SOP #6

Determination of Equivalent Black Carbon (EBC)
Theory and Practical Determination

General summary: Here we explain the methodology of measuring 'equivalent' black carbon (a surrogate of elemental carbon) via incandescent light surface reflectance. Plots of the EBC versus collocated quartz filter elemental carbon are shown for comparison.

REVISION HISTORY			
Revision No.	Change Description	Date	Authorization
1.0		June 3, 2016	Yvvone Ritchie

(Equivalent) Black Carbon analysis

All BC analysis is done in the HERC weighing cleanroom (LSRI Building). After filter weighing is complete (e.g. filters are weighed in triplicate), we measure the equivalent black carbon (EBC) content of filter-captured $PM_{2.5}$. Surface reflectance estimates actual BC content, which, in turn approximates elemental carbon concentrations (Petzold et al., 2013). We outline the steps converting surface reflectance *R* to EBC (in units of μg).

Figure 6.1: Diffusion Systems SSR (left) and calibration plate with optical unit (right).

The rationale for choosing the SSR instead of the Magee Scientific SootScan (Model OT21) Transmissometer: The SootScan had been tested alongside the SSR; however the former was found to have much lower reproducibility in triplicate filter measurements. The cost of the SSR is about $5500, whereas the SootScan was $11,000. With no cost savings and larger standard deviation, black carbon measurement via reflectance is more suitable over transmittance.

Smokestain Reflectometer [EEL43M] Setup procedure

1. Switch SSR instrument on.

The power switch is located on the rear panel of the device. Upon turning the SSR on, the display will read “100” with no decimal place. The device is ready to use once the display begins showing numbers with a single decimal place.

2. Place reflectometer optical unit with circular mask on white panel of calibration standard.

The reflectometer optical unit is the larger cylindrical device. When the device is powered the light inside the reflectometer optical unit should be on. The circular mask is the flatter circular portion, which fits around the bottom end of the reflectometer optical unit. Place the optical unit on top of the white portion of the calibration standard. The readout should be close to 100.0. Try to keep the small hole in the circular mask as centered as possible.

Figure 6.2: Left: Calibration plate (grey and white spaces and). Right: circular mask for holding 25mm filters.

3. Allow ~15 minutes for the system to stabilize.

After this waiting period, the system should be ready to be calibrated. However, initial tests show that the number does not stabilize easily. For instance, the first calibration initially displayed 104.0 which then dropped to 103.4 after 5 minutes.

4. Press ‘CAL’ button to set the 100 point.

After pushing the ‘CAL’ button, the system displays 100.0; however, initial tests show that the number continues to drop slowly.

5. Place optical unit on the grey panel and confirm the reading to be 36 ± 1.5.

Otherwise repeat the calibration process.

Filter tests

1. Blank Teflon filters

Before calibration, compared to the white panel on the calibration standards, a blank Teflon filter reads close to what the white calibration panel reads (~ 1 – 5 points higher) and within 65 points higher on the grey calibration panel.

2. Blank Nuclepore filters

Before calibration, a blank Nuclepore filter reads around 12 points lower compared to the white panel on the calibration standards, and around 9 points higher on the grey calibration panel.

Figure 6.3: Filter placed in circular mask (helps remove stray light).

3. Sampled Teflon and Nuclepore filters

Post-calibration, the filters should be placed at the center of the circular mask. If the filters are not centered, then the device will not display a consistent reading. Small movements of the optical unit do not appear to affect the readings; however, anything that changes the light around the device does cause a drop in the readings. Changing the lighting in the room also affects the readings and how movements affect the readings. With the lights off, small movements do not seem to affect the readings as often.

Leaving the system for an extended period of time shows a periodic fluctuation in readout. Because the values are different based on which surface the reflectometer optical unit is placed on, all sampled filters must be calibrated on the same surface as blanks. Finally, measure the reflectance R of each filters three times (non-consecutively). As with filter weighing, rotate filter measurements in groups of four to obtain 12 measurements, three each, before moving on to a new group of filters.

