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Performance of High-Flow-Rate Samplers for Respirable Crystalline Silica Measurement Under Field Conditions: Preliminary Study

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Abstract

Restoration stone work regularly involves work with high-silica-content materials (e.g., sandstone), but low-silica-content materials (<2 % quartz) such as limestone and lime mortar are also used. A combination of short sample duration and low silica content makes the quantification of worker exposure to respirable crystalline silica (RCS) difficult. This problem will be further compounded by the introduction of lower occupational exposure standards for RCS. The objective of this work was to determine whether higher-flow samplers might be an effective tool in characterizing lower RCS concentrations. A short study was performed to evaluate the performance of three high-flow samplers (FSP10, CIP10-R, and GK2.69) using side-by-side sampling with low-flow samplers (SIMPEDS and 10-mm nylon cyclones) for RCS exposure measurement at a restoration stonemasonry field site. A total of 19 side-by-side sample replicates for each high-flow and low-flow sampler pair were collected from work tasks involving limestone and sandstone. RESULTS. Most of the RCS (quartz) masses collected with the high-flow-rate samplers were above the limit of detection (62 % to 84 %) relative to the low-flow-rate samplers (58 % to 78 %). The average of the respirable mass concentration ratios for CIP10-R/SIMPEDS, GK2.69/10-mm nylon, FSP10/SIMPEDS, and FSP10/10-mm nylon pairs and the range of the quartz concentration ratios for the CIP10-R/SIMPEDS, CIP10-R/10-mm nylon, GK2.69/10-mm nylon, FSP10/SIMPEDS, and FSP10/10-mm nylon pairs included unity with an average close to unity, indicating no likely difference between the reported values for each sampler. Workers reported problems related to the weight of the sampling pumps for the high-flow-rate samplers. Respirable mass concentration data suggest that the high-flow-rate samplers evaluated would be appropriate for sampling respirable dust concentrations during restoration stone work. Results from the comparison of average quartz concentration ratios between high-and low-flow samplers suggest that the higher mass collected by the high-flow-rate samplers did not interfere with the quartz measurement. A sig-nificant portion of the data collected with the high-flow-rate samplers (>82 %) were greater than the limit of detection, which indicates that these samplers are suitable for quantifying exposures, even with low-quartz materials.

Keywords

Respirable crystalline silica; Occupational exposure assessment; Stone masonry

Introduction

Silicosis is one of the oldest, often fatal, occupational diseases and is caused by inhalation of respirable crystalline silica (RCS). Silica is an abundant mineral in Earth's crust, and exposures are documented for workers involved in construction, mining, quarrying, and related industries [1–5]. Despite improvements in work practices and exposure controls, occupational exposure to RCS still remains a challenge for the occupational health and hygiene professional; it is estimated that approximately 5.3×10^6 workers in Europe [6] and approximately 1.7×10^6 workers in the United States [7] are exposed to RCS today.

RCS is classified as a Group 1 carcinogen by the International Agency for Research on Cancer [8]. In Europe, the EU Commission Scientific Committee on Occupational Exposure Limits [9] recommended that a European occupational exposure standard of 0.05 mg/m^3 be implemented to reduce the risk of silicosis. However, in many European countries, including Ireland and the United Kingdom, the occupational exposure limit for RCS is 0.1 mg/m^3. The UK Health and Safety Executive, in their evaluation of scientific evidence on the hazardous effects of RCS [10], described the risk of developing silicosis after 15 years of exposure at 0.1 mg/m^3 as 2.5 %, and there is increasing pressure on regulatory agencies to implement a decreased exposure standard to reduce the risk of silicosis.

