Measuring PM Distribution in a Catalyzed Particulate Filter using a Terahertz Wave Scanner

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  - *Experimental Studies for CPF and SCR Model, Control System, and OBD Development for Engines Using Diesel and Biodiesel Fuels*
  - Partners:

Overview of Presentation

- Objectives of Research
- Terahertz Wave Scanner Background
- Data Organization
- Data Analysis
- Experimental Equipment
- Results
- Summary of Research

Objectives of Research

- Evaluate Methods of Measuring PM Distribution
  - X- Ray
  - Dynamic Neutron Radiography
  - Terahertz
- Establish an Analysis Procedure to Quantify Distribution: Uniformity Index Equations
- Establish Procedures and Instrumentation for Substrate Canning, CPF Loading, and PM Distribution Measurement
- Conduct Testing and Analyze Results
  - 4 Tests and 7 Filter Scans Completed: Loading, Active Regeneration, and Passive Oxidation Conditions
  - Data Used in CPF Model Development and Validation
  - Directions for Future Studies Established

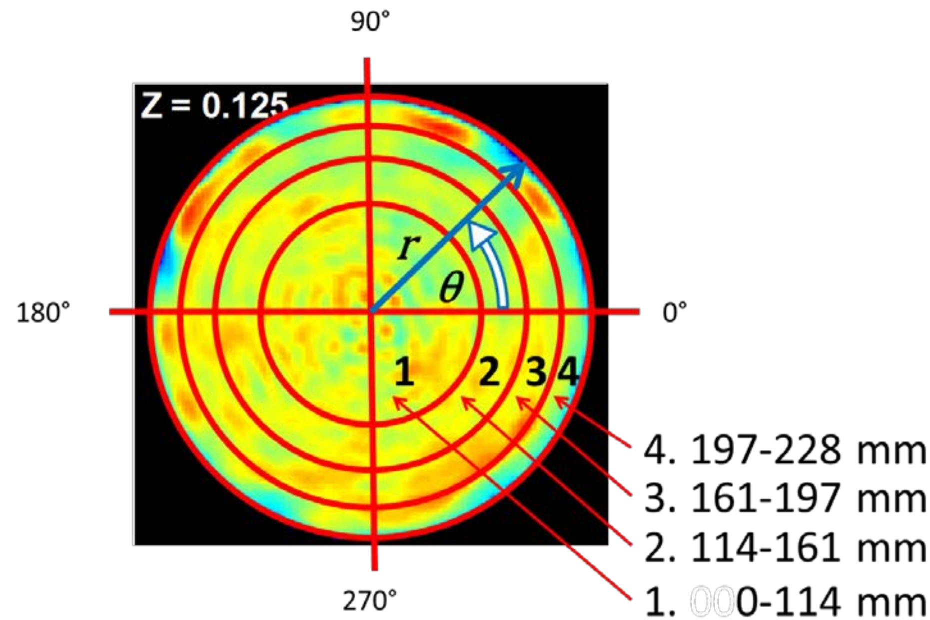
Terahertz Wave Scanner Background

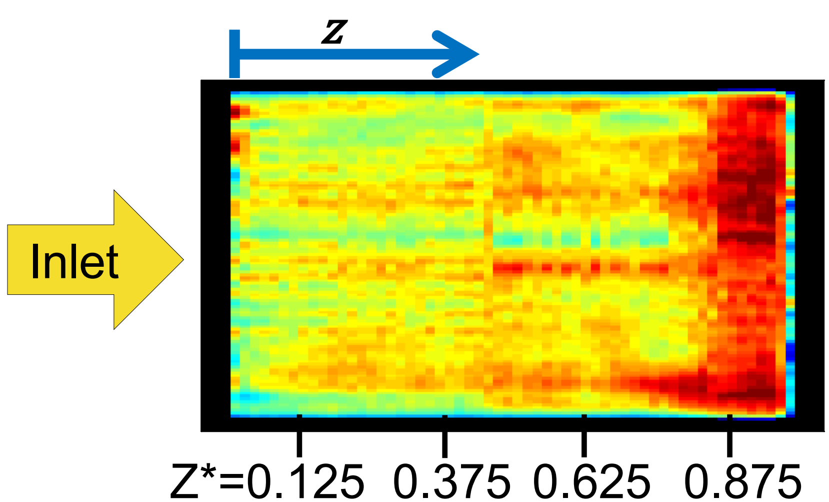
- Advantest TAS7000 3D Imaging Analysis System
- Substrate is Scanned in the r, θ, and z Plane [1]
  - Resolution: 4 x 4 x 4.3 mm Cube
  - 4096 Sample Points in r and θ
  - 64 Axial Sections in z
- Terahertz Waves Enable Spectral Analysis [2]
  - Washcoat, PM, and Ash
  - Change in Frequency Response Correlates to Local PM Loading
- Accurate Results of the Local PM Concentration Obtained by:
  - Removing the Substrate from the Clamshell Can [3]
  - Pre-Scanning the Substrate [1]

