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The Development and Testing of a Prototype Mini-Baghouse to Control the Release of Respirable Crystalline Silica from Sand Movers

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Abstract

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No conflicts of interest.

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Inhalation of respirable crystalline silica (RCS) is a significant risk to worker health during well completions operations (which include hydraulic fracturing) at conventional and unconventional oil and gas extraction sites. RCS is generated by pneumatic transfer of quartz-containing sand during hydraulic fracturing operations. National Institute for Occupational Safety and Health (NIOSH) researchers identified concentrations of RCS at hydraulic fracturing sites that exceed 10 times the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) and up to 50 times the NIOSH Recommended Exposure Limit (REL). NIOSH research identified at least seven point sources of dust release at contemporary oil and gas extraction sites where RCS aerosols were generated.

NIOSH researchers recommend the use of engineering controls wherever they can be implemented to limit the RCS released. A control developed to address one of the largest sources of RCS aerosol generation is the NIOSH mini-baghouse assembly, mounted on the thief hatches on top of the sand mover. This manuscript details the results of a trial of the NIOSH mini-baghouse at a sand mine in Arkansas, November 18 – 21, 2013.

During the trial, area air samples were collected at 12 locations on and around a sand mover with and without the mini-baghouse control installed. Analytical results for respirable dust and RCS indicate the use of the mini-baghouse effectively reduced both respirable dust and RCS downwind of the thief hatches. Reduction of airborne respirable dust ranged from 85% to 98%; reductions in airborne RCS ranged from 79% to 99%. A bulk sample of dust collected by the baghouse assembly showed the likely presence of freshly fractured quartz, a particularly hazardous form of RCS.

Planned future design enhancements will increase the performance and durability of the mini-baghouse, including an improved bag clamp mechanism and upgraded filter fabric with a modified air-to-cloth ratio. Future trials are planned to determine additional respirable dust and RCS concentration reductions achieved through these design changes.

Keywords

respirable crystalline silica; hydraulic fracturing; engineering controls; baghouse; oil and gas extraction

INTRODUCTION

The NIOSH Field Effort to Assess Risks for Chemical Exposures to Oil and Gas Workers began formally in 2010 to evaluate exposure risks for land-based oil and gas extraction workers.[1] NIOSH researchers were the first to systematically evaluate risks for occupational exposures on hydraulic fracturing sites across the U.S.. Identified risks include respirable crystalline silica (RCS) in hydraulic fracturing and volatile organic compounds (VOCs) in flowback operations. [2, 3] (See Figure 1.) Respirable dust is generally smaller than 10 micrometers (μm) in aerodynamic diameter[4] and can be inhaled and retained in the gas exchange region of the lungs. RCS is a particularly hazardous form of respirable dust.

Although occupational exposure to RCS is a widely-recognized hazard in industries such as construction, sandblasting, and mining,[5-13] it was not recognized as a hazard associated with oil and gas extraction until research was undertaken by NIOSH. Hydraulic fracturing is a technique used in oil and gas extraction that involves injection of fluid under high pressure into the wellbore to enhance existing fissures and create new cracks in tight oil and gas formations. This fluid consists of large volumes of water (about 95%), sand or “proppant” (about 4 – 5%), and a much smaller quantity (typically around 1%) of treatment chemicals. After release of hydraulic pressure, the proppant holds the cracks open, so gas or oil can flow from the formation. In addition to sand, resin-coated sand or ceramic proppant may also be used, depending on the formation. Transport and mixing of sand onsite is a major source of generation of RCS aerosols. During testing of the mini-baghouse, sand was the only proppant used.

Although hydraulic fracturing has been in use since the 1940s, its use for recovering oil and gas from tight formations has skyrocketed in the last ten years due to the use of novel drilling techniques. U.S. production of dry natural gas alone increased by 39% from 2004 to 2014. [(14)]

Silica-Related Disease

Silica (SiO_2) is found in a variety of crystalline and non-crystalline forms. The most common forms of crystalline silica are alpha quartz, cristobalite and tridymite, with alpha quartz being by far the most common. [(15)] Inhalation of RCS is most closely identified with the disease silicosis, a scarring of the lungs that causes difficulty in breathing. Acute silicosis can develop in weeks to months following exposure to very high concentrations (tens of milligrams per cubic meter) of RCS.[(16)] Long-term exposure to much lower concentrations of RCS can lead to accelerated or chronic silicosis years to decades later. Silicosis is also a risk factor for developing tuberculosis, kidney and skin disease.[(16)]

Workers exposed to RCS also have higher rates of other respiratory diseases, such as chronic bronchitis and emphysema. [(16)] The International Agency for Research on Cancer (IARC) and the U.S. National Toxicology Program (NTP) classify crystalline silica dust as a human carcinogen. [(15, 17)] Inhalation of sufficient quantities of quartz and cristobalite, two of the most common crystalline forms of silica, can lead to lung cancer, as has been shown in multiple studies. [(15)] Occupational exposure limits for RCS vary. The major U.S. exposure limits and a few selected international limits are summarized in Table I.

Process Description

Contemporary unconventional oil and gas wells are hydraulically fractured in multiple stages. Each stage can require hundreds of thousands to a million pounds of proppant. Proppant is usually delivered on site in dry bulk by tractor-trailers. A fan-compressor pneumatically transfers proppant from the delivery trailer through a hose into multi-bin storage and handling units called sand movers.

