Health and Safety Practices in the Nanomaterials Workplace: Results from an International Survey

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This article reports the findings of an international survey of nanomaterials firms and laboratories regarding their environmental health and safety (EHS) programs, engineering controls, personal protective equipment (PPE), exposure monitoring, waste disposal, product stewardship, and risk beliefs. While many participants reported not believing that nanomaterials pose special risks, nanospecific EHS programs were still widely reported. Most nanospecific EHS programs appeared to build from general EHS programs but included nanospecific workplace engineering controls and recommendations for clothing, gloves, eye protection, and respirators. Organizations with nanospecific EHS programs also reported providing product (safe use) guidance to consumers. However, workplace monitoring and nanospecific waste disposal were uneven and were only associated with the subset of organizations believing in special risks. A majority of organizations expressed a need for more toxicological information and EHS guidance. Overall, this study suggests that nanomaterials firms and laboratories are already attentive to nanospecific EHS and product stewardship issues. However, improved risk communication is needed to further the implementation of related programs. Organizations that are wholly inattentive to EHS would likely engage in nanospecific EHS upon implementing a staffed, general EHS program.

Introduction

Nanomaterials research and development have outpaced scientific knowledge concerning their health and environmental effects, resulting in calls for more nanotoxicological research, risk assessment protocol development, safe handling guidelines, and possible governmental regulation (*1–3*). Potential toxicological concerns for workers in nanomaterials industries and research laboratories, as well as for consumers of nanomaterials-containing products, stem from direct toxicological research findings (*4*) in addition to well-understood, possibly translational, paradigms for the toxicity basis of ultrafine particulates (*5*). Though safe occupational handling approaches for nanomaterials are developing (*1, 6*), their application will depend on actual workplace practices and hazards, as well as the many occupational contexts in which nanomaterials are handled (*7*). Nanomaterials health and safety practices developed by industry could influence future standards and could lower costs of retooling for early adopters. Industrial contributions to best-practice guidelines could also facilitate greater consumer acceptance of nano-based products, ensuring their successful commercialization (*5*) and providing important foundations for guiding consumer safety. However, without knowing about current workplace health and safety practices and innovations, as well as the possible motivations for such practices, it is difficult to either assess their efficacy or to benefit from their wider diffusion within industry.

In this study, organizations worldwide that either produce or handle nanomaterials were invited to participate in a survey to self-report their workplace health and safety and product stewardship practices. The main purpose of this research was to provide a baseline understanding of nanomaterials organizations' stated practices. This project differs from prior surveys in its attention to both EHS and product stewardship, its international scope, its focus on laboratories in addition to firms, and commitment to scholarly dissemination of results. Prior research on the nanomaterials industry is described in a literature review that, along with the initial report of findings from this survey, is available online (http://www.bren.ucsb.edu/~holden/NanoMaterials_EHS_Survey_Project).

Methods

As summarized in Table 1, a questionnaire containing 60 structured, semistructured and open-ended questions was developed for telephone interviews. Early drafts were pretested with nanomaterials experts in academia, industry, and government. Although the survey protocol was developed for oral administration in English, the questionnaire was also translated into Chinese and Japanese for either written or oral administration. The final English-version questionnaire is posted online (http://www.bren.ucsb.edu/~holden/NanoMaterials_EHS_Survey_Project).

Study invitees were identified through a stratified purposive sampling frame by region. The selection criteria included that the organization was either manufacturing, handling, researching, or otherwise using nanomaterials, which were defined as materials with at least one dimension less than 100 nm in size (*1*). Organizations that met these criteria were deemed "nanomaterials organizations" and are referred to as such herein. The sampling frame, ultimately composed of 357 prospective participants worldwide (178 North American, 102 Asian, 69 European, and 8 Australian), including 282 firms and 25 research and 19 university laboratories, was developed through referrals and by searching nanorelated Web sites, articles, conference rosters, and news briefs. The 282 organizations that were contacted represented 17% of the 1700 entries in the NanoVIP worldwide database for nanotechnology firms (*8*) as of September 2006.

Most invitations were initially e-mailed. If invitees responded positively, they were emailed an advance copy of the questionnaire plus a consent form to be completed prior to the interview. The questionnaire was provided in advance to minimize potential misunderstandings and to improve response reliability. Organizations that failed to respond were subsequently e-mailed a link to the web-based survey.

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TABLE 1. Summary of the Questionnaire

topic of question set	exemplar question
information about participants	What is your job title?
organizational characteristics	Where is your organization's home location?
nanomaterial-specific product information	What are all of the different types of nanomaterials that your organization works with?
environmental health and safety programs	Does your organization (or laboratory) offer health and safety training for your employees on the handling of nanomaterials?
containment and exposure controls	Are "nanospecific" facility design and engineering controls used to manage worker exposure to nanomaterials?
spills and waste management	How do you dispose of waste containing nanomaterials?
monitoring of the workplace	Does your organization monitor the workplace for nanoparticles?
risk beliefs	Do you think that there are any special risks associated with the nanomaterials handled or produced in your organization?
product stewardship practices	What forms of guidance information about the safe use of your nanoproducts do you provide to customers?

