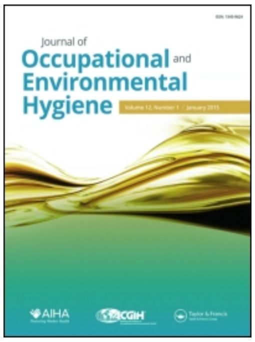

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Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://oeh.tandfonline.com/loi/uoeh20

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To cite this article: J. M. Slagley, H. Paschold & J. M. Engler (2017) Evaluation of coverall field dry aerosol decontamination methods using a manikin, Journal of Occupational and Environmental Hygiene, 14:7, 502-509, DOI: 10.1080/15459624.2017.1296235

To link to this article: http://dx.doi.org/10.1080/15459624.2017.1296235

Accepted author version posted online: 13 Apr 2017.
Published online: 13 Apr 2017.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2017, VOL. 14, NO. 7, 502–509
https://doi.org/10.1080/15459624.2017.1296235

Evaluation of coverall field dry aerosol decontamination methods using a manikin

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ABSTRACT

A full-size manikin dressed in fire-resistant coveralls coated in 120 g of sodium bicarbonate was randomly given one of three treatments for dry aerosol decontamination. The three treatments were high-efficiency particulate air (HEPA) vacuum, a commercially available air shower, and the no treatment control. Immediately after the treatment, the coveralls were doffed and an air sample was taken in the breathing zone of the manikin to estimate airborne total and respirable dust concentrations to an unprotected worker post decontamination. Each treatment was applied four times for a total of 12 trials. Using analysis of variance (ANOVA) with alpha = .05 and Tukey's Honestly Significant Difference multiple comparison post-test, it was determined that HEPA vacuuming was not significantly different from the air shower for respirable dust, but only the air shower was significantly better than no decontamination ($p = .037$). For total dust, HEPA was not significantly different from the air shower, but both were significantly better than no treatment ($p = .007$, $p = .004$, respectively).

KEYWORDS
Aerosol; decontamination; manikin

Introduction

The application of horizontal drilling and hydraulic fracturing (fracking) has encouraged significant growth in natural gas exploration and extraction in the United States.[1] National Institute for Occupational Safety and Health (NIOSH) researchers and Occupational Safety and Health Administration (OSHA) regulators have been working with industry to protect the environment, health, and safety while responsibly developing the natural resource; however, not all associated hazards are well understood.

NIOSH released a 2013 report analyzing airborne silica hazards for workers at fracking sites. Personal breathing zone samples for various jobs frequently exceeded the allowable OSHA 2016 respirable permissible exposure limit (PEL) of 0.05 mg/m^3, with a maximum observed value 55 times the PEL. Some exposures even exceeded the protection factor afforded by the workers' respirators. Researchers reported high exposures for some of the other workers indirectly involved with the silica handling. This suggests the environmental silica released at fracking sites could contribute significantly to bystander exposures.[2] OSHA and NIOSH have published online guidelines to help reduce silica exposures in the industry.[3]

Silica has long been a known hazard in the construction industry. Silica disease is still impacting workers.[4,5] Flanagan et al.[6] found excessive silica exposures associated with several tasks, with 42% of exposures exceeding the assigned protection factor of the respiratory protection used. In an effort to expand the pool of silica exposure data in construction, Flanagan and her colleagues collected 1374 private, university, and public construction industry airborne silica data and found the geometric mean to be 0.13 mg/m^3, far exceeding the OSHA permissible exposure limit of 0.05 mg/m^3.[7] Like fracking exposures, environmental exposures from construction can also pose a risk. Lipton et al.[8] studied time-weighted average (TWA) exposures of bridge surface blasting crews. The TWA measurements were for the task duration. They not only reported high respirable silica exposures (up to 0.20 mg/m^3) for abrasive blasters on bridge decks, they found the highest exposures among traffic controllers on the crews (up to 0.53 mg/m^3).

Silica awareness has been heightened by the March 25, 2016 promulgation of Title 29, Code of Federal Regulations, Part 1910.1053 and Part 1926.1153, *Respirable Crystalline Silica*.[9,10] The construction industry must comply with the standard by September 23, 2017. Hydraulic fracturing must comply by June 23, 2018, with

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the engineering controls provisions being enforced June 23, 2021. Both construction and fracking industries have a need for rapid, repeatable field decontamination of workers. Both heavily rely on subcontractors on multi-employer worksites. The addition of regulated areas under the silica standards will demand an effective dry aerosol decontamination method that is less reliant on individual worker motivation.

