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Field Study

Mass, Number and Surface Area Concentrations of α-Quartz Exposures of Refractory Material Manufacturing Workers

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Abstract: Mass, Number and Surface Area Concentrations of α-Quartz Exposures of Refractory Material Manufacturing Workers: Jyh-Larng CHEN, *et al.* Department of Environmental Engineering and Health, Yuanpei University College of Health Science, Taiwan—This study set out to assess the respirable mass, surface area, and number concentrations of the α-quartz content particles (C_{r-m}, C_{r-s} and C_{r-n}) to which workers were exposed in six different exposure groups, the raw material handling (n=10), crushing (n=12), mixing (n=12), forming (n=10), furnace (n=10), and packaging (n=10), in a refractory material manufacturing plant. For C_{r-m}, the exposure values in sequence were found as: mixing (68.1 μg/m^3)>packaging (55.9 μg/m^3)>raw material handling (53.3 μg/m^3)>furnace (31.0 μg/m^3)>crushing (29.8 μg/m^3)>forming (22.4 μg/m^3). We also found that ~21.2–68.2% of the above Cr-m exceeded the current TLV-TWA for the α-quartz content (50 μg/m^3) suggesting a need for initiating control strategies immediately. We further conducted particle size-segregating samplings in four workplaces: crushing (n=3), mixing (n=3), forming (n=3), and furnace (n=3). We found that all resultant particle size distributions shared a quite similar geometric standard deviation (σ_g; =2.24–2.92), but the process area, associated with higher mechanical energy (i.e., crushing process), contained finer α-quartz content particles (mass median aerodynamic diameter; MMAD=3.22 μm) than those areas associated with lower mechanical energy (i.e., mixing, forming, and furnace; MMAD=6.17, 5.95, and 8.92 μm, respectively). These results gave a ratio of C_{r-m} in the above four exposure groups (i.e., crushing: mixing: forming: furnace=1.00: 2.30: 0.753: 1.04) which was quite different from those of C_{r-s} (1.00: 1.74: 0.654: 0.530) and C_{r-n} (1.00: 1.27: 0.572: 0.202). Our results clearly indicate the importance of measuring particle size distributions for assessing workers' free silica exposures.
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Refractory material is a natural or synthetic non-organic pottery product with a melting point above 1,580°C, and is widely used as furnace lining material for protecting furnace bodies and reducing heat losses. The top two refractory material users in Taiwan are the iron and steel industry (~60–70%) and the cement industry (~10–20%). Other important users include the glass industry, the waste incineration industry, the petrochemical industry, the pottery industry, and the non-ferrous metal industry[1)]. The US National Institute for Occupational Safety and Health (NIOSH) has reported that more than 1.7 million US workers are potentially exposed to respirable crystalline silica[2)]. In Taiwan, the number of workers exposed to free silica has not yet been established, but the statistics data provided by the Labor Insurance Bureau indicate that pneumoconiosis ranked number one among all occupational diseases in 2002. Among all industries, the mining industry and the refractory material manufacturing industry were the top two industries with the largest and second largest amount of silicotic workers[3)].

Indeed, the issue of silica exposure, silicosis, and lung cancer risk has continued to be controversial[4)]. According to an epidemiological study conducted on 1,022 male refractory brick workers employed for at least 6 months between 1954 and 1977, a standard mortality ratio (SMR) of 1.51 for all refractory brick workers was yielded[5]. A mortality study conducted in China on 6266 silicotic and non-silicotic refractory brick workers, employed before 1962 and followed for mortality from 1963 to 1985, found a standardized rate ratio (SRR) of 2.1 for silicotic refractory brick workers[6]. The above results clearly indicate the importance of fully assessing crystalline silica exposures of workers in the refractory material manufacturing industry.

To date, the current threshold limit values (TLVs) published by the American Conference of Governmental Industrial Hygienists (ACGIH) for assessing free silica exposures simply takes both the types of free silica and their corresponding mass concentrations into account. However, the US NIOSH has indicated that several exposure metrics, including the mass, chemical species, surface area, and number concentrations of silica contents, are important factors in the development of silicosis[2]. It clearly indicates the importance of developing methodologies for simultaneously characterizing workers' free silica exposures in mass, surface area, and number concentrations. However, to the best of our knowledge, no research work has yet been done which meets the above purpose. Accordingly in this study, a methodology suitable for fully characterizing free silica exposures of workers in a refractory material manufacturing plant was used for illustration and as proof of principle.

