Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

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To cite this article: Kelsey R. Babik, Matthew M. Dahm, Kevin H. Dunn, Kevin L. Dunn & Mary K. Schubauer-Berigan (2018) Characterizing workforces exposed to current and emerging non-carbonaceous nanomaterials in the U.S., Journal of Occupational and Environmental Hygiene, 15:1, 44-56, DOI: 10.1080/15459624.2017.1376252

To link to this article: https://doi.org/10.1080/15459624.2017.1376252

Accepted author version posted online: 20 Oct 2017.
Published online: 20 Oct 2017.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2018, VOL. 15, NO. 1, 44–56
https://doi.org/10.1080/15459624.2017.1376252

Characterizing workforces exposed to current and emerging non-carbonaceous nanomaterials in the U.S.

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ABSTRACT

Objective: Toxicology studies suggest that exposure to certain types of engineered nanomaterials (ENMs) may cause adverse health effects, but little is known about the workforce in the United States that produces or uses these materials. In addition, occupational exposure control strategies in this industry are not well characterized. This study identified U.S. ENM manufacturers and users (other than carbon nanotubes and nanofibers, which have been characterized elsewhere), determined workforce size, characterized types and quantities of materials used, occupational exposure control strategies, and the feasibility of occupational ENM exposure studies.

Methods: Eligible companies were identified and information was collected through phone surveys on nanomaterials produced or used, workforce size, location, work practices, and exposure control strategies. The companies were classified into groups for additional examinations.

Results: Forty-nine companies producing or using ENMs in the U.S. were identified. These companies employed at least 1,500 workers. Most companies produced or used some form of nanoscale metal. More than half of the eligible companies were suppliers for the coatings, composite materials, or general industries. Each company provided information about worker exposure reduction strategies through engineering controls, administrative controls, or personal protective equipment. Production-scale companies reported greater use of specific exposure control strategies for ENMs than laboratory-scale companies.

Conclusions: Workplaces producing or using ENMs report using engineering and administrative controls as well as personal protective equipment to control worker exposure. Industrywide exposure assessment studies appear feasible due to workforce size. However, more effort must be taken to target industries using specific ENMs based on known toxicological effects and health risks.

KEYWORDS
Engineered nanomaterials; exposure assessment; occupational health

Introduction

Nanotechnology is an emerging field that is poised to impact many areas of industry, the economy, and society. Use of engineered nanomaterials (ENMs) can be found in the pharmaceutical, electronics, cosmetic, energy, and advanced materials industries to name a few.[1] From 2001–2014, the United States government invested almost $20 billion in nanoscale engineering, science, and technology, and is expected to contribute $1.4 billion more in 2017.[2,3] As production and use of ENMs expands in the U.S., more workers will likely be exposed to these materials, but the specific sectors in which they work are unclear.

Along with the growth in the production and use of ENMs is the increasing concern that exposure to these products may cause adverse health effects. Studies have shown various ENMs may agglomerate in the body and can induce oxidative stress, airway inflammation, and toxicity in the lungs.[4–7] Yet, there is a lack of exposure assessment and epidemiologic data on worker exposure to these ENMs as the studies require extensive follow-up time and large worker populations to be informative.[8] A National Institute for Occupational Safety and Health (NIOSH) epidemiology study of U.S. carbon nanotube and nanofiber workers is currently underway to address this gap.[9] A previous study by the same group indicated current exposure control measures in the industry are relatively underdeveloped, particularly in terms of proper use of respiratory protection.[10] Furthermore, other studies suggest dermal exposure to EMNs is also possible in work environments.[11,12] However, there is still a lack of understanding surrounding the workforce handling non-

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carbon-based (non-carbonaceous) ENMs and the occupational exposure control measures within industry.

Guidelines for safe handling approaches and exposure control strategies for ENMs in occupational settings in the U.S. have been released,[13–16] but the extent to which these guidelines are being used during the manufacturing and use of ENMs is unknown. The objective of this study was to identify U.S. ENMs manufacturers and users of non-carbonaceous nanomaterials to determine workforce size, characterize types and quantities of materials used, identify occupational exposure control strategies, and determine the feasibility of occupational ENMs exposure studies. Carbonaceous ENMs were excluded from this evaluation because they were studied in a previous evaluation.[10,17]

Methods

The methods used to identify companies for this study were based on those previously developed.[10,17] Briefly, market research reports,[18–27] internet searches, and information from professional colleagues were used to identify companies potentially manufacturing or using non-carbonaceous ENMs. Eligibility for U.S.-based companies in this study included those self-reported as manufacturing ENMs, using/incorporating ENMs into other products, and conducting research and development (R&D) work with plans to scale up within the next three to five years. While focusing on non-carbonaceous ENMs, data were also collected on those companies reporting the manufacture and/or use of carbonaceous ENMs (i.e., carbon nanotubes/nanofibers, graphene, fullerenes, etc.) if they also manufactured/used some other non-carbonaceous ENM. Additionally, companies that were solely distributors of ENMs or those involved in R&D work for biomedical or pharmaceutical applications were excluded as exposures at distributors was expected to be minimal, and studies[28,29] have shown exposure to ENMs in the biomedical and pharmaceutical industries are well controlled.

