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ABSTRACT

Current recommendations for nanomaterial-specific exposure assessment require adaptation in order to be applied to complicated manufacturing settings, where a variety of particle types may contribute to the potential exposure. The purpose of this work was to evaluate a method that would allow for exposure assessment of nanostructured materials by chemical composition and size in a mixed dust setting, using carbon black (CB) and amorphous silica (AS) from tire manufacturing as an example. This method combined air sampling with a low pressure cascade impactor with analysis of elemental composition by size to quantitatively assess potential exposures in the workplace. This method was first pilot-tested in one tire manufacturing facility; air samples were collected with a Dekati Low Pressure Impactor (DLPI) during mixing where either CB or AS were used as the primary filler. Air samples were analyzed via scanning transmission electron microscopy (STEM) coupled with energy dispersive spectroscopy (EDS) to identify what fraction of particles were CB, AS, or ‘other’. From this pilot study, it was determined that ~95% of all nanoscale particles were identified as CB or AS. Subsequent samples were collected with the Dekati Electrical Low Pressure Impactor (ELPI) at two tire manufacturing facilities and analyzed using the same methodology to quantify exposure to these materials. This method confirmed that CB and AS were the predominant nanoscale particle types in the mixing area at both facilities. Air concentrations of CB and AS ranged from ~8900 to 77600 and 400 to 22200 particles cm⁻³, respectively. This method offers the potential to provide quantitative estimates of worker exposure to nanoparticles of specific materials in a mixed dust environment. With pending development of occupational exposure limits for nanomaterials, this methodology will allow occupational health and safety practitioners to estimate worker exposures to specific materials, even in scenarios where many particle types are present.

KEYWORDS: amorphous silica; carbon black; cascade impactor; exposure assessment; nanomaterial
INTRODUCTION
Nanomaterial use in industrial settings is rising as the advantages of nanomaterials are better understood (Murashov et al., 2012). Nanotechnology offers an enormous potential to companies looking to gain an advantage by incorporating materials that offer improved efficiency, reduced natural resource consumption, or other advantages, and therefore there is a strong impetus to develop new nanomaterials. Consequently, research and development in this field is outpacing research on how to understand health risks associated with exposure to newly developed materials.

In particular, methods for nanomaterial exposure assessment in industrial settings required further development (Bleeker et al., 2013; Kreider et al., 2013; Gordon et al., 2014). Though various researchers and regulatory agencies have published guidelines for exposure assessment of nanomaterials (Methner et al., 2010a, 2010b; NIOSH, 2009; OECD, 2009; Consensus Report, 2011; Ramachandran et al., 2011), most of this guidance lacks recommendations on how best to quantify potential worker exposure to specific materials. Existing strategies focus on conducting screening level exposure assessments, such that ‘hot spots’ for worker exposure are identified, followed by qualitative evaluation of the nature of the exposure (e.g. via microscopy) (Methner et al., 2010a, 2010b; Ramachandran et al., 2011; Consensus Report, 2011), an approach that is also reflected in the currently available scientific literature (Kuhlbusch et al., 2004; Schmoll et al., 2010; Debia et al., 2012; Koivisto et al., 2012; Raynor et al., 2012; Dahm et al., 2013; Kim et al., 2013; Shepard and Brenner, 2014). This paradigm, while currently the best available, does not offer the ability to quantify worker exposure to individual particle types, such as would be necessary if size-specific occupational exposure limits (OELs) were developed for nanomaterials. Furthermore, researchers have noted that changes in particle counts from real-time monitoring can be confounded by alternative sources of particulate, potentially leading to misinterpretation (Kuhlbusch et al., 2004; Shwe et al., 2005; Peters et al., 2009).

The types of sampling equipment commonly recommended for use in nanomaterial exposure assessment have been reviewed elsewhere (Kuhlbusch et al., 2011; Kreider et al., 2013). As indicated by Kuhlbusch et al. (2011), to execute a tiered sampling strategy, a combination of equipment is required to understand the potential for exposure because of limitations on equipment capabilities that prevent complete characterization of exposure. For example, particle counters, while able to provide particle counts for a given size range, cannot distinguish between particle types. Conversely, traditional air sampling equipment can collect samples for off-line chemical analysis, but are often ill-equipped to separate particles by size in the nanoscale.