Surveying was conducted from June to September, 2006. Most telephone interviews were in English; a few were in Chinese by respondent preference. Some surveys in Japan and China were sent and received in writing, then translated to English. In these cases, both the administration and translation were performed by a researcher known by, and of the same nationality as, the respondents. While interviews were preferred for improving the density of responses, written responses were also accepted when language and cultural barriers were likely impediments. All third party-administered surveys were completed in writing. Interviews were audio recorded with participants' permission. Confidentiality was assured by aggregating the results and dissociating participants' identities from responses. Participants were informed at the time of solicitation that participation was anonymous and that results would be published only in an aggregated form. All respondents were required to consent to being surveyed, in writing, prior to the actual interview.

Data were quantitatively and qualitatively coded; unstructured and semistructured questions were coded based on dominant themes (*9*). Because no independent measure of response accuracy was available, responses are described as "reported." Response categories were treated as either independent or dependent variables so that relationships between responses and associated significances could be determined. Relationships were assessed using χ-square analyses of response frequencies for pairwise (independent vs dependent variables) comparisons. Statistical analyses were performed using the PROC FREQ procedure in SAS 9.1 (SAS Institute, Inc.). The analysis scheme is based on answering the following questions (Supporting Information Table S1): (1) What are the relationships between respondents' characteristics and what they do? (2) What are the relationships between respondents' characteristics and what they believe? (3) How does what they believe compare to what they do? (4) How internally consistent are their reported practices with regard to nanospecific EHS? All results of these statistical analyses were tabulated and posted online (http://www.bren.ucsb.edu/~holden/NanoMaterials_EHS_Survey_Project).

Results

Sample Characteristics. Of the 357 organizations invited to participate in the study, 82 accepted, resulting in a response rate of 23%. The response rate (23%) compares favorably to other recent industry-based surveys (*10, 11*). Out of the questionnaires, 39 were administered by phone, 6 by web, and 37 (20 from Japan and 17 from the PRC) in writing. The high response rate from Asian organizations (Table 2) likely resulted from using familiar parties to administer the survey in Asia. Because all third party questionnaires were administered in writing, most organizations in Asia completed written surveys. Asian organizations may be over-represented in the sample since NanoVIP reported as of Fall 2006 that there were three times more nanomaterials firms in North America (ca. 950) than in Asia (ca. 300). The effect of the mode of data collection was evaluated and found to be largely insignificant across responses. As expected, there was a significant geographical bias with regard to the form of the survey, since most Asian organizations (32 of 43, $p = .0001$) completed the survey in writing and most North American organizations (20 of 25, $p = .0001$) participated in telephone interviews.

TABLE 2. Response rate by region

No. contacted	No. respondents	response rate	region
178	25	14%	North America
102	43	41%	Asia
69	11	16%	Europe
8	3	38%	Australia
357	82	23%	overall

Most surveyed organizations (71%, $n = 58$) were firms, rather than research laboratories (28%, $n = 23$), working with nanomaterials at either small or pilot scales (63%, $n = 52$), for less than 10 years (84%, $n = 69$), with fewer than 1000 total employees (79%, $n = 65$), and with less than 50 reportedly handling nanomaterials (84%, $n = 69$). The total years in operation for responding organizations was mostly less than 10 years (57%, $n = 47$), but a significant number were 11 years or older (43%, $n = 35$).

Organizational representatives participating in the interviews included managers, scientists, and EHS personnel, often with multiple interviewees participating in the phone call. Many organizations reported working with more than one type of nanomaterial, with the most frequent being carbon nanotubes ($n = 36$), fullerenes ($n = 15$), quantum dots ($n = 15$), nanowires ($n = 14$), and polymers ($n = 14$), in the form of either powders ($n = 48$) or dispersions ($n = 23$). Organizations reported working in several industries (Supporting Information Figure S1) and having customers in over five market sectors (Figure S2).

