

STATE-OF-THE-ART MONITORING TECHNIQUES

Tables 1 to 3 provide lists of all the state-of-the-art equipment available for monitoring nanoparticles in terms of three metrics, mass, number and surface area concentration. The tables also provide an initial ranking for the equipment according to efficacy, practicability and suitability for use in an industrial workplace. Tables 4 and 5 provide equipment which can be used to collect samples and to characterize the nanoparticles.

Table 1. Air monitoring equipment suitable for measuring *Mass Concentration*.

RATING	DEVICES	REMARKS
1	Cascade impactor	<p>Cascade impactors are the only devices offering a sample cut-off point around 100 nm. i.e. can measure a total mass above 100 nm and also below 100nm (down to approximately 20 nm for low pressure systems).</p> <p>This is the favoured method for determining mass concentration. It is easy to use and can be operated at high flow rates and provides a mass concentration for a defined range of particle sizes. Its approximate cost is 15,000 euro (~ \$19,000). The only disadvantage is that it is not too portable but provided a trolley is provided it can be used in an industrial setting.</p> <p>Attached is one commercially available example, the Model 115 Nano-MOUDI which has cut-points in the nanometer range: 32, 18 and 10 nm..</p> <p>http://www.appliedphysicsusa.com/cascade_impactors.html</p>
2	Tapered Element Oscillating Microbalance (TEOM)	<p>The TEOM is a sensitive real-time monitor that can be used to measure the mass concentration of nanoparticles as a function of time. The main disadvantage is that the TEOM does not provide size information.</p> <p>There is a version of the TEOM that can be used as a personal monitor.</p>
	Size selective personal monitor	<p>There are currently no devices that offer a cut point of 100 nm. Therefore off-line gravimetric or chemical detection is necessary. Also detection rate are low due to the flow air flow rate.</p> <p>Mass may also be derived from size distribution measurements (see below).</p>
	Scanning Mobility Particle Sizer (SMPS)	<p>The SMPS provides a real time size-selective (mobility diameter) number concentration and from this the mass concentration can be determined. The SMPS measures the size of the particles by using positive electrostatic charges on the particles to attract them to a negatively charge rod. The mass concentration will only be an estimate and is dependent on knowing the particle shape and density (if not known they must be estimated). The possible detectable particle size range is from 3 nm to 800 nm (although during monitoring this must be narrowed down to a smaller range. Preliminary exercise should be conducted to determine the setting of the size range of the SMPS before establishing the size range that should be used during the exposure monitoring programme.</p> <p>Note: The initial recommended range is from 10 to 400 nm.</p> <p>Note: The SMPS utilizes a radioactive source (Kr 85) which the manufacturer holds a US NRC general license. The purchaser will need to verify with their state and local agencies to determine if additional registrations or licenses are required.</p> <p>The SMPS cost: 45,000 - 70,000 Euro (~\$57,000 - \$88,000). Commercially available examples from TSI can be viewed the attached link:</p> <p>http://www.tsi.com/Product.aspx?Pid=85</p>
	Electrical Low Pressure Impactor (ELPI)	<p>The ELPI provides a real time size-selective (aerodynamic diameter) active surface-area concentration and from this the mass concentration can be determined. The mass concentration will only be an estimate and is dependent on knowing the particle charge and density (if not known they must be estimated). It is also possible to further analyse size-selected off-line. The ELPI has a wide size range from 7 nm to 10 microns.</p> <p>The ELPI cost: 55,000 Euro (~\$70,000).</p>
CONCLUSION	The cascade impactor is the most suitable technique for measuring mass concentration due to the relatively low cost, ease of use and direct mass measurement.	

Table 2. Air monitoring equipment suitable for measuring *Number Concentration*.

RATING	DEVICES	REMARKS
1	Scanning Mobility Particle Sizer (SMPS)	<p>The SMPS provides a real time size-selective (mobility diameter) number concentration. The SMPS measures the size of the particles by using positive electrostatic charges on the particles to attract them to a negatively charge rod. The possible detectable particle size range is from 3 nm to 800 nm (although during monitoring this must be narrowed down to a smaller range. Preliminary exercise should be conducted to determine the setting of the size range of the SMPS before establishing the size range that should be used during the exposure monitoring programme. Note: The initial recommended range is from 10 to 400 nm.</p> <p>The SMPS cost: 45,000 - 70,000 Euro (~\$57,000 - \$88,000). Commercially available examples from TSI can be viewed the attached link: http://www.tsi.com/Product.aspx?Pid=85</p>
2	Electrical Low Pressure Impactor (ELPI)	<p>The ELPI provides a real time size-selective (aerodynamic diameter) active surface-area concentration. It is also possible to further analyse size-selected off-line. The ELPI has a wide size range from 7 nm to 10 microns.</p> <p>The ELPI cost: 55,000 Euro (~\$70,000).</p>
3	Condensation Particle Counters (CPC)	<p>CPCs provide real time number concentration measurements between their particle diameter detection limits (typically from 10 nm to 1 micron). However they do not provide a size distribution and also without a nanoparticle pre-separator detect particles outside the nano-scale, i.e. > 100 nm (currently there are no suitable pre-separators available). Two devices commercially available are:</p> <ul style="list-style-type: none"> o P-trak (cost : 4,000 - 5,000 Euro (~\$5,000- \$6300), particle size range : from 1 micron to 20 nm, maximum concentration 5×10^5 particles/cc) http://www.tsi.com/Product.aspx?Pid=18 or o CPC 3007 (cost: 6,000 Euro (~\$7500), particle size range: from 1 micron to 10 nm, maximum concentration 1×10^5 particles/cc). TSI make a range of condensation particle counters: http://www.tsi.com/Category.aspx?Cid=163
	Optical Particle Counter	The optical particle counters are not appropriate for measuring number concentration since they are insensitive to particles smaller than approximately 100 nm - 300 nm in diameter.
	Electron Microscopy	Electron Microscopy can be used to provide off-line analysis of samples to measure size-specific aerosol number concentration but this technique would not be suitable for an industrial setting due to the size and cost of the equipment.
CONCLUSION	The SMPS is selected over the ELPI and CPC as the most appropriate monitoring equipment for number concentration due to it providing a full size distribution in a short period of time. The only disadvantages are the expense of the SMPS is greater than the ELPI. Also the SMPS utilizes a radioactive source (Kr 85) which the manufacturer holds a US NRC general license. The purchaser will need to verify with their state and local agencies to determine if additional registrations or licenses are required. The CPC is also worth mentioning due to it being a very cheap and easy to use piece of equipment which will allow nanoparticles to be detected and the overall number concentration measured.	