Method of Research

Personal respirable dust samplings

The whole study was conducted in a refractory material manufacturing plant located in southern Taiwan. All workers of the six process areas, raw material handling (n=10), crushing (n=12), mixing (n=12), forming (n=10), furnace (n=10), and packaging (n=10), were selected for conducting personal respirable aerosol samplings. Through our field observations, workers of each individual exposure group shared quite similar exposure circumstances with similar pollutant sources and environmental conditions, and performed similar work tasks. The above process-based (or task-based) sampling approach has been adopted in other studies for industries with dynamic occupational settings, such as construction[7, 8], geotechnical laboratory workers[9], the slate industry[10], and quartz manufacturing[11].

Personal respirable aerosol samplings were performed by using a sampling train consisting of a nylon cyclone (Part No. 456243, MAS Inc., PA, USA) followed by a 37-mm filter cassette (Cat. No. 225-1. SKC Inc., PA, USA) with a PVC filter (Cat. No. P-503700, Omega Specialty Instrument Co., MA, USA). The sampling flow rates were set at 1.7 L/min and were checked periodically throughout the sampling period (i.e., one workshift).

Particle size segregating samplings

Subjected to workers' willingness, particle size-segregating samplings were conducted in the four process areas of crushing (n=3), mixing (n=3), forming (n=3), and furnace area (n=3), by placing three Marple 8-stage cascade impactors (Model 298, Andersen Sampler Inc.) uniformly distributed in each selected workplace. The sampler consists of eight impaction stages (50% cut-off d_{ae}=21.3, 14.8, 9.8, 6.0, 3.5, 1.55, 0.96, and 0.52 μm, respectively) and a back-up filter (34-mm PVC filter with 5.0 μm pore size). In order to collect analyzable amounts for subsequent analysis, the above particle size-segregating samplings were conducted at each selected site during the same workshift on three consecutive days. The sampling flow rate was set at 2.0 *l*/min and was checked periodically throughout the whole sampling period. In this study, we assumed that the averaged particle size distribution obtained from each workplace was representative of workers' exposures. Thus, worker's respirable aerosol exposure was regarded as a subfraction of total aerosols existing in the given workplace atmosphere.

Sample analysis

All collected samples (including personal respirable samples and samples of each impaction stage and backup filter from particle size-segregating samplings) were analyzed for α-quartz content per NIOSH method 7602[12] by using a Fourier Transform Infrared Spectrometer (FT-IR, Model 510P, Nicolet Instruments Co., Madison, WI, USA). Since purity (in terms of crystallinity, particle size, and presence of other impurities) has a significant effect on the accuracy of determining α-quartz contents in each collected sample, the NIST-SRM 1878 as recommended by Verma and Shaw[13] was used as a calibration standard in this study.

Data analysis

For the exposure profile of the personal respirable α-quartz mass concentration ($C_{r\text{-}m}$) of any given exposure group, its log-normality, geometric standard deviation (σ_g), average exposure level, and fraction exceeding the current TLV were estimated. The log-normality was examined by the W test[14]. The arithmetic mean was used to describe the average exposure level since it provides an effective estimate directly relating to both the average dose and cumulative dose[15]. The method of "minimum variance unbiased estimate" (MVUE) was adopted to estimate the arithmetic mean (AM_{MVUE}). Detailed calculation procedures have been described in the study conducted by Attfield and Hewett[16]. The fraction of exposures that exceeded the current TLV was calculated according to the method suggested by Hewett and Ganser[17].

In this study the environmental wind speed of any given

Table 1. Exposure profiles of the respirable α-quartz mass concentrations ($C_{r\text{-}m}$) for workers of the six selected similar exposure groups (SEGs)