An introductory letter explaining the study along with a survey (Appendix A) was emailed to each company contact before follow-up phone calls were made. This provided companies the opportunity to review the questions as well as the type of data to be collected. Questions asked of the companies included ones about: (1) company demographics (location, length of time working with ENMs, employment size, etc.); (2) ENM characteristics (type, size, shape, quantity manufactured/used, etc.); (3) ENM processing and handling conditions; (4) engineering controls; (5) administrative and work practice controls; and (6) personal protective equipment (PPE).

Phone surveys were conducted from January 2016 to August 2016. For consistency, surveys were administered by a single industrial hygienist. Every attempt was made to interview a company's head environmental safety and health official. When unavailable, those interviewed included material scientists, company presidents and/or chief executive officers, chief technical officers, as well as managers and administrators. Each company was called twice before being considered an unresponsive company. Unresponsive companies were considered to have an unknown eligibility status. There was no measure for accuracy on the collected survey data; therefore, responses are described as reported.

To examine manufacturing status and workforce size, participating companies were classified into three groups. These groups were ENMs primary manufacturers, secondary users, or hybrids. For additional examination of exposure control measures, companies were further classified into two groups based on reported scale of activities, including the reported amount of ENMs produced and/or handled as well as the reported exposure controls measures in use. These groups were those operating at production-scale levels (Group 1) and those operating at laboratory-scale levels (Group 2). Proportions were calculated per group use of ENMs and use of exposure control strategies. To account for companies of unknown eligibility, response rate was calculated using calculations employed by the market research industry[30,31] and compared to the traditional response rate calculation. The eligibility rate ER is

$$ER = \frac{(C + E)}{(C + E + I)}, \quad (1)$$

where C is the number of companies that participated, E is the number of eligible companies that refused to participate, and I is the number of ineligible companies. The response rate RR is

$$RR = \frac{C}{[(ER \times U) + C + E]}, \quad (2)$$

where U is the number of companies of unknown eligibility.

Results

Company participation

Of the 396 companies identified and contacted, 170 were removed from the study due to either ineligibility (n = 160) or refusal to participate (n = 10). From the 226 remaining, 49 (21.7%) participated. A total of 177 did not respond to contact attempts and were categorized as unresponsive and having unconfirmed eligibility. All 49 participating companies provided information about ENMs used, workforce size, worker exposure reduction strategies through engineering controls, administrative controls, or personal protective equipment. All 49 were manufacturing and/or using ENMs in the U.S. The traditional response rate, calculated by dividing the number of participating companies (49) by the number of eligible companies (226) was 21.7%. The eligibility rate (Equation (1)) from the original 396 companies was 27% and the response rate based on known and unknown eligibility rate (Equation (2)) was 46%. As the eligibility of the unresponsive 177 companies is unknown, and using the 27% eligibility rate as an estimator results in a response rate close to 46% (48%), the expected response rate if all eligible companies participated is between 21.7 and 46%.

Company characteristics

Locations of participating companies are shown in Table 1, and were most common in New York, Texas, and California. Geographic location of companies manufacturing or using ENMs was linked to types of ENMs. For instance, a majority of companies manufacturing or using metal oxide nanoparticles were located in the Northeast. Furthermore, those that handle carbonaceous ENMs along with other non-carbonaceous ENMs were predominantly located in the Northeast, South, and West.

More than half (n = 31, 65%) of the participating companies were suppliers for the coatings, composite materials, or various general industries (i.e., non-specific suppliers, ink industry, etc.). The participating companies consisted of 20 (41%) primary manufacturers, 13 (27%) secondary users, and 16 (33%) combinations of both primary manufactures and secondary users (Table 2). The number of employees reported to be handling ENMs at the 20 primary manufacturers (employee size estimates provided from company sources) ranged from 1–87 (491 total), at the 13 secondary users from 3–86 employees (420 total), and at the 16 combination manufacturers/users from 8–310 (677 total). Therefore, the participating companies employed a total of over 1,500 workers directly working with ENMs (Table 2).

As shown in Table 2, the 49 companies were divided into two groups for closer examination, based on production volume or amount of ENMs used and exposure control methods in place for each facility. Group 1 consisted of 20 companies manufacturing or using ENMs with production-scale exposure controls. Group 2 comprised of 29 companies manufacturing or using ENMs with laboratory-scale exposure controls. The 20 Group 1 companies described systems and programs more typical of large-scale manufacturing operations, such as enclosed systems, industrial ventilation for ENM operations areas, and comprehensive mandatory respiratory protection programs. Most of these companies also provided work clothing along with change facilities to their employees. The 29 companies in Group 2 applied laboratory-scale practices (standard chemical fume hoods, biological safety cabinets (BSC), glove boxes) to contain the ENMs being handled. Most of these companies reported having voluntary respiratory protection programs rather than mandatory ones.

