Comprehensive Report

Investigation of Ventilation Engineering Controls for Stone Countertop Fabrication

CHAOLONG QI, PHD, PE

COMMANDER, U.S. PUBLIC HEALTH SERVICE

Division of Field Studies and Engineering
Engineering and Physical Hazards Branch
EPHB Report No. 2024-DFSE-1618
February 2024

Disclaimer

Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC).

In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites. All Web addresses referenced in this document were accessible as of the publication date.

Table of Contents

Abstract

Background

Workplace exposure to respirable crystalline silica (RCS) can cause silicosis, a progressive lung disease marked by scarring and thickening of the lung tissue. Quartz is the most common form of crystalline silica. Crystalline silica is found in several materials, such as brick, block, mortar and concrete. Construction and manufacturing tasks that cut, break, grind, abrade, or drill those materials have been associated with overexposure to dust containing RCS. Stone countertop products can contain >90% crystalline silica and working with this material during stone countertop fabrication and installation has been shown to cause excessive RCS exposures. NIOSH scientists are conducting a study to develop engineering control recommendations for RCS during stone countertop fabrication and installation tasks. The site visits described in this report are part of that study.

Assessment

A NIOSH engineer conducted three site visits to evaluate the effectiveness of ventilation engineering controls in reducing occupational exposure to RCS at a stone countertop fabrication shop. The evaluated engineering control measures included multiple water-wall dust extractors and pedestal fans, in addition to existing wet grinding and wet polishing work practices and a wet floor scrubber for work-area cleanliness. The configuration of evaluated engineering controls was different among the three site visits to evaluate their respective performance and are referred to as Setting 1, Setting 2, and Setting 3 in this report. Under Setting 1 and Setting 3, four dust extractors were deployed in the final grinding/polishing area, and five were deployed in Setting 2. Moreover, a designated dust extractor booth was used for the grinding process in Setting 2 and Setting 3 while the grinding process in Setting 1 took place within an area that was further away from any of the four dust extractors. The three settings were also distinguished by the frequency of wet floor cleaning by floor flushing and the use of a floor scrubber.

During the field evaluations, the NIOSH engineer collected breathing zone air samples to assess the time weighted average (TWA) respirable dust and RCS exposures of workers who performed tasks using wet grinding and polishing tools. Additionally, area samples were collected to assess the overall background TWA respirable dust and RCS concentrations in the sample areas. The NIOSH scientist recorded detailed field notes about the work process to understand conditions leading to measured dust and RCS exposures.

Results

<u>Respirable Dust</u>: For the grinding task, the TWA exposures ranged from 184.7 to 214.3 μg/m^3 under Setting 1, from 62.8 to 80.0 μg/m^3 under Setting 2, and from 65.7 to 75.9 μg/m^3 under Setting 3. For the polishing task, the TWA exposures ranged from 130.1 to 150.5 μg/m^3 under Setting 1, from 135.3 to 152.8 μg/m^3 under Setting 2, and from 49.8 to 72.8 μg/m^3 under Setting 3. For the lamination task, the TWA exposures were only obtained under Setting 1 and ranged from 91.4

to 123.5 μg/m³. For the area samples, the TWA dust concentrations ranged from 94.7 to 112.9 μg/m³ under Setting 1, from 18.2 to 57.9 μg/m³ under Setting 2, and from 47.4 to 84.0 μg/m³ under Setting 3. All of the TWA respirable dust exposures observed under the three research settings were well below the 5 mg/m³ OSHA Permissible Exposure Limit (PEL) for Particulates Not Otherwise Regulated. However, since this dust contained RCS, the observed RCS exposures must be compared with the RCS PEL (50 μg/m³) to determine whether exposures were successfully controlled.

<u>RCS Exposures</u>: For the grinding task, the TWA exposures ranged from 51.5 to 96.9 μg/m³ under Setting 1, which were all higher than the OSHA PEL, from 28.0 to 42.4 μg/m³ under Setting 2, which were all below the OSHA PEL, and from 5.9 to 8.5 μg/m³ under Setting 3, which were all below the action level of the OSHA silica rule (25 μg/m³, above which as an 8-hour TWA, OSHA requires employers to assess the exposures per CFR [2016]). For the polishing task, the TWA exposures ranged from 38.7 to 54.0 μg/m³ and from 29.2 to 53.2 μg/m³ under Settings 1 and 2, respectively, which were below or slightly higher than the OSHA PEL. Under Setting 3, the TWA exposures ranged from 3.1 to 3.4 μg/m³, which were all below the action level of the OSHA silica rule. For the lamination task, the full-shift TWA exposures were only obtained for two days under Setting 1, which were 20.0 and 24.5 μg/m³. For the area samples, the TWA RCS concentrations ranged from 37.7 to 51.4 μg/m³ under Setting 1, which were mostly lower or slightly higher than the OSHA PEL; while it ranged from 5.3 to 25.9 μg/m³ under Setting 2 and from 2.9 to 9.7 μg/m³ under Setting 3, which were substantially lower than the OSHA PEL.

Comparing the exposure data between the first two settings and a Baseline Setting when NIOSH researchers assessed workers' exposures and background area concentrations before additional ventilation engineering controls were identified and implemented, the engineering control and work practice approaches evaluated under Setting 2 showed significantly reduced respirable dust (P = 0.002) and RCS (P = 0.007) concentrations in area samples. The full-shift TWA respirable dust (70.5 ± 8.7 vs 300.0 ± 88.3 μg/m³ with P = 0.007) and RCS (32.9 ± 8.2 vs 120.8 ± 20.2 μg/m³ with P < 0.001) exposures for grinding were also significantly reduced under Setting 2. Although Setting 2 controlled the RCS exposure for grinding and area samples to levels below the OSHA PEL, neither Setting 1 nor Setting 2 appeared to help reduce exposures for the polishing task, with the full-shift TWA RCS exposure for polishing still near the OSHA PEL under both settings.

Setting 3 had elevated respirable dust concentrations in the area samples compared to Setting 2. However, it maintained the same level of exposure control as Setting 2 for the respirable dust during grinding (P = 0.881), and had significantly lower respirable dust (P < 0.001) and RCS (P = 0.031) exposures for polishing than Setting 2. The RCS concentrations from all the samples under Setting 3 were lower than the action level of the OSHA silica rule, driven by the reduced respirable dust exposure that resulted from the combined engineering control measures as well as the low silica content in the stone countertop products used during this site visit.

Conclusions and Recommendations

The RCS exposures for Setting 3 were all considerably lower than the action level of the OSHA silica rule, which can be partially attributed to “Elimination” and “Substitution” in the hierarchy of controls. By working with more stone countertop products that have less or no crystalline silica, the average silica content of all the samples in Setting 3 is only 8.1%. Developing stone countertop products with low or no crystalline silica without introducing other hazards would adhere to the top of the hierarchy of controls and could be effectively incorporated in a layered, overall control strategy.

The following combination of engineering controls and work practices were found to be the most effective at controlling individual RCS exposures for grinding and polishing tasks: (1) designating dust extractors for the grinding task as evaluated in Setting 2 and Setting 3; and (2) training workers to position themselves and workbenches to consistently perform the grinding and polishing within the dust extractor’s hooded enclosure as evaluated during polishing tasks in Setting 3. Using this combination of engineering controls and work practices consistently maintained individual RCS exposures to levels below the OSHA PEL for grinding and polishing tasks.

This evaluation had limitations that could influence the generalizability of the findings. Sampling occurred over 3 days under each of the three specific settings of engineering control measures for comparing their performance on reducing RCS exposures, which may not be representative of other times or seasons at the site when different settings of the control measures may be implemented. The number of hours an employee works can also vary by season, due to changing demand for the product.

In accordance with OSHA worker protection policies, until feasible engineering controls are implemented and proven effective, respirators should continue to be used to protect workers against exposures above recognized occupational exposure limits and the employer should ensure that the company respiratory protection program follows OSHA standards [CFR 2006].

Introduction

Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services, it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Field Studies and Engineering primarily studies the engineering aspects of health hazard prevention and control.

Since 1976, EPHB has conducted assessments of health hazard control technologies on the basis of industry, common industrial process, or specific control techniques. Examples of these completed studies include the foundry industry; various chemical manufacturing or processing operations; spray painting; and the recirculation of exhaust air. The objective of each of these studies has been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest, and to create a more general awareness of the need for, or availability of, an effective system of hazard control.

These studies involve a number of steps or phases. Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concept techniques. Next, in-depth surveys are conducted to determine both the control parameters and the effectiveness of these controls. The results from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

Background for this project

Crystalline silica refers to a group of minerals composed of silicon and oxygen; a crystalline structure is one in which the atoms are arranged in a repeating three-dimensional pattern [Bureau of Mines 1992]. The three major forms of crystalline silica are quartz, cristobalite, and tridymite; quartz is the most common form [Bureau of Mines 1992]. Respirable crystalline silica (RCS) refers to that portion of airborne crystalline silica dust that is capable of entering the gas-exchange regions of the lungs if inhaled; this includes particles with aerodynamic diameters less than approximately 10 micrometers (μm) [NIOSH 2002]. Silicosis, a fibrotic disease of the lungs, is an occupational respiratory disease caused by the inhalation and deposition of RCS dust [NIOSH 1986]. Silicosis is irreversible, often progressive (even after exposure has ceased), and potentially fatal. Because no effective treatment exists for silicosis, prevention through exposure control is essential.

Stone countertops are increasingly popular among consumers in recent years, which leads to an increased number of workers in the industry of stone countertop fabrication. Rose et al. [2019] reported that there were an estimated 8,694 establishments and 96,366 employees in the stone countertop fabrication industry in the United States, based upon an analysis of 2018 data from the Bureau of Labor Statistics.