One or two inspection hatches (or “thief hatches”) are typically located along the top of each bin on a sand mover. These hatches are usually left either open or unlatched when proppant is transferred into the bins from the delivery trailers, to allow for visual inspection of the proppant volume in the bins. Even when the hatches are closed, the air used for sand transfer carries dust out of the hatches because the covers do not seal tightly. Proppant from the bins is discharged onto a conveyor belt that is beneath the sand mover. The conveyor belt brings the sand to a blender truck. In the blender, proppant is mixed with water and other additives before high pressure pumping and injection into the hydrocarbon-bearing formation. Because of the amount of proppant required in modern completions operations, multiple sand movers are commonly used, each depositing sand onto a large transfer belt that delivers the sand to the blender truck. Sand Mover Operators are positioned either at the top rear and above where the sand is discharged, or at the lower rear of the machine and beside where sand is discharged from the end of the conveyor belt (also called the dragon tail).[(2)]

Prior NIOSH Research

In 2010 and 2011, NIOSH researchers collected 111 personal breathing zone (PBZ) air samples for workers with 15 different job titles at 11 hydraulic fracturing sites in five states.[(2)] Job classification was found to associate with exposures to RCS. Sand Mover Operators and Transfer Belt Operators had the highest risks for exposures to RCS, due to their proximity to point sources of sand dust generation. Figure 2 shows a Sand Mover Operator at the topside work station.

Exposures to Sand Mover Operators sometimes exceeded either the OSHA PEL or NIOSH REL by more than a factor of 10, which exceeds the assigned protection factor (APF) of 10 for half-face elastomeric or filtering-facepiece respirators. At one site, a portion of the sand was replaced with ceramic proppant, and risks for exposures to RCS were notably lower. This suggests that product substitution can be a control option, where appropriate .[(2)]

Pneumatic transfer of sand enhances generation of dust. NIOSH researchers identified at least seven primary point sources of dust generation/release including:[(4)]

1. Thief hatches on top of the sand movers during filling,
2. Uncapped fill ports on sand movers during filling,
3. Vehicular traffic at the site,
4. Transfer belt under the sand movers,
5. Sand dropping into the blender tub,
6. Transfer belts between the sand movers and the blender,
7. The end of the sand mover conveyor belt.

Several engineering controls were proposed by NIOSH researchers to control generation of silica-containing aerosols into the workplace atmosphere. These included the mini-baghouse assembly, skirting and shrouding installed along the bottom of the sand mover and near the conveyor belt, and capping unused fill ports.[(2)] To address dust generation from thief hatches on top of sand movers during filling, NIOSH researchers evaluated the mini-baghouse retrofit assembly at a sand mine in Arkansas on November 18 – 21, 2013. Because of the numerous points of silica aerosol generation, additional controls (including engineering and administrative controls) are needed to control silica aerosol emissions from other point sources.

Control Technology

The NIOSH mini-baghouse retrofit assembly consists of a baseplate and clamping assembly and two sections of ductwork connected to a 48-cm (19-inch) diameter, 122-cm (4-foot) long section of baghouse filter material. The bottom section of duct was flanged and bolted to the baseplate, and a band clamp connected the second section of ductwork for each assembly. Another band clamp attached the filter bag to the duct. One long bolt in each corner of the baseplates (4 total per baseplate) can be tightened using a socket wrench to clamp to the inside top of each bin and secure the baseplate tight to the thief hatch opening. A Buna rubber gasket seals the baseplate to the hatch. Mounting or dismounting of each unit takes about 5 minutes, making it easy to remove and re-install the units as necessary when the sand mover is transported. A photo of the assemblies installed in the field is shown in Figure 3.

The mini-baghouse retrofit assembly controls sand dust emissions generated during pneumatic sand filling operations at an air flow rate of approximately 20 cubic meters per minute (700 cubic feet per minute) through the same principles used by commercial baghouses for control of particulate air pollution. When sand is pneumatically transferred into the bins, RCS dust is created from a variety of friction surfaces and impingement of sand against a deflection plate inside the bins. Dust-laden air is forced out through the thief hatches so that it passes through the baghouse filter fabric. A dust cake is formed on the inside surface of the bag which traps additional particulates but allows air to pass through to the bag material. The dust cake that collects against the inside of the filter fabric is shed when air is pulsed at the end of the sand filling operation, causing the cake to drop back into the sand mover.

MATERIALS AND METHODS

For this study, an NOV-APPCO Model FS-30 "Frac Sander" (i.e., sand mover) was used, configured with four interconnected compartments (or bins) and two hatches for each bin. Eight mini-baghouse retrofit assemblies were fabricated in-house by NIOSH and installed on each of the eight 56 cm × 56 cm (22" × 22") thief hatch openings. The study design involved collection of area air samples for respirable particulates and RCS, with the mini-baghouse either installed or absent, while one bin on the FS-30 was filled with 40/70 mesh sand proppant.

Eight trials were conducted. Each trial consisted of a pair of bin filling "runs": one with the mini-baghouse control present, and one with the control absent. Each of the four sand bins on the FS-30 has a different volumetric capacity; bins #2 and #3 were randomly chosen for the test evaluations using a random number generator. The experimental design was intended to evenly sample from bins #2 and #3. Therefore, in the first half of the runs, bin #3 was filled with sand, and in the other half, bin #2 was filled.

Samples for respirable particulates and RCS were collected using SKC® XR 5000® personal sampling pumps (SKC®, Eighty Four, PA), connected in-line to BGI® Model GK 2.69 size-selective cyclones (BGI®, Waltham, MA) to collect the respirable fraction of dust as per BGI specifications. Samples were collected on tared five micron (μm) poly vinyl chloride (PVC) filters in three-piece 37-mm polystyrene sampling cassettes (SKC®, Eighty Four, PA). The sampling trains were pre-calibrated in-line and on-site to 4.2 liters per minute, using Dry Cal Defender 530 calibrators (Bios International, Butler Park, NJ). Post-sampling calibration checks were also performed to confirm consistent pump flow.

Because this trial did not take place during actual oil and gas extraction operations, PBZ samples could not be collected. Area air samples were collected at 12 sampling locations; six were atop the sand mover at each of four corners and at two locations towards the middle of the FS-30, and six locations on the ground at PBZ height. Sampling locations are described in Figure 4. One of the two Sand Mover Operator positions was near the location of sample 4 on top of the sand mover; the other was between sample locations 2 and F, at ground level. Figures 5 and 6 illustrate the sampling trains. All samples were collected for the time required to empty one sand delivery truck into the sand mover. Collection times ranged between 23 and 53 minutes.

