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# Preliminary Characterization of Respirable Rock Dust Generated from Cutting Potash in Laboratory Full-Scale Tests with Radial Picks at Different Stages of Wear

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**Abstract:** Airborne rock dust poses serious long-term health effects to workers in mining and tunneling underground rock environments. When inhaled, respirable crystalline silica particles commonly found in quartz and other minerals will scar sensitive lung tissue and cause irreversible lung diseases. Characteristics such as concentration, type of mineral, particle size, and particle shape can harm workers to various extents. Therefore, this study characterizes airborne rock dust particles that are released from mechanically cutting rock. Laboratory full scale linear cutting tests on samples of potash rock were performed with radial picks to generate dust and were collected with various instruments, including Dorr-Oliver cyclones. Three stages of pick wear were tested: new, moderately worn, and severely worn. Comparisons between different stages of pick wear to dust concentration, size distribution, and particle shape characteristics are drawn from this preliminary study using analytical methods, field-emission scanning electron microscope image capture techniques, and laser diffraction. Although further testing needs to be conducted to make viable and concrete conclusions, a review of the test results reveals a strong tendency in generated airborne and deposited dust to be linked to the bit tip wear, which was influenced by tip surface area geometry, such as a sharp tip, blunt tip, or undulating sharp tips. The moderately worn pick, or the pick with the bluntest tip, in these experiments released the highest concentration of dust. The moderately worn (bluntest) pick also generated particle shapes with the highest aspect ratio compared to the other two picks. Additionally, in terms of the particle size distributions, all the picks generated airborne particle size mean values between 0.7 and 1.2 μm in aerodynamic diameter. As for deposited particle size distributions, all the picks generated particles with the mode of particle aerodynamic diameter sizes at 13 μm. In the end, the results of this preliminary study paired with future testing can confirm and eventually provide the basis for optimum bit management and maintenance systems to control airborne dust exposures.

**Key words:** Respirable rock dust, particle size distribution, particle shape, dust concentration.

## 1. Introduction

The standard mode of production in many of the soft- to medium-strength rock formations is the use of mechanical excavation units such as continuous miners, roadheaders, and drum shearers. These machines use various types of metal picks to strike and break the rock, such as radial picks. However, each time the pick strikes the rock to break it, dust is generated and becomes airborne, which workers can inhale.

Dust inhalation is a concern specifically in the mining and tunneling industry because breathing in rock dust particles less than 10 μm in aerodynamic diameter can cause irreversible lung diseases such as coal-workers' pneumoconiosis [1, 2], silicosis [3, 4], and other life-threatening lung diseases [5-9]. Additionally, since the 2000s, cases of lung diseases in underground mine workers are increasing, especially in coal mines in the Appalachian region [10-13].

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Aside from concentration exposures, researchers are currently investigating possible causes for the increase of workers' lung diseases. There are studies on airborne dust characteristics and other studies on the effects of dust particle characteristics on the lung. For example, there are recent characteristics studies on the shape of particles, the size distribution of particles, nanoparticle influence, mineralogy effects, changes in drilling into roof strata or varying seams, and location of mine [14-19]. Additional lung studies include particle-wall interaction in relation to particle shape [20], non-spherical particle transport and deposition in the lung [21-23], and influence of particle size in the lungs [24, 25]. Although these current comprehensive studies have increased understanding on characteristics of dust particles, it is still uncertain what is harming worker lung health.

There are also limited studies specifically on how pick tip geometry and wear influence dust generation. The previous investigations of pick tip shape influence on dust generation only include an analysis of the concentration of coal dust [26-29]. What the previous findings consistently reveal is that the concentration of coal dust will increase as the pick tips become much blunter.

Therefore, the following study is to contribute to the on-going research in characterizing various rock dusts. With limited research on how the characterizations of airborne potash rock dust change throughout the lifetime of the pick used for drilling rock, this study provides the preliminary characterizations of potash dust when drilled with a new pick, a moderately worn pick, and a severely worn pick. The concentration, mineralogy, particle shapes, and particle size distributions are determined to characterize the dust particles and built upon previous pick wear studies using conical picks [30].

The concentration of dust and silica content were analyzed because these known characteristics cause undesirable health effects. The size distributions of airborne respirable and deposited particles were analyzed because the size of the particle a worker inhales can cause adverse and various health effects. For example, inhalable particles from 100 μm to 10 μm in aerodynamic diameter become trapped in the nose, thoracic particles less than 10 μm become trapped in the region of the lungs where the bronchiole reside, and respirable particles less than 4 μm are able to reach the region of the lungs where the alveoli reside [31]. The deeper into the lungs that silica particles penetrate, such as particles reaching the alveolar region, the more dangerous they can become to human health because they can scar sensitive and critical air sacs [32]. The shapes of the dust particles were analyzed because this is another parameter that can influence the negative effect on human respiratory health [14]. For example, long and narrow particles that are smaller than 10 μm in aerodynamic diameter, such as asbestos with an aspect ratio of 3 or greater, can readily be trapped in the lungs compared to more round particles [33-35]. Or, particles with geometric shapes ranging from spheres to cylinders will have different dynamic shape factors, which influence the speed at which the particle settles [31].

Analytical National Institute for Occupational Safety and Health (NIOSH) methods, scanning electron microscopy, laser diffraction analysis, and image analysis programs are used to determine the concentration, mineralogy, particle shapes, and particle size distributions. Results, along with future studies to confirm preliminary trends in this study, will aid operators in making dust suppression decisions in the underground environment to protect workers.

## 2. Experimental Setup

### *2.1 Sample Preparation and Full Scale Cutting*

When studying the rock excavation process, it is critical to perform the test in full scale. This means that the full-size pick cutting tool is used in cutting the target material with the spacing and depth of penetration used in the field. Full scale tests facilitate more accurate particle size distribution analysis and allow for studies of the both the airborne dust and deposited dust. The deposited dust is dust that settled onto the surface after cutting and could be reintroduced into the air during downstream operations.

To conduct a full scale cutting test, large samples of rock procured from the mine site are cast into a steel box with appropriate concrete to secure the sample in place. For this study, large potash samples received from an underground mine in Canada were cast for cutting tests. Each sample was then installed into the LCM (Linear Cutting Machine) at the EMI (Earth Mechanics Institute) at the CSM (Colorado School of Mines) for full scale cutting tests. As shown in Fig. 1, the potash block cut into three samples is considered fairly homogenous for these experiments. They are considered close to homogenous because throughout cutting each block from top to bottom, the distribution of crystals was fairly uniform and there were no intrusions or rock joint sets throughout the samples.

