PM Sampling Issues

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Size Selective Ambient Samplers
Size Selective Stack Samplers
PM$_{10}$ Samplers – Theoretical Errors

**Common Assumption:**
- Samplers produce a "nominal" cut, because it is commonly assumed that Mass 1 = Mass 2. In other words, the errors offset one another.
- The assumption is only valid when the PSD's are described by a uniform distribution and encompass a sufficient range of particle diameters.

**Note:**
- Mass 1 = Mass 2.
### Characteristics of Various Types of Particulate Matter

<table>
<thead>
<tr>
<th>Source</th>
<th>MMD (μm)</th>
<th>GSD</th>
<th>Particle Density (g/cm³)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urban</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Dust</td>
<td>5.7</td>
<td>2.25</td>
<td>NR</td>
<td>USEPA (1996a)</td>
</tr>
<tr>
<td><strong>Agricultural</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>21.75</td>
<td>NR</td>
<td>NR</td>
<td>Plemons (1981)</td>
</tr>
<tr>
<td>Rice</td>
<td>12.10</td>
<td>2.24</td>
<td>1.46</td>
<td>Parnell et al. (1986)</td>
</tr>
<tr>
<td>Corn</td>
<td>19.57</td>
<td>NR</td>
<td>NR</td>
<td>Plemons (1981)</td>
</tr>
<tr>
<td>Corn</td>
<td>13.70</td>
<td>NR</td>
<td>NR</td>
<td>Wade (1979)</td>
</tr>
<tr>
<td>Corn</td>
<td>13.60</td>
<td>1.80</td>
<td>1.50</td>
<td>Parnell et al. (1986)</td>
</tr>
<tr>
<td>Soybeans</td>
<td>25.17</td>
<td>NR</td>
<td>NR</td>
<td>Plemons (1981)</td>
</tr>
<tr>
<td>Soybeans</td>
<td>30.00</td>
<td>NR</td>
<td>NR</td>
<td>Martin (1981)</td>
</tr>
<tr>
<td>Soybeans</td>
<td>15.50</td>
<td>NR</td>
<td>NR</td>
<td>Wade (1979)</td>
</tr>
<tr>
<td>Soybeans</td>
<td>14.80</td>
<td>1.87</td>
<td>1.69</td>
<td>Parnell et al. (1986)</td>
</tr>
<tr>
<td>Wheat</td>
<td>32.97</td>
<td>NR</td>
<td>NR</td>
<td>Plemons (1981)</td>
</tr>
<tr>
<td>Wheat</td>
<td>14.70</td>
<td>2.08</td>
<td>1.48</td>
<td>Parnell et al. (1986)</td>
</tr>
<tr>
<td>Sorghum</td>
<td>36.92</td>
<td>NR</td>
<td>NR</td>
<td>Plemons (1981)</td>
</tr>
<tr>
<td>Sorghum</td>
<td>15.70</td>
<td>2.16</td>
<td>1.43</td>
<td>Parnell et al. (1986)</td>
</tr>
<tr>
<td>Cotton Gin (Combined Streams)</td>
<td>20 - 23</td>
<td>1.82 - 2.00</td>
<td>1.8 - 2.0</td>
<td>Wang (2000)</td>
</tr>
<tr>
<td>Cotton Lint Fibers</td>
<td>12.94</td>
<td>2.25</td>
<td>NR</td>
<td>Parnell and Adams (1979)</td>
</tr>
<tr>
<td>Cattle Feedlot (Downwind)</td>
<td>14.2</td>
<td>2.25</td>
<td>1.71</td>
<td>Sweeten et al. (1989)</td>
</tr>
<tr>
<td>Swine Finishing House (Aerial)</td>
<td>14.3</td>
<td>2.02</td>
<td>NR</td>
<td>Barber et al. (1991)</td>
</tr>
<tr>
<td>Swine Finishing House (Settled)</td>
<td>18.4</td>
<td>1.99</td>
<td>NR</td>
<td>Barber et al. (1991)</td>
</tr>
<tr>
<td>Swine Production Facility</td>
<td>17.97</td>
<td>NR</td>
<td>NR</td>
<td>Barber et al. (1991)</td>
</tr>
<tr>
<td>Poultry Production Facility</td>
<td>24.0 – 26.7</td>
<td>1.6</td>
<td>NR</td>
<td>Redwine and Lacey (2001)</td>
</tr>
<tr>
<td>Typical Soil</td>
<td>25</td>
<td>2.0</td>
<td>2.5</td>
<td>Pargmann et al. (2000)</td>
</tr>
</tbody>
</table>

