Workplace Health Without Borders (WHWB) Report

Jaipur Project: Coloured Gemstones Processing

A Pilot Study for Worker Health Issues and Interventions

Prepared for:

American Gem Trade Association

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A: Introduction

Worldwide, occupational diseases kill more than 2 million people a year, according to the U.N. World Health Organization (WHO). Tens of millions of workers around the world are exposed to silica dust, which can cause silicosis. Silicosis is a chronic lung disease that decreases lung capacity, eventually impairs the ability to work, and often results in early death due to complications like heart disease. Silicosis also predisposes people to tuberculosis, especially in low and middle income countries, which partially explains the high rates of tuberculosis in countries like India. Since 2014, the International Agency for Research on Cancer (IARC) has considered two of the most common form of silica (quartz and cristobalite) as known human lung carcinogens.[1]

"Silica" refers here only to free crystalline silica (formula SiO_2) which is found widely in the earth's crust, with quartz being the most common crystalline form. Silica should not be confused with amorphous forms of $Si0_2$, such as diatoms, or compounded crystalline forms of silicates, which do not have the same detrimental impacts on health as free crystalline silica.

The American Gem Trade Association (AGTA) contacted Workplace Health Without Borders (WHWB) to assist with its pilot project to investigate and propose solutions for potential workplace exposures to silica dust in the coloured gemstone processing industry in India. Specifically, AGTA decided to launch this project in the city of Jaipur, Rajasthan, because it is a major centre of production that turns raw stones into finished shaped gemstones for use as jewellery. WHWB was invited by AGTA to participate in the Jaipur pilot project because of its previous work in the agate processing industry in Khambat, India, where silica dust levels were assessed, and tools were piloted to reduce workplace silica exposures.

Planning for the Jaipur pilot project began in mid 2017, but by late 2017, AGTA had partnered with GEMHUB, a multisite research team dedicated to sustainable and ethical production of gemstones. GEMHUB deployed researchers from the University of Queensland's Minerals Industry Safety and Health Centre ("UQ"), who are experts at training and education, in the Jaipur pilot project.

Jointly, a field trip to Jaipur from February 26 to March 6, 2018 occurred to investigate and try dust controls that were expected to lead to improved health outcomes among Jaipur's gemstone workers. This report outlines the methods and findings of the investigation and makes recommendations to sustain and promote the successes of the pilot project.

Additionally, a research assistant was left in Jaipur after the field trip, to gather additional information about gemstone industry hazards, and results are provided here as relevant to AGTA's intentions to positively impact the gemstone processing industry in India.

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[1] IARC, https://monographs.iarc.fr/wp-content/uploads/2018/06/mono100C-14.pdf. Accessed October 19, 2018.

B: The Pilot Project and Follow-Up Investigations

AGTA funded and proposed a pilot project to show Jaipur's coloured gemstone industry ways that could be introduced to reduce mineral dust exposure and reduce health risks for the workforce. Based on AGTA's knowledge and expectations for the conditions in Jaipur factories, the following interventions and strategies were proposed:

- Encourage gemstone processors to use wet techniques during cutting, grinding and polishing of gemstones to reduce airborne dust levels generally;
- Implement workplace cleaning using HEPA vacuums to reduce secondary dust exposures (airborne dust exposures caused by dusts that have settled, but become airborne again when disturbed by cleaning using sweeping or other dry techniques);
- Deploy a simple, inexpensive direct reading scientific instrument that could be purchased and left behind after the field visit, to allow Jaipur employers to verify that dust reduction techniques were successful and sustainable in future;
- Validate the reductions in dust levels, and the efficacy of the direct reading instrument purchased and left behind;
- Gather information and audiovisuals to be used in future for educating and training the gemstone processing employers and workers on the health hazards and ways to control risks.

WHWB agreed to participate and contribute as outlined below[2]

- Advising AGTA and UQ in developing educational materials on prevention of silica exposure, videos, and other relevant occupational health information
- Conducting monitoring at the outset of the project, both with control measures and without control measures
- Provide advice on project implementation, including advising a person based in India who will monitor project implementation.

This report summarizes WHWB findings for the monitoring and validation efforts conducted on behalf of AGTA mentioned above. Follow-up efforts in a laboratory to help interpret measurements in the gemstone processing factories were conducted and are included here as relevant to our conclusions.

In addition, WHWB entered into an agreement with GEMHUB[3] to extend the project by funding a research assistant to collect data by means of questionnaires, videos to support UQ's efforts, dust measurements (with AGTA's recommended instruments) and noise measurements. Training and education materials and plans are not discussed further in this report, as the University of Queensland has completed that part of the project. Noise and dust measurements are included here as they are relevant to AGTA efforts in sustaining the efforts to improve the health of gemstone workers.

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[2] Letter to Jeff Bilgore, Doug Hucker, AGTA from WHWB dated January 17, 2018

[3] Letter to Dr. Salim Ali, University of Delaware, from WHWB dated February 21, 2018.

C: Methods and Strategies

Pilot Project for Silica Dust Control

AGTA recruited a few worksites to participate in the pilot using contacts developed by its members who trade in gemstones in Jaipur. Sites allowed us access to measure dust levels during gemstone processing, take observations and, at their discretion, implement additional dust control measures (wet processing and HEPA vacuums for cleaning, if needed), so that we could re-measure dust levels and report on the degree of improvement that could be achieved.

AGTA chose to purchase a particle counter (PCE Instruments model PCE-PCO-1) after consulting with experts from the US MSHA[4] regarding a simple instrument to estimate silica dust levels. Two such instruments were purchased for this purpose and left in India for use after the pilot project was completed. This type of instrument gives an estimate of the number of particles of various size fractions after only about a few seconds of use. Although this "snapshot" measurement has limitations (discussed in Section D), it provides an indication of dust levels quickly and responds to changes in levels nearly instantaneously, without need for laboratory analysis. The instrument can be cycled to gather many datapoints sequentially and record them for downloading afterwards. However, it does not specify whether the particles are silica or another material. Any dust, whether toxic or not, will cause the instrument to respond. In addition, the data generated by this instrument cannot be compared to any accepted worker exposure limits (discussed below).

WHWB provided two occupational hygienists for the project who measured dust levels in multiple ways to assist in the validation of results and conclusions regarding worker health. Firstly, air samples were collected using validated cyclone and filter technique, which require laboratory analysis to determine both the mass of respirable dust (dust that reaches the deepest parts of lung) collected and silica content of the dust[5]. This was done to estimate the health risks associated with silica dust in a manner identical to that recommended by professionals and used by regulators to ensure compliance with worker exposure limits. It requires air samples to be collected over a minimum of two hours, and the filter samples subsequently sent to a laboratory for analysis, which is a slow and expensive process.

Another direct reading instrument (TSI Inc. Brand Sidepak model AM-520) was also used by WHWB, as this scientific direct-reading instrument estimates mass concentration of dust in the air. As legal and scientific exposure limits for silica are expressed in mass per unit volume of air (milligrams per cubic metre, mg/m^3) this instrument was used to study whether a correlation could be developed between the measurements of dust made by the AGTA-recommended PCE-PCO-1 and measurements made in units consistent with health-based exposure limits.

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[4] U.S Mine Safety and Health Administration

[5] Methods 0600 and 7500 published by the US National Institute for Occupational Safety and Health, available at: https://www.cdc.gov/niosh/docs/2003-154/default.html Accessed October 19, 2018

All three methods (particle counter PCE-PCO-1, cyclone/filter, and Sidepak) were deployed side by side in fixed locations near workers processing gemstones (and producing airborne dusts) during our site visits in February. This was done to help describe how the particle counter compares to the other methods which are more appropriate and recommended by hygienists to measure worker exposures to dusts, like silica.

“Respirable dust” is a technical term used to indicate the particle sizes that are capable of depositing in the gas exchange region of the respiratory tract. Dusts that are too large to penetrate to this region of the lung are not associated with silicosis and thus were not important to collect for the purpose of this investigation. This would exclude about half of the dusts that are 4 micrometers in diameter and all dusts greater than 10 micrometers in diameter. For both methods (Sidepak and Cyclone/Filter) recommended by WHWB, we used a standard size selective device to ensure that only the respirable dusts were collected and measured.

Follow-Up Investigation Funded by GEMHUB

During the pilot project visits to sites picked by AGTA, the team observed high noise levels during many of the operations involved in processing gemstones. This led to a decision to conduct a follow-up investigation where a research assistant was employed to collect data from additional gemstone cutters with both the particle counter and a sound level meter app on a smartphone[6]. Two questionnaires were developed by WHWB and UQ for administration during these follow-up visits; one to document workplace observations, and the other to ask workers about hazards[7]. This follow-up was performed between March and September 2018. These sites were recruited based on word of mouth from factories and workers who were included in the pilot study, contacts from AGTA, and a local college that offers programs to various gemstone trades. As a “convenience” selection, the sites were not randomly selected from the gemstone industry but included if they agreed to allow the investigator to enter, observe and take notes.

Sound level measurements were short term, ranging from about a minute or two during the actual task being observed. Results are presented in decibels using A weighting (dBA) which is the accepted measurement to understand risk to hearing from excessive noise. Additional statistical analysis and interpretation of the particle counter data is still underway as discussed below, in section D5.

D: Results and Discussion – Pilot Study

During the field visit for the pilot, 5 locations were observed; three allowed us to take air samples and two of these accommodated us on more than one day.

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[6] Available from https://www.cdc.gov/niosh/topics/noise/app.html

[7] See Appendix A and B

D1. Gemstone Types Encountered

The table below outlines important physical properties of the gemstones observed or anticipated during our field visits.

Table 1

Gem Stone	Specific Gravity	Hardness	Composition
Corundum			
Ruby	~4	9	Al_2O_3
Sapphire	~4	9	Al_2O_3
Crystalline Silica Minerals			
Quartz (various shades and agate)	~2.6	7	SiO_2
Chalcedony	2.7	7	SiO_2
Amethyst	~2.6	7	SiO_2
Non-Crystalline Silica Mineral			
Opal	2.15	7	SiO_2
Beryl (Beryllium Silicates)			
Emerald	2.7-2.8	7.5-8	$Be_3Al_2Si_6O_{18}$
Aquamarine	2.7	7.5-8	$Be_3Al_2SiO_6$
Other Silicates			
Topaz	2.7-2.8	8	$Al_2SiO_4(F,OH)_2$
Peridot	3.2-4.3	6.5-7	(Mg, Fe)2SiO4
Tourmaline	~3.0	7-7.5	$NaMg_3(Al,Mg)_6B_3Si_6O_{27}(OH)$

Many of the gemstone types observed are silicates (peridot, beryl, etc.) and oxides (corundum, ruby, sapphire), which do not contain “free crystalline silica”. We did encounter the presence of “lemon quartz” and amethyst, which are crystalline silica minerals (with minor impurities that impart colour). One location exclusively processed the cryptocrystalline form of silica (chalcedony). As rough stones were observed to have little to no “waste” rock affixed to the rough gems, there was no significant concern with silica contaminated extraneous materials, only for the gem types themselves being inhaled as dust during processing.

D2. Gemstone Cutting Process

The basic steps observed at the gemstone processing facilities visited in February consisted of

- Sorting (manual inspection)
- Cutting
- Shaping and Facet Cutting
- Polishing

In the facilities observed, all gemstones were processed wet using water, kerosene and even olive oil, due to the reported need for cooling and lubrication to protect the gems from fracturing. This wet processing acts to suppress much of the airborne mineral dusts, by engulfing many of the dust particles that can present risk to health and simultaneously enlarging the particle size enough to allow settling.

No workplaces were found to have visible dust clouds, likely due to this wetting. However, because of the high speed of rotation of cutting or grinding wheels, some fine mist containing mineral dusts was suspected to be present in the micron size range, and air sampling performed to determine if crystalline silica aerosols were controlled adequately with the wetting techniques employed.