The LCM, as seen in Fig. 2, is used to simulate full scale cutting tests on rock. The machine is able to simulate real linear cuts in mining operations because it utilizes the same spacing and penetration values used in industry and the physical picks used in operation are installed into the machine. The LCM moves the rock block underneath the bit in a linear manner, forcing the pick to dig into the samples while the normal, drag, and lateral cutting forces are measured and recorded by a high-capacity 3D load cell. The rock cutting parameters that can be changed on the LCM include the spacing between lines of cuts along the surface of the rock, the depth of pick penetration into the rock, and speed of cut. For the experiment, all potash blocks were cut with a 12 cm (4.75 inch) spacing between cut lines, a 2.67 cm (1.05 inch) penetration depth per line, and 250 mm/s (10 inch/s) cut speed. Each individual test, such as only the dust generated from the new pick, was an average of the dust generated from 6 cut lines across the rock surface as seen in Fig. 1. Two additional comparable tests (where each additional test is an average of 6 cut lines) were included and the results presented are an average of the three test sets obtained per pick wear.

*2.2 Dust Collection Setup*

It should be noted that the dust collection setup is not intended to measure the absolute volume of dust. Rather it allows for the measurement of representative dust samples generated with various pick settings for comparative analysis. Consistent representative collections and measurements of the airborne and deposited particles generated in the experiments allow for objective comparison between results for different bit wear conditions.

Two methods for collecting dust were used to obtain representative samples of dust generated from cutting rock. The first method uses Dorr-Oliver cyclones with a 50% cut point of 4 μm aerodynamic diameter particles to collect the airborne rock dust. The second method uses a vacuum (shop-vac) to collect the heavier, deposited, particles left behind along the line of cut

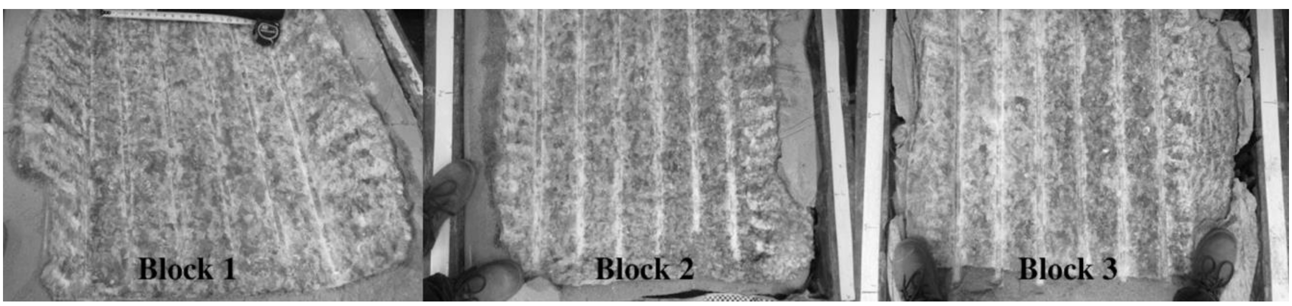


**Fig. 1 Looking down on each of the 3 potash blocks used for full scale cutting.**
Block 1 was used for the new pick, Block 2 was used for the moderately worn pick, and Block 3 was used for the severely worn pick. The length and width of each block was 1 m × 0.9 m (3.5 feet × 3 feet) respectively.

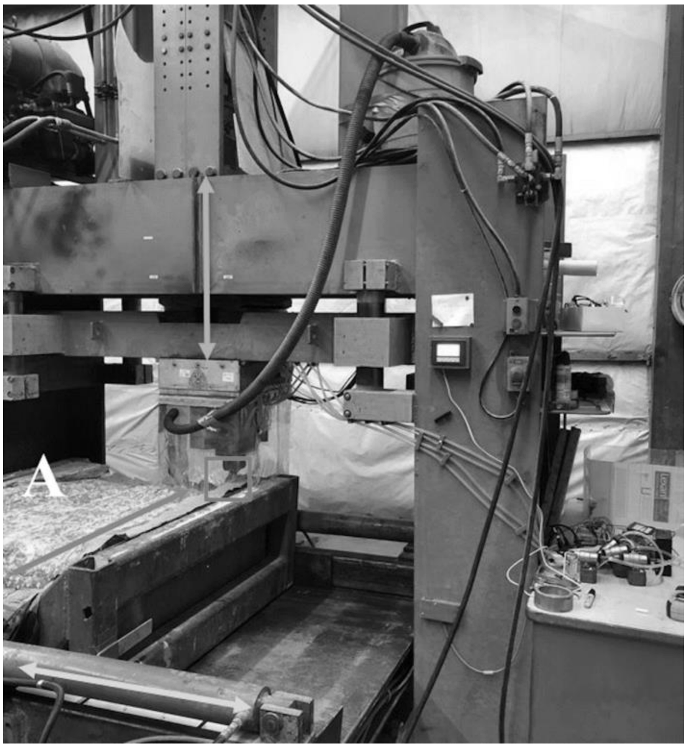


**Fig. 2 Linear cutting machine.**
"A" shows the potash rock block cast into the metal box, the square encompasses the location of the pick within the dust curtain, the horizontal arrow forward to back shows the movement of the box under the stationary pick to generate cuts, the horizontal left to right arrows indicate sideways movement of box to index the pick for the next cut, and the vertical arrows show the movement of the frame to control the penetration of cuts.

(crushed zone under the bit) on the surface of the rock after each cut. The particles collected with the vacuum are referred to as the deposited materials that would be transported into downstream operations if the cuts were performed in a real mine. In order to minimize any cross-contamination of deposited materials, a new filter was installed before each dust collection and the inside of the vacuum, including the suction hose and collection bucket, was cleaned with pressurized air.

The 10 mm Dorr-Oliver cyclones remove larger airborne particles and deposit the respirable particles onto either 37 mm diameter PC (Polycarbonate) filters or 37 mm diameter PVC (Polyvinyl Chloride) filters. A clear dust curtain is installed around the cutting area to ensure a fixed volumetric space, confine the dust generated during cutting, and keep out environmental particles as seen in Fig. 2. Four cyclones are placed inside the dust curtain equidistantly and evenly spaced around the pick to collect dust with the various filters. PC filters are used for this experiment because the substrate is best suited to analyze particles in a scanning electron microscope [19, 36]. PVC filters are used to obtain the concentration and mineralogy because the material has a stable weight [37-40]. The cyclones were connected with Tygon® tubing to air pumps running at 1.7 L/min, the recommended flow rate to use for maximizing collection efficiency [41]. Due to humidity changing the collection efficiency of cyclones [42-45], tests were conducted within a range that does not affect collection efficiency, which was between 20% and 30% humidity. The new pick was tested at 20%, the moderately worn pick tested at 29%, and the worn pick tested at 24% humidity, which are all humidity values that could be present in a mine operation.