An issue with enforcing an exposure limit of less than 0.1 mg/m^3 relates to the sensitivity of the current analytical techniques, x-ray diffraction (XRD) [11,12], and infrared analysis (IR) [13]. As explained by Stacey in 2007 [14], the theoretical limit of detection (LOD) of the analytical techniques (5 to 10 μg per sample, equivalent to 0.005 to 0.01 mg/m^3 for an 8-h sample collected at 2.2 l/min) is diffi-cult to achieve in real samples because of issues such as sampling times less than 8 h, measurement precision, interferences in the sample, and reliable calibration standards. Using respirable aerosol sample collectors operating at 1.7 to 2.2 l/min, it will therefore be difficult to demonstrate compliance with a reduced occupational exposure limit (OEL) of less than 0.1 mg/m^3, especially when measuring work tasks lasting less than 8 h. One option available to increase the sample mass collected for RCS analysis is to use high-flow-rate samplers. Commercially available high-flow-rate samplers include the CIP10-R [15], the GK2.69 cyclone [16], and the FSP10 cyclone [17]. The feasibility of using these high-flow samplers to increase the sample mass collected and improve the reliability of RCS measurement at low RCS concentrations has been evaluated in laboratory studies [18–20].

Lee et al. [19] showed that the high-flow-rate samplers collected 2 to 11 times more dust (based on gravimetric analysis) than low-flow-rate samplers (10-mm nylon and Higgins-Dewell-type cyclones). The samplers overestimated exposure to respirable particles relative to the ISO/CEN/ACGIH respirable convention curve; however, two of the samplers evaluated, the GK2.69 and FSP10 cyclones, provided relatively less biased estimates of RCS when flow rates were adjusted to 4.4 and 11.2 l/min, respectively. Stacey and Thorpe [18] similarly recommend the use of high-flow-rate samplers, specifically, the FSP10 cyclone (GSA Mess-gerätebau GmbH) and the GK2.69, but results from their field trials suggest that further work is needed to address pump flow-rate performance. A further issue that needs to be addressed is worker discomfort due to pump weight.

The increased mass collected by high-flow-rate samplers also improved the reliability of analytical measurements of RCS by Fourier transform IR and XRD, especially for environments with low silica concentrations [20]. However, Stacey [14] cautions that high-flow-rate samplers might not be appropriate for dusty environments with low silica concentrations, as large filter loadings might cause absorption effects with XRD analysis and be unsuitable for direct on-filter IR.

Few studies [18] have evaluated the use of high-flow-rate samplers in real occupational environments. Such studies are required in order to assess the samplers' practical use in the field and to validate results from laboratory studies. Restoration stonemasons regularly work with low-silica-content materials such as limestone and lime mortar. Because of the duration of the work tasks involving such materials—for example, repointing a limestone building—it is often not possible to quantify RCS exposures using traditional sampling techniques with sample collectors operating between 1.7 and 2.2 l/min. The objective of this study was to evaluate three high-flow-rate samplers (CIP10-R, GK2.69, and FSP10) for RCS exposure measurement at a restoration stonemasonry field site during work activities involving limestone and sandstone.

Materials and Methodology

Low-Flow-Rate Samplers

The low-flow-rate samplers included in this study were (i) the Safety in Mines Personal Dust Sampler (SIMPEDS) (Model 116000B plastic cyclone, Casella, Bedford, UK) with 25-mm 5-μm pore size polyvinyl chloride (PVC) filters (GLA 5000; SKC Ltd, Dorset, UK) sampling at a flow rate of 2.2 l/min with a Sidekick pump (SKC Ltd) and (ii) the 10-mm nylon cyclone (Sensidyne, Clear-water, FL) with 37-mm 5-μm pore size PVC filters (GLA 5000; SKC Ltd) sampling at a flow rate of 1.7 l/min with a Sidekick pump (SKC Ltd) (Table 1).

High-Flow-Rate Samplers

The high-flow-rate samplers included in this study were (i) CIP10-R (Arelco ARC, Paris, France) with polyurethane foam in a rotating cup sampling at a flow rate of 10 l/min, (ii) GK2.69 (BGI Inc., Waltham, MA) with 37-mm 5-μm pore size PVC filters (GLA 5000; SKC Ltd) sampling at a flow rate of 4.4 l/min with an SKC Legacy pump (SKC Inc., Eighty Four, PA), and (iii) FSP10 GSM (Gesellschaft für Schadstoffmesstechnik GmbH, Neuss, Germany) with 37-mm 5-μm pore size PVC filters (GLA 5000; SKC Ltd, Dorset, UK) sampling at a flow rate of 11.2 l/min with an SG10-2 pump (GSM GmbH) (Table 1).