Table 3. Air monitoring equipment suitable for measuring Surface Area Concentration.

RATING	DEVICES	REMARKS
1	Diffusion Charger	<p>The Diffusion Charger provides a real-time measurement of aerosol active surface-area. The diffusion charger measures the charge on the particles and then determines the surface area for nanoparticles in the range of 10 nm to 800 nm,</p> <p>Note: Active surface-area does not scale directly with geometric surface-area above 100 nm. Also not all commercially available diffusion chargers have a response that scales with particle active surface-area below 100 nm.</p> <p>Diffusion chargers are only specific to nanoparticles if used with an appropriate inlet pre-separator.</p> <p>Cost 6,000 -7,000 Euro (~\$7500 - \$8800).</p>
2	Electrical Low Pressure Impactor (ELPI)	<p>The ELPI provides a real time size-selective (aerodynamic diameter) active surface-area concentration. It is also possible to further analyse size-selected off-line. The ELPI has a wide size range from 7 nm to 10 microns.</p> <p>Note: Active surface-area does not scale directly with geometric surface-area above 100 nm.</p> <p>The ELPI cost: 55,000 Euro (~\$70,000).</p>
3	Electron Microscopy	<p>Electron Microscopy can be used to provide off-line analysis of samples and can provide information on particle surface-area with respect to size and the morphology (shape) of the particles. TEM analysis provides direct information on the projected area of collected particles, which may be related to geometric area for some particle shapes.</p>
	Scanning Mobility Particle Sizer (SMPS)	<p>The SMPS provides a real time size-selective (mobility diameter) number concentration. The data may then be used to estimate the aerosol surface-area. This estimate is typically based on assuming the particles are spherical.</p> <p>The SMPS cost: 45,000 - 70,000 Euro (~\$57,000 - \$88,000).</p>
	SMPS and ELPI used in parallel	<p>The combined use of the SMPS and ELPI allow the differences in measured mobility and aerodynamic diameters to be used to infer particle fractal dimension, which can be further used to estimate surface-area. This provides an estimate which is based on assuming the particles are spherical.</p>
	TSI Model 3550 surface area monitor	<p>The Model 3550 Nanoparticle Surface Area Monitor is a recently launched marketed as an instrument to measure the surface area of particles deposited in different regions of the lung. It is marketed as providing a simple and fast solution for measuring the surface area –dose relationship. The scientific community are still uncertain as to the value of this new device.</p> <p>http://www.tsi.com/Product.aspx?Pid=262</p>
CONCLUSION	<p>The Diffusion Charger is selected as the most appropriate monitoring equipment for measuring surface area since it provides a real time measurement over a wide detection range. It is also considerable less expensive than the ELPI and could be made battery driven and be quite portable < 5 kg. Once it is tested more widely, the TSI model 3550 may or may not prove to be the instrument of choice for measuring surface area.</p>	

Table 4. Equipment suitable for Particle Collection.

RATING	DEVICES	REMARKS
1	Thermal precipitator & size selector	<p>The thermal precipitator and size selector can be used for collecting samples. The HSL (UK) are in possession of one of these. VTT (Finland) also have techniques and equipment to allow the collection of nanoparticles to allow off-line measurements.</p>
2	Collection of charged particles.	<p>The Nanometer Aerosol Sampler (NAS) allows you to sample charged particles, like those from the output of a Differential Mobility Analyzer (DMA), onto sample substrates for further analysis. A commercially available example is linked below.</p> <p>http://www.tsi.com/Product.aspx?Pid=84</p>
3	Cascade Impactors	<p>Cascade Impactors (see table 1) can also be used to collect samples for subsequent observation and analysis.</p>

Table 5. *Equipment suitable for **Particle Characterisation**.*

RATING	DEVICES	REMARKS
1	Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM)	Off-line analysis. Electron microscopic analysis (SEM and TEM) may be used to characterize particles according to structure, size and morphology.