SEGs	$C_{r\text{-}m}$ profile				
	n	Lognormality	σ_g	$AM_{(MVUE)}$ (μg/m^3)	95% confidence interval (μg/m^3)
Raw material handling area	4	Yes	2.24	53.3	18.6–88
Crushing area	3	Yes	2.32	29.8	9.15–117
Mixing area	12	Yes	2.34	68.1	20.6–269
Forming area	6	Yes	2.89	22.4	4.48–115
Furnace area	5	Yes	2.08	31.0	16.2–99.5
Packaging area	6	Yes	2.01	55.9	28.4–109

workplace atmosphere was measured during the entire sampling period by using a hot-wire thermal anemometer (S101 thermal anemometer, ± 0.01 m/s). The wind speed data were applied to an aerosol sampler aspiration efficiency model[18] to further convert the measured particle size distributions of the α-quartz content (i.e., for those directly obtained from the field) to that existing in the workplace atmosphere (i.e., total α-quartz aerosols). Assuming the average personal respirable α-quartz mass concentration (i.e, $C_{r\text{-}m}$ obtained from personal respirable samplings) is a subfraction of the total α-quartz mass concentration ($C_{t\text{-}m}$), which allows us to determine the respirable α-quartz mass concentration of each respirable particle size range ($C_{r\text{-}m\text{-}i}$) according to the respirable aerosol sampling criterion suggested by the International Standards Organization (ISO) in 1992. Finally, the obtained $C_{r\text{-}m\text{-}i}$ was used to determine both surface area and number concentrations of the respirable α-quartz content of each respirable particle size range ($C_{r\text{-}s\text{-}i}$ and $C_{r\text{-}n\text{-}i}$) and the whole respirable particle size range ($C_{r\text{-}s}$ and $C_{r\text{-}n}$) for each individual exposure group. Detailed calculation procedures are presented in the following Results and Discussion section.

Results and Discussion

Exposure profiles of the respirable α-quartz content mass concentrations for workers of different exposure groups

Table 1 shows the exposure profiles of the respirable α-quartz content mass concentrations for all the investigated exposure groups. All exposure profiles were found to be log-normally distributed confirming our field observations; i.e., workers of each individual exposure group did shared quite similar exposure circumtances, in terms of their pollutant sources, environmental conditions, and work tasks. The arithmetic mean exposure levels ($C_{r\text{-}m}$) in sequence for all selected exposure groups were found as: mixing (68.1 μg/m^3)>packaging (55.9 μg/m^3)>raw material handling (53.3 μg/m^3)>furnace (31.0 μg/m^3)>crushing (29.8 μg/m^3)>forming (22.4 μg/m^3). Workers of the mixing area, packaging area, and raw material handling area were found to have the top three exposure levels and this might be because these workers were involved in directly handling dusty materials. Workers of the crushing area were found to have the second lowest exposure level, even though they were also involved in directly handling dusty materials. The reason for this might be because they mainly stayed in the control room to monitor and operate the crushing machines during the workshift. The third lowest exposure was found for the workers of the furnace areapossibly due to the enclosure and negative pressure inside the furnace. The lowest exposure concentration was found for forming area workers and it could be the result of the involvement of wet methods in the work tasks.

Table 2 shows the fractions of exposures exceeding the current TLV-TWA for α-quartz (50 μg/m^3) for each selected exposure group. It can be seen that >50% of exposures in the top three exposure groups (mixing, packaging, and raw material handling) exceeded the current TLV-TWA for α-quartz. Even for those with lower exposure levels, the fractions of their exposures exceeding the current TLV-TWA were still quite severe (range=21.2–27.8%). The above results clearly indicate the need for initiating an appropriate control strategy to reduce workers' α-quartz exposures. In particular for those workers performing work tasks in the mixing area, the raw material handling area, and the packaging area.

Size distributions of α-quartz content particles obtained from the four selected workplace atmospheres

Figure 1 shows particle size distributions of the total and respirable α-quartz mass content ($C_{t\text{-}m}$ and $C_{r\text{-}m}$). In addition, the ratios of the respirable α-quartz mass content with respect to total α-quartz mass content ($C_{r\text{-}m}/C_{t\text{-}m}$) for the crushing, mixing, forming, and furnace areas are also presented. For $C_{t\text{-}m}$, we found the crushing area workers were exposed to the finest α-quartz content particles (with a mass median aerodynamic diameter (MMAD)=3.22 μm). This might be because the crushing process involves in the highest mechanical energy, and hence results in

Table 2. Fractions of workers' exposures exceeding the current TLV-TWA for α-quartz (=50 μg/m³) for the six selected similar exposure groups (SEGs)