As no workplaces were found processing gems completely dry, there was no opportunity to intervene and test before and after implementing wetting as a dust control, as anticipated (based on the information provided by AGTA) during the planning stages of our project. All workplaces observed cleaned floors with wet mopping, which meant that the introduction of HEPA vacuums is unlikely to improve control of exposure to dusts during cleaning. Wet mopping of settled dusts promotes accumulation on the mop and discourages re-suspension of dusts into air.

D3. Air Sampling – Mass Based Results

The results of our air sampling using the Sidepak and filter/cyclone methods at the three sites are summarized in the table below (with lab results in Appendix C). The samples were task- based, meaning that we sampled for a period of time during actual operations, and not for the full work shift. This is commonly done to conservatively estimate worker exposures, as full shift sampling can include breaks in the day when workers are typically not exposed to airborne contaminants and thus lead to lower results.

Table 2

			Average Concentration		
			Sidepak/ Cyclone	Filter/Cyclone	
Factory #	**Location Description**	**Duration**	**Respirable Dust**	**Respirable Dust**	**Silica**
		Minutes	**mg/m3**	**mg/m3**	**mg/m3**
1	Cutting Room (amethyst)	113	0.32	0.26	0.05
1	amethyst polish	198	0.153	<0.17	<0.017
1	amethyst cut	173	0.153	0.24	0.025
2	polishing aquaprase	122	0.184	<0.24	<0.024
2	polishing aquaprase	122	0.134	<0.24	<0.024
2	sizing and polishing aqua	144	0.183	0.3	<0.025
2	aquaprase cut	267	0.275	0.15	<0.011
2	aquaprase shape	261	0.13	0.15	<0.011
3	Cutting Ruby	153	0.161	<0.19	<0.019

Notes:
mg/m3 = milligrams per cubic metre of air
Silica = crystalline silica
"<" indicates that results were below the level of detection by laboratory analysis

Acceptable limits for silica-containing airborne dusts are typically 0.05 to 0.10 mg/m^3 for a full 8 hour shift . Traditionally, limits like these were set to protect against silicosis, as silica was not confirmed to be a lung cancer risk. One influential scientific organization[8] in North America in 2009 adopted a guideline limit for silica of 0.025 mg/m^3 for a full 8-hour shift, which is intended to protect against silicosis and reduce cancer risks. However, the U.S. National Institute for Occupational Safety and Health (NIOSH) still publishes a limit of 0.05 mg/m^3, which is also intended to protect against silicosis and reduce risks of cancer.[9]

From Table 2 it is observed that where a gemstone containing pure silica is being cut (results highlighted in yellow), airborne levels are below the limits for prevention of silicosis but bordering on concern for lung cancer for chronic lifelong exposures. For polishing, even for the site with amethyst, silica measurements were acceptable since below the most stringent limit. The Chalcedony site, despite being 100% silica, also did not result in levels that exceeded the most stringent limit. The single sample from the ruby processing site was not unexpected; no airborne silica was found, confirming the observation that any extraneous minerals attached to the raw rubies does not contain appreciable amounts of silica.

For other relatively non-toxic dusts, historically called 'nuisance' or 'not otherwise classified' dusts, the exposure limit for the respirable size fraction is 3 mg/m^3 in many jurisdictions, and higher under U.S. OSHA legal requirements. As the highest respirable dust level measured in these sites was 0.3 mg/m^3

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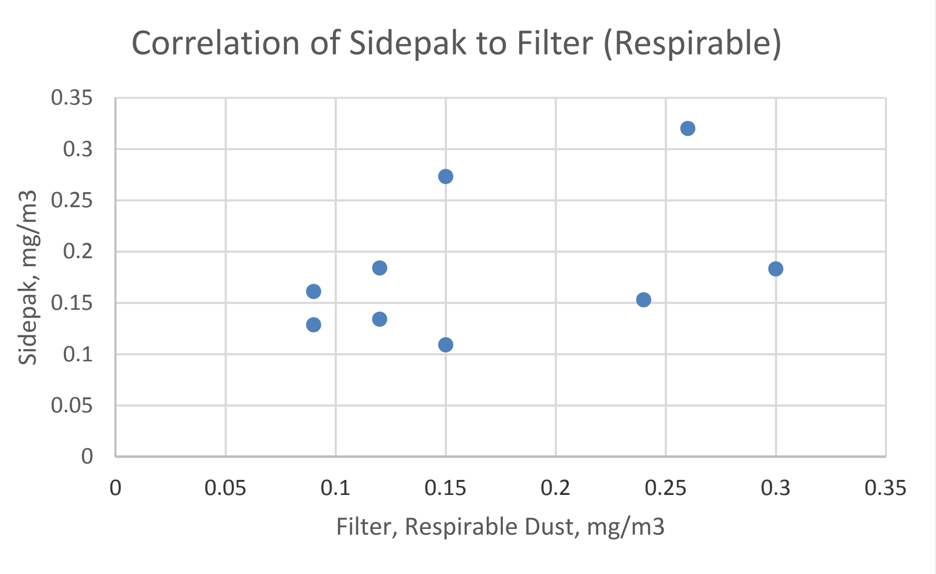
[8] American Conference of Governmental Industrial Hygienists (ACGIH). Threshold Limit Values (2018 ed)
[9] https://www.cdc.gov/niosh/npg/npgd0684.html Accessed October 19, 2018

(10% of the exposure limit), non-silica containing mineral dusts, which can be considered nuisance materials, are not an exposure concern.

As the Sidepak instrument estimates dust concentration using optical techniques, it is not expected to give results identical to the accepted cyclone and filter method. To see how useful it could be in future, the graph below compares results to the mass of respirable dust (not just silica) measured on the filters:



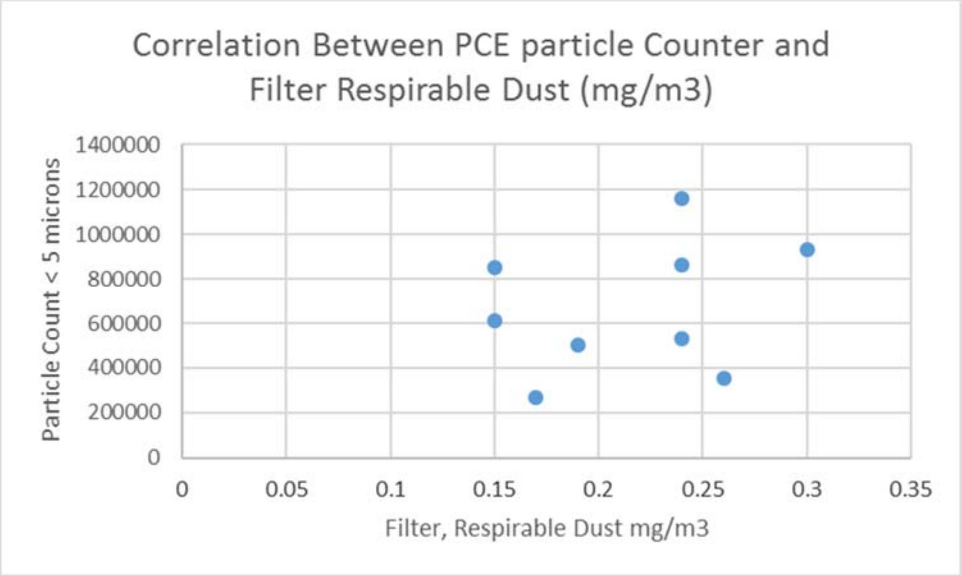
This is visually promising but not precisely matching data between the filter and Sidepak. These results are not totally unexpected as the Sidepak is affected by particle composition, and density, which varied among the 3 sites that participated in the study because of differing gemstones being processed. Also there are only 9 data points, and at levels that are generally low (for nuisance dusts, not for silica).

D4. Air Sampling – Count Based Results

The data from the particle counter are not shown in table 2 as these are not directly comparable to the health guidelines and limits discussed above. A snapshot of what the particle counter data look like is shown below;

The numeric data visible in the instrument display indicate the number of particles per unit volume of air in various size ranges of interest (all expressed in micrometers (microns); 0.3, 0.5, 1.0, 2.5, 5.0 and 10 microns. Ideally to use these counts for comparison to levels of concern for health we would compare the cyclone/filter results to the particle counter and derive a simple “correction factor” to interpret the particle counter.

As a first attempt to derive a simple correction factor, we considered that the particle size range of concern includes 50% of the particles at 4 microns and increasingly more of the particles as they get smaller. This segregation of particles by size defines the “respirable” size fraction. As we configured the particle counter to repeatedly sample and record results alongside our filter/cyclone, we postulated that perhaps the average of particle counts less than 5 micrometers may correlate with the dust level determined by the cyclone/filter, which was graphed below;



As is visible on the graph and determined by simple statistical means (Pearson correlation coefficient =0.29), the particle counter does not always increase with higher dust concentrations in a manner that allows it to reproducibly predict the mass concentration in air. Thus, no simple means to interpret the particle counter data was derived with the limited data we have (9 samples ranging from 2 to 4 hours). This is not totally unexpected as the sites sampled had different gemstone types (with different densities, composition and potentially thus optical properties) and thus the particle counter may respond differently to each type of dust it measures.

E. Results and Discussion: Laboratory Work on Count-Based Dust Measurements

As another attempt to convert particle counts to mass-based results for the pilot data collected in gemstone factories, laboratory work was conducted at the University of Toronto in November 2018. A graduate student was recruited to collect short term side-by-side measurements. Two of the dust sampling instruments were used in this laboratory experiment; the PCE-PCO-1 particle counter and the Sidepak. Silica flour[10] , which is pure crystalline silica, was dispersed and suspended in air in a laboratory chamber and one-minute samples taken sequentially by both instruments simultaneously. These data were fitted to an equation to predict the mass concentration from the particle counter data, using Sidepak estimates of the airborne silica concentration. The results and details of the experiment and data analysis are included in the student's report in Appendix D.

From the laboratory work, we applied the equation derived to convert our pilot study data collected in Jaipur. This is shown below where we compare the predicted mass concentration to the 9 long term concentrations measured by filter and cyclone.

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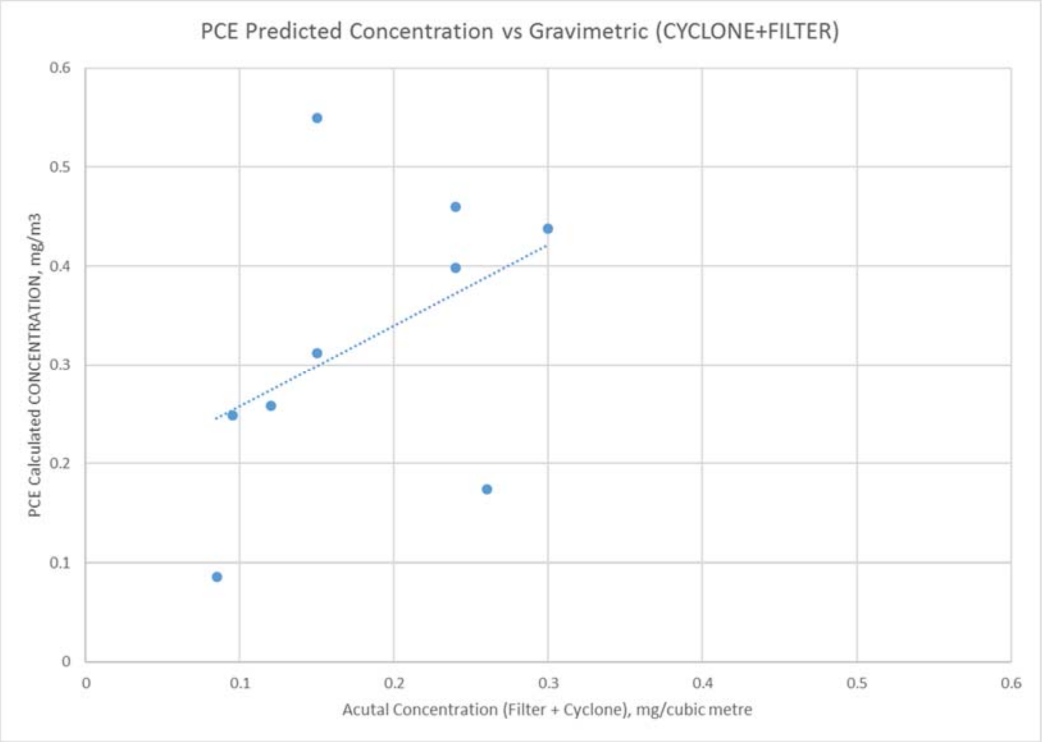
[10] Imsil brand microcrystalline silica, >98% pure, Grade A-8, Unimin Speciality Minerals.



