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ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

Final Technical Report

Project Title: Development of a New Rock Dust Sampling Instrument

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Acknowledgment/Disclosure

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Common Terms

Rock Dust: Pulverized limestone, 100 percent, by mass, passes through a sieve of 20 meshes per linear inch and 70 percent or more passes through a sieve of 200 meshes per linear inch. The particles when wetted and dried do not cohere to form a cake and cannot be dispersed into separate particles by a light blast of air, and does not contain more than 5 percent combustible matter or more than a total of 4 percent free and combined silica (SiO_2).

Total Inert Content (TIC): The percentage of incombustible mass within a dust sample, including moisture and ash content. This value is expressed as percent of incombustible mass to the total mass of sample.

Total Percentage Ash (ASH %): The percentage of incombustible ash within a dust sample, excluding moisture content. This value is expressed as percent of ash mass to the total mass of sample.

Dust Sampling Device (DSD): The physical device developed from this project to take a dust sample.

Brush and Pan Method (BaP): The current method of collecting a dust sample as outlined in the Coal Mine Safety and Health General Inspection Procedures Handbook (MSHA, 2013) using a brush and metal pan.

Coal Dust Explosibility Meter (CDEM): Device developed by NIOSH (Harris et al., 2012) that reads the reflectivity of a sample and outputs an expected TIC range.

Nozzle Angle: Angle between the horizontal dust surface and center-line of the nozzle orifice.

Nozzle Height: Height of the nozzle tip from the horizontal sampling surface.

Charging Pressure: Pressure at which the device is charged to ensure expected operation.

Line Pressure: Pressure readout for input line that is connected to device.

Sample Chamber: The specific portion of the device where the dust and compressed air interact during the sampling process.

Scour Length: The length of the visible scour left in the dust surface after sampling.

Scour Depth: The maximum depth of the visible scour left in the dust surface after sampling.

Scour Width: The total width of the visible scour left in the dust surface after sampling. When multiple nozzles are in use, this width is the total width including gaps between the scour patterns left by each nozzle.

Sample Mass: The measurable mass of a sample taken with the DSD or BaP method.

1 Executive Summary

The disaster at the Upper Big Branch (UBB) mine in 2010 that killed 29 miners demonstrated the destructive violence of a coal dust explosion. According to the MSHA investigation (Page et al., 2011), a small initial methane-air explosion ignited by the longwall shearer entrained coal dust that had not been properly inertized by sufficient amounts of rock dust. Rock dust, when entrained into the air with the combustible coal dust, acts to suppress the explosion when properly applied in the correct proportions. A major contributing factor to this explosion was that mine operators did not have a reliable and repeatable way of objectively sampling mine dust for analysis of its combustible and inert composition. On the morning of the explosion, 7 of the 9 belt entries evaluated by UBB examiners required additional rock dusting. These assessments were not based on sampling and testing, but rather on visual, subjective estimates of the mine dust's shade of gray.

2013 MSHA inspector guidelines (MSHA, 2013, pp. 5-12) require mine dust sampling with a brush and dust pan, removing the "uppermost 1/8th inch (approximate depth)" of the mine dust layer with an upper threshold depth of 0.25 inches. This method is systemically flawed: First, it is difficult to consistently maintain the required sampling depth of 1/8 or 0.125 inches with the brush and pan (BaP). Given the guidelines explicitly states that the sampling depth should not go deeper than 0.25 inches, it is understood that inspectors may not be able to consistently maintain the sample depth to 0.125 inches. Second, sampling to a given target depth creates a mixing problem: Per the findings by Sapko et al. (1987) and Edwards and Ford (1988), 0.120 inches (3 mm) of rock dust overlaid by 0.005 inch (0.13 mm) of pure coal dust would still be explosive, even though a 0.125-inch deep sample taken at this location would yield 96% inert content by volume and an even higher inert content by weight. Furthermore, the brush action is questionable since the bristles may dislodge dust particles with much greater force compared to those forces generating air entrainment in a mine explosion.

The primary objective for this research was to develop and test a handheld, pneumatic mine dust sampling device (DSD) for underground coal mines that collects a coal-rock dust sample from the mine floor, roof or ribs from air-entrained dust, i.e., by mimicking the dust entrainment process that occurs during a mine explosion. Over three years, researchers at the Colorado School of Mines completed five tasks to design, develop and test several versions of the DSD. Extensive lab and in-mine testing of the DSD and traditional BaP methods, Computational Fluid Dynamic (CFD) modeling, and validation of sample results for inert content by Coal Dust Explosibility Meter (CDEM) resulted in a final DSD prototype that can be used by mine employees and inspectors to reliably and repeatably determine the total inert content (TIC) of mine dust. Researchers also wrote a User's Manual with operating instructions and best practices for mine dust sampling with the DSD. Researchers designed and tested various nozzle and trigger types and configurations, DSD bodies, air pressures and sample collection methods. Researchers also observed ease of use and other variables as they finalized the design. The DSD design was verified with a CFD model detailing the fluid flow interaction between the air and dust layer inside the DSD. A patent has been filed, and researchers will try to manufacture and market the DSD to the industry.

The DSD works by blowing a puff of air of defined pressure and duration over deposited mine dust, entraining a dust sample in air just like a mine explosion would. The DSD then traps the sample for subsequent analysis of its explosive properties. The use of pneumatic dust entrainment is superior to the BaP method, as the brush action does not properly mimic the explosion process. This proved to be especially relevant on non-horizontal surfaces with a thin layer of dust and in high humidity environments. Researchers confirmed that DSD sampling is more consistent at targeting the 1/8th inch sample depth. The DSD also provided a more accurate sample when comparing the TIC from the CDEM results to those of the BaP method. The DSD is operated using a portable compressed air tank with a minimum operating pressure of 50 psig.

As an outcome of this research, the DSD will benefit the coal mining industry through the prevention of coal dust explosions. Mine operators and inspectors using the DSD will be able to quickly and reliable assess whether the amount of rock dust is sufficient to maintain a TIC that meets MSHA regulations. The DSD may also help reduce costs related to excessive rock dusting.

This project also illuminated the need for further research of explosion scouring effects on various surfaces. Past USBM and NIOSH research of dust entrainment during coal dust explosions has focused solely on flat, horizontal, non-compacted dust surfaces. These testing scenarios often do not represent the conditions in actual underground coal mines, where the dust surface is undulating similar to sand on a beach. MSHA (2013) inspector guidelines prescribe a sampling depth of 1/8th inch that was established based on more recent NIOSH research. The actual depth of dust entrained by an explosion may be deeper along the peaks and shallower in the valleys of undulating dust surfaces. Researchers propose examining an undulating dust surface using CFD modeling along with laboratory and in-mine DSD sampling. Additionally, variations in dust compaction and density are also not being considered in the MSHA (2013) guidelines. Researchers found that dust compaction will affect dust entrainment in an explosion and recommend further investigations to improve the scientific understanding of the mine dust entrainment process on various surfaces and dust conditions during explosions. This may lead to further refinement of the DSD design and recommendations for better representative mine dust sampling.

2 Problem Statement and Objective

The disaster at the Upper Big Branch (UBB) mine in 2010 demonstrated the destructive violence of a coal dust explosion. Historically, nearly all mine disasters with heavy death tolls have been coal dust explosions, including the 1907 Monongah mine explosion (362 fatalities) and the 1968 Farmington mine explosion (78 fatalities). The UBB explosion instantly killed 29 miners from either blunt force trauma or Carbon Monoxide poisoning. According to the MSHA investigation (Page et al., 2011), a small initial methane-air explosion ignited by the longwall shearer entrained coal dust that had not been properly inertized by sufficient amounts of rock dust. Rock dust, when also entrained into the air with the combustible coal dust, acts to suppress the explosion when properly applied in the correct proportions. The coal dust explosion violently propagated through 80 km (260,000 linear feet) of mine entries (Page, 2011). This event was the worst mining disaster in the U.S. in almost 40 years.

Figure 1 shows a map of the UBB mine, the star indicating the longwall tailgate where the explosion started. Figure 2 shows the area around the longwall that was affected by the explosion. This area is visible in the northern part of the mine map in Figure 1.

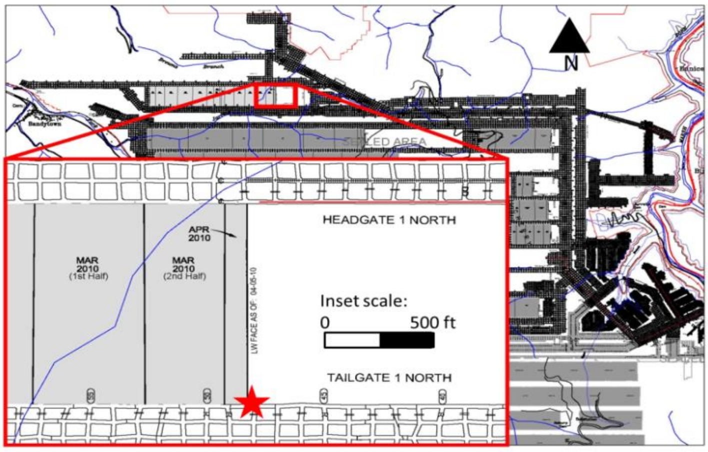

Figure 1. Upper Big Branch mine map showing the longwall detail (modified after Stricklin, 2011). The red star marks the tailgate corner where the explosion started.

A major contributing factor to this explosion was that mine operators did not and still do not have a reliable and repeatable way of objectively sampling mine dust for analysis of its combustible and inert composition. On the morning of the explosion, 7 of the 9 belt entries evaluated by UBB examiners required additional rock dusting. These assessments were not based on sampling and testing, but rather on visual, subjective estimates of the mine dust's shade of gray: when properly rock dusted, none of the darker black coal dust is visible. More importantly, it would have been difficult to assess how much additional rock dust was required in order to render the mine entries safe because samples were not taken and tested. MSHA investigators (Page et al., 2011, p. 159) concluded that over 90% of the near 1,400 dust samples collected at UBB were non-compliant.

For the prevention of coal dust explosions, U.S. mines rely solely on powdered stone dust (typically, limestone or dolomite; usually referred to as "rock dust") distributed over layers of coal dust throughout the mine entries on floor, roof and ribs. Regulation 30 CFR §75.403 was revised in 2011 and now requires a minimum of 80% incombustible matter for all mine entries.

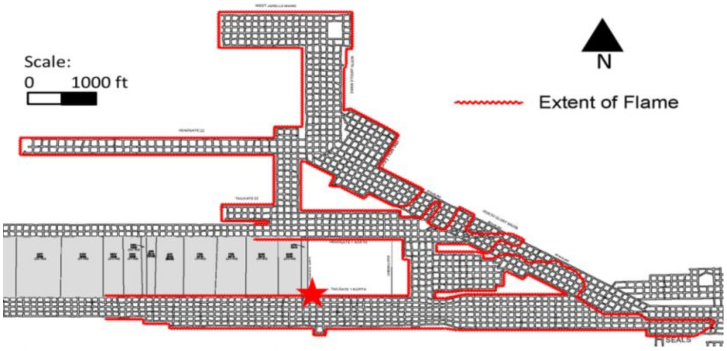

Figure 2. Extend of explosion flame at Upper Big Branch (after Page et al., 2011)

At the time of the UBB explosion, MSHA inspector guidelines recommended sampling rock dust by taking a "band" sample around the perimeter of the entry, using a brush and pan to collect dust up to 25 mm (1 inch) deep off the floor, ribs and roof (MSHA, 2008; Harris et al., 2012). Such samples likely do not accurately determine explosibility because the sample includes dust well below what would be entrained in an explosion. In order to participate in or extinguish an explosion, mine dust must first be entrained in air. The air blast from an initial explosion typically scours up only the top 2 – 3 mm (about 0.08 to 0.13 inches) (Harris et al. 2012), as shown in Figure 3.

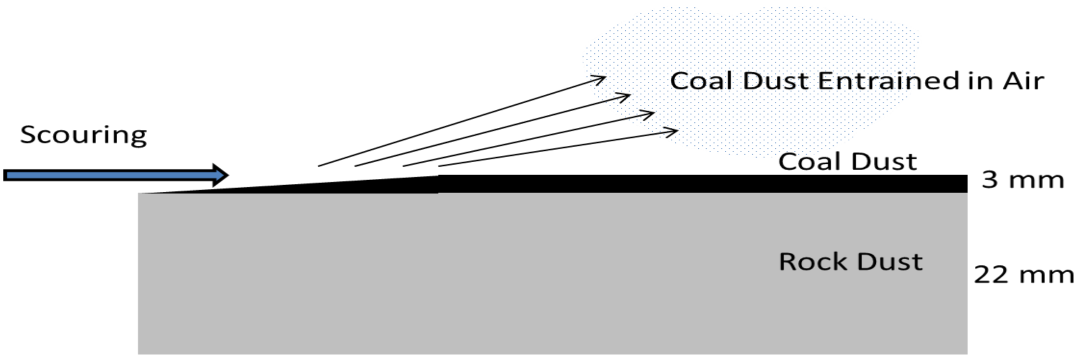

Figure 3. Schematic cross section view of coal dust layered over top of rock dust. An explosion will primarily scour up and entrain the top layer of mine dust.

Research by Sapko et al. (1987), Edwards and Ford (1988, p. 8) and others have shown that a 0.12 mm thin top layer (0.005 inch, or about the thickness of a single sheet of paper) of coal dust is already sufficient for propagation of a coal dust explosion.

Following the UBB disaster, the MSHA inspector guidelines (MSHA, 2013, pp. 5-12) were revised to require dust sampling with a brush and dust pan, only removing the "uppermost 1/8th inch (approximate depth)" of the mine dust layer with an upper threshold depth of 0.25 inch. This method is systemically flawed: First, it is difficult to consistently maintain the required sampling depth of 1/8 or 0.125 inches with the brush and pan (BaP). Given the guidelines explicitly states that the sampling depth cannot go deeper than 0.25 inch, it is understood that inspectors will not be able to consistently maintain the sample depth to the 0.125 inch. Second, sampling to a given target depth creates a mixing problem: Per the findings by Sapko et al. (1987) and Edwards and Ford (1988), 0.120 inch (3 mm) of rock dust overlaid by 0.005 inch (0.13 mm) of pure coal dust would still be explosive, even though a 0.125 inch deep sample taken at this location would yield 96% inert content. Assuming a specific gravity of 1.3 for coal and 2.2 for limestone, and equal packing desities for the coal and limestone particles, the mixture would have an inert content of 97.5% by weight. Furthermore, the brush action is questionable since the bristles may be able to dislodge dust particles with much greater force compared to those forces generating entrainment in air flow.

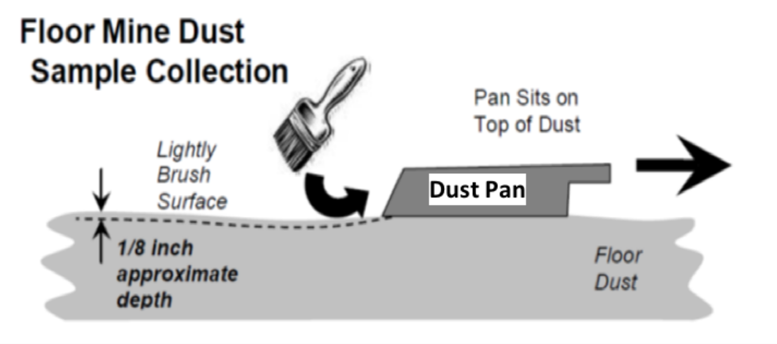

Figure 4. Illustration of mine dust sampling procedure with BaP method (modified from MSHA, 2013)

Currently, a valid method does not exist to assess whether wet or coagulated ("caked") mine dust will participate in an explosion. According to 30 CFR §75.2, rock dust should be able to be dispersed by a "light blast of air", but a scientific definition of what a "light blast" means does not exist. Therefore, it is up to interpretation of whether mine dust is indeed dispersible, or whether it is "caked" such that it will not participate in an explosion. Currently, areas considered too wet (i.e., where it is unlikely that an explosion would disperse and entrain dust) may be "bypassed" (MSHA 2013, p. 5-17) from sampling. Still, research by Cybulski (1975) has shown that wet coal dust can be entrained in the air and propagate a coal dust explosion. The pneumatic action of the DSD mimics the entrainment action by air to produce a valid sample unless the mine dust is truly too wet.

Finally, when assessing the level of explosion protection in rock dusted mine entries, it is important to not only sample the mine floor, but all other surfaces where coal dust can gather, including the ribs, roof, wire meshing, cables, pipelines, belt structure, etc. According to Sapko et al. (1987), if the amount of coal dust deposited near the roof is increased by a factor of three, this will require a significant increase in the amount of rock dust in the floor layer (from 86 to 95%) to stop a dust explosion from propagating. The brush technique to a depth of approximately 0.125 inch does not lend itself well to sampling from non-horizontal and non-flat surfaces. The DSD is capable of collecting relevant samples from a wide variety of mine surfaces where coal dust can settle, thereby providing an objective assessment of rock dust inertization quality.

The primary objective for this research project was to develop, build, and test a prototype handheld, pneumatic mine dust sampling device (DSD) for use in underground coal mines that collects a coal-rock dust sample from the mine surfaces by mimicking the explosion process. The DSD works by blowing a puff of air over deposited coal and rock dust to entrain the dust sample in the air as in a mine explosion, and then capture the sample for subsequent analysis of its explosibility properties. The DSD is intended for use by rock dusting crews, mine examiners, and mine inspectors to assess the quality of rock dusting. If used in conjunction with the NIOSH-developed Coal Dust Explosibility Meter (CDEM), sampling will yield a near-instant quantitative assessment of proper coal and rock dust proportions. Following successful completion of the prototype, as part of this research proposal, researchers plan to work with a manufacturer to produce, make commercially available, and market the DSD to the mining industry, within 2 years.

3 Research Approach

The research for the project was accomplished by completing the 5 research tasks outlined below.