Sample Preparation

Field Site Description—Field data were collected at five stonemasonry field sites. Four of the sites were restoration stonemasonry workshops managed by the Commissioners for Public Works in Ireland, who are responsible for the restoration and maintenance of historic properties in Ireland. The work sites were chosen because the National University of Ireland, Galway is engaged in an ongoing project [21] to evaluate RCS exposures of restoration stonemasons working at these sites. Within each of the workshops, stone workers were employed as either stone cutters or stonemasons, and each workshop contained the following stonemasonry tools: water-cooled primary cutting saw and hand tools including a disc polisher/cylinder polisher; 5-in., 9-in., and 12-in. angle grinders; pneumatic chisels; hand chisels; brushing tools; and hand punches. At the time of the study, workers were working with either sandstone or limestone. One additional field site, operated by a self-employed stonemason working with sandstone paving, was also included in the study.

Sample Preparation

Prior to sampling, filters and foams were preconditioned in a temperature-and humidity-controlled laboratory at the School of Physics, National University of Ireland, Galway (NUIG) for 24 h. Pre-weighing was performed in this laboratory. Before weighing, filters and foams were passed under a static eliminator (Sartorius, YIB01-OUR ionizing blower, Sartorius, Göttingen, Germany). Pre-weighing of PVC filters and of PVC filters and cassettes (SIMPEDS) was performed using a Sartorius M55-F Microbalance (Sartorius, Göttingen, Germany). Rotating cups with foam of CIP10-R were pre-weighed using an analytical balance (Mettler AE240, Mettler, Toledo, OH). Pre-weighed filters (37-mm PVC filters) were placed into filter holders, sealed, and labeled to prevent contamination. In the field, all pumps were precalibrated using a primary air flow meter (DryCal DC Lite, model 717-KLS, BIOS International, NJ). The flow rate of the CIP10-R was initially calibrated to 10 l/min with a CIP10 calibration bench (Arelco, ARC) in the laboratory, and the rotational speed of the cup was checked using a tachometer in the field.

Sample Collection

Contextual information was recorded during the measurement period, including details about the task, tools, and materials and worker feedback on the sampling equipment.

Side-by-side sampling with six combinations of high- and low-flow-rate samplers was performed. Because of the limited number of workers, personal sampling was conducted only for the FSP10–10-mm nylon cyclone pair and the FSP10–SIMPEDS cyclone pair. Other pairs of high- and low-flow-rate samplers were placed as near to the worker as physically possible by placing the samplers at 1.5 m using a tripod. Tripods were positioned approximately 0.5 to 1.5 m from the worker. A total of 19 pairs for each combination of samplers were collected. Sample duration depended on visual estimation of apparent respirable dust mass concentration and varied from 10 to 60 min (median: 30 min). In some cases it was decided not to continue sampling for the full work task, to avoid overloading the high-flow sampler filters.

Sample Analysis

All sampling trains were post-calibrated; PVC filters, polyurethane foams, and cassettes with PVC filters were returned to the laboratory at NUIG and pre-conditioned and post-weighed, and dust concentrations were calculated. Samples were hand-carried to the National Institute for Occupational Safety and Health (NIOSH) (Morgantown, WV) for analytical analysis at their contract laboratory following NIOSH Method 7500 (NMAM, 4th ed.) [12]. Each filter was removed from the plastic sample holder and transferred to a 15-ml vial. Care was taken to include all particulate matter. If any visible particulate remained in the holder, it was wiped and included for analysis. Then, approximately 10 ml of tetrahydrofuran (THF) was added to each sample vial. The samples were mixed by vortex and then placed in an ultrasonic bath for 10 min. Each sample suspension was transferred to a silver-membrane filter. First, a silver-membrane filter was placed in the vacuum filtration unit. Then, 2 ml of THF solvent was placed onto the filter. The sample suspension was vortexed and immediately added onto the silver membrane filter. The sample vial was rinsed with three separate 2-ml portions of THF. Each rinse was added to the sample on top of the silver-membrane filter. Finally, vacuum was applied to deposit the suspension onto the filter. The silver-membrane filter was then transferred to an aluminum sample plate and placed in the automated sample changer for analysis via XRD. Quartz was the only polymorph of RCS determined to be present. The LOD for quartz was 6 μg. Prior to analysis, dusts from the CIP10-R polyurethane foams were extracted by adding isopropyl alcohol to the foam in its rotating cup, which was then placed in an ultrasonic bath for 5 min, filtered onto a 37-mm PVC filter, rinsed with isopropyl alcohol, and allowed to dry.

