Supplementary Information

Contents

1. Linking CNT aerosol characteristics with bulk material characteristics
2. Aerosol particle ‘equivalent diameter’ concepts – aerodynamic, diffusion and mobility
3. Effective density
4. Sensitivity of deposition models to key aerosol parameters
5. Supplementary References
1. **Linking CNT aerosol characteristics with bulk material characteristics**

Predicting the characteristics of airborne CNT particles from information on the bulk material properties (e.g. Jackson et al. 2015; Poulsen et al. 2017) is not straightforward. The physical characteristics (e.g. particle size, form) of CNT particles when aerosolized may be very different to those of the individual CNT themselves or that of the bulk material. The diameter and rigidity of the tubes may have an important bearing on the ability of the CNT to remain as individual straight fibers, to bend, or to agglomerate into larger structures (Wang et al. 2015). The ‘dustiness’ of a material (a measure of the propensity for aerosolization due to mechanical action) may be linked with potential exposure levels, and assessment of the dustiness of CNT shows wide variability in both the mass and number of particles evolved from aerosolization procedures (Evans et al. 2013; Totaro et al. 2016; Dazon et al. 2017).

This high variability reinforces the point made by Erdely et al. (2016) and Ellenbecker et al. (2018) that all CNT are not equal from the standpoint of risk characterization.

However, although dustiness provides information on bulk release, it does not provide a direct link between the particle size and shape distribution within the bulk powder and that for the aerosol, for differing CNT types. Some studies have examined both bulk and aerosol CNT morphology via TEM in the course of characterising the material used in in vivo studies (e.g. Ma-Hock et al. 2009; Kasai et al. 2014, 2016) and generated via different techniques (Ku and Kulkarni, 2015), but very few experimental studies focused specifically on exploring these links have been undertaken to date. Ku and Birch (2019), in a targeted study, found a strong correlation between dustiness and bulk density for fibrous materials, but a weaker relationship for non-fibrous materials. CNT with lower bulk densities also remained airborne within the test chamber for longer, potentially leading to increased workplace exposure in the event of release. Importantly, they also showed that increasing CNT bulk density (for all
CNT tested, with bulk densities < 0.16 g cm\(^{-3}\)) leads to increased aerodynamic diameter, but decreased mobility diameter (see Supplementary Material for a definition of these terms), for the aerosol produced. This could provide a useful connection between a property of the bulk material, measurable via a standardized methodology (WHO, 2012), to aerosol characteristics which govern lung deposition and which are commonly measured using aerosol instrumentation.

2. **Aerosol particle ‘equivalent diameter’ concepts – aerodynamic, diffusion and mobility diameters**

*Sphere-like particles*

There are several definitions of aerosol particle diameter, depending on factors such as particle shape, density, and the nature of external forces acting on the particle (Hinds, 1999). As the aerodynamic diameter and diffusion play a key role in determining the pattern of particle deposition in the respiratory tract (Finlay, 2001), it is useful to consider these concepts further. A tutorial on ‘equivalent diameters’ and their relationships is given by DeCarlo *et al.* (2004) and we briefly summarise below those points most relevant for respiratory particle deposition in general and for CNT in particular.

*Aerodynamic diameter*, \(d_{ae}\), is defined as the diameter of a unit density sphere (\(\rho_0 = 1000 \text{ kg m}^{-3}\)) with the same terminal settling velocity as the particle of interest. For a spherical particle, aerodynamic diameter is related to physical diameter, \(d\), and particle density, \(\rho_p\), by

\[
d_{ae} = d \sqrt{\frac{\rho_p}{\rho_0} \frac{C_c(d)}{C_c(d_{ae})}}
\]  

(S1)
where $C_c$ is the slip correction factor, required for particles with diameters approaching the mean free path of air molecules, $\lambda$ (~ 67 nm), given by

$$C_c(d) = 1 + Kn \left[ C_1 + C_2 \exp \left( -\frac{C_3}{Kn} \right) \right] \quad (S2)$$

where $Kn = 2\lambda/d$ is the Knudsen number and $C_1$, $C_2$ and $C_3$ are constants (Allen and Raabe, 1985).