SEGs	Fractions above TLV-TWA (%)		
	Mean	95% confidence interval	
		Lower	Upper
Raw material handling area	51.0	14.3	89.3
Crushing area	26.2	16.7	56.8
Mixing area	68.6	13.9	96.8
Forming area	21.2	7.98	45.6
Furnace area	27.8	13.2	43.2
Packaging area	56.3	26.5	78.5

the generation of the finest α-quartz content particles. Very similar MMADs of 6.17 and 5.95 μm, but coarser than that in crushing area, were found for α-quartz content particles in the mixing and forming areas, respectively. This might be because the same raw materials and similar mechanical forces (but less than that for the crushing process) were involved in both the manufacturing processes of these areas. On the other hand, the largest MMAD (=8.92 μm) was found in the furnace area possibly because it was relatively easier for α-quartz content particles to escape from the furnace because of the negative pressure inside the furnace body. Finally, we also found that all measured size distributions were consistent in the form of single-mode with geometric standard deviations (σ_g)<3.0. These results confirmed our initial observation that workers of each individual exposure group shared quite similar exposure circumstances.

In principle, the magnitude the ratio of $C_{r\text{-}m}/C_{t\text{-}m}$ is affected by both MMAD and σ_g for particle size distributions collected from the selected workplaces. Because all the four selected workplaces shared a quite similar σ_g (range=2.24–2.92), it is not so surprising to see that $C_{r\text{-}m}/C_{t\text{-}m}$ decreased (79.8%, 66.5%, 60.2% and 37.4% for crushing, forming, mixing, and furnace, respectively) with increase in their corresponding MMADs (3.22 μm, 5.95 μm, 6.17 μm, and 8.92 μm, respectively), since only α-quartz content particles with d_{ae} <10 μm fell to the respirable particle size range.

Comparisons of mass, surface area and number of α-quartz exposure concentrations for the workers of different exposure groups

Table 3 shows the calculated total respirable mass, surface area, and number concentrations of the α-quartz content particles ($C_{r\text{-}m}$, $C_{r\text{-}s}$, and $C_{r\text{-}n}$ in μg/m³, cm²/m³, and #/m³, respectively) for the crushing area workers. Here, $C_{t\text{-}m\text{-}i}$ (in μg/m³) represents the total mass concentration of the α-quartz content particles on the ith impaction stage of the Marple 8-stage cascade impactor, and $C_{t\text{-}m}$ (in μg/m³) is the summation of $C_{t\text{-}m\text{-}i}$ representing the total mass concentration of the α-quartz content existing in the given workplace atmosphere. Similarly, $C_{r\text{-}m\text{-}i}$, $C_{r\text{-}s\text{-}i}$, and $C_{r\text{-}n\text{-}i}$ (in μg/m³, cm²/m³, and #/m³, respectively) represent the respirable mass, surface area, and number concentrations of the α-quartz content particles on the ith impaction stage of the Marple 8-stage cascade impactor, and $C_{r\text{-}m}$, $C_{r\text{-}s}$, and $C_{r\text{-}n}$ represent their corresponding summations. The respirable aerosol fraction (F_{Ri}) of the ith impaction stage adopted in this study was suggested by the International Standards Organization (ISO) in 1992. The 50% cut-off equivalent volume diameter ($d_{v\text{-}i}$ in μm) of the ith impaction stage was calculated according to its corresponding 50% cut-off aerodynamic diameter ($d_{ae\text{-}i}$ in μm), assuming that α-quartz content particles had a consistent shape factor of unity and a density (ρ) of 2.65 g/cm³. Based on the above definitions and assumptions, $C_{r\text{-}m}$, $C_{r\text{-}s}$, and $C_{r\text{-}n}$ were obtained by using the following equations:

$$d_{v\text{-}i} = d_{ae\text{-}i} \cdot 2.65^{-0.5} \quad (1)$$

$$C_{r\text{-}m\text{-}i} = C_{t\text{-}m\text{-}i} \cdot F_{Ri} \quad (2)$$

$$C_{r\text{-}n\text{-}i} = (C_{r\text{-}m\text{-}i} \cdot 10^{-6})/\{[2.65/(10^{-2})^3] \cdot [(1/6) \cdot \pi \cdot (d_{v\text{-}i} \cdot 10^{-6})^3]\} = C_{r\text{-}m\text{-}i} \cdot 10^6/[2.65 \cdot (1/6) \cdot \pi \cdot d_{v\text{-}i}^3] = C_{r\text{-}m\text{-}i}\,(720702/d_{v\text{-}i}^3) \quad (3)$$

