Nanoscale Materials

Evaluating an air monitoring technique

By Tracy L. Zontek, Burton R. Ogle and Randall Ogle

NANOTECHNOLOGY is an expanding field that involves the manipulation of materials practically on an atomic scale. The properties of materials at the nano (10^{-9} meter) scale are different than what has been traditionally documented; the laws of quantum physics take over.

This technological revolution has created exciting new opportunities in fields such as medicine, dentistry, materials science, electronics, optics, energy, hazardous waste processing and many consumer products. Springston (2008) provides an overview of the occupational safety and health challenges of nanotechnology. The purpose of this study was to evaluate an air monitoring protocol (DOE, 2007) adopted by DOE's Nanoscale Science Research Centers (NSRC) for use during research and development processes that use nanoscale materials. Since no OSHA or NIOSH analytical reference method for nanoparticles is available and given the lack of standards or regulations for safe levels of nanoparticles, basic industrial hygiene concepts and instrumentation were used to determine whether nanoscale materials were being released and to ensure that controls were adequate.

Toxicology

Nanoparticles are defined as those *engineered* materials that have at least one dimension of 1 to 100 nanometers (nm). Ultrafine particles, typically smaller than 100 nm, are created incidental to processes (e.g., combustion); nanoparticles, while of similar size, are defined as those created intentionally (NIOSH, 2006).

Since nano-sized materials may exhibit different characteristics than larger materials with the same chemical composition, the health effects from nanoparticles may not be the same. In the realm of safety and health, nanoscale materials must be considered of unknown toxicity, and practitioners must apply the precautionary principle. This principle assumes that materials of unknown toxicity are both acutely and chronically toxic, thus asserting a conservative approach and minimizing employee exposure (National Academy of Sciences, 1993).

This monitoring approach relies on current chemical and toxicological data as a starting point, while recognizing that nanoscale materials may enter the body and cause systemic effects in unique ways. For example, it has been suggested that nanoparticles can enter intact skin (Tinkle, Antonini, Rich, et al., 2003; Ryman-Rasmussen, Riviere & Monteiro-Riviere, 2006); travel to the brain via the olfactory nerve (Oberdörster, Sharp, Atudorei, et al., 2004; Oberdörster, Oberdörster & Oberdörster, 2005); and easily enter the bloodstream through the respiratory system and translocate to other organs (Takenaka, Karg, Roth, et al., 2001; Nemmar, Hoet, Vanquickenborne, et al., 2002; Oberdorster, Sharp, Atudorei, et al., 2002).

Nanoparticles can cross cell membranes and interact with subcelluar structures thus impairing function (Moller, Hofer, Ziesenis, et al., 2002; Moller, Brown, Kreyling, et al., 2005; Li, Sioutas, Cho, et al., 2003; Geiser, Rothen-Rutishauser, Kapp, et al., 2005). The toxicity of ultrafine or nanoscale materials can be greater than that of the same mass of larger particles, as demonstrated in both cell culture and rodent experiments (Oberdörster, Ferin, Gelein, et al., 1992; Oberdörster, Ferin & Lehnert, 1994; Oberdörster, Ferin, Soderholm, et al., 1994; Lison, Lardot, Huaux, et al., 1997; Tran, Buchanan, Cullen, et al., 2000; Brown, Wilson, MacNee, et al., 2001; Duffin, Tran, Clouter, et al., 2002; Barlow, Clouter-Baker, Donaldson, et al., 2005).

When working on a nanoscale, particle characteristics such as solubility, shape, surface chemistry, surface area and others may influence toxicity more strongly than mass alone (Oberdörster, et al., 2005; Duffin, et al., 2002; Maynard & Kuempel, 2005;

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Donaldson, Aitken, Tran, et al., 2006). In particular, increased surface area, valued in materials sciences and nanotechnology applications, may create emerging toxicological impacts that have not been seen in these materials previously.

Studies have suggested that insoluble ultrafine particles are more toxic than larger materials, resulting in adverse biological outcomes such as inflammation, tissue damage and possibly lung tumors (Oberdörster, et al., 1992; Oberdörster, Ferin, Lehnert, 1994; Oberdörster, Ferin, Soderholm, et al., 1994; Lison, et al., 1997; Tran, et al., 2000; Brown, et al., 2001; Duffin, et al., 2002; Barlow, et al., 2005; Lee, Trochimowicz & Reinhardt, 1985; Oberdörster & Yu, 1990; Heinrich, Fuhst, Rittinghausen, et al., 1995; Renwick, Brown, Clouter, et al., 2004).