EHS Programs. Across all geographical regions, the majority of organizations (89%, $n = 73$) reported implementing a general EHS program. Fifty-seven (70%) also reported either implementing a nanospecific EHS program or providing formal training for employees on the safe

TABLE 3. Significant Distributions of Nanospecific EHS Program and Engineering Controls[a]

	neither nanospecific EHS or formal training	both nanospecific EHS and formal training	total[b]	$p\ \chi^2$	no engineering controls	only fume hoods	fume hood + plus additional controls	no fume hood — other controls	total	$p\ \chi^2$
Asia	17 (39.5)	26 (60.5)	43 (100.0)	0.092	7 (16.3)	9 (20.9)	15 (34.9)	12 (27.9)	43 (100.0)	0.0002
Europe	4 (36.4)	7 (63.6)	11 (100.0)		1 (9.1)	0 (0.0)	9 (81.8)	1 (9.1)	11 (100.0)	
North America	3 (12.0)	22 (88.0)	25 (100.0)	0.019	1 (4.0)	0 (0.0)	20 (80.0)	4 (16.0)	25 (100.0)	0.019
general EHS program and EHS full time equivalent (FTE) personnel										
no general EHS and no FTE	9 (100.0)	0 (0.0)	9 (100.0)	0.0001	4 (44.4)	2 (22.2)	1 (11.1)	2 (22.2)	9 (100.0)	0.002
general EHS but no FTE	2 (15.4)	11 (84.6)	13 (100.0)		1 (7.7)	3 (23.1)	4 (30.8)	5 (38.5)	13 (100.0)	0.094
general EHS plus FTE	14 (23.3)	46 (76.7)	60 (100.0)	0.029	4 (6.7)	4 (6.7)	41 (68.3)	11 (18.3)	60 (100.0)	0.002

[a] Note: significance was determined through Fisher's exact χ^2 test. Cells report number of organizations. Row percentages are reported in parentheses. [b] Totals are calculated across the row for each set of dependent variables.

TABLE 4. Significant Distributions of General PPE and Laboratory Wear and Glove Recommendations[a]

	no PPE rec's	recommend PPE	PPE required	total[b]	$p\ \chi^2$	no laboratory wear or glove rec's	laboratory wear or glove rec's	total	$p\ \chi^2$
Asia	10 (23.3)	10 (23.3)	23 (53.5)	43 (100.0)	0.092	14 (32.6)	29 (67.4)	43 (100.0)	0.039
Europe	2 (18.2)	2 (18.2)	7 (63.6)	11 (100.0)		2 (18.2)	9 (81.8)	11 (100.0)	
North America	3 (12.0)	2 (8.0)	20 (80.0)	25 (100.0)		3 (12.0)	22 (88.0)	25 (100.0)	
general EHS program and EHS full time equivalent (FTE) personnel									
no General EHS and no FTE	5 (55.6)	2 (22.2)	2 (22.2)	9 (100.0)	0.004	5 (55.6)	4 (44.4)	9 (100.0)	0.028
general EHS but no FTE	4 (30.8)	1 (7.7)	8 (61.5)	13 (100.0)		5 (38.5)	8 (61.5)	13 (100.0)	
general EHS plus FTE	6 (10.0)	11 (18.3)	43 (71.7)	60 (100.0)	0.007	9 (15.0)	51 (85.0)	60 (100.0)	0.007

[a] Note: significance was determined through Fisher's exact χ^2 test. Cells report number of organizations. Row percentages are reported in parentheses. [b] Totals are calculated across the row for each set of variables.

handling of nanomaterials, and of these, 26 (46%) reported both. Twenty-two (25%) reported that they either conduct or contract for toxicological testing of their nanomaterials, but several mentioned that materials testing was limited due to the expense. When evaluated by geographical region (i.e., Asia, Europe, or North America), it was only in North America that a majority (88%, $p = 0.02$) of organizations reported having a nanospecific EHS program and/or a formal nanospecific EHS training program (Table 3).

Research laboratories were more likely to report the absence of nanospecific EHS programs ($n = 6$, 66.7%, $p = 0.021$), whereas most other firms reported having nanospecific EHS programs ($n = 44$; 75. 9%, $p = 0.052$). Almost three-quarters of organizations reported that there were impediments to implementing a nanospecific health and safety program ($n = 44$, 71%, $p = 0.02$). Of these, 37 (84 %) described impediments external to the organization, particularly, lack of useful information and consistent guidelines ($n = 31$, 71%). Internal impediments ($n = 12$, 27%) included costs concerns, low priority of EHS concerns, and poor information dissemination.

Two important relationships were found between general EHS programs and nanospecific programs. First, across all regions, nanospecific EHS and training programs were absent when there was no staffed, general EHS program ($p = 0.0001$). Consistently, having a staffed, general EHS program was a reliable predictor for nanospecific EHS and training programs ($p = 0.03$) (Table 3). Also, general EHS programs appeared to provide the foundations for nanospecific programs as most organizations reporting a staffed, general EHS program also reported requiring nanospecific PPE ($n = 43$, 71.7%, $p = 0.007$); respirator use ($n = 27$, 45%, $p = 0.025$); providing clothing, glove ($n = 51$, 85%, $p = 0.007$), and eye protection recommendations ($n = 49$, 81.7%, $p = 0.0003$); and using nanospecific exposure controls in addition to fume hoods ($n = 41$, 68.3% $p = 0.002$) (Tables 3−5). However, as discussed below, workplace monitoring and nanospecific waste disposal were negatively related with nanospecific EHS practices, suggesting that these were extra measures viewed differently from general and nanospecific EHS programs.