ENM characteristics

More than a quarter of the participating companies reported manufacturing or using more than one type of ENM (n = 13, 27%). A total of 27 different types of ENMs (carbonaceous and non-carbonaceous) were reported to be manufactured or used by the respondents (Table 1). The group "unspecified metal oxide nanoparticle" was counted as one kind of ENM. The most common group of non-carbonaceous ENMs reportedly manufactured or used by the 49 companies was the metal oxide nanoparticles, including specified and unspecified (n = 37, 76%). The most commonly reported ENM from this set was TiO_2 (n = 8; 16%), followed by Fe_2O_3 (n = 7; 14%). The second most common group of ENMs reported manufactured or used was nanoscale metals (n = 14, 29%). Due to company proprietary concerns, most companies manufacturing or using nanoscale metals did not disclose specific metals. However, the most commonly reported manufactured or used nanoscale metal was nano silver (Ag; n = 3, 6%). Other carbonaceous nanomaterials commonly reported to be produced included graphene (n = 10, 20%), carbon nanotubes/fibers (n = 5, 10%), cellulose, fullerenes, and dendrimers (each n = 1, 2%) (Table 1).

The quantity of ENMs manufactured or used ranged from 1–136,050,000 kg for metal oxide nanoparticles, 0.024–3,628 kg for nanoscale metals, and 0.01–5,000 kg for other nanomaterials (Table 2) with a cumulative production total from all participants of roughly 136 million kg of ENMs.

Engineering controls

The majority of participating companies reported using some form of engineering controls to reduce worker exposure (Table 3). The most common engineering control used in both Group 1 and Group 2 was a chemical fume hood (n = 36, 73%). Local exhaust ventilation

Table 1. Locations of companies manufacturing or using engineered carbonaceous and non-carbonaceous nanomaterials in the U.S.

	U.S. Region (%) [a]				
Nanomaterial Type	Northeast	South	Midwest	West	Total Manufacturing/Using ENM [b]
Carbonaceous					
Graphene	3 (30%)	3 (30%)	1 (10%)	3 (30%)	10
CNT/CNF	2 (40%)	2 (40%)	0	1 (20%)	5
Cellulose	1 (100%)	0	0	0	1
Metal Oxides					
TiO2	6 (75%)	1 (13%)	0	1 (13%)	8
ZnO	4 (80%)	0	1 (20%)	0	5
Al2 O3	3 (60%)	0	1 (20%)	1 (20%)	5
Fe2 O3	4 (57%)	0	1 (14%)	2 (29%)	7
SiO2	2 (40%)	0	0	3 (60%)	5
Metal Nanoparticles					
Unspecified Metal Nanoparticles	3 (43%)	0	1 (14%)	3 (43%)	7
Various Nanoscale Metals [c]	7 (50%)	3 (21%)	2 (14%)	2 (14%)	14
Others [d]	5 (33%)	6 (40%)	2 (13%)	2 (13%)	15
Total in Region [e]	18 (37%)	12 (24%)	8 (16%)	11 (22%)	49

[a]Based on U.S. Census regions. Northeast includes ME, NH, VT, MA, CT, RI, NY, PA, NJ; South includes WV, MD, DE, DC, VA, KY, TN, NC, SC, GA, FL, AL, MS, AR, LA, OK, TX; Midwest includes OH, IN, MI, WI, IL, MO, IA, MN, ND, SD, NE, KS; West includes MT, WY, CO, NM, AZ, UT, ID, NV, WA, OR, CA. No eligible companies found in AK, AL, DC, GA, HI, IA, ID, KS, KY, MN, MO, MS, MT, ND, NH, NV, OK, OR, RI, SC, SD, TN, UT, VT, WI, WV, WY.
[b]Companies were counted once for each type of material manufactured/used and for each region in which it manufactured/used.
[c]Various nanometals include Al, Ag, Au, Cu, Fe, In, Ni, Si, W, Zn, Zr, and others.
[d]Others include boron-nitride nanotubes, other carbonaceous nanomaterials, quantum dots, and unspecified nanopowders and polymers.
[e]Each company manufacturing/using multiple materials was counted only once.

(LEV) was also commonly reported in both groups, often described to be custom built for ENM handling or specific laboratory or R&D operations. Respondents in both groups also reported using modified or custom-built engineering controls such as material-specific enclosed systems for high-exposure tasks or clean-room-like walk-in spaces for environmentally sensitive tasks. Similar findings regarding use of engineering controls were seen when examining engineering control use by type of ENM, regardless of company activity level (Table 4a). Some companies considered ENMs in composite materials or in solution to be encapsulated and/or unable to generate dust and therefore not requiring the use of engineering controls to control potential worker exposures.

Work practice and administrative controls

As with engineering controls, most participating companies reported using multiple forms of work practice and administrative controls (Table 5). Those companies that mentioned not having any administrative controls tended to only have one or two employees.

Most companies provided health and safety training (n = 30, 61%), including training for material spill control and storage protocols. Five companies (25%) in Group 1 reported having both written procedures as well as employee training for material spill control and storage while Group 2 had six companies (21%) with written procedures and four (14%) with employee training. For both groups, all companies with spill control and storage training had written procedures. Similar findings regarding use of work practice and administrative controls were seen when examining reported administrative control use by type of ENM, regardless of company activity level (Table 4b).

Some companies described specific administrative controls such as requiring ENMs be in solution when handling outside of a chemical fume hood, and others reported use of sticky mats at points of egress between ENM and non-ENM handling areas to reduce tracking ENMs from one point to another. One manufacturer also reported performing industrial hygiene monitoring that included testing for airborne particulate exposure as well as heat and noise exposure. However, the air monitoring was reportedly done using condensation particle counters, real-time measuring instruments that count total, non-specific, number of particles. Note that questions about other workplace or administrative controls were not directly asked during data collection and were solely anecdotal; therefore, the responses may not be representative of all participating companies.