One hundred and ninety two samples were collected over four days during the eight runs used for evaluation of the control. Half of the air samples (96) were collected while using the mini-baghouse, and half were collected with the mini-baghouse absent. Temperature, relative humidity, and wind speed and direction were recorded continuously. The samples were equilibrated for two hours, static charges neutralized, and the samples were weighed and analyzed for respirable dust according to NIOSH method 0600, and for RCS according to NIOSH Method 7500 (Bureau Veritas, Novi, Michigan). [(18)]

For RCS analyses, the PVC filters were removed from the cassettes and folded two times to retain the particulates. The filter was moistened with a drop of isopropyl alcohol, and the filter cassette was wiped with the filter to collect any sample material retained onto the cassette wall. The filter was dissolved, and the sample transferred onto a silver-membrane filter for analysis by X-ray diffraction to determine the mass of quartz, cristobalite, or tridymite that could be present.

A bulk sample of dust collected by the mini-baghouse was sent to an AIHA-accredited analytical laboratory (Bureau Veritas, Kennesaw, Georgia) for examination of particle count, size and shape using a scanning electron microscope (SEM). Another bulk sample was sent to the same laboratory for analysis by NIOSH method 7500 to determine percent silica and to evaluate for interferences (e.g., limestone) to XRD analysis.

RESULTS

The concentrations for dust and for RCS were determined by dividing the mass of particulate collected on the filter (as determined by the laboratory) by the total volume of air sampled or pulled through the air sampling train (product of the collection time and the volumetric flowrate). Quartz was the only silicate mineral reported by the laboratory. Weather data for all trials are presented in Tables II and III.

NIOSH analytical methods include the analytical limit of detection (LOD), or the lowest amount of the analyte which can be distinguished from background. A related, and typically threefold greater value, is the analytical limit of quantitation (LOQ), above which a specified level of precision is achieved. Above the LOQ, the false negative rate is negligible unless certain interfering substances are present. [18] For most samples of respirable dust, the LOD was 50 micrograms and the LOQ was 150 micrograms. For most samples of RCS, the LOD was 5 micrograms and the LOQ was 17 micrograms.

Of the 96 area samples collected with the mini-baghouse control absent, 63 (65.6%) were <LOD for respirable dust; and 34 (35.4%) were <LOD for RCS. This is explained by the wind direction during the trials. Samples upwind of the bin being filled (and RCS aerosols generated) were not “exposed” to RCS aerosols, even in the absence of controls, hence < LOD. In stagnant air, it is anticipated that more uncontrolled samples would be above the LOD because of greater dispersion of RCS aerosols into a more quiescent atmosphere. Of the 96 area samples collected with the mini-baghouse in place, 90 (93.7%) were calculated to be <LOD for respirable dust, and 50 (52.1%) were <LOD for RCS.

All of the area air samples collected near the Sand Mover Operator's station (sampling location 4) atop the sand mover were above the LOD for both respirable dust and RCS when the NIOSH mini-baghouse retrofit assembly was not used. Conversely, when the mini-baghouse was in place, only two of eight samples at this same location were above the LOD for respirable dust and five of the eight samples were above the LOD for RCS.

Figure 6 is a photograph taken during a run in which the mini-baghouse units were not installed on the thief hatches. In this photograph, the cloud of dust escaping from the thief hatches is clearly visible. In contrast, Figure 7 is a photograph taken during a run in which the mini-baghouse units were installed. No visible dust is present.

DISCUSSION

Treatment of Concentrations <LOD

For calculation and statistical purposes, numerical values for samples <LOD are often estimated using a value such as the LOD divided by the square root of 2 (i.e., divided by 1.414), but this approximation is not recommended for datasets in which over half of the samples are non-detectable (< LOD).[19] Because the number of data points <LOD was so large, data were analyzed by a maximum likelihood estimation method (MLE) using the NLMIXED procedure in SAS/STAT 12.1 (SAS Institute, Inc., Cary, NC) according to the method described by Jin et al. for datasets with repeated measures containing large numbers of non-detectable values.[20]

MLE is a statistical method used to fit models and estimate the distribution of measurements <LOD when the data fit a lognormal distribution, which is typically the case for airborne particulates. The resulting MLE parameter estimates can be used to calculate the geometric mean and the geometric standard deviation of the data set. The MLE method results in less bias than substituting a constant value, such as the LOD divided by the square root of 2. The method performs well with datasets in which up to 80% of values are <LOD. [20] Using the method of Jin et al. [20] made it possible to calculate percent reductions in respirable dust and RCS concentrations for this dataset, despite the high number of concentrations below the LOD.

Performance of the NIOSH Mini-Baghouse Retrofit Assembly in this Study

Wind directions were recorded as vector azimuth angles. Wind direction is measured clockwise from the due north direction, which is indicated in Figure 4. Wind towards the north is denoted as an angle of 0°. Average wind directions during this evaluation were in a range of 28° to 171° (See Tables II and III.). Because average wind direction was never at an angle less than 28° or greater than 171°, some sampling locations were consistently upwind; concentrations of aerosols collected at these sampling locations were consistently low (typically <LOD), regardless of whether the mini-baghouse was in place or absent. Any aerosols collected by the samplers at the upwind locations likely originated from sources other than the sand mover (e.g., windblown soils). Aerosol concentrations at these upwind locations were therefore not influenced by the mini baghouse on the thief hatches, and were not used in calculations of effectiveness in reducing airborne respirable dust and RCS.

Concentrations of respirable dust and RCS at sampling locations 1 – 6 atop the sand mover were consistently greater than those measured at the ground level locations A – F. This is explained by the characteristics of respirable aerosols being inherently buoyant in air and settling at rates considerably slower than larger, non-respirable particles. Consequently, respirable aerosols remain suspended longer compared to larger and heavier aerosols.