Data Analysis

Net mass and mass concentration ratios (respirable dust and quartz) were calculated and compared by dividing the net mass or mass concentration from the high-flow sampler by the net mass or mass concentration from the paired low sampler. Outliers, defined as ratios of less than 0.3 and greater than 3.0, and data below the LOD were removed from the data set. Twenty-three quartz samples collected from the SIMPEDS combinations were removed because their values were less than the LOD; all these samples were collected on tasks involving limestone. Thirty-eight quartz samples collected from the 10-mm nylon sampler combinations were removed because their values were less than the LOD. There were 161 valid quartz samples. There were 225 valid respirable dust samples. However, because of environmental variables that are not controlled in the field, unlike in the laboratory, the number of samples required to show a difference between samplers can be very large. For inhalable samples, Lee et al. [22] estimated that a minimum of 30 pairs was required to prove a difference greater than 35 % (or similarity within 35 %) at a p-value of 0.05 and a confidence level of 80 %. It is possible that smaller numbers may be required to prove similar differences in respirable dust samples, but it is still likely that the number of samples needs to be more than just a few. Thus only those comparisons in which the number of valid pairs is reasonably large (for example, greater than 11) should be considered as indicating a likely difference between samplers.

Results

Contextual Information

Samples were collected on different dates and on real work activities, and so the number of sample replicates for the various sample heads and materials differs between Tables 2 and 3. Work sampled using the 10-mm nylon sampler combinations involved McMonagles sandstone (60 % quartz), and work sampled using the SIMPEDS combinations involved Killarney sandstone (33 % to 52 % quartz) [23]. In many cases the sandstone was damp before use, as it was stored outside, and in some cases (9 of the 19 SIMPEDS trials) the sandstone was pre-soaked by the workers before use. All of the SIMPEDS trials except one (performed outdoors) were carried out in a partially enclosed environment (similar to that shown in Fig. 1). Seven out of the 19 trials involving the 10-mm nylon cyclone were conducted outdoors; the remainder were carried out in a partially enclosed environment similar to that in Fig. 1. Exposure controls used by the workers varied; some wore respiratory protective equipment such as positive air purifying respirators or disposable respirators, and local exhaust ventilation in the form of a movable extraction arm (Nederman Extraction Arm Original) connected to a Nederman L-PAK 250 compact stationary high-vacuum unit was used when available (7 of the SIMPEDS trials and 11 of the 10-mm nylon trials).

Exposure Concentrations

Average respirable mass concentrations and RCS concentrations collected with high-flow-rate and SIMPEDS cyclones are presented in Table 2, and average respirable mass concentrations and RCS concentrations collected with high-flow-rate and 10-mm nylon cyclones are presented in Table 3. A number of samples were removed because of field or laboratory errors (five samples from Table 2). In general, high concentrations of both respirable dust (5 to 43.7 mg/m^3) and RCS (3.3 to 27 mg/m^3) were collected for all tasks involving sandstone, and lower concentrations of respirable dust (1 to 8.3 mg/m^3) and RCS (<LOD to 0.47 mg/m^3) were collected for tasks involving limestone.

