Determination of Response of Real-time SidePak AM510 Monitor to Secondhand Smoke, Other Common Indoor Aerosols, and Outdoor Aerosol

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Supplemental Materials:

SidePak Optical Response:

The photometer optical response can be described by equation 1:

$$R = \int c_n\ f(d_p)\ P_{scat}(d_p, \lambda, m)\ \mathrm{d}d_p = \int c_n\ f(d_p)\ \frac{\pi}{4} d_p^2 Q_{scat}^{\theta}(d_p, \lambda, m)\ \mathrm{d}d_p \qquad [1]$$

R is the flux of light collected by the detector in the presence of many particles in the sensing volume of the photometer; c_n is the number concentration of the particles; d_p is the particle diameter; $f(d_p)$ is the probability density function of the particle size distribution; λ is the wavelength of the monochromatic laser light; m is the refractive index of the particle material; $P_{scat}(d_p, \lambda, m)$ is the flux of monochromatic light scattered by a single particle into the receiver aperture of an optical system[1]; and $Q_{scat}^{\theta}(d_p, \lambda, m)$ is the scattering cross section within the scattering angle ($28° \le \theta \le 152°$). Therefore, the photometer response R is dependent on the number concentration of particles, the particle size distribution, and the optical properties of the particles.

The mass concentration c_m of a polydisperse aerosol is:

$$c_m = \rho_p \int c_n f(d_p) \frac{\pi}{6} d_p^3 \mathrm{d}d_p \qquad [2]$$

The relationship between the photometer optical response and the particle mass concentration can be expressed as the ratio of the two:

$$\frac{R}{c_m} = \frac{\int c_n\ f(d_p)\ \frac{\pi}{4} d_p^2 Q_{scat}^{\theta}(d_p, \lambda, m)\ \mathrm{d}d_p}{\rho_p \int c_n f(d_p) \frac{\pi}{6} d_p^3 \mathrm{d}d_p} = \frac{3\int f(d_p) d_p^2 Q_{scat}^{\theta}(d_p, \lambda, m) \mathrm{d}d_p}{2\rho_p \int f(d_p) d_p^3 \mathrm{d}d_p} \qquad [3]$$

We can define a dimensionless size parameter $\alpha = \pi d_p / \lambda$, which indicates the relative size of the particle (d_p) versus the wavelength of the laser light (λ). Photometers underestimate the particle concentration for both very small ($\alpha << 1$) and very large particles ($\alpha >> 1$). Only for a particle with sizes comparable to the wavelength is the ratio of the photometer optical response to the particle mass concentration approximately constant, reflecting an approximately linear relationship between the two.

Factors Affecting the Calibration Factor

As mentioned in the main paper, the default calibration factor of 1 for the SidePak monitor is accurate for Arizona Test Dust. Arizona Road Dust aerosol has a density of 2.65 μg/m^3, a refractive index of 1.54, and its size is lognormally distributed with a geometric mass mean diameter (GMD) of 2.12 μm and a geometric standard deviation (GSD) of 1.57[2]. If the aerosol being measured has different density, size distribution, shape, or refractive index, the calibration factor is expected to vary. If the size distribution, shape, and refractive index is assumed to be comparable to Arizona Road Dust, then particle density becomes the dominant factor, and it is proportional to the calibration factor[2,3].

The average calibration factor for secondhand smoke (0.29) is approximately three-tenths that of the default calibration factor. Particle density is a major contributor to this difference: the density for secondhand smoke particles is between 1-1.12 μg/m[4, 4-6]. This is approximately four-tenths the density of Arizona road dust (ρ = 2.65 μg/m^3). Reported GMD values for secondhand smoke are around 0.2 - 0.5 μm, much smaller than for Arizona road dust[7-9]. Reported values of the real refractive index for secondhand smoke range from 1.45 to 1.62 [10-13]. If we were to assume secondhand smoke has the same real refractive index as Arizona road dust (1.54), the smaller size distribution by itself would cause less light scattering and thus lead to a higher calibration factor. Therefore, it appears that the real refractive index for the secondhand smoke we generated must have been on the large side of the range of values reported in literature, since the calibration factor for cigarette smoke is smaller than that for Arizona road dust.

Aerosols produced by incense smoke are spherical droplets with a density of 1.06 $\pm$0.08 g/cm^3 and a GMD of 0.27 - 0.29 μm (GSD = 1.4 - 1.6)[14]. A similar GMD of 0.262 $\pm$ 0.049 μm was reported elsewhere[15]. The calibration factor of incense smoke was comparable to that of the secondhand smoke, perhaps due to the apparent similarities in its density and size distribution.