Unfortunately, a large amount of dust that contains RCS can be produced during stone countertop fabrication and installation. On average, granite naturally contains 72% crystalline silica by weight [Blatt and Tracy 1997], and engineered quartz stone can contain about 90% quartz grains by mass in a polymer matrix [Phillips et al., 2013]. An outbreak of silicosis was reported in Israel [Kramer et al., 2012], where 25 patients were identified who shared an exposure history of having worked with engineered quartz stone countertops without dust control or respiratory protection. In addition, 46 silicosis cases were reported in Spain among men working in the stone countertop cutting, shaping, and finishing industry [Pérez-Alonso et al., 2014]. The first silicosis case in the US for a worker who had worked with engineered quartz stone countertops was reported in 2015 [Friedman et al. 2015]; and NIOSH and OSHA [2015] released a Hazard Alert on worker exposure to silica during countertop manufacturing, finishing and installation. More recently, Rose et al. [2019] reported 18 silicosis cases, including two fatalities, among U.S. workers in the stone countertop fabrication industry in California, Colorado, Texas, and Washington; and Fazio et al. [2023] reported 52 silicosis cases, including 10 fatalities, in the state of California alone. A systematic evaluation, optimization, and improvement in engineering control measures for processes involved in stone countertop fabrication and installation can give manufacturers, fabricators, and occupational safety and health professionals best-practice recommendations for consistently reducing RCS exposures below the NIOSH Recommended Exposure Limit (REL) of 0.05 mg/m^3 (50 µg/m^3).

A review of workplace inspections conducted by the state of Washington's Department of Labor and Industries found overexposures to RCS (above the OSHA Permissible Exposure Limit (PEL)) and violation of rules on engineering controls in 9 of 18 stone countertop shops inspected [Lofgren 2008]. Data from the OSHA's Integrated Management Information System (IMIS) reveals that citations issued for exceeding the PEL for RCS jumped from an average of 4 per year during 2000-2002 to an average of 59 per year during 2003-2011 at stone countertop fabrication shops and installation sites. These results indicate that dust control methods did not appear to be well implemented among shops in this industry. In 2016, OSHA published a new PEL of 0.05 mg/m^3 (50 µg/m^3) as an 8-hr time weighted average (TWA) for RCS [CFR 2016], emphasizing the importance of addressing these overexposures.

The research reported here seeks to reduce workers' exposures and associated health risks in the stone countertop fabrication and installation industries by evaluating, optimizing, and improving engineering control measures, validating their effectiveness through field studies, and disseminating the results through NIOSH reports, articles in professional and trade journals, and a NIOSH Internet topic page. The long-term objective of this study is to provide practical recommendations for effective dust controls that will prevent overexposures to RCS during stone countertop fabrication and installation.

Background for this study

Field studies by NIOSH [2016a; 2016b; 2016c] in relatively large stone countertop fabrication shops found that cutting was mostly performed by machines operated remotely, such as bridge saws or water-jet cutters, but final grinding and polishing of the stone edge profiles was exclusively conducted by workers using handheld grinders and polishers. Those manual tasks, particularly grinding, led to the highest RCS exposure among workers in these shops. The NIOSH studies reported overexposure to RCS for the workers conducting grinding and some polishing tasks, even when traditional wet methods were employed. A recent NIOSH study [2021] reported that the RCS exposure for workers conducting grinding tasks can be reduced to levels below the OSHA PEL by supplementing the traditional wet methods, that incorporate a water supply directly within the grinders, with an additional sheet-water-wetting method. While such effective wetting methods are being optimized for implementation, additional and more effective engineering control measures are needed for these tasks to further reduce exposures. In another survey report by NIOSH [2019] the results showed a 78.7% exposure reduction of RCS when actively performing grinding tasks inside a mobile dust control booth running at an average airflow velocity of 133.6 ± 8.1 (mean ± standard deviation) feet per minute (fpm) across the workbench.

In the current study reported here, a NIOSH engineer conducted three site visits to evaluate the effectiveness of ventilation engineering controls in reducing occupational exposure to RCS at a stone countertop fabrication shop. The configuration of evaluated engineering controls was different among the three site visits to evaluate their respective performance and are referred to as Setting 1, Setting 2, and Setting 3 in this report. The evaluated engineering control measures included multiple water-wall dust extractors and pedestal fans, in addition to existing wet grinding and wet polishing work practices and a wet floor scrubber for work-area cleanliness. The dust extractors were designed to function similarly to the dust control booth evaluated previously [NIOSH 2019] by moving the dust generated from grinding/polishing quickly away from the workers and capturing the dust with the moving wall of water. The field evaluations under the three engineering control settings consisted of collecting: 1) personal breathing zone (PBZ) air samples to assess the worker's TWA respirable dust and RCS exposures; and 2) area air samples to assess the TWA RCS concentration in the background air of the final grinding/polishing areas. This study was reviewed and approved by the NIOSH IRB (Protocol 20-NIOSH-06). [§]

Evaluation Site and Process Description

Introduction

The evaluation site is a stone countertop fabrication shop. Its products include granite, engineered quartz, and occasionally, marble countertops. The shop building consists of a fabrication area and an attached office area. The fabrication area was on the ground floor, while the office area was split between the first and second stories. The doors separating the office and fabrication areas were kept closed to prevent dust from entering the office area. There were signs beside these doors reminding personnel to wear their respirators and hearing protection before entering the fabrication area. Large stone countertop slabs were transported into the shop at one end of the building and the completed products were transported out of the shop at the other end.

Process Description

The countertop fabrication process began at one end of the facility where the stone slabs were received and stored. The stone slabs were first cut into smaller pieces using bridge saws and water-jet cutters. After the initial cutting, some stones also went through a lamination process, depending upon the design requirements of the product. During the lamination process, workers cleaned and dried the stone surfaces, wet cut thin stone strips with a miter saw supplied with water, and glued these thin strips of stone to the larger countertop pieces to form countertop edges. Some initial grinding of the stone surfaces and edges were also conducted at this step using a handheld pneumatic wet grinder (GPW-215CR, Gison Machinery Co., Ltd., Taiwan) with diamond grinding cup wheels (coarse and medium ratings). This grinder runs a maximum speed of 11,000 revolutions per minute (RPM) at 90 pounds per square inch (PSI), and it abraded the surface and allowed the glue to adhere to the stone. After the glue cured, the stone assembly went to CNC machines and other large machines that shaped, edged and profiled them. All of these machines were equipped with water sprays to suppress dust. After this process was completed, the stones were sent to the final grinding and polishing area. Workers used handheld tools equipped with water to manually grind and polish the edges of stones. One worker used a pneumatic wet grinder (GPW-216, Gison Machinery Co., Ltd., Taiwan, running ~7,000 RPM at 90 PSI) with diamond grinding cup wheels (coarse, medium and fine ratings) for final grinding of the stone edges. About a half dozen workers used pneumatic wet polishers of a variety of models (~4,500 RPM at 90 PSI) with resin bonded polishing discs for final polishing. All the workers involved in the production process wore elastomeric, half-face air-purifying respirators with either P100 cartridges or combination P100 and

[§] See 45 C.F.R. part 46; 21 C.F.R. part 56 organic vapor cartridges. Other personal protective equipment worn included hearing protection, eye protection, rubber safety shoes, and aprons.

Control Technologies

All the handheld pneumatic wet grinders and polishers in this study used water to suppress dust as a dust control measure. Each tool has a water valve to adjust the amount of water used so the workers may use different water flow rates for their tools per their own preferences. Therefore, the water flowrate in the tools was not monitored in this study.

The polishers were all equipped with a center-water-feed feature, as shown in Figure 1(a). During operation, water continuously flows through a hose connected at the end of the polisher handle and releases from the center of the polishing disc. The grinder used in the final grinding/polishing process during the first two site visits (Setting 1 and Setting 2), as shown in Figure 1(b), supplied water to the diamond grinding cup wheel through a water spray nozzle pointing at the edge of the cup wheel. The grinder used in the lamination process, as shown in Figure 1(c), incorporated both the center-water-feed and a double-nozzle water spray. The double-nozzle delivers water pointing at the edge of the cup wheel from two nozzles at each side of the cup wheel. In the third site visit (Setting 3), the grinder was equipped with both the center-water-feed and a single-nozzle water spray as shown in Figure 1(d).

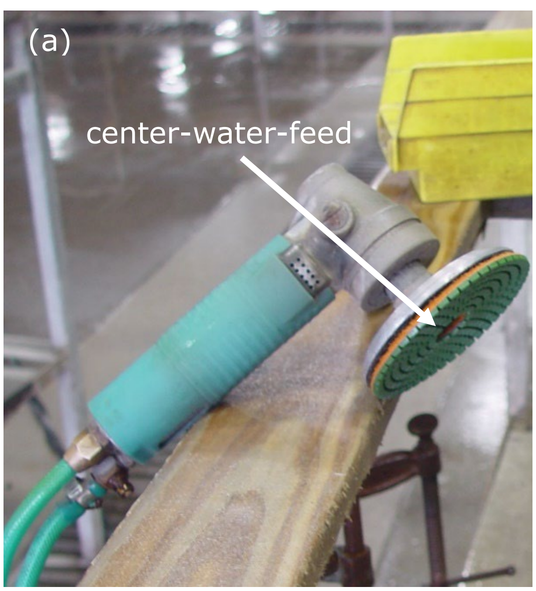


Figure 1 – (a) a handheld pneumatic wet polisher used in the final grinding/polishing process; (b) a handheld pneumatic wet grinder used in the final grinding/polishing process (Setting 1 and Setting 2); (c) a handheld pneumatic wet grinder used in the lamination process (Setting 1); (d) a handheld pneumatic wet grinder used in the final grinding/polishing process (Setting 3). Photos by NIOSH.

Additional dust control measures evaluated in this study included multiple water-wall dust extractors manufactured by T.C. Turrini Claudio srl (Model MB40 and MB60, Italy), pedestal fans (Model: D-TJ-PSC-6P-051A, 30″ diameter, TPI Corporation, Johnson City, Tennessee), and a wet floor scrubber (Model CT105, IPC Eagle, Burnsville, MN). Table 1 lists the key specifications of the two models of the dust extractors provided by their manufacturer. For both models, the designed air flowrate and dimension of the dust extractors translate to a designed average airflow velocity of ~129 fpm at their entrance plane, which refers to the vertical plane where airflow enters the dust extractor's front end along the ceiling and two side walls of the extractor's hooded enclosure. With the designed airflow velocity, the dust extractor is capable of capturing the dust generated in/near the extractor's hooded enclosure.

Table 1 – Key specifications of the water wall dust extractors.