Data Organization

- Axial Sections Split into:
  - 4 Equal Area Radial Sections
  - 5° Angular Increments
- 288 Analysis Points per Axial Section
- Θ: Angle of Rotation
- $Z^* = \dfrac{\textit{Distance from Inlet}}{\textit{Total Axial Length}}$

  $Z^* = 1 \rightarrow \; z = 280 \text{ mm}$





Data Analysis

- γ: Uniformity Index
- σ: Standard Deviation of PM Density
- $\overline{w}$: Measured PM Density in the Substrate After Loading
- w_i: PM Density in Individual Analysis Points
- $\overline{w_l}$: Average of w_i Values
- n: Number of Analysis Points Used
- **Uniformity Index ≥ 0.95: Distribution Considered Uniform**

$$\gamma = 1 - \left(\frac{\sigma}{\overline{w}}\right)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(w_i - \overline{w_l})^2}{n}}$$

Experimental Equipment

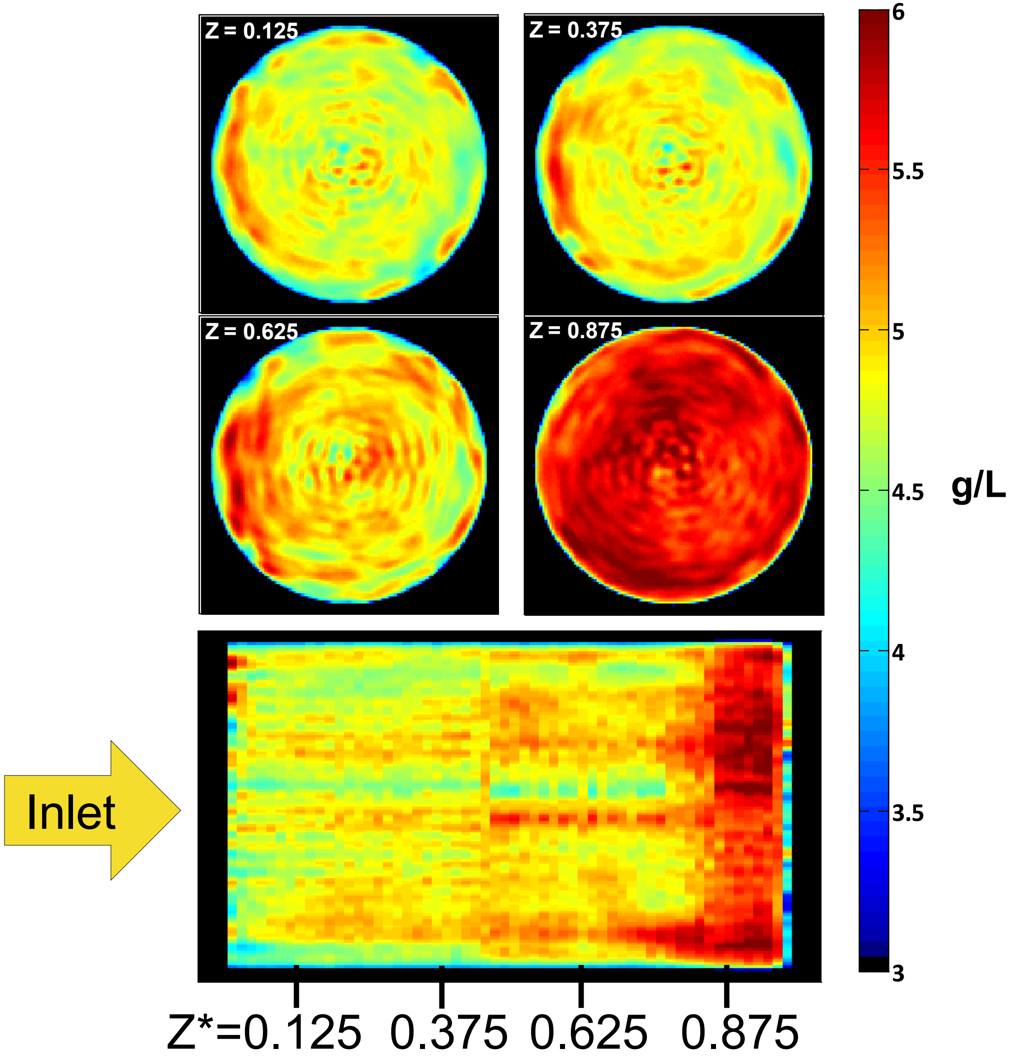
- 2010 Cummins ISB 224 kW Engine Using ULSF
- 2010 Catalyzed Cordierite Substrate
  - Diameter: 228 mm
  - Length: 280 mm
  - 28 Thermocouples
- Pressure Drop, Gaseous Emissions, Temperatures, PM
- Engine Calibration Modified During CPF Loading
- Passive Oxidation and Active Regeneration Engine Conditions

Speed (RPM)	% of Full Load	DOC Inlet Temp. (°C)	Avg. CPF Temp. (°C)	CPF Space Velocity (1/hr)	NO_2/PM Ratio
1400	49	361	372	74k	80