While protective measures such as coveralls and respirators will mitigate worker exposure, not all workers wear protection or don it correctly. Workers at the dust site will wear respirators, but remove these when away from the immediate area. Residual contamination on coveralls, even after decontamination, may present a hazard to the unprotected workers and others. McDonagh and Byrne report up to 67% of hazardous aerosols can be resuspended from clothing.[11] This source of cross-contamination may also present a source of OSHA citations and penalties for workplace exposure; [12] however, further exposure may be presented to other individuals if the worker brings contaminated clothing home for cleaning.[13] Perkins et al.[14] found significant levels of settled asbestos fibers (>100,000 structures per cm^2) in 14 of 15 vacuum samples of living quarters for road crews in an Alaskan study, suggesting a real problem of possible resuspension due to poor decontamination of dry aerosols.

The two main methods of personal field decontamination for dry aerosols are high efficiency particulate air (HEPA) vacuuming and air showers with HEPA filters. The OSHA silica standard calls for HEPA vacuuming or wet methods. Wet methods are best used for working surfaces and are impractical for worker clothing, especially in cold climates. There is also an allowance for blowing dust off with compressed air as long as all exhaust air is captured so as to not present a hazard. [9]

In 2007, Cecala et al.[15] investigated and reported methods of personal decontamination of aerosols by three methods:

- HEPA vacuum,
- compressed air blow-off without dust cloud capture, and
- air shower with collection of dust cloud.

HEPA vacuum and air showers are viable options; however, compressed air use without capturing the dust cloud is prohibited by OSHA. The compressed air method without dust cloud capture was evaluated due to its continued common practice in the field. The researchers found no statistically significant difference in decontamination effectiveness between HEPA vacuuming and compressed air. There was a statistically significant difference between the air shower and either the HEPA vacuum or compressed air.

While vacuuming is a very effective method of decontamination, difficulties exist with the method. As with much of the equipment in safety and health, the worker must be adequately motivated, trained, and prepared to effectively protect themselves with the systems provided by management. The process of vacuum decontamination takes significant time, about 5–6 min for the worker and a fellow-worker assistant. The time element suggests the use of multiple units, with associated capital expenses, to optimally discharge workers after their shifts or before breaks.[15]

Air showers, available from multiple manufacturers, are the other category of aerosol decontamination. They are typically designed to blow off the contaminant, then capture the dust cloud and exhaust it, often with HEPA filtration. The forced air can be provided by either compressed air or air blowers. The compressed air systems deliver effective volume and velocity; however, besides possible OSHA issues, they require periodic cycles to recharge tank pressure and generate high noise levels. A prototype compressed air system presented ambient noise (no air running) of 87 dBA in the chamber and up to 101 dBA during active decontamination.[15] The blower system utilizes large fans for continuous air delivery, but with a significant electrical power demand.

When evaluating decontamination effectiveness, direct-reading instruments (DRIs) are superior to traditional gravimetric methods due to the short duration of post-decontamination particle suspension. The recommended NIOSH method for silica sampling is method 7500.[16] Method 7500 specifies a minimum collection volume of 400 L and a flow rate of 2.5 L/minute. The minimum sample time with concentrations at the PEL would be 160 min. Workers leaving a regulated area would remove contamination then go to perform other tasks. They would not necessarily stand in the same location. For decontamination experiments to mimic field conditions, the measurements would have to be quick, thus DRIs are needed for the assessment. Using several assumptions, DRIs can estimate the mass/volume concentration of dry aerosols to compare decontamination methods.

A review of industrial hygiene literature failed to locate specific silica decontamination studies using DRIs to estimate mass/volume concentrations for measuring decontamination effectiveness, although DRIs have been used in studies for dry aerosol exposures for many years.[6] The Cecala et al.[15] study used difference in mass of coveralls before and after decontamination treatment. The series of anthrax particle resuspension studies,[17–19] used DRI particle counters but not for mass/volume concentrations and not for evaluating decontamination effectiveness. The McDonagh and Byrne studies used an aerosol particle sizer to estimate mass/volume concentrations to show that physical activity[20] and particle size[11] affect the resuspension of aerosols from clothing.

