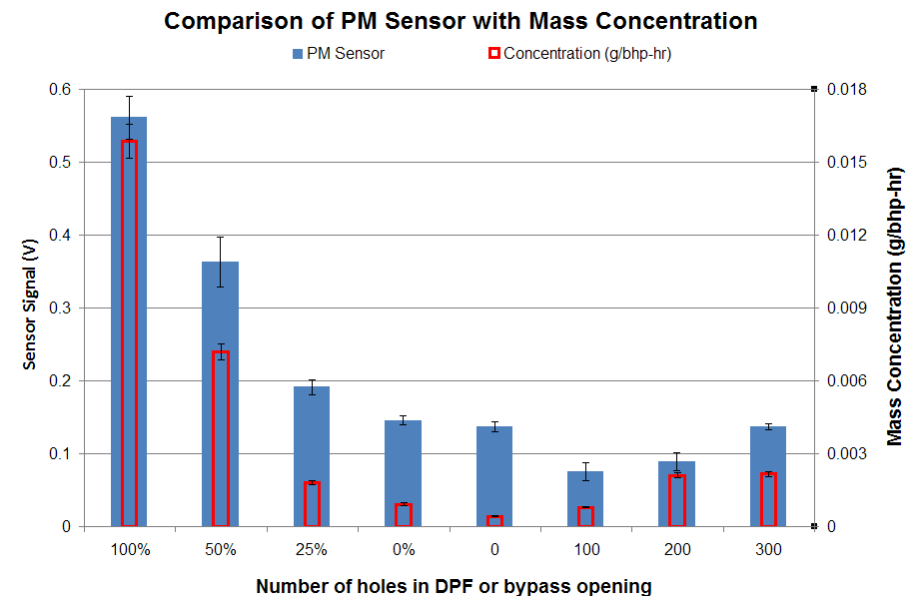
*Preliminary DPF failure modes show sensor has capability to respond to changing levels of DPF failure*

# Bypass and Failed DPF measurements



- Rate of change of mass penetration for bypass openings more uniform than in DPF.
- Initial failure modes of DPF did not achieve threshold level .

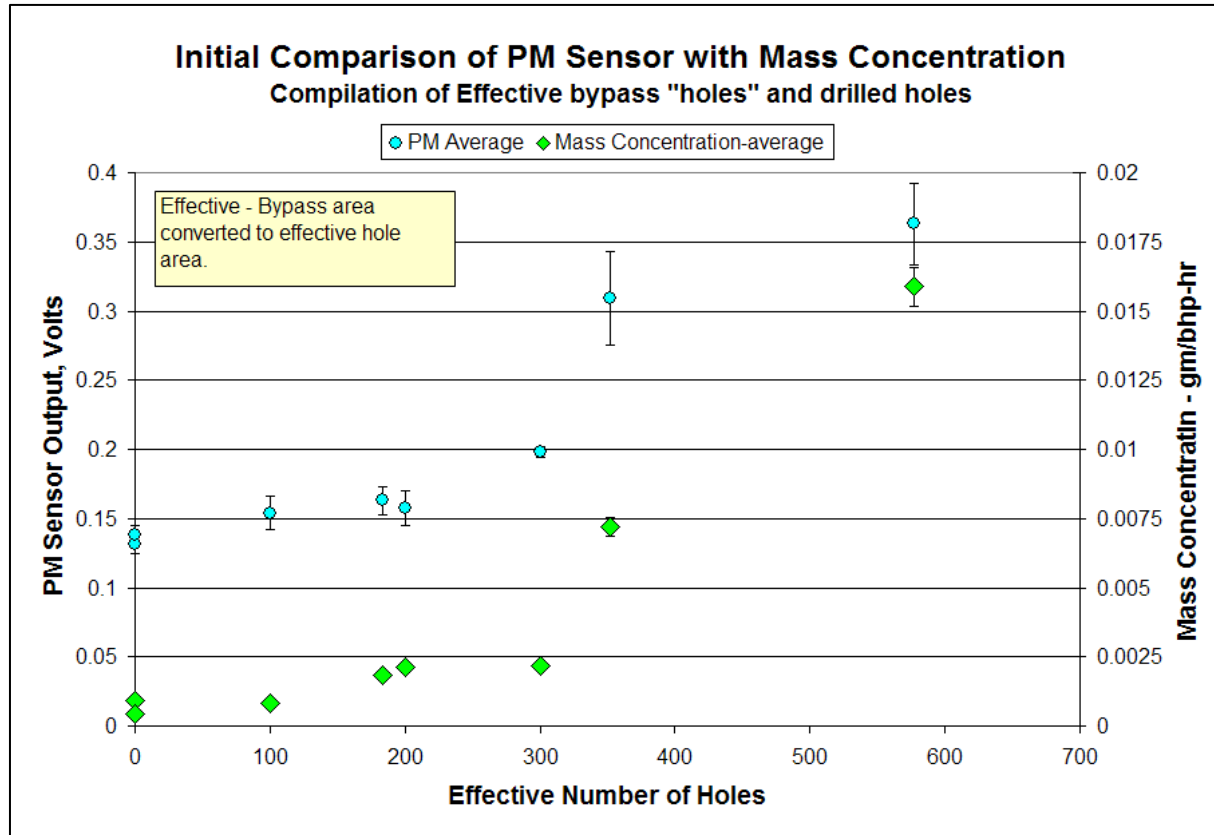
- PM sensor roughly follows mass concentration for bypass modes.
- Response for functioning DPF indicates possible minimum operational level of sensor