The cyclones and pumps are integrated within an automated dust collection system as seen in Fig. 3. This system minimizes human error in sampling dust particles during full scale cutting tests and additionally clears out dust from prior cuts to flush out the system. Human error is minimized because the system controls all the pump to run or shut off at the same time with a timer, therefore ensuring each cyclone collects for the same duration. Dust is also cleared out from the system with clean air that passes through a High Efficiency Particle Air (HEPA) filter and displaces old air through the thick black tubes as seen in Fig 2. To control the automated dust collection system, a laser measuring the displacement of the rock box sends signals to the data interface. The data interface, or the CLICK® programmable logic controller, uses the laser readings to open and close the electric ball valves with programed times. This controls when the pumps draw in air to collect dust and additionally when the flushing system turns on to clear out dust after a cut. The automated dust collection system ensures consistency and therefore, comparability, between dusts generated with the various picks.

A rotameter is incorporated into the system to verify pump flow rates before and after rock cutting as shown in Fig. 3. The rotameter and pumps are calibrated before testing with a Bios International® DC-1 DryCal Flow Calibrator. A TSI SidePak AM510™ real-time concentration monitor is used to ensure the flush system removes all particles in the dust curtain before the next cut begins. Additionally, the ambient air within the dust curtain is collected before testing to ensure the air inside the dust curtain is clear of outside pollutants.

The filters in two-piece cassettes are placed directly in-line after the cyclones and the filter-cyclone setup is installed upright as close to the pick tip as possible inside the dust curtain. The rest of the automated dust collection setup is outside the dust curtain at the side of the LCM. Therefore, about 5 feet of Tygon® tubing per filter-cyclone setup is used to connect the filter-cyclone setups to the pumps.

Due to limited rock sample and the nature of cutting potash rock, one sample of dust averaged from 6 cut lines was collected for each pick wear while cutting. For example, the 4 cyclones collected dust during the time it took the LCM to cut 6 parallel cut lines across the sample and the deposited particles were collected after the 6 cut lines were completed. Therefore, the dust studied is the dust generated from cutting multiple lines with the same pick wear. Additional future rock cutting needs to take place to confirm the preliminary potash dust results from this study.


**Fig. 3 Dust collection system.**

(A) Data acquisition interface and power unit that controls when dust is collected and flushed out of the system, (B) Solenoid ball valves to control the air flow through the cyclones, (C) Pumps running at 1.7 L/min, (D) Real-time dust concentration monitor, (E) Rotameter placed in-line before and after testing to ensure pump is running at 1.7 L/min.

### *2.3 Pick Wear Quantification*

Three radial bits were used for experimentation with a new, moderately worn, and severely worn wear level. They were all the same model bits that were used in full-scale borer miner units in underground potash mines in Canada. The moderately worn and the worn picks were previously used in the operation to cut potash. The worn pick was used at the external position (gage area) where they cover more footage for more cuts on the machine compared to the moderately worn pick.

To quantify the wear, the tip height and tip width were measured. Pick tip height is measured from the insertion ledge near the base to the top of the tip. Additionally, the pick tip width is measured across the tip when looking directly at the tip from the front view. The new pick, never previously used to cut rock, had the longest tip height and most narrow tip width, the worn pick had the shortest dimensions, and the moderately worn pick had dimensions between the two as seen in Fig. 4. The height and width dimensions agree with the amount of wear on each pick. For example, as the pick wear increases, the tip height decreases and the tip width increases [46].

### *2.4 Characterization of Dust Particles*

Three overarching characteristic studies were performed on the airborne dust samples collected via the cyclones and one characteristic study was performed on the deposited particles collected via the vacuum. Industry standard for concentration and mineral presence, particle shape, and size distribution analyses were performed on the respirable samples collected with the cyclones and the size distribution was performed on the deposited particles collected from the rock sample surface.

2.4.1 NMAM (NIOSH Manual of Analytical Methods) 0600 and 7500 Analytical Methods

The procedures prescribed by the NMAM 0600 (particulates not otherwise regulated, respirable) and NMAM 7500 (silica, crystalline, by XRD (X-Ray Diffraction), filter deposition) were performed on the dust generated. The US Mine Safety and Health Administration (MSHA) uses these methods to evaluate worker exposure limits and guide dust control decisions in the work place. The NMAM 0600 reveals the concentration of dust over a specific amount of time and the NMAM 7500 reveals the cristobalite, quartz, and tridymite amounts detected over the same amount of time. Overall concentration and amount of silica are important to know because workplaces need to abide to specific exposure concentration and silica levels [32, 47].

For these experiments, standard pre-weighted PVC filter cassettes were obtained from a third-party lab with accredited laboratory ID: 100967. After dust collection, the filter cassettes were sent back to the lab for the analytical methods to be conducted.

2.4.2 Particle Shapes

The roundness, aspect ratio, and roughness values were calculated for particles less than 10 µm aerodynamic diameter. Roughness, or the undulation along the perimeters, is calculated because it is possible that the shape's ruggedness can give the particle a different dynamic shape factor. With changing dynamic shape factors, the particle's settling velocity changes [31]. And therefore, it is possible that the particles can travel differently through the respiratory system [22, 23] and could cause different health effects.

To determine the particle shapes, a FE-SEM (Field Emission Scanning Electron Microscope) and an image-analysis computer program were used to take and process images from the PC filter surfaces. A Tescan FE-SEM at a voltage of 15 kV and BSE (Back Scattering Electron) detection was used to obtain images. For each test run where dust was collected for each pick wear, 20 images evenly spaced across each PC filter were captured to obtain a reasonable representative sample of particles. Then, Clemex Vision PE® software (Vision Lite & PE 8.0, Clemex, Quebec) was used to process the images, detect particles,