4. Calculating EBC concentration using surface reflectance:

The intensity I of light decreases relative to initial intensity I_0 through path length x according to Beer's law:

$$\frac{I}{I_0} = \exp(-b_{abs}x)$$

where b_{abs} (m^{-1}) is the absorption coefficient of light. Path length x is equivalent to the volume V of sampled air divided by the filter area A so that $x = V/A$. Since reflectance requires light to pass through the filter medium twice (be it Teflon or Nuclepore), the relative reflectance R measured through a path length $2x$ (hence $2V/A$) is

$$\frac{R}{R_0} = \exp(-\frac{2V}{A} b_{abs})$$

Due to multiple refractions, factor 2 above could larger, as high as 2.8, depending on the structure of the filter and deposit (Edwards, Ogren, Weiss, & Charlson, 1983). The EBC absorption coefficient b_{abs} is taken to be proportional with black carbon mass concentration [EBC] via the specific absorption coefficient σ (m^2/g):

$$\mathbf{[EBC] = } b_{abs}/\sigma$$

Magee Scientific recommends using a σ of 16.6 m^2/g at a wavelength of 880 nm to determine the EBC concentration. There is a large variability in σ, where studies have used values ranging from 5 - 25 m^2/g (Bond & Bergstrom, 2006) with values 9- 12 m^2/g more appropriate at urban sites (referenced at 550 nm).

Since our SSR uses an incandescent spectrum of light, a visible-centered wavelength of 550 nm is considered to be an appropriate reference point. Therefore a default value of 10 m^2/g has been chosen knowing that the "real" value *could* be a factor of 2 smaller or larger.

In theory each site will have its own empirically derived value of σ. Thus far only one collocation was deemed successful; an empirically derived value of σ = 19.6 ± 3.6 m^2/g (equivalently 0.196 ± 0.036 $cm^2/\mu g$) for the Beijing (CHTS) site. In terms of uncertainty, it is clear the potential 100% uncertainty in σ dominates the uncertainty in EBC.

For a given values of σ we can relate the airborne concentrations of black carbon [EBC] to the surface reflectance R:

$$\mathbf{[EBC]} = \frac{A}{2V\sigma}\ln\left(\frac{R_0}{R}\right) + C$$

Where V is total air sampled, A is the filter area, and C is a calibration constant set to zero here. The aerosol-exposed filter diameter is 2.0 cm, hence A = 3.14 cm^2, so that $A/2\boldsymbol{\sigma}$ = 16 μg (generic site) **or** 8.23 μg (Beijing site). The reference SSR reflectance is, by design, R_0 = 100 (i.e. blank filters) so that

$$[\mathbf{EBC}] \approx \frac{\mathbf{16}\ \mu g}{\boldsymbol{V}} \times \mathbf{ln}\left(\frac{\mathbf{100}}{\boldsymbol{R}}\right) \quad [\boldsymbol{units} = \frac{\mu g}{m^3}]$$

The linear response range for surface reflectance measurements is **between R = 20 and 90** (Taha, Box, Cohen, & Stelcer, 2007). If R = 80 and V = 5.76 m^3 , then [EBC] = 0.62 μg/m^3 (excluding Beijing). Most measureable values lie between 0.3 and 10 μg/m^3.

Flow volume V varies at from site to site in order to prevent clogging of Nuclepore filters. Presently the maximum 100% sample duty volume is 5.76 m^3 (for 24 hours of sampling at 4 lpm), while the present minimum volume is 15% (Beijing, China), at 0.864 m^3. The detection limit in Beijing is therefore sensitive to these changes.

Notes:

- Discussion of elemental vs. light-absorbing (black) carbon: (Bond & Bergstrom, 2006)
- Comparison between different traffic-related particle indicators: Elemental carbon (EC), $PM_{2.5}$ mass, and absorbance: (Cyrys et al., 2003)
- Comparison of OC/EC combustion, transmittance, and reflectance measures: (Quincey, Butterfield, Green, Coyle, & Cape, 2009)
- EC concentrations determined via thermal optical transmittance and light absorbing carbon from Teflon filters: (Noullett, Jackson, & Brauer, 2006)