	Height (meter)	Depth (meter)	Width (meter)	Number of vacuum cleaners	Air flowrate (m^3/h; CFM)	Specified dust collection (%)
MB60	2.30	0.98	6.08	3	33,000; 19423	98.3
MB40	2.30	0.98	4.08	2	22,000; 12949	98.3

Each dust extractor has a running waterfall along the width of its rear wall to capture the mist and dust in the air carried in by the airflow. Larger dust settles into the water tank at the bottom of the unit, and smaller dust gets captured by vacuum cleaners inside the unit through an atomization and filtration process. The vacuum cleaners exhaust the filtered air through the top of the unit. Water drained from the atomization and filtration process recirculates back to the front of the unit as the waterfall layer. In addition to moving the generated dust quickly away from the nearby workers, these dust extractors also function as air cleaners for the lamination and final grinding/polishing areas as they continuously capture the dust in the areas and exhaust filtered clean air back to the building.

In Setting 1 and Setting 2, both the lamination and final grinding/polishing areas were equipped with a few pedestal fans intended to provide additional airflow blowing past the work process and toward the dust extractors. However, during the field surveys, the fans were not consistently used and were often placed far away from the dust extractors to allow room for clearance around the workbenches. In addition to the air cleaning controls, a dedicated site worker cleaned the floor of the fabrication areas using the floor wet scrubber in all three settings. This was in addition to the routine floor flushing in the area (water was directed to the channel drains surrounding this area for recycling after onsite water treatment) and intended to help reduce the overall background RCS concentration. The wet grinding and polishing processes generated a large amount of sludge on the floor, which is a mixture of water and dust from the processes. Scrub-cleaning and flushing the floor were proactively protective measures that reduced the chance of the sludge drying and resuspension of RCS particles.

Engineering Control Settings

In this study, three engineering control settings for the control technologies mentioned above were evaluated. Table 2 lists the details of the three settings as well as a baseline engineering control setting, which only includes the water suppression for the grinders and polishers, as a comparison. NIOSH reports [2016a, 2021] cover more detailed information on the Baseline Setting and the data from this setting when NIOSH researchers assessed workers’ exposures and background area concentration before additional ventilation engineering controls were identified and implemented.

Table 2 – Engineering Control Settings in this study.

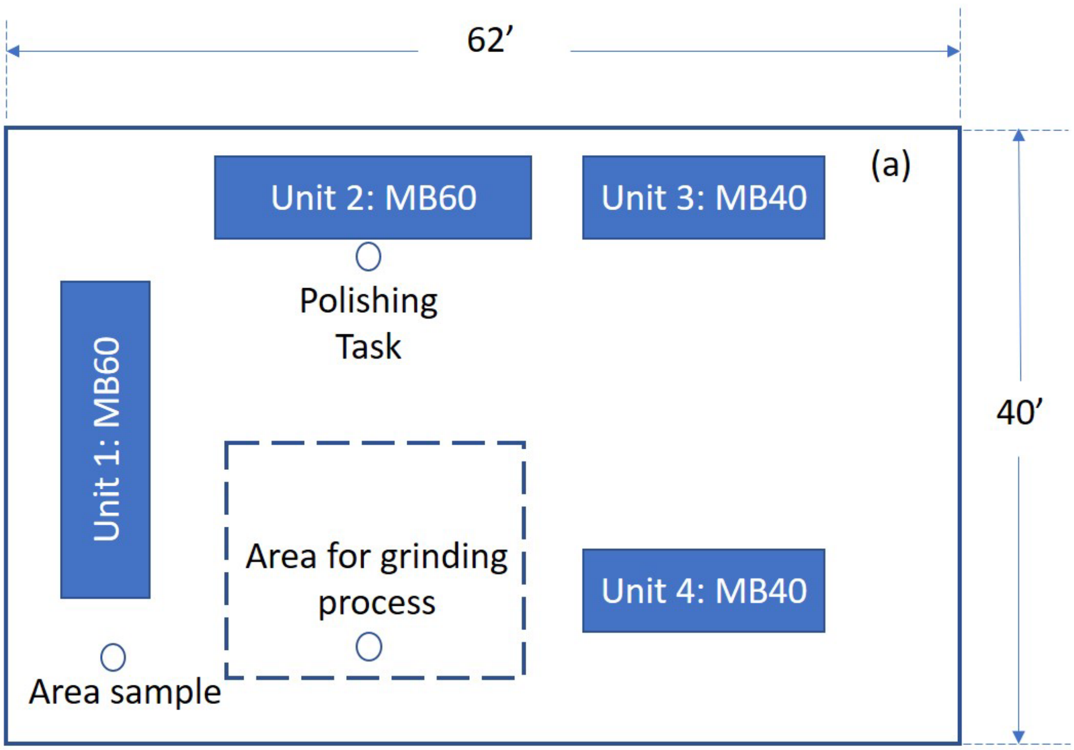
	Baseline Setting	Setting 1	Setting 2	Setting 3
Wetting method for grinder	Single nozzle water spray	Single nozzle water spray	Single nozzle water spray	Single nozzle water spray + center-water-feed
Wetting method for polisher	center-water-feed	center-water-feed	center-water-feed	center-water-feed
Use of pedestal fans	No	Yes	Yes	No
Number of dust extractors in the final grinding/polishing area	0	4	5	4
Number of dust extractor in the lamination area	0	2	2	3
Designated dust extractor for the grinding process	n/a	No	Yes	Yes
Frequency of wet floor scrubbing	n/a	1-2 times per day	Every 2 hours	1-2 times per day
Frequency of wet floor flushing	n/a	1-2 times per day	1-2 times per day	Every 2 hours

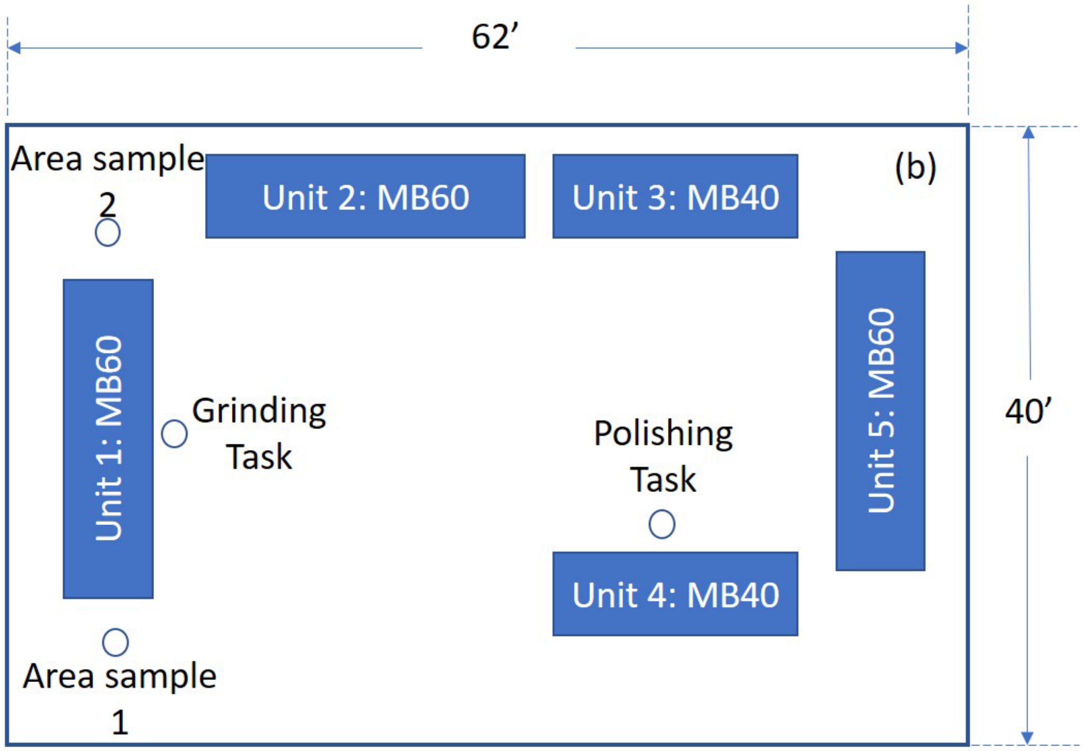
Notes: n/a means “not applicable”.

As shown in Table 2, one major difference among the three settings is the layout of the final grinding/polishing area with different numbers of dust extractors. Figure 2 illustrates this difference as well as the sampling locations. In addition, a designated dust extractor was used for the grinding process in Setting 2 and Setting 3 while the grinding process in Setting 1 took place within an area estimated by the dashed line in Figure 2(a), which was further away from any of the four dust extractors. Figure 3(a) shows a photo taken at the final grinding/polishing area under Setting 1. The worker at the near end of the photo was conducting a grinding task and the other worker at the far end was conducting a polishing task in front of a MB60 dust extractor. The worker who conducted the grinding task worked almost exclusively in front of Unit 1 dust extractor (MB60) under Setting 2 as marked in Figure 2(b) and exclusively in front of Unit 4 dust extractor (MB40) under Setting 3 as marked in Figure 2(c). Figure 3(b) shows a picture taken for this worker conducting the grinding task in Setting 2. Under all three settings, once the grinding task was complete, the worker pushed the stones on workbenches to the group of workers performing the polishing tasks in front of one of the dust extractors. As marked in Figure 2, the participating worker who conducted the polishing task worked exclusively in front of a designated dust extractor in all three settings.

Another major difference among the three settings is the frequency of wet floor cleaning by either the floor scrubber or the floor flushing. Figure 4 shows a picture of a worker conducting the wet floor scrubbing task in the final grinding/polishing area. The housekeeping measure of floor cleaning should reduce the overall background RCS concentration by reducing the resuspension of the silica dust on the floor. Setting 2 increased the frequency of using the floor scrubber while Setting 3 increased the frequency of floor flushing.

Setting 3 stopped using pedestal fans with the concern of dispersing dust in undesirable directions, e.g., blowing dust towards a nearby worker if the fans were accidentally moved by the traffic in the shop. Also, the grinder used in Setting 3 was equipped with both a single-nozzle water spray and center-water-feed to increase its wetting effectiveness. The workers in Setting 3 reported to have received enhanced training to follow workplace practices of 1) positioning themselves upstream of the airflow from the handheld tools to the dust extractors; and 2) adjusting the workbenches to perform the grinding or polishing task inside or near the dust extractor's hooded enclosure as much as possible, as illustrated in Figure 3(c) in comparison to Setting 2 shown in Figure 3(b). These practices should improve the dust capture by the dust extractors.