The proportion of RCS sampled in the respirable dust was greater with the SIMPEDS combinations than with the 10-mm nylon combinations, and there was more variability in the proportion of RCS in respirable dust in the 10-mm nylon trials (0.2 to 0.4, compared with 0.6 to 0.7 for SIMPEDS). Sample data are not compared to the OEL because in some cases, as a result of overloading of the high-flow sampler filters, sampling was stopped before the end of the work task. Previous studies [21] show that exposures to RCS when grinding or cutting sandstone regularly exceed the OEL.

Respirable Dust Mass Concentration and Net Mass Comparison

Average and standard deviations of the respirable mass concentration and net mass ratios of the FSP10, CIP10-R, and GK6.29 to the 10-mm nylon and SIMPEDS cyclones are shown in Table 4.

Quartz Mass Concentration and Net Mass Comparison

Average and standard deviations of the quartz mass concentration ratios and net mass ratios of the FSP10, CIP10-R, and GK6.29 to the 10-mm nylon and SIMPEDS cyclones are shown in Table 5. None of the quartz mass concentration ratio data collected for the GK2.69 comparison to the SIMPEDS could be used because the values were less than the LOD (*n* =6) or were outliers (<0.3 [*n* =12] or >3.0 [*n* =1]) and so were not included in data analysis.

A scatter plot of quartz mass (micrograms) collected with high- and low-flow-rate samplers with reference lines of LOD (6 μg) and LOQ (limit of quan-tification) (20 μg) is shown in Fig. 2. Most of the masses collected with the high-flow samplers were above the LOD (CIP10-R, 86 % [*n* =37]; FSP10, 84 % [*n* =38]) as compared with the low-flow samplers (SIMPEDS, 78 % [*n* =55]; 10-mm nylon, 58 % [*n* =57]). Sixty-two percent of masses collected with the GK2.69 (*n* =38) were above the LOD. Values below the LOD are not indicated in Fig. 2.

Practical Experience

During the field study, the researcher made some notes regarding the practical use of the sampling equipment. Most of the negative feedback was related to the FSP10 and GSA SG10-2 pumps. There was no attachment on the FSP10 to attach the sampler to the worker, and workers complained that the FSP10 was very heavy and bulky. The GSA SG10-2 pump was difficult to attach to and remove from the sampling harness, and the outlet was in a poor location, which meant that it frequently got blocked during sampling. The workers complained that the GSA SG10-2 pump was very noisy, and that the Legacy pump was very heavy.

Discussion and Conclusion

The performances of three high-flow-rate samplers in collecting respirable crystalline silica (RCS) (quartz) samples in an occupational setting were evaluated in this study. Although this study was affected by low sample numbers and high standard deviations, some trends are evident in the data.

The ratios of RCS to respirable dust in samples collected in the SIMPEDS sample pairs were higher than the corresponding ratios for the 10-mm nylon pairs (Table 2 compared to Table 3). Furthermore, there was more variability in the ratios calculated for the 10-mm nylon sample combinations. This variation is likely a result of a number of factors, although determining the relative contributions from those factors would require further study. It is likely that there is greater analytical variation in the lower absolute mass of RCS on filters collected in the 10-mm nylon combinations. There was also likely an effect of wind velocity on outdoor sampling, as evidenced by the slightly higher ratios for the GK2.69 sampler, which has a downward-pointing inlet. Finally, the difference in quartz concentrations of the sandstone used in the two trials (33 % to 52 % quartz in the SIMPEDS studies; 60 % in the 10-mm nylon studies) likely reflects a difference in the grain size of the quartz. Airborne sandstone particles are formed from breaking the cement binding the quartz grains together, and it might be that the sandstone with a greater quartz content had larger grains, thus producing airborne particles that were perhaps larger than could be sampled in the respirable fraction.

For those sampler pairs with more than 11 valid pairs, the average of the respirable mass concentration ratios between the CIP10-R and SIMPEDS, the GK2.69 and 10-mm nylon cyclone, the FSP10 and 10-mm nylon, and the FSP10 and SIMPEDS were close to unity (the range of results includes 1.0), suggesting that these samplers would be appropriate for sampling respirable dust concentrations during restoration stone work activities. For the other combinations, in which the number of valid pairs was less than 11, the results likely were affected by the small sample numbers.