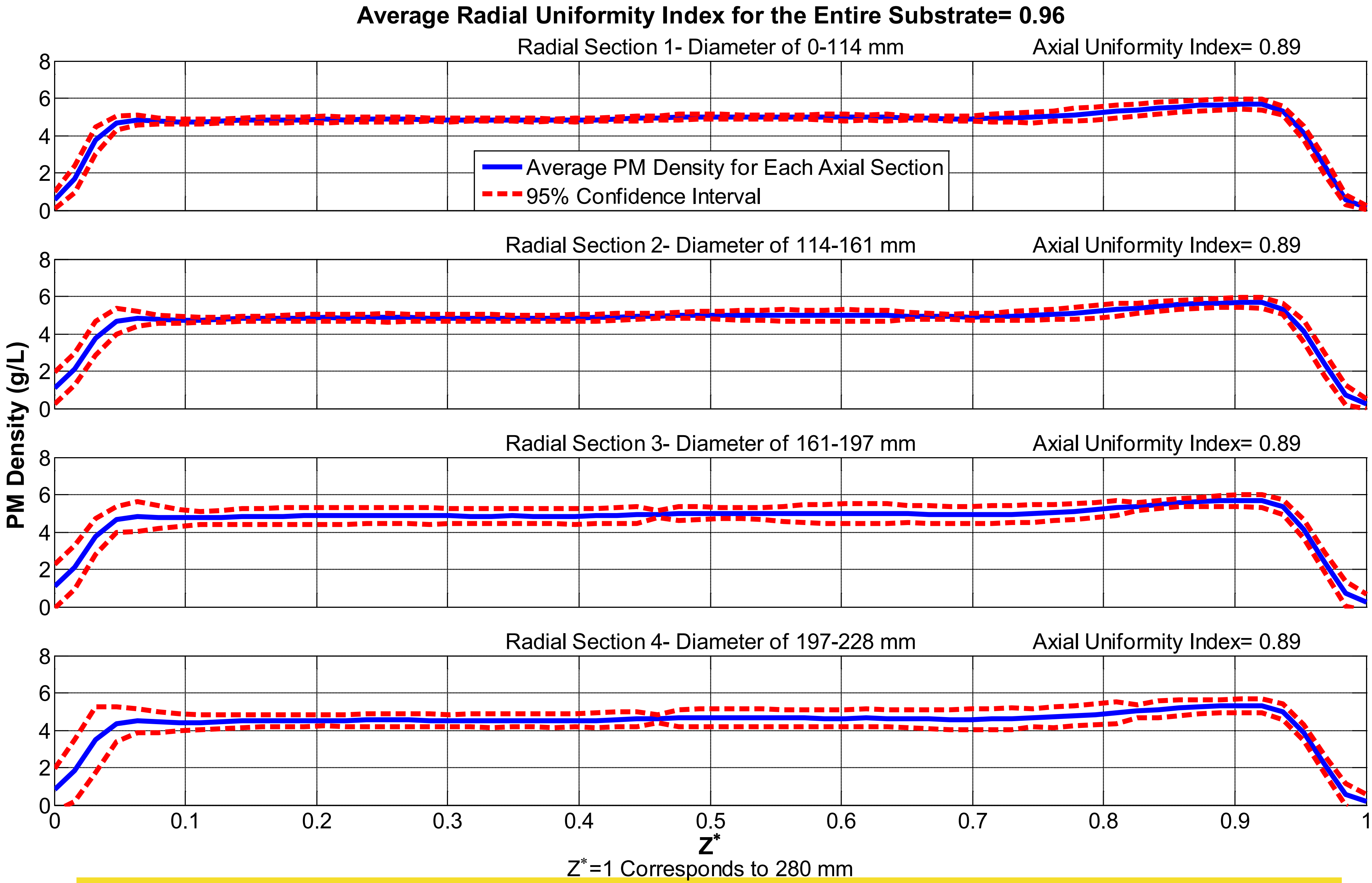
- Active Regenerations Completed with In-Cylinder Dosing