Real-time instruments afford the best method to estimate exposures, but with several minor limitations such as particle size distribution, counting efficiency, shape, and density differences from calibration aerosols. Methods have been shown in the literature to account for these limitations.[21–23] These methods should be adequate for the purposes of comparing decontamination method effectiveness.

Research statement

Silica exposures in the fracking and construction industries with multi-employer worksites common demand a rapid, repeatable dry aerosol decontamination method. Direct-reading instruments are required to measure decontamination method effectiveness due to the short time duration. Three common treatments were evaluated.

Methods

A full-sized manikin was dressed in fire-resistant coveralls. The fire-resistant coveralls used were 88% cotton/12% nylon Workrite FR (Westex, Oxnard, CA). They were laundered in the same manner before each trial. Researchers weighed out 120 g of sodium bicarbonate and applied it to the manikin's coveralls by hand rubbing on front and back of the torso and limbs. Previous pilot tests were conducted to determine appropriate contaminant mass. Sufficient mass was needed to provide airborne measurements after decontamination, but beyond 120 g excess contaminant would fall off during application. No studies of typical coverall contamination mass were found for reference. Sodium bicarbonate was used as a simulant for silica dust to avoid exposures to the researchers. Sodium bicarbonate is somewhat similar to silica in light scattering properties, and the density difference was included in the calculations to estimate concentration (see Table 1). The manikin was then placed inside the air shower booth, the door closed, and the dust allowed to settle for 30 min. Previous pilot studies showed that 30 min was sufficient for dust to settle back to background concentration levels. At 30 min, researchers applied the randomly selected decontamination treatment.

Table 1. Test aerosol properties compared to silica.

Aerosol	ρ (g/cm^3) [24]	Refractive index[25,26]
Silicon dioxide	2.65	1.54
Sodium bicarbonate	2.20	1.50

Figure 1. HEPA vacuum treatment protocol showing vacuum crevice device nozzle strokes applied to the front of the manikin.

Three treatments were randomly applied to the contaminated manikin 4 times for a total of 12 trials. The first treatment was a HEPA vacuum decontamination protocol. The HEPA vacuum (Dayton, Lake Forest, IL) was a model 22XJ54 with 45.5 L capacity producing 6.7 m^3/min of air flow at 178 cm of static pressure.[27] The manikin was vacuumed with a downward motion from shoulder to waist in four straight movements on the front and four on the back of the torso. Then two vacuum movements were applied to each arm and leg. The entire protocol took approximately 2.5 min. A visualization of the protocol is in Figure 1.

The second treatment was a commercially-available air shower shown in Figure 2 (MASHH, Halen Hardy, Bellwood, PA). The air shower used a blower rather than a compressed air source common in other air showers. The booth of the air shower was 2.4 m^3 (1 m deep, 1 m wide at the door, and 2.2 m high). The blower air enters the booth via both an overhead opening and a vertical linear "air knife" nozzle 2.5 cm wide by 1.6 m high supplying air at a velocity of approximately 13.5 m/sec at the manikin. The shower protocol calls for the worker to turn around twice in the booth so that the air knife is applied to all sides. This was accomplished by mounting the manikin to a turntable which could be actuated from outside of the closed booth. The cycle time was 30 sec, so the manikin rotation speed was approximately 4 revolutions per minute. All air was exhausted through floor grates and directed through a

Figure 2. Air shower chamber with manikin showing the overhead air supply.

HEPA filter incorporated into the air shower. The final treatment was a control of no decontamination.