$$C_{r\text{-}s\text{-}i} = C_{r\text{-}n\text{-}i} \cdot [\pi \cdot (d_{v\text{-}i} \cdot 10^{-2})^2] = [C_{r\text{-}m\text{-}i}\,(720702/d_{v\text{-}i}^3)] \cdot [\pi \cdot d_{v\text{-}i}^2 \cdot 10^{-4}] = C_{r\text{-}m\text{-}i}\,(226/d_{v\text{-}i}) \quad (4)$$

$$C_{r\text{-}m} = \sum_{i=1}^{8} C_{r\text{-}m\text{-}i} \quad (5)$$

$$C_{r\text{-}n} = \sum_{i=1}^{8} C_{r\text{-}n\text{-}i} \quad (6)$$

$$C_{r\text{-}s} = \sum_{i=1}^{8} C_{r\text{-}s\text{-}i} \quad (7)$$

Table 4 summarizes $C_{r\text{-}m}$, $C_{r\text{-}s}$, and $C_{r\text{-}n}$ for the crushing,

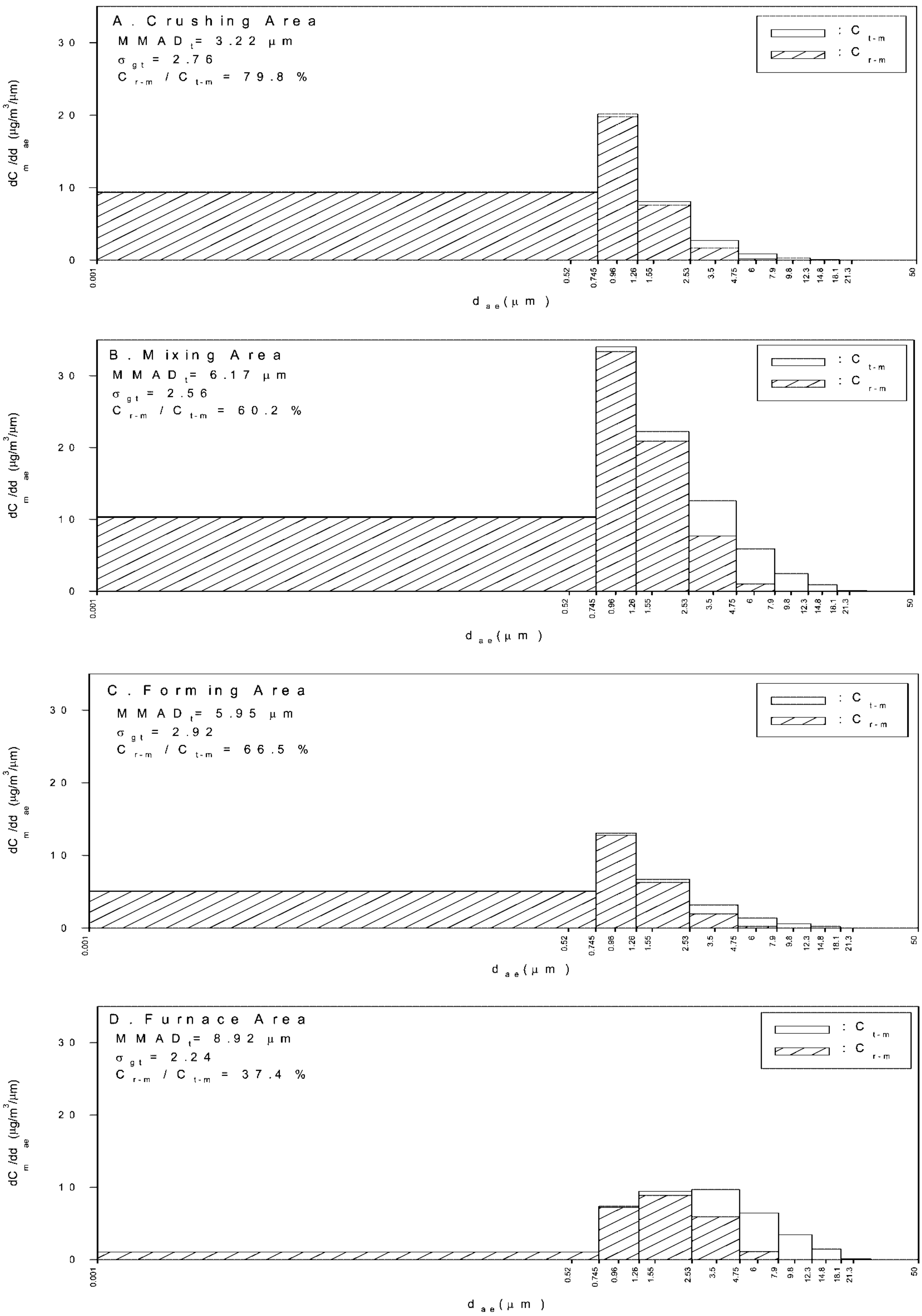

Fig. 1. Size distributions of the total and respirable α-quartz content particles ($C_{t\text{-}m}$ and $C_{r\text{-}m}$) and the fractions of the respirable α-quartz content contained in total α-quartz content ($C_{r\text{-}m}/C_{t\text{-}m}$) for the A) crushing, B) mixing, C) forming, and D) furnace areas.

Table 3. Calculated respirable mass, surface area, and number concentrations of the α-quartz content of each respirable particle size range ($C_{r\text{-}m\text{-}i}$, $C_{r\text{-}s\text{-}i}$, and $C_{r\text{-}n\text{-}i}$) according to the corresponding total α-quartz mass concentration ($C_{t\text{-}m\text{-}i}$) measured in the crushing area