In practice, many airborne particles diverge by varying degrees from spherical, including carbon nanotubes. A common approach to dealing with this is to include a dynamic shape factor, $\chi$, in (S1) and to use the volume equivalent diameter, $d_{ve}$, (the diameter of a spherical particle of the same volume as the actual particle of interest) in place of $d$ (DeCarlo et al. 2004). The dynamic shape factor is generally greater than 1, meaning the aerodynamic diameter of non-spherical particles is less than for spherical particles.

The diffusion equivalent diameter, $d_d$, is defined with reference to the particle translational diffusion coefficient, $D$, and is closely related to the concept of particle mobility, $B$, the drift velocity per unit force experienced by a particle (Einstein, 1905),

$$D = kTB = \frac{kTC_c(d_d)}{3\pi\mu d_d} \quad (S3)$$

where $k$ is the Boltzmann constant, $T$ is absolute temperature and $\mu$ is the viscosity of the fluid. Diffusion diameter is related to volume equivalent diameter, $d_{ve}$, by the relationship (Kasper, 1982)

$$\frac{d_d}{C_c(d_d)} = \chi \frac{d_{ve}}{C_c(d_{ve})}. \quad (S4)$$

For spherical particles (with or without internal voids), $\chi = 1$ and $d_d = d_{ve} = d$. For ‘broadly-spherical’ particles, diffusion diameter approximately equates to volume equivalent
diameter so for ‘broadly-spherical’ CNT agglomerate particles, volume equivalent diameter should be a reasonable first approximation to diffusion diameter – indeed this was shown to be the case for particles of mobility diameter 100 – 400 nm for the projected area diameter, which correlates well with volume equivalent diameter, of MWCNT particles obtained from TEM images (Ku and Kulkarni, 2015). However, the error in this assumption increases as particle shape deviates further from spherical, and for larger particles (Rogak et al. 1993; Park et al. 2004; DeCarlo et al. 2004). For irregular particles and aggregates, $\chi > 1$ and $d_d$ is always greater than $d_{ve}$ (DeCarlo et al. 2004). Estimated shape factors for individual (‘fiber-like’) MWCNT are high (e.g. 1.9 - 2.7, Chen et al. 2012), while those for ‘broadly-spherical’ CNT agglomerates may be lower (e.g. 1.7 - 2.3, Wang et al. 2015).

Electrical mobility diameter, often referred to simply as mobility diameter, $d_m$, is defined as the diameter of a sphere with the same mobility in an applied electric field as the aerosol particle in question. This concept is introduced here as it is strictly the quantity measured by many aerosol instruments, especially in the sub-micron size range, e.g. SMPS. For aerosol particles carrying a single electric charge $e$, this quantity is identical to the diffusion equivalent diameter described above and it is important to note that for this reason the two terms are often used synonymously in the literature.

Fiber-like particles

For non-spherical particles, orientation affects their aerodynamic and diffusion behavior in an air flow. When there is a flow velocity gradient, for example in fully-developed laminar flow, long, straight fibers may become oriented parallel to the flow (Chen, X. et al. 2016), while rotational Brownian motion acts to randomise orientation. Generally, the latter dominates for fibers up to a few micrometres in length. Within the laminar flow
regime, the larger the Reynolds number, Re (ratio of inertial to viscous forces), the greater the
(parallel) alignment with flow (Bernstein and Shapiro, 1994). However, as Reynolds number
increases yet further (Re > 2000), flow becomes turbulent, leading to an increasingly random
alignment once more (Chen, X. et al. 2016).