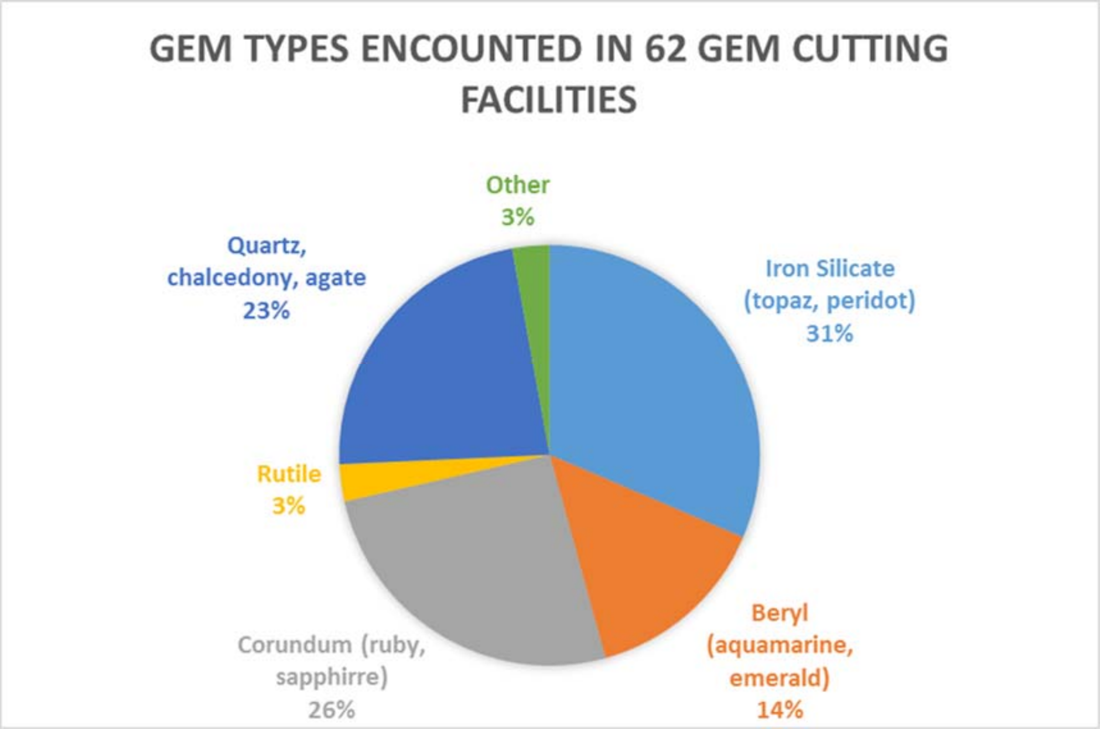
The resultant correlation (Pearson correlation coefficient = 0.44) does not suggest that our laboratory derived equation is sufficient to allow the PCE data to accurately predict silica dust levels from the gemstone field data. Again, this is likely due in part to the variety of gemstone dust in the air where we sampled (different density and potentially optical properties compared to the silica flour used in the laboratory experiment). Also, with only 9 field samples it is difficult to get enough data to be sure that the method is robust enough to use in future.

If AGTA wishes to try to use the particle counter for silica, further laboratory and field work is recommended to see if trends can be predicted with the instrument. With further data from environments where silica-containing dust is present in the absence of other interfering dusts, it may be possible to screen for high levels of silica in some gemstone processing facilities.

F: Results and Discussion – Follow-Up Surveys

F1. Characteristics of Sites Included in the Study

A total of 62 gem processing facilities were recruited into the follow-up survey. Tabular results can be found in Appendix E. In total, these sites were visited 169 times. The average number of workers present in these 62 facilities was 4.52, which ranged from 1 to 25 workers per site. The types of gemstones being processed were noted at each visit and are summarized in the graph below.



In the sites recruited, silica-containing gemstones were encountered just over one-fifth of the time (dark blue in the pie chart above), while the majority of gemstones processed did not contain crystalline silica.

For dust control, only 2 of 62 sites reported doing a task dry, but this was only for cleaning. All sites indicated that they immersed the gems in water or dripped water onto the gems while cutting, polishing or shaping. Thus even when silica-containing gemstones are being processed, wetting is already widely used, which helps to suppress dusts.

All 62 sites reported using a combination of dry sweeping and wet mopping daily to remove any settled dust from the work surfaces and floors. This indicates that dusts will not accumulate on surfaces to become airborne by subsequent disturbance if cleaning is thorough.

No sites indicated that dust masks or respirators were being used by their workers during gem processing nor cleaning.

F2. Noise Measurements and Controls

The analysis of data from spot noise measurements at a total of 62 gemstone factories visited is summarized in the table below, aggregated by task being conducted. However, not all factories allowed measurements, and thus the noise results below were collected where permission was given. Hence, not all tasks were sampled at each of the 62 factories visited.

Table 3

Task	Mean Sound Pressure Level (dBA)	Sound Pressure Level Range (minimum to maximum, dBA)	Number of Factories Where Measured (n)
Rough stone cutting	94.9	92-98	3
Stone shaping	83.4	74-99	56
Stone Polishing	83.0	72-98	55
Stone Mounting on Polishing Spike	80.9	74-88	28

Since these noise measurements were not collected with calibrated scientific instruments, and only are short term measurements, they are not directly comparable to health-based limits. Health-based limits for excessive noise are based on full shift (8 hour) average sound pressure levels. However, the results are indicative of potential risk to hearing and thus further interpretation is provided. Many jurisdictions suggest an 8-hour limit of 85 dBA[11] for protection of hearing for workers. Therefore, the data collected suggest that shaping, mounting stones on a polishing spike and polishing can present a risk of hearing loss for these workers, but not always. Stone cutting was likely to be a risk for hearing loss as the samples collected were consistently well over 85 dBA. Use of hearing protection in the form of ear plugs is expected to provide sufficient protection on average to protect hearing for gemstone workers. However, the survey found that no facility provided personal protective equipment (muffs, plugs) to reduce noise exposure for its' workers.

F3. Worker Questionnaire

From the 62 gem processing facilities, 75 workers consented to participate individually and provide answers verbally posed by the research assistant. Tabular results can be found in Appendix F. Most indicated they worked full time (6 to 8 hours per day) for 6 or 7 days per week normally. Most have worked in the gem processing industry for at least 10 years, and nearly 40% of them had worked over 15 years in the industry.

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[11] For example, this guideline is published by the U.S National Institute for Occupational Safety and Health. See https://www.cdc.gov/niosh/topics/noise/default.html .

Workers confirmed that wet processing of gems is nearly always done, and that no protective masks or respirators are used. Dust cleaning frequency corresponded to what employers reported (daily) and the type of cleaning techniques (dry sweeping and wet mopping) also were reported similarly to what was reported by employers in the workplace questionnaire (section F2, above).

Workers overwhelmingly believe that their workplaces are not noisy, and that the levels in their workplace will not harm their hearing. This is possibly why none indicate that they wear hearing protection. These findings indicate the need to train workers on what levels of noise can harm their hearing and how to best protect themselves from the potentially high levels found at specific tasks in gemstone processing.

G. Key Achievements and Conclusions

Our results indicate that silica may not be a widespread concern in the coloured gemstone processing facilities in Jaipur. Many facilities process gemstones that do not contain silica. In the sites visited, wet techniques for processing (cutting, shaping and polishing) gemstones were already employed and are supplemented by wet mopping to clean the workshops which further controls dust exposures.

In the facility sampled where a pure silica gemstone was processed, dust levels in close proximity to the wet cutting process were not high enough to warrant concern for silicosis, and complies with the limit designed to reduce lung cancer risk. Wet polishing, even of the pure silica gemstones, did not result in silica levels that require further action to reduce risks to health from silicosis. This could be verified with additional sampling across a broader spectrum of sites to confirm whether this applies generally in the industry.

Based on our results, the use of wetting for cutting, shaping and polishing is already in widespread use for coloured gemstones. In facilities that handle pure silica products (like amethyst), further reductions in silica dust levels may be warranted to reduce risk of lung cancer. These can be achieved by use of personal protective equipment (respirators) and/or installation of engineering controls like local exhaust ventilation.

Based on a non-random survey of 62 gemstone factories, noise exposure during gemstone processing may present a risk of hearing loss. Workers could be protected by use of hearing protection such as ear plugs, which substantively reduce noise exposures . Any worker in close proximity to noisy cutting tasks should be trained about the hazards of noise, and informed about how to protect their hearing.

Through laboratory testing, we have derived an equation for converting results from the particle counter to mass-based concentrations. However, when applied to our field results, the correlation was weak. Therefore, while the particle counter may be useful for before-and-after measurements to assess dust control effectiveness, it may not prove helpful or easy to interpret for screening facilities that have silica concerns. Further laboratory testing is recommended if AGTA wants to recommend this type of instrument to screen for levels of concern to health. This will also require the user to recognize which gemstone types contain silica, so that the instrument can be used in an environment where results are not impacted by other dusts in air that arise from non-silica materials.

APPENDIX A – Workplace Observations Questionnaire

Gemstone Dust Exposure and other Health Hazards – VISUAL OBSERVATIONS OF WORKPLACES

Business Name____

ADDRESS ____

Factory # ____________________(assigned by Sid)

Survey date _________________________

1. Total Number of Worker Present ____

2. How Many workers are doing the following:

Job Description	**Number of Workers**	**Number of workers sitting on floor**	**Number of Workers on Seat or bench**	**Number of workers standing**	**Dust Controls Observed (see coding below)**
Manager or Owner					
Grading, inspecting stone or finished gems					
Rough Stone cutter					
Rough Stone Shaping					
Stone Facet cutting					
Polishing Stones					
Mounting stone on metal spike					
Distributing or moving gems					
Cleaning					
Drilling holes					
Other: Specify					

Dust Control Coding:

D = dry
WD = water drip, with rubber tubing
WI = wet immersion, with wheel partially submerged in water reservoir
WS = wet the stone by dipping in water before applying stone to wheel
CO = Chrome oxide (green paste) applied
OM = oil (eg olive oil, hair oil) manually applied with fingers
KM = kerosene or mineral spirits, manually applied with fingers
RP = respiratory protection
SM = surgical mask
FM = cloth over the face

3. Gem Stone Types: (Check all that apply DURING the site visit)

- ☐ Topaz, Periodot (Fe silicates)
- ☐ Aquamarine, Morganite Emerald (“Beryl”)
- ☐ Ruby, Sapphire (all colours) = “Corundum” (Al_2O_3)
- ☐ Amethyst (purple or other colours)
- ☐ Quartz, Chalcedony, agate
- ☐ Rutile (star sapphire, star ruby)
- ☐ Other (describe): ____

4. ASK OWNER/MANAGER:

How is settled dust waste cleaned and disposed of? Check all that apply.