Silica containing aerosols are released from thief hatches approximately 10-15 feet above ground; because of this, the suspended respirable fraction had some degree of dilution from wind before reaching the PBZ height of the samplers located around the sand movers. Dilution and distance helps to explain why respirable particulate concentrations collected on the ground (at PBZ height) near the sand mover were comparatively (but consistently) lower than respirable dust and silica concentrations collected at sampling locations atop the sand mover.

To calculate the effectiveness of the mini-baghouse control, only data from the four locations with the highest measured uncontrolled concentrations of respirable dust and crystalline silica (i.e., locations 3, 4, 5 and 6) were used; all of these locations were atop the sand mover. Even at these locations, 3 of the 16 samples taken without the mini-baghouse in place resulted in concentrations of RCS <LOD, and 9 of the 16 samples for respirable dust were <LOD. The authors believe the most plausible explanation for the large number of samples <LOD was the presence of wind diluting and dispersing aerosol concentrations to <LOD.

As shown in Tables IV and V, significant reductions in respirable dust and in RCS were achieved at these sampling locations by use of the mini-baghouse. Reductions in the geometric mean concentration of respirable dust ranged from 85% to 98%, while reductions in the geometric mean concentration of RCS ranged from 79% to 99% at these sampling locations.

A reduction of 98% in the concentration of respirable dust was measured in area samples located at or near the Sand Mover Operator's station (sampling location 4) when the mini-baghouse was in use. For RCS, the percent reduction at this same location was 99%. These values demonstrate a high degree of airborne particulate reduction and effectiveness of the

NIOSH mini-baghouse retrofit assembly in controlling both respirable particulates in general and RCS, specifically.

It is important to note that the area air samples collected during this study are not predictive of exposure risks for workers at hydraulic fracturing sites because workers' exposures are influenced by task-based activities and workers often move between different locations, and may do different work during a working day. PBZ samples (not static area samples) would be needed to characterize worker exposures. A study of PBZ samples under actual hydraulic fracturing operations is needed to determine worker exposure risks with this control present. During the study by Esswein et al. with no dust control, 74% of the full-shift PBZ samples for Sand Mover Operators exceeded all occupational exposure limits for RCS (>0.1 mg/m^3). [2]

Analysis of a bulk sample collected from the mini-baghouse filter bags by NIOSH method 7500 [18] showed it to be 64% silica (quartz) by weight. The size range of the sample, shown in Figure 8, indicates that the greatest percentage of particles were between 1 and 2 microns, which is in the respirable size range. Also, the bulk sample collected from the mini-baghouse filter bags was notably finer than the 40/70 mesh sand transferred into the sand delivery trucks and had the appearance and feel of talcum powder. This is likely due to proppant disintegration from frictional and impact forces on the sand grains when the dense material is pneumatically moved from the sand delivery truck into the bin of a sand mover. Further evidence of proppant disintegration can be seen in an SEM photo of a sample of collected particles. Figure 9 shows that the particles included a mixture of both smooth and angular shapes and that some of the particles in that sample appear to be fractured.

Observations and Limitations of the Study

Several dust leaks were observed during this study and the release of dust from these leaks is believed to have positively biased some results, possibly contributing to certain samples being > LOD and > LOQ. A screw cap on a fill port was inadvertently left off (fill port not capped and sealed) on bin #1 during trial 1 and possibly also trial 2; visible dust leaked from this location before the cap was replaced. Dust leaks around the base of the mini-baghouse were observed several times on the first day of testing. Tightening of the clamp bolts helped to stop these leaks. Some dust leakage was also observed at the joint between the two pieces of ductwork and the band clamp on the mini-baghouse (See Figure 10.) Dust also leaked visibly from the slide gates below several of the bins on the second day of testing. Those leaks may have had the effect of making the control appear to be less effective than if the leaks were not present during these trials.

Because of the prevailing winds, many of the air samples obtained during this study contained respirable particulate matter at concentrations <LOD. This resulted in not all of the data being useful or used to calculate a representative value for the effectiveness of the mini-baghouse control. However, using the method of Jin et al. [20], a percent reduction in respirable dust and RCS by use of the mini-baghouse control could be calculated for sampling locations that were downwind and nearby the thief hatch point sources of dust generation.

The mini-baghouse is a prototype unit; these trials were the initial evaluation of the technology and a future evaluation is planned for the next iteration. As with any new technology, improvements can be made to enhance effectiveness. During these trials, the authors noted that the filter bags showed a tendency to "blind" after several runs, that is, static pressure measurements indicated the baghouse fabric material used in this evaluation became less transparent to airflow (static pressure increased faster from run to run). This necessitated using pulsed air from the fan compressor to "shock" the bags and manually agitating the bags to help slough the accumulated dust cake. In some cases, the bags needed to be shocked and agitated several times during a single run to keep pressures within the acceptable range.

Use of the mini-baghouse will make it impossible for sand mover operators to use open thief hatches for visual inspection of sand levels in the sand mover. If it is judged necessary to keep track of sand levels, an alternate method of doing so will be required.

The baghouse fabric chosen for this evaluation may not have been optimal, and the air-to-cloth ratio may have been too high for this application. Air-to-cloth ratio is calculated by dividing the volumetric flowrate of air by the surface area of filter bag material. A low air-to-cloth ratio is needed to give an acceptable pressure drop during dust cake accumulation and filtration. According to officials at the company that provided the sand trucks used in the study (MAC Trailer, Alliance, OH), the fan compressor on the sand delivery truck should deliver a minimum of 20 cubic meters per minute (700 cubic feet per minute) of air when moving silica sand. With a 48-cm (19") diameter by 122-cm (4-foot) long bag mounted on each of the two hatches on each bin of the sand mover (a total of 8 hatches), the air-to-cloth ratio is approximately 16; an optimal air-cloth range is likely between 4 and 10 for this application. The high air-to-cloth ratio and the presence of fabric blinding likely explains failure (the bag developed a tear) of one of the bags during a ninth trial, when all four bins were filled simultaneously. (See Figure 11.)