1. Design and Development: Researchers developed and tested a mine dust sampling device (DSD). The DSD creates a defined air blast pressure, pulse duration, and air velocity to realistically simulate mine explosion conditions. Researchers tested a variety of nozzles, and fine-tuned the nozzle geometry, the dip angle of the nozzles, and the geometric parameters of the sampler in the process.

2. Analysis and Improvement with CFD: Computational Fluid Dynamics (CFD) modeling was used in the design of the DSD by simulating the sample collection, air and dust flow process. This modeling ensured consistency and repeatability of the sampling procedure and verified that the mine dust entrainment process is comparable to that of a coal dust explosion.

3. Laboratory Testing: Researchers conducted comprehensive testing of several DSD versions in the laboratory. Tests were conducted on known dust layers deposited on horizontal and inclined surfaces to verify the correct function of the DSD and to compare sampling results with those obtained by conventional pan-and-brush dust sampling per MSHA's Inspector Handbook guidelines.

4. Controlled Lab and In-Mine Testing: Following successful prototype design and verification, researchers tested the device as a proof-of-concept in an actual mine environment and demonstrated sampling accuracy and relevance through documenting inertization effectiveness against the conventional pan and brush method. DSD sampling results were compared to conventional brush sampling using laboratory inert content analysis to document the improvement.

5. Documentation: Researchers developed DSD best practices and guidelines for rock dust sampling for mine operators, rock dusting crews, mine examiners and inspectors, and documented the research through reports.

The following sections summarize the research approach activities and stages of the project team that achieved the project objectives.

3.1 Initial Parameter Evaluation

Researchers developed a testing strategy to identify the potential parameters of the device that affect testing outcomes and results. To do this, a simple testing mount was constructed to allow the researchers to vary individual, specific parameters while keeping all other parameters constant. After initial development attempts, a mount setup was selected that used an adjustable rod system to mount varying nozzle configurations for testing. This mount system was used to independently change the nozzle height and nozzle angle with minimum adjustments. As an initial trigger system for the air blast, an air gun trigger, gauge, and valve regulator were assembled to allow the researchers to control the input pressure and release duration. This trigger system was directly attached to the main compressor line in the testing area, and the line pressure was verified with an in-line regulator. This trigger system was then attached to 0.25 inch inner diameter vinyl tube that acted as the nozzle exhaust for the initial testing. A photo of the initial testing system and setup is shown in Figure 5. A diagram of the airflow through the setup is shown in Figure 6.

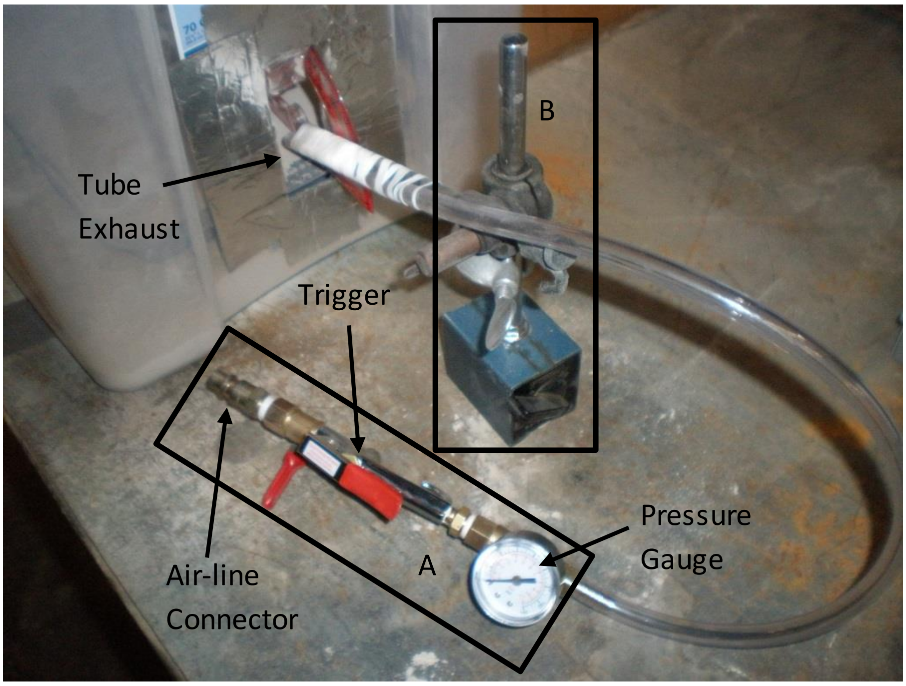

Figure 5. Initial testing system and setup for nozzle angle, pulse pressure and duration parameter evaluation. The trigger system is shown in Box A and the mount system is shown in Box B.

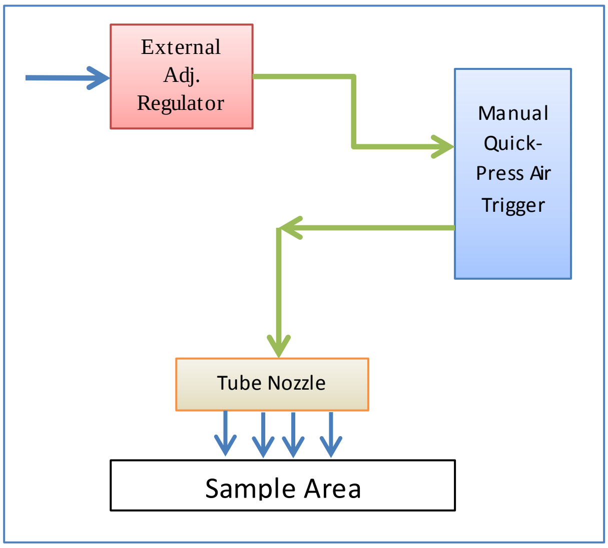

Figure 6. Diagram of system setup. The manual, quick-press air trigger is shown in Box A of Figure 5.

Researchers then evaluated how to create a testing medium from which data on the scouring process could be collected with relative ease and reproducible outcomes. Researchers used coal mine quality rock dust from a local mining supplier that was approved for use in coal mines. Researchers conducted a particle size distribution analysis on the pulverized limestone to verify that 30 CFR 75.2 requirements were met. This rock dust was used throughout the rest of the project's testing cycles, including the Edgar Experimental Mine tests, but excluding on-site coal mine tests where onsite rock dust was used. Figure 7 shows the results of the size distribution test. To contain the rock dust, a 2-inch-deep metal pan with dimensions 16x9 inch was used. For testing, the pan was filled to 2.5 inches and then leveled off with a straight scraping tool to create a flat, consistent testing surface. The dust bed and exhausting end of the testing apparatus were placed within a larger plastic bin to contain the airborne dust. Researchers measured the change in depth from the leveled off flat surface with a set of calipers and the scour length with a standard metal ruler. This method of scour depth and length measurements was used as the standard measurement procedure until testing with the BaP began (see Section 3.8.1 for modified scour measurement procedure).

With the initial setup complete, researchers examined the effects of pressure and nozzle angle on the scour depth, as depth is the limiting criterion for the scour pattern. The nozzle height was fixed at zero inches above the dust surface to achieve a maximum scour length. Multiple tests were run at 10, 15, 20, 25, 30, 30, 40 and 45 psig with the tube exhaust at a 30-degree nozzle angle, and then repeated at the same pressures for 20, 10 and 0 degree nozzle angles. Figure 8 shows the results of these initial tests.

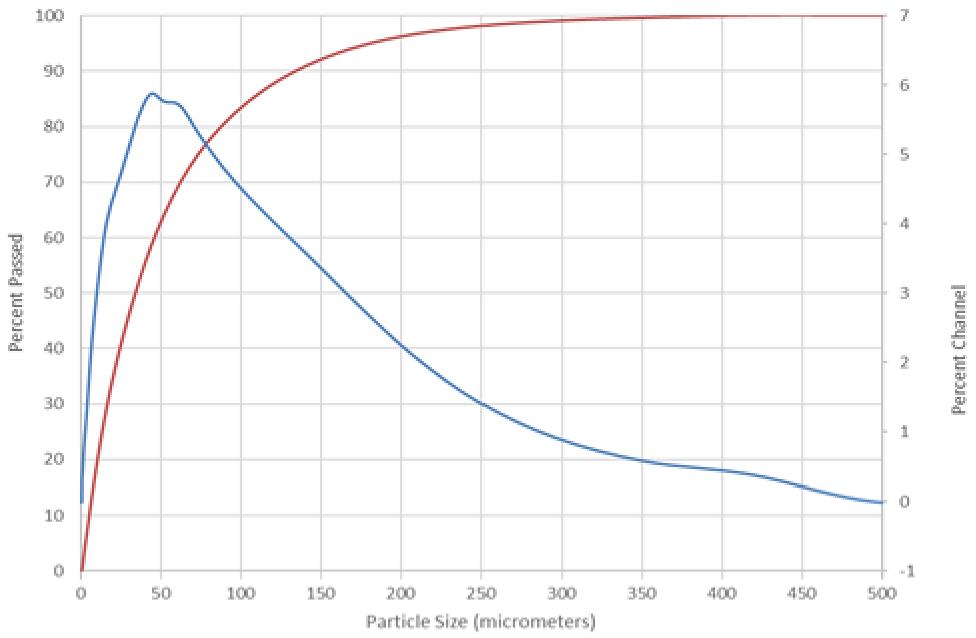

Figure 7. Particle distribution of pulverized limestone used for testing medium. Red line shows %Pass on primary (left) axis and blue line shows %Channel on secondary (right) axis.

3.1.1 Results from Initial Parameter Evaluation

From initial testing that showed lower nozzle angles were less varied, researchers concluded that a nozzle angle at 20 degrees or lower would increase repeatability in future tests. These lower angle results were mostly below the upper threshold of 0.25 inch scour depth and close to the target 0.13 inch required, and allowed researchers to use a wider range of pressures in future testing. For the tests conducted at 0 degrees nozzle angle there were no discernable or measurable scour patterns. At this nozzle angle, the air does not make sufficient contact with the dust surface to entrain dust and generates almost no movement of the particles. The same tests were repeated using a 0.5 inch inner diameter vinyl tube. Under the given pressure conditions, this larger nozzle did not create a noticeable scour, suggesting that the air velocity generated at the nozzle exhaust was too low to entrain dust.

3.1.2 Conclusions from Initial Parameter Evaluation

The initial parameter evaluation provided information about the impact pressure and nozzle angle had on the scour depth. In the testing configuration, nozzle angles at or below 20 degrees brought the scour depth results closer to the 0.125 inch target outlined in the Coal Mine Safety and Health General Inspection Procedures Handbook (MSHA, 2013). It was apparent from the results that the lower angle scour depths were more consistent and more closely clustered together. However, the exhaust orifice size impacted scour depth, as indicated during testing by the larger diameter vinyl tube leaving no scour imprint visible. This indicated that researchers needed to look at narrower nozzle options to focus the air pressure directly to the dust surface. The testing of different sizes and quantities of nozzle orifices allowed researchers to gather data on the impact that pressure has on scour depth, and focus on maximizing scour depth and sample mass against the required pressure. These initial outcomes laid the groundwork for further progress toward Task 1 of the research approach.

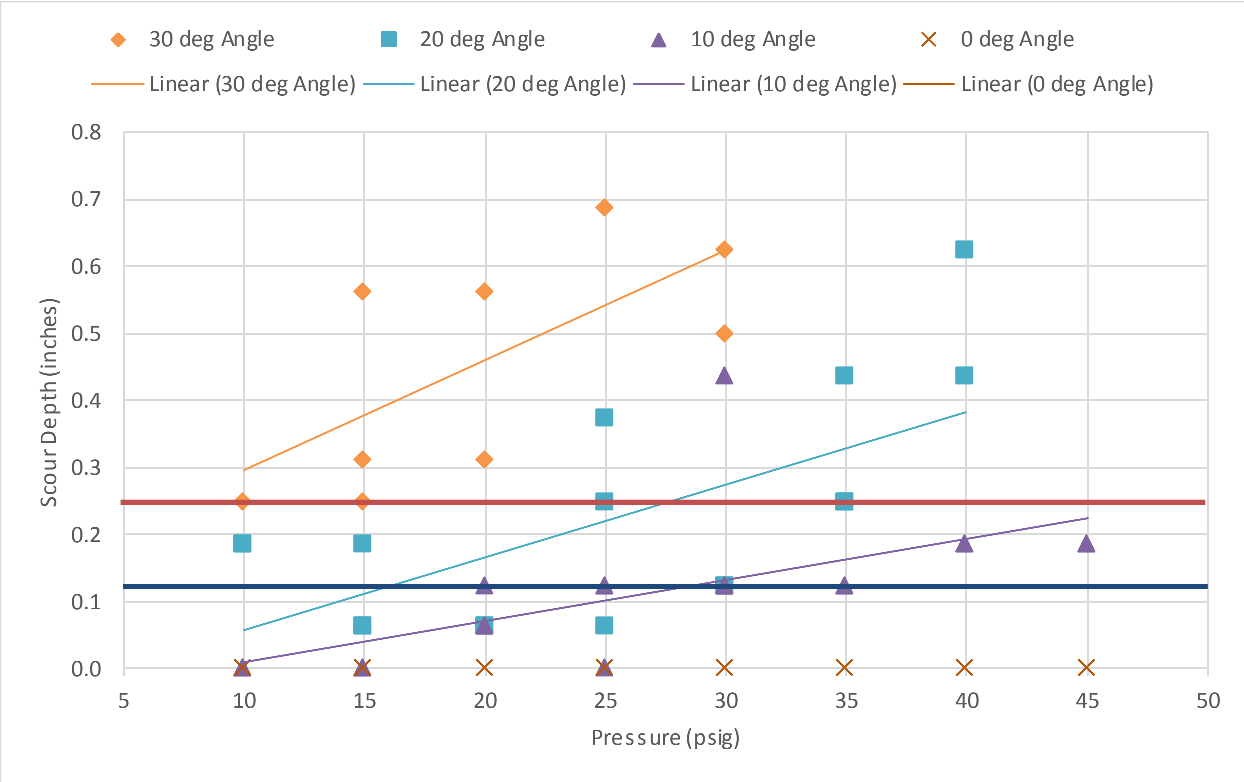

Figure 8. Comparison of scour depth to nozzle angle and pressure for 0.25 inch vinyl tube exhaust (n=65). The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

3.2 Nozzle Evaluation

Based on the outcomes of the initial vinyl tube testing, a number of different nozzles with varying styles, widths, and exhaust orifices were selected to further examine the impact the nozzles had on the airflow pattern and scour profile. The following sections summarize the results of these initial nozzle tests.

3.2.1 2.5 inch Swivel Nozzle, 20 Holes at 5/64 inch Diameter Each

The first nozzle tested was a 2.5 inch swivel nozzle with 20 exhaust holes at 5/64 inch diameter each that was designed to work with a 0.25 inch inner diameter Loc-Line® coolant hose. This was the widest nozzle selected for evaluation. Figure 9 shows the schematic for the nozzle tests. Figure 10 shows the 2.5 inch swivel nozzle along with a dimension drawing. To see the effect of nozzle height, researchers fixed the nozzle tips at 0.25 inch above the dust surface. These sets of tests were run at a 20-degree nozzle angle and pressure was varied from 20 to 85 psig. No scouring pattern was visible until pressures of 75 psig were reached, thereby eliminating the tests results below 75 psig from this analysis. Researchers stopped at 85 psig since the operating limit of the lab's compressor is a maximum of 90 psig. The results of this dataset are shown in Table 1. Though inconsistent, the results showed the scour depth was close to the 0.125 inch target sampling depth.

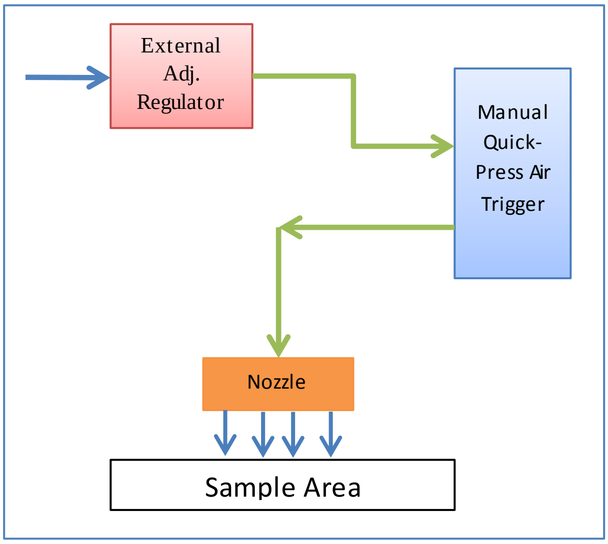

Figure 9. Diagram of nozzle setup for 2.5 inch Swivel Nozzle.

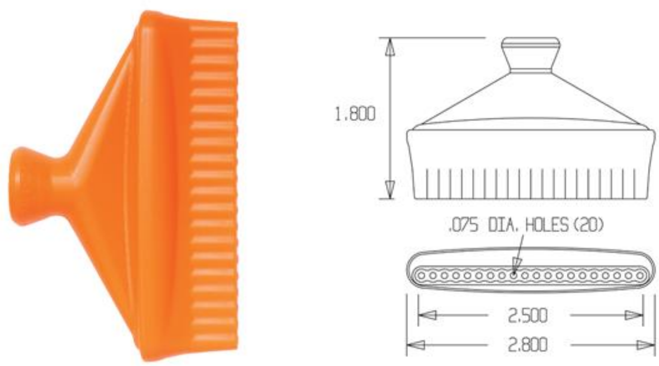

Figure 10. Photo (left) and dimension diagram (right) of the 2.5 inch swivel nozzle. Dimensions shown in inches (McMaster-Carr 2016).

Table 1. Results of 0.25 inch nozzle height tests with 2.5 inch Loc-Line Swivel Nozzle.