Chemical speciation by size is a desirable characteristic for nanomaterial exposure assessment, particularly in the case of mixed dust environments like industrial manufacturing settings. Previously, most nanoparticle exposure assessment has been conducted in laboratory environments where there is a single material of interest. However, in industrial settings, background concentrations of particulate can be high, and identifying ‘hot spots’ for potential nanomaterial exposure using particle counters and other equipment is limited due to (i) inability to measure relatively small temporal or spatial changes in nanoparticle concentration relative to high background particulate concentrations and generalized mixing in the industrial facility and (ii) challenges identifying a relevant or applicable background concentration, (Iavicoli et al., 2013; Kim et al., 2013). Particle counters are thus more readily applicable to scenarios where background particle concentrations are lower and/or only specific isolated activities result in particulate release. To attempt to bridge the gap between existing methods and desired quantitative exposure assessment outcomes, this study aimed to develop a methodology to quantitatively evaluate nanoparticle exposure in a mixed dust environment, using the tire manufacturing environment as an example.

This effort first required the evaluation and implementation of a sampling methodology that would allow for quantitative measurement of particles by type and size at a tire manufacturing facility. Tire manufacturers use nanostructured materials, specifically carbon black (CB) and amorphous silica (AS), as fillers in tires. Tire manufacturing facilities contain multiple types of particulate aside from CB and AS, including rubber fume, rubber dust, and particulate from other process-related operations and the indoor environment (Williams et al., 1980; Heitbrink and McKinnery, 1986; Dost et al., 2000). Both CB and AS have primary particles found in the nanoscale,
although these particles aggregate and agglomerate such that agglomerate size is much larger than 100 nm (Table 1) (Rwei, 1991; Donnet et al., 1993). It is acknowledged that the intermolecular bonds formed within agglomerates resist breaking except under conditions of extreme sheer forces (ASTM, 2013). Therefore, it was hypothesized that workers at tire manufacturing facilities would not be exposed to nanoscale particles of CB or AS. To investigate this hypothesis, a sampling methodology able to size fractionate airborne particles and provide a substrate on which to collect them for speciation is required; particle counting alone would be insufficient.

The selected methodology to address this question paired the use of a cascade impactor, to size-fractionate particles, with electron microscopy and energy dispersive spectroscopy (EDS) to identify the chemical composition of particles by size. This proposed combined methodology was first pilot-tested (Phase 1) in a single manufacturing facility to assess whether the sampling and analytical method could generally be used to quantify the relative proportion of collected nanoparticles, including particles of interest and incidental particles. In Phase 2, the proposed methodology was used to estimate chemistry-specific nanoparticle number concentrations by size.

**METHODS**

**Sampling and analytical method selection**

A low pressure cascade impactor (LPI) was selected to assess nanoscale CB and AS exposure. LPIs separate particles based on inertia, and collect the particles onto substrates placed on stages that correspond to a particular size range. An impactor was selected as the best instrument because it can both separate nanoparticles from larger particles, and also allow for offline analysis of the substrates to distinguish CB and AS from other particles present the environment. Based on equipment availability, Phase 1 of the study utilized a Dekati Low Pressure Impactor (DLPI; Dekati Ltd., Tampere, Finland) and Phase 2 utilized the Dekati Electrical Low Pressure Impactor (ELPI).

To characterize nanoparticle exposures in environments where multiple sources exist, it is essential to obtain chemical and morphological data on measured particulate. Scanning transmission electron microscopy (STEM, Hitachi S-5500) was chosen as the analytical method because it allows for a more complete characterization than either scanning electron microscopy or transmission electron microscopy alone. STEM was coupled with EDS to identify chemical composition of the particles identified via microscopy.

**Phase 1 sampling: qualitative evaluation of potential exposure to nanoscale CB and AS**

Phase 1 sampling was conducted at a tire rubber compounding facility using the DLPI. This instrument collects particles up to ~10 µm based on inertial impaction and deposits them onto 13 size-specific stages, including three stages in the nanoscale (D50s of 108, 60, and 30 nm). Twenty-five millimetre diameter polycarbonate foil substrates were placed on each stage per manufacturer specifications. The purpose of this initial sampling was 2-fold: (i) to test whether the selected LPI with polycarbonate foil substrates could be combined with the STEM analysis to estimate the fraction of specific particle types collected on each stage, (ii) to verify that the sampling times, chosen based on airborne particle concentrations, would lead to appropriate particle loading on the substrates.