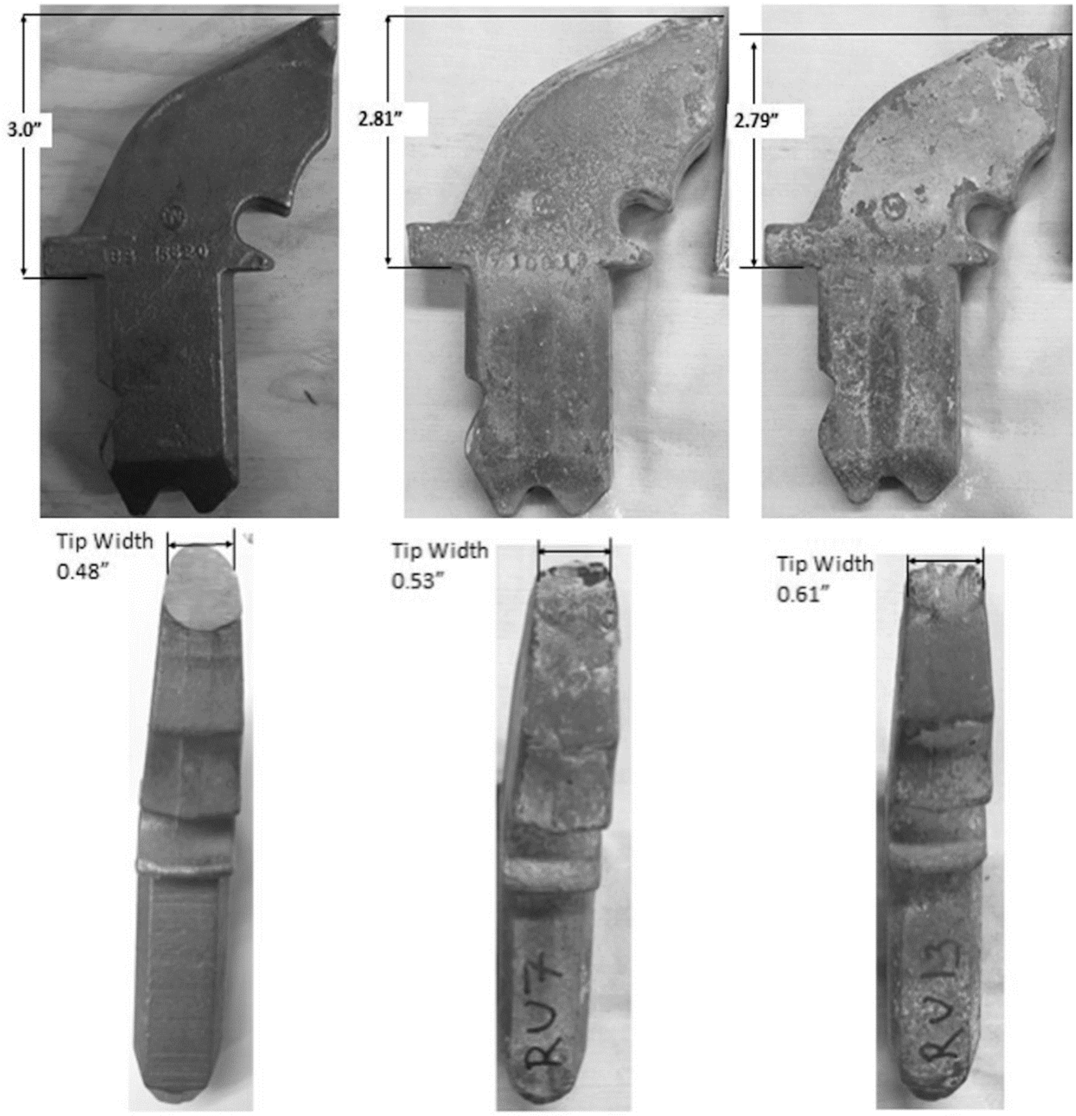


**Fig. 4 Pick tip heights in the top row and pick tip widths in the lower row for the new (left), moderately worn (middle), and severely worn (right) picks used in the full scale cutting.**

and perform calculations of roundness, aspect ratio, and roughness of particles. The Clemex Vision PE® software was programed to detect the particles with binarization by gray thresholding [48-50] to distinguish the difference between particles and the background. The process moving from an SEM image to grey thresholding, to highlighting individual particles is shown in Fig. 5. Other commands were also added to the program, such as bridging and object transfer, which separates particles that are clumped together and removes particles intersecting the edge of the image during detection, respectively.

Any particles detected less than 0.25 μm in diameter were removed from the data set because the image-analysis program would start to detect and count the unrepresentative filter media holes as particles, as the holes were 0.2 μm in diameter. Additionally, from the average of 20 images per filter sample, the computer program detected a total of 159 particles generated from the new pick, 1,593 particles generated from the moderately worn pick, and 397 particles generated from the severely worn pick. Without knowing how many particles would be detected from the images, more than 20 images should have been captured from

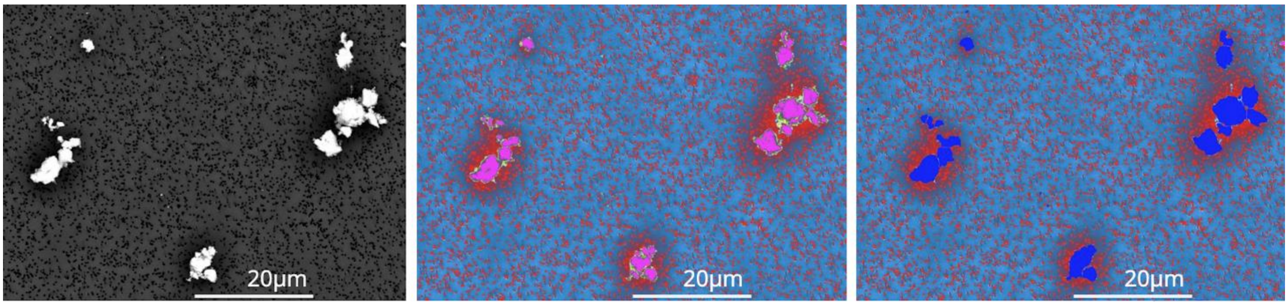


**Fig. 5 Raw SEM image (left), the image under grey thresholding (middle), and the program identifying and highlighting individual particles in blue (right) that will then be analyzed for shape features.**

the new pick and severely worn pick filters. However, there are still enough particles detected on each filter to provide a viable sample size to perform strong statistical tests. It is hypothesized that the variance in sample number differences is due to the new pick generating less overall dust, as noted in the concentrations generated, as compared to the moderately worn pick, which generated a much higher overall concentration of dust.