Engineered Exposure Controls. Except for six nonresponses, all organizations reported using some form of engineering controls with most (66%) reporting fume hoods (Supporting Information Figure S3). Of these, 27 (49%) reported using some kind of exhaust filtration, although 12 were unsure of the type; 21 (38%) reported not using exhaust filtration, and 7 did not respond. Eight reported using high-efficiency particulate air (HEPA) filters, two reported "standard" non-HEPA filters, and two reported using wet scrubbers for removing water-soluble organic materials. Some respon-

TABLE 5. Significant Distributions of Respiratory and Eye Protection Recommendations[a]

	no respiratory rec's	respirator	respirator + dust mask	dust mask only	total[b]	$p\ \chi^2$	eye protection not recommended	eye protection recommended	total	$p\ \chi^2$
Asia	17 (39.5)	13 (30.2)	9 (20.9)	4 (9.3)	43 (100.0)		16 (37.2)	27 (62.8)	43 (100.0)	
Europe	3 (27.3)	4 (36.4)	0 (0.0)	4 (36.4)	11 (100.0)	0.032	4 (36.4)	7 (63.6)	11 (100.0)	
North America	10 (40.0)	11 (44.0)	3 (12.0)	1 (4.0)	25 (100.0)		3 (12.0)	22 (88.0)	25 (100.0)	0.034
general EHS program and EHS full time equivalent (FTE) personnel										
no general EHS and no FTE	6 (66.7)	0 (0.0)	1 (11.1)	2 (22.2)	9 (100.0)	0.025	6 (66.7)	3 (33.3)	9 (100.0)	0.016
general EHS but no FTE	6 (46.2)	3 (23.1)	2 (15.4)	2 (15.4)	13 (100.0)		7 (53.9)	6 (46.2)	13 (100.0)	0.047
general EHS plus FTE	18 (30.0)	27 (45.0)	10 (16.7)	5 (8.3)	60 (100.0)	0.025	11 (18.3)	49 (81.7)	60 (100.0)	0.0003

[a] Note: significance was determined through Fisher's exact χ^2 test. Cells report number of organizations. Row percentages are reported in parentheses. [b] Totals are calculated across the row for each set of variables.

dents stated that, when handling dry powders, fume hood exhaust fans would be "off" to prevent nanomaterials loss and that the glass shield was relied upon to reduce worker exposure.

Some respondents described specialized or modified engineering controls such as an in-line conveyor for transferring dry powder feedstocks from bags to reactors that also mechanically disposed of used bags into segregated drums, with the system operating inside a HEPA-filtered enclosure. Sixteen organizations, predominantly firms ($n = 14$) and in North America ($n = 10$), reported enclosing nanomaterials operations to prevent worker exposure. Most reports of absent engineering controls and all reports of fume hoods as the sole control came from Asian organizations ($p = 0.00002$) (Table 3). In comparison, more North American organizations reported additional controls to fume hoods ($n = 20$, 80%, $p = 0.019$).

Across all organizations, the absence of nanospecific engineering controls corresponded to the absence of PPE recommendations (66.7%, $p = 0.002$), laboratory wear and gloves (66.7%, $p = 0.004$), eye protection (77.8%, $p = 0.002$), and respiratory protection (77.8%, $p = 0.01$). However, most organizations reporting nanospecific EHS programs ($n = 38$, 66.7%, $p = .015$), and most organizations with fewer employees handling nanomaterials ($n = 17$, 54.8%, $p = 0.034$) reported using engineering controls in addition to fume hoods. Interestingly, organizations with additional engineering controls beyond fume hoods more frequently recommended protective laboratory wear, gloves (86.9%, $p = 0.02$), and eye protection (82.6%, $p = 0.01$). However, the use of added engineering controls appeared unrelated to specific nanorelated risk beliefs. Further, most organizations (56.8%) using additional engineering controls beyond fume hoods did not report workplace monitoring ($p = 0.03$). Together, these results suggest that nanospecific PPE recommendations (including laboratory wear, gloves, eye protection, and respiratory protection) go hand-in-hand with special engineering controls as elements of nanospecific EHS programs. However, in the absence of nanospecific PPE or similar recommendations, nanospecific engineering controls are not used. Thus, nanospecific engineering controls appear to be added elements to basic nanospecific EHS programs that center on PPE and similar precautions.