The size distribution of wood smoke is subject to many factors including the temperature, degree of combustion, and atmospheric relative humidity[16]. For example, one study[17] found that low-temperature burning conditions produced particles with a GMD of 0.534 $\pm$ 0.036 µm, versus 0.243 $\pm$ 0.024 µm for high-temperature burning conditions. Flameless decomposition of beech wood smoke was reported to have a of GMD 1.5 µm (GSD = 1.9) in another study[18]. Despite these variations, wood smoke particles are generally smaller in size than Arizona road dust. The particles from burning small wood chips are expected to resemble wood smoke generated at a higher, more efficient burning temperature with a greater oxygen supply, and thus should be smaller than Arizona test dust as well. The real refractive index for wood smoke is around 1.53[19].

Our experimental results yielded an average calibration factor of 0.77 for smoke from burning wood chips (Douglas Fir). The lower density of wood smoke particles (ρ = 1.30 $\pm$ 0.02 g/cm^3)[19], by itself, will reduce the calibration factor by half compared to Arizona Road Dust. However, the slightly lower real refractive index and the smaller size distribution will both decrease the amount of scattered light, increasing the expected calibration factor to more than 0.5.

Smoke from burnt toast has a lognormal size distribution with a mass median diameter of 0.43 µm (GSD = 1.6)[18]. However, the density and refractive index of the aerosol are unknown, making it difficult to infer which factors lead to the calibration factor of 0.79. However, a few general observations can be made. The density of smoke from burnt toast is likely to be roughly comparable to that of other combustion processes involving vegetative materials, leading by itself to reductions in the calibration factor by half to two-thirds. Thus, the size distribution and/or the refractive index must be smaller in order to cause a sizeable decrease in light scattering (and thereby increase the calibration factor back up towards 1).

References for Supplementary Materials:

1. J. Gebhart. *Optical direct-reading techniques: light intensity system, in Aerosol Measurement: Principles, Techniques, and Applications.* P.A. Baron and K. Willeke, eds, Wiley – Interscience, New York, 2001, 419 – 454.
2. X. Wang, G. Chancellor, J. Evenstad, J.E. Farnsworth, A. Hase, G.M. Olson, A. Sreenath, J.K. Agarwal. *Aerosol Sci Tech*, 2009, **43**, 939 – 950.
3. P.T. O'Shaughnessy, J.M. Slagley. *Am Ind Hyg Assoc J*, 2002, **63**, 578 – 585.
4. P.T. Chang, L.K. Peters, Y. Ueno. *Aerosol Sci Tech,* 1985, **4**, 191 – 207.
5. W. Li, P.K. Hopke. *Aerosol Sci Tech*, 1993, **19**, 305 – 316.
6. P.J. Lipowicz. *J Aerosol Sci*, 1988, **19**, 587 – 589.
7. C.L. Benner, J.M. Bayona, F.M. Caka, H. Tang, L. Lewis, J. Crawford, J.D. Lamb, M.L. Lee, L.D. Hansen, and D.J. Eatough. *Environ Sci Technol,* 1989, **23**, 688 – 699.
8. M.J. Kleeman, J.J. Schauer, G.R. Cass. *Environ Sci Technol*, 1999, **33**, 3516 – 3523.
9. N.E. Klepeis, M.G. Apte, L.A. Gundel, R.G. Sextro, W.W. Nazaroff. *Aerosol Sci Tech*, 2003, **37**, 780 – 790.
10. M. Kerker, K.J. Sculley, W.A. Farone, A.J. Kassman. *Appl Optics*, 1978, **17**, 3030 – 331.
11. Y. Ishizu, T. Okada. *J Colloid Interf Sci*, 1978, **66**, 234 – 239.
12. D.D. McRae. *J Colloid Interf Sci*,1982, **87**, 117 – 123.
13. Y. Ishizu. *J Colloid Interf Sci*, 1983, **95**, 586 – 588.
14. Y.S. Cheng, W.E. Bechtold, C.C. Yu, I.F. Hung. *Aerosol Sci Tech*, 1995, **23**, 271 – 281.
15. C.R. Yang, T.C. Lin, F.H. Chang. *Environ Pollut*, 2007, **145**, 606 – 615.
16. V.S. Kozlov, M.V. Panchenko. *Combust Explo Shock*, 1996, **32**, 577 – 586.