62’
40’
(b)
Area sample 2
Unit 2: MB60
Unit 3: MB40
Unit 1: MB60
Grinding Task
Polishing Task
Unit 5: MB60
Unit 4: MB40
Area sample 1

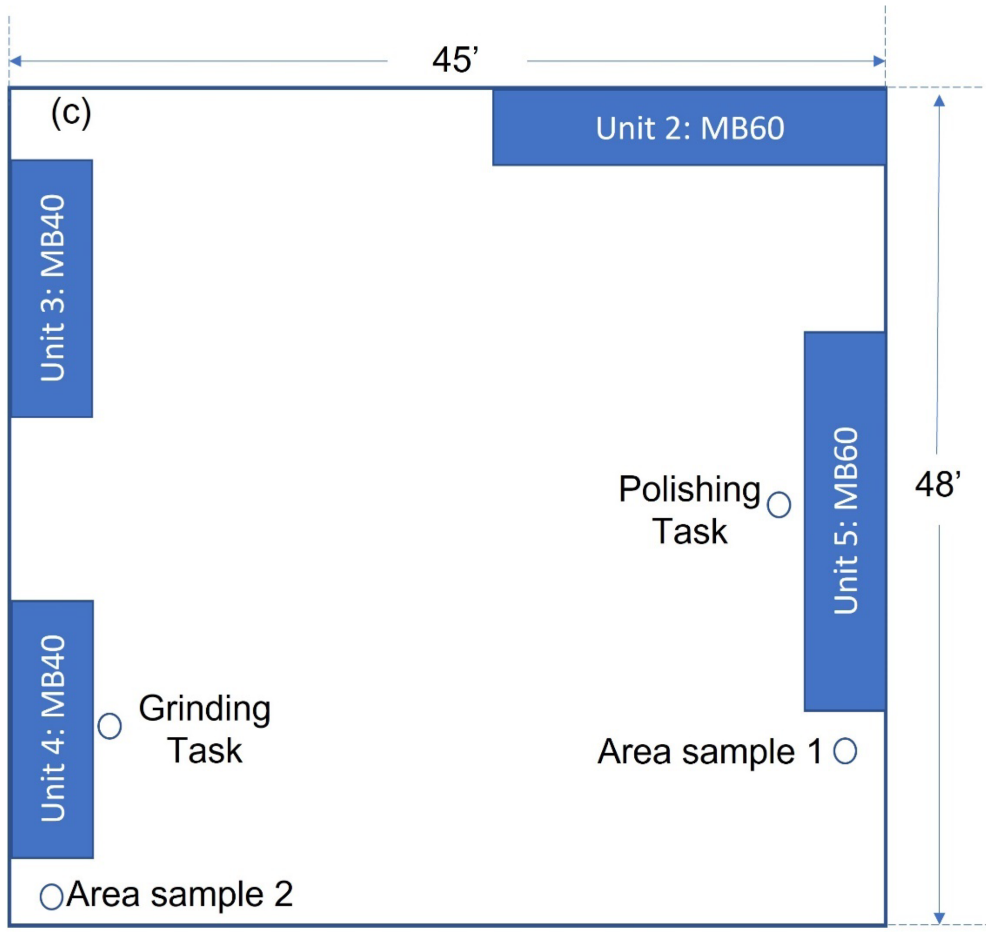


Figure 2 – Final grinding and polishing area and the locations of the dust extractors and area sampling (a) Setting 1; (b) Setting 2; (c) Setting 3.


(a)


(b)

Figure 3 – (a) Two workers working in front of a MB60 water wall dust extractor (Unit 1 in Figure 2a) in the final grinding/polishing process in Setting 1; (b) a worker conducting the grinding task in front of a MB60 water wall dust extractor in Setting 2; (c) a worker conducting the grinding task in front of a MB40 water wall dust extractor in Setting 3. Photos by NIOSH.

Figure 4 – A worker operating a CT105 wet scrubber to clean the floor of the fabrication area. Photo by NIOSH.

Occupational Exposure Limits and Health Effects

As a guide to the evaluation of the hazards posed by workplace exposures, NIOSH investigators use mandatory and recommended Occupational Exposure Limits (OELs) when evaluating chemical, physical, and biological agents in the workplace. Generally, OELs suggest levels of exposure to which most workers may be exposed up to 10 hours per day, 40 hours per week for a working lifetime without experiencing adverse health effects. It is, however, important to note that not all workers will be protected from adverse health effects even though their exposures are maintained below these levels. A small percentage may experience adverse health effects because of individual susceptibility, a pre-existing medical condition, and/or hypersensitivity (allergy). In addition, some hazardous substances may act in combination with other workplace exposures, the general environment, or with medications or personal habits of the worker to produce health effects even if the occupational exposures are controlled at the level set by the exposure limit. Combined effects are often not considered in the OEL. Also, some substances are absorbed by direct contact with the skin and mucous membranes, thus increasing the overall exposure. Finally, OELs may change over the years as new information on the toxic effects of an agent become available.

Most OELs are expressed as a TWA exposure. A TWA exposure refers to the average airborne concentration of a substance during a normal 8- to 10-hour workday. Some substances have a recommended Short-Term Exposure Limit (STEL) or ceiling values which are intended to supplement the TWA where there are recognized toxic effects from higher exposures over the short-term.

In the U.S., OELs have been established by Federal agencies, professional organizations, state and local governments, and other entities. The U.S. Department of Labor OSHA PELs [CFR 2017] are occupational exposure limits that are legally enforceable in covered workplaces under the Occupational Safety and Health Act. NIOSH recommendations are based on a critical review of the scientific and technical information available on the prevalence of health effects, the existence of safety and health risks, and the adequacy of methods to identify and control hazards [NIOSH 1992]. They have been developed using a weight of evidence approach and formal peer review process. Other OELs that are commonly used and cited in the U.S. include the Threshold Limit Values (TLVs®) recommended by American Conference of Governmental Industrial Hygienists (ACGIH®), a professional organization [ACGIH 2023]. ACGIH® TLVs are considered voluntary guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards".

OSHA requires an employer to furnish employees a place of employment that is free from recognized hazards that are causing or are likely to cause death or serious physical harm [Occupational Safety and Health Act of 1970, Public Law 91–596, sec. 5(a)(1)]. Thus, employers are required to comply with OSHA PELs. Some hazardous agents do not have PELs, however, and for others, the PELs do not reflect the most current health-based information. Thus, NIOSH investigators encourage employers to consider the other OELs in making risk assessment and risk management decisions to best protect the health of their employees. NIOSH investigators also encourage the use of the traditional hierarchy of controls approach to eliminating or minimizing identified workplace hazards. This includes, in preferential order, the use of: (1) elimination of the hazardous agent, (2) substitution of the hazardous agent, (3) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation) (4) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (5) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection).

Respirable Crystalline Silica Exposure Limits

When dust controls are not used or maintained or proper practices are not followed, RCS exposures can exceed the NIOSH REL, the OSHA PEL, or the ACGIH TLV. NIOSH recommends an exposure limit for RCS of 0.05 mg/m^3 as a TWA determined during a full-shift sample for up to a 10-hr workday during a 40-hr workweek to reduce the risk of developing silicosis, lung cancer, and other adverse health effects [NIOSH 2002]. When source controls cannot keep exposures below the NIOSH REL, NIOSH also recommends minimizing the risk of illness that remains for workers exposed at the REL by substituting less hazardous materials for crystalline silica when feasible, by using appropriate respiratory protection, and by making medical examinations available to exposed workers [NIOSH 2002]. In cases of simultaneous exposure to more than one form of crystalline silica, the concentration of free silica in air can be expressed as micrograms of free silica per cubic meter of air sampled (μg/m^3) [NIOSH 1975].

$$\mu\mathrm{gS}_i O_2/\mathrm{m}^3 = \frac{\mu\mathrm{gQ}+\mu\mathrm{gC}+\mu\mathrm{gT}+\mu\mathrm{gP}}{V} \quad (1)$$

Where Q is quartz, C is cristobalite, and T is tridymite, P is “other polymorphs”, and V is sampled air volume.

The current OSHA PEL for RCS is 0.05 mg/m^3 (50 μg/m^3) as an 8-hr TWA [CFR 2016]. The ACGIH TLV for α-quartz (the most abundant toxic form of silica, stable below 573°C) and cristobalite (respirable fraction) is 0.025 mg/m^3 (25 μg/m^3) [ACGIH 2013]. The TLV is intended to mitigate the risk of pulmonary fibrosis and lung cancer.

Methodology

Sampling Strategy

Under each engineering control setting, three PBZ air samples were collected on three days for each participating worker (three participants under Setting 1 for conducting grinding, polishing and lamination tasks, respectively; and two participants under Setting 2 and Setting 3 for conducting grinding and polishing tasks, respectively). In addition, concurrent area air samples were collected in the final grinding/polishing area each day (one location under Setting 1, and two locations under Setting 2 and Setting 3, as marked in Figure 2). Samples in Setting 1 and Setting 2 were taken for the full shifts, with the sampling paused during the lunch breaks so that only the working time was sampled. Prior to the site visit for Setting 3, the shop made an improvement on its process design to minimize the need for manual grinding. Therefore, the worker performing the grinding task spent a considerable amount of time in the later part of the shift on polishing. To make the task-based evaluation comparable to previous settings, the samples in Setting 3 were only taken in the morning shift of each day when the workers exclusively performed one task (grinding or polishing).