Personal Protective Equipment (PPE). Most organizations (82%, $n = 67$) across all geographical regions reported making nanospecific PPE recommendations to employees, whereas 15 (18.3%) did not or did not respond. As above, reports of requiring PPE appeared to be a proxy for conventional safety practices as they were significantly associated with a number of other health and safety practices, including the implementation of nanospecific health and safety programs ($n = 45$, 84.9%, $p = 0.0001$), the use of nanospecific engineering controls in addition to fume hoods ($n = 34$, 64.2%, $p = 0.028$), as well as specific recommendations for laboratory wear and gloves ($n = 53$, 100%, $p = 0.0001$), eye protection ($n = 49$, 92.5%, $p = 0.0001$), and respirator use ($n = 24$, 45.3%, $p = 0.0001$). However, organizations requiring PPE were relatively split along either workplace monitoring (42.3%) or not (57.7%; $p = 0.01$), and nearly equal proportions (39.6 and 37.7%, $p = 0.004$) reported disbelieving versus believing in special risks associated with nanomaterials (Table 6). As above, these results suggest that PPE requirements were basic elements of reportedly nanospecific EHS programs. Furthermore, most respondents indicated that their PPE recommendations were primarily based on either conventional chemical hygiene criteria, such as chemical compatibility, or cost factors. Reported choices of PPE would support this (Supporting Information Figures S4−S6). Still, nanospecific recommendations were described, including that employees wear a disposable, typically plastic, body covering over their work clothes during high exposure activities and wear long gloves pulled over sleeves to minimize wrist exposure. Other recommendations included antistatic shoes to prevent ignition by static charges, sticky mats at laboratory entrances to prevent accidental nanomaterial transfers, and one organization reported advising employees who inhaled nanoparticles to consume milk and unrefined sugar as a prophylactic against toxic effects of fine particulates, a practice supported by research using rats (*12, 13*).

Most (63.4%, $n = 52$) organizations reported recommending some kind of respiratory protection when working with nanomaterials, of which, 30 advocated respirators alone, 22 called for respirators or disposable dust masks, and 9 recommended dust masks only. One organization recommended the use of a self-contained breathing apparatus. The overall frequency of reports for respiratory protection appeared to be independent of the specific nanomaterial reported. However, organizations working with nanomaterials in both the dry powder and solution phases were more likely to report respirator use ($n = 19$, 52.8%, $p = 0.036$), and organizations working with nanomaterials only in solutions or embedded in a matrix were more likely not to make respiratory recommendations ($n = 11$, 52.4%, $p = 0.0001$). These findings suggest that organizations tune their respiratory protections to the phase of nanomaterials. However, two organizations that exclusively recommended dust masks

TABLE 6. Significant Distributions of Reported Risk Beliefs by Selected Practices[a]

	no risk	risk	uncertain	no response	total[b]	$p\ \chi^2$
neither nanospecific EHS or formal training	16 (64.0)	3 (12.0)	3 (12.0)	3 (12.0)	25 (100.0)	
both nanospecific EHS and formal training	19 (33.3)	22 (38.6)	9 (15.8)	7 (12.3)	57 (100.0)	0.041
no PPE recommendations	8 (53.3)	4 (26.7)	1 (6.7)	2 (13.3)	15 (100.0)	
recommend PPE	6 (42.9)	1 (7.1)	1 (7.1)	6 (42.9)	14 (100.0)	0.002
PPE required	21 (39.6)	20 (37.7)	10 (18.9)	2 (3.8)	53 (100.0)	0.004
do not monitor the workplace	27 (50.9)	10 (18.9)	9 (16.9)	7 (13.2)	53 (100.0)	
monitor the workplace	7 (28.0)	14 (56.0)	3 (12.0)	1 (4.0)	25 (100.0)	0.012
no nanospecific waste disposal	32 (47.1)	18 (26.5)	8 (11.8)	10 (14.7)	68 (100.0)	
nanospecific disposal practices	3 (21.4)	7 (50.0)	4 (28.6)	0 (0.0)	14 (100.0)	0.038

[a] Note: significance was determined through Fisher's exact χ^2 test. Cells report number of organizations. Row percentages are reported in parentheses. [b] Totals are calculated across the row for each set of variables.