Despite the initiative to synthesize individual nanoscale materials, they typically do not remain as discrete nanoparticles; instead, agglomeration takes place. Johnston, Finkelstein, Mercer, et. al, (2000), and Oberdörster, Oberdörster and Oberdörster (2005) demonstrated that aged polytetrafluoroethylene (PTFE) fume was much less toxic than freshly generated fume due to an increase in particle size (agglomeration) and changes in surface chemistry. Although PTFE is not a freely engineered nanoparticle, it is likely the changes in size and toxicity provide a parallel.

Industrial Hygiene

With limited toxicological information, no OSHA permissible exposure limit or other guideline (ACGIH, NIOSH) to evaluate exposure, and with nanoparticles exhibiting properties that may enter the body much more easily than other materials, SH&E professionals must draw on established principles and take a conservative approach to ensure that employees are adequately protected. As with all contaminants, it is essential that levels of freely engineered nanoscale materials be determined and controlled to reduce exposure in the workplace.

Traditional industrial hygiene measurements of particles are typically mass-based; current research suggests that surface area, activity and particle count may be more accurate measurements to avoid toxicological effects (NIOSH, 2006). Inhalation is the most common route of exposure for airborne particles and the amount of deposition in the respiratory system is determined by the particle's aerodynamic diameter.

In a discrete unagglomerated form, nanoparticles have small aerodynamic diameters and, thus, can move into the alveolar region of the lungs. Nanoparticles that have agglomerated tend to have larger aerodynamic diameters, causing them to deposit in the nasopharyngeal or tracheo-bronchial region. When considering deposition in the lungs, a useful parameter to measure is the particle size distribution of the nanoaerosol.

Particles can be chosen on a size-selective basis via use of cascade impactors or cyclones, and this method may be particularly insightful if the fraction collected on the smallest stage can be analyzed with microscopy. For example, when performing industrial hygiene monitoring with a cyclone, the respirable portion of the aerosol is captured on a filter. The filter (polycarbonate or mixed cellulose ester) can then be analyzed with electron microscopy to see particle size and shape, and compare the air sample against a bulk sample of the actual material. Rickabaugh and Ogle (2009) provided an overview of this sampling strategy and electromicrographs of naturally occurring and engineered nanoscale materials. Due to the fact that a large fraction of inhaled nanoparticles will deposit in the alveolar region of the lungs (Keskinen, Pietarinen & Lehtimaki, 1992), air monitoring methods that capture the respirable fraction (less than 10 µm) of the aerosol distribution should be used; however, it does not give safe or unsafe levels.

Gravimetric analysis (mass of respirable samples) can capture nanoparticles; however the mass of nanoparticles is negligible. Further, the known toxicity of materials is based on the health effects of larger particles and the current OSHA standards are likely many times greater than the amount of mass collected for nanoparticles. Since nanoscale particles may have different characteristics than their bulk material, a mass measurement can estimate how much potentially entered the lungs, but not its toxicological impact. It is important to document respirable employee exposure to correlate with toxicological data in the future; however, it provides little immediate quantitative information.

Types of Monitors

To overcome that lag time between taking measurements and receiving results, it is desirable to use a direct reading aerosol monitor to determine the particle size distribution or count. Many commercially available monitors do not accurately measure particles less than 300 nm, the size that potentially may affect human health by entering into the deep alveolar region of the lung and traveling systemically throughout the body.

The best resolution can be obtained from the scanning mobility particle sizer (SMPS); however, its size, radioactive source and cost are prohibitive for most workplaces. An electrical low pressure impactor (ELPI) is another option; it determines aerosol size distributions by aerodynamic diameter using a corona charger and can preserve particles for further analysis (Brouwer, Gijsbers & Lurvink, 2004). These instruments are ideal for taking area measurements but are not personal monitoring devices due to their large size and limited mobility.