For a ‘fiber-like’ particle, modelled as an ellipsoid whose polar axis forms an angle $\theta$
with the direction of flow, aerodynamic diameter is related to the fiber’s physical properties
(Oseen, 1927)

$$d_{ae} = \sqrt{\frac{3\rho_e d_f \beta d c(e)}{2\rho_0 C_{f}(d)\left(\frac{\sin^2\theta + \cos^2\theta}{d_{f,\perp}} + \frac{d_{f,\parallel}}{d_{f,\parallel}}\right)}} \quad (S5)$$

where, $d_f$, $L$, and $\beta (= L/d_f)$ are, respectively, fiber diameter (the physical diameter of the
fiber/ellipsoid, not the particle equivalent diameter), length and aspect ratio and $d_{f,\perp}$ and $d_{f,\parallel}$
are the Stokes diameters for a fiber oriented perpendicular and parallel to the direction of
motion, given by

$$d_{f,\perp} = \frac{8/3(\beta^2 - 1)d_f}{2\beta^2 - 3\ln(\beta + \sqrt{\beta^2 - 1}) + \beta} \quad (S6)$$

$$d_{f,\parallel} = \frac{4/3(\beta^2 - 1)d_f}{2\beta^2 - \ln(\beta + \sqrt{\beta^2 - 1}) - \beta} \quad (S7)$$

Since no exact expression exists to calculate the slip correction factor for ellipsoids, here the
approximation method of Dahneke (1973) is used, whereby a slip-equivalent diameter, $d_e$,
which depends on $d_f$, $\beta$ and $\theta$, is used in place of the physical diameter $d$ in Equation (S2).

For an ellipsoid oriented parallel to the flow direction, $\theta = 0$ and Equation (S5) is only
dependent on $d_{f,\parallel}$. Similarly, for orientation perpendicular to the direction of motion, as may
occur under gravitational settling (Ku et al. 2006), $\theta = 90^\circ$ and Equation (S5) depends only on $d_{f,\perp}$. Assuming an average orientation due to Brownian rotation, Equation (S5) reduces to

$$
\frac{d_{ae}}{d_a} = \sqrt{\frac{3\rho_f d_f^2 \beta}{2\rho_0 C_e(d_a) \left( \frac{2/3}{d_{f,\perp}} + \frac{1/3}{d_{f,\parallel}} \right)}}
$$

(S8)

Various parameterizations for aerodynamic diameters have also been developed, including that of Oyabu et al. (2011),

$$
d_{ae} = 1.3 \rho^{\frac{1}{3}} d_f^{\frac{1}{6}} L^{1/2}
$$

(S9)

originally derived from data for gravitational settling of asbestos fibers (Stöber, 1972). This yields aerodynamic diameters of similar order to the orientation-specific calculations above, and closely fits the ‘perpendicular’ result for asbestos. However, results diverge for smaller fiber diameters – Stöber (1972) states that the parameterization is valid outside the slip regime and for $L >> d_f$ – and the validity of the application of this simple relation to CNT has not been experimentally verified.

Diffusion equivalent diameter for ‘fiber-like’ particles, modelled again as ellipsoids forming an angle $\theta$ with the direction of motion, can be expressed as (Asgharian et al. 1988)

$$
\frac{C_e(d_a)}{d_a} = C_e(d_a) \left( \frac{\sin^2 \theta}{d_{f,\perp}} + \frac{\cos^2 \theta}{d_{f,\parallel}} \right).
$$

(S10)

As with aerodynamic diameter, for parallel and perpendicular orientation with respect to motion Equation (S10) is dependent only on $d_{f,\perp}$ and $d_{f,\parallel}$ respectively, and similarly for random orientation,

$$
\frac{C_e(d_a)}{d_a} = C_e(d_a) \left( \frac{2/3}{d_{f,\perp}} + \frac{1/3}{d_{f,\parallel}} \right)
$$

(S11)
Parallel and random alignments relative to direction of motion are expected to represent the scenario encountered in the upper and lower regions of the lung respectively.