NR – Data not reported in the reference.
Theoretical Ratios of Ambient PM$_{10}$ Sampler to True Concentrations (PSD – GSD = 2.0)

- **Ratio range for a 5.7 µm MMD PSD**
  - $0.92 < \text{Ratio} < 0.99$ (a < Ratio < b)
  - *Acceptable PM$_{10}$ sampler measurement to meet PLC*
  - $138 < x < 149 \mu g/m^3$ (Ratio * 150 µg/m$^3$)

- **Ratio range for a 10 µm MMD PSD**
  - $0.95 < \text{Ratio} < 1.05$ (c < Ratio < d)
  - *Acceptable PM$_{10}$ sampler measurement to meet PLC*
  - $142 < x < 158 \mu g/m^3$ (Ratio * 150 µg/m$^3$)

- **Ratio range for a 20 µm MMD PSD**
  - $1.05 < \text{Ratio} < 1.39$ (e < Ratio < f)
  - *Acceptable PM$_{10}$ sampler measurement to meet PLC*
  - $158 < x < 209 \mu g/m^3$ (Ratio * 150 µg/m$^3$)

$a < \text{Ratio} < b$, $c < \text{Ratio} < d$, and $e < \text{Ratio} < f$ are the acceptable ratio ranges for 5.7, 10 and 20 µm particles, respectively based on the interaction of the PM$_{10}$ sampler performance characteristics and particle size distribution.
Theoretical Ratios of Ambient PM$_{10}$ Sampler to True Concentrations (PSD – GSD = 1.5)

**Ratio range for a 5.7 µm MMD PSD**
0.87 < Ratio < 0.96 (a < Ratio < b)
Acceptable PM$_{10}$ sampler measurement to meet PLC
131 < x < 144 µg/m$^3$ (Ratio * 150 µg/m$^3$)

**Ratio range for a 10 µm MMD PSD**
0.92 < Ratio < 1.07 (c < Ratio < d)
Acceptable PM$_{10}$ sampler measurement to meet PLC
138 < x < 161 µg/m$^3$ (Ratio * 150 µg/m$^3$)

**Ratio range for a 20 µm MMD PSD**
1.81 < Ratio < 3.43 (e < Ratio < f)
Acceptable PM$_{10}$ sampler measurement to meet PLC
271 < x < 514 µg/m$^3$ (Ratio * 150 µg/m$^3$)

a < ratio < b, c < ratio < d, and e < ratio < f are the acceptable ratio ranges for 5.7, 10 and 20 µm particles, respectively based on the interaction of the PM$_{10}$ sampler performance characteristics and particle size distribution.
Theoretical Ratios of Ambient PM$_{2.5}$ Sampler to True Concentrations (PSD – GSD = 2.0)

Ratio range for a 5.7µm MMD PSD
0.92 < Ratio < 1.34 (a < Ratio < b)
Acceptable PM$_{2.5}$ sampler measurement to meet PLC
32 < x < 47 µg/m$^3$ (Ratio * 35 µg/m$^3$)

Ratio range for a 10µm MMD PSD
0.99 < Ratio < 1.77 (c < Ratio < d)
Acceptable PM$_{2.5}$ sampler measurement to meet PLC
35 < x < 62 µg/m$^3$ (Ratio * 35 µg/m$^3$)

Ratio range for a 20µm MMD PSD
1.18 < Ratio < 2.80 (e < Ratio < f)
Acceptable PM$_{2.5}$ sampler measurement to meet PLC
41 < x < 98 µg/m$^3$ (Ratio * 35 µg/m$^3$)

a < ratio < b, c < ratio < d, and e < ratio < f are the acceptable ratio ranges for 5.7, 10 and 20µm particles, respectively based on the interaction of the PM$_{2.5}$ sampler performance characteristics and particle size distribution.
Theoretical Ratios of Ambient PM$_{2.5}$ Sampler to True Concentrations (PSD – GSD = 1.5)

- **Ratio range for a 5.7µm MMD PSD**
  - $1.24 < \text{Ratio} < 2.96$ ($a < \text{Ratio} < b$)
  - Acceptable PM$_{2.5}$ sampler measurement to meet PLC
  - $43 < x < 104 \mu g/m^3$ ($\text{Ratio} \times 35 \mu g/m^3$)