Location of the instrument and time affect the measured concentration and aerosol size distribution when using an SMPS and ELPI (Ku & Maynard, 2005); therefore, instrument placement during air monitoring and interpretation of results should be carefully considered. For example, sampling results may vary significantly if the instrument is placed 1 ft from the process versus 5 ft away due to factors such as air currents and agglomeration of nanoscale materials.

Surface area is an increasingly important indicator for toxicological implications; however, it is not routinely measured in the field of industrial hygiene. The epiphaniometer can measure Fuchs (active) sur-

Abstract: *The field of nanoscale materials brings great advances and equal concerns about the safety of the materials. A study was conducted to evaluate an industrial hygiene air monitoring protocol for nanoparticles developed by the Department of Energy's Nanoscale Science Research Centers for processes in a research environment. Key data were analyzed, namely, particle count, particle size distribution and morphology that may be linked to toxicological effects with future study.*

In the realm of safety and health, nanoscale materials must be considered of unknown toxicity, and practitioners must apply the precautionary principle.

face area of aerosols by attaching radioactive ions; however, the radioactive source and lack of temporal resolution make it impractical for most workplaces (NIOSH, 2006). Portable aerosol diffusion chargers measure aerosol surface area for particles less than 100 nm, but may underestimate for particles greater than 100 nm (Ku & Maynard, 2006; TSI Inc., 2006). A new instrument uses counter-flow diffusion charging to measure the surface area of aerosols ($\mu m^2/cc$) that reach either the alveolar or tracheobronchial regions of the respiratory system according to the International Commission on Radiological Protection (1994) lung deposition model (TSI Inc., 2006). Surface area estimation is possible if the particle distribution remains constant. Additional research is needed to identify the factors that cause nanoscale materials to agglomerate and deagglomerate and the rate at which each occurs.

Maynard (2003) has developed a calculation to estimate surface area using the number and mass concentration, assuming geometric standard deviation of the lognormal distribution; however, estimates may not be accurate depending on the distribution itself (DOE, 2007).

A condensation particle counter (CPC) is able to grow and detect particles from 10 nm to greater than 1 µm. Although this type of instrument does not give a particle size distribution, it provides real-time concentration of particles, depicted as particles/cc, and can provide immediate feedback to determine whether any material, regardless of size, is being released. NIOSH (2006) suggests using a CPC in parallel with an optical particle counter, using the difference in the counts to determine concentration by size.

NIOSH has proposed a sampling strategy that characterizes nanoparticles to the fullest extent. First, a CPC can be used to identify sources and determine whether engineering controls and work practices are adequate. Transmission electron microscopy can confirm size and distribution of particles. Surface area measurements can be made with a portable diffusion charger. Last, personal air monitoring using a respirable cyclone with particulate being captured on a filter for electron microscopy or other chemical analysis can approximate employee exposure. This strategy is similar to the DOE (2007) NSRC Approach to Nanomaterial ES&H.

To effectively characterize exposure, background measurements must be taken in order to determine whether nanoparticles are becoming entrained in the workplace. Other processes in the area and background particle levels may obscure the measurement of the freely engineered nanoscale materials of interest to the investigator. Further, infiltration of ambient sources of nanoscale materials must be controlled for when determining concentrations. Due to the small mass collected, gravimetric measurements are somewhat limited, and current OSHA or ACGIH limits are not likely to be appropriate or adequately protective. Field observations are essential to link increased concentrations of nanoparticles with specific operations in order to evaluate and control employee exposure.

Study Methods

To obtain background and baseline measurements on work with freely engineered nanoscale materials, researchers were asked to engage in the air monitoring study. The pool was limited to researchers working with freely engineered nanoscale materials during the study time frame. The study followed the protocol published in the NSRC's Approach to Nanomaterial ES&H Attachment 1 as feasible (DOE, 2007). This protocol calls for use of the following equipment: CPC, aerosol spectrometer, active sampling using a high-volume pump and filter, and passive sampling using an SEM stub.

Particle counts (particles/cc) were measured with the CPC (TSI model 3007). Following manufacturer guidelines, the CPC contained fresh isopropyl alcohol, completed a 600-second start-up, and was checked with a zero filter prior to each study. The CPC flow rate was initially checked with a DryCal primary standard. The instrument can measure particles from 0.01 to greater than 1 µm with a concentration range of 0 to 100,000 particles/cc. The CPC was run in log mode 1 (output every 1 second) and output signal recorded with software that is included.