Figure S1 shows the variability in aerodynamic diameter with length for individual ‘fiber-like’ CNT particles of assumed density 1.75 g cm$^{-3}$, for a range of fiber diameters, chosen to reflect typical dimensions for SWCNT (2 nm), the range of MWCNT fiber diameters observed (10, 50 and 90 nm) and, for comparison, asbestos fibers (500 nm, density 2.5 g cm$^{-3}$). It is clear that the aerodynamic diameter is primarily governed by fiber diameter, especially for thinner fibers, but also increases with fiber length. As a ‘rule of thumb’, aerodynamic diameters are 2.5 – 4 times larger than fiber diameters, with thinner and longer fibers towards the higher end of this range and thicker, shorter fibers towards the lower end. Aerodynamic diameters for fibers aligned parallel to the flow are higher than fibers aligned randomly, which in turn are higher than fibers aligned perpendicular to the flow direction. As SWCNT have not yet been observed in exposure environments as individual fibers, aerodynamic diameters for most (CNT) ‘fiber-like’ particles (with typical lengths mainly < 10 µm) are likely to be in the approximate range 40 – 340 nm, and hence deposition efficiency via impaction and sedimentation is likely to be relatively low, as these mechanisms are not particularly effective for particles with aerodynamic diameters smaller than ~ 500 nm.

The relationship between diffusion equivalent diameter and length for fibers of a range of diameters is shown in Figure S2. Parallel and random alignment relative to direction of motion are expected to represent the scenario encountered in the upper and lower regions of the lung respectively. Diffusion equivalent diameter for ‘fiber-like’ particles increases both with their length and diameter, and for typical ‘fiber-like’ MWCNT (fiber diameters 10 to 90 nm, lengths 0.1 to 10 µm) range between 50 nm to 1 µm, and for asbestos fibers between 300 nm and several microns. Diffusion-mediated deposition is therefore likely to be low for asbestos fibers, but possible for shorter and thinner MWCNT. Given that, as outlined above,
expected deposition by aerodynamic mechanisms (other than possibly interception) is low, decreasing diffusion diameter (a factor of both fiber length and fiber diameter) is expected to lead to higher deposition efficiency in the lung. Conversely to aerodynamic diameter, diffusion diameters in perpendicular orientation are larger than in random orientation, which in turn are larger than parallel orientation.

3. Effective density

Particle ‘effective density’ is a quantity increasingly reported in CNT toxicological studies, commonly as a means of linking the diffusional and aerodynamic diameters and/or mass of the particles and hence, the behavior of the particles, via measured properties of the aerosol. However, as described by DeCarlo et al. (2004), there are several definitions of effective density, depending on exactly which parameters are measured, and comparing effective densities derived from measurements using different instruments, or using the incorrect definition for the application in question, could lead to substantial errors.

Three definitions of effective density $\rho_{eff}$ defined by DeCarlo et al. (2004), based respectively on i) measurement of particle mobility and mass, ii) fitting between regions of overlap on multiple measurement instruments, and iii) measurement of particle aerodynamic and mobility diameter, are as follows:

$$\rho_{eff} = \rho_p \left( \frac{d_{am}}{d_m} \right)^3 = \frac{6m_p}{\pi d_m^3}, \quad (S12)$$

where in the second term $m_p$ is particle mass, which can be applied to the particle population as a whole (e.g. via measurement with Tapered Element Oscillating Microbalance, TEOM, or similar instrument; Morawska et al. 1999; or via Quartz Crystal Microbalance, QBM; Sarangi...
et al. 2016) as well as to individual particles (e.g. via measurement with Aerosol Particle Mass analyser, APM; McMurry et al. 2002);

\[ p_{eff}^{II} = \frac{p}{\chi}, \quad (S13) \]

where the value of \( \rho_{eff} \) is obtained through fitting multiple data sets from different measurement instruments e.g. SMPS and APS (Khlystov et al. 2004), but cannot separately provide both particle density and shape factor information without further measurements or constraints; and

\[ \rho_{eff}^{III} = \frac{d_a}{d_m} \rho_0. \quad (S14) \]

As \( \chi \) increases i.e. as particles get more irregular, the effective density obtained from each of the expressions above decreases below the density of the equivalent spherical particle, with the greatest change, in order, \( \rho_{eff}^{I} < \rho_{eff}^{III} < \rho_{eff}^{II} \) (DeCarlo et al. 2004).