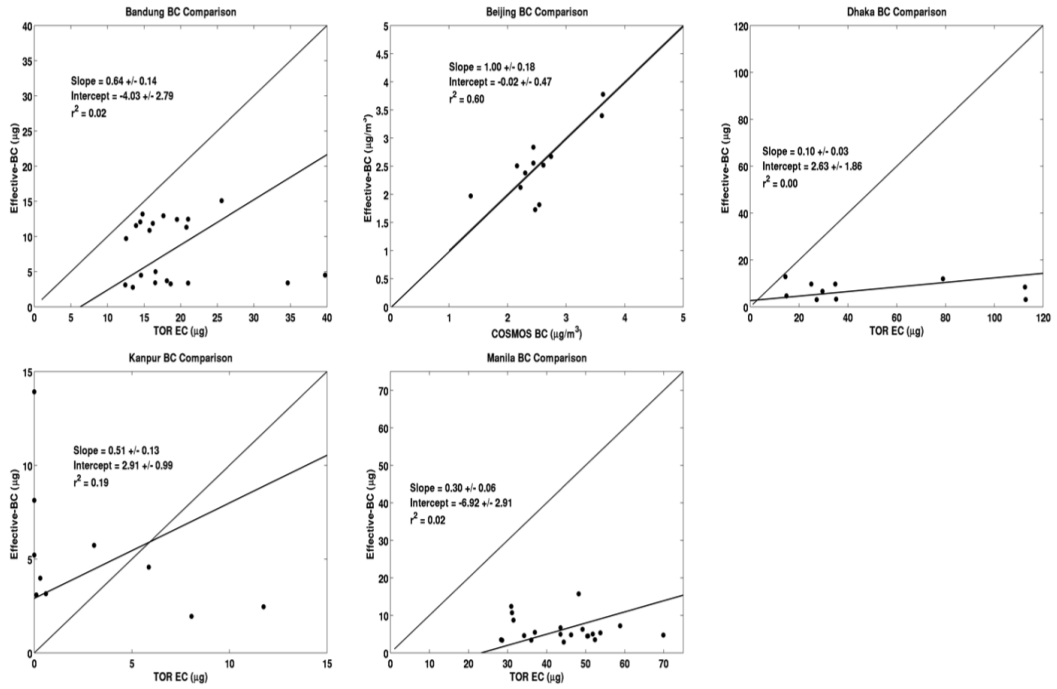

Figure 6.4: EC/E-BC comparisons for five SPARTAN locations (Bandung, Beijing, Dhaka, Kanpur, and Manila). E-BC obtained from SPARTAN $PM_{2.5}$ Teflon filters, EC obtained from 37mm Harvard Impactor $PM_{2.5}$ quartz filter OC/EC pyrolysis (*c.f.* section 12b).