CONCLUSIONS

The presence of RCS aerosols generated by forces created during pneumatic transfer of sand during hydraulic fracturing operations has been determined to pose occupational health exposure risks to workers at hydraulic fracturing sites.[2] The NIOSH mini-baghouse control evaluated in this research was shown to be effective in reducing the quantity of respirable dust and RCS aerosols released during bin filling operations. Reductions of RCS and respirable dust in a range of 79% to 99% downwind of the thief hatches were demonstrated in this study. While PBZ samples were not collected, observed area sample concentrations collected near working positions atop the sand mover sometimes exceeded the REL and/or TLV levels, even when the mini-baghouse control was in place. Results from this study demonstrate the effectiveness of the technology. Enhancements to the technology (e.g., control of leaks in ductwork and baseplate seals, selection of an alternative baghouse fabric, alterations to air-to-cloth ratio) will be considered in a future iteration to achieve further reductions in RCS and respirable dust aerosols.

RECOMMENDATIONS

Opportunities exist to further enhance the performance of the NIOSH mini-baghouse retrofit assembly with an improved clamping mechanism, substitution of alternative filter bag fabrics that enhance release of the dust cake, different air-to-cloth ratios, and an improved sealing surface on the bottom of the assembly. Additional field evaluations are planned following engineering enhancements to the mini-baghouse retrofit assembly.

The observation of fractured silica particles in the bulk sand sample collected during sand moving is a cause for concern, due to evidence that freshly-fractured silica particles have increased toxicity.[(21)] Research performed by the NIOSH Respiratory Diseases Research Program (RDRP) showed that inhalation of freshly fractured silica caused more oxidant injury and inflammation than inhalation of aged silica. [(22)] In future research, it would be appropriate to determine whether fractured silica particles such as those observed have been freshly-fractured during sand moving operations.

In addition to the NIOSH mini-baghouse, several commercial technologies exist for control of RCS aerosols during sand moving operations. These technologies have yet to be evaluated for their efficacy. Studies should be performed and published, quantifying the concentration of RCS aerosols when these technologies are in use.

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FIGURE 1.
Clouds of dust are visible as sand trucks are unloaded at a hydraulic fracturing site. Photo courtesy of Michael Breitenstein, NIOSH.

FIGURE 2.
Sand Mover Operator at his work station on top of the sand mover, arrows point to the open thief hatches. Photo courtesy of Eric Esswein, NIOSH.

FIGURE 3.

NIOSH mini-baghouse assemblies installed on eight thief hatches atop a sand mover during filling operations. Photo courtesy of Mike Gressel and Jerry Kratzer, NIOSH.

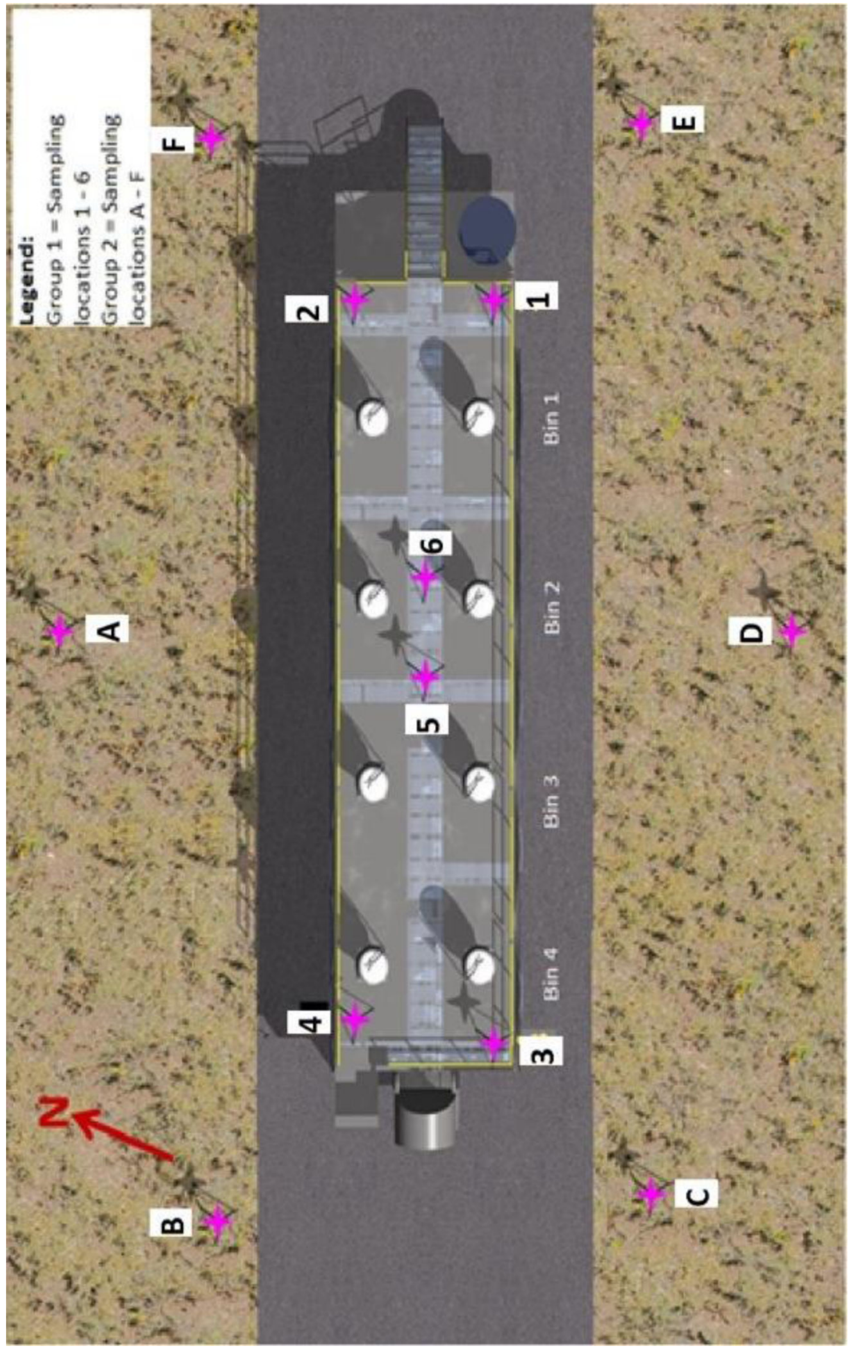

FIGURE 4.