Because CB is essentially elemental carbon (EC), it was important to minimize potential for interference with other EC sources in the facility. To that end, the facility selected for the study used only electric forklift trucks during the study period; no other significant sources of diesel exhaust were evident.

A DustTrak™ aerosol monitor (TSI Incorporated, Shoreview, MN, USA) was also used to monitor real-time mass concentrations, with particle cut size of

<table>
<thead>
<tr>
<th>Material</th>
<th>Primary particle size (nm)</th>
<th>Aggregate size (nm)</th>
<th>Agglomerate size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amorphous silica, precipitated</td>
<td>2–40</td>
<td>100–500</td>
<td>1000–40 000</td>
</tr>
<tr>
<td>Carbon black</td>
<td>5–100</td>
<td>70–500</td>
<td>10 000–100 000</td>
</tr>
</tbody>
</table>

Table 1. Summary of physical dimensions of carbon black and amorphous silica structures.
10 µm during sampling to determine appropriate sampling durations. In addition, respirable dust samples were collected and analyzed as described in NIOSH 7500, to determine whether crystalline silica, a potential confounder for AS, was present at the facility.

Four samples were collected using the DLPI, with two each collected during rubber mixing with CB (grades N650 and N772) and AS, respectively, as the primary filler. Raw materials are introduced into the rubber compounding process during mixing and are mixed together in a Banbury mixer under elevated temperature and shear forces (White et al., 2009). The sampling devices were placed on a cart near the mixer operator's station, located ~15–30 feet from the chute where CB and AS were introduced into the mixer. For all sampling locations, there were other nearby operational mixers, though the raw materials introduction was significantly further from the cart than the mixer of interest. Samples were collected using the DLPI for 5–10 min. Local exhaust ventilation was present and operational at the mixer during sampling.

Polycarbonate foil collection substrates were prepared for STEM analysis using ISO method 10312, in which the foils were sectioned, sputter coated with carbon, placed onto TEM grids, and dissolved using acetone. Elemental spectra on ~100 particles per impactor stage were obtained using EDS. Particles were selected for analysis according to the following steps. First, the substrate was scanned at low magnification to identify a suitable area for evaluation (e.g. the filter is fully cleared and the grid intact), after which an area just outside of the impaction spots, where particles or structures are in a clear monolayer with minimal contact, was identified for analysis. An appropriate magnification was selected to identify 15–20 particles or structures within the display. Bright field and secondary images and corresponding EDS spectra for each particle in the field were collected. This process was repeated until 100 structures were analyzed; 100 structures are considered sufficient for characterizing the distribution of fibre types on an air sample based on NIOSH 7400. For each field, a background spectrum was also collected in a location absent of particles to characterize the potential influence from the grid and coating. Each spectrum was analyzed for primary composition and the particles were characterized as CB, AS, or ‘other’. This information was used to calculate the percentage of these particle types collected on each stage.

Phase 2 sampling: quantitative evaluation of potential exposures to nanoscale CB and AS

In Phase 2, the pilot-tested sampling method was used to quantify nanoscale CB and AS exposures by size in the tire manufacturing environment. Phase 2 sampling was performed in the same facility as Phase 1 and a second tire manufacturing facility. At the second facility, sampling was again conducted at the mixer, in a location ~15 feet from the chute where CB and AS were introduced. As with Facility 1, other mixers were operational in the same area, though the exact number of operational mixers at the time of each sample is unknown. Local exhaust ventilation was present and operational during sampling. In Phase 2, the ELPI was used for sampling as it separates and collects particles based on the same principles as the DLPI, and also measures real-time number concentration by charging incoming particles and detecting them using electrometers on each stage. The ELPI has four stages that collect nanoscale particles, (D50s of 108, 60, 30, and 17 nm when flow rate is 10 L/min). Based on the Phase 1 results which confirmed the existence of CB and AS particles in the nanoscale (<108 nm), the quantitative analysis was focused on the smaller stages and therefore, unlike with Phase I, the four largest stages of the ELPI were sprayed using a silicone-based spray (Dekati DS-515) as recommended by the manufacturer to minimize potential particle bounce.