Particle roundness was calculated to determine how close to a perfect circle the particle of interest is via Eq. (1). Particle aspect ratio is calculated to determine the elongation of particles via Eq. (2). Particle roughness is calculated to determine the smoothness of the particle perimeter via Eq. (3). Convex perimeter is used to determine the particle roughness, where the convex perimeter is the perimeter of the object if a rubber band were placed around the particle, as shown in Eq. (4). With this, *length* is the longest measurement across an object, *width* is the shortest distance measured across an object [48].

$$\text{Roundness} = \frac{4\ (\text{area})}{\pi\ (\text{length})^2} \quad (1)$$

$$\text{Aspect Ratio} = \frac{\text{length}}{\text{width}} \quad (2)$$

$$\text{Roughness} = \frac{\text{ConvexPerimeter}}{\text{Perimeter}} \quad (3)$$

$$\text{Convex Perimeter} = \sum \text{ferets}\left[2\tan\left(\frac{\pi}{2(\text{number of ferets})}\right)\right] \quad (4)$$

2.4.3 Size Distribution

Using the 20 images obtained from the FE-SEM and the Clemex image analysis program, the individual respirable airborne particles detected on the PC filters were also measured for physical diameter. Because not all particles are perfectly round, the circular diameter is measured and calculated as if the object were a 2D shape as seen in Eq. (5). These physical diameters were then converted to aerodynamic diameters with the aerodynamic diameter conversion equation (Eq. (6)), which included factoring in the slip correction factor and Cunningham correction factors as seen in Eqs. (7)-(9) [31]. Size distribution curves are generated with the aerodynamic diameter values.

$$\text{circular diameter} = d_p = 2 \times \sqrt{\frac{A}{\pi}} \quad (5)$$

$$\text{aerodynamic diameter with slip correction} = d_a = d_p\left(\frac{C_{dp}}{C_{da}}\right)^{0.5}\left(\frac{\rho_p}{\rho_0 \times \chi}\right)^{0.5} \quad (6)$$

$$\text{Cunningham correction factor} = C_{dp} = 1 + \frac{(6.21\times 10^{-4})T}{d_p} \quad (7)$$

$$\text{Cunningham correction factor} = C_{da} = 1 + \frac{(6.21\times 10^{-4})T}{d_{a,\ no\ slip}} \quad (8)$$

$$\text{aerodynamic diameter with slip correction} = d_{a,no\ slip} = d_p \times \sqrt{\frac{\rho_p}{\rho_0 \times \chi}} \quad (9)$$

where,

$A$ = area

$d_p$ = physical diameter of particle measured

$T$ = temperature = 293 K = 20 ℃

$\rho_p$ = density of potash particle = 2,400 kg/m$^3$ [51]

$\rho_0$ = density of water = 1,000 kg/m$^3$

$X$ = dynamic shape factor = 1.36 for quartz [31]

The deposited dust left behind on the surface of the rock after each cut was collected for size distribution analysis, as these particles can be reintroduced into the air during operations. A Microtrac sync instrument, which uses laser diffraction methods, was used to obtain the physical particle size distribution for the deposited dust. The Microtrac sync follows the international standard ISO (International Organization for Standardization) 13320:2020 for laser diffraction particle size analysis. The physical diameters obtained were also converted to aerodynamic diameters using the previously explained process and equations.

## 3. Results

### *3.1 NMAM 0600 and 7500 Concentrations*

The NMAM 0600 results include the concentration of dust where units are given as milligrams per cubic meters of air drawn in. The NMAM 7500 results include the mineralization in amounts of cristobalite, quartz, and tridymite present in each sample in units of micrograms per sample. Results for the NMAM analytical methods are presented in Table 1.

It should be noted that NMAM 7500 is focused on the mineralogy of the dust with focus on three compounds that have severe and common impact on the respiratory system. It is most suitable for comparing different jobsites with various mineralogy of the rock that is being mined. However, in the initial phases of testing in this study, the potash samples cast in specialized grout do not necessarily represent a variety of mineral content.

### *3.2 Particle Shapes*

The roundness, roughness, and aspect ratio of the individual respirable particles generated from new, moderately worn, and severely worn cutting tests were analyzed. FE-SEM images of the particles were run through the image analysis program to identify individual particles and perform the shape calculations. Twenty FE-SEM images equally spaced apart on the PC filters were obtained for all the dust samples correlating to each pick wear; 159 particles were identified on the samples from testing with new bit, 1593 from the moderately worn bit, and 397 from the severely worn bit. A sample of the FE-SEM images from each pick wear are shown in Fig. 6.

The histograms presented in Fig. 7 reveal the particle shape results from the identified particles. Roundness values of one indicate an overall round shape. From this value, the deviation from a round shape can be further analyzed in the roughness, or how rugged the edges are, and the aspect ratio, or how elongated the particle is. Roughness values of one indicate smooth edges and aspect ratio of one indicates a square, or compact particle.

### *3.3 Size Distributions*

#### 3.3.1 Airborne Particles

The size distributions of airborne, respirable particles were determined from the images obtained by FE-SEM. Fig. 8 shows the results for the aerodynamic diameter size distribution of airborne particles obtained from the new, moderately worn, and severely worn pick. The mean particle aerodynamic diameters are 1.2 µm for the new pick, 0.8 µm for the moderate pick, and 0.7 µm for the severely worn pick.

**Table 1 NMAM 0600 and 7500 analytical methods results displayed as the average of three test sets.**

| Analysis | Result | New pick | Moderately worn pick | Severely worn pick |
|---|---|---|---|---|
| NMAM 0600 | Unit | mg/m$^3$ | mg/m$^3$ | mg/m$^3$ |
| | Concentration | 2.8 | 19.1 | 13.5 |
| NMAM 7500 | Unit | µg/sample | µg/sample | µg/sample |
| | Cristobalite | 0 | 0 | 0 |
| | Quartz | 0 | 43 | 31 |
| | Tridymite | 0 | 0 | 0 |

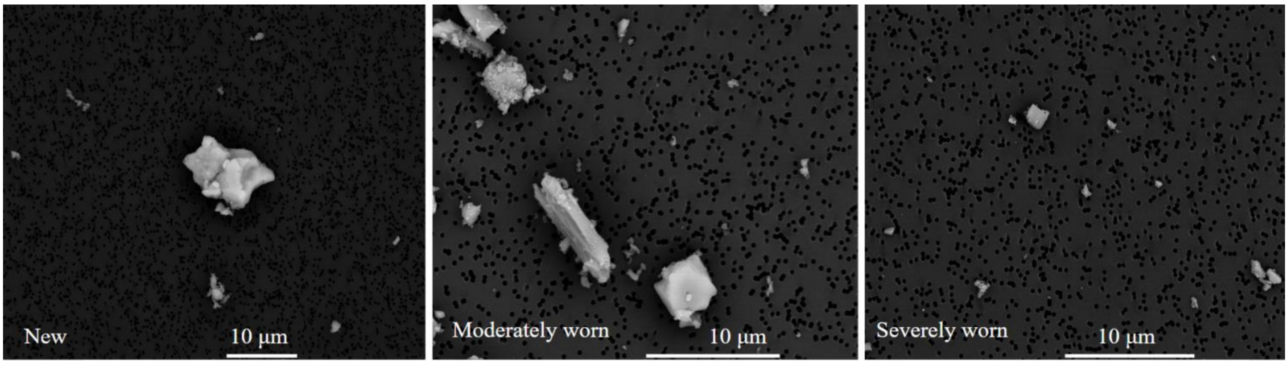


**Fig. 6 An example of the FE-SEM images obtained from the PC filters where respirable particles were captured and later analyzed for roundness, roughness, and aspect ratio. Twenty similar images were obtained for each scenario that were analyzed.**