Test 1: Loading Scan Results

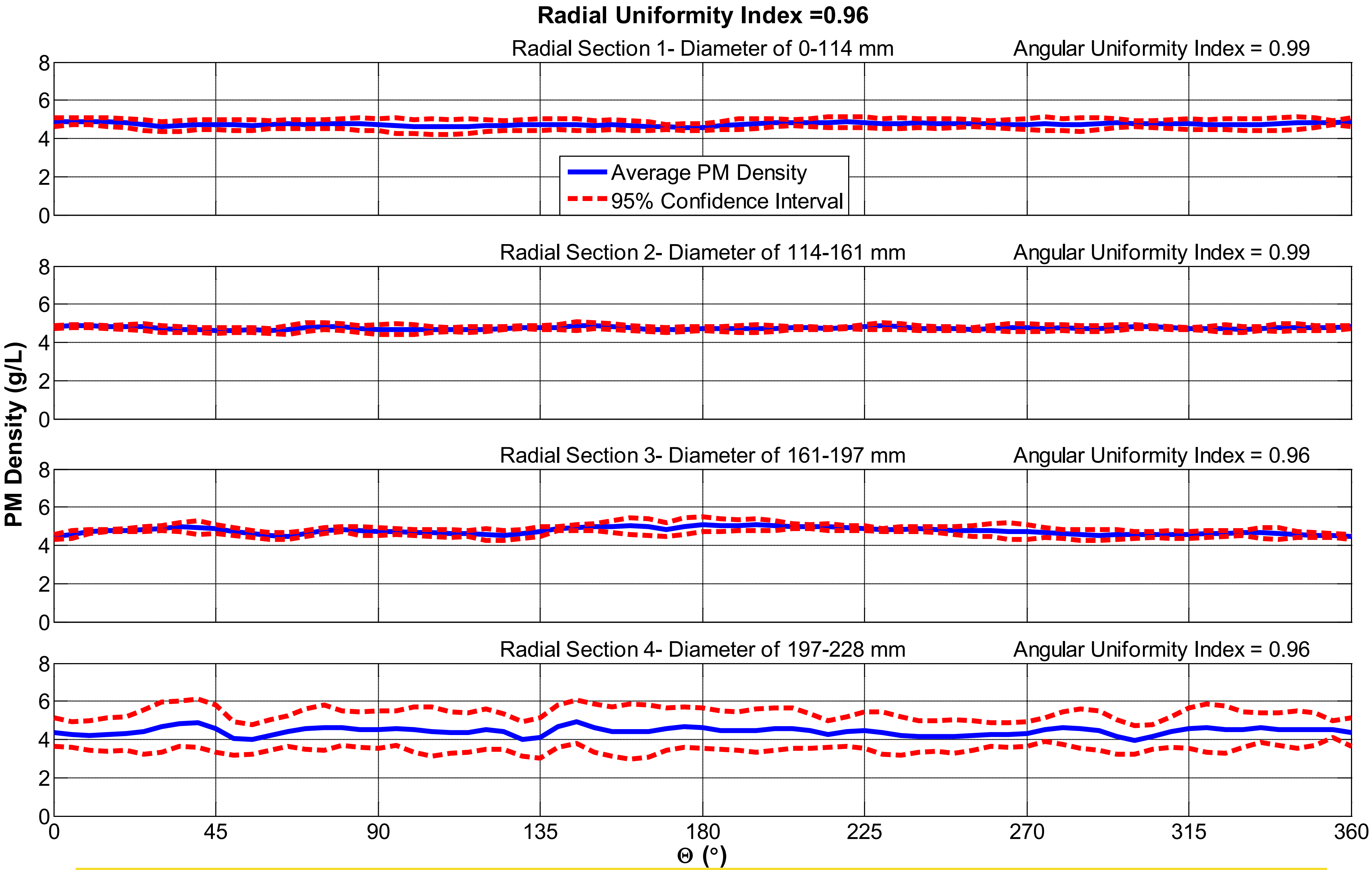
- Substrate Loaded to 5.0 g/L
- Scan Taken Post Loading
- First 85% of Axial Length: 4.8 g/L
- Last 15% of Axial Length: 5.6 g/L
    - 12% Higher than Filter Average
- Axial PM Distribution: $\gamma = 0.89$
- Radial PM Distribution: $\gamma = 0.96$