Nozzle Pressure (psig)	Nozzle Angle (deg.)	Nozzle Height (inch)	Scour Width (inch)	Scour Length (inch)	Scour Depth (inch)
75	20	0.25	2.8	1.25	0.16
75	20	0.25	2.9	1.125	0.03
80	20	0.25	3	1.75	0.22
80	20	0.25	2.9	1.25	0.03
85	20	0.25	3.0	1.625	0.16

3.2.2 Dual 1.5 inch Swivel Nozzles, 16 holes per nozzle at 3/64 inch Diameter Each

Researchers ran two nozzles with a smaller orifice size in parallel in an attempt to increase the scour width. The air line between the vinyl tubing and nozzles was split using Loc-Line® connectors to allow dual operation, as shown in Figure 12. The nozzles chosen for this dual setup were two 1.5 inch swivel nozzles with 16 holes at 3/64 inch diameter each that were designed to work with the 0.25 inch inner diameter Loc-Line® coolant hose. A picture and dimension drawing of the nozzle are shown in Figure 11. Additionally, researchers needed a method to capture the sample mass that was being displaced by the air. As a first attempt, a rectangular plastic box with dimensions 12x5x4 inch was placed on the dust bed at varying distances from the nozzle exhaust. The plastic box had one short end removed to allow the dust to be pushed into the container. The container could then be weighed after each test to determine the sample mass. A diagram of this is arrangement shown in Figure 13.

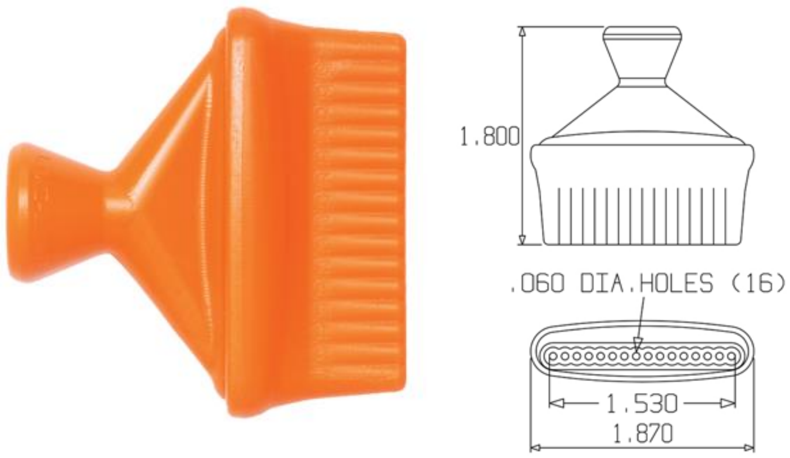

Figure 11. Picture (left) and dimension drawing (right) of the 1.5 inch swivel nozzle. Dimensions shown in inches (McMaster-Carr 2016).

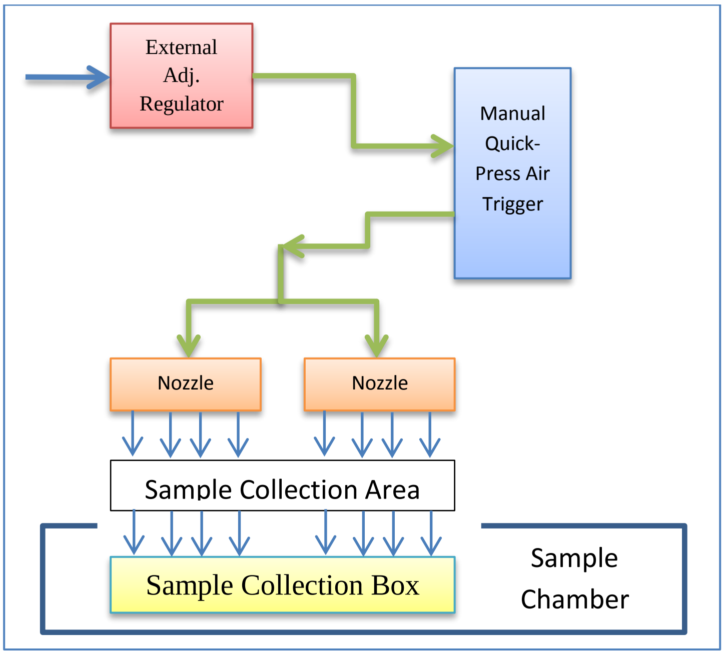

Figure 12. Diagram of dual nozzle setup used with 1.5 inch swivel nozzles and plastic collection box.

For this round of tests, the nozzle height was reduced to 0 inch from the dust surface, i.e. touching the surface. Line pressure was maintained at 85 psig, but the nozzle angle was adjusted to 5, 10, and 15 degrees throughout the tests. The scour depth ranges and averages for the varying nozzle angles are found in Figure 14. The results met expectations by showing a steady trend of increasing scour depth with increased nozzle angle.

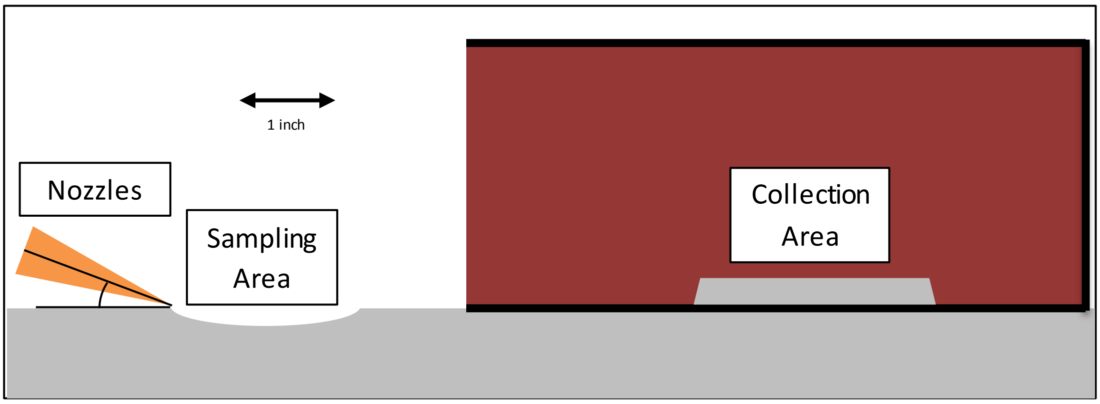

Figure 13. Diagram of swivel nozzles (orange) and sample collection box (dark red) on dust surface (grey).

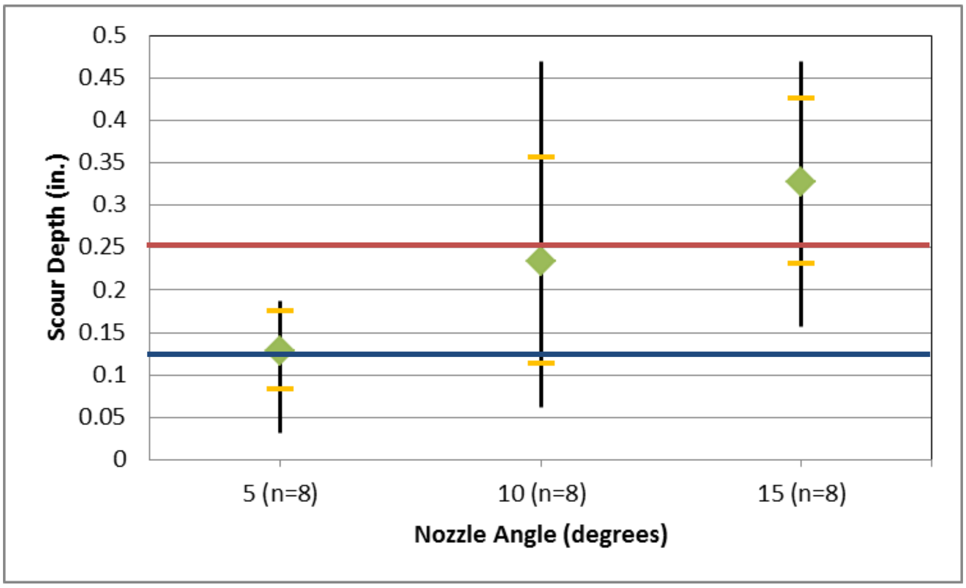

Figure 14. Scour depth maximum, minimum and average for varying nozzle angle with dual nozzle setup used with 1.5 inch swivel nozzles and plastic collection box. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

The distance from the sample collection box to the nozzle tips was also varied between 1.5, 2.0, 2.5 and 3.0 inch during this round of testing to see the effect of scour length on sample mass collection. Figure 15 shows the results. Generally, sample mass increased as the collection box was moved further away from the nozzles.

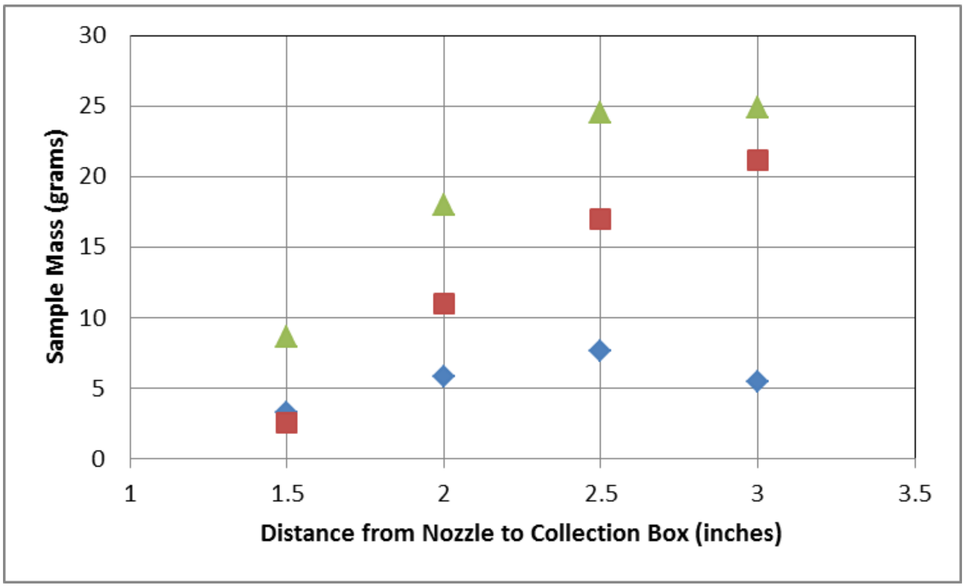

Figure 15. Sample mass collected based on distance from nozzles with dual nozzle setup used with 1.5 inch swivel nozzles and plastic collection box. Blue diamonds denote 5 degree nozzle angle, red squares denote 10 degree nozzle angle and green triangles denote 15 degree nozzle angle. Each point is the average of n=2 samples.

3.2.3 6-inch Air Knife

Theorizing that an air knife would provide a more even air distribution over the sampling area, researchers conducted a number of tests using a 6 inch aluminum air knife. The air knife was attached to the current testing setup through one of the side ports, as shown in Figure 16. The air coming out of the air knife is released perpendicular to the dust surface and then adheres to the Coanda profile to turn 90 degrees until it is moving parallel to the dust surface, as shown in Figure 17. Figure 18 shows a photo of the air knife setup with the collection box and dust bed. The air knife was tilted to 5 and 10-degree nozzle angles and nozzle heights varied between 0.0, 0.125 and 0.25 inches. A line pressure of 85 psig was maintained throughout the round of testing. Table 2 shows the results of the air knife testing.

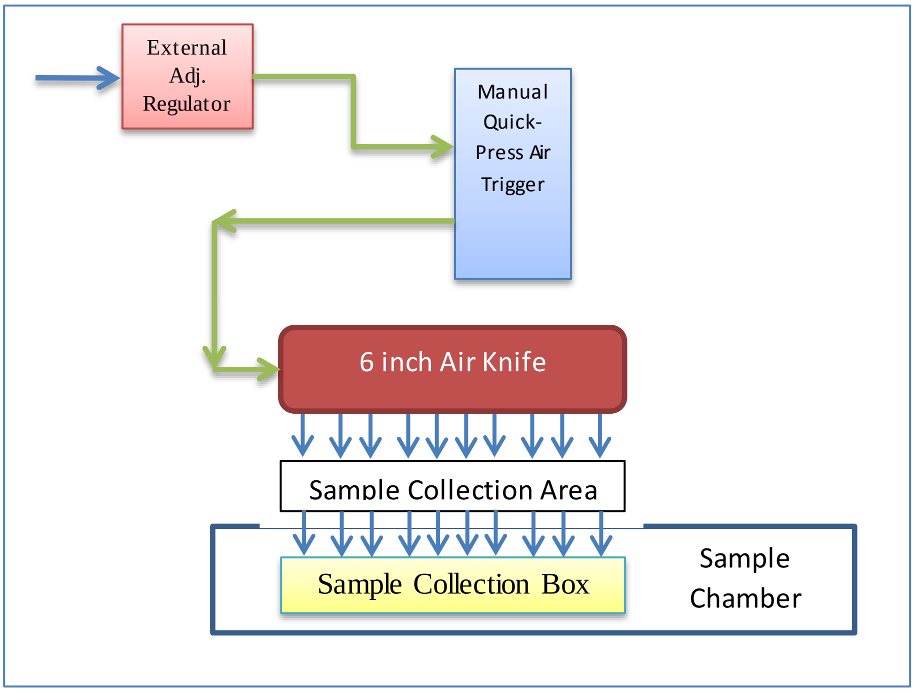

Figure 16. Diagram of air knife setup with trigger and air-line system.

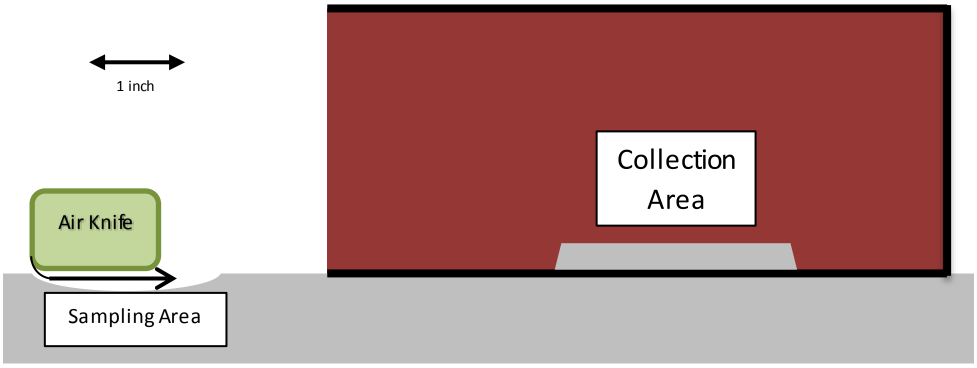

Figure 17. Diagram of air knife (green) and sample collection box (dark red) on dust surface (grey).

Figure 18. Photo of air knife with dust bed and collection box. Image inverted along vertical center match Figure 17.

Table 2. Results of 6-inch air knife testing at various nozzle angles and nozzle heights.

Line Pressure (psig)	Nozzle Angle (deg)	Nozzle Height (in)	Scour Width (in)	Scour Length (in)	Scour Depth (in)	Sample Box Distance (in)	Sample Mass (g)
85	5	0	5.9	1.5	0.41	1.5	38.7
85	5	0	5.8	1.5	0.34	1.5	37.5
85	10	0.125	5.8	2.5	0.41	2.5	23.5
85	10	0.125	6.3	2.5	0.28	2.5	20.1
85	10	0.125	6.3	2	0.28	2.5	12.9
85	10	0.25	1.3	1.5	0.28	1.5	4
85	10	0.25	1.5	1.25	0.13	1.5	2.1
85	5	0.25	1.5	1.25	0.094	1.5	0.9
85	5	0.25	0.25	0.5	0.094	1.5	0.2

The results of the air knife tests showed a general trend of decreased scour depth in relation to increasing height and decreased nozzle angle. This decrease in scour depth corresponded to a sharper decline in the collected sample mass. At the target scour depth, the mass collected was too low to use in a low temperature ashing test or with a CDEM. Due to how the air flow wraps around the air knife at 90 degrees, the proximity of the dust surface caused inconsistent depth profiles and scour width. This finding indicated that small variations on the dust surface cause an uneven sample collection over the scour area and rendered the sampling process inconsistent.

With the introduction of wider nozzles, it became apparent that a balance between pressure and scour width is important. With the vinyl tube testing, the width was only 0.25 inch, concentrating the air in a narrow scour profile. With the swivel nozzles or the air knife, the air stream spread over 2.5 to 6 inches width.

3.2.4 Conclusions from Nozzle Evaluation

It was evident to researchers that the air knife configuration was too difficult to incorporate into the DSD design due the potential of uneven dust surfaces in mines. If the air knife experienced difficulty with the almost perfectly flat surface created for the lab testing, it would be too sensitive to variations present in a real mine environment. The scour results with the Loc-Line® nozzles were more consistent with the increasing nozzle angles and led researchers to continue to use the nozzles in the next steps of the design process. The smaller orifice diameters and larger scour width for the dual 1.5 inch swivel nozzles made them a better choice than the 2.5 inch swivel nozzle.

3.3 New Trigger System Design with Dual 1.5 inch Swivel Nozzles

Next, researchers developed a trigger system to deliver air pulses of consistent pressure and duration to the nozzles. Researchers added a charging vessel operated with a three-way-valve. While the valve was depressed, the charging vessel was charged with a defined amount of air under a pressure set by the regulator. Upon release of the valve, the vessel discharged a defined burst of air through the nozzles. Figure 19 shows the 3-port control valve with a spring return, palm button trigger. A cylindrical charging vessel was built to act as an air storage container. As shown in Figure 19, the charging vessel was connected to the control valve to allow the vessel to be charged when the palm button was pressed, and to release the air through the nozzles when the button was released. Figure 21 illustrates the set-up in a schematic. The trigger and charging vessel gave researchers control over the amount and timing of the air release that was not possible with the manual valve system.