*PM sensor indicates initial correlation with mass concentration*

# Sensor response to “failure” rates

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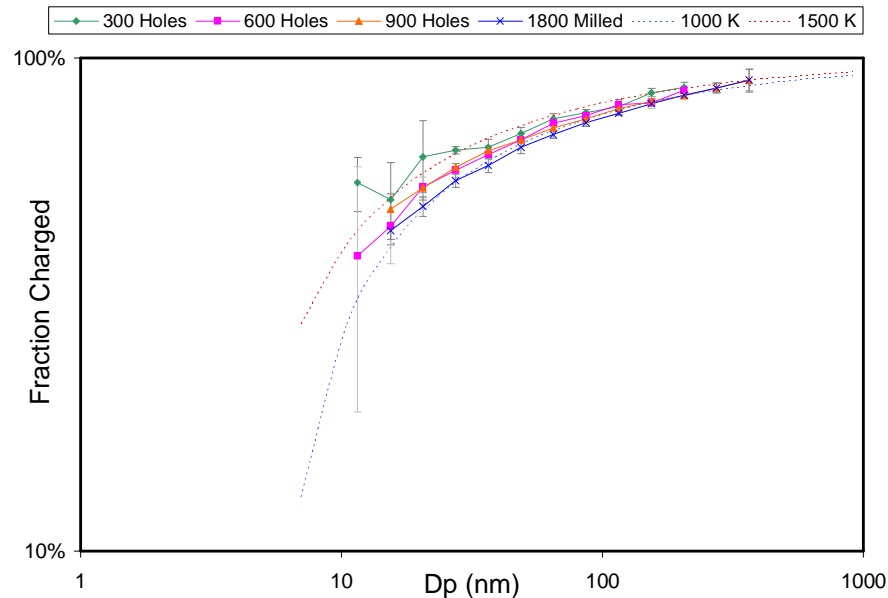


- Bypass opening converted to “ area equivalent” number of holes
- Non-linearity observed in sensor response
- Maximum rate of change of sensor response starts at mass concentrations near OBD threshold level.

*PM sensor correlates with “equivalent area” of failed DPF, but with low sensitivity*