PPE controls

Almost all of the participating companies reported using some form of PPE, including respiratory protection, to

Table 2. Number of employees and quantity handled by nanomaterial type and operation level.

	Group 1: Production Level-Based Controls						Group 2: Laboratory Level-Based Controls					
	Primary (n = 7)		Secondary (n = 3)		Hybrid (n = 10)		Primary (n = 13)		Secondary (n = 10)		Hybrid (n = 6)	
Nanomaterial Type	No. Directly Handling ENM	Quantity (kg/yr) Handled	No. Directly Handling ENM	Quantity (kg/yr) Handled	No. Directly Handling ENM	Quantity (kg/yr) Handled	No. Directly Handling ENM	Quantity (kg/yr) Handled	No. Directly Handling ENM	Quantity (kg/yr) Handled	No. Directly Handling ENM	Quantity (kg/yr) Handled
Carbonaceous												
Graphene	n/p	n/a	n/p	n/a	43	30–47164	22	0.024–24	35	0.024–104	5	0.024
CNT/CNF	15	n/p	n/p	n/a	6	0.0005 – 1	19	0.024	n/p	n/a	5	0.024
Cellulose	1	9,000	n/p	n/a	n/p	n/a	n/p	n/a	n/p	n/a	n/p	n/a
Metal Oxides												
TiO2	42	n/p	n/p	n/a	310	45–136,050,000	4	24–120	50	n/p	25	1
ZnO	72	n/p	n/p	n/a	n/p	n/a	4	24–120	38	0.024	n/p	n/a
Al2 O3	30	n/p	n/p	n/a	20	100	7	0.024–120	30	0.024	n/p	n/a
Fe2 O3	34	16	n/p	n/a	20	100	4	24–120	38	0.024	25	1
SiO2	n/p	n/a	n/p	n/a	30	45–100	n/p	n/a	30	0.024	28	0.024–1
Metal Nanoparticles												
Unspecified Metal Nanoparticles	5	50	n/p	n/a	10	45–90	3	234	42	0.024–104	n/p	n/a
Various Nanometals [a]	15	n/p	12	n/p	28	0.024–3628	30	0.024	86	0.024–104	40	52
Others [b]	49	112.5	3	5,000	70	2	48	0.01–120	21	0.2–104	4	n/p
Unspecified Nanomaterial(s)	87	n/p	15	n/p	n/p	n/a	n/p	n/a	20	n/p	8	n/p

[a]Various nanometals include Al, Ag, Au, Cu, Fe, In, Ni, Si, W, Zn, Zr, and others.
[b]Others include boron-nitride nanotubes, other carbonaceous nanomaterials, quantum dots, and unspecified nanopowders and polymers.
n/a: not applicable.
n/p: information not provided for proprietary reasons.
Nine companies did not provide information for proprietary reasons.

Table 3. Number and proportion of companies using various engineering control methods.

Manufacturing Type	*n*	Using at Least One EC	Using Multiple EC	LEV	LEV w/ HEPA	Chemical Fume Hoods	Biological Safety Cabinets	Ventilated Enclosures/Glove Boxes	Enclosed Process	Separate Ventilation for Office Areas
Group 1: Production Scale-Based Controls	20	**18** (90%)	**16** (80%)	**10** (50%)	**5** (25%)	**14** (70%)	**1** (5%)	**7** (34%)	**8** (40%)	**14** (70%)
Group 2: Laboratory Scale-Based Controls	29	**23** (79%)	**19** (66%)	**11** (38%)	**7** (24%)	**22** (76%)	**4** (14%)	**9** (31%)	**3** (10%)	**10** (34%)
Total	49	**41** (84%)	**35** (71%)	**21** (43%)	**12** (24%)	**36** (73%)	**5** (10%)	**16** (33%)	**11** (22%)	**24** (49%)

Cells report number of companies (bold) as well as proportions.
EC: engineering control(s); HEPA: high-efficiency particulate air filtration; LEV: local exhaust ventilation.

minimize worker exposure to ENMs (Tables 6 and 7). When examined by type of ENM, similar findings were seen regarding respirator use (Table 4c). Roughly half the companies in both groups reported not knowing what type of cartridges were used in conjunction with the air purifying respirators (APRs). The most commonly reported known cartridge used in both groups was the P100. Over a third of companies in both groups were uncertain of how frequently respiratory protection was used (Group 1: 40% unsure; Group 2: 31% unsure). However, 20% of companies in Group 1 reported daily use of respiratory protection, while 17% of companies in Group 2 reported weekly use of respiratory protection and another 17% reported using respiratory protection as certain tasks required.

Similar to the responses about engineering controls, some companies considered ENMs in composite materials or in solution to be encapsulated and/or unable to generate dust and therefore not requiring the use of PPE or respiratory protection to control potential worker exposures.

Discussion

Industry characteristics

This study attempted to identify all emerging, non-carbonaceous ENMs in the U.S., the companies that produce or use them, the workforce size, and the exposure control measures. It also captured companies

Table 4a. Number and proportion of companies by ENM use using engineering control methods.