Test 1: Loading
Axial PM Density Distribution in Each Radial Section

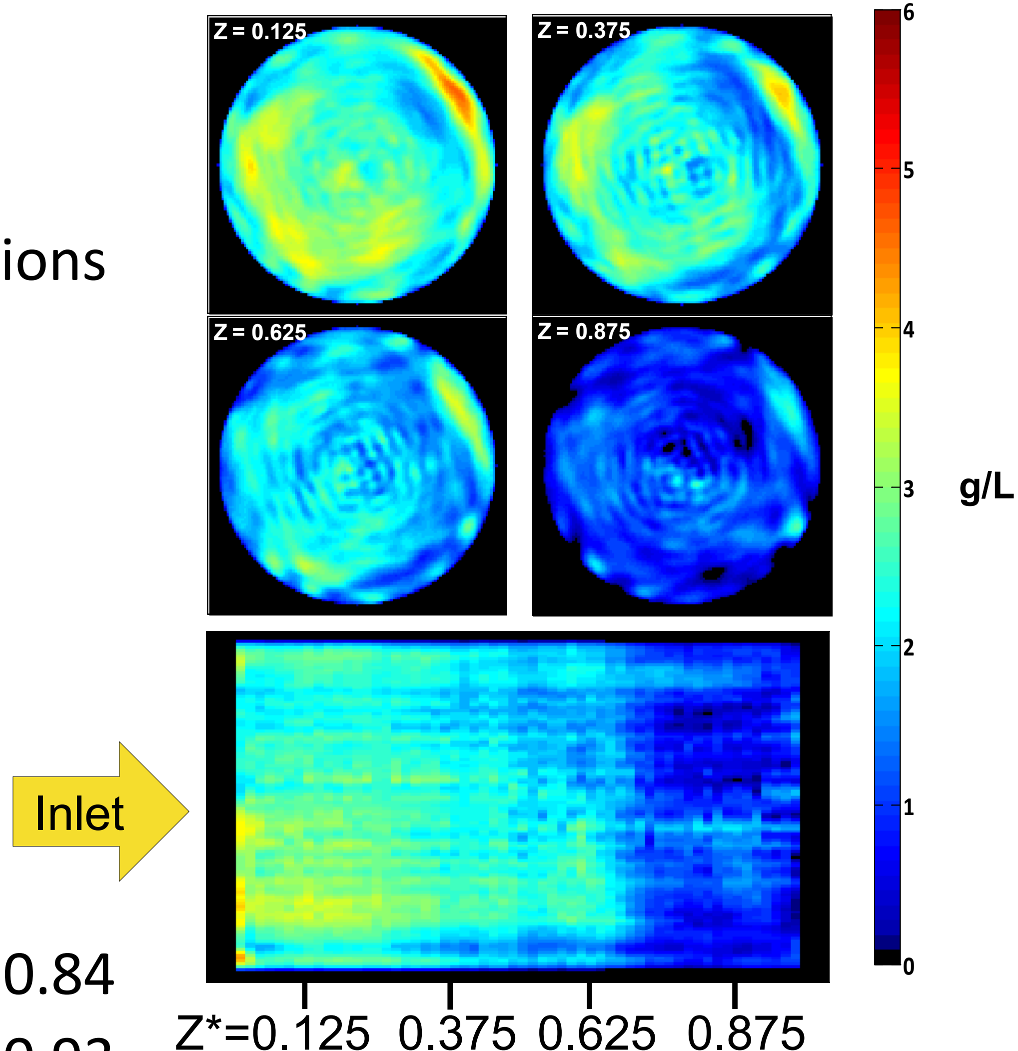


Test 1: Loading
Angular PM Density Distribution in Each Radial Section at Z*= 0.125



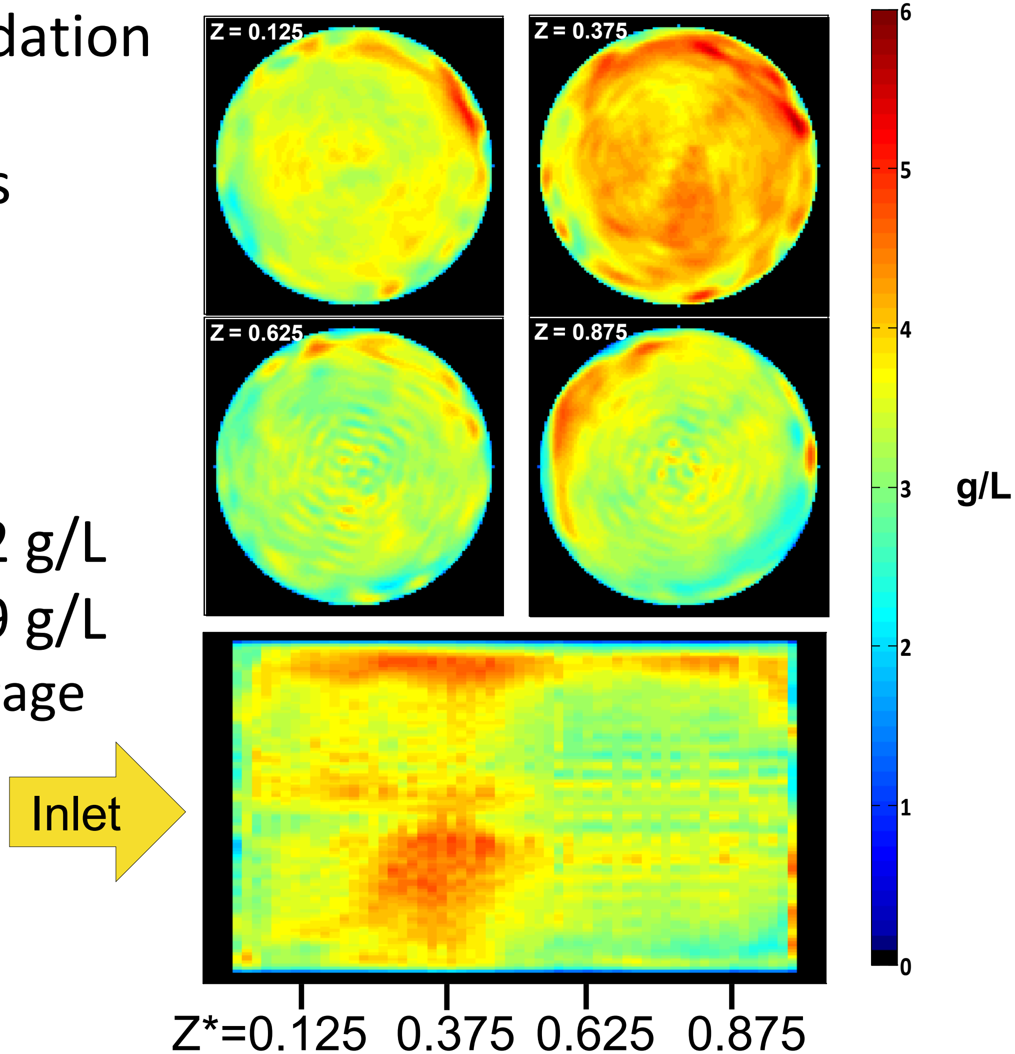
Test 1: Active Regeneration Scan Results