At each facility, four impactor samples were collected, with two collected during CB mixing and two collected during AS mixing processes. All Phase 2 impactor samples were collected for 10 min. Polycarbonate substrates were prepared and analyzed in the same manner as Phase 1 to estimate the percentage of CB and AS particles on each stage. Because the ELPI provides real-time particle number concentration for a given size bin, the size-specific particle number concentrations were used in conjunction with the resulting percentages for each particle type to generate exposure concentration estimates for CB and AS by stage.

RESULTS

Phase 1

The objective of the Phase 1 was to determine if the combination of a cascade impactor with off-line analysis by STEM with EDS could be used to establish proportions of various particle types for each
collection stage. The CB and AS particles collected with the DLPI had distinct spectra and STEM images (Fig. 1A–D). Furthermore, under the established sampling conditions, particle loading was suitable for microscopic analysis.

In all samples collected using the DLPI, CB and AS were the predominant particle types across all size bins (Table 2). CB constituted about 54%, AS 31%, and ‘other’ particles ~15% by number of all analyzed particles collected on stages less than ~10 microns. For analyzed particles collected on the nanoscale stages (e.g. 30, 60, and 108 nm), CB made up 54%, AS 43%, and ‘other’ particles 2% by number of collected nanoparticles. Specific distributions by sample type are detailed in Fig 2A–D. Both CB and AS were observed in all four samples, in spite of noted use of a primary filler with each sample, likely because the mixers are not isolated in an enclosure and multiple mixers were operational during the air sampling.

Because EDS cannot distinguish amorphous forms of silica from crystalline silica, simultaneous sampling for crystalline silica was conducted. Crystalline silica was not detected (detection limit = 0.006 mg m⁻³), confirming the absence of this material as a confounding source of silicon.

**Phase 2**

Upon determination that CB and AS could be reliably distinguished from other particles and that their proportions could be established, Phase 2 was initiated to assess the extent of worker exposure to nanoscale CB and AS during tire rubber compounding at two facilities. At Facilities 1 and 2, CB and AS were again found to be the predominant particle types in each of the four samples (Figs 3A–D and 4 A–D, respectively). By number, the majority of the particles collected at Facility 1 were in the nanoscale (17–108 nm); of these, CB and AS were identified as the predominant types of nanoparticles. At Facility 2, three of the four samples indicated that the majority of the nanoscale particles were CB and AS, while one sample had greater than 50% of the nanoparticles designated as ‘other’ (Table 3). Nanoscale concentrations of each material type across both facilities are presented in Table 4. Overall, a higher concentration of nanoparticles was detected at Facility 2 compared to Facility 1, with the difference predominantly driven by the greater concentration of ‘other’ nanoparticles at Facility 2 (Fig. 5A,B).

EDS analysis indicated that many of the ‘other’ particles from Facility 2 were iron-rich (Fig. 6). During sampling, it was noted that torch cutting or welding was ongoing ~30 m from the sampling location. Both the chemical composition and morphology of these particles were consistent with that previously seen in welding fume samples (Farrant et al., 1989; Karlsen et al., 1992; Jenkins and Eagar, 2005).

Given the non-detectable results for crystalline silica during Phase 1, sampling for background crystalline silica was only performed during Phase 2 sampling at Facility 2. Results showed that crystalline silica was likewise not detectable at Facility 2, and therefore unlikely to interfere with the identification of AS. Further, staff at Facility 2 confirmed that crystalline silica-containing materials were not used in their process.

**DISCUSSION**

The purpose of this study was to evaluate a novel method to quantitatively estimate exposure to nanoparticles of specific materials in mixed dust environments. The selected method combined the use of the ELPI with data from electron microscopy to estimate air concentrations of materials of interest. The ELPI has recently been used in industrial settings to understand worker exposures, but has yet to be implemented to estimate quantitative exposure to individual materials of interest, as was developed using this method (Debia et al., 2012; Kim et al., 2013). To test the methodology, sampling was conducted in a tire manufacturing facility, an environment with many particle types, (Williams et al., 1980; Heitbrink and McKinnery, 1986; Dost et al., 2000). The focus of the sampling was on detection of AS and CB, nanostructured materials used during rubber compounding. Because these materials aggregate and agglomerate into micron-sized structures, it was speculated that there would be no worker exposure to nanoscale CB or AS. However, using the method developed herein, nanoscale forms of CB and AS were identified near the mixer at concentrations ranging from ~8900 to 77 600 and 400 to 22 200 particles cm⁻³, respectively.