	Graphene	CNT/CNF	Cellulose	Metal Oxide Nanoparticles	Unspecified Metal Oxide Nanoparticles	Various Nanometals	Others
n	10	5	1	13	7	14	15
Using at Least One EC	**9** (90%)	**5** (100%)	n/a	**10** (77%)	**6** (88%)	**12** (86%)	**12** (80%)
Using Multiple EC	**7** (70%)	**4** (80%)	n/a	**9** (69%)	**5** (71%)	**12** (86%)	**9** (60%)
LEV	**6** (60%)	**3** (60%)	n/a	**8** (62%)	**5** (71%)	**12** (86%)	**8** (54%)
LEV w/ HEPA	**3** (30%)	**3** (60%)	n/a	**5** (38%)	**1** (14%)	**5** (36%)	**2** (14%)
Chemical Fume Hoods	**8** (80%)	**5** (100%)	n/a	**9** (69%)	**5** (71%)	**10** (71%)	**11** (74%)
Biological Safety Cabinets	**1** (10%)	**0** (0%)	n/a	**4** (31%)	**1** (14%)	**1** (7%)	**1** (7%)
Ventilated Enclosures / Glove Boxes	**5** (50%)	**4** (80%)	n/a	**6** (46%)	**2** (29%)	**5** (36%)	**4** (27%)
Enclosed Process	**2** (20%)	**0** (0%)	n/a	**1** (8%)	**1** (14%)	**3** (21%)	**4** (27%)
Separate Ventilation for Office Areas	**7** (70%)	**2** (40%)	n/a	**8** (62%)	**2** (29%)	**4** (29%)	**5** (34%)

Cells report number of companies (bold) as well as proportions.
Metal Oxide Nanoparticles includes: TiO_2, ZnO, Al_2O_3, Fe_2O_3, SiO_2
CNT/CNT: carbon nanotube/fiber; EC: engineering control(s); HEPA: high-efficiency particulate air filtration; LEV: local exhaust ventilation; PPE: personal protective equipment; SOP: standard operating procedure.

Table 4b. Number and proportion of companies by ENM use using administrative control methods.

	Graphene	CNT/CNF	Cellulose	Metal Oxide Nanoparticles	Unspecified Metal Oxide Nanoparticles	Various Nanometals	Others
n	10	5	1	13	7	14	15
Using Multiple Admin Conts.	**7** (70%)	**3** (60%)	n/a	**8** (62%)	**4** (57%)	**9** (64%)	**9** (60%)
Restricted Access	**6** (60%)	**2** (40%)	n/a	**4** (31%)	**2** (29%)	**5** (36%)	**6** (40%)
Spill Control & Storage	**4** (40%)	**2** (40%)	n/a	**5** (38%)	**2** (29%)	**6** (43%)	**5** (34%)
HEPA Filtered Vacuums	**3** (30%)	**3** (60%)	n/a	**5** (38%)	**2** (29%)	**2** (14%)	**4** (27%)
H&S Training	**6** (60%)	**4** (80%)	n/a	**9** (69%)	**3** (43%)	**10** (71%)	**9** (60%)
Substitution: Material or Process	**1** (10%)	**1** (20%)	n/a	**1** (8%)	**0** (0%)	**2** (14%)	**1** (7%)
Written Safety Plan	**3** (30%)	**1** (20%)	n/a	**6** (46%)	**2** (29%)	**4** (29%)	**3** (20%)
Dust Clean-Up	**4** (40%)	**3** (60%)	n/a	**4** (31%)	**3** (43%)	**6** (43%)	**7** (47%)
Written Housekeeping Program	**3** (30%)	**3** (60%)	n/a	**5** (38%)	**1** (14%)	**3** (21%)	**2** (14%)
Equipment Maintenance SOP	**2** (20%)	**2** (40%)	n/a	**4** (31%)	**1** (14%)	**2** (14%)	**3** (20%)
Hand Washing Protocol	**4** (40%)	**3** (60%)	n/a	**3** (23%)	**2** (29%)	**5** (36%)	**4** (27%)
Food Prohibited in Process Areas	**3** (30%)	**2** (40%)	n/a	**5** (38%)	**4** (57%)	**6** (43%)	**7** (47%)
Lab Coats Laundered at the Worksite	**4** (40%)	**2** (40%)	n/a	**5** (38%)	**1** (14%)	**4** (29%)	**3** (20%)
Change Facilities	**3** (30%)	**1** (20%)	n/a	**2** (15%)	**0** (0%)	**2** (14%)	**2** (14%)
Showers	**0** (0%)	**1** (20%)	n/a	**5** (38%)	**1** (14%)	**4** (29%)	**2** (14%)

Cells report number of companies (bold) as well as proportions.
Metal Oxide Nanoparticles includes: TiO_2, ZnO, Al_2O_3, Fe_2O_3, SiO_2
CNT/CNT: carbon nanotube/fiber; EC: engineering control(s); HEPA: high-efficiency particulate air filtration; LEV: local exhaust ventilation; PPE: personal protective equipment; SOP: standard operating procedure.

Table 4c. Number and proportion of companies by ENM use using PPE control methods.