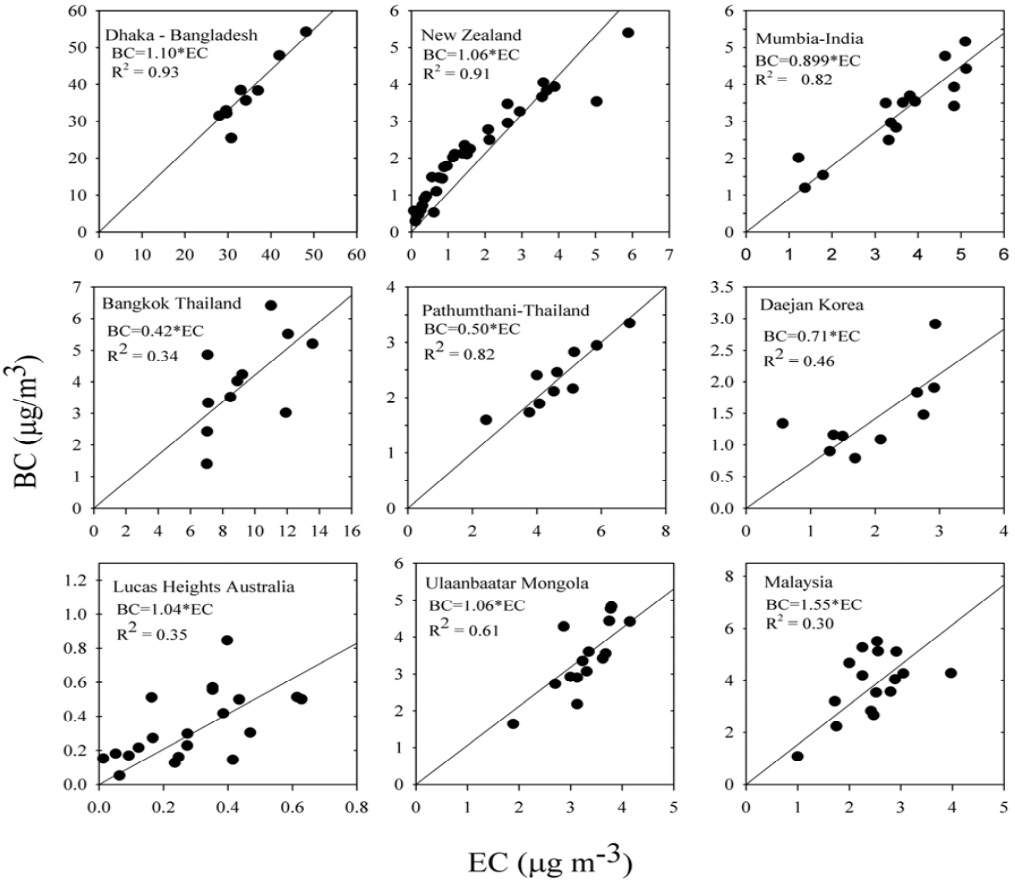

Figure 6.5: $PM_{2.5}$ filter comparisons for nine sites. E-BC via 0.45 micron nuclepore filters versus EC via quartz filter OC/EC pyrolysis (Salako et al., 2012)**.**

References

Bond, T. C., & Bergstrom, R. W. (2006). Light Absorption by Carbonaceous Particles: An Investigative Review. *Aerosol Science and Technology*, *40*(1), 27–67. doi:10.1080/02786820500421521

Cyrys, J., Heinrich, J., Hoek, G., Meliefste, K., Lewne, M., Gehring, U., … Brunekreef, B. (2003). Comparison between different traffic-related particle indicators: Elemental carbon (EC), PM2.5 mass, and absorbance. *J Expo Anal Environ Epidemiol*, *13*(2), 134–143.

Edwards, J. D., Ogren, J. A., Weiss, R. E., & Charlson, R. J. (1983). Particulate air pollutants: A comparison of British “Smoke” with optical absorption coefficient and elemental carbon concentration. *Atmospheric Environment (1967)*, *17*(11), 2337–2341. doi:http://dx.doi.org/10.1016/0004-6981(83)90233-0

Noullett, M., Jackson, P. L., & Brauer, M. (2006). Winter measurements of children's personal exposure and ambient fine particle mass, sulphate and light absorbing components in a northern community. *Atmospheric Environment*, *40*(11), 1971–1990. doi:http://dx.doi.org/10.1016/j.atmosenv.2005.11.038

Petzold, A., Ogren, J. A., Fiebig, M., Laj, P., Li, S.-M., Baltensperger, U., … Zhang, X.-Y. (2013). Recommendations for reporting "black carbon" measurements. *Atmospheric Chemistry and Physics*, *13*(16), 8365–8379. doi:10.5194/acp-13-8365-2013

Quincey, P., Butterfield, D., Green, D., Coyle, M., & Cape, J. N. (2009). An evaluation of measurement methods for organic, elemental and black carbon in ambient air monitoring sites. *Atmospheric Environment*, *43*(32), 5085–5091. doi:http://dx.doi.org/10.1016/j.atmosenv.2009.06.041

Salako, G. O., Hopke, P. K., Cohen, D. D., Begum, B. A., Biswas, S. K., Pandit, G. G., … Davy, P. (2012). Exploring the variation between EC and BC in a variety of locations. *Aerosol and Air Quality Research*, *12*(1), 1–7.

Taha, G., Box, G. P., Cohen, D. D., & Stelcer, E. (2007). Black Carbon Measurement using Laser Integrating Plate Method. *Aerosol Science and Technology*, *41*(3), 266–276. doi:10.1080/02786820601156224

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