Sampling Procedures

Both PBZ and area samples for respirable dust were collected at a flow rate of 4.2 liters per minute (L/min) using a battery-operated sampling pump (Gilian GilAir Plus, Sensidyne LP, Clearwater, FL) calibrated before and after each day’s use using a DryCal Primary Flow Calibrator (Bios Defender 510, Mesa Laboratories, Inc., Lakewood, CO). For PBZ samples, a sampling pump was clipped to the sampled worker's belt worn at his waist. The pump was connected via Tygon® tubing and a tapered Leur-type fitting to a pre-weighed, 37-mm diameter, 5- µm pore-size polyvinyl chloride (PVC) filter supported by a backup pad in a three-piece filter cassette sealed with a cellulose shrink band (in accordance with NIOSH Methods 0600 and 7500) [NIOSH 1998, NIOSH 2003]. The front portion of the cassette was removed and the cassette was attached to a respirable dust cyclone (model GK2.69, BGI Inc., Waltham, MA). At a flow rate of 4.2 L/min, the GK2.69 cyclone has a 50% cut point (D_{50}) of 4.0 µm [BGI 2011]. D_{50} is the aerodynamic diameter of the particle at which penetration into the cyclone declines to 50% [Vincent 2007]. The cyclone was clipped to the sampled workers' shirts near their breathing zone. The sample set for the area sample was installed on a tripod with customized mounts for holding the sampling pump and cyclone approximately 5 ft above the ground. In addition to the air samples, two field blank samples were taken on each sampling day. Bulk dust samples (two for Setting 1, and one for Setting 2 and Setting 3, respectively) were also collected from the settled dust near the workers' workbenches in accordance with NIOSH Method 7500 [NIOSH 2003].

The filter samples were analyzed for respirable dust according to NIOSH Method 0600 [NIOSH 1998]. The filters were allowed to equilibrate for a minimum of two hours before weighing. A static neutralizer was placed in front of the balance (model AT201, Mettler-Toledo, Columbus, OH) and each filter was passed over the neutralizer before weighing. The limit of detection (LOD) and the limit of quantitation (LOQ) of the respirable dust analysis are listed in Table 3.

Table 3 – The limit of detection (LOD) and the limit of quantitation (LOQ) for all the sample analysis.

Engineering Control Setting		Air Samples (µg/sample)				Bulk Samples (%)		
		respirable dust	quartz	cristobalite	tridymite	quartz	cristobalite	tridymite
1	LOD	20	5	5	10	0.3	0.3	0.5
	LOQ	76	17	17	33	0.99	0.91	1.7
2	LOD	20	5	6	10	0.3	0.3	0.5
	LOQ	53	17	21	33	0.83	0.83	1.7
3	LOD	10	5	5	10	0.5	0.5	1.0
	LOQ	49	17	17	33	1.9	1.9	3.3

Crystalline silica analysis of air and bulk dust samples was performed using X-ray diffraction according to NIOSH Method 7500 [NIOSH 2003]. The LODs and LOQs for quartz, cristobalite, and tridymite in both air samples and bulk samples are also listed in Table 3.

Flow Measurement

An air velocity meter (VelociCalc® 9565-P, TSI Inc., Shoreview, MN) was used to measure the air flow velocity near the middle of the entrance plane of each dust extractor at the height of the workbenches (about 40” off the ground). The velocity meter logged data every second, and recorded the average flow velocity for 60 seconds of continuous measurement.

Results

Silica Content in Air and Bulk Samples

No respirable dust or crystalline silica was detected on any of the field blank samples. The bulk dust samples were collected from surfaces near the workbenches of the sampled workers. The two samples under Setting 1 contained 37% and 42% quartz, respectively, and the sample under Setting 2 contained 33% quartz. The bulk dust sample collected in Setting 3 was determined by the lab to be insufficient to perform a bulk dust sample analysis. No cristobalite or tridymite was detected in the bulk samples.

Table 4 – Respirable Silica Masses, Respirable Dust Masses, and Percent Silica.

Engineering Control Setting	Day	Task	Respirable dust (µg/ sample)	Respirable quartz (µg/ sample)	Respirable cristobalite (µg/ sample)	RCS (µg/ sample)	Silica content (%)
1	Day 1	grinding	400.0	100.0	13.0	113.0	28.3
		polishing	280.0	61.0	11.0	72.0	25.7
		lamination	170.0	42.0	3.5*	45.5	26.8
		area	47.0	15.0	8.7	23.7	50.4
	Day 2	grinding	340.0	88.0	6.9	94.9	27.9
		polishing	260.0	83.0	9.7	92.7	35.7
		lamination	190.0	34.0	3.5*	37.5	19.8
		area	210.0	62.0	8.1	70.1	33.4
	Day 3	grinding	440.0	150.0	52.0	202.0	45.9
		polishing	270.0	90.0	22.0	112.0	41.5
		lamination	140.0	39.0	21.0	60.0	42.9
		area	180.0	56.0	16.0	72.0	40.0
2	Day 1	grinding	140.0	46.0	11.0	57.0	40.7
		polishing	250.0	40.0	14.0	54.0	21.6
		area 1	44.0	14.0	4.2*	18.2	41.5
		area 2	34.0	5.6	4.2*	9.8	29.0
	Day 2	grinding	170.0	71.0	19.0	90.0	52.9
		polishing	290.0	82.0	15.0	97.0	33.5
		area 1	110.0	45.0	4.2*	49.2	44.8
		area 2	64.0	27.0	8.3	35.3	55.2
	Day 3	grinding	120.0	39.0	15.0	54.0	45.0
		polishing	290.0	83.0	18.0	101.0	34.8
		area 1	110.0	15.0	7.4	22.4	20.4

Engineering Control Setting	Day	Task	Respirable dust (µg/ sample)	Respirable quartz (µg/ sample)	Respirable cristobalite (µg/ sample)	RCS (µg/ sample)	Silica content (%)
		area 2	94.0	14.0	4.2*	18.2	19.4
3	Day 1	grinding	77.0	9.0	-	9.0	11.7
		polishing	77.0	3.5*	-	3.5*	4.6
		area 1	87.0	3.5*	-	3.5*	4.1
		area 2	77.0	7.4	-	7.4	9.6
	Day 2	grinding	77.0	9.9	-	9.9	12.9
		polishing	57.0	3.5*	-	3.5*	6.2
		area 1	57.0	3.5*	-	3.5*	6.2
		area 2	67.0	7.3	-	7.3	10.9
	Day 3	grinding	77.0	6.0	-	6.0	7.8
		polishing	67.0	3.5*	-	3.5*	5.3
		area 1	67.0	3.5*	-	3.5*	5.3
		area 2	77.0	10.0	-	10.0	13.0

Notes: data with a * means the sampled data was below the LOD and a value of LOD/SQRT(2) was used in the calculation; "-" means no value is assigned to the data, which was below the LOD since no cristobalite was detected in any sample of the same site visit.

Table 4 presents the respirable dust and RCS masses reported for every air sample collected in this study. All of the air samples contained respirable dust and quartz in amounts that exceeded their respective LODs listed in Table 3. All but six air samples in Setting 1 and 2 had detectable amounts of cristobalite, but none of the 12 samples in Setting 3 had detectable amounts of cristobalite. No tridymite was detected in any air samples. Thus, only the quartz and cristobalite results were used in the calculation of the crystalline silica content of the air samples in Setting 1 and 2, while cristobalite was excluded in the calculation for Setting 3. The six samples in Setting 1 and 2 with cristobalite below the LOD were estimated to have LOD/SQRT(2) of 3.5 and 4.2 µg under Setting 1 and 2, respectively based on the LOD listed in Table 3 for cristobalite following Hewett and Ganser [2007]. Similarly, six samples in Setting 3 had quartz below the LOD and were estimated to have LOD/SQRT(2) (3.5 µg) quartz. All the samples have respirable dust masses below the 2 mg upper limit specified by the NIOSH Methods 0600 [NIOSH 1998].

Based on the data presented in Table 4, the RCS content for each air sample was calculated and is listed in the last column. Under Setting 1, the 12 air samples contained from 19.8 to 50.4% crystalline silica, with a mean of 34.9% and a standard deviation of 9.4%; under Setting 2, the 12 air samples contained from 19.4 to 55.2% crystalline silica, with a mean of 36.6% and a standard deviation of 12.2%; and under Setting 3, the 12 air samples contained from 4.1 to 13.0% crystalline silica, with a mean of 8.1% and a standard deviation of 3.3%. The lower silica content within the samples in Setting 3 is likely due to the increased use of newly-formulated engineered stone that has reportedly lower silica content.

Respirable Dust and Respirable Crystalline Silica Results

Table 5 reports the TWA exposures to respirable dust and RCS for the area samples and participating workers. The sampling time for seven samples in Setting 1 and Setting 2 was slightly over 8 hours (480 min) each, and it was well short of 8 hours for two samples. As mentioned earlier, the samples in Setting 3 were only taken in the morning shift of each day when the worker exclusively performed one task (grinding or polishing). The work tasks conducted by the participating workers during the field investigation were reported to be consistent with their full-shift regular work routine, except for the worker who performed grinding in Setting 3 whose full-shift exposure is likely lower than that in the morning shift due to performing more polishing task in the afternoon with lower exposure. Thus, the TWA exposures reported in Table 5, regardless of the actual sampling time, are generally considered to be representative or the worst-case scenario of the 8-hour full-shift exposures these workers would experience under the respective engineering control settings. The exception to this statement is the lamination task worker, as the lamination process at this site only included a very short amount of time dedicated to cutting and grinding stones while most of the time was spent setting up the stones and gluing. The exposure of the worker conducting the lamination task was highly dependent upon the actual amount of cutting and grinding needed during the sampling periods. The lamination worker's TWA RCS exposure while conducting lamination was well below the OSHA PEL of 50 $\mu g/m^3$ on the first two days under Setting 1 when sampled over a full-shift. However, his TWA exposure was observed to be higher on the third day, when he was sampled for a shortened work period (269.8 min) due to an early departure. It is uncertain how representative this data point is for full-shift of lamination at this site because the worker's proportion of actual time spent cutting and grinding was not known and therefore couldn't be compared to the other two days when full-shift exposures were much lower. As a result, this data point is excluded from the overall data analyses. During the research conducted under Setting 2 and Setting 3, the one-person research team lacked sufficient time to track the lamination worker's times spent on cutting due to numerous other activities being simultaneously monitored and sampled. Thus, the lamination process was not evaluated for these two settings.