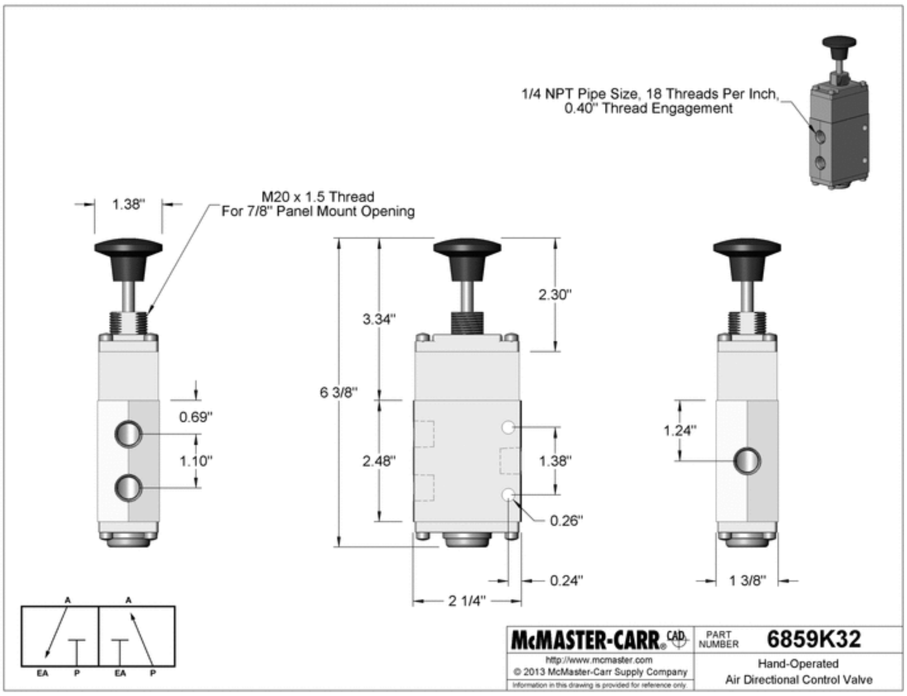

Figure 19. 3-D model information for 3-port air directional control valve used in second trigger system (McMaster-Carr 2016).

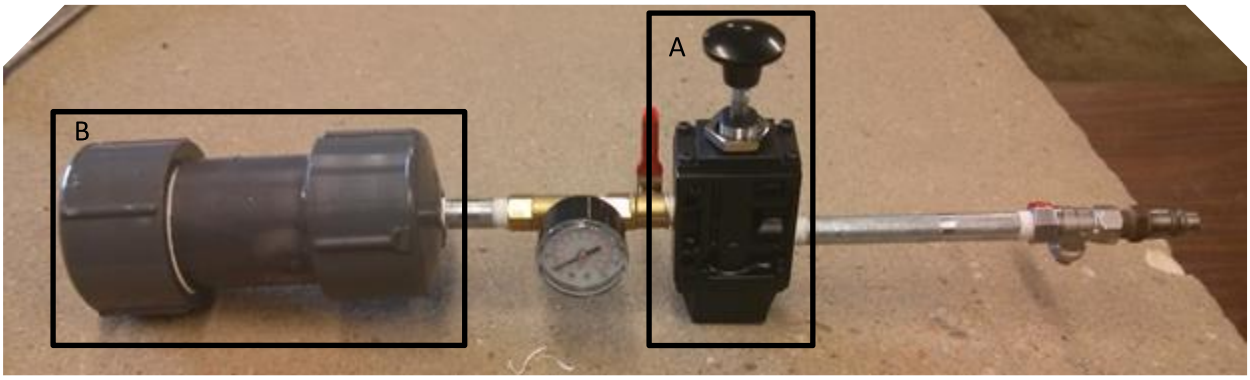

Figure 20. 3-port air directional control valve (Box A) and charging vessel (Box B) in combination to form new trigger system. Red lever is a ball valve installed in case researchers needed to section the charging vessel from the control valve.

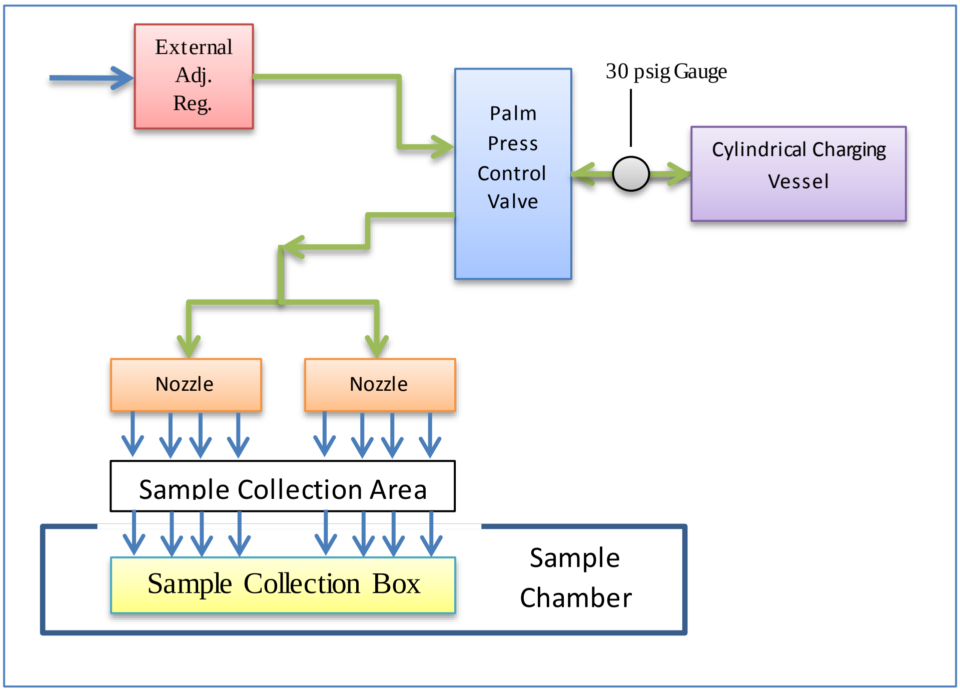

Figure 21. Diagram of new trigger system in conjunction with input airline and nozzles.

3.3.1 6-degree Nozzle Angle and 0.0 inch Height with New Trigger System

The initial volume of the charging vessel was 18 cubic inches based on a calculation of required pulse length and outflow from the vessel through the nozzles. Initial tests with this vessel size were conducted with the nozzles set at an angle of 6 degrees, nozzle height at 0.0 inch, and charging vessel pressure set between 20, 25, 30 and 35 psig. The distance between the collection box and nozzles was varied between 2.5 and 3 inch during testing. The scour depth range and average for each pressure is seen in Figure 22.

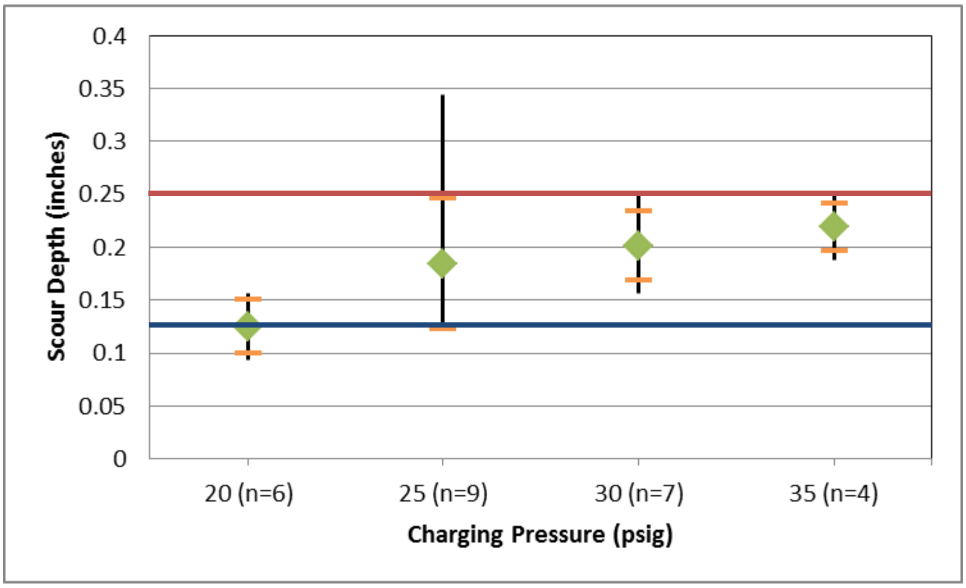

Figure 22. Scour depth results for dual 1.5 inch swivel nozzles at 6-degree nozzle angle with palm button control valve and 18 cubic inch charging vessel. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

With the new trigger system, there was a reduction in the required pressure to attain scour depths near the target depth of 0.125 inch. The ranges of scour depths for the 10, 30 and 35 psig tests were tighter, indicating the new trigger system created a more consistent scour pattern. The range at 25 psig was larger than the other 3 pressures, but the average scour depth trended closely with the other pressures. The collected data is in Figure 23. Even though sample mass was not a limiting criterion, researchers tracked the collected mass and noted variations and inconsistencies between tests. The 3 inch collection distance indicated a drop in mass collected at the 35 psig range, and the 2.5 inch collection distance dipped for 30 psig, but then increased to a higher value at 35 psig. One potential cause for the mass variations was the elongation of the scour length seen with the new trigger system. Multiple tests reached or exceeded the 2.5 inch collection distance, which may have led to a potential trapping of the sample mass under the collection box, instead of being entrained and lifted into the collection box.

3.3.2 4-degree Nozzle Angle and 0.0 inch Height with New Trigger System

Follow up tests with this vessel size were conducted with the nozzles set at an angle of 4 degrees, nozzle height of 0.0 inch, and pressure adjusted between 20, 25, 30, 35 and 40 psig. Researchers expected that the scour depth could potentially decrease with the lower nozzle angle and decided to add tests at 40 psig pressure. The distance between the collection box and nozzles was varied again between 2.5 and 3 inch during testing. The scour depth range and average for each pressure are in Figure 24.

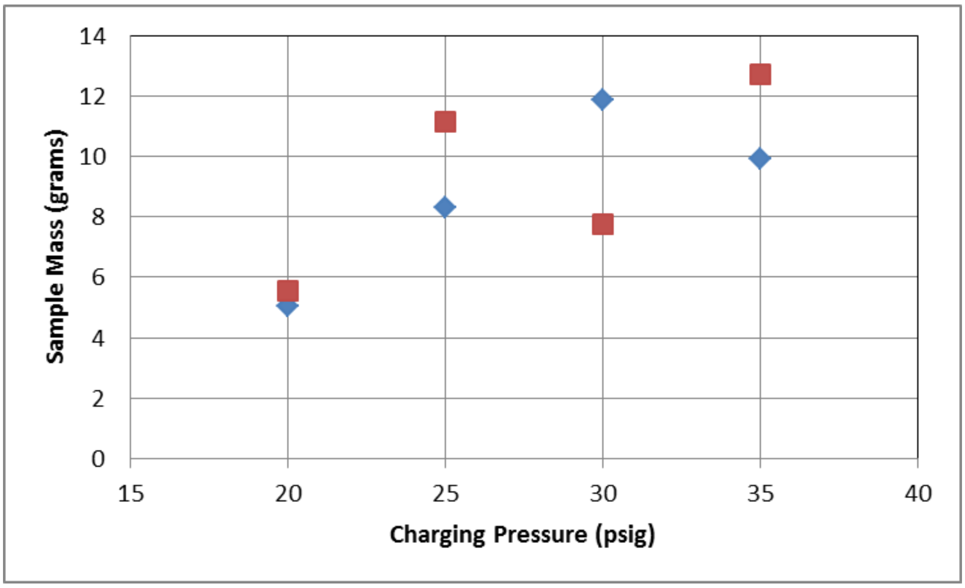

Figure 23. Sample mass results for dual 1.5 inch swivel nozzles at 6-degree nozzle angle with palm button control valve and 18 cubic inch charging vessel. Red squares denote 2.5 inch collection distance and blue diamonds denote 3.0 inch collection distance. For 2.5 inch collection distance n(20)=3, n(25)=7, n(30)=2 and n(35)=2. For 3.0 inch collection distance n(20)=3, n(25)=2, n(30)=5 and n(35)=2.

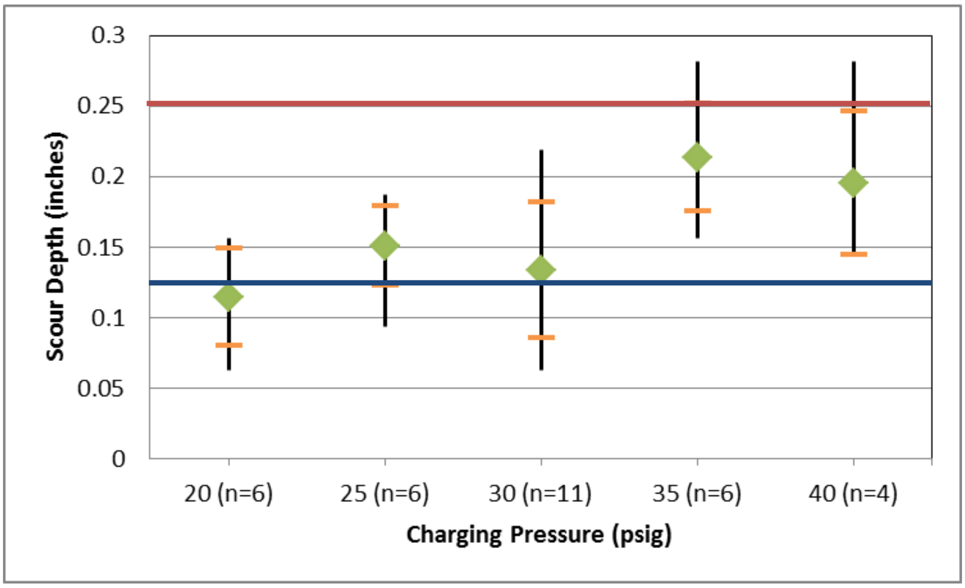

Figure 24. Scour depth results for dual 1.5 inch swivel nozzles at 4-degree nozzle angle with palm button control valve and 18 cubic inch charging vessel. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

At 20, 30 and 35 psig, the average depth was similar to the 6-degree nozzle angle results. However, the range of scouring depths was larger. The 40 psig tests showed a lower scour depth than expected when compared to the 35 psig results. The collected sample mass results in Figure 25 show that the tests conducted with the 2.5 in collection distance for 40 psig were lower than the trend would have predicted. Overall, the sample mass results indicate the 4-degree nozzle angle was better than the 6 degree nozzle angle. Next, researchers lowered the nozzle angle to 2 degrees.

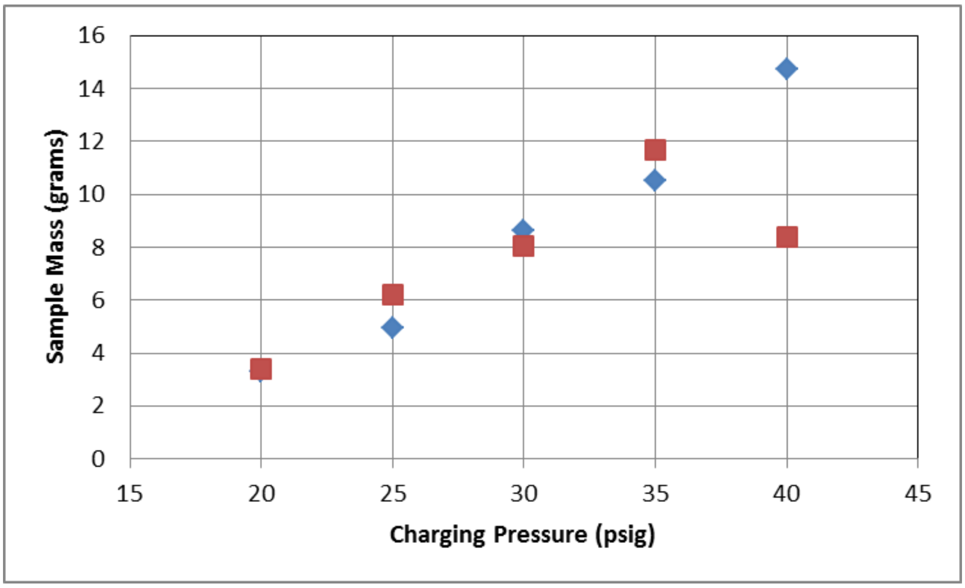

Figure 25. Sample mass results for dual 1.5 inch swivel nozzles at 4 degree nozzle angle with palm button control valve and 18 cubic inch charging vessel. Red squares denote averages for 2.5 inch collection distance and blue diamonds denote averages for 3.0 inch collection distance. For 2.5 inch collection distance n(20)=3, n(25)=3, n(30)=6, n(35)=2 and n(40)=1. For 3.0 inch collection distance n(20)=3, n(25)=3, n(30)=5, n(35)=3 and n(40)=3.

3.3.3 2-degree Nozzle Angle and 0.0 inch Height with New Trigger System

The next series of tests was conducted with the nozzles set at an angle of 2 degrees, nozzle height of 0.0 inch, and pressure adjusted between 20, 25, 30, 35 and 40 psig. The distance between the collection box and nozzles was varied again between 2.5 and 3 inch during testing. The scour depth range and average for each pressure is in Figure 26.