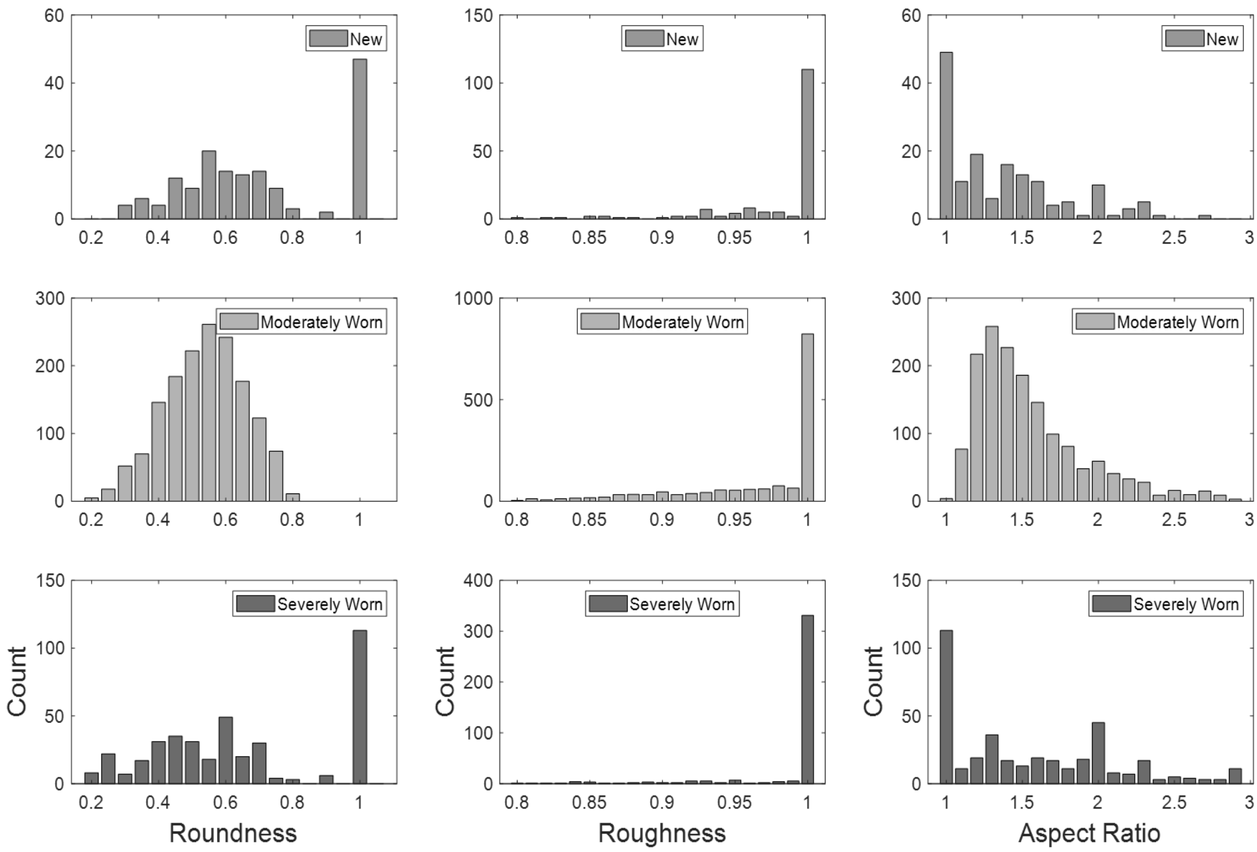


**Fig. 7 Histogram results for the roundness, roughness, and aspect ratio of the particles generated from full scale cutting tests with new, moderately worn, and severely worn picks.**

3.3.2 Deposited Particles

A size distribution count analysis was generated with the Microtrac sync laser diffraction instrument for the deposited particles that could become airborne again in downstream operations of an industry setting. Fig. 9 presents the aerodynamic diameter size count distributions for dusts generated with the new, moderately worn, and severely worn picks.

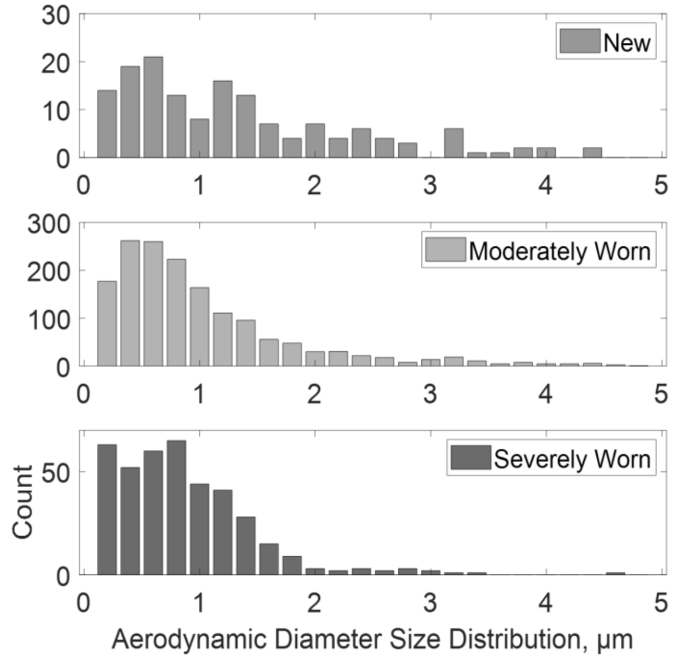


**Fig. 8 Histograms of the aerodynamic diameter size distributions of airborne particles generated from cutting with new, moderately worn, and severely worn pick tips.**