- Substrate Loaded to 5.0 g/L
- Scan Taken Post Active Regeneration
  - PM Loading: 2.0 g/L
- Active Regeneration Conditions
  - 500 °C
  - 59% Oxidized
- First 60% of Axial Length: 2.5 g/L
- Last 40% of Axial Length: 0.9 g/L
  - 55% Lower than Filter Average
- Axial PM Distribution: $\gamma = 0.84$
- Radial PM Distribution: $\gamma = 0.93$



Test 3: Passive Oxidation Scan Results

- Substrate Loaded to 5.8 g/L
- Scan Taken Post Passive Oxidation
  - PM Loading: 3.3 g/L
- Passive Oxidation Conditions
  - 52 Min. Run Time
  - Avg. Temp.: 372 °C
  - Inlet NO_2 Conc.: 256 ppm
  - 45% Oxidized
- Last 60% of Axial Length: 3.2 g/L
- 25-40% of Axial Length: 3.9 g/L
  - 28% Higher than Filter Average
- Axial PM Distribution: $\gamma = 0.91$
- Radial PM Distribution: $\gamma = 0.96$



Summary of Research

- Terahertz Wave Scanner
  - High Resolution Data
  - Versatile System
- Analysis Method Developed
  - Axial Uniformity Index
  - Radial Uniformity Index
  - Angular Uniformity Index
- Procedures to Ensure Repeatability Established
- Experimental Equipment Requirements Established
- 4 Tests and 7 Filter Scans Completed

	Loading	Active Regeneration	Passive Oxidation
Axial Distribution	γ= 0.89	γ= 0.83	γ= 0.91
	PM Density Near Outlet: 12% Higher than Average	PM Density Near Outlet: 55% Lower than Average	PM Density Near Center: 28% Higher than Average
Radial Distribution	γ= 0.96	γ= 0.93	γ= 0.96
		Distribution Is Uniform Below 40% PM Oxidation	
Angular Distribution	γ= 0.97	γ= 0.94	γ= 0.96
	Uniformity Index is Higher Near the Centerline: γ= 0.97-0.99		

Uniform PM Density

Non- Uniform PM Density

Questions?

Thank You.