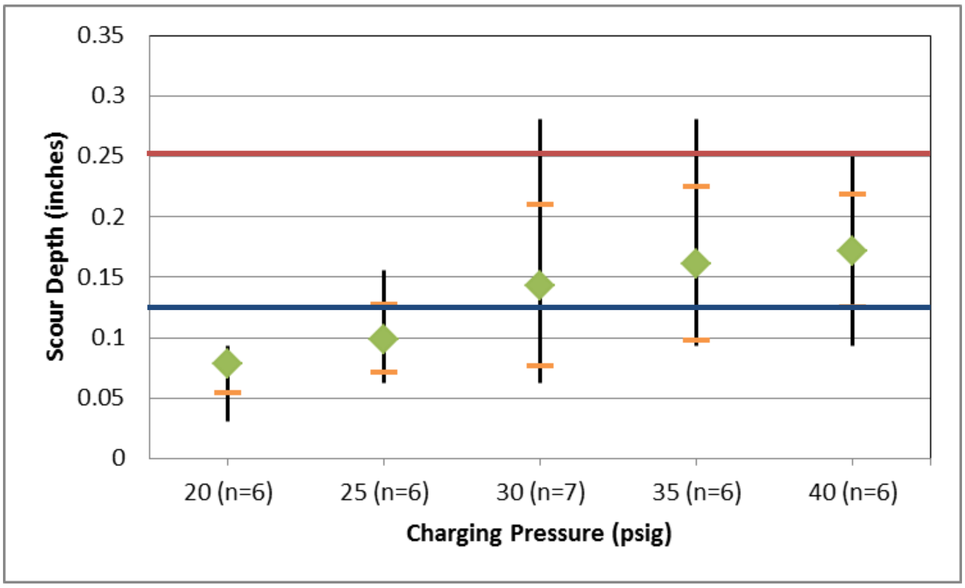

Figure 26. Scour depth results for dual 1.5 inch swivel nozzles at 2-degree nozzle angle with palm button control valve and 18 cubic inch charging vessel. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

The average scour depth at a 2-degree nozzle angle was even more consistent than the 4 degree results. The scour depth averages seemed to rise consistently with each 5 psig increase in charging pressure. However, the depths decreased with the lowering of the angle, suggesting that more of the air did not participate in the scouring action, and instead rebounded off the surface. The average collected masses for the 2.5 and 3.0 inch collection distances also showed a reduction compared to the 4-degree angle, as shown in Figure 27. The trend for the 2-degree angle sample mass did not follow a similar linear trend as seen in the 4-degree test results.

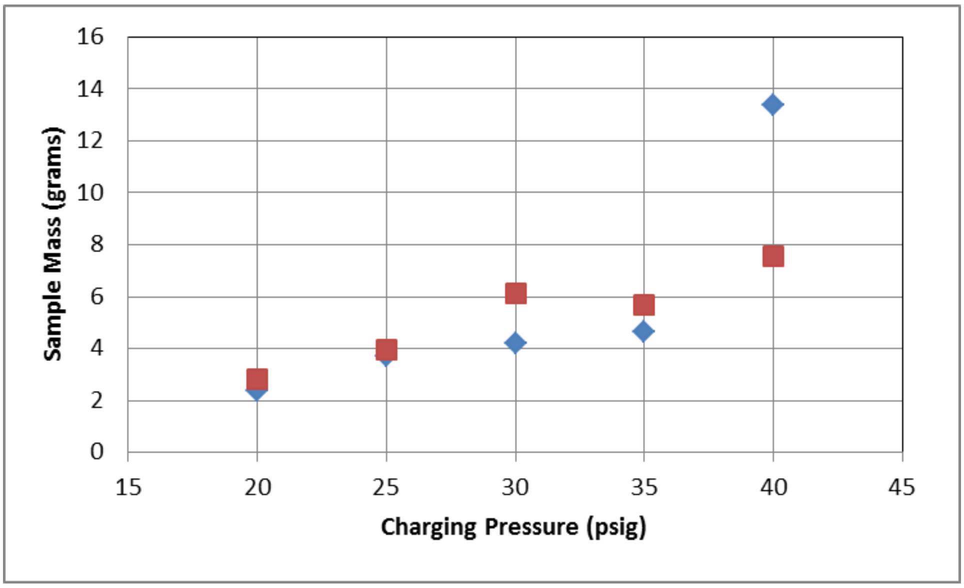

Figure 27. Sample mass results for dual 1.5 inch swivel nozzles at 2-degree nozzle angle with palm button control valve and 18 cubic inch charging vessel. Red squares denote averages for 2.5 inch collection distance and blue diamonds denote averages for 3.0 inch collection distance. For 2.5 inch collection distance n(20)=3, n(25)=3, n(30)=3, n(35)=3 and n(40)=3. For 3.0 inch collection distance n(20)=3, n(25)=3, n(30)=4, n(35)=3 and n(40)=3.

3.3.4 4-degree Nozzle Angle at 0.25 and 0.5 inch Height with New Trigger System

Researchers decided to further examine the 4-degree setting to determine the impact of nozzle height on the scour depth and mass collection. The height was adjusted between 0.25 and 0.5 inch. The charging pressure was varied from 20 to 40 psig in 5 psig increments at the different heights. The distance for the sample collection box was fixed at 4 inch. The scour depth results for the two nozzle heights are shown in Figure 28 and Figure 29. The data shows that the average scour depth was deeper at the 0.5 in height than the 0.25 inch height at each of the charging pressures tested. When compared to the previous results at 4 degree nozzle angle and 0.0 inch height, as shown in Figure 24, the average scour depths for the 0.25 inch nozzle height were lower except at 30 and 40 psig. When comparing the 0.0 in nozzle height average scour depths to the 0.5 inch height data, the scour depth is consistently higher at all charging pressures.

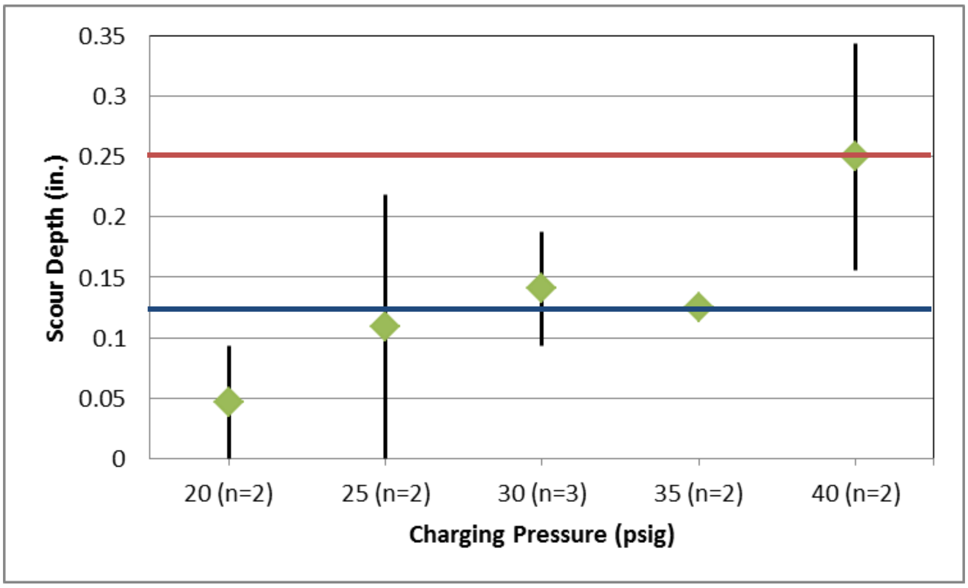

Figure 28. Scour depth results for dual 1.5 inch swivel nozzles at 4-degree nozzle angle and 0.25 inch nozzle height with palm button control valve and 18 cubic inch charging vessel. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

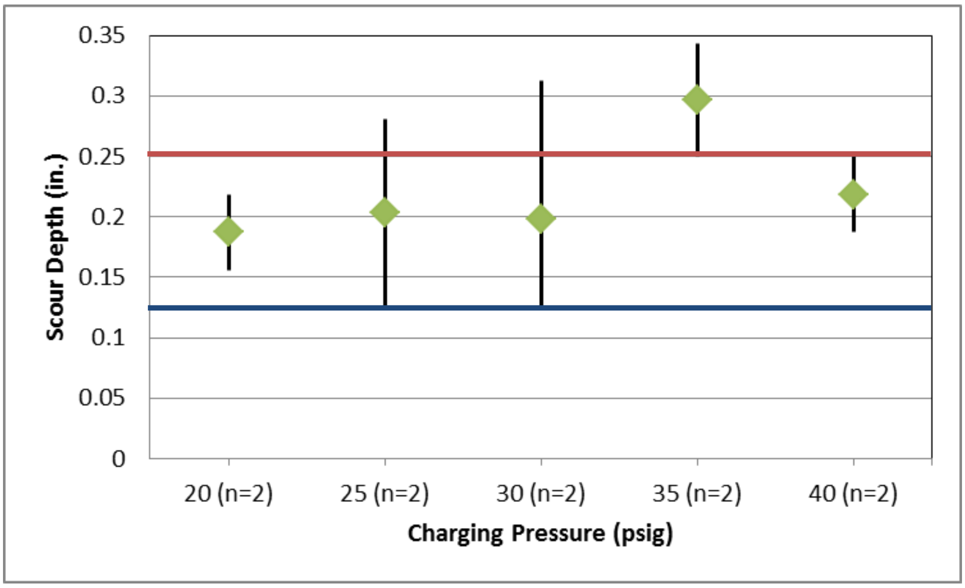

Figure 29. Scour depth results for dual 1.5 inch swivel nozzles at 4-degree nozzle angle and 0.5 inch nozzle height with palm button control valve and 18 cubic inch charging vessel. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

Researchers examined data for the different nozzle heights to determine how the scour depth results affected the sample mass collection averages, shown in Figure 30. Both mass averages followed a trend of the highest average collected mass at 30 psig charging pressure, with decreases in the 35 and 40 psig tests. The 0.25 inch nozzle height showed a dip at the 35 psig pressure, consistent with the decrease in the scour depth seen previously in Figure 28.

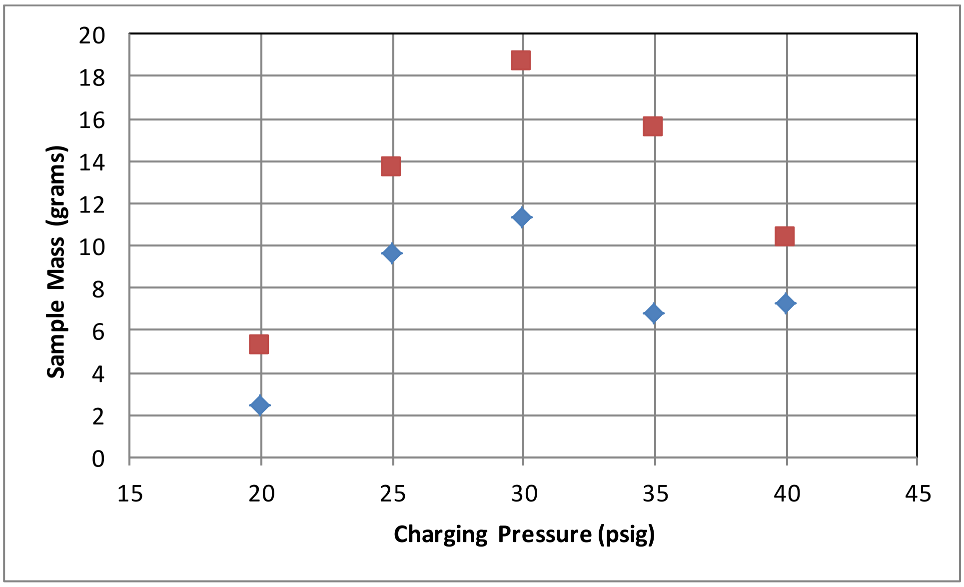

Figure 30. Sample mass results for dual 1.5 inch swivel nozzles at 4 degree nozzle angle and varying nozzle height with palm button control valve and 18 cubic inch charging vessel. Red squares denote averages for 0.25 inch chamber height and blue diamonds denote averages for 0.5 inch chamber height. For 0.25 inch chamber height n(20)=2, n(25)=2, n(30)=3, n(35)=2 and n(40)=2. For 0.5 inch chamber height n(20)=2, n(25)=2, n(30)=2, n(35)=2 and n(40)=2.

3.3.5 Impact of Air Channel at 5 degree Nozzle Angle and 0.0 inch Nozzle Height and Dual 1.5 inch Swivel Nozzles with New Trigger System

Researchers decided to run an additional round of testing at a 5-degree nozzle angle and 0.0 inch nozzle height using dual, 1.5 inch swivel nozzles. The distance for the collection box was set at 3.0 in from the nozzle exhausts. The major change for this set of tests was the addition of a 4x6x0.5 inch open channel placed over the end of the nozzles and the sampling area as seen in Figure 31 and Figure 32. Researchers anticipated that this channel would help focus the air stream to the sampling surface and increase the movement of dust into the sample collection area. The air channel was used in half of the tests to provide a baseline at the 5-degree nozzle angle and 0.0 nozzle height. These tests were conducted at 25 psig as a base pressure of comparison.

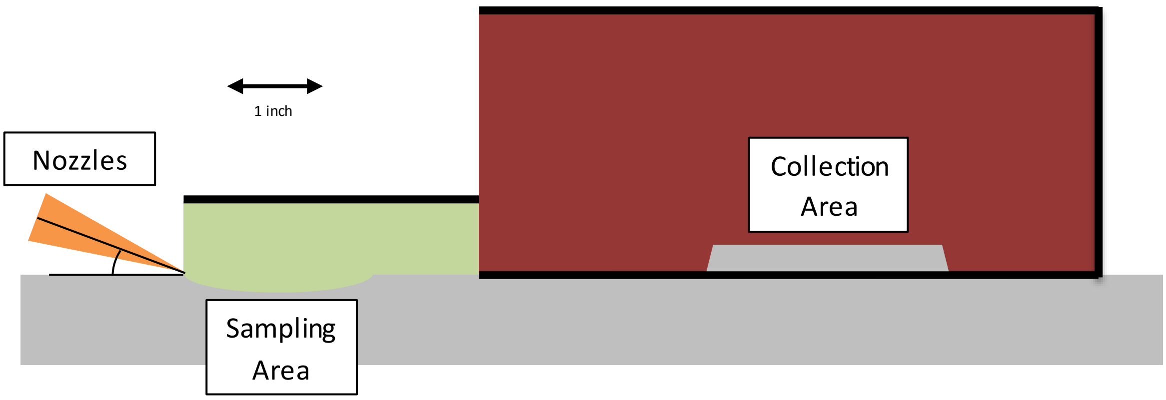

Figure 31. Diagram of swivel nozzles (orange), air chamber (light green) and sample collection box (dark red) on dust surface (grey).

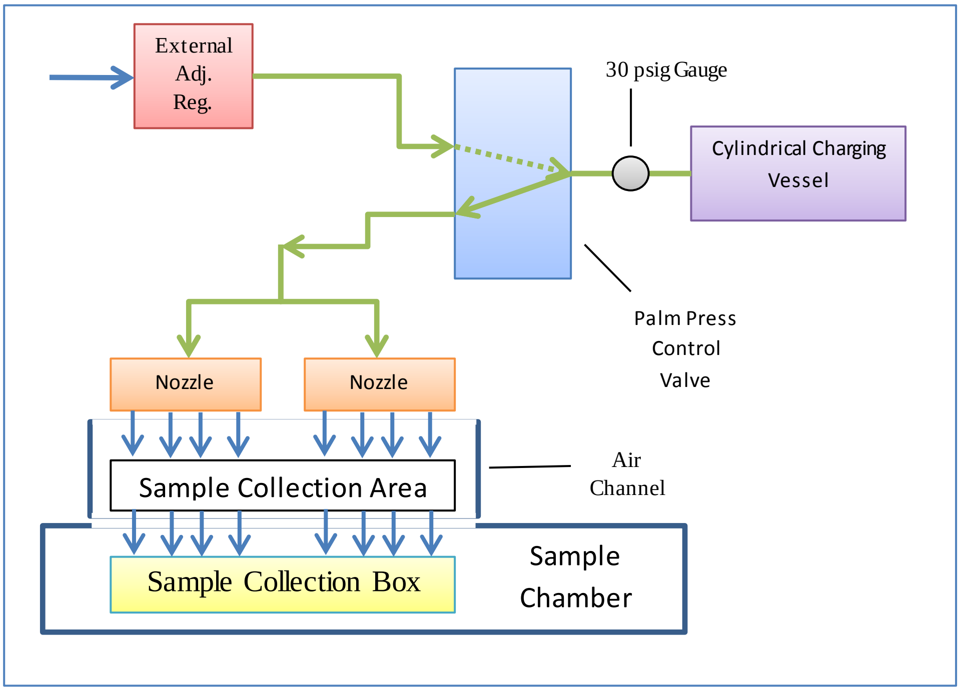

Figure 32. Diagram of new trigger system in conjunction with input air line and nozzles showing coverage of sample chamber with addition of air channel. Dotted line indicates new airflow path when control valve is engaged.

The scour depth results are presented in Figure 33. The air channel did not provide the improvement in scour depth consistency and sample mass that the researchers were expecting. The range of scour depths between the two setups was comparable, but the tests with the air channel showed a decrease in scour depth instead of an increase. The average sample mass reflected this decrease, with the tests without the air channel averaging 11 grams per test, while the tests with the air channel averaged 9.7 grams per test.