# Charge Measurement Results during DPF Failure

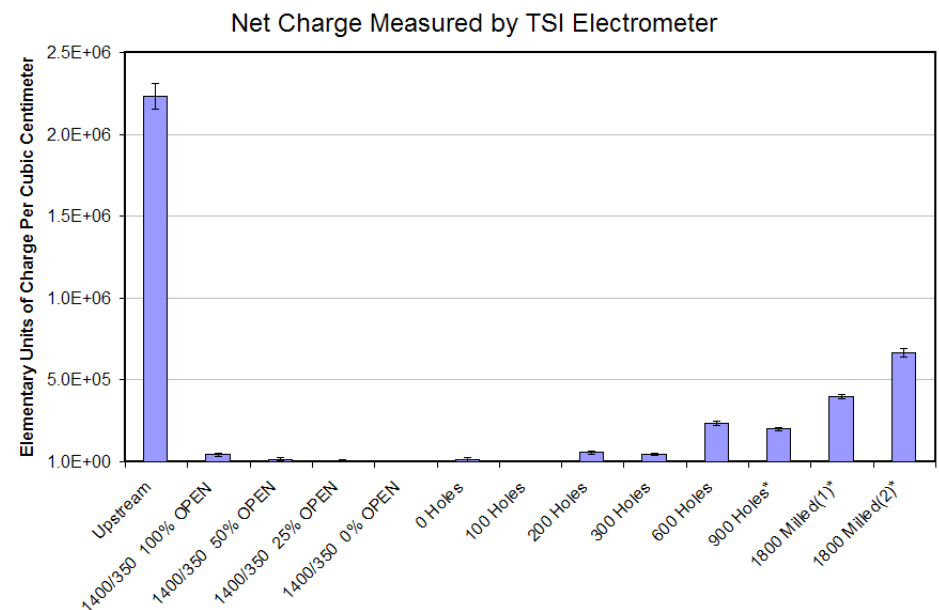
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Fraction of charged particles vs.. DPF failure

- Minimal number of nucleation mode particles are charged
- Fraction of charged accumulation mode particles remains relatively constant over all failing modes

- Net charge for both the bypass and DPF smaller than upstream levels.
- Effect of charged particle removal by DPF needs to be determined



Pre- and Post-DPF Net Charge

*Increase in the penetration of Net charge with increase in open area of the DPF*



# Effect of engine substitution on sensor response

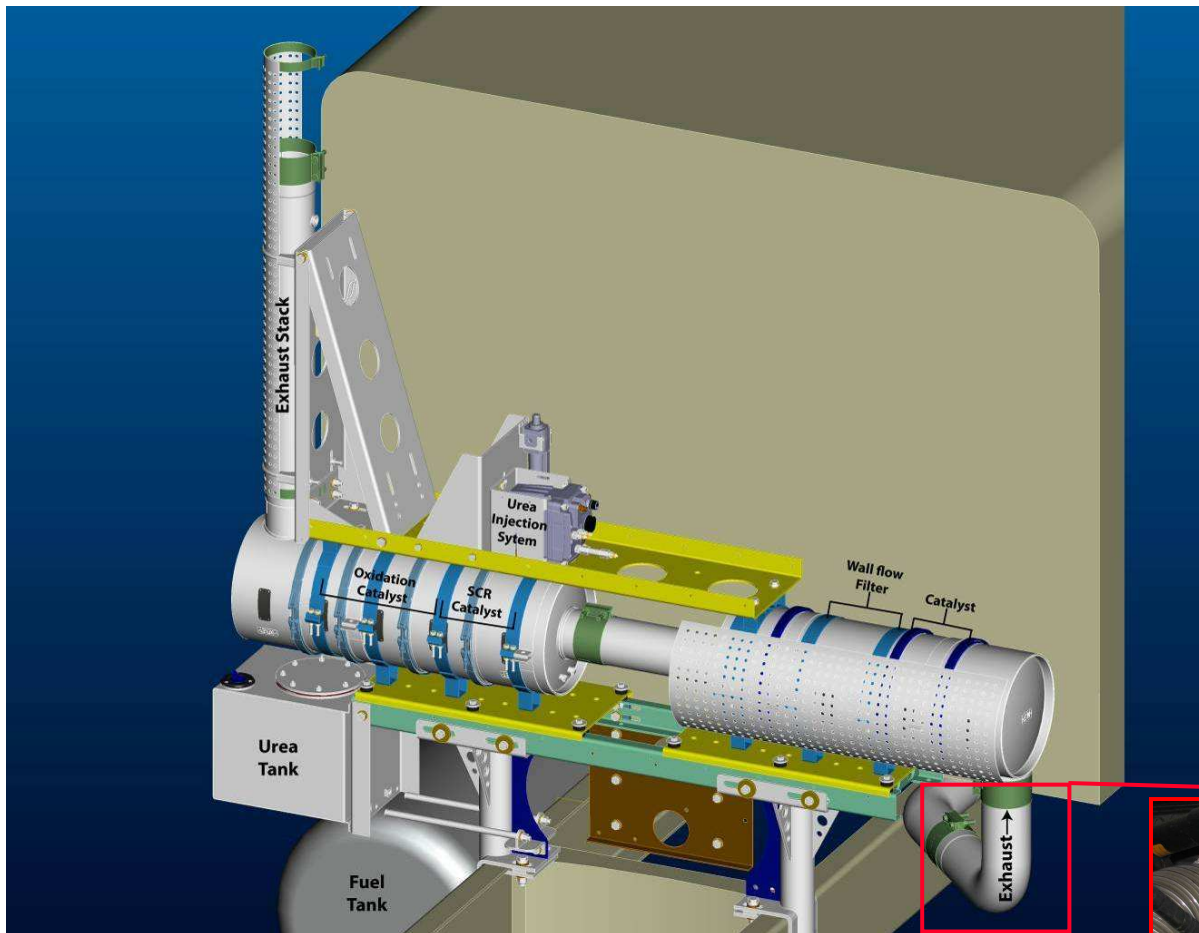
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- Sensor response reduced when new engine substituted
- Potential Issues
  - Reduced sensor response occurred even with larger number of holes in DPF
  - Difference in new exhaust configuration
  - Substitute engine operated to produce similar mass and charge concentration in exhaust upstream of DPF
  - Sensor saw increase in vibration and signal noise
- Response differences raise concern in applying over wide range of engines.