- ☐ Sweep or shovel dry dust
- ☐ Wet mopping
- ☐ Wash down the drain
- ☐ Not specially disposed, just removed from immediate work area
- ☐ Other (describe):____

How often is settled dust waste cleaned and disposed of?

- ☐ Never
- ☐ Once per day
- ☐ Once per week
- ☐ Other (specify) ____

If Dust if cleaned, when is it cleaned and disposed of?

- ☐ Beginning of day
- ☐ End of day
- ☐ Other (specify) _______________________________________

Noise and Lighting:

Job Description	Noise Levels Measure (dBA)	Lighting Levels (lux)	Noise Controls Observed (see coding below)
Grading, inspecting stone or finished gems			
Rough Stone cutter			
Rough Stone Shaping			
Stone Facet cutting			
Mounting stone on metal spike			
Distributing or moving gems			
Drilling holes			
Other: Specify			

Hearing Protection Codes:

EP = ear plugs

? Other ____

Ergonomics/Posture

Note any aids for ergonomics (check all that apply)

- ☐ Knee support
- ☐ Sit on a cushion or blanket
- ☐ Arm rest for work at benches
- ☐ Back rest on chairs/stools
- ☐ Stretch breaks often, as work permits

Other _______________________________________

APPENDIX B – Worker Questionnaire

Gemstone Dust Exposure and other Health Hazards

Notes to surveyor:

The purpose of this survey is to collect information on awareness and experience of gemstone workers to health hazards. It is important to identify who answered these questions so we can follow up at a later time to see how things have changed.

Use a five digit code (e.g. 12345) to protect the participant's anonymity, and keep page 2 and 3 of this survey separate from page 3-8 after collecting the answers.

Survey participant (name)____________________________________

Five digit code identifier _______________________________

Factory # ____________________(Industrial estate, home or small factory"office"

Survey date _________________________

Informed Consent Guidance Script and Record for Awareness Survey

You are invited to participate in a survey to better understand health hazards at your workplace. This study will be collected by the following
- The University of Queensland (Australia)
- Workplace Health without Borders ("WHWB") in Canada
- AGTA

We may want to do a follow-up survey in the future, and this is why we are recording your name. Your participation in this study is completely voluntary, and can be withdrawn at any time. Just let us know verbally if you want us to stop the questions and leave. The scientists intend to publish the study and its results in a journal. We will not share your name or personal identification with anyone outside of the study, including in the written report.

Do you have any questions? (Concerns and questions are to be addressed and documented on the back of this form).

If you have further questions or concerns you may contact the Office of Research Ethics at the University of Queensland, at ethics.review@ or phone number (write this down for them if they ask)

Do you agree to participate in the study as just described? Yes ________ No _____

Five Digit Code ___________________________________

1. Please indicate:

- ☐ Male
- ☐ Female

2. What work are you doing at present (check al that apply)?

- ☐ Owner/manager
- ☐ Rough Stone cutter
- ☐ Shaping stone
- ☐ Faceting
- ☐ polishing
- ☐ Attaching stone to metal rod
- ☐ Supervisor/work distributor/quality control
- ☐ Driller
- ☐ Cleaning
- ☐ Other Specify ____

3. From where do you work now?

- ☐ Home
- ☐ Employer's Home
- ☐ Employer's Factory
- ☐ Other (describe): ______________________________

4. How long do you work each day?

- ☐ 3 Hours or less
- ☐ 3-6 Hours
- ☐ 6-8 Hours
- ☐ >8 Hours

5. How may days per week do you work?

_____________ number per week typically

6. Please indicate your age range:

- ☐ Under 20 years old
- ☐ 20-29 years old
- ☐ 30-45 years old
- ☐ 46-60 years old
- ☐ Over 60 years old

7. What is your highest level of education?

- ☐ None
- ☐ 1-8 years
- ☐ More than 8 years Specify highest level achieved:__________________________

8. Can you read?

- ☐ Yes
- ☐ No

9. For how long have you been working in the gemstone industry?

- ☐ 0-5 years
- ☐ 5-9 years
- ☐ 10-15 years
- ☐ More than 15 years

10 . Do you think that breathing workplace dust can be harmful to health?

- ☐ Yes
- ☐ No
- ☐ Not sure

11. ***If Yes to Question 10***, how did you learn that workplace dust could be harmful? Check all that apply.

- ☐ Friends/Family members
- ☐ Other workers
- ☐ Doctor/heath workers
- ☐ Newspaper
- ☐ Government
- ☐ Employer
- ☐ I don’t remember
- ☐ Other: ______________________________

12. ***If Yes to Question 10***, which dust can be harmful to health? Check all that apply.

- ☐ Dust that is visible in the air
- ☐ Very small/fine dust in the air, even if not visible
- ☐ Don’t know
- ☐ Other (describe): ____

13. Is the air where you work dusty when working?

- ☐ Yes, a lot
- ☐ A little
- ☐ No, not at all

14. What do you think are good ways to minimize the dust someone breathes in? Check all that apply.

- ☐ Fan that blows dusty air away from worker
- ☐ Water drip on the wheel
- ☐ Wet the wheel by applying water with your fingers
- ☐ Wetting the stone by dipping in it water
- ☐ Enclose/cover the equipment
- ☐ Move others into a different room away from indoor
- ☐ Dust Mask (if mask, note type used – surgical ☐ or disposable respirator ☐)
- ☐ Scarf or cloth around mouth and nose
- ☐ Other (describe) ____

AWARENESS MESSAGE:

It is the very fine smallest dust particles, even those not normally visible, that reach the deepest part of the lungs and can cause damage.

<u>Therefore you and your co-workers must be protected from all dust, but most importantly the very finest dust</u>.

This is also the dust that is hardest to capture with cloth, jute bags and enclosures that are not sealed.

15. In your workplace, do you use any methods to reduce the amount of dust you and/or your co-workers breathe in?

- ☐ Yes, all the time
- ☐ Sometimes
- ☐ No, not at all

16. **If *yes OR sometimes* to question 15**, which methods do you use? (check all that apply)

- ☐ Fan that blows dusty air away from worker____________months
- ☐ Water drip on the wheel __________________________months
- ☐ Wheel is partially immersed in water all the time ______________months
- ☐ Wetting the stone when cutting or polishing _______________month
- ☐ Enclose/cover the equipment ____________________months
- ☐ Move others into a different room away from dust _______________month
- ☐ Dust Mask ________________months
- ☐ Scarf or cloth around mouth and nose _________________months
- ☐ Other (describe): ___________________________________ _______months

17. How long have you been using these methods? (Write number of <u>months</u> beside method above)

18 . ***If sometimes or no to question 15***, why don't you use methods to reduce the amount of dust you breathe in? Check all that apply.

- ☐ I do not think dust is unhealthy
- ☐ Employer doesn't provide anything
- ☐ I do not think it makes a difference
- ☐ It is too expensive
- ☐ It is too time consuming
- ☐ It reduces my production
- ☐ I don't know
- ☐ Other (describe): ____

19. How is settled dust waste cleaned and disposed of? Check all that apply.

- ☐ Sweep or shovel dry dust
- ☐ Wet mopping
- ☐ Wash down the drain
- ☐ Not specially disposed, just removed from immediate work area
- ☐ Other (describe):____

20. How often is settled dust waste cleaned and disposed of?

- ☐ Never
- ☐ Once per day
- ☐ Once per week
- ☐ Other (specify) ____

21. If Dust if cleaned, when is it cleaned and disposed of?

- ☐ Beginning of day
- ☐ End of day
- ☐ Other (specify) ____

Noise:

22. Do you think that noise levels in your workplace are high?

- ☐ Yes
- ☐ No

23. Do you think that noise levels in your workplace can cause harm to your hearing?

- ☐ Yes
- ☐ No
- ☐ Not sure?

AWARENESS MESSAGE:

High levels of noise can cause loss of hearing or other problems, like ringing sounds in the ears even when there is no noise. Once your hearing is lost, you cannot be treated to make it better.

24. Have you ever worn hearing protection devices?

- ☐ Yes, which type ____
- ☐ No
- ☐ Not sure?

25. **If yes to Question 24**, how long have been using hearing protection devices?

- ☐ Months (specify) _________________________________

- ☐ Years (specify) _____________________________

Ergonomics/Posture

26. In which position do you normal work? (check all that apply)

- ☐ Sitting on the floor
- ☐ Sitting on a chair or bench
- ☐ Standing

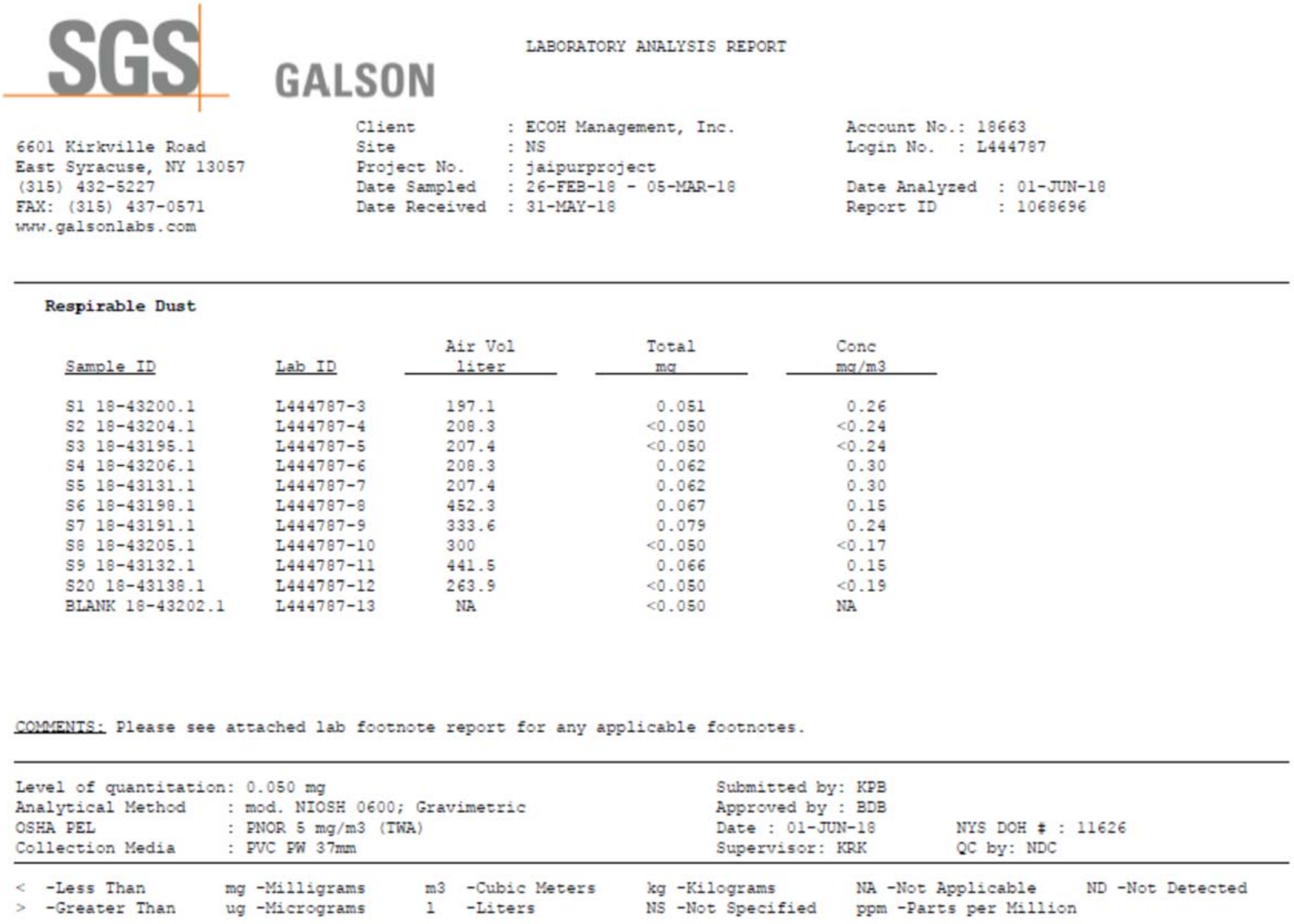
27. If the answer to Question 26 is sitting on the floor; Do you normally work with the following? (check all that apply)

- ☐ A knee support to hold your knee up
- ☐ Sit on a cushion or blanket
- ☐ I get up and stretch whenever I feel stiff or uncomortable

---

Thank you very much for your time; your input is greatly appreciated.