- **Ratio range for a 10µm MMD PSD**
  - $2.85 < \text{Ratio} < 13.14$ ($c < \text{Ratio} < d$)
  - Acceptable PM$_{2.5}$ sampler measurement to meet PLC
  - $100 < x < 460 \mu g/m^3$ ($\text{Ratio} \times 35 \mu g/m^3$)

- **Ratio range for a 20µm MMD PSD**
  - $14.81 < \text{Ratio} < 183.5$ ($e < \text{Ratio} < f$)
  - Acceptable PM$_{2.5}$ sampler measurement to meet PLC
  - $518 < x < 6,423 \mu g/m^3$ ($\text{Ratio} \times 35 \mu g/m^3$)

$a < \text{Ratio} < b$, $c < \text{Ratio} < d$, and $e < \text{Ratio} < f$ are the acceptable ratio ranges for 5.7, 10 and 20µm particles, respectively based on the interaction of the PM$_{2.5}$ sampler performance characteristics and particle size distribution.
Theoretical Ratios of Stack PM$_{10}$ Sampler to True Concentrations (PSD - GSD = 2.0)

Ratio range for a 5.7 μm MMD PSD
0.87 < Ratio < 1.0 (a < Ratio < b)
Acceptable PM$_{10}$ sampler measurement to meet PLC
131 < x < 150 μg/m$^3$ (Ratio * 150 μg/m$^3$)

Ratio range for a 10 μm MMD PSD
0.91 < Ratio < 1.08 (c < Ratio < d)
Acceptable PM$_{10}$ sampler measurement to meet PLC
137 < x < 162 μg/m$^3$ (Ratio * 150 μg/m$^3$)

Ratio range for a 20 μm MMD PSD
1.0 < Ratio < 1.60 (e < Ratio < f)
Acceptable PM$_{10}$ sampler measurement to meet PLC
150 < x < 240 μg/m$^3$ (Ratio * 150 μg/m$^3$)

Regulated PM$_{10}$ property line
concentration (PLC) = 150 μg/m$^3$

- Cutpoint = 11.0 μm; Slope = 1.79
- Cutpoint = 10.0 μm; Slope = 1.9
- Cutpoint = 9.0 μm; Slope = 1.87

a < ratio < b, c < ratio < d, and e < ratio < f are the acceptable ratio ranges for 5.7, 10 and 20 μm particles, respectively based on the interaction of the PM$_{10}$ sampler performance characteristics and particle size distribution.
PM$_{10}$ Stack Sampler Performance Criteria

- **PM$_{10}$ Efficiency Envelope**
- **PM$_{10}$ Sampler Collection Curves**
  - Cutpoint 9 μm; Slope 1.87
  - Cutpoint 10 μm; Slope 1.90
  - Cutpoint 11 μm; Slope 1.76

### Collection Curves Details
- **Aerodynamic Diameter (μm)**
- **Percent Efficiency**

- **Gas Velocities**
  - $17 < \text{Gas Velocity} < 27$ m/s
  - $9 < \text{Gas Velocity} < 17$ m/s
  - $\text{Gas Velocity} < 9$ m/s
PM$_{2.5}$ Stack Sampler Performance Criteria
Theoretical Ambient Particle Size Distribution (Vanderpool, 2010)
Stack Sampling - Field Evaluation Results

<table>
<thead>
<tr>
<th>Feeder Dust</th>
<th>B Overflow Dust</th>
<th>#1 A &amp; B Stick Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMD = 6.0 µm</td>
<td>MMD = 8.0 µm</td>
<td>MMD = 6.4 µm</td>
</tr>
<tr>
<td>GSD = 1.6</td>
<td>GSD = 1.7</td>
<td>GSD = 1.8</td>
</tr>
<tr>
<td>PM₁₀ = 86.3%</td>
<td>PM₁₀ = 66.9%</td>
<td>PM₁₀ = 78.3%</td>
</tr>
<tr>
<td>PM₂.₅ = 3.26%</td>
<td>PM₂.₅ = 1.26%</td>
<td>PM₂.₅ = 4.89%</td>
</tr>
</tbody>
</table>