The focus of this research activity was to compare the TWA exposure data for the final grinding and polishing tasks as well as TWA concentrations in area samples under the evaluated engineering control settings. Extrapolating TWA exposures based on tasks (e.g., grinding, polishing, and area samples) and shifts of varying durations into 8-hour TWA exposures was not helpful to the engineering control effectiveness comparisons and was not conducted. However, the comparison of the data with the OSHA PEL and action level may offer helpful context when discussing the control effectiveness.

Under Setting 1, the exposures from grinding were noticeably higher than those from the other two tasks and the area samples. The full-shift TWA respirable dust exposures ranged from 184.7 to 214.3 $\mu g/m^3$ for grinding, from 130.1 to 150.5

μg/m^3 for polishing, from 91.4 to 101.5 μg/m^3 for lamination (as aforementioned, full-shift exposures data were only available on Day 1 and Day 2 for lamination), and from 94.7 to 112.9 μg/m^3 for the area samples. The full-shift TWA RCS exposures ranged from 51.5 to 96.9 μg/m^3 for grinding, from 38.7 to 54.0 μg/m^3 for polishing, from 20.0 to 24.5 μg/m^3 for lamination, and from 37.7 to 51.4 μg/m^3 for the area sample.

Under Setting 2, the exposures from grinding and polishing were noticeably higher than those from the area samples. The full-shift TWA respirable dust exposures ranged from 62.8 to 80.0 μg/m^3 for grinding, from 135.3 to 152.8 μg/m^3 for polishing, and from 18.2 to 57.9 μg/m^3 for the area sample. The full-shift TWA RCS exposures ranged from 28.0 to 42.4 μg/m^3 for grinding, from 29.2 to 53.2 μg/m^3 for polishing, and from 5.3 to 25.9 μg/m^3 for the area sample.

Under Setting 3, the TWA respirable dust exposures ranged from 65.7 to 75.9 μg/m^3 for grinding, from 49.8 to 72.8 μg/m^3 for polishing, and from 47.4 to 84.0 μg/m^3 for the area sample. The TWA RCS exposures ranged from 5.9 to 8.5 μg/m^3 for grinding, from 3.1 to 3.4 μg/m^3 for polishing, and from 2.9 to 9.7 μg/m^3 for the area sample.

Table 5 – Respirable Dust and RCS Exposure Results.

Engineering Control Setting	Day	Task	Volume (L)	Sampling time (min)	TWA respirable dust exposure (μg/m^3)	TWA RCS exposure (μg/m^3)
1	Day 1	grinding	1866.7	450.4	214.3	60.5
		polishing	1861.0	449.1	150.5	38.7
		lamination	1860.0	448.9	91.4	24.5
		area	461.1	110.4	101.9	51.4
	Day 2	grinding	1841.0	436.8	184.7	51.5
		polishing	1824.9	433.7	142.5	50.8
		lamination	1872.8	445.0	101.5	20.0
		area	1860.5	441.6	112.9	37.7
	Day 3	grinding	2083.6	495.9*	211.2*	96.9*
		polishing	2074.8	495.1*	130.1*	54.0*
		lamination	1133.4	269.8	123.5†	52.9†
		area	1901.7	453.5	94.7	37.9
2	Day 1	grinding	2033.2	484.1*	68.9*	28.0*
		polishing	1847.1	439.8	135.3	29.2
		area 1	1855.8	441.9	23.7	9.8
		area 2	1867.3	430.9	18.2	5.3
	Day 2	grinding	2124.8	505.9*	80.0*	42.4*
		polishing	2092.9	498.3*	138.6*	46.3*
		area 1	1899.0	452.1	57.9	25.9
		area 2	1867.2	444.6	34.3	18.9
	Day 3	grinding	1911.9	455.2	62.8	28.2
		polishing	1897.3	451.7	152.8	53.2
		area 1	2046.4	487.2*	53.8*	10.9*

Engineering Control Setting	Day	Task	Volume (L)	Sampling time (min)	TWA respirable dust exposure (μg/m³)	TWA RCS exposure (μg/m³)
		area 2	2050.8	488.3*	45.8*	8.9*
3	Day 1	grinding	1056.1	250.6	72.9	8.5
		polishing	1058.3	250.8	72.8	3.3
		area 1	1035.8	245.7	84.0	3.4
		area 2	977.4	232.7	78.8	7.6
	Day 2	grinding	1171.6	278.1	65.7	8.4
		polishing	1145.6	271.9	49.8	3.1
		area 1	1201.8	285.9	47.4	2.9
		area 2	1209.1	289.4	55.4	6.0
	Day 3	grinding	1015.1	241.6	75.9	5.9
		polishing	1029.6	244.0	65.1	3.4
		area 1	1040.2	247.7	64.4	3.4
		area 2	1031.8	246.4	74.6	9.7

Notes: data annotated with a "*" indicates that the sampling time exceeded 8 hours and thus might be directly comparable against recognized occupational exposure limits (OELs); data annotated with a "†" were excluded from the overall data analyses because of the significantly shortened sampling period compared to other samples in the same Setting.

Airflow velocity of the dust extractors

Table 6 lists the airflow velocity measured at the middle of the entrance plane of the dust extractors on eight days during the study (the air velocity meter was not available for Day 1 under Setting 1). Units 1-5 were located at the final grinding/polishing area in different settings as marked on Figure 2. Units 6 and 7 were located at the lamination area.

On some occasions in Setting 1 and Setting 2, the measured airflow velocity was apparently higher than the other measured data, so these outliers are marked with * in Table 6. This was due to a pedestal fan setup nearby. Excluding those data points that may have been affected by the pedestal fans, the airflow velocity of the 6 measured units under Setting 1 were in a narrow range with a mean of 111 fpm and a standard deviation of 12 fpm, and they are close to the average airflow velocity for the 5 measured units under Setting 2 (a mean of 96 fpm and a standard deviation of 22 fpm) and the 4 measured units under Setting 3 (a mean of 93 fpm and a standard deviation of 18 fpm). They were all slightly lower than the average designed airflow velocity at the entrance plane of the dust extractors which was 129 fpm as derived from the manufacturer's specifications.

Table 6 – Airflow velocity of the dust extractors (fpm)

Engineering Control Setting	Day	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7
1	Day 2	180*	103	100	123	-	119	228*
	Day 3	108	130	225*	146	-	109	97
2	Day 1	280*	54	97	134	84	-	-
	Day 2	75	87	108	116	62	-	-

Engineering Control Setting	Day	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7
	Day 3	96	95	112	106	119	-	-
3	Day 1	-	109	128	85	90	-	-
	Day 2	-	63	76	72	98	-	-
	Day 3	-	92	107	95	103	-	-

Notes: data with a * indicates that they may be affected by pedestal fans setup nearby; "-" means no value is available.

Data analyses and discussions

Table 7 lists a summary of the statistics of data analyses for the exposure data. Data listed for Baseline Setting are full-shift TWAs from two previous studies with the wetting of the grinding/polishing tools as the only control measure. More specifically, the data from area samples (6 samples) collected under the Baseline Setting were full-shift TWAs from the previous report by NIOSH [2021]; and the data of grinding (4 samples), polishing (5 samples) and lamination (2 samples) tasks of Baseline Setting were full-shift TWAs from NIOSH [2016a].

All the TWA respirable dust exposures reported in Table 7 were well below the 5 mg/m^3 OSHA PEL for Particulates Not Otherwise Regulated. However, since this dust contained RCS, the observed RCS exposures must be compared with the RCS PEL in order to determine whether exposures were successfully controlled.

Table 7 – Summary Statistics of Data Analyses

		grinding	polishing	lamination	area
TWA respirable dust exposure (µg/m^3)	Baseline Setting	300.0 ± 88.3	76.4 ± 8.4	104.5*	171.7 ± 56.4
	Setting 1	203.4 ± 16.3	141.0 ± 10.3	96.5*	103.2 ± 9.2
	Setting 2	70.5 ± 8.7	142.3 ± 9.3	-	39.0 ± 16.2
	Setting 3	71.5 ± 5.2	62.5 ± 11.7	-	67.4 ± 14.2
TWA RCS exposure (µg/m^3)	Baseline Setting	120.8 ± 20.2	14.4 ± 3.3	25.5*	47.3 ± 20.2
	Setting 1	69.6 ± 24.0	47.8 ± 8.1	22.3*	42.3 ± 7.9
	Setting 2	32.9 ± 8.2	42.9 ± 12.4	-	13.3 ± 7.6
	Setting 3	7.6 ± 1.5	3.3 ± 0.2	-	5.5 ± 2.7
Silica content (%)	Baseline Setting	41.5 ± 7.3	19.0 ± 3.7	25.0*	27.1 ± 6.1
	Setting 1	34.0 ± 10.3	34.3 ± 8.0	23.3*	41.3 ± 8.6
	Setting 2	46.2 ± 6.2	30.0 ± 7.3	-	35.0 ± 14.4
	Setting 3	10.8 ± 2.7	5.4 ± 0.8	-	8.2 ± 3.5

Notes: data with a * does not have a standard deviation as only two samples are available; "-" means no value is available.

Comparing Setting 1 to Baseline Setting

Comparing Setting 1 and Baseline Setting, the silica content is not statistically different for all the three tasks and area samples (P = 0.353 for grinding; 0.066 for polishing; 0.780 for lamination; and 0.082 for the area sample).

Area samples: the area samples, under Setting 1, do have a significantly lower respirable dust concentration (*P* = 0.030). This suggests that the additional control measures under Setting 1 may help capture the respirable dust in the area. However, the RCS concentration in area samples under Setting 1 is only slightly lower than that of the Baseline Setting (*P* = 0.618), and is still near the OSHA PEL and NIOSH REL of 50 $\mu g/m^3$. This is likely due to the apparently higher silica content in the samples of Setting 1 (41.3% vs 27.1%, *P* = 0.082).

Grinding: the RCS exposure for grinding under Setting 1 is significantly reduced (*P* = 0.042) with the added control measures compared to the Baseline Setting. However, the reduction on respirable dust exposure is apparent but not statistically significant (*P* = 0.114). Although the worker was expected to experience high exposures during active grinding, he also spent a considerable amount of time during the full-shift moving stone slabs and taking measurements on stone dimensions when his exposure may be close to the background concentration measured by the area samples. Therefore, the reduced exposure for the grinding task can be possibly attributed to both the direct benefit of the additional control measures and the indirect benefit of a reduced background concentration in the area. However, the reduced level of RCS exposure (69.6 ± 24.0 $\mu g/m^3$) under Setting 1 is still moderately higher than the OSHA PEL and NIOSH REL of 50 $\mu g/m^3$.