APPENDIX C– Lab Results for Filter Samples



SGS GALSON

LABORATORY ANALYSIS REPORT

6601 Kirkville Road
East Syracuse, NY 13057
(315) 432-5227
FAX: (315) 437-0571
www.galsonlabs.com

Client : ECOH Management, Inc.
Site : NS
Project No. : jaipurproject
Date Sampled : 26-FEB-18 - 05-MAR-18
Date Received : 31-MAY-18

Account No.: 18663
Login No. : L444787

Date Analyzed : 01-JUN-18
Report ID : 1068696

Respirable Dust

Sample ID	Lab ID	Air Vol liter	Total mg	Conc mg/m3
S1 18-43200.1	L444787-3	197.1	0.051	0.26
S2 18-43204.1	L444787-4	208.3	<0.050	<0.24
S3 18-43195.1	L444787-5	207.4	<0.050	<0.24
S4 18-43206.1	L444787-6	208.3	0.062	0.30
S5 18-43131.1	L444787-7	207.4	0.062	0.30
S6 18-43198.1	L444787-8	452.3	0.067	0.15
S7 18-43191.1	L444787-9	333.6	0.079	0.24
S8 18-43205.1	L444787-10	300	<0.050	<0.17
S9 18-43132.1	L444787-11	441.5	0.066	0.15
S20 18-43138.1	L444787-12	263.9	<0.050	<0.19
BLANK 18-43202.1	L444787-13	NA	<0.050	NA

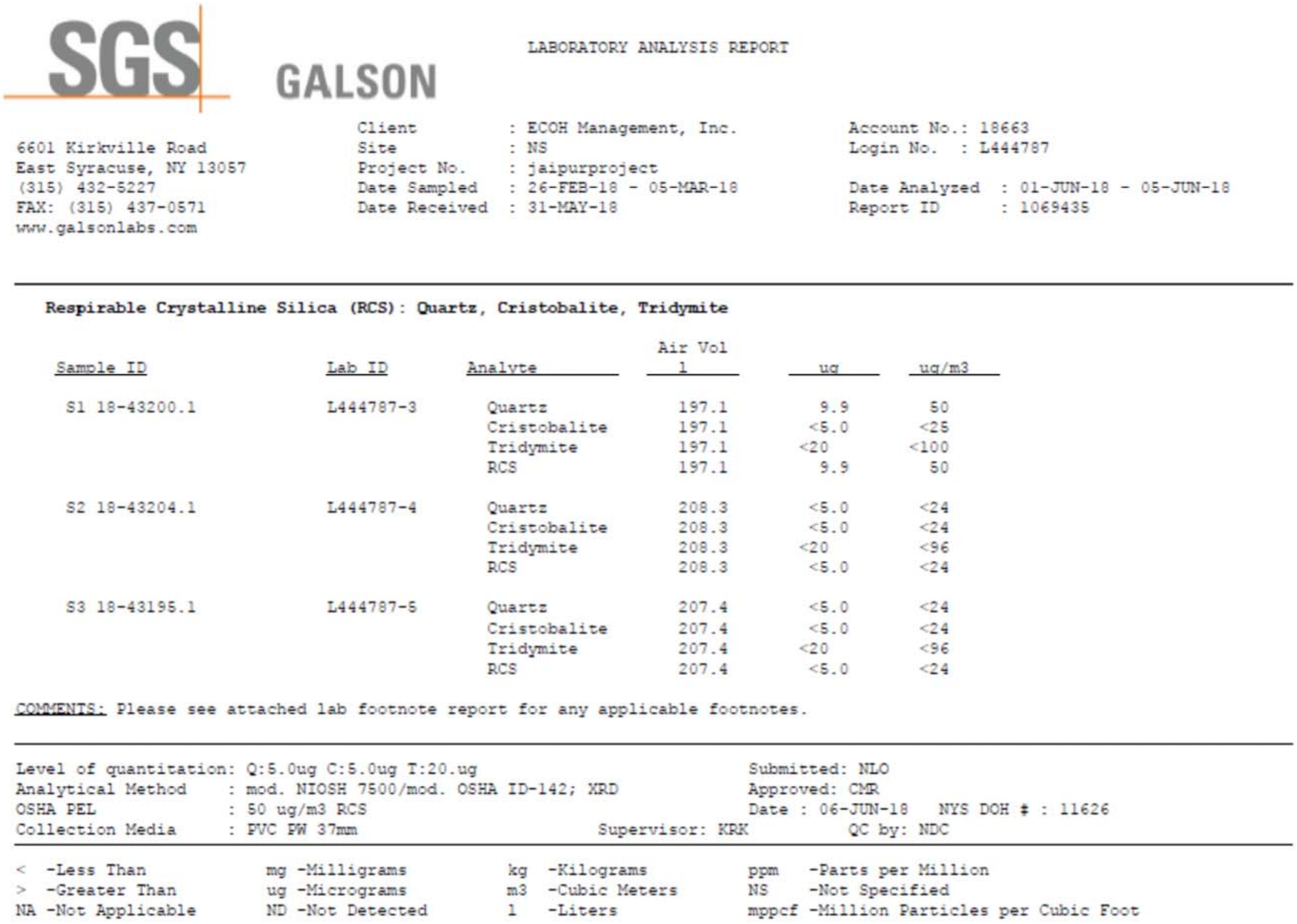
COMMENTS: Please see attached lab footnote report for any applicable footnotes.

Level of quantitation: 0.050 mg
Analytical Method : mod. NIOSH 0600; Gravimetric
OSHA PEL : PNOR 5 mg/m3 (TWA)
Collection Media : PVC PW 37mm

Submitted by: KPB
Approved by : BDB
Date : 01-JUN-18
Supervisor: KRK

NYS DOH # : 11626
QC by: NDC

< -Less Than
> -Greater Than
mg -Milligrams
ug -Micrograms
m3 -Cubic Meters
l -Liters
kg -Kilograms
NS -Not Specified
NA -Not Applicable
ppm -Parts per Million
ND -Not Detected



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Date Sampled : 26-FEB-18 - 05-MAR-18
Date Received : 31-MAY-18

Account No.: 18663
Login No. : L444787

Date Analyzed : 01-JUN-18 - 05-JUN-18
Report ID : 1069435

Respirable Crystalline Silica (RCS): Quartz, Cristobalite, Tridymite

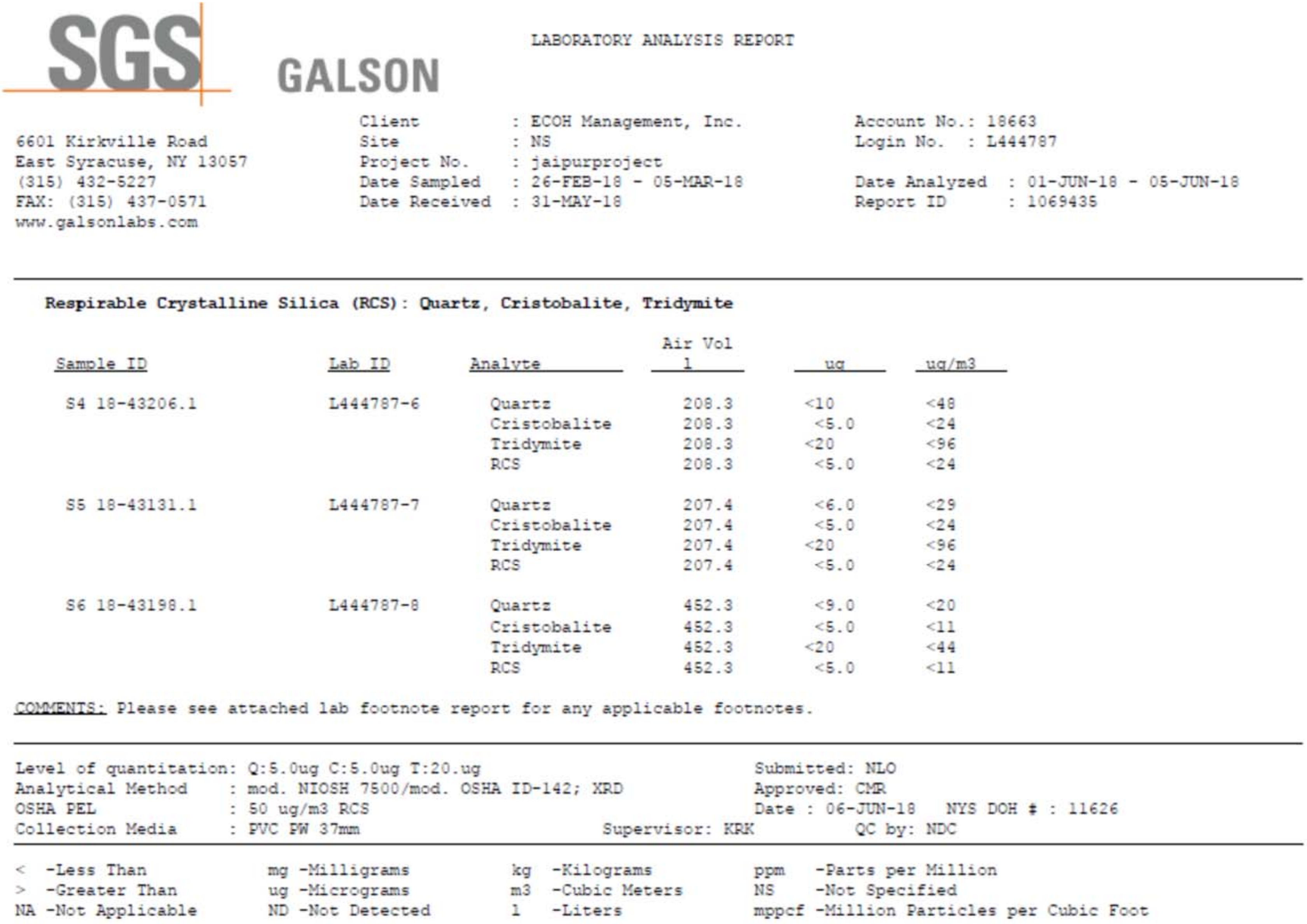
Sample ID	Lab ID	Analyte	Air Vol l	ug	ug/m3
S1 18-43200.1	L444787-3	Quartz	197.1	9.9	50
		Cristobalite	197.1	<5.0	<25
		Tridymite	197.1	<20	<100
		RCS	197.1	9.9	50
S2 18-43204.1	L444787-4	Quartz	208.3	<5.0	<24
		Cristobalite	208.3	<5.0	<24
		Tridymite	208.3	<20	<96
		RCS	208.3	<5.0	<24
S3 18-43195.1	L444787-5	Quartz	207.4	<5.0	<24
		Cristobalite	207.4	<5.0	<24
		Tridymite	207.4	<20	<96
		RCS	207.4	<5.0	<24

COMMENTS: Please see attached lab footnote report for any applicable footnotes.