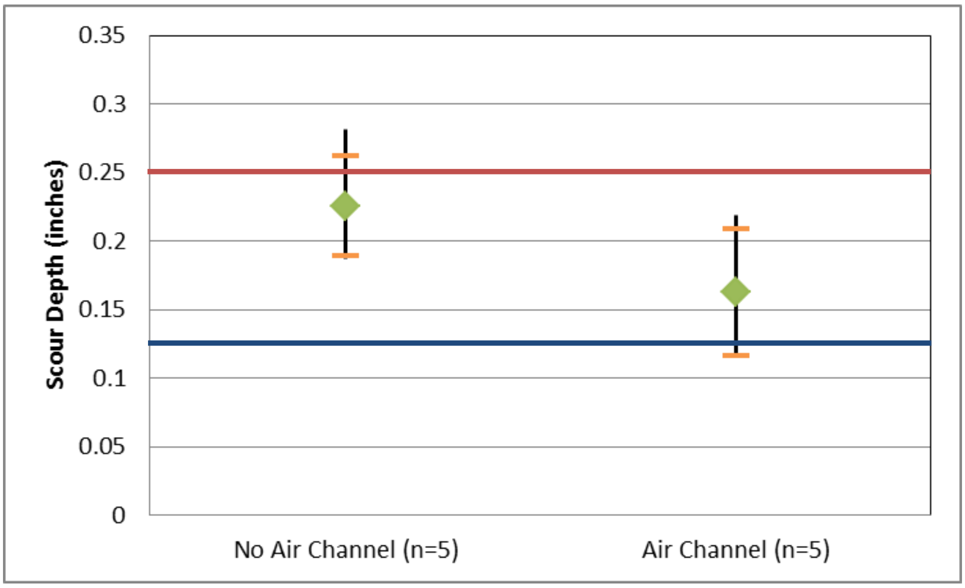

Figure 33. Scour depth results for dual 1.5 inch swivel nozzles at 5-degree nozzle angle and 0.0 inch nozzle height with palm button control valve and 18 cubic inch charging vessel. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

3.3.6 Conclusions for Dual 1.5 inch Swivel Nozzles with New Trigger System

Testing with the new trigger system demonstrated to researchers that use of a charging vessel with a set volume and control valve with automatic return provided a tighter range of values, while also reinforcing the expected data trend between scour depth and pressure. It became evident that the release timing of the air gun trigger used in previous testing may have been a contributing factor to the fluctuation of the scour depth results.

The inconsistencies in sample mass collected with the new trigger system were in part due to the design of the collection box. Dust that was entrained by the scouring action of the compressed air did not completely move to the collection box. Rather, dust was pushed vertically and settled back onto the sampling area and even backwards onto the nozzles. Due to the open nature of the collection box and no containment between the nozzles and collection area, researchers concluded that mass could not be properly measured and the dust collection process needed improvement. The outcomes from these tests allowed researchers to begin designing an initial prototype in accordance with Task 1.

3.4 DSD Versions 1.0 and 1.1

Researchers developed and built DSD Version 1.0 that contained dual 1.5 inch swivel nozzles and the collection box in one unit. The sample chamber for this design was 11.25x5.5x2.75 inches. The nozzles protruded 2 inches into the box and the sample collection lip for the bottom of the box was 3.5 inch from the nozzle exhausts. The nozzle angles were set at 5 degrees. To provide additional support for the prototype on the dust surface, two 1-inch wide wings were added along the outside of the sampling chamber next to the sampling port. Along with providing support, these wings also helped to provide a better seal for the dust in the area where scouring was to occur. The same palm button control valve and 18 cubic inch charging vessel were used with this new version and were connected to the nozzle system by a 0.25 inch inner diameter air hose. A cross section diagram of the DSD Version 1.0 is shown in Figure 34. Figure 35 shows a bottom view of DSD version 1.1. A diagram of the trigger system with the DSD Version 1.0 is shown in Figure 36. This new version was no longer attached to a bracket or mount and rested on the dust surface.

In addition to the new design, researchers made changes to the test bed procedure to better replicate the settled dust that is prevalent in underground coal mines. Researchers created a sifting box that allowed for the creation of an even layer of rock dust on a flat plywood surface. The thickness of the testing surface was reduced to 1 inch deep to reduce preparation time. This new sifter setup also allowed for multiple tests to be conducted on the same dust layer to better identify if variations in the dust preparation procedure had an impact on the scour and mass collection data.

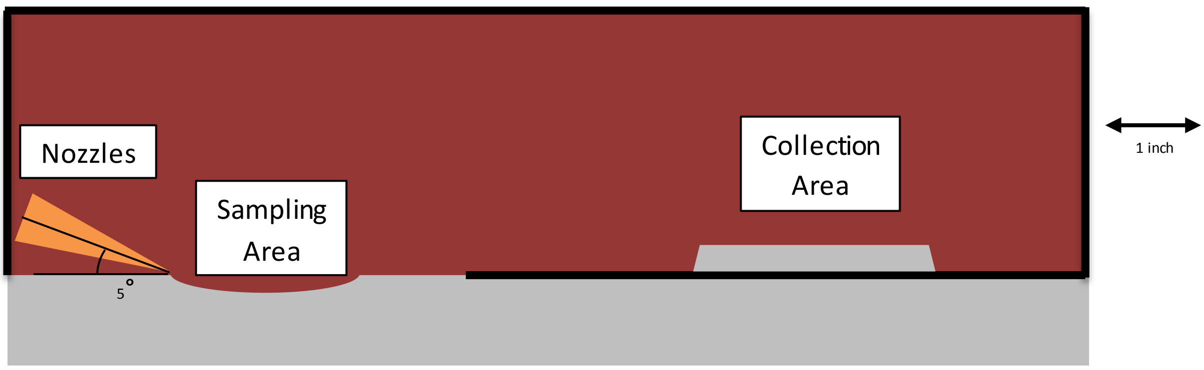

Figure 34. Diagram of nozzles (orange), sample chamber (dark red) and dust layer (grey) for DSD Version 1.0.

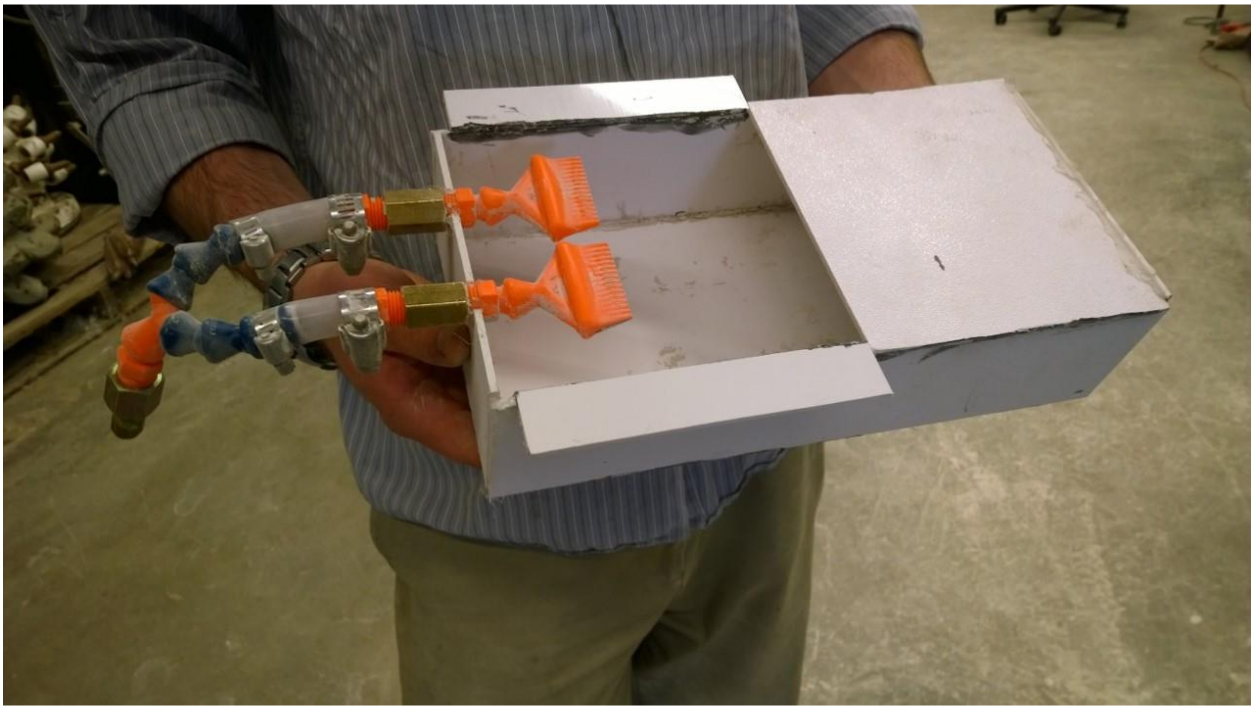

Figure 35. Photo of bottom view of DSD Version 1.

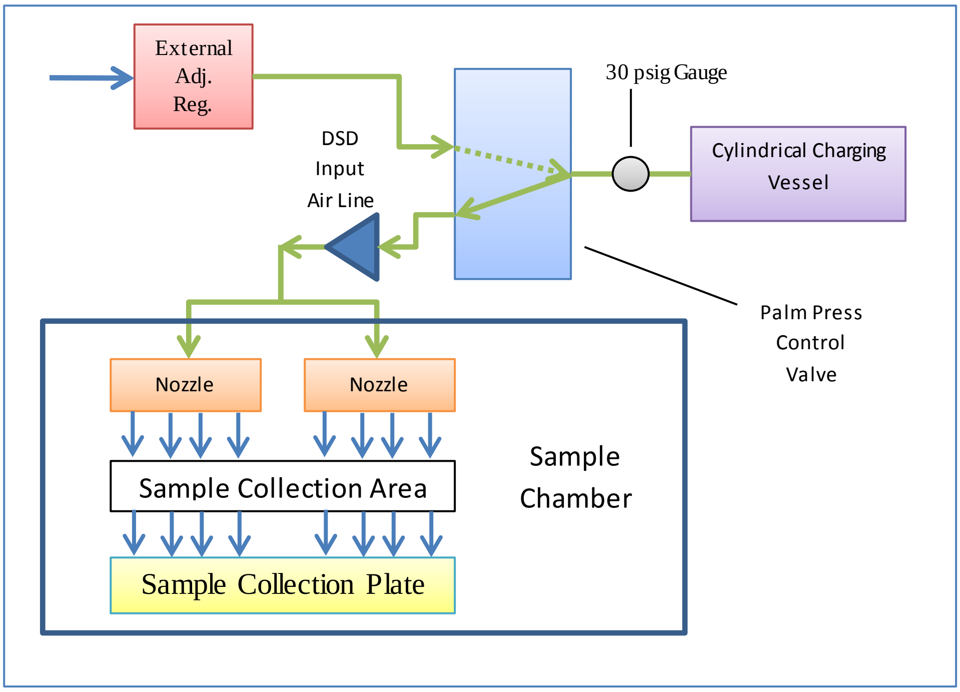

Figure 36. Diagram of trigger system in conjunction with DSD version 1.0.

3.4.1 DSD Version 1.0 Testing

Initial testing with the DSD Version 1.0 was conducted with the full 3.5 inch length between the nozzles and the collection plate. The results of these initial tests are shown in Figure 37, and confirmed that the scour depth increased as indicated by the air channel test shown previously in Figure 32. All three pressures tested with the DSD Version 1.0 overshot the target sample depth of 0.125 inch and had average depths near or above the 0.25 sample depth upper threshold.

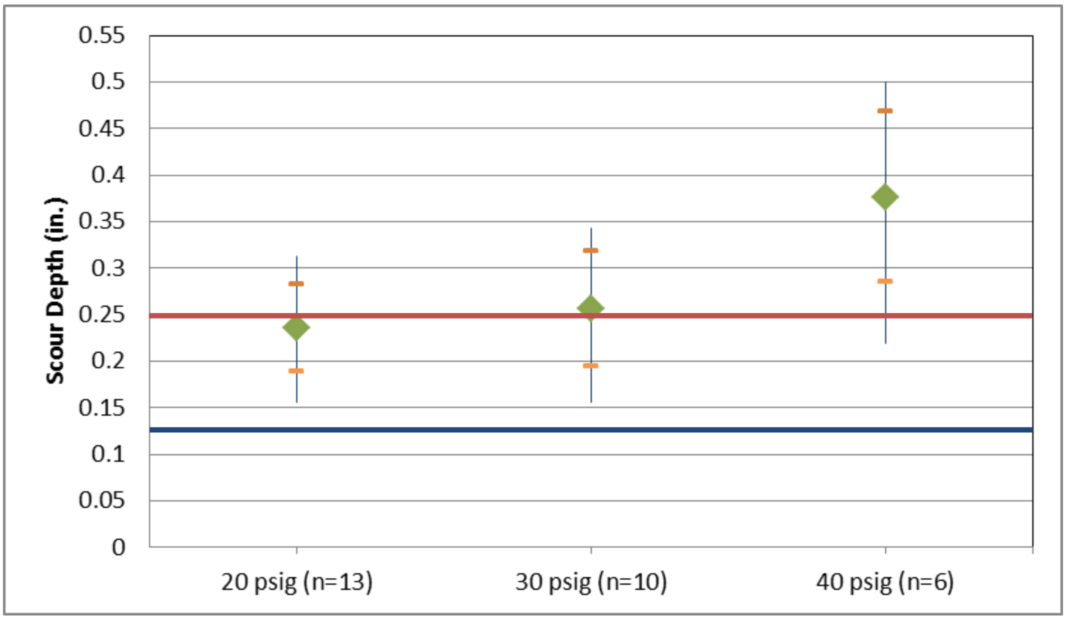

Figure 37. Scour depth results for DSD version 1.0 with 3.5 inch collection distance. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

Researchers also looked at the collected mass results for the DSD Version 1.0, shown in Figure 38. While conducting initial tests with the new version, it was noticed that some air and dust was escaping under the DSD where it made contact with the dust bed surface. Researchers also identified that portions of the entrained dust sample were being blown back onto the nozzles and not onto the collection chamber.

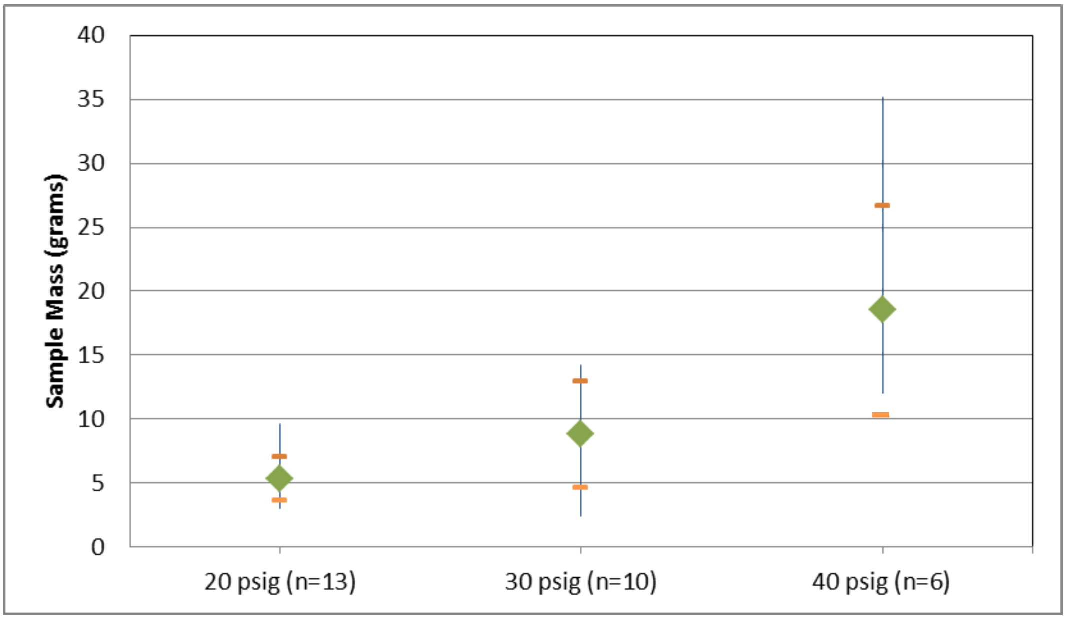

Figure 38. Sample mass results for DSD version 1.0 with 3.5 inch collection distance. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

3.4.2 DSD Version 1.1 Testing

To eliminate pressure buildup inside the sampling chamber, two 0.125 inch inner diameter relief holes were added, one on each side panel of the DSD. Researchers also sought to mitigate the recirculation of dust onto the nozzles by inserting a divider wall near the exhausts of the nozzles. Additionally, insertable plates were made to adjust the sample collection distance from 3.5 inch to 2.0 or 1.5 inch. This modified design of DSD Version 1.0 is labeled DSD Version 1.1. Figure 39 shows a cross section diagram of DSD Version 1.1 and Figure 40 shows the side and bottom of DSD Version 1.1.

Tests were conducted at 15, 20 and 25 psig at collection distances of 1.5, 2.0 and 3.5 inch to achieve a scour depth close to the recommended 0.125 inches. The scour results for these tests are shown in Figure 41, and the sample mass results shown in Figure 42. The results for the 3.5 inch collection distance are inconsistent, as they do not follow a generally increasing trend as expected. The 2.0 and 1.5 inch collection tests did follow an increasing trend with the increase in charging pressure and resulted in scour depth averages close to the 0.125 inch target depth. Three of the tests at 20 psig with the 3.5 inch collection distance were identified as having a deep impression on the dust from the nozzles, indicating that the DSD may have sunk into the dust surface and caused an increase in the scour depth. If the three tests were removed from the data, the 20 psig average depth for 3.5 inch collection distance would be 0.16 inch. This result is still higher than would be expected, given the average depths for the 15 and 25 psig tests at the 3.5 inch collection distance. The collected sample mass results trended well with the measured scour depth data, which indicated to researchers that the DSD was collecting samples in a proportionate manner to the scour profile.