The aerosol spectrometer used was a GRIMM SubMicron Aerosol Spectrometer (GRIMM Technologies model 1.108). It can measure particle size ranges in 15 channels ranging from greater than 0.3 µm to greater than 10 µm, with a count range from 1 to 2 million counts per liter. It was run with output averaged over 1 minute and output signal recorded and analyzed using manufacturer software.

The air sampling train was created based on ASTM D 6095, Standard Test Method for Determining Airborne Single-Crystal Ceramic Whiskers in the Workplace Environment by Scanning Electron Microscopy (ASTM, 2001). The sampling train was assembled using a 25 mm electrically conductive cassette assembly with an extension cowl containing a 0.1 µm nucleopore filters and support pad. The filter assembly was suspended open-face and upside down at approximately 45°, as described in ASTM D 6059 and NIOSH Method 7402, Asbestos by TEM (Schlecht & O'Connor, 1994).

A passive air monitor, consisting of a scanning electron microscope stub (mesh grid made of copper), a collection substrate and a protective mesh cap, was used to provide information on morphology and chemical composition. The passive sampler can yield particle concentration and size distribution (Wagner & Leith, 2001; Wagner & Macher, 2003; Maynard, Baron, Foley, et al., 2004). The filters from the active sampling and passive monitoring were analyzed by the RJ Lee Group using electron microscopy.

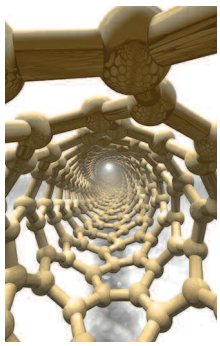
Study Results

A total of eight research groups were working with freely engineered nanoscale materials during the study time frame; one researcher was monitored twice using the same material in different amounts, resulting in nine sampling campaigns. Only one process warranted the use of the entire sampling protocol.

Table 1

Results of the CPC Air Monitoring

Sampling campaign	Location/activity	Range (p/cc)	Mean (p/cc)	Median (p/cc)	*SD* (p/cc)	Total time (s)
1	Room background	1789 - 2438	2070	2033	164.38	66
1	Placing nanomixture (Less than 1 g TiO_2 mixture) into u-tube reactor	1645 - 2362	1789.76	1736	94.99	151
1	Removing materials from previous u-tube that was removed from reactor	1397 - 1984	1564.97	1534	117.98	91
1	Background taken deep in hood	2007 - 2924	2391.99	2517	151.33	120
1	Preparing catalyst, weighed 1 g TiO_2 and placed in hood with stir bar	1374 - 3192	2337.78	2474.5	496.87	120
2	Room background	10100 - 11798	11226.93	11273.5	340.95	120
2	Transferring carbon nanotubes (less than 50 g) from boat into container, in hood	10595 - 12416	11242.99	11254.5	254.59	180
2	Determining if nanoparticles are emitted from previous samples by opening storage containers and moving them around, completed in hood	9383 - 12631	10949.01	11062	563.16	780
3	Room background	3387 - 4420	3776.3	3715.5	190.82	482
3	Cleaning graphite die and transferring nanotubes (< 50 g) into die, completed in hood	3911 - 4780	4420.55	4398	114.1	277
4	Room background	4651 - 5125	4869.95	4878	90.75	120
4	Preparing hot press	4408 - 5099	4815.04	4819.5	104.71	240
4	Placing die in hot press, nanomaterial packed in die. Spike occurred when door to hot press was opened. The nanomaterial being measured was not the cause of this spike.	4640 - 7904	6077.32	6155.5	488.67	360
5	Room background	970 - 1344	1214.19		50.58	426
5	Grinding 1 g BaF in hood	1161 - 1929	1580.73	1581.5	164.38	540
5	Hood background	1481 - 1887	1665.16	1666	78.83	145
6	Room background	1684 - 2221	1969.71	1985	97.05	119
6	Preparing material (1 g BaF) for X-ray diffraction	1713 - 2432	2103.9	2111	116.88	480
7	Room background	5367 - 6402	5866.47	5825	264	79
7	Followed PI who moved quartz tube from CVD to hood, transferred approximately 70 g of carbon nanoscale materials (with metals) from boat into container, then broke carbon nanoplates to determine if particles were generated. No spikes were noted.	4134 - 6606	5509.254	5685	588.83	747
8	Room background	1174 - 1327	1243.11	1245	29.7	171
8	Preparation of the slurry on a single crystal silicon plate for X-ray diffraction. ZnS (1 g) and MeOH mixed together in this process.	1131 - 1353	1227.12	1226	38.46	518
8	Removing sample from XRD	1083 - 5470	1373.24	1356	259.13	665
9	Cleanroom area of room 217, room background	0 - 53	5.33	2	10.08	60
9	Dismantling enclosure, removing robot (quartz tube containing nanohorns is closed)	0 - 105	26.17	27	15.79	300
9	Quartz tube opened on one end, nanohorns scraped from sides and 3M vacuum used at other end to force material into collection chamber (HEPA filter). Use of 3M vacuum caused numerous spikes.	6 - 85185	1312.246	26	6114.613	840
9	Using Nilfisk HEPA vacuum and methanol soaked Kimwipes to clean quartz tube and other parts	0 - 49	26.25	27	8.71	900
9	Removing collection chamber which contains nanohorns on a HEPA filter	5 - 36	16.21	15	6.14	180
9	Cleaning parts used to connect collection chamber to quartz tube using methanol soaked Kimwipes and Nilfisk HEPA vacuum	8 - 46	26.54	23	7.64	480
9	Placing collection device, tools, and container in glove bag (takes place in laminar flow hood)	6 - 35	19.53	17	5.85	240
9	Glove bag sealed, harvesting nanotubes takes place in glove bag, in laminar flow hood	4 - 51	28.13	29	6.37	1200
9	Glove bag opened, as items removed they are wiped with methanol soaked Kimwipe and Nilfisk vacuum	10 - 242	36.82	26	23.49	300
9	Glove bag taped shut and final clean up takes place	6 - 171	26.11	17	14.37	660