Level of quantitation: Q:5.0ug C:5.0ug T:20.ug
Analytical Method : mod. NIOSH 7500/mod. OSHA ID-142; XRD
OSHA PEL : 50 ug/m3 RCS
Collection Media : PVC PW 37mm

Submitted: NLO
Approved: CMR
Date : 06-JUN-18 NYS DOH # : 11626
Supervisor: KRK QC by: NDC

< -Less Than	mg -Milligrams	kg -Kilograms	ppm -Parts per Million
> -Greater Than	ug -Micrograms	m3 -Cubic Meters	NS -Not Specified
NA -Not Applicable	ND -Not Detected	l -Liters	mppcf -Million Particles per Cubic Foot



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Account No.: 18663
Login No. : L444787
Date Analyzed : 01-JUN-18 - 05-JUN-18
Report ID : 1069435

Respirable Crystalline Silica (RCS): Quartz, Cristobalite, Tridymite

Sample ID	Lab ID	Analyte	Air Vol l	ug	ug/m3
S4 18-43206.1	L444787-6	Quartz	208.3	<10	<48
		Cristobalite	208.3	<5.0	<24
		Tridymite	208.3	<20	<96
		RCS	208.3	<5.0	<24
S5 18-43131.1	L444787-7	Quartz	207.4	<6.0	<29
		Cristobalite	207.4	<5.0	<24
		Tridymite	207.4	<20	<96
		RCS	207.4	<5.0	<24
S6 18-43198.1	L444787-8	Quartz	452.3	<9.0	<20
		Cristobalite	452.3	<5.0	<11
		Tridymite	452.3	<20	<44
		RCS	452.3	<5.0	<11

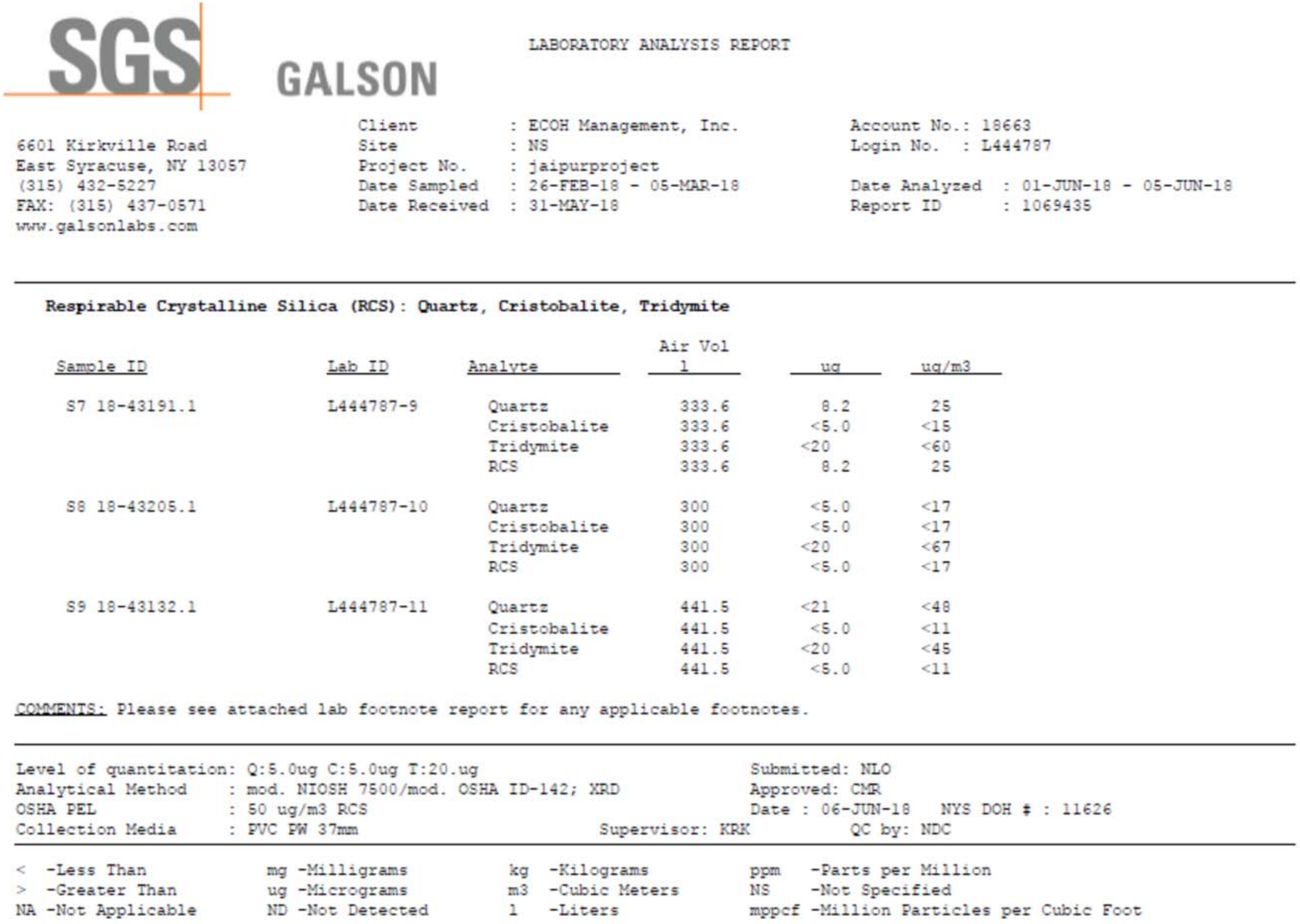
COMMENTS: Please see attached lab footnote report for any applicable footnotes.

Level of quantitation: Q:5.0ug C:5.0ug T:20.ug
Analytical Method : mod. NIOSH 7500/mod. OSHA ID-142; XRD
OSHA PEL : 50 ug/m3 RCS
Collection Media : PVC PW 37mm

Supervisor: KRK

Submitted: NLO
Approved: CMR
Date : 06-JUN-18 NYS DOH # : 11626
QC by: NDC

< -Less Than
> -Greater Than
NA -Not Applicable
mg -Milligrams
ug -Micrograms
ND -Not Detected
kg -Kilograms
m3 -Cubic Meters
l -Liters
ppm -Parts per Million
NS -Not Specified
mppcf -Million Particles per Cubic Foot



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Account No.: 18663
Login No. : L444787

Date Analyzed : 01-JUN-18 - 05-JUN-18
Report ID : 1069435

Respirable Crystalline Silica (RCS): Quartz, Cristobalite, Tridymite

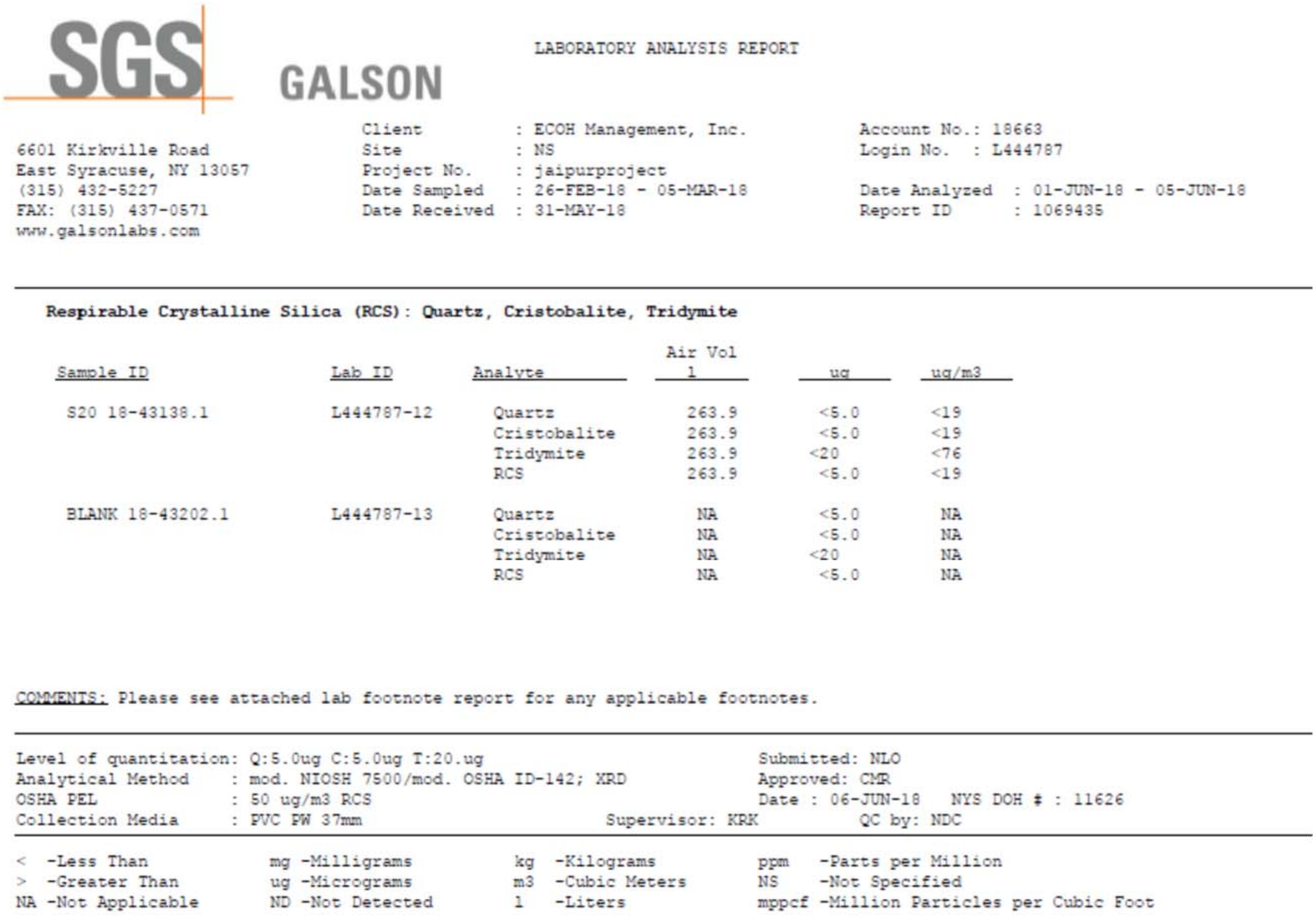
Sample ID	Lab ID	Analyte	Air Vol l	ug	ug/m3
S7 18-43191.1	L444787-9	Quartz	333.6	8.2	25
		Cristobalite	333.6	<5.0	<15
		Tridymite	333.6	<20	<60
		RCS	333.6	8.2	25
S8 18-43205.1	L444787-10	Quartz	300	<5.0	<17
		Cristobalite	300	<5.0	<17
		Tridymite	300	<20	<67
		RCS	300	<5.0	<17
S9 18-43132.1	L444787-11	Quartz	441.5	<21	<48
		Cristobalite	441.5	<5.0	<11
		Tridymite	441.5	<20	<45
		RCS	441.5	<5.0	<11

COMMENTS: Please see attached lab footnote report for any applicable footnotes.

Level of quantitation: Q:5.0ug C:5.0ug T:20.ug
Analytical Method : mod. NIOSH 7500/mod. OSHA ID-142; XRD
OSHA PEL : 50 ug/m3 RCS
Collection Media : PVC PW 37mm
Supervisor: KRK

Submitted: NLO
Approved: CMR
Date : 06-JUN-18 NYS DOH # : 11626
QC by: NDC

<	-Less Than	mg	-Milligrams	kg	-Kilograms	ppm	-Parts per Million
>	-Greater Than	ug	-Micrograms	m3	-Cubic Meters	NS	-Not Specified
NA	-Not Applicable	ND	-Not Detected	l	-Liters	mppcf	-Million Particles per Cubic Foot



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Date Analyzed : 01-JUN-18 - 05-JUN-18
Report ID : 1069435

Respirable Crystalline Silica (RCS): Quartz, Cristobalite, Tridymite

Sample ID	Lab ID	Analyte	Air Vol l	ug	ug/m3
S20 18-43138.1	L444787-12	Quartz	263.9	<5.0	<19
		Cristobalite	263.9	<5.0	<19
		Tridymite	263.9	<20	<76
		RCS	263.9	<5.0	<19
BLANK 18-43202.1	L444787-13	Quartz	NA	<5.0	NA
		Cristobalite	NA	<5.0	NA
		Tridymite	NA	<20	NA
		RCS	NA	<5.0	NA

COMMENTS: Please see attached lab footnote report for any applicable footnotes.