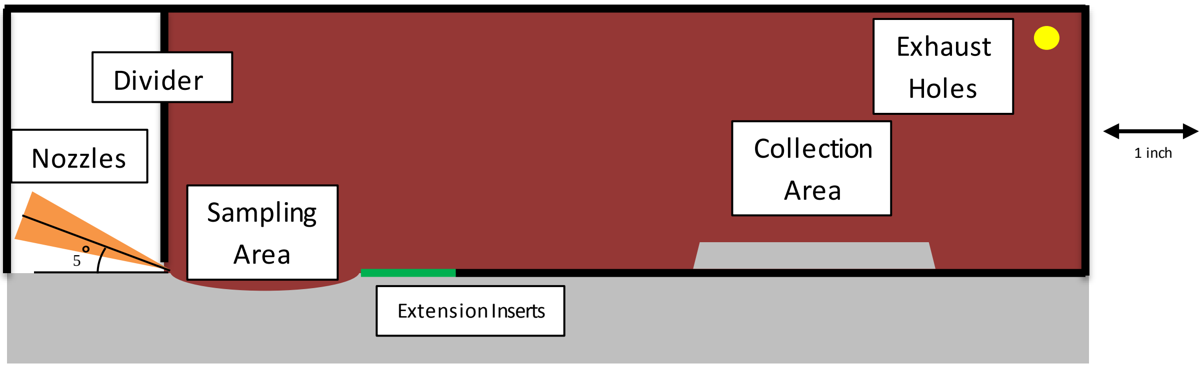

Figure 39. Diagram of nozzles (orange), sample chamber (dark red) exhaust holes (yellow), collection plate extension inserts (green) and dust layer (grey) for DSD version 1.1.

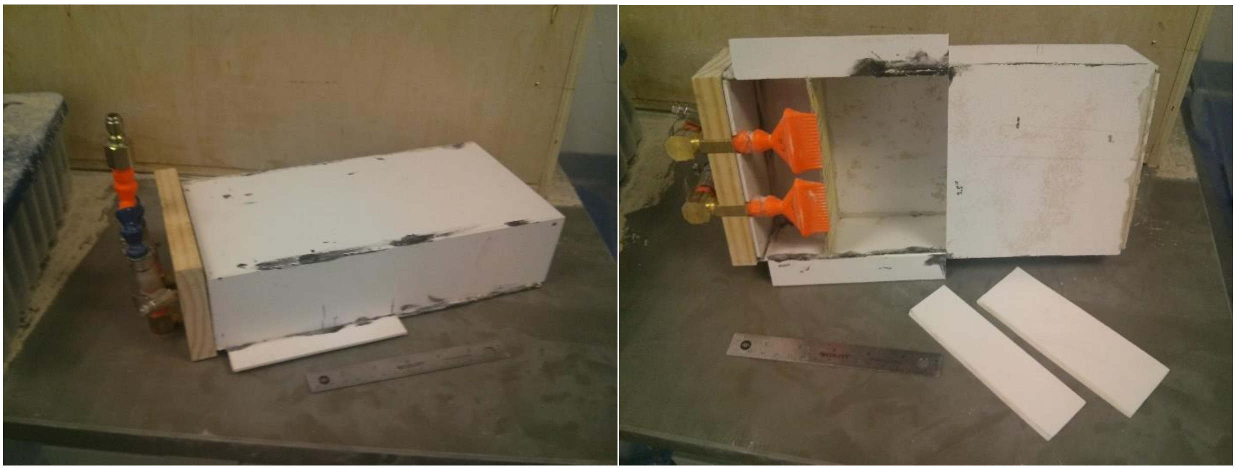

Figure 40. Photo of side (left) and bottom (right) view of DSD Version 1.1 with collection plate extension inserts shown in right photo next to 6 inch ruler.

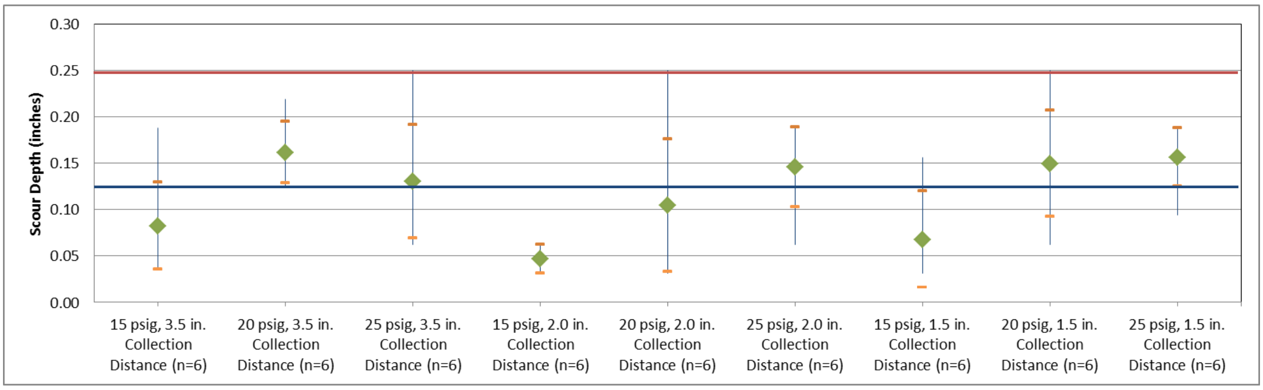

Figure 41. Scour depth results for DSD version 1.1 with 3.5, 2.0 and 1.5 inch collection distance. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

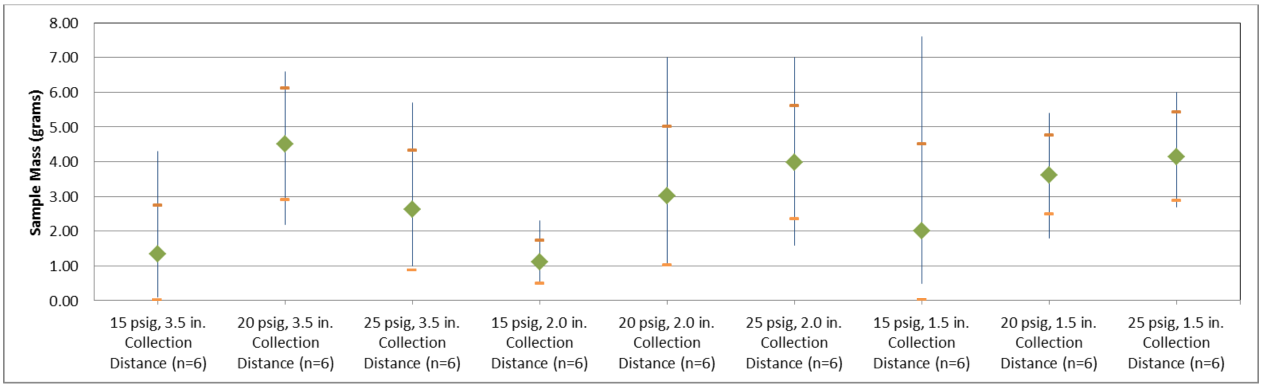

Figure 42. Sample mass results for DSD Version 1.1 with 3.5, 2.0 and 1.5 inch collection distance. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

3.4.3 Conclusions for DSD Versions 1.0 and 1.1

The inclusion of the sample chamber for DSD Versions 1.0 and 1.1 resolved the mass collection inconsistencies present in the previous nozzle testing with the trigger system. Researchers were successful in designing a version that scoured the upper portion of the dust layer and collected sufficient amounts of dust for analysis with the CDEM. With the combination of the nozzles and collection plate into one unit, placement of the DSD became a factor in understanding variations in the results. With the new design, researchers had to visually inspect placement of the sampler and the imprint left on the dust to identify if a test was conducted correctly. Tests identified as having been placed too deep into the dust or that did not make contact with the dust surface would be flagged in the data to allow researchers to understand how the DSD versions were performing.

3.5 DSD Version 2.0

The next goal for researchers was to redesign the DSD into a more compact version that also allowed for easy storage of the dust sample taken during each test. DSD Versions 1.0 and 1.1 required a large, even surface along to ensure a good seal between sampler and dust surface. Furthermore, researchers believed that the volume of the sample chamber could be reduced. The width was shortened to 4 inches, and the chamber was also narrowed to the width of the dual 1.5 inch swivel nozzles. The 1-inch wings were extended to the full length of the sampling chamber to provide maximum support and sealing.

With Version 2.0, researchers removed the back wall of the sampler. A 6.5 by 6 inch plastic sandwich was secured to the open end with an elastic band. The box height was initially reduced to 1.125 inches. During testing, the box height was further reduced to 0.5 and 0.25 inches to test the effect of the sample chamber height on scour depth and mass collection. During testing, the dust sample was pushed into the sample collection bag. The device was then be picked up, tilted, and tapped to release any dust from the inside of the sample chamber. The bag was then removed and a new bag secured to the DSD for a new sample.

No mechanical changes were made in the air delivery system between DSD Version 1.1 and Version 2.0. The nozzle angles were fixed at 5 degrees. A cross section diagram of the DSD Version 2.0 is shown in Figure 43. Figure 44 shows a side and bottom view of DSD Version 2.0. A diagram of the trigger system with the DSD Version 2.0 is shown in Figure 45.

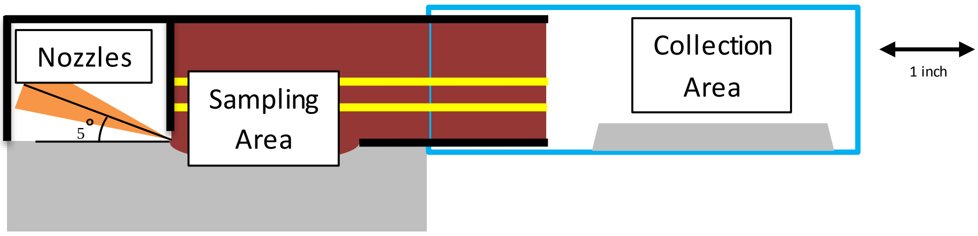

Figure 43. Diagram of nozzles (orange), sample chamber (dark red) and dust layer (grey) for DSD Version 2.0. Blue rectangle shows the bag placement and yellow lines the chamber height reductions when inserts added.

Figure 44. Photo of side (left) and bottom (right) view of DSD Version 2.0. A 6 inch ruler is provided for scale.

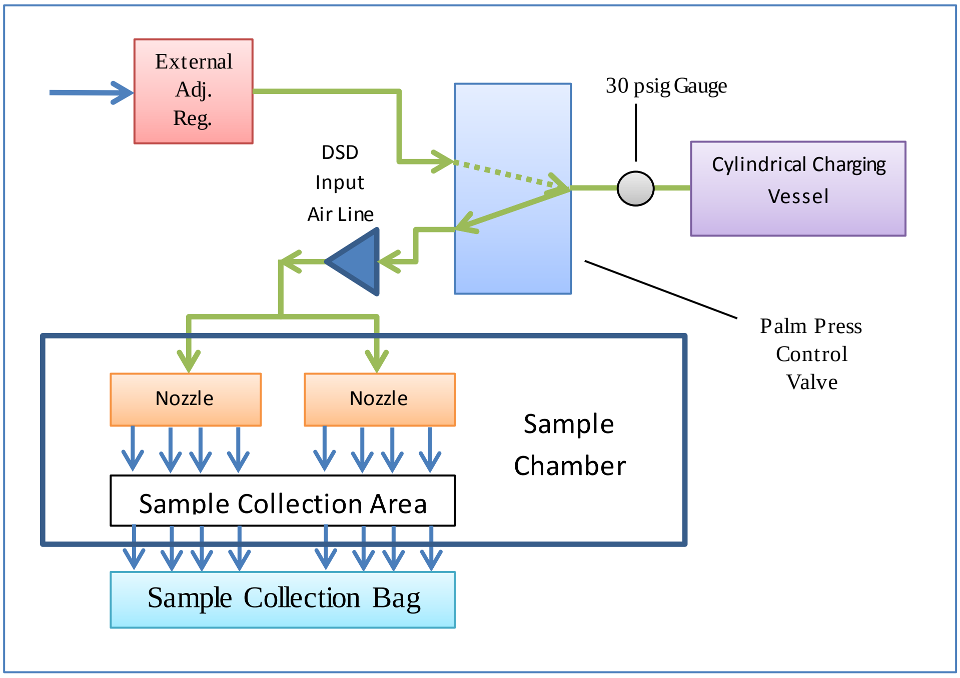

Figure 45. Diagram of trigger system in conjunction with DSD Version 2.0. Dotted line indicates new airflow path when control valve is engaged.

3.5.1 DSD Version 2.0 Testing

The scour depth results at the 3 chamber heights are shown in Figure 46. Figure 47 shows sample mass results. The scour depth results with the 1.125 inch sample chamber height decrease with increasing charging pressures. At 0.5 and 0.25 inch sample chamber heights, the scour depth results increased with increasing pressure and were close to the target scour depth. When comparing the scour depth and sample mass results for DSD Version 2.0 to the results of DSD Version 1.1, it is seen that the 0.5 and 0.25 inch chamber height tests were close in average to the Version 1.1 values. The inconsistency with the 1.125 inch chamber height prompted researchers to use computational fluid dynamics (CFD) modeling to investigate and determine the optimum chamber design.

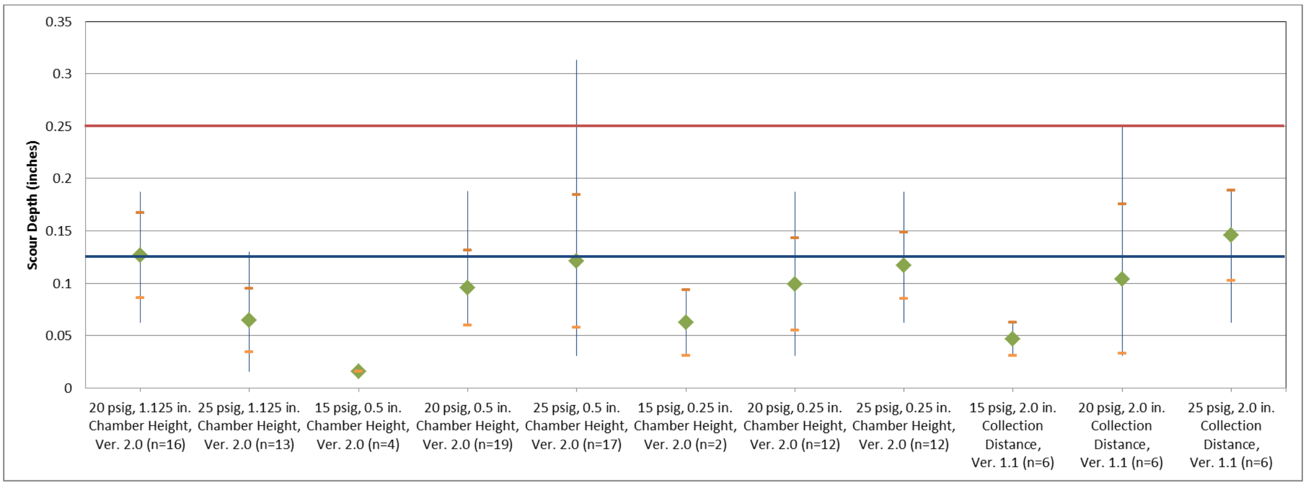

Figure 46. Scour depth results for DSD Version 2.0 with 1.125, 0.5 and 0.25 chamber heights. Included are the 15, 20 and 25 psig scour depth results from DSD Version 1.1 at a 2.0 inch collection distance for reference. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

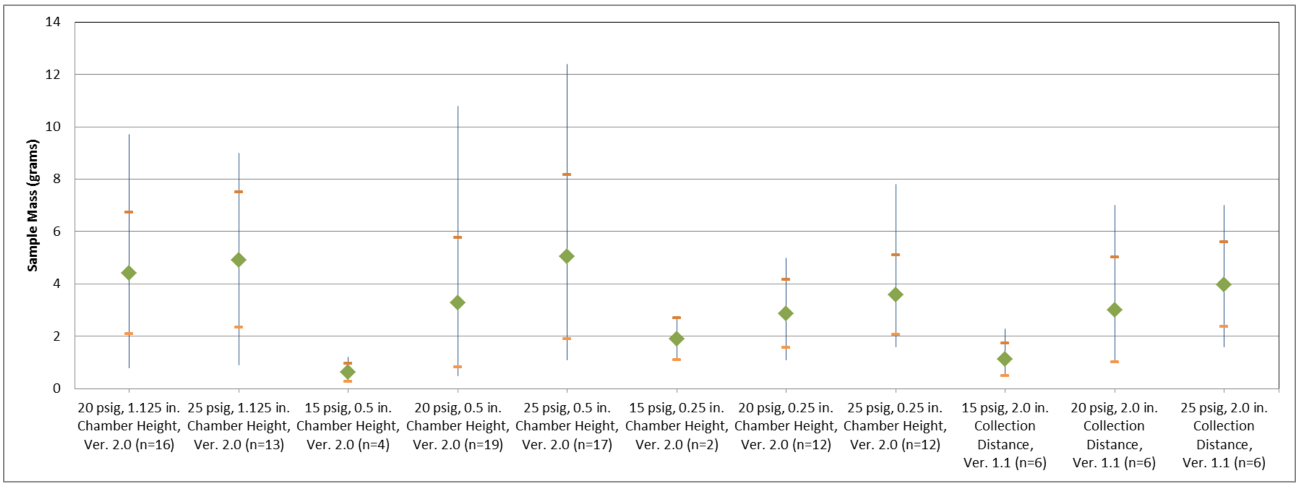

Figure 47. Sample mass results for DSD Version 2.0 with 1.125, 0.5 and 0.25 chamber heights. Included are the 15, 20 and 25 psig sample mass results from DSD Version 1.1 at a 2.0 inch collection distance for reference. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

3.5.2 CFD Modeling Results for DSD Version 2.0

Researchers felt comfortable with the design and size of the DSD Version 2.0 and began work on research approach Task 2 of modeling the DSD using CFD modeling. To do this, the DSD Version 2.0 design was replicated in CFD using ANSYSTM Fluent, as shown in Figure 48. The green layer represents the dust phase of the model, while the red section represents the sampler cavity.