	Graphene	CNT/CNF	Cellulose	Metal Oxide Nanoparticles	Unspecified Metal Oxide Nanoparticles	Various Nanometals	Others
n	10	5	1	13	7	14	15
Using Multiple PPE	**9** (90%)	**5** (100%)	n/a	**11** (85%)	**6** (88%)	**12** (86%)	**11** (74%)
Lab Coats	**7** (70%)	**4** (80%)	n/a	**9** (69%)	**6** (88%)	**9** (64%)	**11** (74%)
Tyvek Suits	**3** (30%)	**2** (40%)	n/a	**5** (38%)	**1** (14%)	**4** (29%)	**3** (20%)
Work Shoes/Shoe Covers	**4** (40%)	**2** (40%)	n/a	**6** (46%)	**3** (43%)	**6** (43%)	**4** (27%)
Eye and Face Protection	**8** (80%)	**5** (100%)	n/a	**9** (69%)	**6** (88%)	**12** (86%)	**11** (74%)
Respirators	**9** (90%)	**5** (100%)	n/a	**10** (77%)	**4** (57%)	**11** (79%)	**10** (67%)
Gloves	**9** (90%)	**5** (100%)	n/a	**11** (85%)	**6** (88%)	**12** (86%)	**11** (74%)

Cells report number of companies (bold) as well as proportions.
Metal Oxide Nanoparticles includes: TiO_2, ZnO, Al_2O_3, Fe_2O_3, SiO_2
CNT/CNT: carbon nanotube/fiber; EC: engineering control(s); HEPA: high-efficiency particulate air filtration; LEV: local exhaust ventilation; PPE: personal protective equipment; SOP: standard operating procedure.

that were using carbonaceous ENMs along with the non-carbonaceous ENMs. The number of companies manufacturing or using non-carbonaceous ENMs is small, with most of the companies being in the Northeast region of the U.S. Similar findings were reported in a previous NIOSH survey on industry characteristics in engineered carbonaceous nanomaterials manufacturers.[17] Yet based on the response rate of 46%, the number of companies manufacturing or using ENMs is likely closer to 100, based on a simple extrapolation. Compared to the carbonaceous nanomaterial industry which averages about 10 workers per company,[32] the ENMs workforce size is larger averaging about 17 workers per company directly handling the ENMs. Again, based on the response rate of 46%, it is likely the reported workforce size of approximately 1,500 is closer to 2,000, based on a simple extrapolation.

No one ENM stood out as the most common material manufactured or used; rather, the metal oxide nanoparticles were the most commonly handled ENMs. This group also had the highest number of employees directly handling ENMs. The most commonly used metal oxide

Table 5. Number and proportion of companies using various work practice and administrative control methods.

Manufacturing Type	*n*	Using Multiple Admin Conts.	Restricted Access	Spill Control & Storage Training	HEPA Filtered Vacuums	H&S Training	Substitution: Material or Process	Written Safety Plan	Dust Clean-Up	Written Housekeeping Program	Equipment Maintenance SOP	Hand Washing Protocol	Food Prohibited in Process Areas	Lab Coats Cleaned the Worksite	Change Facilities	Showers
Group 1: Production Scale-Based Controls	20	**14** (70%)	**10** (50%)	**7** (34%)	**5** (25%)	**15** (75%)	**2** (10%)	**7** (34%)	**7** (34%)	**6** (30%)	**5** (25%)	**5** (25%)	**6** (30%)	**8** (40%)	**6** (30%)	**6** (30%)
Group 2: Laboratory Scale-Based Controls	29	**17** (59%)	**10** (34%)	**9** (31%)	**7** (24%)	**15** (52%)	**3** (10%)	**7** (24%)	**11** (38%)	**6** (21%)	**4** (14%)	**8** (28%)	**12** (41%)	**5** (17%)	**3** (10%)	**3** (10%)
Total	49	**31** (63%)	**20** (41%)	**16** (33%)	**12** (24%)	**30** (61%)	**5** (10%)	**14** (29%)	**18** (37%)	**15** (31%)	**9** (18%)	**13** (27%)	**18** (37%)	**13** (27%)	**9** (18%)	**9** (18%)

Cells report number of companies (bold) as well as proportions.
HEPA: high-efficiency particulate air filtration; LEV: local exhaust ventilation; SOP: standard operating procedure.

Table 6. Number and proportion of companies using personal protective equipment control methods.

Manufacturing Type	*n*	Using Multiple PPE	Lab Coats	Tyvek Suits	Work Shoes/Shoe Covers	Eye and Face Protection	Respirators	Gloves
Group 1: Production Scale-Based Controls	20	**18** (90%)	**15** (75%)	**11** (55%)	**13** (65%)	**16** (80%)	**18** (90%)	**18** (90%)
Group 2: Laboratory Scale-Based Controls	29	**26** (89%)	**22** (76%)	**3** (10%)	**5** (17%)	**24** (83%)	**20** (69%)	**25** (86%)
Total	49	**44** (90%)	**37** (78%)	**14** (29%)	**18** (37%)	**40** (81%)	**38** (78%)	**43** (88%)

PPE: personal protective equipment; HEPA: high-efficiency particulate air filtration; LEV: local exhaust ventilation.

nanoparticle was TiO_2, which is consistent with reports indicating it to be one of the most prevalent metal oxide nanoparticles in industry,[13,33,34] historically having been used in the paints, cosmetics, paper, and food industries, for instance. However, this material has been in production at the nanoscale for a number of years and some work has been done to characterize the industry's occupational exposure to TiO_2.[13,35,36] For the other metal oxide nanoparticles, Debia et al. suggests occupational exposure to nanoparticles containing iron, including nano-iron oxide (Fe_2O_3), is likely given the quality of evidence surrounding its reported use in industry.[37] However, studies show conflicting results relating to its toxicity and impact on human health.[38–40]