Air sampling locations for test of mini-baghouse. Computer rendering developed by Kenneth Strunk, NIOSH Spokane, and modified by Barbara Alexander, NIOSH DART.

FIGURE 5.

Air sampling train installed on upper corner of sand mover. Photo courtesy of Mike Gressel and Jerry Kratzer, NIOSH.

FIGURE 6.
Sampling train located in the middle of the top of the sand mover during an uncontrolled trial run. Note visible cloud of silica-containing aerosols released from thief hatch opening when mini-baghouse is not in place. Photo courtesy of Mike Gressel and Jerry Kratzer, NIOSH.

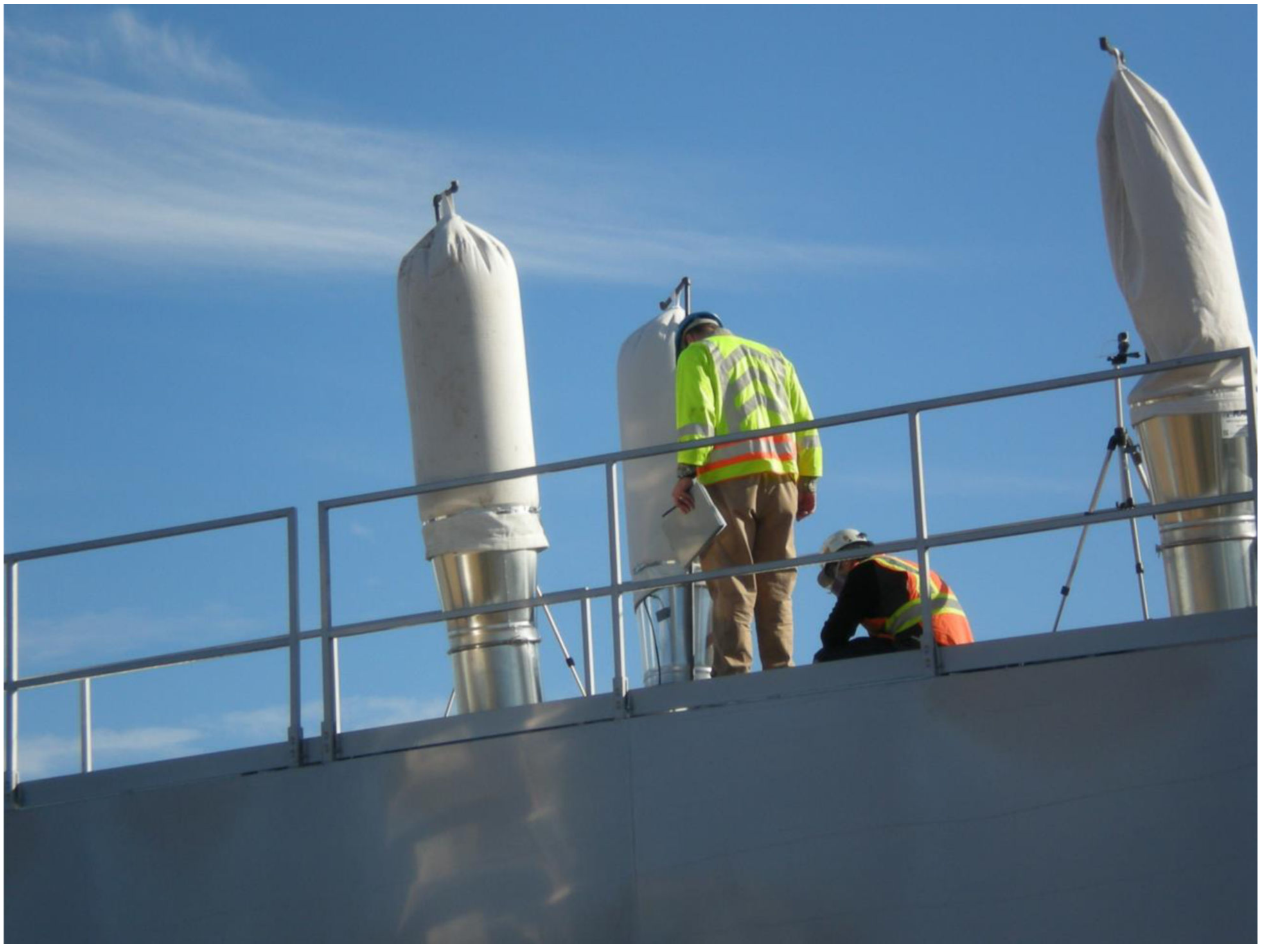

Figure 7.
Sampling run with mini-baghouse in place. No visible dust is being released. Photo courtesy of Mike Gressel and Jerry Kratzer, NIOSH.