CTM-039 Results

<table>
<thead>
<tr>
<th>Sampler/True</th>
<th>Exhaust</th>
<th>PSD Analysis of Method 5 Filter</th>
<th>PSD Analysis of Method 5 Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% &lt; 10µm</td>
<td>% &lt; 2.5µm</td>
<td>% &lt; 10µm</td>
</tr>
<tr>
<td>Stick Machine</td>
<td>73%</td>
<td>28.3%</td>
<td>78%</td>
</tr>
<tr>
<td>Overflow</td>
<td>67%</td>
<td>16.8%</td>
<td>67%</td>
</tr>
<tr>
<td>Feeder</td>
<td>81%</td>
<td>36.0%</td>
<td>86%</td>
</tr>
</tbody>
</table>

Note: PSDs are in terms of ESD not AED (conservative estimates)
**AERODYNAMIC DIAMETER:** describes a particle’s inertial behavior

(Vanderpool, 2010)

\[ D_p = 4.0 \, \mu m \text{ (equiv. physical diameter)} \]
\[ \rho_p = 2 \, \text{g/cc (particle density)} \]
\[ K = 1.3 \text{ (dynamic shape factor)} \]

\[ D_a = D_p \left( \frac{\rho_p}{K \rho_a} \right)^{0.5} \]

\[ \rho_a = 1 \, \text{g/cc} \]

\[ V_s = 2.8 \, \text{m/hr} \]
# 2004 NRI Grant – Errors Associated with PM Stack Samplers

## Study Results

<table>
<thead>
<tr>
<th></th>
<th>PM$_{10}$ Over-Sampling</th>
<th>PM$_{2.5}$ Over-Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Limestone</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate = 32 g/m$^3$</td>
<td>123%</td>
<td>700%</td>
</tr>
<tr>
<td>Rate = 148 g/m$^3$</td>
<td>133%</td>
<td>606%</td>
</tr>
<tr>
<td><strong>Starch</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate = 32 g/m$^3$</td>
<td>477%</td>
<td>30000%</td>
</tr>
<tr>
<td>Rate = 148 g/m$^3$</td>
<td>444%</td>
<td>25316%</td>
</tr>
</tbody>
</table>

*Limestone - MMD = 7.0 µm ESD; GSD = 1.71; $\rho = 2.62$ g/cm$^3$*

*Starch - MMD = 15.1 µm ESD; GSD = 1.33; $\rho = 1.26$ g/cm$^3$*
Ambient Sampler Errors – Field Studies

![Diagram showing oversampling rates in field measurements compared to theoretical values. The x-axis represents different runs, and the y-axis shows oversampling rates in percent. The red bars represent field measurements, and the blue bars represent theoretical values with D50=10.5 and Slp=1.6.]
Ambient PM\textsubscript{10} Sampler – Actual Errors \{Cotton Gin\}

- MMD = 13.4 \, \mu m
- GSD = 2.0
- D\textsubscript{50} = 24.1 \, \mu m
- Slope = 2.9

True PM\textsubscript{10} = Sampler PM\textsubscript{10}

True PM\textsubscript{10} = 0.55 \times \text{Sampler PM\textsubscript{10}}

R\textsuperscript{2} = 0.81
Ambient PM$_{10}$ Sampler – Actual Errors \{Cattle Feed Yard\}

- $MMD = 18.7 \mu m$
- $GSD = 2.2$
- $D_{50} = 19.2 \mu m$
- Slope $= 2.4$

True PM$_{10}$ Concentration $= 0.797 \times$ Sampler Measured Concentration

- $R^2 = 0.998$
- $D_{50} = 10.5$, Slope $= 1.6$

True PM$_{10}$ Concentration $= 0.540 \times$ Sampler Measured Concentration

- $R^2 = 0.602$
Ambient PM\textsubscript{10} Sampler – Actual Errors

\{Almond Orchard – Harvesting\}

- True PM\textsubscript{10} Conc. = 0.84 \times \text{Sampler Measured Conc.}
  - MMD = 15.1 \mu m
  - $R^2 = 0.995$
  - GSD = 2.0
  - $D_{50} = 11.3 \mu m$
  - Slope = 3.3

- True PM\textsubscript{10} Conc. = 0.72 \times \text{Sampler Measured Conc.}
  - $R^2 = 0.91$
So why are the actual differences larger than the theoretical differences?