TABLE 7. Significant Distributions of Monitoring and Disposal of Nanowaste As Hazardous[a]

	do not monitor the workplace	monitor the workplace	total*	$p\ \chi^2$	do not dispose waste as hazardous	dispose of waste as hazardous	total	$p\ \chi^2$
Asia	33 (84.6)	6 (15.4)	43 (100.0)	0.003	9 (81.8)	2 (18.2)	11 (100.0)	0.003
Europe	6 (54.6)	5 (45.5)	11 (100.0)		5 (45.5)	6 (54.6)	11 (100.0)	
North America	11 (44.0)	14 (56.0)	25 (100.0)	0.004	5 (21.7)	18 (78.3)	25 (100.0)	0.02
general EHS program and EHS full time equivalent (FTE) personnel								
no general EHS and no FTE	8 (88.9)	1 (11.1)	9 (100.0)		1 (50.0)	1 (50.0)	2 (100.0)	
general EHS but no FTE	6 (54.6)	5 (45.5)	11 (100.0)		3 (42.9)	4 (57.1)	7 (100.0)	
general EHS plus FTE	39 (67.2)	19 (32.8)	58 (100.0)		15 (38.5)	24 (61.5)	39 (100.0)	

[a] Note: significance was determined through Fisher's exact χ^2 test. Cells report number of organizations. Row percentages are reported in parentheses. * Totals are calculated across the row for each set of variables.

also reported working only with nanomaterials as dry powders. The most common respirator specification reported was the P100, and the reported frequency of filter change varied (Supporting Information Figure S7).

Workplace Monitoring. Most (68%, or 53 out of 78) organizations reported not monitoring the workplace for nanoparticles, including 33 (85%) of Asian (p = 0.003) organizations (Table 7). Slightly more than half (14 of 25, p = 0.004) of North American organizations reported monitoring. Although all but two reports of monitoring came from organizations that had implemented nanospecific EHS programs (n = 23, 43.4%, p = 0.002), most organizations with nanospecific EHS programs reported not monitoring the workplace (n = 30, 56.6%, p = 0.002). Organizations that reported monitoring were significantly more likely to describe nanomaterials risks (n = 14, 56%, p = 0.012) (Table 6). Most organizations reported monitoring particle concentration (n = 13) and size (n = 10) and most frequently reported using condensation particle counters (CPC) or other types of particle counters (n = 13). Respondents also reported other approaches, including scanning mobility particle sizers (SMPS, n = 3) or other means of particle collection, such as witness plates, for size analyses by electron microscopy (n = 5). Two respondents described portable respirometers used within workers' breathing zones to collect airborne particles for analysis. Four respondents described using devices that cannot measure at the nanoscale.

Waste Disposal. Participants were asked how they dispose of waste containing nanomaterials, including whether or not they treated nanomaterials waste as hazardous and further as "nano-specific." Sixty percent (n = 29) of respondents (n = 48) reported disposing of nanomaterial waste as hazardous, and most of these were firms. Most North American firms (n = 18, 78.3%, p = 0.02) disposed of their nanowaste as hazardous, whereas only two Asian firms (18.2%, p = 0.003) reported doing so (Table 7). Still, the majority of organizations reporting nanospecific EHS programs (n = 44, 77.2%, p = 0.05), and thus the majority of firms (n = 45, 77.6%, p = 0.056), reported not having nanospecific waste disposal practices. The decision to use nanospecific waste disposal practices was related to a belief in special risks associated with nanomaterials, as indicated by 78.6% of respondents who either reported a belief in risks or were uncertain (p = 0.04) (Table 6).

Product Stewardship. Respondents were asked whether they provided customer guidance for safely using their "nanoproducts", that is, products containing either integrated or unincorporated nanomaterials. In the event that the organization did not have buying customers, the definition of customers (in telephone interviews only) was broadened to include the exchange of nanomaterials between laboratories or departments. Most (67.1%, n = 55) organizations reported providing formal guidance for safely using their products, particularly small (n = 18, 54.6%, p = 0.048) and pilot (n = 17, 89.5%, p = 0.018) scale operations and organizations handling carbonaceous nanomaterials (n = 22, 55%, p = 0.034). Most organizations with more than 1000 employees did not provide safe use guidance (n = 9, 56.3%, p = 0.038). The most common form of guidance was material safety data sheets (MSDS) for bulk material (Supporting Information Figure S8). Most reports of "product information sheets" (n = 20, 83.3%, p = 0.0003) and "technical instructions" (n = 11) came from Asian organizations.

Respondents were also asked about the guidance they provided for the safe disposal of their nanoproducts. Thirty-three (40%) organizations reported providing some form of disposal guidance, 27 (33%) reported none, and 22 (27%) did not respond. The most frequently described methods of transmitting disposal guidance to customers were through personal interactions (n = 7) and through MSDSs (n = 7). Two organizations reportedly providing MSDSs stated that guidance for disposal was not included in the document. Thirteen organizations reported recommending to their customers that nanomaterials be disposed as a hazardous waste, and most of these ($n = 10$) were located in Europe or North America (25.6%, $p = 0.032$).