Impaction stage (i)	50% cut-off $d_{ae\text{-}i}$ (μm)	$C_{t\text{-}m\text{-}i}$ (μg/m^3)	F_R	$C_{r\text{-}m\text{-}i}$ (μg/m^3)	50% cut-off $d_{v\text{-}i}$ (μm)	$C_{r\text{-}s\text{-}i}$ (cm^2/m^3)	$C_{r\text{-}n\text{-}i}$ (#/m^3)
1	21.3	0.147	0	0.000	13.1	0	0
2	14.8	0.462	0	0.000	9.09	0	0
3	9.8	1.17	0.01	0.012	6.02	4.42×10^{-1}	3.88×10^{1}
4	6	2.88	0.17	0.489	3.69	3.00×10^{1}	7.04×10^{3}
5	3.5	5.78	0.61	3.52	2.15	3.71×10^{2}	2.55×10^{5}
6	1.55	9.44	0.94	8.88	0.952	2.11×10^{3}	7.41×10^{6}
7	0.96	10.2	0.98	9.98	0.590	3.83×10^{3}	3.51×10^{7}
8+filter	0.52	6.96	0.99	6.89	0.319	4.89×10^{3}	1.52×10^{8}
Sum		$C_{t\text{-}m}$=37.0		$C_{r\text{-}m}$=29.8		$C_{r\text{-}s}$=1.12×10^{4}	$C_{r\text{-}n}$ = 1.95×10^{8}

The respirable aerosol fraction (F_R) was calculated as suggested by the International Standards Organization (ISO) in 1992. The 50% cut-off equivalent volume diameters ($d_{v\text{-}i}$) were calculated according their corresponding 50% cutoff aerodynamic diameters ($d_{ae\text{-}i}$) of the eight impaction stages of the Marple cascade impactor, assuming α-quartz bearing particles had a consistent shape factor of unity and a density of 2.65 g/cm^3. The summations of $C_{t\text{-}m\text{-}i}$, $C_{r\text{-}m\text{-}i}$, $C_{r\text{-}s\text{-}i}$, and $C_{r\text{-}n\text{-}i}$ represent the total mass, respirable mass, respirable surface area, and respirable number concentrations ($C_{t\text{-}m}$, $C_{r\text{-}m}$, $C_{r\text{-}s}$, and $C_{r\text{-}n}$), respectively.