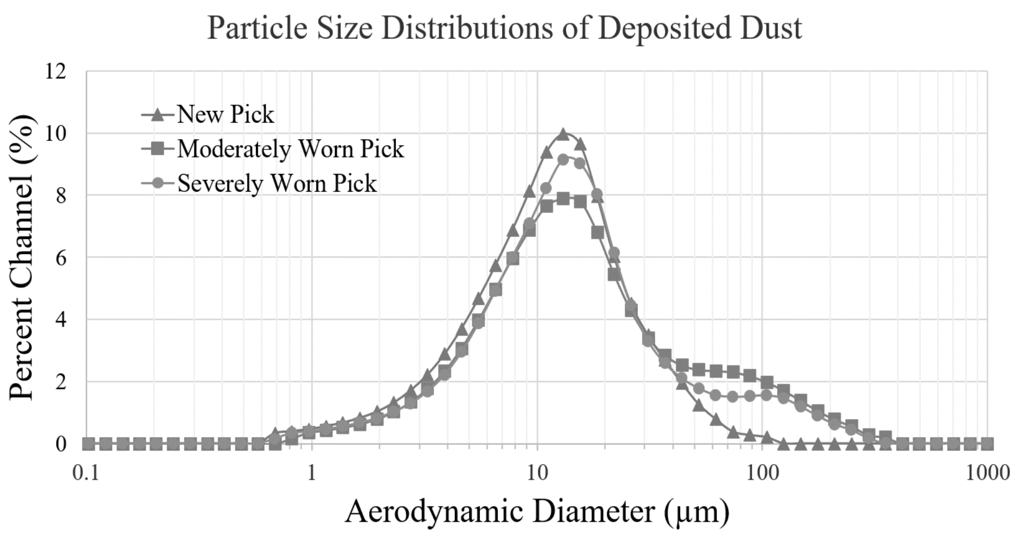


**Fig. 9 Size distribution curves for the deposited dust particles that could pose health issues in downstream operations when handled or transferred.**

## 4. Analysis and Discussion

A review of the test results reveals a strong tendency in generated airborne and deposited dust to be linked to the bit tip wear, which is influenced by tip surface area geometry. This has been observed by previous studies where the amount of dust generated is linked to the pick wear or linked to the surface area geometry of the picks [28, 46, 52-55]. For example, the new picks in previous studies contain the smallest amount of geometric surface area in contact with the rock and the severely worn picks contain the largest amount of geometric surface area in contact with the rock. For this reason, the geometric surface areas of the radial picks used in the experiments were determined.

After further investigation, the surface areas of the pick tips were measured 5 mm down from the highest point to observe how dust characteristics change in relation to surface area geometry in contact with the rock, or tip "bluntness". The bluntest pick, or the moderately worn pick, has the most surface area exposed during cutting. This pick also generated the highest concentration of dust and the most oblong particle shapes. As seen in Fig. 10, the pick tip surface areas exposed to rock are plotted with the various concentration measures obtained. Concentrations for tests with penetration depths at 0.6″ and 1.5″ were also added, where no dust was collected for the lowest surface area due to collection failure. Fig. 10 visually shows that there is a possible correlation between pick tip surface area geometry and concentration: as pick tip area increases, dust concentration increases. No statistical test was performed on these data due to the incomplete dataset where there are missing concentration data for the new pick at the added penetration depths.

Therefore, instead of viewing the picks as new, moderately worn, and severely worn in relation to the tip for these experiments, the bits could be categorized by geometric tip shape for evaluating their potential for dust generation. For example, the new pick could be viewed as a sharp pick tip, the moderate pick could be viewed as a blunt pick tip, and the severely worn pick could be viewed as an undulating sharp pick tip.

### *4.1 NMAM 0600 and 7500 Concentrations*

The NMAM 0600 results for the new, moderately worn, and severely worn picks reveal that the moderately worn pick (or the bluntest pick) generated the highest amount of dust and the new (sharpest) pick generated the least amount of dust, which is confirmed by the FE-SEM analysis of the PC filters. A KS (Kolmogorov-Smirnov) statistical test was performed between the pick wear concentration data, which included the two duplicate similar tests. Using a *p*-value threshold of 0.05, the *p*-value result of 0.0033 between the new (sharp) pick and moderately worn (blunt) pick suggests that the null hypothesis of similar

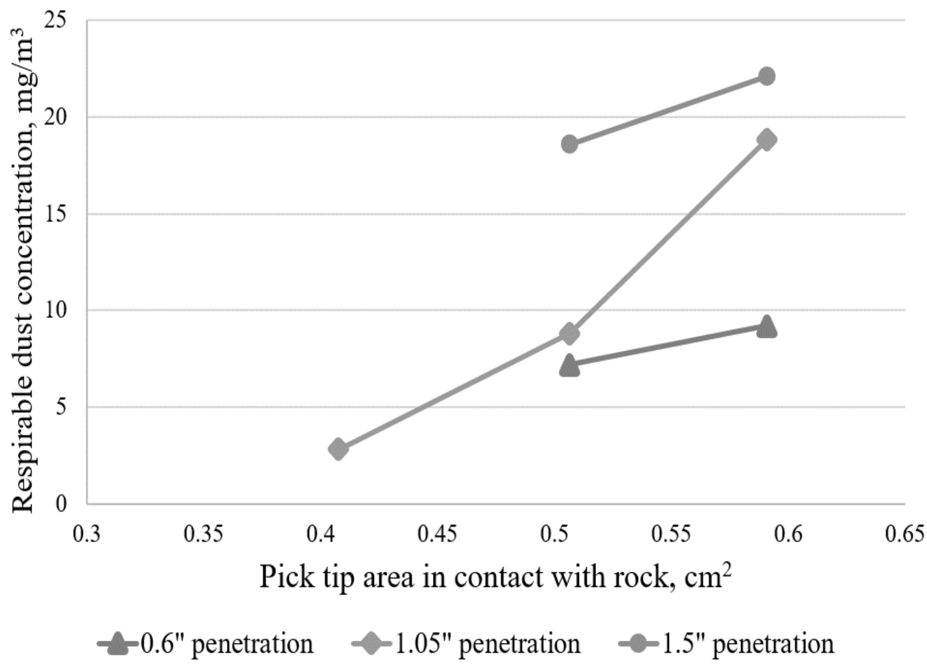


**Fig. 10 The concentrations of dusts obtained from the various surface areas of pick tips exposed to rock while cutting at additional penetration depths.**

distributions is rejected. Therefore, there is strong statistical evidence that pick wear affects the concentration of dust generated while cutting in terms of a new pick versus a moderately worn (sharp versus blunt) pick.

Concrete recommendations to mining and tunneling operations cannot be made on which pick generates the most dangerous dust to workers because the results obtained in full scale cutting are limited. However, for these laboratory tests in the experimental environment, the dust generated from the moderately worn (blunt) pick could be considered the most dangerous to human health because the moderate pick generated the highest concentration of dust particles less than 10 μm in aerodynamic diameter.