Depending on the particle size distribution, measurement of the quantities involved may not always be feasible e.g. particles larger than \(~1 \) micron are not measurable using most common SMPS systems. Hence effective density according to the definition \( \rho_{eff}^{III} \) has, to our knowledge, not been reported in previous studies of CNT particles. There are examples of CNT studies using definitions \( \rho_{eff}^{I} \) (Ku and Kulkarni, 2015) and \( \rho_{eff}^{II} \) (Mitchell et al. 2007).

DeCarlo et al. (2004) state that, for ‘mildly irregular’ particles (\( \chi < 1.2 \)), the difference between \( \rho_{eff}^{I} \) and \( \rho_{eff}^{III} \) is less than 10\%, so whilst this approach may not be possible for fiber-like CNT particles (for which other morphological characterization may be more appropriate), for broadly-spherical CNT particles these two definitions of effective density could possibly be used interchangeably without introducing significant errors. However,
values for $\rho_{\text{eff}}^{II}$ could be significantly higher than $\rho_{\text{eff}}^{I}$ or $\rho_{\text{eff}}^{III}$ for the same aerosol (DeCarlo et al. 2004).

The appropriate choice of definition for effective density may be different depending on the exact application. For example, in converting between mobility and aerodynamic diameters, as when assessing deposition efficiency via a range of mechanisms in a computational model, $\rho_{\text{eff}}^{III}$ would ideally be used; whilst for assessing mass concentration based on mobility measurements, $\rho_{\text{eff}}^{I}$ may be most appropriate. It is also possible that more than one definition is required at different points during a study; as outlined in the main text, the dose calculation requires estimates of both airborne concentration and deposition efficiency, which could involve both $\rho_{\text{eff}}^{I}$ and $\rho_{\text{eff}}^{III}$ at the relevant stage. For this reason, the more particle characteristics which can be measured via a range of different instrumentation in toxicological studies, the greater the prospect of being able to use the most appropriate definition of effective density for the situation, reducing potential errors, and hence the better the ultimate estimate of dose is likely to be.

4. Sensitivity of deposition models to key aerosol parameters

As key inputs into models designed to estimate deposition efficiency (and hence dose) for inhaled particles, any inaccuracies in measurements or assumptions about e.g. particle mean or median diameter, geometric standard deviation (GSD) or log-normality of the size distribution, or particle density, could lead to significant errors in the output of the models. The majority of models assume a single log-normal distribution. It is clear that in some cases, reported size distributions are not necessarily either (or both) unimodal or log-normal throughout an exposure period (e.g. O’Shaughnessy et al. 2014). Because of the large
variability in aerodynamic and diffusion sizes of typical airborne CNT, reflected in their typically high GSD, the error in retrieved deposition efficiency due to either non-log-normality of the distribution or inaccurate mean/median diameter could be high. In addition, the (typically low) density of broadly-spherical CNT agglomerates could significantly change their deposition behavior relative to unit density particles (Oberdörster and Kuhlbusch, 2018).

The effects of these factors on predicted deposition efficiencies have been explored using the MPPD model (v 3.04, Miller et al. 2016; ARA, 2018). Although, as described in the main text, a range of models are available for predicting deposition in the respiratory tract, MPPD has been chosen here as it is the most widely used in nanotoxicology studies. It has a number of advantages: it is freely accessible, easy to use and covers humans, rats and mice, it is regularly updated, and the latest version includes a fiber deposition module. The model has an excellent pedigree, being based on extensive previous work (e.g. Asgharian and Anjilvel, 1998); however, it is important to reflect that this and other well-known and widely used models show a degree of variability in their predictions which is less marked for total deposition but can be non-trivial for regional deposition, despite the similarities of the underlying approaches. There are a number of reasons for this, including the use of different airway models and dimensions and minor differences in the deposition formulae used (Kuempel and Tran, 2002; Hofmann, 2011; Majid et al. 2015).