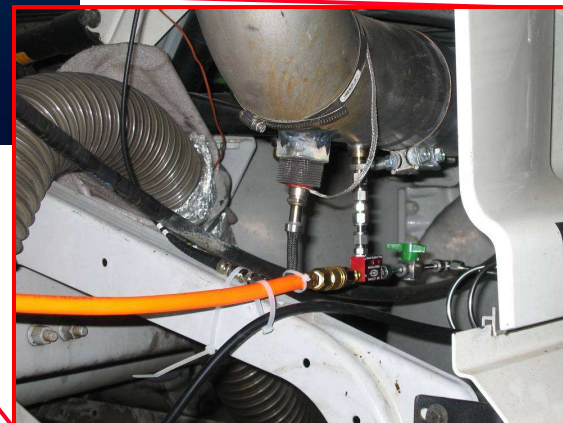
*Different sensor response seen between engines*

# Sensor ruggedness testing

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- Preliminary measurements were made with the sensor mounted on a heavy duty Diesel truck driven under highway conditions.
- Sensor installation to observe physical effects on the sensor
- Vibration reduction mounting used for one sensor.
- Post test examination of sensor indicated no adverse physical effects



# Summary and conclusions

- **For PM sensor tested under this program.**

- The sensor operated over extended time periods without mechanical failures (coating de-lamination or degradation).
- The sensor does not appear to quantitatively detect variation in mass concentrations down at a level sufficient for OBD detection of DPF faults.
  - Select tests indicate detection capability at or below the 0.03 gm/bhp-hr mass concentrations, but with large variance in sensor response.
- Initial on-engine measurements produced a rough correlation between PM sensor response and mass concentration, but only at high failure levels of the DPF.
  - Testing on a second engine, however, indicated that sensor response was drastically reduced.
  - Signal-noise, while improved through amplification and signal processing still remains a limitation.
  - Additional sensor evaluation indicated that internal probe connections may be one cause of the noise.
- A preliminary correlation between the particle charge and exhaust mass concentration has been observed.
  - Additional quantification of the charge on the exhaust particles is necessary for understanding this environment

- **Changes in the PM sensor response on a different engine suggest that a single post-DPF sensor solution may not work.**

- Initial data analysis indicates that a two sensor solution is more promising, relying on the relative signal change between upstream and downstream sensors.
- Pre- and Post- signal differentiation (either integrated spectral or time based) could develop a “finger print” to recognize DPF failure

# ***Recommendations and next steps***

- **Continued evaluation of the PM sensor in the post-DPF environment, specifically using a two-sensor solution (upstream and downstream PM sensors).**
  - Experimental investigation of time-based and frequency-based processing methods with a down-select to provide a quantitative sensor response for DPF failure.
  - Develop a threshold trigger for DPF failure indication (triggered when the post-DPF sensor signal is “sufficiently close” to the pre-DPF signal). Would not be useful for determining OBD levels until at the point of failure.
  - Further investigate the “discreet voltage filtering ” characteristic of a single sensor to exclude sensor voltages below a certain “noise” threshold.
- **A more complete understanding of the charging process in the exhaust and the interaction of particle charge distributions within the DPF may would assist in understanding of sensor limitations.**

# Acknowledgements

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