Beliefs about Nanomaterials Risks. When asked if they believed there were any special risks associated with nanomaterials that they either handled or produced, 35 (43%) organizations reported that there were none, 25 (30%) described risks, and 12 (15%) reported either not knowing or not having enough information. Of those describing risks, 12 (40%) organizations specified inhalation, 6 (19%) flammability, 1 (3%) dermal, and 1 (3%) environmental, and 11 (35%) generalized regarding risks. Organizations in Asia tended to report that there were no risks ($n = 21$, 48.8%, $p = 0.017$; Table 6), as did all organizations working with metals or metal oxides other than quantum dots ($n = 30$, 85.7% $p = 0.043$). Reasons reported for believing in the absence of special risks included that risks were unlikely because of the small quantities of materials handled, the materials' compositions, embedment in matrices, and that they were unsubstantiated based on current toxicological knowledge. Other reasons for reporting no risks included precautions taken through work practices and control systems or because risks were related to bulk chemical composition and therefore not "special." Nineteen respondents (44%) did not specify why they believed there were no special risks.

As above, organizations reporting a belief in nanomaterials' special risks were more likely to monitor the workplace ($n = 14$, 58.3%, $p = 0.001$) and implement nanospecific waste practices ($n = 7$, 50%, $p = 0.038$). In contrast, organizations with nanospecific EHS programs ($p = 0.041$) and those that require PPE ($p = 0.004$) were ambivalent about risk, reporting both risk and no risk related to their nanomaterials, rather than uncertainty (Table 6). This suggests that the presence of these practices was unrelated to whether or not there was a belief in special risks related to their nanomaterials. In either the "no risk" or "not sure" belief categories, precaution may explain having nanospecific EHS training and/or programs. In the "risks described" category, either knowing risks motivated nanospecific EHS training and/or programs or developing the latter out of precaution led to better risk understanding, but additional research would be required to differentiate these two explanations.

Discussion

The most important findings in this study regard the relationships between organizations' reported implementation of nanospecific EHS programs, specific EHS practices and beliefs related to risk. Two findings in particular have useful policy implications: (1) investing in a general EHS program should be encouraged because it appears as a precursor to implementing nanospecific EHS programs by nanomaterials organizations, and (2) achieving a more complete understanding of risks through better knowledge dissemination and risk communication is needed if workplace monitoring and nanospecific waste disposal programs are to become more widespread. Organizations overwhelmingly reported the lack of information and best-practice guidance from industry and governments as impeding their efforts in nanospecific EHS. The lack of information was further evidenced by some reported practices that appeared suboptimal, particularly in PPE, monitoring, and waste disposal. Taken together, organizations with general EHS programs were the ones most able to use available information to voluntarily protect workers. Clearly, they need more information regarding nanomaterials hazards and approaches, but in the meantime they are using what they know. Organizations that are not currently protecting workers and consumers at even the most basic level would improve their performance with nanomaterials by investing in a general EHS program.

Although these outcomes are significant for this study, we acknowledge that the study scope and structure have limitations that should be considered. At the time of research, there was no definitive or reliable source of information about the identities and locations of all nanomaterials organizations, thus introducing bias into the sampling. Consistent with the survey approach, all responses were self-reported and there was no independent verification (e.g., site visits) of collected data. However, with the promise of confidentiality and supporting protocols, there was neither incentive for nor evidence of dishonesty, as organizations' answers were mostly internally consistent across the questionnaire. Some bias arose from the self-selected nature of the participant pool. The voluntary nature of this survey could not avoid such bias and, although the promise of confidentiality was intended to minimize bias and to attract actors of all kinds, neither elimination nor quantification of such bias was possible. On the other hand, even assuming that the organizations most active in nanospecific EHS and product stewardship were mainly captured in the sample, the insights from this study are perhaps more useful because the respondents still reported a range of responses and activities that were statistically significant and not wholly indicative of what might be "best practices" in nanospecific EHS and product stewardship.

Globally, general principles of "prudent practice" include minimizing chemical exposures, avoiding underestimation of risk, providing adequate ventilation, implementing chemical hygiene programs, and attending to permissible exposure limits (PEL) and threshold limit values (*14*). NIOSH (*1*) and ORC Worldwide (*15*) have interim recommendations for prudent measures to minimize nanomaterials exposure, including establishing risk management plans. In that respect, organizations that reported risks as rationales for EHS choices appeared prudent. However, inhalation hazards with powders and dermal hazards with solutions are discussed in the nanotoxicological research literature (*4, 5, 16, 17*) and in NIOSH guidelines (*1, 18, 19*), but the survey responses often revealed choices of PPE that were either nonspecific to nanomaterials characteristics or were not in keeping with available good practice guidelines. And concern for dermal exposure was relatively low.

There were also numerous reports of apparently inadequate engineering controls, including specifying practices to protect samples rather than workers, turning off fume hood fans when handling nanopowders, and infrequently using HEPA exhaust filtration systems. Systematic examination of engineering controls for preventing exposure to engineered nanoparticles is in its early stages (*20, 21*), but NIOSH and EPA do emphasize engineering controls over PPE (*1, 21*), and ORC Worldwide recommends ventilation as only supplemental containment (*15*). Thus, closed, ventilated compartments are recommended for material transfer operations (*22*). This differs from conventional chemical hygiene recommendations that emphasize laboratory ventilation (*14*).