The lower concentration generated from the severely worn (undulating sharp) pick tip compared to the moderately worn (blunt) pick could be attributed to the severely worn (undulating sharp) pick having less surface area in contact with the rock. However, from a practical point of view during pick wear, whether the pick tip becomes blunt or undulating during wear, the dust concentration is higher than the dust concentration generated from the new (sharp) pick. Therefore, the hierarchy of controls for dust exposures needs to be utilized, such as increasing water suppression systems, as the radial picks wear.

The NMAM 7500 results simply show that there are trace amounts of quartz from some of the samples, which could potentially harm workers. Due to limited resolution for these studies, results were not further analyzed. The NMAM 7500 test is most suitable for comparing quartz levels between different rock types and jobsites.

### *4.2 Particle Shapes*

Analyzing the histograms for the roundness values, the moderately worn (blunt) pick rarely generated particles that were circular shaped (where a roundness value of one indicates a uniformly shaped particle). This pick generated longer, oblong, particles as confirmed in the aspect ratio values favoring values between 1.1 and 1.8. On the other hand, the aspect ratios of samples obtained when using the new (sharp) and severely worn (undulating sharp) picks show a different trend in particle shapes, which reveal more round particles with a favored aspect ratio of one.

The histograms in Fig. 7 show that the roundness, roughness, and aspect ratio are similar between the samples of dust collected when using the new (sharp) pick and the severely worn (undulating sharp) pick. Meanwhile, there is a difference in the roundness and aspect ratio characteristics of the moderately worn (blunt) pick when compared to the other two. The KS statistical test was performed between data sets to test the hypothesis that the distribution of particle shapes generated from the moderate pick (blunt) is the same as the distribution from the new (sharp) and severely worn (undulating sharp) pick. A significance level of 0.05 was used in the statistical analysis. Therefore, *p*-values below 0.05 provide strong statistical evidence to reject the hypothesis test.

The KS tests provide evidence that there is a difference between the moderately worn (blunt) pick distribution when compared to the new (sharp) pick and severely worn (undulating sharp) pick distributions for roundness, aspect ratio, and roughness parameters. The *p*-values obtained for the distributions compared between the moderately worn pick to the other picks were all below the 0.05 threshold. Additionally, when comparing the new and severely worn pick distributions, KS test *p*-values all at or near the 0.05 threshold provide strong evidence that the new (sharp) and severely worn (undulating sharp) picks generate particles of similar shape characteristics.

The results show that the moderately worn (blunt) pick generated particles that are slightly longer in shape compared to the new (sharp) and severely worn (undulating sharp) pick. However, recent studies reveal that for particles between 0.01 μm and 10 μm in aerodynamic diameter, the particle size has greater influence on lung deposition as compared to aspect ratio [23]. Therefore, although the particle shapes could be a function of the surface area geometry of the bit in the direction of cutting, it would be more beneficial to consider the particle size distributions generated when reducing dust hazards during the life of a cutting tool.

### *4.3 Size Distributions*

#### 4.3.1 Airborne Particles

The size distributions of respirable particles for all three pick types favor particles less than 5 µm in aerodynamic diameter as seen in Fig. 8. The aerodynamic diameter mean values for the datasets are 0.7 µm, 0.8 µm, and 1.2 µm, for new, moderate, and severely worn picks respectively. With this, the dataset means were compared with Student's *t*-tests to see similarities in the mean values with a 0.05 *p*-value threshold. No *p*-values were above the threshold, therefore indicating strong evidence that all the datasets are different from one another.

Although the means of all the datasets are statistically different, the dust generated in rock excavation with each state of bit wear contains a majority of particles that can penetrate deep into the lungs. All bits could be considered dangerous to human health if not controlled or contained because they all generate respirable-size particles.

#### 4.3.2 Deposited Particles

Fig. 9 shows that all the measured particle size distributions for the material collected after full scale cutting tests are similar between the new, moderate, and severely worn pick conditions. Each distribution is single modal, with the peak around 15 µm in the inhalable region. The mode for each distribution is 13 µm in aerodynamic diameter. The moderately worn (blunt) pick generated slightly more particles in the 50 µm to 100 µm diameter range when compared to the dust sized generated by the new (sharp) and severely worn (undulating sharp) picks.

All picks can be potentially harmful in downstream operations because all picks generate similar size distributions of deposited particles that contain thoracic and respirable sized particles. These particles can become airborne during transport, transfer, or drop locations and can be breathed in further downstream to potentially cause health issues.

In the end, the wear pattern of the bits should be observed during operation and if the continued wear leads to wider tip and bluntness, operators could expect a higher generation of dust with higher aspect ratio particles. It should be noted that the results presented in this article are based on limited initial testing with only three test sets per pick wear. Therefore, results are not yet considered universally applicable to all rock excavation scenarios. Additional testing with different picks, such as conical picks with controlled wear geometry, and rock types, such as sandstone and limestone, are underway to evaluate the impact of cutting tool wear on the characteristics of dust.

Although similar dust results are expected in the real mining environment due to the linear action of rock cutting in the lab closely paralleling the size and caliper of operational equipment, further duplicate samples need to be cut and confirmed before the results can be applied to practice. With further testing, results can be used to determine and optimize the hierarchy of dust controls when pick wear can be easily monitored via machine input power and mined material output. Therefore, with further potash rock cutting experiments, operations could eventually use the research data paired with known amounts of their pick wear during operations to limit worker exposure to hazardous dust characteristics.

## 5. Conclusion

Dust exposures can become more dangerous to workers in ~~hard~~ rock cutting environments in terms of particle concentration, mineralogy, shape, and size distribution depending on the geometry of the radial pick tip. In terms of concentration and particle shape, picks with one sharp tip (new picks) or picks reshaped in the process of cutting that form a narrow tip configuration (severely worn picks) generate lower concentrations of dust and create slightly more round-shaped particles. On the other hand, picks with blunt tips (moderately worn picks) generate higher concentrations of dust and generate slightly more elongated particles. If future experiments confirm this trend in dust characteristics, then increasing dust suppression systems should be considered to mitigate the amount of respirable dust particles that are generated by radial bits with blunting tips as they potentially pose more harm to respiratory health.

In terms of the particle size distribution, all the picks used in these laboratory tests generated airborne particle size mean values between 0.7 and 1.2 µm in aerodynamic diameter. All the picks also generated deposited particles with the mode of particle aerodynamic diameter sizes at 13 µm. Therefore, appropriate dust mitigation systems should be in place for all geometric tips cutting rock in order to limit exposures to dust particle sizes that can penetrate deep into the lungs.

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