Polishing: both RCS and respirable dust exposures for polishing are unexpectedly higher in Setting 1 than in Baseline Setting (*P* = 0.001 for respirable dust and 0.012 for RCS). It should be noted that the full-shift samples for polishing from NIOSH [2016a] had respirable dust and RCS masses around or lower than their respective LOQs due to the lower flow rate used in the samplers (2.5 L/min), which may introduce some systematic bias for comparison. The same survey reported by NIOSH [2016a] also included some samples with shorter sampling time using the same sampler and pump as those used in this study (Gilian GilAir Plus, Sensidyne LP, Clearwater, FL, flow rate of 4.2 L/min) to evaluate the effect of different stone types. The six short-term samples when polishing both engineered stone and granite had TWA exposures of 156.8 ± 24.1 $\mu g/m^3$ for respirable dust and 34.3 ± 13.6 $\mu g/m^3$ for RCS, and they are close to the TWA exposures found in Setting 1 of this study (*P* = 0.212 for respirable dust and 0.108 for RCS).

Lamination: the additional control measures of Setting 1 do not appear to improve the lamination process exposures. However, under both settings, the full-shift TWA RCS exposures during this process were below the OSHA PEL and NIOSH REL of 50 $\mu g/m^3$. This is possibly because the lamination worker only spent a very short amount of time cutting and grinding stones while spending most of the time on set-up and gluing.

Comparing Setting 2 to Baseline Setting

Comparing Setting 2 and Baseline setting, the silica content is not statistically different for grinding (*P* = 0.402), polishing (*P* = 0.105), and area samples (*P* = 0.258).

Area samples: the area samples for Setting 2 have significantly lower respirable dust ($P = 0.002$) and RCS ($P = 0.007$) concentrations, suggesting that this setting of the additional control measures indeed helped clean the background air in the final grinding/polishing area. The background RCS concentration in this area was well below or near the action level (25 μg/m^3) of the OSHA silica rule [CFR 2016].

Grinding: the respirable dust exposure for grinding is significantly reduced ($P = 0.013$) under Setting 2, averaging about only 24% of the exposure level under Baseline Setting. Similarly, the RCS exposure under Setting 2 is only about 27% of that under Baseline Setting ($P = 0.001$). Similar to the aforementioned explanation, the reduced exposure for the grinding task can be possibly attributed to both the direct benefit of Setting 2 when working close to a designated dust extractor and the indirect benefit of a significantly reduced background RCS concentration in the area. It is worth noting that RCS exposure for grinding is lower than the OSHA PEL and NIOSH REL of 50 μg/m^3 on all three days under Setting 2, which is only 47% of that in Setting 1 ($P = 0.106$), and marks significant evidence of improved exposure controls.

Polishing: similar to the results in Setting 1, both RCS and respirable dust exposures are higher in Setting 2 than in Baseline Setting ($P < 0.001$ for respirable dust and 0.052 for RCS). The potential bias among the data in Baseline Setting discussed earlier is also true in this comparison. However, neither RCS ($P = 0.601$) nor respirable dust ($P = 0.886$) exposures for polishing are significantly different between Setting 1 and 2. In fact, the exposure levels are almost identical for the two sets of data. Both settings of added control measures do not seem to help reduce exposures for the polishing task, and the RCS exposure for polishing is still near the OSHA PEL and NIOSH REL. Unlike the grinding task, the workers conducting the polishing task spend most of their time actively polishing during the full-shift, so their indirect benefit from a cleaner background is limited. In addition, although the dust extractors are moving dust away from their PBZs, the active polishing process also continuously feeds dust into their PBZs. Therefore, the intended benefits from the additional controls of both settings may not materialize under these two settings. Nevertheless, the TWA RCS exposures for polishing have been mostly below or just slightly higher than the OSHA PEL and NIOSH REL.

Comparing Setting 3 to Setting 2 and Baseline Setting

The silica content in the samples from Setting 3 is significantly lower than that from Setting 2 ($P = 0.004$ for grinding, 0.027 for polishing, and 0.005 for area samples). In fact, the average silica content of all the samples in Setting 3 is 8.1%, which is only 22% of the average silica content of all the samples in Setting 2 (36.5%). As mentioned earlier, the increased use of engineered stones of new formulation that have reportedly lower silica content during the site visit for Setting 3 was likely the main reason for the observed lower silica content in the air samples. NIOSH [2023] reported that laboratory evaluations of engineered stone formulas with lower silica content indeed resulted in correspondingly lower RCS generation from grinding, leading to potentially lower RCS exposure than grinding certain granite stones.

Area samples: the area samples for Setting 3 have significantly higher respirable dust concentration (P = 0.009) than those for Setting 2. However, they are still significantly lower than the Baseline Setting (67.4 ± 14.2 μg/m^3 vs 171.7 ± 56.4 μg/m^3 with P = 0.005). These results suggest that although the dust control measures in Setting 3 did not clean the background air in the final grinding/polishing area as well as those in Setting 2, they still represented a significant improvement over Baseline Setting. In addition, Setting 3 benefited from lower silica content, with area samples for Setting 3 having 58.6% lower RCS concentrations than those for Setting 2 (5.5 ± 2.7 μg/m^3 vs 13.3 ± 7.6 μg/m^3), although the difference is not statistically significant (P = 0.055). The background RCS concentration in the final griding/polishing area for Setting 3 is well below the action level (25 μg/m^3) of the OSHA silica rule [CFR 2016].

Grinding: the respirable dust exposure for grinding has no significant difference between Setting 3 and Setting 2 (P = 0.881). In fact, they are almost identical, suggesting that both settings controlled the respirable dust exposure equally well compared to Baseline Setting. The RCS exposure in Setting 3 is significantly reduced from a low level in Setting 2 (7.6 ± 1.5 μg/m^3 vs 32.9 ± 8.2 μg/m^3 with P = 0.030) due to the much lower silica content. RCS exposure for grinding in Setting 3 is lower than the action level of the OSHA silica rule [CFR 2016]. Even if the material used in Setting 3 had had the same average silica content as in Setting 2, the RCS exposure for grinding in Setting 3 would still have been lower than the OSHA PEL and NIOSH REL of 50 μg/m^3 on all three days due to the effectiveness of the work practices and engineering controls in place under Setting 3.

Polishing: both respirable dust and RCS exposures in Setting 3 are significantly reduced compared to the results in Setting 2 (P < 0.001 for respirable dust and P = 0.031 for RCS). The significantly reduced RCS exposure (3.3 ± 0.2 μg/m^3), which is much lower than the action level of the OSHA silica rule [CFR 2016], can be partially attributed to the much lower silica content in Setting 3, as explained above. However, the significantly reduced respirable dusts exposure in Setting 3 suggests that the dust control measures and workplace practices in Setting 3 were also successful in controlling the respirable dust from the polishing task, which was not effectively controlled in Setting 1 and Setting 2. Even if the material used in Setting 3 had had the same average silica content as that observed in Setting 2, the RCS exposure for polishing in Setting 3 would still have been lower than the OSHA PEL and NIOSH REL of 50 μg/m^3 on all three days.

Ventilation Settings and Workplace Practice

The average airflow velocity measured for all the deployed dust extractors was slightly reduced from Setting 1 to Setting 3 as shown in Table 6. Reduced airflow velocity may negatively affect the control effectiveness of these dust extractors. Monitoring the airflow velocity may help determine the maintenance schedule of the dust extractors. The airflow velocities measured in this study also support that the improvement on exposure reduction under Setting 3 and Setting 2 compared to

Setting 1 was mainly due to the changes listed in Table 2 and not due to any change in dust extractor performance.

Setting 2 cleaned the background air in the final grinding/polishing area better than Setting 3, possibly due to the use of pedestal fans as this was one of the major differences between the two settings. Pedestal fans, when positioned properly, can increase the air velocity to move the dust toward the dust extractors, thus helping reduce the background dust concentration in the area. However, they need to be constantly monitored because the frequent movement of workbenches around the area may accidently alter their positions. In an undesirable scenario, they may be changed to positions and orientations that blow dust toward nearby workers. It is unclear whether the change of floor cleaning frequency and methods between Setting 2 and Setting 3 may have contributed to the observed difference.

In Setting 3, the respirable dust concentrations from grinding, polishing and area samples were in a narrow range, suggesting that the dust extractors were effective in removing the dust away from the workers' PBZ and capturing them. This result is likely due to the improved workplace practice of enhanced training of the workers to 1) position upstream of the dust source, and 2) adjust the workbench to perform the grinding or polishing task inside or near the dust extractor's hooded enclosure as much as possible. In addition, without the use of pedestal fans in Setting 3, the chance of accidently blowing dust toward nearby workers, thus increasing their exposure, was also reduced. As mentioned earlier, the dust extractor is capable of capturing the dust at the designed airflow velocity only within or near the extractor's hooded enclosure. The airflow velocity drops rapidly outside of the enclosure, which is shallow under the three settings in this study (0.98 m as listed in Table 1). Therefore, the training of workers on positioning themselves and the workbenches to take full advantage of the dust extractor's hooded enclosure is especially important on reducing the RCS exposures when using the dust extractors as a control measure. Overall, the change to working with engineered stone materials that contain lower crystalline silica, engineering controls and workplace practices in Setting 3 mark a successful combination that reduced workers' RCS exposure well below the OSHA PEL and NIOSH REL.

Conclusions and Recommendations

Controlling exposures to occupational hazards is the fundamental method of protecting workers. Traditionally, a hierarchy of controls has been used as a means of determining how to implement feasible and effective controls. One representation of the hierarchy of controls can be summarized as follows:

- Elimination
- Substitution
- Engineering Controls (e.g., ventilation)
- Administrative Controls (e.g., reduced work schedules)
- Personal Protective Equipment (PPE, e.g., respirators)

The idea behind this hierarchy is that the control methods at the top of the list are potentially more effective, protective, and economical (in the long run) than those at the bottom. Following the hierarchy normally leads to the implementation of inherently safer systems, ones where the risk of illness or injury has been substantially reduced.