Level of quantitation: Q:5.0ug C:5.0ug T:20.ug
Analytical Method : mod. NIOSH 7500/mod. OSHA ID-142; XRD
OSHA PEL : 50 ug/m3 RCS
Collection Media : PVC PW 37mm

Submitted: NLO
Approved: CMR
Date : 06-JUN-18 NYS DOH # : 11626
Supervisor: KRK QC by: NDC

<	-Less Than	mg	-Milligrams	kg	-Kilograms	ppm	-Parts per Million
>	-Greater Than	ug	-Micrograms	m3	-Cubic Meters	NS	-Not Specified
NA	-Not Applicable	ND	-Not Detected	l	-Liters	mppcf	-Million Particles per Cubic Foot

APPENDIX D – Laboratory Work to Convert Particle Counter to Mass Concentration

Estimating Concentration Using a Particle-Counting Dust Monitor

CHL7001H F Directed Reading
November 26, 2018
Adam Debly

Executive Summary

Direct reading monitors represent a common means of collecting high-resolution information on silica dust levels in the air for purposes such as compliance testing and control implementation. The purpose of this experiment was to develop a process to calculate a concentration in milligrams per cubic meters based on the output data from the Particle Counter PCE-PCO 1 (PCE Instruments UK Ltd.). Silica dust was generated by aerosolizing A-15 silica flour inside a calm air dust chamber while measuring dust concentration using a DustTrak 8520, a DustTrak 8533 and a PCE-PCO 1. Based off experimental data, a function was created to predict concentration using PCO 1 data. The accuracy of this tool was verified by comparing predicted concentration with actual concentration using t-testing and linear regression. Based on the results, it can be concluded that the functions generated represent a suitable method of estimating silica mass concentration using PCO 1 particle count data. To address methodological limitations in this investigation, the function generated should be verified in test conditions more reflective of real-world exposure conditions.

Introduction

Crystalline silica is a chemically inert mineral commonly found in rocks and used extensively in abrasives, building materials, metal processing and many other areas (Yassin, Yebesi, & Tingle, 2005). When powdered and aerosolized, crystalline silica represents a serious inhalation risk, having the potential to cause silicosis in highly exposed individuals (Yassin et al., 2005). Both the particle size and concentration are critical in assessing the risk of airborne silica (Yassin et al., 2005). Millions of workers are exposed to silica worldwide, and it is imperative that adequate tools are available to assess the severity of exposures and inform exposure reduction strategies (Yassin et al., 2005). Most regulatory bodies set limits for the respirable fraction of crystalline silica, in units of milligrams per cubic meter. The National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH) both report occupational exposure limits of 0.05 mg/m^3 for respirable crystalline silica (Yassin et al., 2005).

The Particle Counter PCE-PCO 1 is a low-cost handheld laser particle counter intended for indoor air quality assessment or analysis of potentially hazardous aerosols (PCE Americas Inc., 2018). Although the instrument returns the particle count in each of 6 particle size ranges, it does not return mass concentration for any fraction of dust. A similar instrument by PCE is now available, the PCO 2, which does indicate a mass concentration for aerosols sampled (PCE Americas Inc., 2018). However, there is currently no method of estimating concentration from previously recorded PCO 1 data. PCE's series particle counter software does not allow for the derivation of concentration from existing PCE-PCO 1 data (PCE Americas Inc., 2018).

Representing PCO 1 results in units used by dust monitors and regulations worldwide would allow users to interpret PCO 1 measurements much more effectively. It would also make the results of this instrument much more useful when assessing sources of exposure, methods of exposure control, or communicating results to non-professionals. Importantly, this functionality would allow for more meaningful re-analysis of data collected using PCO 1 monitors. Overall, adding a mass concentration output to this generally effective instrument would address its most substantial shortcoming.

The purpose of this study was to develop and test a means of converting existing particle count data collected using a PCE-PCO 1 instrument to mass concentration data for silica aerosols.

Materials and Methods

Direct Reading Instruments

The PCO 1 returns the number of particles in six non-overlapping size ranges: 0.3 µm, 0.5 µm, 1.0 µm, 2.5 µm, 5.0 µm, and 10 µm. The instrument is only 50% efficient in counting particles less than 0.3 µm or below. These size fractions are not clearly defined within the manual for this product or in information available on the product's website (PCE Americas Inc., 2018). Because of this, there is uncertainty as to what particle sizes each of these ranges truly include. However, it is clear when using the instrument to measure an aerosol with different sized particles that the smallest size ranges always have the highest number of particles, and no size range ever has more particles than one below it in size. This indicates that the ranges are non-cumulative or non-overlapping. For example, this would mean that the 0.5 µm range includes particles greater than 0.3 µm in aerodynamic diameter but equal to or below 0.5 µm.

The maximum sample number of the PCO 1 in one run is 100 measurements. The minimum interval between tests was three seconds. It appears that this instrument double-counts all interval periods, resulting in a recorded sample length of approximately 66 seconds for each sample.

The TSI DustTrak 8533 reports the concentration of PM1, PM2.5, PM10, and the respirable and total dust fractions. The cyclone-equipped TSI DustTrak 8520 was set up to record concentration for the respirable fraction. To match the PCO 1, both DustTraks were set to a log interval of one minute and set to collect 100 measurements.

Dust Chamber Measurement Procedure

A standard laboratory fume hood was used for the experiment by fully lowering the sash and sealing all openings. Instruments were placed beside each other near the center of the fume hood (Figure 1).

Figure 1. Dust chamber, aerosol generator, and direct reading instruments prior to experiment.

The silica aerosol was generated by placing approximately 20 g of A-15 silica flour into an SKC Pyrex® glass bubble tube from a glass midget impinger. The dispersion tube was replaced onto the tube and air was forced down the dispersion tube through tigon tubing running from a small compressor to the impinger inlet. When activated, the turbulence inside the impinger tube would aerosolize the silica dust and force the dust out horizontally from the impinger outlet port. After each addition, a small axial fan was activated briefly to distribute the aerosol throughout the chamber. When the DustTrak reading decreased to 0.009 mg/mg, more dust was generated.

Data Processing

TSI TrakPro software version 4.7.1.0 was used to download data from both the DustTrak 8520 and 8533 to output ASCII data files. To export the PCO 1 data, PCE's series particle counter software version 1.1.1.0 was used to combine the individually stored samples into a single data frame. All further data analysis was conducted within RStudio version 1.1.453.

Concentration Function Development

Because the DustTrak 8520 and 8533 returned virtually identical results, only the results of the DustTrak 8533 were used to develop and corroborate the calculations. For the purpose of this experiment, it was assumed that particles were perfectly spherical with a density of 2.65 g/cm^3 (National Toxicology Program, 2009).

Equation 1. Summary of function for calculating the concentration contributed by each size range sampled by the PCO 1. Note that this equation is applied to all size ranges from 0.3 μm to 5.0 μm, and the products summed to combine all size ranges.

$$Z = (W \times C \div V) \times \left(H \times \frac{4}{3}\pi \times (D/2)^3\right) \times (\rho \times \mathrm{N})$$

Name	Value	Description
Z	Variable	Concentration contributed by each size range (mg/m^3)
W	Variable	Weighting factor based on the respirable convention
C	Variable	Particle count for size range
V	0.00283 m^3	Air volume sampled by the PCO 1 (2.83 L/min) in 60 seconds
H	$10^{-12}\ cm^3/\mu m^3$	Conversion factor for cubic centimeters from cubic micrometers
D	Variable	Titular aerodynamic diameter of each size range
ρ	2.65 g/cm^3	Density of silica
N	$10^3\ (mg/cm^3)/(g/cm^3)$	Conversion factor for milligrams from grams per cubic centimeter

To convert the number of particles in six size ranges measured by the PCO 1 into a format comparable to the respirable convention, weighting factors were created for each of the size ranges from 0.3 µm to 5.0 µm. Using the respirable particulate curve from ISO 7708:1995, a weighting factor was approximated for each of the size ranges (Figure 2). The 10s µm was excluded from all calculations, as it would receive a weighting factor of zero (Figure 2).

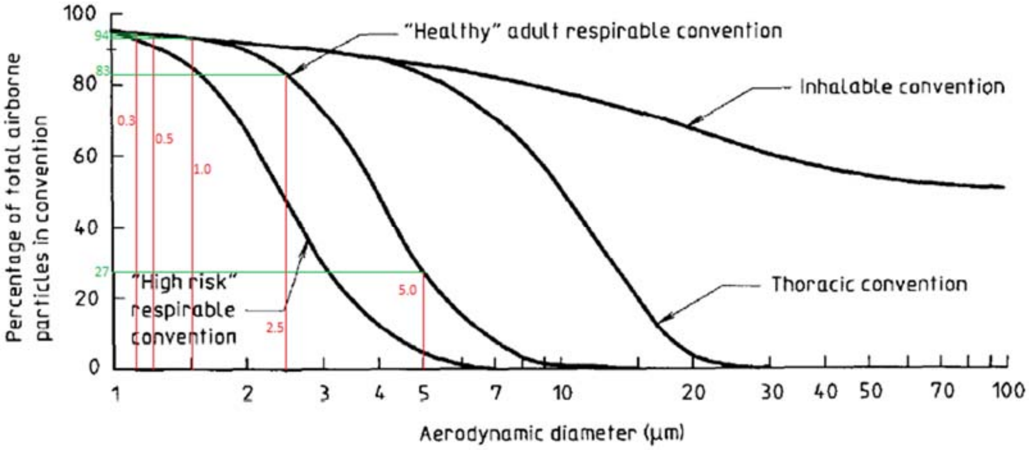

Figure 2. Respirable particulate curve, showing the percentage of total airborne particles for all relevant size ranges measured by the PCO 1, adapted from ISO 7708:1995.

To calculate the number of particles per cubic meter, this weighting factor was multiplied by the number of particles in each range and divided by 0.00283 m^3, the volume of air analysed by the PCO 1 per sample (Equation 1). Next, the volume per particle was counted by converting the titular diameter of each size range into a sphere measured in cm^3 (Equation 1). Finally, this was multiplied by the density of silica in milligrams per cubic centimeter (Equation 1). This approximation of concentration was calculated by minute for 100 PCO 1 samples and matched by time with DustTrak 8533 concentration measurements. Data from both instruments were ln-transformed and compared using a linear regression (Figure 3).