Since nanoscale particles may have different characteristics than their bulk material, a mass measurement can estimate how much potentially entered the lungs, but not its toxicological impact.

The CPC was used in all air monitoring campaigns to determine whether particles were being released and to assess the need for the full air monitoring protocol. Table 1 (p. 37) provides the results of the CPC data, relevant background measurements, materials and processes. It is important to note that monitoring took place at the source of the nanoscale materials, not the employee breathing zone. Only air monitoring campaign #9 yielded results that were outside of background measurements.

For the purposes of this study, unacceptable measured concentrations were those greater than the mean plus three times the standard deviation of the background sample. This strategy was chosen as a starting point to determine whether a release of particles actually occurred and to account for background levels in the room or facility. This strategy cannot be easily applied while monitoring is taking place; the industrial hygienist must monitor the levels and more qualitatively determine whether airborne particle concentrations have spiked above background levels. It was critical to observe activities and work practices during sampling.

For each sampling campaign, the measured background is listed, as is the specific activity that took place during the air monitoring. In addition, researchers' work practices were observed. In sampling campaign #9, the data obtained from the aerosol spectrometer indicated that the particle size distribution was primarily between 300 and 500 nm, with 300 nm being the lower limit of detection for this instrument. These results are reported in Figure 1.

The SEM images indicated that there were no discrete nanohorns; only amorphous carbon was found. Due to the HEPA vacuum emissions, these data are inconclusive at best.

In addition to air monitoring performed while freely engineered nanoscale materials were being used, additional area background measurements were taken using the CPC in areas of current or future work performed with nanoscale materials. The purpose of these measurements was to document background particulate concentrations using the CPC. These results are expressed in Table 2.

Discussion

This discussion focuses on the use of the instruments in the protocol as well as lessons learned from implementing the protocol.

The CPC was extremely effective to identify background levels and spikes due to particle generating processes in the research environment. The instrument is easy to use as long as it is consistently held in a horizontal position to avoid flooding the optics. For data to be useful, a background particle concentration must be carefully recorded prior to initiation of research processes. A room background, as well as chemical hood background, should also be taken with conditions similar to those that will be used during research processes (e.g., other equipment that may be used in room or hood, hood sash height).