Only two sampler pair combinations had more than 11 measurements for quartz concentration ratios, but the mass concentration ratios for all combinations that had data (CIP10-R and SIMPEDS and 10-mm nylon; the GK2.69 and 10-mm nylon and the FSP10 and 10-mm nylon and SIMPEDS) were close to unity (range includes 1.0). This suggests that the greater quartz mass collected by the high-flow-rate samplers did not interfere with the quartz measurements. Eighty-six percent and 84 % of quartz masses collected with the CIP10-R and FSP10 were above the LOD of the analytical method, compared with 78 % and 58 % of the quartz masses collected with the SIMPEDS and 10-mm nylon. Many of the samples greater than the LOD related to work tasks involving limestone, which indicates that the high-flow samplers would be appropriate for sampling RCS concentrations in work activities involving low-silica-content (<2 %) materials. The experience here, where large numbers of the traditional low-flow-rate samplers yielded quartz mass results below the LOD or between the LOD and the LOQ, points to a challenge for planning future comparisons of high-flow-rate and low-flow-rate samplers in the field.

Finally, anecdotal evidence based on discussions with the workers during the field study suggests that sampling pumps such as the GSA SG10-2 pump are not comfortable to wear and could interfere with work activities. Solutions to address pump weight and increase worker comfort during sampling need to be sought.

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FIG. 1.

Restoration stonemason wearing the FSP-10 paired with the SIMPEDS cyclone, close by on the tripod, CIP10-R/SIMPEDS and GK2.69/SIMPEDS sampler combinations.

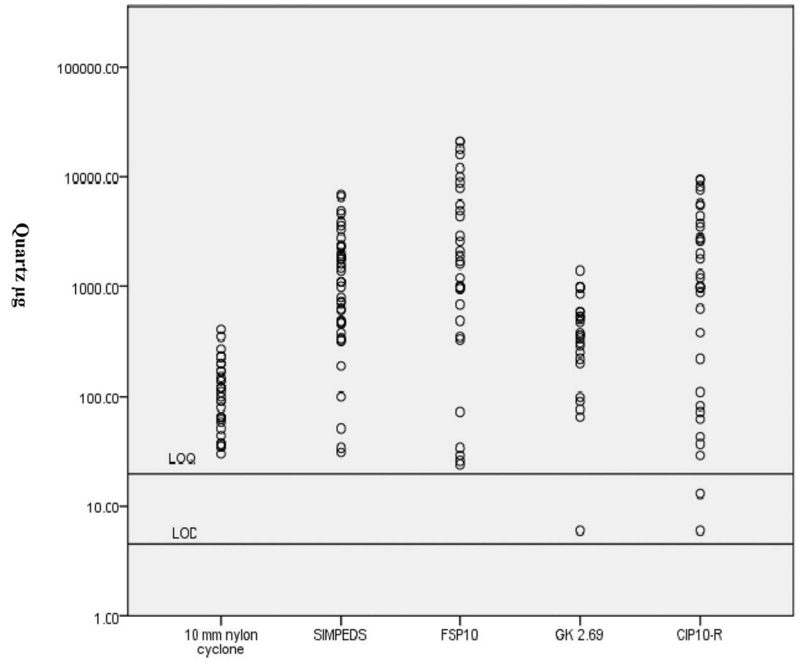

FIG. 2.

Scatter plot of quartz masses collected with the CIP10-R, GK2.69, FSP10, SIMPEDS cyclone, and 10-mm nylon cyclone samplers, showing an LOQ of 20 µg and an LOD of 6 µg from NMAM 7500.

TABLE 1

Comparison of high- and low-flow-rate samplers employed in this study.