Figure S3 shows the effect of varying density on particle deposition efficiency for a range of particle size distributions with GSD = 1.7, while Figure S4 shows the effect of varying GSD on particle size distributions for densities 0.1 and 1 g cm$^{-3}$, from MPPD using rat (Sprague-Dawley Asymmetric, 250 g body weight) and human (Yeh & Schum 5-lobe, Oronasal-Mouth Breather – results, not shown, for Nasal breathing are qualitatively similar) airway morphometry. Failing to account for the lower density of CNT agglomerates could cause deposition efficiency in both rats and human lungs to be overestimated by up to a factor
of 2 to 3 for the smallest particles (mass median aerodynamic diameter (MMAD) < 0.1 µm), although the effect is much reduced for larger particles e.g. at 3 µm MMAD there is no significant impact.

Broader particle size distributions (larger GSD) can either increase or decrease the overall deposition efficiency, depending on the slope of the deposition efficiency curve itself at the MMAD. For example, if a ‘peak’ in deposition (e.g. 3-5 µm in humans, Figure S5) corresponds to the MMAD of the particle size distribution, a broader distribution will have longer ‘tails’ of larger and smaller particles, both of which have lower deposition efficiency than the mid-sized particles, lowering overall deposition efficiency, as observed in Figure S4 for 3 µm MMAD particles in humans and 1 µm MMAD particles in rats. However, in general, the trend is for higher GSD distributions to show slightly higher deposition efficiencies for both species, although the effect is not as important as for neglecting density; deposition efficiency for particles in the MMAD range 0.1 to 1 µm with GSD of 2.4 (compared with GSD of 1.7) are higher by a factor of 1.06-1.18 for density 1 g cm\(^{-3}\), and a factor of 1.12-1.21 for density 0.1 g cm\(^{-3}\). Nevertheless, errors of this magnitude may make a significant difference to calculated deposited dose or lung burden in in vivo studies. This analysis highlights the importance of adequately assessing the delivered CNT particle aerosol characteristics for use in deposition modelling.
Figure S1. Predicted aerodynamic equivalent diameters of ‘fiber-like’ CNT particles of a range of fiber diameters, and a typical asbestos fiber* (diameter 500 nm, density 2.5 g cm$^{-3}$), for random (Rand, solid lines), parallel (Par, long dashes) and perpendicular (Perp, short dashes) orientation to airflow, and from the parameterization of Oyabu et al. (2011) (symbols).
Figure S2. Predicted diffusion equivalent diameters of ‘fiber-like’ CNT particles of a range of fiber diameters, and a typical asbestos fiber* (diameter 500 nm, density 2.5 g cm\(^{-3}\)), for random (Rand, solid lines), parallel (Par, long dashes) and perpendicular (Perp, short dashes) orientation to airflow.
Figure S3. Variability in deposition efficiency (tracheobronchial + pulmonary) with particle effective density, retrieved from MPPD v.3.04 for a) rat (Sprague-Dawley Asymmetric, 250 g body weight) and b) human (Yeh & Schum 5-Lobe, Oronasal-Mouth Breather) for a range of particle size distributions with GSD 1.7 and mass median aerodynamic diameters ranging from 0.03 to 10 µm (other model input parameter values MPPD defaults).
Figure S4. Variability in deposition efficiency (tracheobronchial + pulmonary) with geometric standard deviation (GSD) in particle size distribution, retrieved from MPPD v.3.04 with airway morphometry of rat (Sprague-Dawley Asymmetric, 250 g body weight) with particle density a) 1 g cm\(^{-3}\) and b) 0.1 g cm\(^{-3}\), and human (Yeh & Schum 5-Lobe, Oronasal-Mouth Breather) with particle density c) 1 g cm\(^{-3}\) and d) 0.1 g cm\(^{-3}\), for mass median aerodynamic diameters ranging from 0.03 to 10 µm (other model input parameter values MPPD defaults).
Figure S5. Predicted deposition in the alveolar region (open symbols) and the whole respiratory tract (filled symbols) from aerodynamic (blue curves) and diffusion (red curves) mechanisms calculated using the ICRP Human Respiratory Tract Model (ICRP, 1994).
5. Supplementary References

Allen MD, Raabe OG. 1985. Slip correction measurements of spherical solid aerosol particles in an improved Millikan apparatus. Aerosol Sci Technol. 4(3):269–286.