The CPC used was capable of data logging. It is advisable to log each activity for which data will be analyzed separately. This facilitates development of graphs and descriptive statistics. It is important to note that spikes (increases in particle concentration above background level) were seen due to doors opening/closing, heating processes (e.g., the furnace) and other equipment present in the room. These can be excluded from calculations if there is no chance the particles are ambient freely engineered nanoscale materials. Logging each research activity individually also allows these spikes to be avoided when data are analyzed.

When data logging, task level data should be recorded temporally in order to correctly interpret data. It is also advisable to record actual conditions in photos or video. In most cases, this type of monitoring will require two people to complete effectively. Synchronization of time on all instruments also facilitates data analysis.

The CPC was not used to collect employee exposure data; rather it identified any release of nanoscale particles at the source. This is a departure from traditional industrial hygiene monitoring. Since there are no OSHA, NIOSH, ACGIH or other limits for nanoscale materials forthcoming, a departure from background concentrations is necessary to identify releases and determine how to control them. Because of the CPC's size and the need to keep it horizontal, it is not likely an instrument that will be adapted to collect employee breathing zone samples.

Brouwer, Gijsbers and Lurvink (2004) report that comparison of CPC and SMPS data over time indicates an association between number concentration of particles in the ultrafine range for welding fume tested in the workplace and laboratory. Ku and Maynard (2006) also note the total number concentration should be considered carefully as agglomeration takes place and SEM revealed single particles were rarely present. Similar to Brouwer, et al.'s study, this study found an association between GRIMM data and CPC concentrations, although the GRIMM was stationary and the CPC was moved to the worst-case scenario for release of nanoscale materials.

Use of the monitors together allowed for real-time discovery of spikes with no regard to particle size (CPC) and later analysis of the particle size distribution (GRIMM). Further, analysis of SEM stub revealed no nanoscale materials, an additional confirmation of the controls and work practices currently in place.

The GRIMM provided particle size distribution but did not measure particles less than 300 nm. Maynard, et al. (2004), found that single-walled carbon nanotubes created via laser ablation were tight structures that are difficult to break down. Since nanoscale materials have the propensity to agglomerate, this size discrimination may be adequate. The utility of the GRIMM data particle size distribution can help predict lung deposition and potential health effects, as well as control methodologies. It is a stationary direct reading instrument that can be affected by movement and surrounding processes. Along with the differences in cut rate, the data collected from the GRIMM may differ from that collect-

ed from the CPC due to temporal and spatial differences, as noted by Brouwer, et al. (2004).

Active and passive air samples with electron microscopic analysis can provide confirmation of particle size distribution, morphology and count. These data are invaluable to confirm other air monitoring results and determine whether contaminants are from a research process, discrete or agglomerated nanoscale materials, or the result of other research processes or anthropogenic particles.

In all instances, placement of analytical detection equipment will affect sampling results. An effort was made to place equipment as close to the research as possible without interfering or creating safety hazards.

It was interesting to note that particle spikes were found due to unanticipated equipment issues (e.g., use of a HEPA vacuum that did not have an enclosed motor, a heat exchanger on laser enclosure, heating of furnaces, doors opening/closing). Engineering controls and work practices were effective overall, as depicted by the lack of particulate spikes in the data.

Application of this protocol in research settings is well founded; however, the amount of equipment, time and labor may be limiting for some organizations. In addition, its use in a manufacturing environment is likely to be severely hampered due to confounding measurements from surrounding equipment and processes (e.g., welding, grinding, cutting) that may create particles. A strong understanding of process and background measurements is necessary to correctly interpret data.