After the treatment was applied, researchers removed the coveralls to the floor of the booth and took air samples from the breathing zone of the manikin. Air sampling was conducted with a Met One HHPC 6 six-channel optical particle counter (OPC) (Met One, Grants Pass, OR). The OPC was factory-calibrated to polystyrene latex particles.[28] The OPC used an isokinetic sampling probe and had reported counting efficiency of 100% at particle sizes > 0.45 µm. The particle size bins were set to 0.3, 0.5, 0.7, 1.0, 5.0, and 10.0 µm. OPC sample duration was 21 sec at 2.8 L/min and samples were collected at 1 min post-doff. The selection of 1 min post-doff was to simulate the approximate time workers would be expected to remove respiratory protection. Also, McDonagh and Byrne[20] showed maximum particle resuspension concentration from worker clothing for low-physical activity at 1.5 min. The 1 min post-doff sample start time was planned to capture the maximum particle resuspension. Further, a pilot study was performed tracking data each minute for 30 min. The highest concentrations were generally before 5 min, so the first minute was selected for consistency. Spatial variation was not confirmed since the sample location was in the manikin's breathing zone at the same location each time. After air sampling was completed, the contaminated coveralls were removed and placed in a bag, the booth door was shut, and the shower was run for another cycle on the naked manikin to remove residual surface contamination.

Four trials were run for each of the three treatments for a total of 12 trials over a period of two days. Treatment order was randomized to reduce bias over time. The trials were conducted in a warehouse over two days. The average relative humidity was 66.56% on day one and 61.83% on day two. Since the test dust was hygroscopic, differences in relative humidity between days may have biased results. However, the humidity was similar between the test days. Background particle counts were taken for each trial and subtracted from the trial measurements. The particle counts for each bin were used to estimate a mass concentration after Hinds.[29] The density of sodium bicarbonate and the assumption of spherical particle shape with diameter of the midpoint size for each bin was used in to estimate mass concentration.

All particles were included for total dust estimates. For respirable dust estimates, the respirable deposition fraction was estimated using the American Conference of Governmental Industrial Hygienists (ACGIH) equation below.[30] Midpoint particle diameter for each bin was substituted for aerodynamic particle diameter (d_{ae}) in the calculations:

$$RPM\ (d_{ae}) = IPM\ (d_{ae})\ [1 - F\ (x)]\ , \qquad (1)$$

where *F(x)* is the cumulative probability function of the following:

$$x = \frac{\ln\ (d_{ae}/\Gamma)}{\ln\ (\Sigma)}, \qquad (2)$$

where

$$\begin{aligned} \Gamma &= 4.25\ \mu m \\ \sum &= 1.5 \\ d_{ae} &= \text{aerodynamic particle diameter } (\mu\text{m}) \\ \text{IPM } (d_{ae}) &= \text{inhalable particle collection efficiency} \\ \text{RPM } (d_{ae}) &= \text{respirable particle collection efficiency.} \end{aligned}$$

Previous pilot tests indicated that laundered uncontaminated coveralls treated similarly resulted in background-corrected airborne total and respirable concentrations <0.00002 mg/m^3. As this was less than a tenth of the lowest observed concentration it was assumed that the coverall fiber contribution to the particle count was negligibly different from background. The experimental measurements were thus background corrected without an additional step of adjusting for clean coverall fiber contribution.

Table 2. Total dust concentrations by decontamination treatment.

Treatment	None	HEPA Vacuum	Air Shower
n (number of samples)	4	4	4
Min-max (mg/m^3)	1.898–2.853	0.115–0.333	0.00006–0.147
Arithmetic mean (mg/m^3)	1.693	0.229	0.048
Standard deviation	0.880	0.096	0.069

Table 3. Respirable dust concentrations by decontamination treatment.

Treatment	None	HEPA Vacuum	Air Shower
n (number of samples)	4	4	4
Min-max (mg/m^3)	0.0056–0.0338	0.0020–0.0066	0.00006–0.0037
Arithmetic mean (mg/m^3)	0.0168	0.0046	0.0018
Standard deviation	0.0121	0.0020	0.0019

Results

The background-corrected calculated total and respirable dust concentration results of the 12 trials are in Tables 2 and 3 with mean and standard deviation. Note that when a background measurement of particles for a size bin was higher than the trial measurement for the same size bin, a value of zero was substituted for the censored data point. Due to the particle size distribution of the test dust, the two smaller bins below 1 µm were heavily censored. The background particle counts were generally within 1–2 orders of magnitude of the measured particle counts. The concentration values were heavily dependent on the larger particle counts, since the measurements were mass concentrations.

Statistical Package for the Social Sciences (SPSS) (IBM, Armonk, NY) was used to run an analysis of variance (ANOVA) at an $\alpha = 0.05$ with either total or respirable dust concentration as the dependent variable. The categorical independent variable was the decontamination treatment. Both total and respirable dust models were found significant ($p = .002$ and $p = .034$, respectively). The ANOVA summaries are presented in Tables 4 and 5. Tukey's Honestly Significant Difference (HSD) was applied as post-test analysis to compare treatments.