Backup Slides

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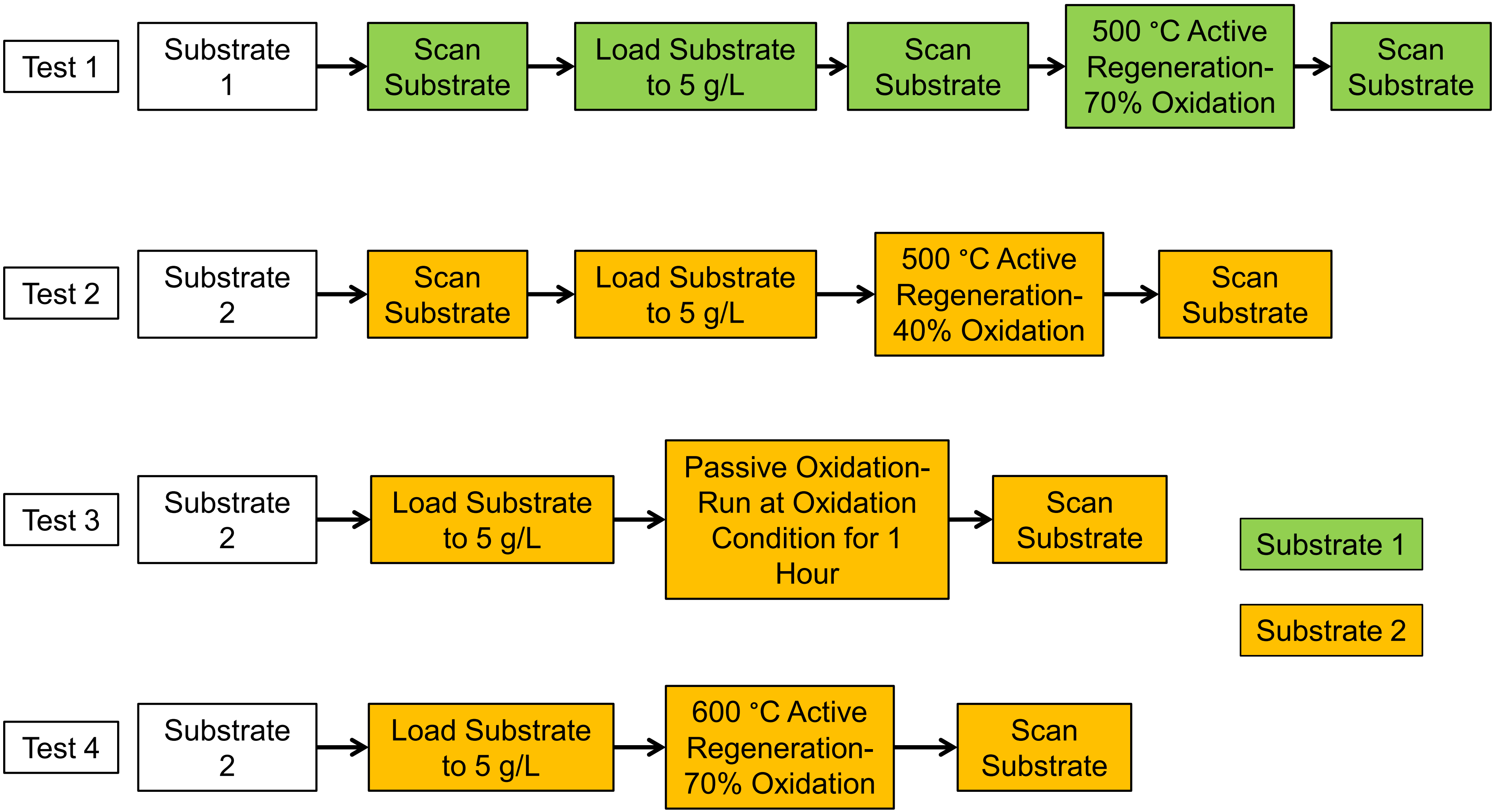
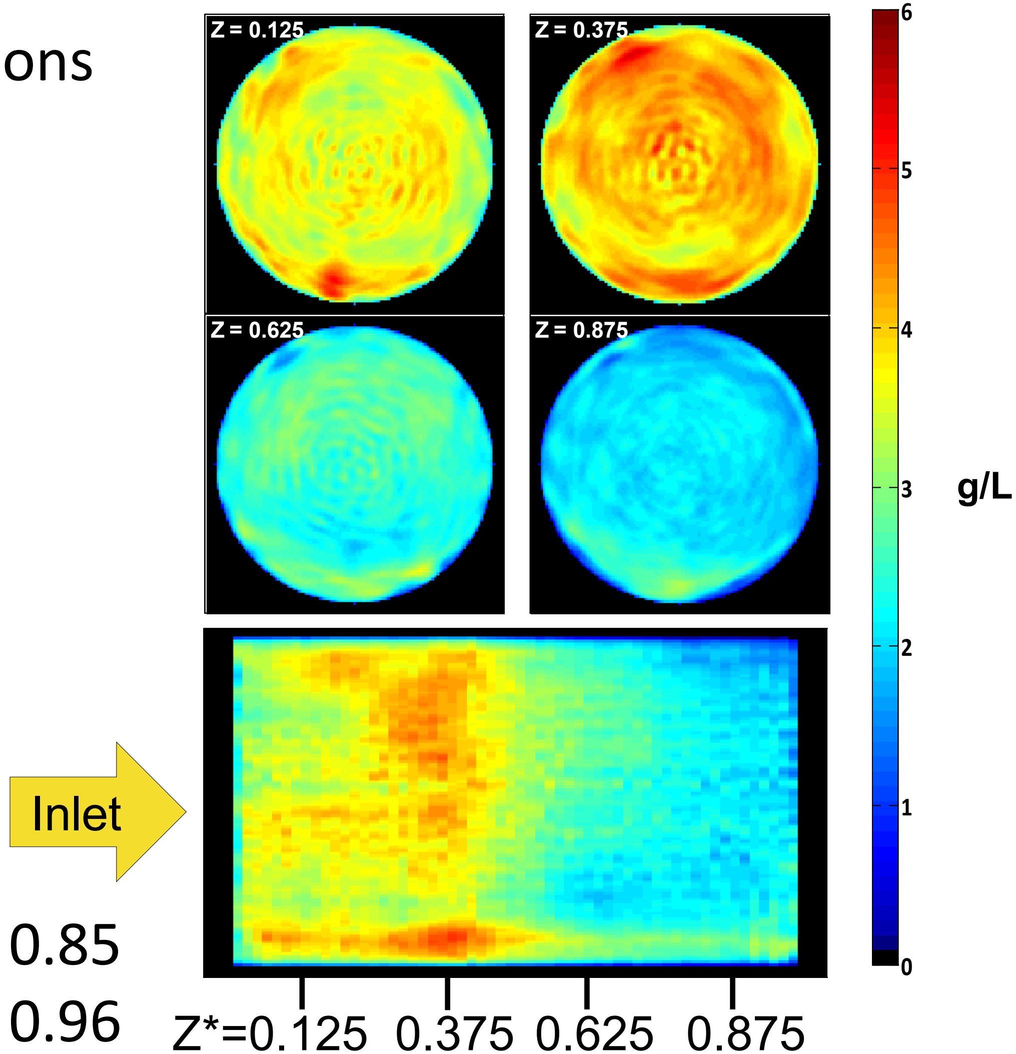
Experimental Plan