Figure 1

Concentration of 300-500 nm Particles

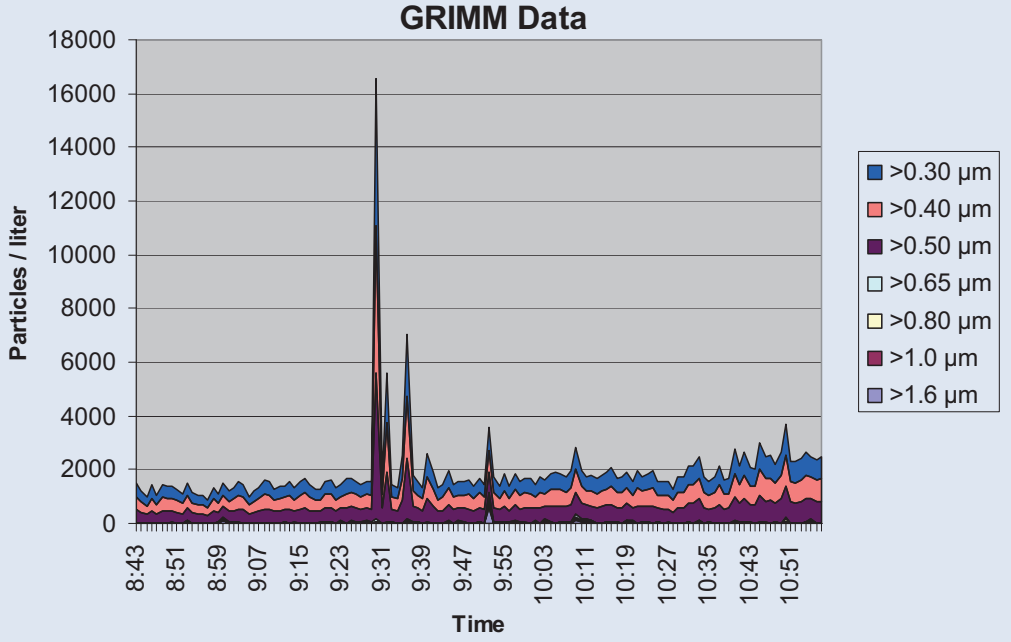


Table 2

Background Measurements

Building	Location	Range (p/cc)	Mean	*SD*	Time (s)
1	Ground floor - main entrance	6330 - 8260	7360	413.2	571
1	First floor	484 - 6830	1270	889.9	8318
1	First floor in empty research lab	2750 - 4390	3700	272.8	9706
1	Second Floor	665 - 3200	1530	413.3	10328
1	Third floor	673 - 3250	1710	583.9	20512
2	First floor - XRD lab	1174 - 1327	1243	29.7	171
2	First floor TEM lab, in laminar flow hood	4 - 897	399	199	605
2	First floor SEM lab	4344 - 6182	5596	249.42	705
2	First floor SEM lab	7995 - 13051	10938	903.73	559

For each sampling campaign, the measured background and the specific activity that took place during the air monitoring were noted. Researchers' work practices were also observed. Additional area background measurements were taken as well.

Conclusion

The industrial hygiene ambient air monitoring collected key data that may link to toxicological studies, namely, particle count, particle size distribution and morphology. Identification and control of any possible peaks or releases of nanoscale particles can be accomplished with this protocol. Background sampling is necessary to understand the existing aerosol structure in the workplace. The CPC is a portable, real-time instrument that allows identification of particle releases and effectiveness of control methodologies, although it can be limited by particle size. The GRIMM provides real-time, albeit stationary, aerosol size distributions while the passive dosimeter and active sampling along with electron microscopy can confirm morphology, count and materials.

Future study should attempt to replicate the air monitoring protocol and question its assumptions and value for industrial hygiene assessment. In addition, due to the large surface area of nanoscale materials and possible correlation to toxicological studies, other technology should be employed to measure particle surface area. Use of an electrostatic or thermal precipitator should also be investigated to attract particles onto collection media. ■

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Learning Roadmap

- Nanoscale materials may exhibit chemical and physical properties and potentially health effects that are different than the bulk parent material.
- Airborne concentrations of nanoscale materials can be measured using direct reading instruments and through integrated sampling.
- These techniques are useful to identify releases and characterize the aerosol, as well as to minimize airborne concentrations through typical industrial hygiene controls.
- Background measurements (there is always some concentration of particles in the air) must be understood in order to identify when there is a potential release of nanoscale materials.
- Sampling instruments used included a condensation particle counter (CPC) (real-time particle concentration), aerosol spectrometer (provided aerosol size distribution), integrated air monitoring with high-volume pump and passive dosimeter.
- CPC was most useful to quickly identify potential releases and correlate activities to airborne concentration.
- Releases were identified from unenclosed HEPA vacuum motor and other process equipment; work practices (glove bags, wet methods) by researchers were effective.
- Electron microscopy is ultimately needed to determine whether methods have captured and measured nanoscale materials or larger particles.

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