Controls characteristic

The results of the survey indicate U.S.-based ENM manufacturers and users are reporting the use of exposure control strategies, including engineering and administrative controls as well as PPE including respiratory protection. Most of the participating companies reported using multiple types of engineering control measures for reducing worker exposure to airborne particulates such as the use of HEPA-filtered LEV systems, chemical fume hoods, or enclosed production processes. Most companies also reported use of administrative controls and PPE when control use was examined by type of ENM. However, production-scale companies reported greater use of exposure control strategies for ENMs than laboratory-scale companies. While company contacts throughout each group reported understanding the need to control and reduce worker exposure to ENMs, improvement can be made in areas like proper selection of engineering control and respiratory protection.

The most significant finding from this survey in terms of control measures is that less than half of the companies reported using filtering and elastomeric half/full face pieces for respiratory protection. These forms of respiratory protection have been shown to effectively protect from exposure to CNTs and other nanoparticles, and NIOSH makes clear that disposable face masks (i.e. surgical masks, not N95 dust masks) are not to be used in place of NIOSH-approved respirators for protection against nanoparticles like CNTs.[15] However, as there are limited toxicology data on the health endpoints of exposure to these non-carbonaceous ENMs, the same levels of protection NIOSH recommends for CNT exposure might not be applicable in all non-carbonaceous EMNs situations. In these cases, companies manufacturing and/or using ENMs should follow the precautionary principle to protect workers until the true hazards of the material are known. The 11 companies not using respiratory protection reported it was unnecessary since the operations were totally enclosed. While NIOSH recommends the use of enclosed systems to reduce exposure to ENMs,[16] leaks in enclosures or proper use may result in the emissions to the work environment. A comprehensive exposure and

Table 7. Number and proportion of companies using respiratory protection control methods.

Manufacturing Type	*n*	Use Any Form of Respiratory Protection	Use Multiple Forms of Respiratory Protection	Disposable Dust Mask	Half Face APR	Full Face APR	PAPR	SCBA
Group 1: Production Scale-Based Controls	20	**18** (90%)	**7** (35%)	**5** (25%)	**11** (55%)	**5** (25%)	1 (5%)	**1** (5%)
Group 2: Laboratory Scale-Based Controls	29	**20** (69%)	**7** (24%)	**8** (28%)	**14** (48%)	**7** (24%)	**4** (14%)	**1** (3%)
Total	49	**38** (78%)	**14** (29%)	**13** (27%)	**25** (51%)	**12** (24%)	**5** (10%)	**2** (4%)

Cells report number of companies (bold) as well as proportions.
APR: air purifying respirator; PAPR: powered air purifying respirator; SCBA: self-contained breathing apparatus.

engineering control assessment can provide more definitive evidence on the effectiveness of these control approaches and the need for respiratory protection. Therefore, regular exposure monitoring should be conducted to confirm that material is not escaping the enclosure and respiratory protection can be used if emissions are uncontrolled. One of the 11 companies further reported that respiratory protection would not be needed even if the process was not enclosed because of the belief that the material in use was inert. Similar responses were found in a previous NIOSH survey focusing on the engineered carbonaceous nanomaterial industry.[10] Currently, the only recommended exposure limits for ENMs are those set by NIOSH for CNT/CNF and TiO_2.[13,14] For all other ENMs, NIOSH has recommended that respirator use be considered even for enclosed processes if measurement data indicate that nanomaterial exposure is not well controlled.[41] As more recommended exposure limits become available for airborne nanoparticles, it will be possible to use the traditional NIOSH respirator selection logic to select respiratory protection with an assigned protection factor that is sufficient to provide protection against the actual airborne concentration of nanoparticles in the workplace.

While it is difficult to generalize about the appropriate types of exposure controls for each company given that numerous factors can influence control selection, a prudent risk-management approach suggests that steps should be taken to keep exposures as low as possibly achievable until more is known. This can be done through implementing a risk management plan.[42] When controlling potential exposures within a workplace, NIOSH has recommended a hierarchical approach as a means to reduce worker exposures. The basis for the hierarchy of controls is to eliminate the hazard when possible by substituting it with a less hazardous material or, if not feasible, controlling the hazard at or as close to the source as possible through engineering controls. Administrative controls and PPE, including respiratory protection, are to be use, respectively, as final efforts to further reduce exposures.[16,43]

Although there have been several best practice guidelines for managing the risks of nanomaterials published, including the NIOSH RELs previously mentioned, there are no mandatory occupational exposure limits (OELs) for nanomaterials. The lack of mandatory OELs for other ENMs is due to the diversity of ENMs being produced, their varying sizes, shapes, and compositions, which make it difficult to develop standard exposure limits that would cover them all. Another limitation to establishing OELs is that there is no consensus on a standard protocol for monitoring airborne nanomaterials. Exposure assessors are still debating what should be measured: particle number, surface area, mass concentration, or a combination of these.[44–46]

In general, this survey indicates that while some companies have adopted the best-known practices for ENM exposure controls, many companies are still using underdeveloped control strategies. This could be due to the industry's lack of consensus regarding the existence of risks or accepted exposure limits, making it difficult to justify reducing exposures, therefore slowing the adoption and dissemination of best practice exposure control strategies. However, until widely accepted exposure limits with validated air monitoring procedures become readily available for the more widely used ENMs, industrial hygiene and safety professionals from companies in this industry should consider factors specific to their company that would warrant particular control strategies. These include the physical form of the nanomaterial, task duration, frequency, and quantity of ENMs being handled. General best practice guidelines provided by trusted organizations should be followed to control workplace exposures to these materials. These efforts will help to minimize the potential for exposure to nanomaterials.