Table 4. Summary of the calculated exposure concentrations of $C_{r\text{-}m}$, $C_{r\text{-}s}$, and $C_{r\text{-}n}$ for crushing, mixing, forming, and furnace area workers

Concentration	Workers			
	Crushing	Mixing	Forming	Furnace
$C_{r\text{-}m}$ (μg/m^3)	29.8	68.1	22.4	31.0
$C_{r\text{-}s}$ (cm^2/m^3)	1.12×10^{4}	1.96×10^{4}	7.35×10^{3}	5.96×10^{3}
$C_{r\text{-}n}$ (#/m^3)	1.95×10^{8}	2.49×10^{8}	1.12×10^{8}	3.94×10^{7}

mixing, forming, and furnace area workers obtained by this study based on the above equations. In principle, the magnitudes of $C_{r\text{-}s}$ and $C_{r\text{-}n}$ are affected not only by $C_{r\text{-}m}$, but also by the corresponding MMAD and σ_g of the involved particle size distributions. Again, because the selected four workplaces shared a quite similar σ_g (range=2.24–2.92), $C_{r\text{-}s}$ and $C_{r\text{-}n}$ were mainly affected by both their corresponding $C_{r\text{-}m}$ and MMAD. Based on this, because crushing area workers were exposed to finer particles (MMAD= 3.22 μm) than mixing area workers (MMAD=6.17 μm) their ratios of $C_{r\text{-}s}$ ($1.96 \times 10^4/1.12 \times 10^4$=1.74) and $C_{r\text{-}n}$ (=$2.49 \times 10^8/1.95 \times 10^8$=1.27) were somewhat different from that of $C_{r\text{-}m}$ (68.1/29.8=2.30). In particular, it should be noted that the change in the above ratios from $C_{r\text{-}m}$ to $C_{r\text{-}n}$ (i.e., from 2.30 to 1.27) was greater than that from $C_{r\text{-}m}$ to $C_{r\text{-}s}$ (i.e., from 2.30 to1.74). The above results could be due to $C_{r\text{-}n\text{-}i}$ α ($720702/d_{v\text{-}i}^3$) (see equation 3) but $C_{r\text{-}s\text{-}i}$ α ($226/d_{v\text{-}i}$) (see equation 4) for any given $C_{r\text{-}m\text{-}i}$. On the other hand, since both mixing area and forming area workers were exposed to particle size distributions with similar MMADs (6.17 and 5.95 μm, respectively) the change in their ratios from $C_{r\text{-}m}$ (68.1/22.4=3.06) to $C_{r\text{-}s}$ ($1.96 \times 10^4/7.35 \times 10^3$=2.66) (i.e., from 3.06 to 2.66) was not so different from that from $C_{r\text{-}m}$ to $C_{r\text{-}n}$ ($2.49 \times 10^8/1.12 \times 10^8$=2.23) (i.e., from 3.06 to 2.23). Finally although both crushing and furnace area workers had similar $C_{r\text{-}m}$ (ratio=31.0/29.8=1.04), the latter had much lower in both $C_{r\text{-}s}$ (ratio=$5.96 \times 10^3/1.12 \times 10^4$=0.530) and $C_{r\text{-}n}$ (ratio=$3.94 \times 10^7/1.95 \times 10^8$=0.202) mainly because of their exposures to much coarser particles (MMAD= 8.92 μm).

It is true that dusts found in workplaces contain not only α-quartz content but also various kinds of materials. In other words, although we measured particle size distributions of the α-quartz content, the resultant particle size distributions are only representative of those α-quartz bearing particles unless we prove that the α-quartz content was completely separate from the other materials. In particular, it should be noted that even particles containing the same mass fraction of α-quartz content might still result in significant differences in both number and surface area fractions. But according to the geological structure of silica sand, silica sand tends to stay in layers apart from other materials[19]. Therefore, in this study we assumed that the measured α-quartz content was completely separate from other materials. Indeed, the above assumption might result in uncertainties in estimating both number and surface area concentrations. Nevertheless, the results obtained in this study do clearly indicate that workers of different exposure groups, although sharing quite comparable mass concentrations, might have quite different exposure levels in both surface and number concentrations when they are exposed to α-quartz content particles with different size distributions.

Conclusions

We found that workers of the process areas who were involved in directly handling dusty materials had higher respirable α-quartz mass exposure levels than the others. Although theer were significant differences in exposure levels among all the selected exposure groups, this study yielded respirable α-quartz mass exposures exceeding the current TLV-TWA by 21.2–68.2% for all selected exposure groups. The above results clearly indicate the need for initiating an appropriate control strategy to reduce workers' α-quartz exposures immediately. We found that workers of different process areas were exposed to α-quartz content particles with different particle size distributions. This indicates that workers of different exposure groups, although sharing quite comparable mass exposure concentrations, might have quite different exposure levels in both surface and number concentrations. Our results clearly indicate the importance of conducting particle size segregating samplings for assessing workers' free silica exposures.

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