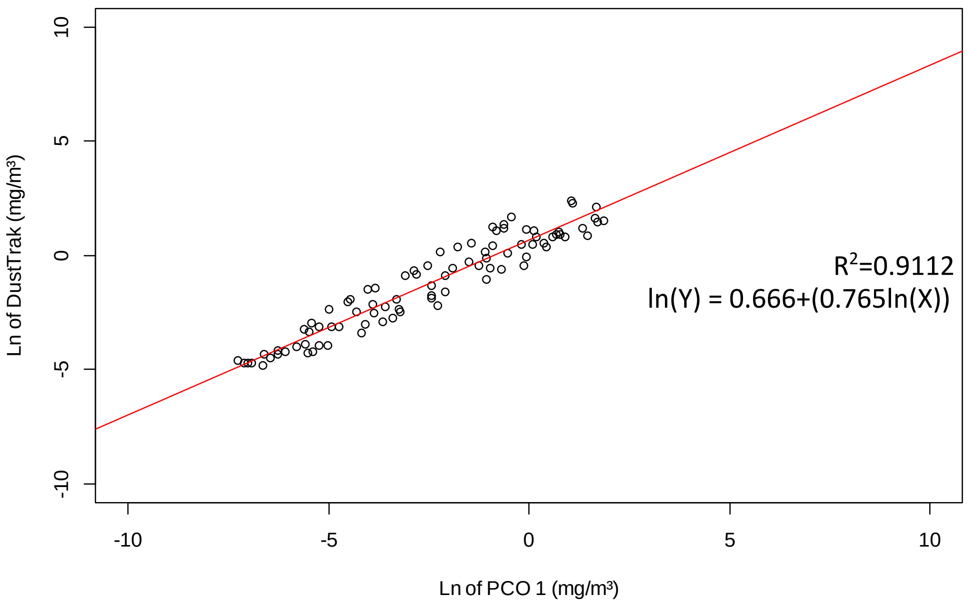

Figure 3. Linear regression of ln-transformed 88 DustTrak concentration samples time-matched with 88 concentrations calculated from PCO 1 particle count information, showing a high degree of correlation.

The coefficients of the linear equation relating the two ln-transformed variables were incorporated into a function to convert the sum of concentration contributed by each size range (mg/m^3) of the PCO to a mass concentration reflecting DustTrak data, and by extension, true aerosol concentration (Equation 2).

Equation 2. Conversion function to estimate Y, actual concentration (mg/m^3) by Z, the summed output of Equation 1 for each size range of PCO 1 data from 0.3 µm to 5.0 µm.

$$Y = e^{\left((7650 \ln(Z) + 6659)/10000\right)}$$

Concentration Function Testing

The combined efficacity of equations one and two was assessed by repeating the aerosol generation and testing procedure described previously and comparing calculated concentration with concentration measured by a DustTrak 8533.

After normality verification using Shapiro-Wilk testing for both the predicted and actual concentration, they were compared using a Wilcoxon rank sum test. The analysis was limited to DustTrak readings below 3.5 mg/m^3, as values above this were rare in the original dataset and thus unlikely to be predicted accurately. In addition, pure silica aerosols of this concentration would not be reflective of real-world exposure situations.

Results

Predicted and actual concentration were not normally distributed according to Shapiro-Wilk tests (p= 2.208e-15 and p= 1.144e-14 respectively). When ln-transformed, neither the predicted nor the actual concentrations were normally distributed according to Shapiro-Wilk tests (p=0.00049 and p=9.736e-06 respectively). As a result of the non-normality, a nonparametric Wilcoxon rank sum test was applied to the untransformed data.

Based on the results of the paired Wilcoxon rank sum test of the predicted and actual concentration, the alternate hypothesis that the true mean difference in the pairs is not equal to zero was rejected (p= 0.4004). Based on the test, it can be concluded that there is no statistically significant difference between actual and predicted concentrations.

The predicted mean concentration of 0.372 mg/m^3 was very similar to the actual concentration measured by the DustTrak 8533 of 0.322 mg/m^3. Overall, the predicted concentration data appeared to be very similar to the actual concentration measured using the DustTrak 8533 (Figure 4).

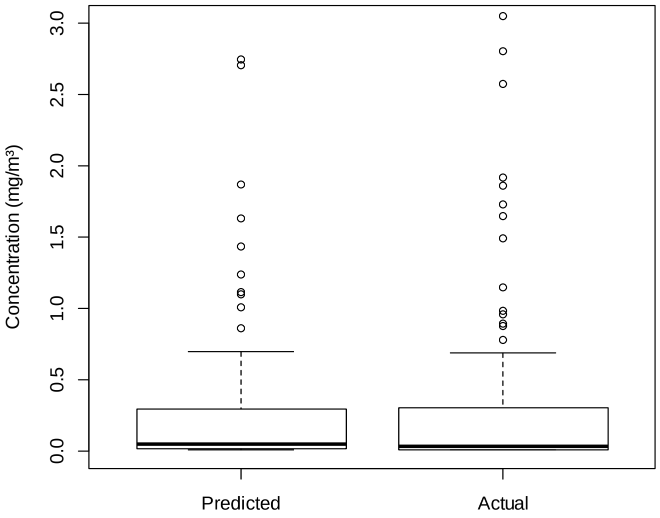

Figure 4. Concentration (mg/m^3) measured using a DustTrak 8533 and predicted concentration (mg/m^3) estimated using PCO 1 particle count data,

When viewed over time, the overall trend in predicted and actual concentration appear to demonstrate a very high degree of agreement (Figure 5). However, higher concentrations appeared to be predicted with less accuracy than low concentrations (Figure 5).

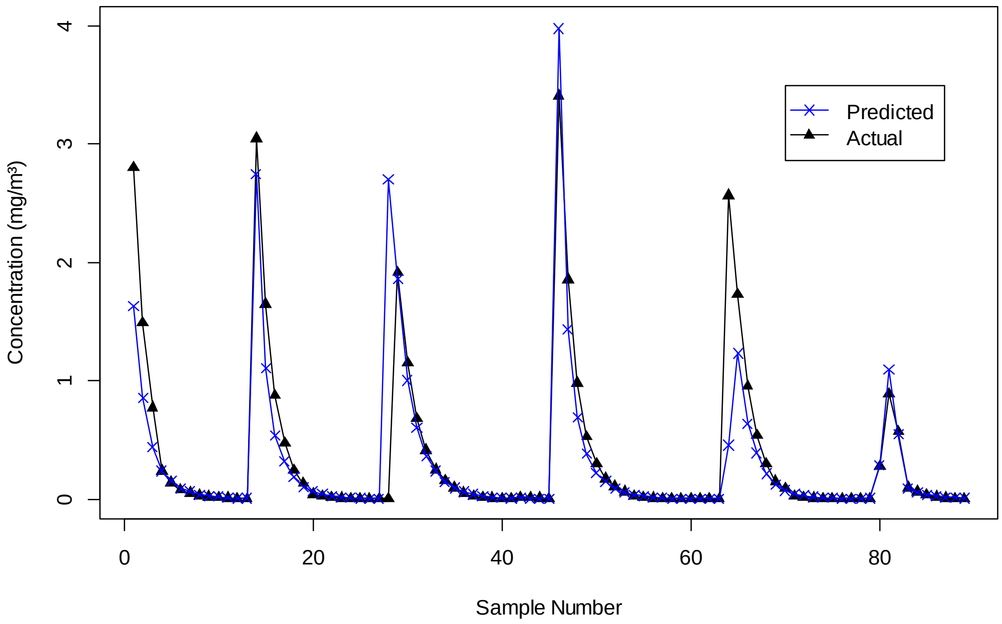

Figure 5. Concentration (mg/m^3) measured using a DustTrak 8533 matched by time with predicted concentration (mg/m^3) from a PCO 1, using sample number as a proxy of time.

Comparison of the ln-transform of the predicted and actual concentrations using linear regression also demonstrates a high degree of correlation and similarity (Figure 6). The line of best fit generated using the least squares method has an approximate slope of one and an approximate intercept of 0, indicating that actual concentration is approximately equal to actual concentration (i.e. y=x). In addition, the R squared value of 0.86 indicates that the data are closely fitted to the regression line (Figure 6).

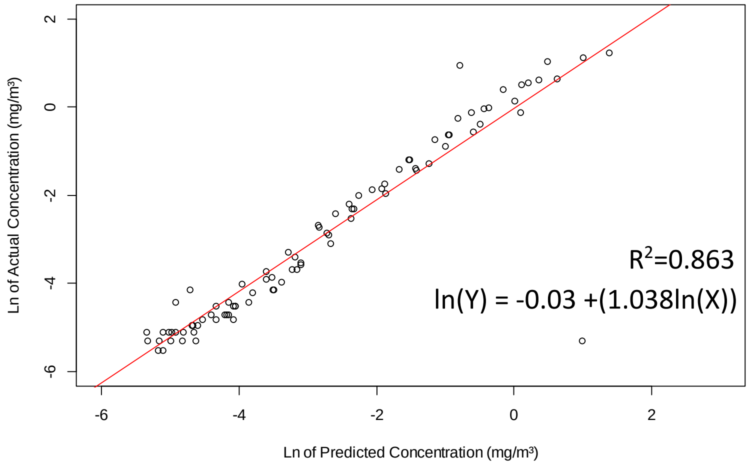

Figure 6. Linear regression of ln-transformed 89 DustTrak concentration samples time-matched with 88 concentrations predicted using PCO 1 particle count information, showing a high degree of correlation.

Discussion

Based on the results, it can be concluded that the functions generated represent a suitable method of estimating silica mass concentration using PCO 1 particle count data. This was supported by nonparametric testing, linear regression and observation of data collected over time.

This experiment was complicated by differences in the method of storing time in TSI and PCE equipment. TSI equipment labels concentration readings consistently in 60 seconds intervals. This is not the case with the PCO 1 even when sample duration is set to 60 seconds with a minimum delay of 3 seconds between samples. In this instance, samples are approximately 66 seconds long, possibly from counting the three-second delay period twice and the 60 second sampling period once. Aside from this, the difference between subsequent samples was not identical for all samples in the run. Functionally, this led to some one-minute samples behind slightly longer than others. One solution to this issue would be to generate aerosols that are consistent over time, or to develop advanced methods to synchronize PCE and TSI data. The differences in which these instruments store time made it challenging to ensure that samples truly occurred in the exact same time period. This likely had the effect of reducing the association between predicted and actual concentration by incorrectly paring some points (Figure 5, Figure 6). This would have the effect of reducing the association found in the linear regression of predicted and actual concentration (Figure 6). Similarly, imperfect time synchronization of the instruments likely biased the Wilcoxon rank sum test of the data towards the alternate hypothesis.

Due to the preliminary nature of this investigation, numerous limitations intrinsic to the experiment should be acknowledged. For simplicity, single PCO 1 runs were used to develop and test the conversion function, comprising of approximately 90 points each. This was acceptable, but more accurate predictions are possible by combining multiple sampling runs.

For simplicity in all calculations, the titular aerodynamic diameter (e.g. 0.5 µm) ascribed to each size range was assumed to be reflective of all particles for its respective range. An alternate method would be to set the particle diameter for each range equal to the value halfway between its titular diameter and the bin below. For example, 0.75 µm could be used as the actual particle diameter for the 1.0 µm range. This was not done, as the specific size range of particles in each bin for a given sample is unknown, and the true definition of each bin itself also remains unknown. This may have led to inaccuracy in the estimation of particle volume, but the likelihood and effect of this are unknown.

The simplistic method of aerosol generation resulted in a “boom and bust” silica concentration over time, with very high concentrations directly after dust addition (Figure 5). This is not reflective of all exposure scenarios and may have introduced experimental error from the presumably different response times of the two instruments that would not arise when measuring a more consistent concentration over time.

Because of the small, still-air chamber used in testing and validation, the degree to which function generated applicable to real-world exposure scenarios remains unclear. In addition, experiments were conducted using pure silica aerosols, which may not reflect all dust compositions encountered. Because the conversion function was only tested below a concentration of 3.5 mg/m3, it may not be applicable to higher concentrations, in the event that a pure silica aerosol is encountered in that concentration.

The results suggest that equation one adequately produces an estimate of mass concentration using particle count. The efficacity of the two equations together should be verified in test conditions more reflective of real-world exposure conditions with more comprehensive time-handling methods. Further testing should include larger room sizes, longer test lengths, and consistently low silica concentrations. In addition, the effect of non-silica particulates on mass concentration estimates should be investigated.

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APPENDIX E – Tabular Results from Workplace Data Follow-Up Survey

See attached excel file entitled, “Factory combined 8jan2019”

APPENDIX F – Tabular Results from Worker Follow-Up Survey

See attached excel file entitled, “Worker Survey cleaned”