Although impactor sampling typically requires the use of an adhesive to prevent particle bounce from larger to smaller stages, an adhesive could not be used in this study because of interference with STEM analysis. The potential for particle bounce was evaluated...
Figure 1  Representative spectra and images of CB and AS particles. (A) CB spectra (B) CB image (CB particle from 60 nm stage) (C) AS spectra (D) AS image (AS particle from 108 nm stage).
Table 2. Summary of distribution of particles by particle type for all stages and nanoscale stages based on DLPI sampling at Facility 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>% of particles for all stages</th>
<th>% of particles for nanoscale stages*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>53.9</td>
<td>54.3</td>
</tr>
<tr>
<td>AS</td>
<td>31.4</td>
<td>43.4</td>
</tr>
<tr>
<td>Other</td>
<td>14.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

*Nanoscale stages = 30, 60, and 108 nm stages.

during Phase 2 by comparing the particle number distributions across the stages under conditions in which an adhesive was present versus absent. The nanoparticle number distribution did not differ between the two conditions (data not shown). Therefore, particle bounce was unlikely to influence the measurement of particle number concentrations in this study.

Another concern with cascade impactors is potential for particle blowoff subsequent to overloading. To address this issue, we verified that, based on real-time measurement of particulate air concentrations, our sampling time was appropriate and would not lead to loading exceeding the manufacturer recommended maximum deposition per stage of 1 mg. Because the exact amount of collection associated with overloading is dependent on the type of substrate used and the type of particles being collected, the potential for impactor overloading should be evaluated for other scenarios utilizing this methodology.

One of the limitations of existing nanomaterial exposure assessment methodologies is the inability to quantitatively characterize potential exposures to specific materials by size range. In fact, this limitation has been identified as a hindrance to the development...
of nano-specific OELs, because currently established methodologies preclude quantitative exposure assessment of specific particle types and thus implementation of such OELs would be challenging (Hansen and Baun, 2012; van Broekhuizen and Dorbeck-Jung, 2013; Gordon et al., 2014). Of the few OELs established for nanomaterials (e.g. the NIOSH RELs for nanoscale TiO$_2$ and carbon nanotubes) (NIOSH, 2011, 2013), none use a number-based metric for exposure (e.g. # cm$^{-3}$). Though there is still disagreement on the best dose metric for predicting nanomaterial toxicity, some propose that particle number or total surface area are better predictors of toxicity than particle mass (Oberdörster et al., 2005; Monteiller et al., 2007; Lison et al., 2008; Abbott and Maynard, 2010; Becker et al., 2011). Furthermore, because nanoparticles often weigh very little, mass-based analytical methods may suffer from challenges with detection limits. For example, for carbon nanotubes, NIOSH indicates that their proposed REL is not health-based, but rather was established based on a detection limit for carbon nanotubes (NIOSH, 2013).

This proposed methodology would allow one to develop number-based OELs that could be implemented to assess potential risk to workers. In the absence of OELs, industrial hygiene practitioners could use this methodology in combination with information from toxicological studies to inform about potential worker health risks. For example, based on a review of the toxicological literature for nanoscale forms of CB and AS, exposure concentrations measured in this study are well below particle-based No-Observable Adverse Effect Levels (NOAELs) for both materials (Sayes et al., 2010; Kim et al., 2011). It should also be noted that real-time monitoring of PM10 levels indicated that particulate levels at all sampling locations were well below the mass-based OELs for CB and AS (data not shown).

Though this proposed methodology offers many potential advantages for the industrial hygiene...
community, it is not without limitations. First, the method is only applicable to environments with chemically and/or physically distinct particles contributing to the aerosol. For example, microscopic analysis and EDS for CB could be confounded by the presence of diesel exhaust particles, which retain morphological and chemical signatures nearly identical to CB (Fernandes et al., 2003). In this study, all sampling was conducted in facilities that do not operate diesel or propane powered equipment.