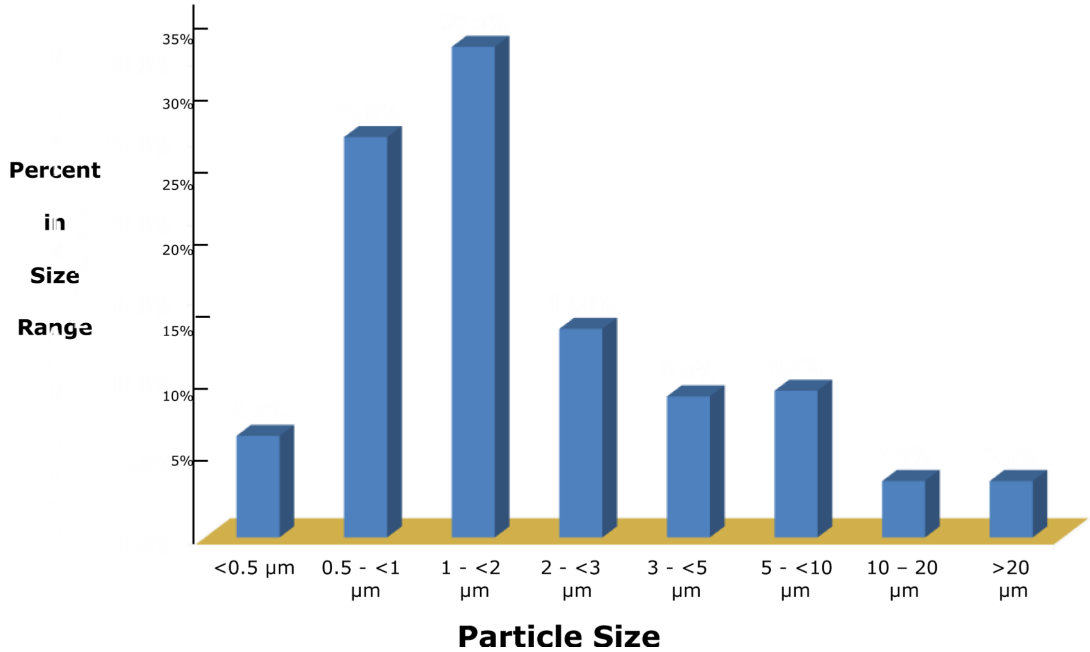

FIGURE 8.

Results of scanning electron microscopy analyses to determine particle size distribution for a bulk dust sample collected by the mini-baghouse retrofit assembly.

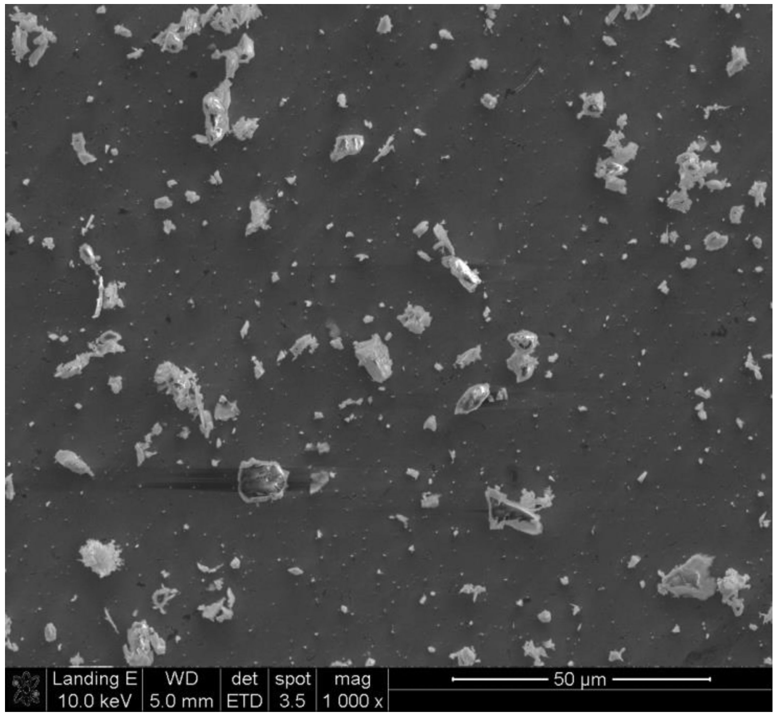

FIGURE 9.

Rounded and angular dust particles coll ected in the mini-baghouse during bin filling operations. SEM image courtesy of Arthur Miller, NIOSH Spokane.