The results of Tukey's HSD post-test ($\alpha = 0.05$) comparison among the treatments for total and respirable dust are in Tables 6 and 7.

For total dust concentration, there was no difference between air shower and HEPA vacuum treatments ($p = .868$). Both treatments resulted in significantly lower post-doff airborne total dust concentration than no treatment (air shower $p = .004$, HEPA vacuum $p = .007$).

For respirable dust concentration, there was no difference between air shower and HEPA vacuum treatments ($p = .844$). There was also no difference between HEPA vacuum and no treatment ($p = .087$), although measured concentrations were generally lower. The air shower treatment resulted in significantly lower post-doff airborne respirable dust concentration than no treatment ($p = .037$).

Table 4. Analysis of variance for total dust concentration by treatment group.

Source	DF	Sums of Squares	Mean Square	F Ratio	Prob > F
Model	2	6.5046	3.2523	12.3685	0.0026
Error	9	2.3666	0.2630		
Total	11	8.8712			

Table 5. Analysis of variance for respirable dust concentration by treatment group.

Source	DF	Sums of Squares	Mean Square	F Ratio	Prob > F
Model	2	0.00051115	0.000256	5.0194	0.0343
Error	9	0.00045826	0.000051		
Total	11	0.00096941			

Table 6. Tukey's HSD post-test for total dust concentration with group means displayed.

		Subset	
Treatment	n	1	2
Air shower	4	0.048 mg/m^3	
HEPA vacuum	4	0.229 mg/m^3	
No treatment	4		1.693 mg/m^3

Discussion

The results of the study indicate that the two forms of field decontamination for dry aerosols were not significantly different for airborne total dust exposures, although the air shower treated coveralls appeared visually cleaner than the HEPA vacuumed coveralls. However, the air shower treatment resulted in statistically lower airborne total and respirable dust exposures than no treatment. The HEPA vacuum treatment was significantly better than no treatment for total dust, but not significantly better for respirable dust. This may be because the protocol applied focused on repeatability, not thoroughness. The intent of a repeatable protocol was to limit the influence of variation in worker motivation. HEPA vacuums work well when workers are motivated to thoroughly remove dust. When workers are less motivated, the amount of remaining dust is higher. Also, as McDonagh and Byrne showed

Table 7. Tukey's HSD post-test for respirable dust concentration with group means displayed.

		Subset	
Treatment	n	1	2
Air shower	4	0.0018 mg/m^3	
HEPA vacuum	4	0.0046 mg/m^3	0.0046 mg/m^3
No treatment	4		0.0168 mg/m^3

in the physical activity studies using an Irish Reel, moving the clothing through the dust cloud tended to lodge particles deeper into the weave.[20] The effect on the observed differences between treatments could be that the air shower treatment tended to drive particles deeper into the weave of the coveralls, whereas HEPA vacuuming would remove particles. This would make particles harder to dislodge from the air showered coveralls to present an airborne hazard when doffing.

A limitation is the use of a surrogate dust, sodium bicarbonate, when the dust of interest is respirable quartz silica. For optical methods of estimating mass/volume concentrations, the three key factors are particle size distribution, density, and refractive index (the latter two factors shown in Table 1).[21] Particle size distributions will vary not only between two dusts, but also simply in different regions of the same dust cloud. The OPC device did record particles in all the size bins, but background correction removed the particles in the smallest bin. An example background-corrected sodium bicarbonate size distribution from the tests is given in Figure 3. While this does not match the calibration dust for the instrument, the same test dust was used for all of the measurements so that any biases would be the same to compare the treatments. However, counting efficiency is size dependent, so differences between the test dust and actual field dust may affect decontamination outcomes in the field. Density was taken into consideration for the calculated estimates of concentration as compared to the calibration dust of the OPC. Sodium bicarbonate is 83% of the density of silica. The density would make a difference in how quickly dust settles from the air around a worker, and how well the decontamination treatments work. Since silica is denser, it would be expected to be more difficult to remove from the coveralls than sodium bicarbonate. However, the respirable fraction of either dust would seem be light enough to be similarly removed by the decontamination protocols. McDonagh and Byrne