Table 3. Summary of distribution of particles by particle type for nanoscale stages (17, 30, 60, and 108) by facility and sample run.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Primary filler in rubber mix</th>
<th>CB (%)</th>
<th>AS (%)</th>
<th>Other (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CB sample 1</td>
<td>51.5</td>
<td>40.7</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>CB sample 2</td>
<td>31.2</td>
<td>57.9</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td>AS sample 1</td>
<td>59.3</td>
<td>38.8</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>AS sample 2</td>
<td>42.2</td>
<td>56.2</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>CB sample 1</td>
<td>34.0</td>
<td>4.4</td>
<td>61.7</td>
</tr>
<tr>
<td></td>
<td>CB sample 2</td>
<td>75.6</td>
<td>0.3</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td>AS sample 1</td>
<td>39.6</td>
<td>27.4</td>
<td>33.0</td>
</tr>
<tr>
<td></td>
<td>AS sample 2</td>
<td>74.6</td>
<td>5.2</td>
<td>20.2</td>
</tr>
</tbody>
</table>
to limit the potential confounders; this approach may not always be feasible for all manufacturing environments.

Secondly, as is true with most sampling equipment for nanomaterials, this methodology does not allow for collection of personal samples. In this study, samples were collected in the area where the mixer operator works, in an effort to best characterize their work environment. However, the operator is often moving between several locations within that vicinity during their shift, and thus this area measurement may differ from personal measurement. To date, personal sampling devices with the characteristics essential for conducting quantitative exposure assessment for nanoscale particles of specific materials are still under development (Tsai et al., 2012). However, previous studies conducted at tire manufacturing facilities indicate that air concentrations of bulk particulate are similar between personal samples collected from the mixer operator and area samples collected near the mixer, indicating that for this specific scenario, the difference might not be appreciable (Williams et al., 1980; Heitbrink and McKinnery, 1986).

Third, the analytical method is labour-intensive, and thus this method might only be used in scenarios where quantitative data is essential. For example, under circumstances where screening level assessments suggest particle concentrations are near to or in excess of health-based screening values, this method would allow for clarification of the particulate sources and concentrations of the materials of interest. Most exposure assessment guidance for nanomaterials suggests a tiered approach; this methodology could be used for high level exposure assessment in a tiered strategy.

Table 4. Total nanoparticle concentration (summed from nanoscale stages of 17, 30, 60, and 108 nm) for CB, AS, and ‘other’ by facility and sample run.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Primary filler in rubber mix</th>
<th>CB (# cm⁻³)</th>
<th>AS (# cm⁻³)</th>
<th>Other (# cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CB sample 1</td>
<td>13 343</td>
<td>10 541</td>
<td>2005</td>
</tr>
<tr>
<td></td>
<td>CB sample 2</td>
<td>11 947</td>
<td>22 170</td>
<td>4166</td>
</tr>
<tr>
<td></td>
<td>AS sample 1</td>
<td>21 972</td>
<td>14 399</td>
<td>708</td>
</tr>
<tr>
<td></td>
<td>AS sample 2</td>
<td>8 897</td>
<td>11 859</td>
<td>331</td>
</tr>
<tr>
<td>2</td>
<td>CB sample 1</td>
<td>10 512</td>
<td>13 481</td>
<td>19 081</td>
</tr>
<tr>
<td></td>
<td>CB sample 2</td>
<td>77 587</td>
<td>3 555</td>
<td>24 735</td>
</tr>
<tr>
<td></td>
<td>AS sample 1</td>
<td>25 042</td>
<td>17 301</td>
<td>20 883</td>
</tr>
<tr>
<td></td>
<td>AS Sample 2</td>
<td>25 059</td>
<td>20 393</td>
<td>7 879</td>
</tr>
</tbody>
</table>

Figure 5  Total number of nanoscale particle (sum of particle concentrations from 17, 30, 60, and 108 nm stages) by type detected at (A) Facility 1 and (B) Facility 2 during Phase 2.
CONCLUSIONS
The methodology described in this article provides a quantitative exposure assessment approach to estimate worker exposure to specific nanomaterials in a mixed dust environment. Though a labour-intensive method, this approach could be integrated into industrial hygiene monitoring strategies for nanomaterials to provide worker exposure estimates by particle size, as needed. While OELs do not yet exist for most nanomaterials and there is no consensus on the best metric by which to measure exposure to nanomaterials, this approach provides industrial hygienists with the tools to measure number-based exposures by size to specific materials in a mixed dust setting.

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