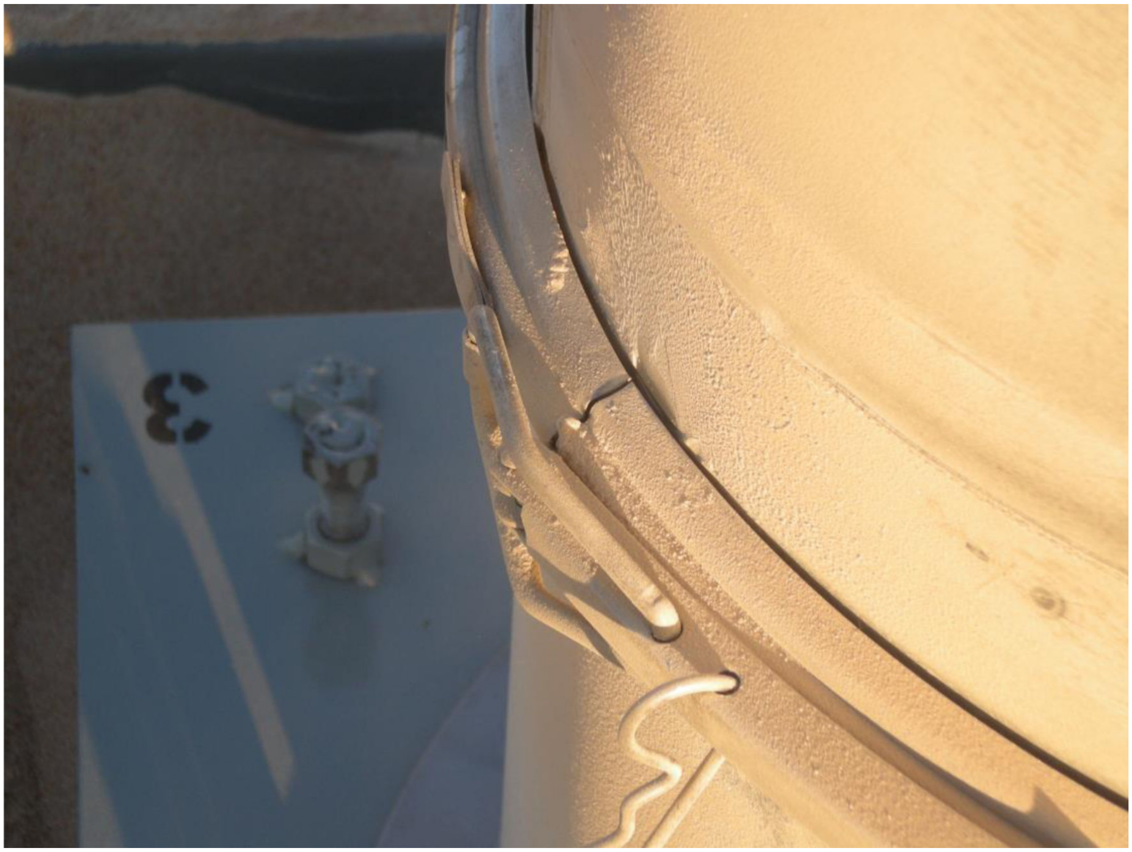

FIGURE 10.
Dust leakage visible at the band clamp connecting two sections of ductwork on the mini-baghouse. Photo courtesy of Mike Gressel and Jerry Kratzer, NIOSH.

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FIGURE 11.

Failure of filter bag during test of mini-baghouse. Photo courtesy of Mike Gressel and Jerry Kratzer, NIOSH.

TABLE I

Occupational Exposure Limits for respirable crystalline silica

Agency	Limit	Time-weighted Average Exposure Limit
National Institute for Occupational Safety and Health (NIOSH) [23]	Recommended Exposure Limit (REL)	$\mathrm{REL} = 0.05\frac{\mathrm{mg}}{\mathrm{m}^3}$
Occupational Safety and Health Administration (OSHA) General Industry (for dust containing >1% quartz) [24]	Permissible Exposure Limit (PEL)	$\mathrm{PEL}\left(\frac{\mathrm{mg}}{\mathrm{m}^3}\right) = \frac{10}{(\%\ \mathrm{silica}) + 2}$
American Conference of Governmental Industrial Hygienists (ACGIH) (α-quartz and cristobalite) [25]	Threshold Limit Value (TLV®)	$\mathrm{TLV} = 0.025\frac{\mathrm{mg}}{\mathrm{m}^3}$
Canada Labour Code (for respirable fraction of quartz and cristobalite)	Occupational Exposure Limit (OEL)	$\mathrm{OEL} = 0.025\frac{\mathrm{mg}}{\mathrm{m}^3}$
United Kingdom	Workplace Exposure Limit (WEL)	$\mathrm{WEL} = 0.1\frac{\mathrm{mg}}{\mathrm{m}^3}$

TABLE II

Weather data for trials in which bin 3 was filled.

Trial	Avg. Wind Direction (degrees)*	Avg. Wind Speed (meters per second)	Avg. Temperature (° Centigrade)	Avg. %Relative Humidity
1 ON	28	1.7	19	25.6
1 OFF	40	1.3	18	29.2
2 ON	75	1.7	10	48.8
2 OFF	81	1.9	10	49.4
3 ON	70	1.8	12	44.5
3 OFF	101	2.6	13	38.8
4 ON	{74}	{2.3}	{14}	{32.8}
4 OFF	**	**	**	**

Bracketed {} numbers show that data was not collected for the full period of the trial.

*Azimuth angle of the wind vector, measured clockwise from due north, with wind towards the north being an angle of 0°.

**Missing data.

TABLE III

Weather data for trials in which bin 2 was filled.

Trial	Avg. Wind Direction (degrees)*	Avg. Wind Speed (meters per second)	Avg. Temperature (° Centigrade)	Avg. %Relative Humidity
5 ON	171	2.4	9	57.6
5 OFF	132	1.7	7	64.0
6 ON	171	2.7	11	54.5
6 OFF	164	2.6	13	46.4
7 ON	165	2.2	16	33.4
7 OFF	{154}	{2.4}	{16}	{34.9}
8 ON	163	2.0	12	74.7
8 OFF	157	2.1	13	83.1

Bracketed {} numbers show that data was not collected for the full period of the trial.

*Azimuth angle of the wind vector, measured clockwise from due north, with wind towards the north being an angle of 0°.

TABLE IV

Reductions in respirable particulate concentrations using the NIOSH mini-baghouse control.

Sampling Location	Geometric Mean* – control off (mg/m^3)	Minimum – control off (mg/m^3)	Maximum – control off (mg/m^3)	Geometric Mean* – control on (mg/m^3)	Minimum – control on (mg/m^3)	Maximum – control on (mg/m^3)	Reduction* (%)
3 (n=16)	1.5	<LOD	54.7	0.15	<LOD	1.6	90
4 (n=16)	9.7	2.2	33.5	0.24	<LOD	1.1	98
5 (n=16)	0.73	<LOD	3.9	0.047	<LOD	<LOD	93
6 (n=16)	0.51	<LOD	2.1	0.078	<LOD	<LOD	85

*** Geometric Means and % Reduction values were estimated using the maximum likelihood estimation (MLE) method, due to the large number of non-detectable (<LOD) values in the dataset.**

TABLE V

Reductions in Respirable Crystalline Silica (RCS) aerosols using the NIOSH mini-bagiouse control.

Sampling Location	RCS Geometric Mean* – control off (mg/m^3)	RCS Minimum – control off (mg/m^3)	RCS Maximum – control off (mg/m^3)	RCS Geometric Mean* – control on (mg/m^3)	RCS Minimum – control on (mg/m^3)	RCS Maximum – control on (mg/m^3)	Reduction* (%)
3 (n=16)	0.43	<LOD	19.7	0.090	0.03	0.5	79
4 (n=16)	4.1	1.0	12.6	0.053	<LOD	0.4	99
5 (n=16)	0.33	0.05	1.7	0.026	<LOD	0.1	92
6 (n=16)	0.20	<LOD	1.7	0.032	<LOD	0.1	84

*** Geometric Means and % Reduction values were estimated using the maximum likelihood estimation (MLE) method, due to the large number of non-detectable (<LOD) values in the dataset.**