17. J. Tissari, J. Lyyränen, K. Hytönen, O. Sippula, U. Tapper, A. Frey, K. Saarnio, A.S. Pennanen, R. Hillamo, R.O. Salonen, M.R. Hirvonen, J. Jokiniemi. *Atmos Environ*, 2008, **42**, 7862 – 7873.

18. D.W. Weinert, T.G. Cleary, G.W. Mulholland, P.F. Beever. *Fire Safety Science -- Proceedings of the Seventh International Symposium*, 2002, 209 – 220.

19. W.W. Foster. *Brit J Appl Phys*, 1959, **10**, 416 – 420.

Table S1: $PM_{2.5}$ measurements determined by gravimetric method and by 13 SidePak monitors for 4 different concentration levels in a small environmental chamber in March, 2008

$PM_{2.5}$ Measurements (μg/m^3)		**Exp1**	**Exp2**	**Exp3**	**Exp4**
Gravimetric Method		467.5	65.7	124.2	205.4
SidePak Monitors	KSP1	1686.0	239.1	439.8	720.6
	KSP2	1652.4	252.4	458.2	779.1
	SP2	1668.3	212.1	392.8	723.2
	SP3	1829.9	262.1	493.2	837.0
	SP4	1867.1	286.3	523.6	875.7
	SP6	1565.7	240.2	436.2	733.0
	SP7	1598.2	237.4	446.5	733.4
	SP8	1616.0	233.4	442.7	739.8
	SP9	1572.3	220.1	413.4	706.0
	SP10	1594.8	230.2	429.0	727.9
	SP12	1535.7	227.9	427.9	701.1
	SP13	1549.5	231.7	432.0	712.0
	SP14	1564.6	231.5	424.2	719.5
SidePaks Mean		1638.5	238.8	443.0	746.8
SidePaks SD		104.0	19.1	33.7	52.9

Table S2: $PM_{2.5}$ measurements determined by gravimetric method and by 16 SidePak monitors for 4 different concentration levels in a small environmental chamber in June, 2009

$PM_{2.5}$ Measurements (μg/m^3)		**Exp1**	**Exp2**	**Exp3**	**Exp4**
Gravimetric Method		446.4	234.6	55.8	113.9
SidePak Monitors	KSP1	1698.2	908.0	210.9	465.5
	KSP2	1638.5	876.4	204.4	455.7
	SP2	1737.2	863.1	171.6	422.3
	SP4	1883.1	1018.6	235.3	522.2
	SP6	1420.0	818.9	176.1	353.8
	SP7	1580.2	860.5	204.8	446.8
	SP8	1538.4	836.3	192.2	426.5
	SP9	1502.8	804.2	183.8	410.5
	SP10	1553.2	841.4	200.0	438.2
	SP11	1540.7	829.4	183.6	415.3
	SP12	1572.0	849.1	197.7	437.1
	SP13	1503.6	816.9	191.9	421.5
	SP14	1613.1	868.5	199.2	452.8
	SP15	1585.0	857.3	205.1	448.2
	SP16	1712.9	914.1	206.1	461.7
	SP17	1685.3	912.6	212.3	470.8
SidePaks Mean		1610.3	867.2	198.4	440.6
SidePaks SD		112.7	52.5	15.5	35.7

Source Strengths and Emission Rates:

Table S3. Summary of source durations, peak $PM_{2.5}$ concentrations, decay rates, source emission rates, and total emissions determined for indoor combustion sources based on 6 sets of 4 experiments

	Cigarette Smoke	Double Strength Incense[a]	Thin Incense	Wood Chips[b]	Toasting Bread
Source Duration (min)	5	5	1.5	--	12.2
Peak Conc. (mg/m^3)	0.30	0.57	0.31	0.83	1.0
Decay Rates (h^{-1})	0.45	0.49	0.57	0.57	0.60
Emission Rate g (mg/min)	2.8	5.4[c] 2.7[e]	9.6[d] 1.6[e]	--	4.2
Total Emission G (mg)	14	27	14	39	51

[a] one of the duplicated calibration experiments with double strength incense sticks was excluded from the source emission rate calculation, because the chamber was inadvertently opened for around 1 min while the source was emitting; [b] the source duration for wood chip smoke was relatively short and could not be accurately measured; [c] total emission rate for 2 incense sticks; [d] total emission rate for 6 incense sticks; [e] emission rate per incense stick