The significantly reduced RCS exposure for Setting 3 demonstrated the benefit of "Substitution" in the hierarchy of controls. Working with more stone countertop products that have less crystalline silica in Setting 3 resulted in the average silica content of all the samples in this setting being was only 8.1%. Applying this silica content percentage to all the TWA respirable dust exposure data in Table 5 would lead to RCS exposures in all of the evaluated dust control settings of this study that are below the OSHA PEL. Thus, developing stone countertop products with low or no crystalline silica without introducing other hazards would adhere to the top of the hierarchy of controls and could be effectively incorporated in a layered, overall control strategy.

The research activities reported here sought to evaluate the intervention effectiveness of engineering control options while considering the hierarchy of controls. With the additional control measures adopted under Setting 1, the full-shift TWA RCS exposures for grinding ranged from 51.5 to 96.9 μg/m^3, which were reduced from the range of 93 to 140 μg/m^3 under the less-controlled Baseline Setting. However, the RCS exposures for grinding under Setting 1 were still higher than the OSHA PEL of 50 μg/m^3; while they ranged from 28.0 to 42.4 μg/m^3 under Setting 2, which were all below the OSHA PEL. The TWA RCS exposures for polishing ranged from 38.7 to 54.0 μg/m^3 and from 29.2 to 53.2 μg/m^3 under Setting 1 and 2, respectively, which were below or slightly higher than the OSHA PEL. The TWA RCS concentration for area samples ranged from 37.7 to 51.4 μg/m^3 under Setting 1; while it ranged from 5.3 to 25.9 μg/m^3 under Setting 2. In Setting 3, the TWA RCS exposures ranged from 5.9 to 8.5 μg/m^3 for grinding, from 3.1 to 3.4 μg/m^3 for polishing, and from 2.9 to 9.7 μg/m^3 in the area samples, which were all considerably lower than the OSHA PEL and the action level of the OSHA silica rule. Although the reduced RCS exposures in Setting 3 can be largely attributed to the significantly lower silica content in the respirable dust in this site visit, the consistently lowered concentration of respirable dust, especially for the polishing task, marks an additional important improvement over Setting 2. In fact, even assuming to use the average silica content in Setting 2, the RCS exposure in Setting 3 for both grinding and polishing would still be lower than the OSHA PEL.

The results from this study demonstrate that the incremental improvements in control conditions between Baseline Setting, Setting 1, Setting 2, and Setting 3 were successful in reducing TWA RCS exposures. Setting 3 was particularly successful in reducing the TWA RCS exposures in the final grinding/polishing area and both grinding and polishing tasks below the OSHA PEL and NIOSH REL of 50 μg/m^3. The full-shift RCS exposure for lamination from Setting 1 was considerably lower than the OSHA PEL and NIOSH REL, possibly due to the shorter time spent on cutting and grinding. The successful reduction in exposure to both RCS and respirable dust suggests that the combination of control measures and workplace practices documented in Setting 3 is likely to consistently maintain individual RCS exposures for grinding and polishing beneath the OSHA PEL and NIOSH REL. The workplace practices include training workers to position themselves and workbenches to consistently perform the grinding and polishing within the dust extractor's hooded enclosure. Continued use of control conditions similar to or above and beyond Setting 3, enhanced housekeeping and OSHA-compliant respiratory protection programs should continue to keep workers safe from inhaling harmful levels of RCS.

This evaluation had limitations that could influence the generalizability of the findings. Sampling occurred over 3 days under each of the three specific settings of engineering control measures and workplace practices for comparing their performance on reducing RCS exposures, which may not be representative of other times or seasons of the site when different settings of the control measures may be implemented. The number of hours an employee works can also vary by season, due to changing demand for the product.

The exposure data presented in this report were exclusively collected for research purposes as part of the project Engineering Control of Silica Dust from Stone Countertop Grinding and Polishing, funded by the NIOSH National Occupational Research Agenda (NORA).

A review of the respiratory protection program [CFR 2006] was beyond the scope of this survey. All the workers involved in the production process at this site wore elastomeric, half-face air-purifying respirators with either P100 cartridges or combination P100 and organic vapor cartridges. Therefore, NIOSH recommends that these respirators should continue to be used until sufficient dust control is implemented, and that the employer ensures that the respiratory protection program follows the OSHA standards [CFR 2006].

References

ACGIH® [2023]. 2023 TLVs® and BEIs®: threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

Blatt H, Tracy RJ [1997]. Petrology (2nd ed.). New York: Freeman. p. 66. ISBN 0-7167-2438-3.

Bureau of Mines [1992]. Crystalline silica primer. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Branch of Industrial Minerals, Special Publication.

CFR [2006]. 29 CFR 1910.134. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

CFR [2016]. 29 CFR 1926.1153 and 29 CFR 1910.1053. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

CFR [2017]. 29 CFR 1910.1000. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

Fazio JC, Gandhi SA, Flattery J, Heinzerling A, Kamangar N, Afif N, Cummings KJ, Harrison RJ [2023]. Silicosis Among Immigrant Engineered Stone (Quartz) Countertop Fabrication Workers in California. JAMA Intern Med, 183(9):991-998.

Friedman GK, Harrison R, Bojes H, Worthington K, Filios M [2015]. Notes from the field: silicosis in a countertop fabricator - Texas, 2014. Morb Mortal Wkly Rep, 64(5):129-130.

Kramer MR, Blanc PD, Fireman E, et al [2012]. Artificial Stone Silicosis: Disease Resurgence Among Artificial Stone Workers. Chest, 142(2):419-424.

Lofgren, D.J [2008]. Result of inspections in health hazard industries in a region of the state of Washington. J. Occup. Environ. Hyg. 5:367–379.

NIOSH [1975]. Criteria for a recommended standard – Occupational exposure to crystalline silica. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, HEW Publication No. (NIOSH) 75-120.

NIOSH [1986]. Occupational respiratory diseases. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 86-102.

NIOSH [1992]. Recommendations for occupational safety and health: compendium of policy documents and statements. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 92-100.

NIOSH [1998]. Particulates not otherwise regulated, respirable. NIOSH Manual of Analytical Methods (NMAM®), 4th ed., 2nd Supplement, Schlecht, P.C. & O'Connor, P.F. Eds. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 98-119.

NIOSH [2002]. NIOSH Hazard Review: Health Effects of Occupational Exposure to Respirable Crystalline Silica. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2002-129.

NIOSH [2003]. Silica, crystalline, by XRD (filter redeposition). NIOSH Manual of Analytical Methods (NMAM®), 4th ed., 3rd Supplement, Schlecht, P.C. & O'Connor, P.F. Eds. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2003-154.

NIOSH [2016a]. Evaluation of Crystalline Silica Exposure during Fabrication of Natural and Engineered Stone Countertops. By Zwack LM, Victory KR, Brueck SE, Qi C. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, HHE Report No. 2014-0215-3250.
https://www.cdc.gov/niosh/hhe/reports/pdfs/2014-0215-3250.pdf

NIOSH [2016b]. Engineering Control of Silica Dust from Stone Countertop Fabrication and Installation, In-depth field survey report for the Houston, TX field survey. By Qi C, Echt A. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, EPHB Report NO. 375-11a.
https://www.cdc.gov/niosh/surveyreports/pdfs/375-11a.pdf

NIOSH [2016c]. Engineering Control of Silica Dust from Stone Countertop Fabrication and Installation, In-depth field survey report for the Mendota Heights, MN field survey. By Qi C, Lo L. Cincinnati, OH: Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, EPHB Report No. 2020-DFSE-165.
https://www.cdc.gov/niosh/surveyreports/pdfs/375-12a.pdf

NIOSH [2019]. Field Evaluation of a Mobile Dust Control Booth for Stone Countertop Grinding. By Qi C, Echt A. Cincinnati, OH: Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, EPHB Report No. 375-12a.
https://www.cdc.gov/niosh/surveyreports/pdfs/2020-DFSE-165.pdf

NIOSH [2021]. Engineering Control of Silica Dust from Stone Countertop Fabrication and Installation – Evaluation of Wetting Methods for Grinding. By Qi C, Echt A. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, EPHB Report NO. 2021-DFSE-710.
https://www.cdc.gov/niosh/surveyreports/pdfs/2021-DFSE-710.pdf

NIOSH [2023]. Characterization of Airborne Dust Generated from the Grinding of Natural and Engineered Stone Products. By Thompson D, Qi C. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, EPHB Report NO.

2023-DFSE-1489. https://www.cdc.gov/niosh/surveyreports/pdfs/2023-DFSE-1489.pdf

NIOSH, OSHA [2015]. Worker exposure to silica during countertop manufacturing, finishing and installation. National Institute for Occupational Safety and Health, Occupational Safety and Health Administration. DHHS (NIOSH) Publication No. 2015–106, OSHA HA–3768–2015.
https://www.osha.gov/Publications/OSHA3768.pdf

Pérez-Alonso A, Córdoba-Doña JA, Millares-Lorenzo JL, Figueroa-Murillo E, García-Vadillo C, Romero-Morillo J [2014]. Outbreak of silicosis in Spanish quartz conglomerate workers. International J. Occup. and Environ. Health, 20(1): 26-32.

Phillips ML, Johnson DL, Johnson AC [2013]. Determinants of respirable silica exposure in stone countertop fabrication: a preliminary study. J. Occup. Environ. Hyg., 10(7):368-373.

Rose C, Heinzerling A, Patel K, et al [2019]. Severe silicosis in engineered stone fabrication workers - California, Colorado, Texas, and Washington, 2017-2019. Morb Mortal Wkly Rep, 68(38): 813-818.

Vincent JH [2007]. Aerosol sampling. Chichester, West Sussex, England: John Wiley&Sons, Ltd. Pp. 203.

Delivering on the Nation's promise: Promoting productive workplaces through safety and health research

Get More Information

Find NIOSH products and get answers to workplace safety and health questions:

1-800-CDC-INFO (1-800-232-4636) | TTY: 1-888-232-6348
CDC/NIOSH INFO: cdc.gov/info | cdc.gov/niosh
Monthly *NIOSH eNews*: cdc.gov/niosh/eNews