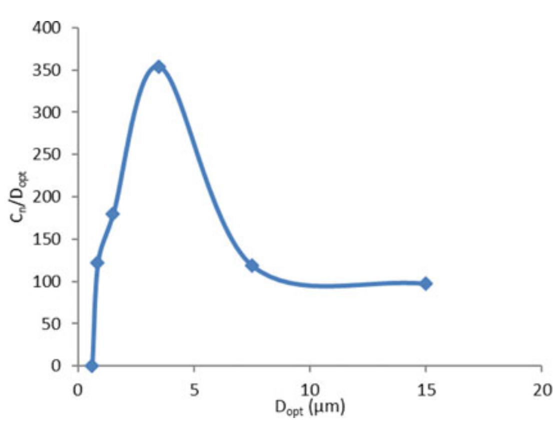

Figure 3. Example particle size distribution of sodium bicarbonate test dust.

concluded that the weave of the fabric of the protective clothing was also very important in particle resuspension with a tight weave pattern resulting in less particle resuspension.[20] Since the same coverall type was used throughout the present experiments, this should not contribute to observed differences in decontamination method effectiveness. Last, refractive index was nearly the same for both dusts (1.50 vs. 1.54). In summary, the difference in the two dusts can be accounted for optically, but there still may be a difference in the effectiveness of decontamination methods from what was observed in this experiment. For instance, sodium bicarbonate is more hygroscopic than silica and with the absorption of moisture can become glued to the fabric making it harder to dislodge. Also, silica and sodium bicarbonate differ in their ability to build up a static charge. A stronger charge would make it harder to dislodge. The difference in particle size distribution between the test dust and silica may also affect the comparison. Silica dust may be smaller in diameter. Small diameter particles may be blown deeper into the garment by the air shower treatment, depending on material weave, and not be airborne to expose workers. However, HEPA vacuuming may be less effective in removing smaller particles, leaving small surface particles available to be re-entrained to the air during the doffing process. This may explain why the HEPA vacuum treatment was statistically better than no treatment for total dust consisting of larger particles, but not different for respirable dust of smaller particles. The difference between the treatments may be more pronounced with small silica test dust. Regardless, it was assumed that these differences, while important, would not disprove the comparison between decontamination methods using the same conditions and test dust.

Even with the limitations of the experiment, some useful information can be gleaned. The long-standing dry aerosol decontamination method of HEPA vacuuming works as well as the tested air shower. However, only the air shower was statistically better than nothing for respirable dust. Since respirable dust is the important fraction for silica, the results of this study suggest the air shower would be preferred. Also, for the fracking and construction industries with dynamic multi-employer worksites, an air shower system reduces the variation in effectiveness from worker motivation. It also requires only the worker being decontaminated to use it compared to the buddy system for HEPA vacuum methods. And the cycle time is 30 sec instead of 2–3 min per person for a HEPA vacuum. The air shower had lower cycle time, lower (though not significantly so) average airborne concentration, and lower variability in measurements compared to the HEPA vacuum protocol. There was no statistical difference between the two treatments, but there are several points that suggest the air shower treatment would be superior to HEPA vacuuming in the field.

Conclusion

Personal decontamination is extremely important for housekeeping and hazard control in conjunction with regulated areas and proper personal protective equipment use. Two decontamination treatments were compared with a no treatment option for personal dry aerosol decontamination. Both air shower and HEPA vacuum treatments were statistically similar, but only the air shower was significantly better than no treatment for respirable dust exposure. That coupled with other practical factors such as time and repeatability suggest that the air shower method may be superior, but more costly for dry aerosol control. Considering silica in fracking and construction industries, and the nature of their workforce, the cost may be worth the investment. The 2016 OSHA promulgation of the silica standards and the continued incidence of silica-related disease demand continued research to improve control options to reduce exposure risk to workers.

Acknowledgments

The manufacturer of the air shower provided no-cost access to their production site to perform the experiments. The United States Air Force School of Aerospace Medicine provided an equipment loan of the optical particle counter. Students Daniel Cavanaugh and Francis Slagley assisted with data collection.

Disclaimer

This document is the work of the authors and does not represent the position of the United States Department of Defense or the United States Air Force.

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