Asgharian B, Yu CP, Gradon L. 1988. Diffusion of fibers in a tubular flow. Aerosol Sci Technol. 9:213–219.

Bernstein O, Shapiro M. 1994. Direct determination of the orientation distribution function of cylindrical particles immersed in laminar and turbulent shear flows. J Aerosol Sci. 25(1):113–136.

Dahneke BE. 1973. Slip correction factors for nonspherical bodies–III the form of the general law. J Aerosol Sci. 4(2):163–170.

Dazon C, Witschger O, Bau S, Payet R, Beugnon K, Petit G, Garin T, Martinon L. 2017. Dustiness of 14 carbon nanotubes using the vortex shaker method. J Phys Conf Ser. 838:012005.

Einstein A. 1905. On the motion, required by the molecular-kinetic theory of heat, of particles suspended in a fluid at rest. Ann Phys. 17:549–560.

Erdely A, Dahm MM, Schubauer-Berigan MK, Chen BT, Antonini JM, Hoover MD. 2016. Bridging the gap between exposure assessment and inhalation toxicology: Some insights from the carbon nanotube experience. J Aerosol Sci. 99:157–162.

Evans DE, Turkevich LA, Roettgers CT, Deye GJ, Baron PA. 2013. Dustiness of fine and nanoscale powders. Ann Occup Hyg. 57(2):261–277.

Finlay WH. 2001. The Mechanics of Inhaled Pharmaceutical Aerosols. San Diego: Academic Press.
Kasper G. 1982. Dynamics and measurement of smokes. I Size characterization of nonspherical particles. Aerosol Sci Technol. 1(2):187–199.

Kuempel ED, Tran CL. 2002. Comparison of human lung dosimetry models: Implications for risk assessment. Ann Occup Hyg. 46(S1):337–341.

Majid H, Hofmann W, Winkler-Heil R. 2015. Comparison of stochastic lung deposition fractions with experimental data. Ann Occup Hyg. 56:278–291.

Morawska L, Johnson G, Ristovski ZD, Agranovski V. 1999. Relation Between Particle Mass and Number for Submicrometer Airborne Particles. Atmos Environ. 33:1983–1990.

Oseen CW. 1927. Neuere methoden und ergebnisse in der hydrodynamic. Leipzig: Akademische Verlagsgesellschaft.

Park K, Kittelson D, McMurry P. 2004. Structural properties of diesel exhaust particles measured by transmission electron microscopy (TEM): Relationships to particle mass and mobility, Aerosol Sci Technol. 38(9):881–889.

Rogak SN, Flagan RC, Nguyen HV. 1993. The mobility and structure of aerosol agglomerates. Aerosol Sci Technol. 18(1):25–47.

Stöber W. 1972. Dynamic shape factors of nonspherical aerosol particles. In: Mercer TT, Morrow PE, Stöber, W, editors. Assessment of Airborne Particles: Fundamentals, Applications and Implications to Inhalation Toxicity. Springfield (IL): Charles C. Thomas Publisher Ltd.

Totaro S, Cotogno T, Rasmussen K, Pianella F, Roncaglia M, Olsson H, Riego Sintes JM, Crutzen HR. 2016. The JRC Nanomaterials Repository: A unique facility providing representative test materials for nanoEHS research. Regul Toxicol Pharmacol. 8: 334–340.
[WHO] World Health Organization. 2012. Bulk Density and Tapped Density of Powders. Geneva: WHO. Document QAS/11.450 FINAL.