- Test Plan Established for Task 7 of DOE Grant

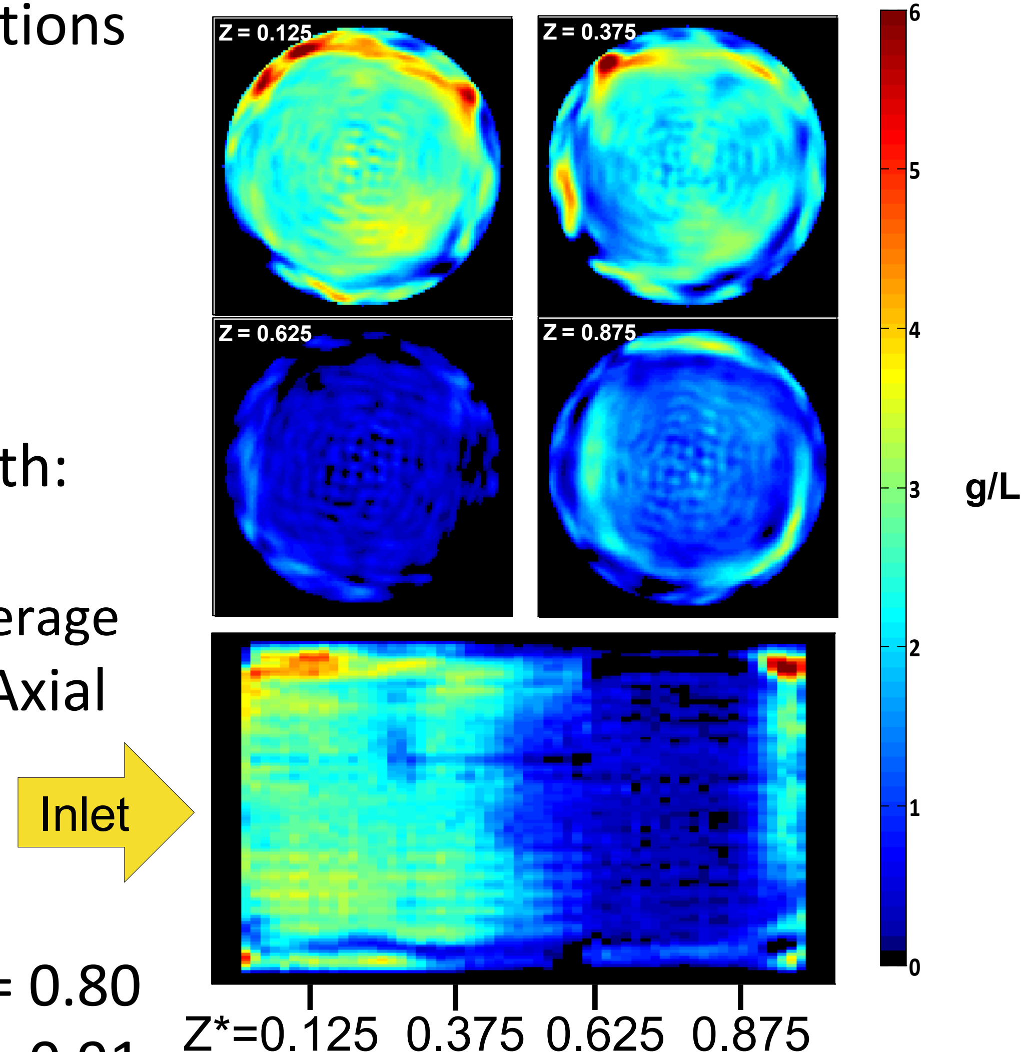
Test 2: Active Regeneration Scan Results

- Substrate Loaded to 5.2 g/L
- Active Regeneration Conditions
  - 500 °C
  - 41% Oxidized
- Scan Taken Post Active Regeneration
  - PM Loading: 3.0 g/L
- First 40% of Axial Length: 3.7 g/L
- Last 60% of Axial Length: 2.2 g/L
  - 26% Lower than Filter Average
- Axial PM Distribution: $\gamma = 0.85$
- Radial PM Distribution: $\gamma = 0.96$



Test 4: Active Regeneration Scan Results

- Substrate Loaded to 5.1 g/L
- Active Regeneration Conditions
  - 600 °C
  - 69% Oxidized
- Scan Taken Post Active Regeneration
  - PM Loading: 1.5 g/L
- From 40-90% of Axial Length: 0.7 g/L
  - 53% Lower than Filter Average
- First 40% and Last 10% of Axial Length: 2.5 g/L
  - 67% Higher than Filter Average
- Axial PM Distribution: $\gamma = 0.80$
- Radial PM Distribution: $\gamma = 0.91$



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Determination of g/L PM Loading

- Prior to PM Loading
  - Weigh the Substrate: m_o (g)
  - Scan the Substrate
    - s_o: Individual Values for Frequency Absorption (dB)
    - $\bar{s_o}$: Average of s_o
- After PM Loading
  - Weigh the Substrate: m_f (g)
  - Scan the Substrate
    - s_f: Individual Values for Frequency Absorption (dB)
    - $\bar{s_f}$: Average of s_f
- $\bar{w}$: Measured PM Density in the Substrate After Loading (g/L)
- L: Size of the Filter (L)
- T_{abs}: Difference in Average Scan Values (dB)
- B: Quantitative Coefficient ((g/L)/dB)
- w_c: Calculated Value of PM Density (g/L)

$$\bar{w} = \frac{(m_f - m_o)}{L}$$

$$T_{abs} = \bar{s_f} - \bar{s_o}$$

$$B = \frac{\bar{w}}{T_{abs}}$$

$$w_c = B(s_f - s_o)$$