Sampler		Flow Rate, l/min	Sampling Media	Pump
10-mm nylon cyclone (Sensidyne, USA)		1.7	PVC filter (37 mm, 5-μm pore size)	Sidekick
SIMPEDS cyclone (Casella, UK)		2.2	PVC filter (25 mm, 5-μm pore size)	Sidekick
CIP10-R (Arelco ARC, France)		10	Polyurethane foam	—
GK2.69 (BGI Inc., USA)		4.4	PVC filter (37 mm, 5-μm pore size)	SKC Legacy
FSP10 (BIA, Germany)		11.2	PVC filter (37 mm, 5-μm pore size)	SG10-2

TABLE 2

Summary of average respirable dust concentrations and respirable crystalline silica concentrations collected using CIP-10R, FSP-10, GK2.69, and SIMPEDS cyclone.

Sampler	Task	Material	Number of Samples	Sampling Time, min	Average Respirable Dust Mass Concentration, mg/m^3	Average RCS Mass Concentration, mg/m^3
CIP-10R	Cutting and grinding	SS	14	10 to 40	27	15.7
CIP-10R	Grinding	LS	4	30	5.8	0.24
GK2.69	Cutting and grinding	SS	15	10 to 40	5	3.3
GK2.69	Grinding	LS	4	30	1	<LOD
FSP10	Cutting and grinding	SS	14	10 to 40	34.2	25.0
FSP10	Grinding	LS	4	30	8.3	0.21
SIMPEDS	Cutting and grinding	SS	43	10 to 40	40	27.0
SIMPEDS	Grinding	LS	11	30	8	0.47

Notes: SS, sandstone; LS, limestone; <LOD, less than the limit of detection.

TABLE 3

Summary of average respirable dust concentrations and respirable crystalline silica concentrations collected using CIP-10R, FSP-10, GK2.69, and 10-mm nylon cyclone.

Sampler	Task	Material	Number of Samples	Sampling Time, min	Average Respirable Dust Mass Concentration, mg/m^3	Average RCS Mass Concentration, mg/m^3
CIP-10R	Cutting	SS	11	15	32	7.0
CIP-10R	Grinding	LS	8	60	2	0.07
GK2.69	Cutting	SS	11	15	20.8	8.6
GK2.69	Grinding	LS	8	60	1.4	<LOD
FSP10	Cutting	SS	11	15	43.7	12.7
FSP10	Grinding	LS	8	60	6	0.04
10-mm nylon	Cutting	SS	33	15	14.5	5.0
10-mm nylon	Grinding	LS	24	60	1.4	<LOD

Notes: SS, sandstone; LS, limestone; <LOD, less than the limit of detection.

TABLE 4

Respirable dust mass concentration ratio and respirable dust net mass ratio of high-flow samplers to 10-mm nylon and SIMPEDS cyclones.

	Reference Cyclone	CIP10-R	GK2.69	FSP10
Mass concentration ratio	10-mm nylon	2.0 ±0.54 (*n* =5)	1.4 ±0.7 (*n* =16)	1.4 ±0.73 (*n* =6)
	SIMPEDS	0.8 ±0.3 (*n* =17)	0.4 ±0.2 (*n* =4)	11 ±0.8 (*n* =13)
Net mass ratio	10-mm nylon	12 ±3 (*n* =5)	3.5 ±2 (*n* =16)	11 ±7 (*n* =6)
	SIMPEDS	3.7 ±1 (*n* =17)	0.7 ±0.3 (*n* =4)	5.3 ±4 (*n* =13)

TABLE 5

Quartz mass concentration ratio and quartz net mass ratio of high-flow samplers to 10-mm nylon and SIMPEDS cyclones.

	Reference Cyclone	CIP10-R	GK2.69	FSP10
Mass concentration ratio	10-mm nylon	1.15 ±0.7 (*n* =6)	1.7 ±0.7 (*n* =9)	1.24 ±0.6 (*n* =6)
	SIMPEDS	1.1 ±0.3 (*n* =13)	No data	1 ±0.8 (*n* =4)
Net mass ratio	10-mm nylon	7 ±4 (*n* =6)	1.6 ±0.7 (*n* =9)	8 ±4 (*n* =4)
	SIMPEDS	4.5 ±2 (*n* =13)	No data	5 ±2.3 (*n* =4)