Strengths and limitations

To the authors' knowledge, this is the first study that attempted to solely characterize the U.S.-based non-carbonaceous ENM industry and its workforce. Other studies[34,37,47] examined the kinds of ENMs used in industry as well as the reported workforce exposure to ENMs, but these encompassed both U.S. and non-U.S. companies and data were gathered indirectly through literature searches. Others, like Piccinno et al.[48] and Conti et al.[47] used a more direct approach to examine ENM production amounts, but did so on a global scale. Furthermore, the systematic approach to collecting information on workforce size and exposure control characteristics across the entire industry with the use of one industrial hygienist to reduce variability in information collected, adds to the strength of this study's results. Comparison to data collected by other groups using similar methods in both U.S.- and internationally focused studies suggests that this study's sampling method adequately captured U.S.-based ENM manufacturers and users.[10,17,47]

This study also has limitations that could affect the characterization of the industry and impact the feasibility determination of future occupational ENM exposure studies, such as selection bias. Since companies participated on a voluntary basis, they may have chosen to participate because of their familiarity with health and safety issues or use of engineering controls, administrative controls or PPE surrounding ENMs. However, given that several different types of ENM manufacturers and users did participate, insight can still be achieved about the exposure control strategies each utilizes.

In addition, the number of companies and workers in the U.S. handling ENMs is likely an underestimation given the response rate and exclusion of distributors and pharmaceutical developers/manufactures. Yet a report by the Pew Research Center suggests response rates in these types of surveys are generally low (between 25 and 9%), indicating the response rate for this study are slightly above average. While expanding the study to include pharmaceutical workers would increase the number of workers handling ENMs, it would also bias the exposure control results as this industry has been successful in reducing worker exposures to pharmaceutical nanomaterials.[28,29] Additionally, many companies reported using the words "nano" and "nanotechnology" in their names because the work their product does occurs at the nanoscale level. Furthermore, the number of companies no longer in business at the time of the survey suggests that the ENM workforce fluctuates as companies either go out of business or are purchased by other companies. When possible, business relationships between companies were recorded in a NIOSH database for future studies.

Furthermore, there was no way to verify the results from the respondents. However, since participation was voluntary and companies were assured that all data would be published in aggregate form and company-identifying information would not be reported, there was little motivation for dishonest responses. Additionally, a NIOSH study[49] focusing on the carbon nanotube industry (but also including other ENMs) used a similar survey when recruiting companies and was able to validate that company answers were truthful when researchers visited those companies to conduct exposure assessments.

Based on the reported size of the ENM industry, industry-wide exposure assessment studies are likely feasible; however, they will not be without challenges. The first of these challenges will be exposure measurement. Currently, there is no consensus in protocol for ENM air monitoring. Available exposure assessment methods are able to differentiate particles according to size and mass but not elemental identity without using multiple methods for verification (i.e., electron microscopy in conjunction with elemental analysis).[44,45] Additionally, the few NIOSH validated methods for assessing occupational exposure to ENMs[13,14] do so indirectly by employing a combination of real-time measurements and filter-based air sampling, the latter of which use existing NIOSH analytical methods that were developed for detecting micron-sized particles.[46] Second, determining which group of ENMs to focus efforts, or even which ENM within a group, poses a challenge due to the diversity of these materials. Most current toxicology data on ENMs are based on in vitro studies, the results of which may not be applicable to realistic occupational exposure scenarios.[5,38,39,50] However, this data gap promotes conducting exposure assessment studies using human-relevant doses for toxicological studies so that future findings can be compared between human and animal studies.

Conclusions

This study identified a workforce of over 1,500 workers within 49 companies manufacturing and using ENMs in the U.S. Based on the company response rate of 46%, the number of companies is likely closer to 100 with a workforce in the 2,500–3,000 range. The materials most commonly produced were metal oxide nanoparticles. Workplaces producing or using these materials report using engineering controls (86%) and administrative controls (63%) as well as personal protective equipment (90%) to control worker exposure. Industrywide exposure assessment studies appear feasible due to workforce size and overall number of companies. However, 100% of companies should be using some form of these controls. More effort must be taken to target industries using specific ENMs based on known toxicological effects and health risks. Furthermore, industrywide exposure assessment studies will be useful in identifying the extent of occupational exposure to these materials.

Acknowledgments

The authors thank all the companies who voluntarily participated in the survey, Dr. Chuck Geraci and Ms. Laura Hodson for assistance in conceptualizing the project, Mr. Jeffery Shire for providing assistance in identifying companies and contact information on potentially eligible companies, and Mr. Lian Luo for developing the database used for the study. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

Funding

This study was funded by the National Institute for Occupational Safety and Health Nanotechnology Research Center.

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