<table>
<thead>
<tr>
<th></th>
<th>Concentration ($\mu g/m^3$)</th>
<th>MMD ($\mu m$)</th>
<th>GSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSP</td>
<td>1,207</td>
<td>13.4</td>
<td>2</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>812</td>
<td>11.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

- **Bottom Line!**
  - Cutpoint = 24.1 $\mu m$  
    {compared to 10 $\mu m$}
  - Slope = 2.9  
    {compared to 1.5}

- **Causes**
  - High Concentrations
  - PSD Characteristics
  - Poor sampler placement
Effects of Varying PM$_{10}$ SPC

(PSD: MMD = 5.7 μm; GSD = 2.25)

- **(a) Ratio = 0.93**
  - Acceptable PM$_{10}$ sampler measurement to meet PLC = 139 μg/m$^3$ (Ratio * 150 μg/m$^3$)

- **(b) Ratio = 0.99**
  - Acceptable PM$_{10}$ sampler measurement to meet PLC = 149 μg/m$^3$ (Ratio * 150 μg/m$^3$)

- **(c) Ratio = 1.05**
  - Acceptable PM$_{10}$ sampler measurement to meet PLC = 159 μg/m$^3$ (Ratio * 150 μg/m$^3$)

- **(d) Ratio = 1.14**
  - Acceptable PM$_{10}$ sampler measurement to meet PLC = 171 μg/m$^3$ (Ratio * 150 μg/m$^3$)

- **Proposed PM$_{10}$ property line concentration (PLC) = 150 μg/m$^3$**

- **(b) Cutpoint = 10 μm**
  - Slope = 2.0

- **(c) Cutpoint = 14 μm**
  - Slope = 1.2

- **(d) Cutpoint = 14 μm**
  - Slope = 2.0

- **Cutpoint = 14 μm**
  - Slope = 2.5

- **Cutpoint = 10 μm**
  - Slope = 1.5

- **Cutpoint = 10 μm**
  - Slope = 1.2
Effects of Varying PM$_{10}$ SPC
(PSD: MMD = 20 µm; GSD = 1.5)

(a) Ratio = 1.4
Acceptable PM$_{10}$ sampler measurement to meet PLC = 204 µg/m$^3$ (Ratio * 150 µg/m$^3$)

(b) Ratio = 4.4
Acceptable PM$_{10}$ sampler measurement to meet PLC = 666 µg/m$^3$ (Ratio * 150 µg/m$^3$)

(c) Ratio = 4.8
Acceptable PM$_{10}$ sampler measurement to meet PLC = 725 µg/m$^3$ (Ratio * 150 µg/m$^3$)

(d) Ratio = 7.5
Acceptable PM$_{10}$ sampler measurement to meet PLC = 1,128 µg/m$^3$ (Ratio * 150 µg/m$^3$)

Sampler Concentration

Sampler Cutpoint (µm)

Proposed PM$_{10}$ property line
concentration (PLC) = 150 µg/m$^3$
Comparing Material Collected from PM\textsubscript{10} samplers

- Both samples were collected using Method 201a (PM\textsubscript{10} sampler)
- Filter comparison only
- Concentration based on filter mass only
  - Plant A – 48 mg/dscm
  - Plant B – 60 mg/dscm
- Concentration < 10 \, \mu m
  - Plant A – 48 mg/dscm
    - \{48 \times 0.96 = 46\}
  - Plant B – 34 mg/dscm
    - \{60 \times 0.56 = 34\}
Questions

1) Health based studies – are the PM data used in the studies comparable?
   A. Are we comparing apples to apples?

2) If I stand at the property line that separates Plant A and B will Plant B’s (higher PM$_{10}$ sampler based concentration) emissions more negatively impact my health?

3) If I’m evaluating regional PM air quality models using FRM PM sampler concentrations, how good are my modeling results?
   A. Garbage in – garbage out

4) Are these plants being equally regulated?

5) How will you answer the same questions for PM$_{2.5}$?
   1) The PSD differences are greater
Dispersion Modeling
Tower Sampler {PM sampler heads and anemometers located at 1.0, 2.0, 3.0, 4.5, 7.25, and 10.0 meters}

Stand Alone Sampler {PM sampler head located at 2.0 meters}
2 Tower Sites:
1 – TEOM
2 – PM10 Samplers
2 – PM2.5 Samplers
1 - Tower
Recommendations

- Development of alternative ambient and stack sampling methodologies
  - TSP or total particulate matter sampling coupled with particle size analysis
- Development of ambient PM\textsubscript{10} and PM\textsubscript{2.5} sampler placement guidelines
- Development of dispersion modeling correction factors for low level sources