NIOSH also recommends monitoring the workplace for nanomaterials (*1*), but few surveyed organizations reported monitoring, and the described practices may not be sufficient to fully ascertain worker risks from nanomaterials exposure. The most frequently reported instruments were condensation particle counters and SMPS. However, whereas ORC rated SMPS as the best instruments for measuring particle concentration (*23*), nanomaterial surface area and chemistry are probably more related to toxicity than either particle density or mass concentration (*18, 21*). ORC identified diffusion chargers as the best instrumentation for monitoring surface area-based concentration; such instruments are portable and provide real-time measurements of aerosol-active surfaces. Yet the results of this survey would suggest that neither general nor specific monitoring recommendations are widely recognized by nanomaterials organizations. Reports of monitoring appear among a subset of organizations reporting conventional safety practices such as PPE, respirator, and eye protection recommendations, and that subset consisted of those believing that there are special risks associated with the nanomaterials that they handle.

Most respondents reported adhering to conventional waste disposal practices rather than considering nanospecific characteristics. Although not nanospecific, this appears consistent with current guidelines: ORC Worldwide recommends disposing of small amounts of nanomaterials as "special waste" (by incineration, chemical treatment, or encasement) unless its chemistry requires hazardous waste disposal (*24*), and UCOP recommends disposal of all waste nanoparticles according to hazardous chemical waste guidelines (*25*). Such recommended practices, however, may not fully account for the novel hazards posed by nanomaterial waste (*1, 24*), and organizations reporting nanospecific waste practices were also more likely to report a belief in special risks associated with their nanomaterials.

At the time of this research, neither ORC Worldwide nor NIOSH published recommendations for either nanomaterials product stewardship or how organizations should work with their customers or end users concerning product safety and end-of-life. The International Council of Chemical Association's (ICCA) "Responsible Care" program encourages transparency and communication between stakeholders to improve environmental health and chemical safety throughout the product life-cycle. The details constitute a useful framework for promoting product stewardship, but they are not specific to nanomaterials products. Nonetheless, most of the surveyed organizations reported providing some form of guidance, mainly MSDS, for the safe use, but not safe disposal, of their products containing nanomaterials. Yet, standard MSDS do not address nanomaterials characteristics and would have to be modified to effectively communicate nanospecific information related to safety and product stewardship.

Overall, this baseline research into workplace nanomaterials-specific EHS and product stewardship practices suggests that such practices are immature due mainly to a dearth of toxicological and other scientific information. Organizations worldwide are not in consensus regarding the existence of risks that would justify special attention to nanomaterials EHS. Yet, industries are reporting that they have programs and are reporting practices, demonstrative of precautionary, "just in case," attitudes. This indicates that they are sensitive to nanomaterials EHS concerns even when not necessarily making nanospecific choices. The association between the implementation of a general EHS program and a nanospecific EHS program indicates the importance of attention to EHS overall. When organizations adopt such general approaches, based on this research, they are also likely to add features specific to nanomaterials; some reports evidence innovation or at least departure from general chemical hygiene practices. Still, there is variation between organizations in terms of the scope of their EHS programs, and firms, rather than laboratories, appeared to lead in the adoption of nanospecific safety practices. Moreover, organizations that monitor the work environment represent a more intensive level of EHS precaution as they appear to do so based on belief in risks associated with the nanomaterials that they handle. These organizations appear more attuned to risk and are taking what steps they can to confront them. In this regard, reports of monitoring are important because they indicate proactive efforts toward ascertaining and minimizing potential risk despite many methodological and procedural uncertainties. The source of this attention to risk, whether out of concern for occupational safety or for legal liability or other reason, is beyond the scope of the current study and should be attended to in future research.

On the basis of this research, improved transmission of toxicological and other nanomaterials-related research-based information should help nanomaterials organizations make improved, nanospecific choices in their EHS and product stewardship programs. Improved risk communication, perhaps across and within organizations, is likely to lead to more comprehensive EHS programs that include workplace monitoring, appropriate use of engineering controls, and nanospecific waste disposal practices. The general lack of end-of-life guidance for handling nanomaterials suggests the need for a common understanding of best practices regarding product stewardship. Finally, efforts in information dissemination and risk communication should be global so that practices disseminate geographically and across the full range of nanomaterials organizations worldwide.

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Supporting Information Available

Detailed reporting of the data analysis strategy, sample characteristics; and detailed reported engineering controls and PPE. This material is available free of charge via the Internet at http://pubs.acs.org.

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