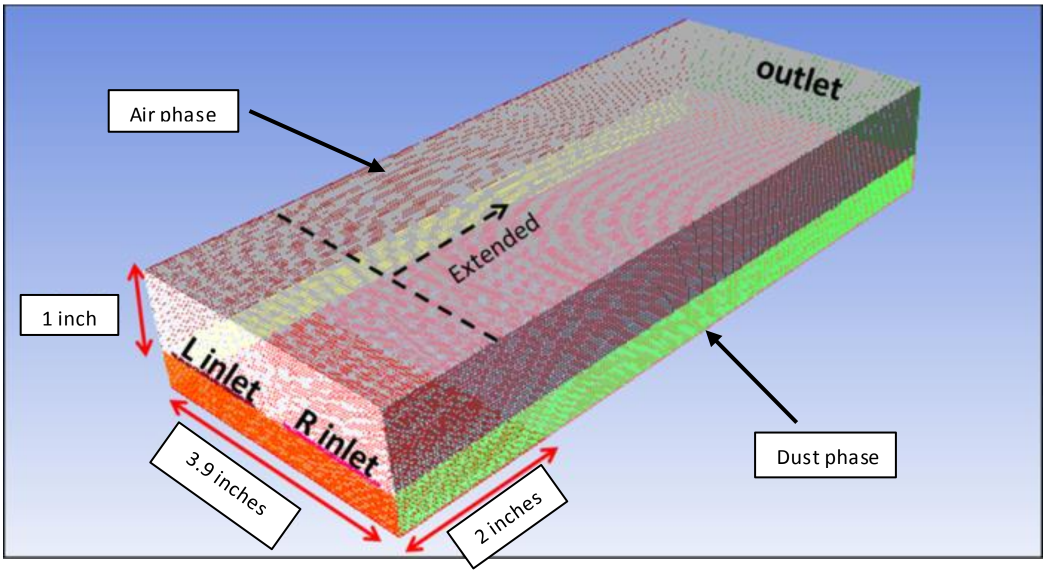

Figure 48. CFD - geometry design showing sections of red (air phase) and green (dust phase).

The quality of the CFD mesh has a significant impact on solvability and modeling results. Mesh refinement and inflation were used near the interface between the dust and air phases. Reduction of the mesh size demonstrated the mesh independence of the model.

The solver used for the analysis was the k-epsilon type with standard wall functions. Eulerian models with two phases, gas and solid, were used to replicate the expected interactions of the air and dust. Figure 49 shows a side view of the DSD air model at .308 seconds with an initial input velocity of 15.3 m/s at the nozzle exhausts. This view shows the DSD has a higher velocity profile near the nozzle exhausts, which decreases as the airstream expands into the sample cavity. Figure 50 shows an isometric view of the air velocity shown as streamlines coming out of the nozzle exhausts under the same parameters. Researchers identified that a zone of recirculation was present above the nozzle exhausts in the sample chamber, which could lead to entrained dust not being pushed into the sample collection bag and resettling into the scour profile.

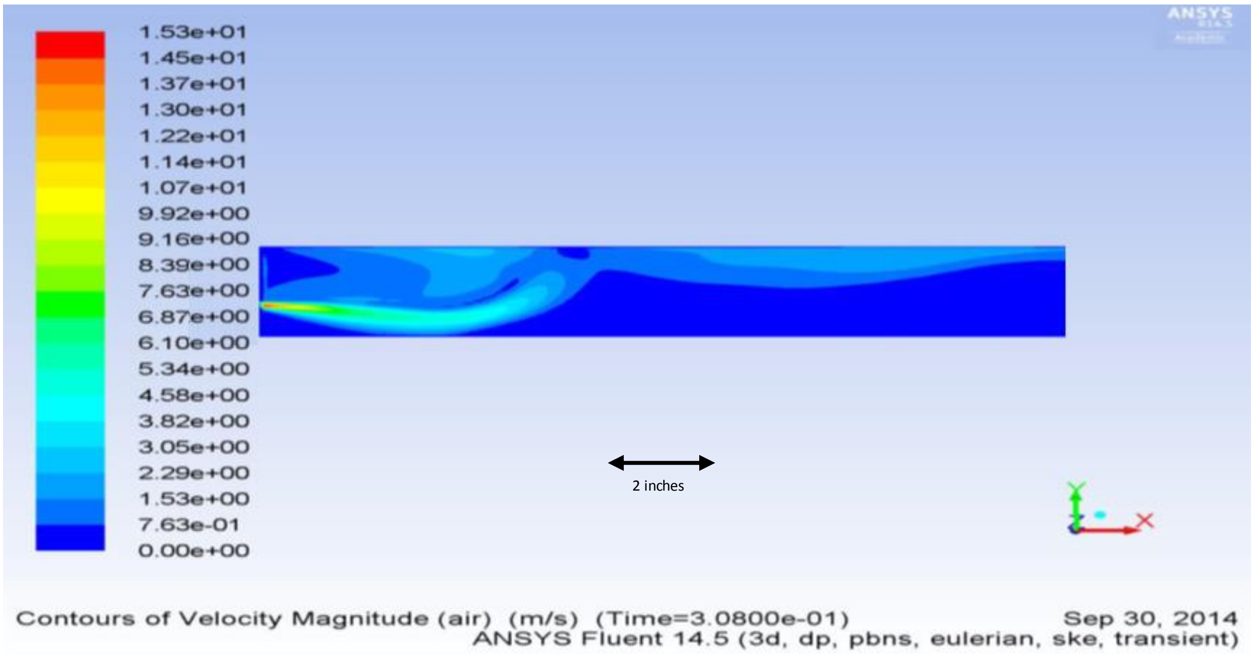

Figure 49. Side view of CFD DSD model showing air velocity with a nozzle angle of 5 degrees and initial velocity of 15.3 m/s at nozzle exhaust. No dust is present in the model at this time.

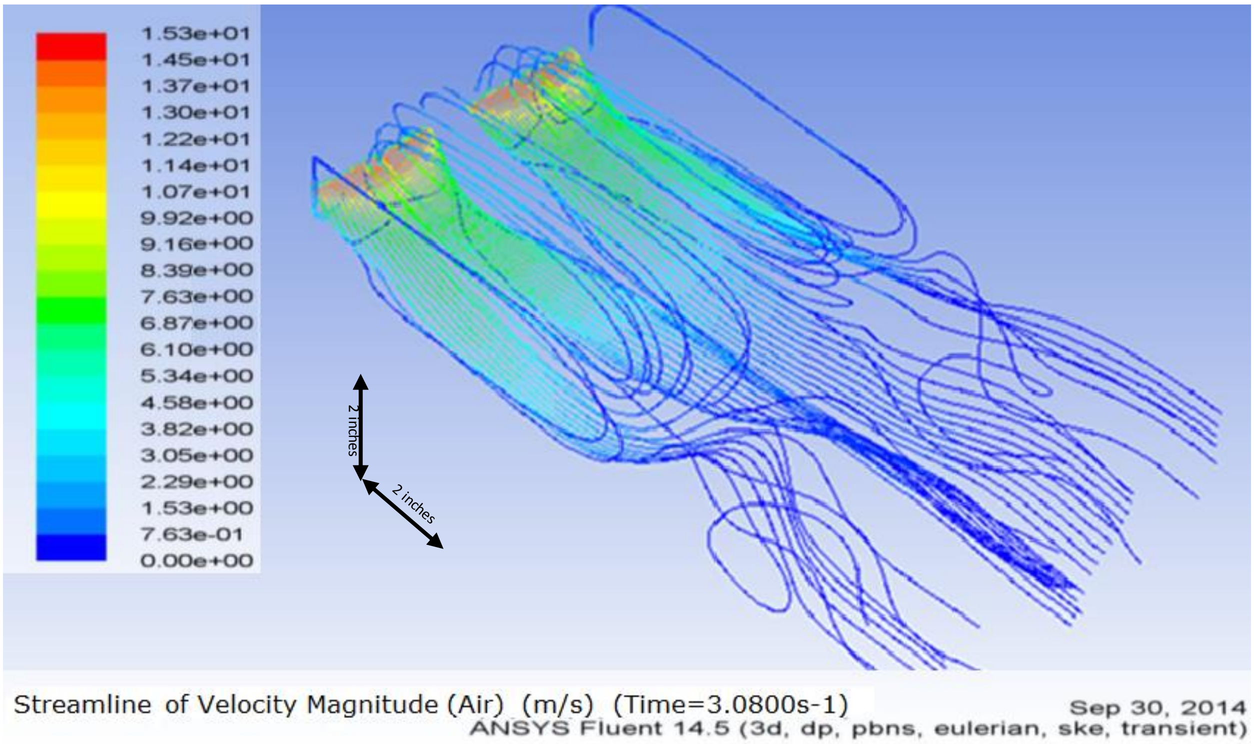

Figure 50. Streamline of velocity magnitude for air within DSD CFD model with a nozzle angle of 5 degrees and initial velocity of 15.3 m/s at nozzle exhaust.

3.5.3 Conclusions for DSD Version 2.0

Researchers were able to successfully replicate the results of the DSD Version 1.1 with the reduced size and new collection method of DSD Version 2. The 0.5 and 0.25 inch sample chamber height results closely matched the average scour depth values from the similar Version 1.1 tests and produced similar or higher sample mass collection results. Researchers believe this was due to the sample collection bag's ability to expand, allowing the air to move across the collection plate and into the bag. The elastic band secured the bag well, as there were no noticeable issues with leakage or the sample bag blowing off. The size of the DSD Version 2 was manageable and able to be utilized in an underground coal mine. Researchers were able to design the sampler without any electronic or electric components that allowed it to be used in all parts of an underground coal mine. The airflow results from the CFD model revealed that a recirculation zone was occurring above the nozzle exhaust and needed to be eliminated. To address this recirculation, researchers decided to design and verify a new DSD version with both physical testing and a new CFD model.

3.6 DSD Version 3.0

Researchers set out to accomplish two goals with the next version design: 1) eliminate the recirculation identified through CFD modeling of the rectangular sampling chamber design, and 2) house all the components of the DSD as one unit. Researchers brainstormed several ideas to keep the airflow and entrained dust moving into the collection bag. The first concept to eliminate eddies and straighten the flow pattern was to add a second set of 1.5 inch swivel nozzles one inch above the original nozzles. All 4 nozzles were connected to the control valve with angles set at 5 degrees. To accommodate the second row of nozzles, the sampling chamber was increased to a height of 2 inches. A diagram of the new sample chamber and nozzle configuration is shown in Figure 51.

To combine all of the DSD components as one compact unit, researchers explored different regulator and control valve options to miniaturize the current equipment. The 18 cubic inch charging vessel was redesigned to allow the trigger mechanism to mount close to the sampling chamber. Researchers replaced the pressure regulator with a more compact model and changed the push-button control valve to a twist activator valve. Images of both the new regulator and new control valve are shown in Figure 52. An overhead and bottom view of DSD Version 3.0 are shown in Figure 53 and a diagram of the combined components of the DSD version are shown in Figure 54.

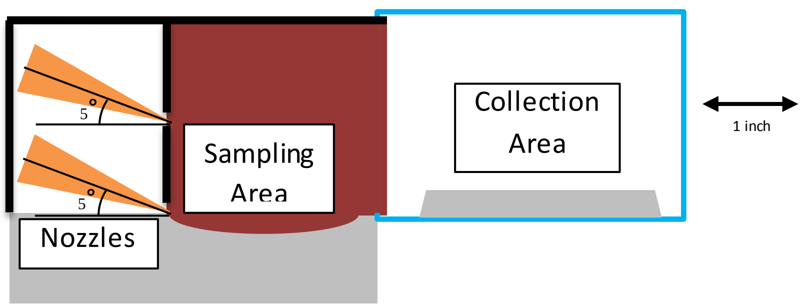

Figure 51. Diagram of nozzles (orange), sample chamber (dark red) and dust layer (grey) for DSD Version 3.0. Blue rectangle shows the sample bag placement.

Figure 52. Photo of panel mount pressure regulator (left) and twist activated control valve (right) (McMaster-Carr 2016).

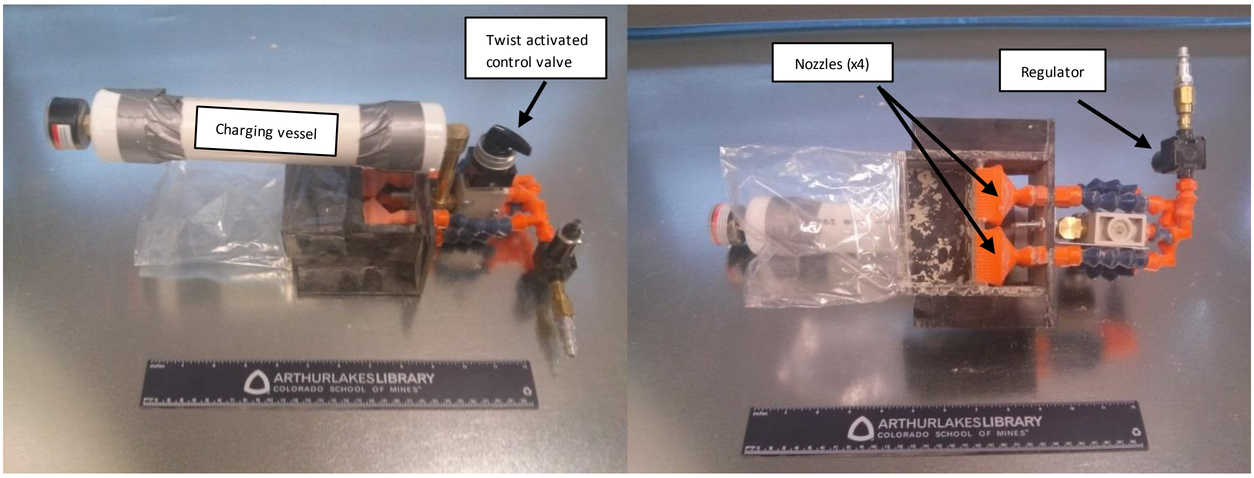

Figure 53. Photo of overhead (left) and bottom (right) views of DSD Version 3.0. A 12 inch ruler is provided for scale.

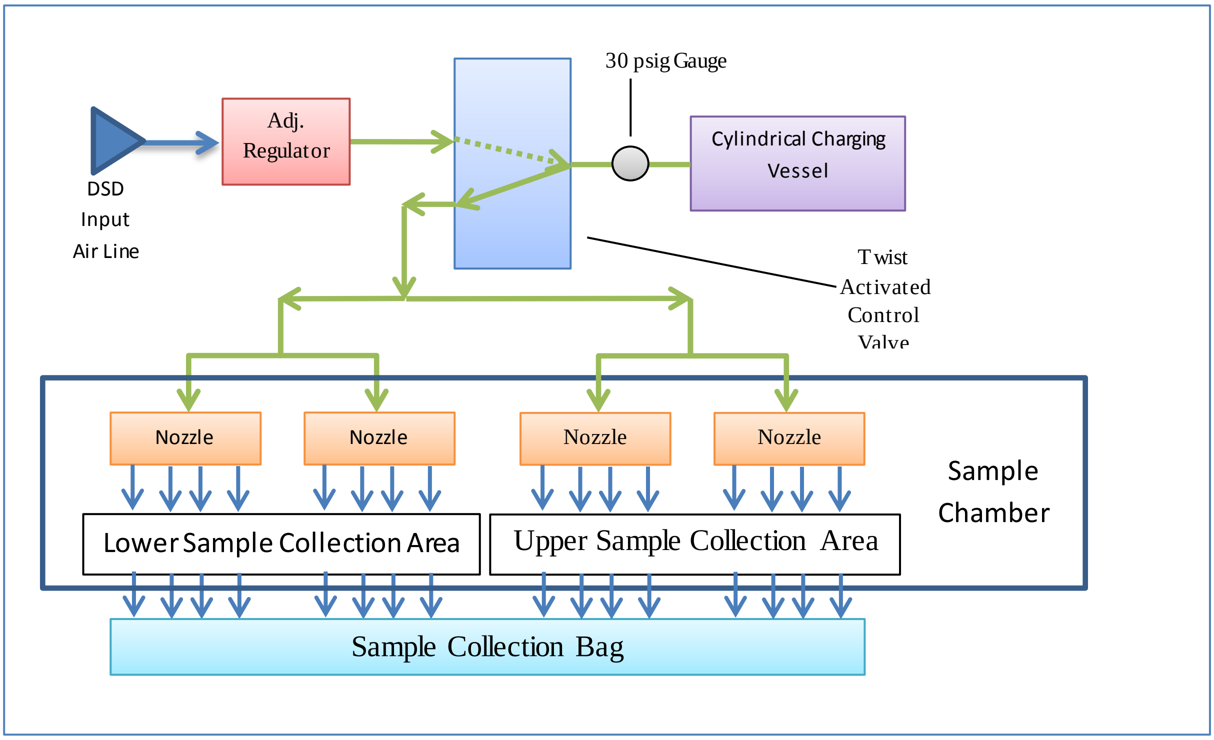

Figure 54. Diagram of combined components for DSD Version 3.0. Dotted line indicates new airflow path when control valve is engaged.

3.6.1 DSD Version 3.0 Testing

Testing with DSD Version 3.0 was conducted at pressures of 25, 30, 35 and 40 psig. Due to doubling the number of nozzles, researchers concluded that the charging pressure had to effectively be doubled to maintain the current velocities through the exhaust of each nozzle. Additionally, half of the 40 psig tests resulted in the sample collection bag being partially or completely detached from the DSD during testing. Due to this persistent issue, the 40 psig results could not be analyzed. Three of the 35 psig tests also had partial detachment from the DSD during testing. The scour depth and sample mass results for testing with DSD Version 3.0 are shown in Figure 55 and Figure 56.

DSD Version 3.0 had a similar performance range as Versions 1.1 and 2.0. Evaluating Version 3.0, researchers concluded that the second row of nozzles assisted in the movement of dust towards the sample collection bag as intended and prevented recirculation above the scour. This helped move dust into the collection bag. Still, the maximum scour depths were lower than the results from the Version 2.0 testing. Researchers were not satisfied with the performance of Version 3.0 and conducted further CFD modeling to improve both entrainment and collection functions.

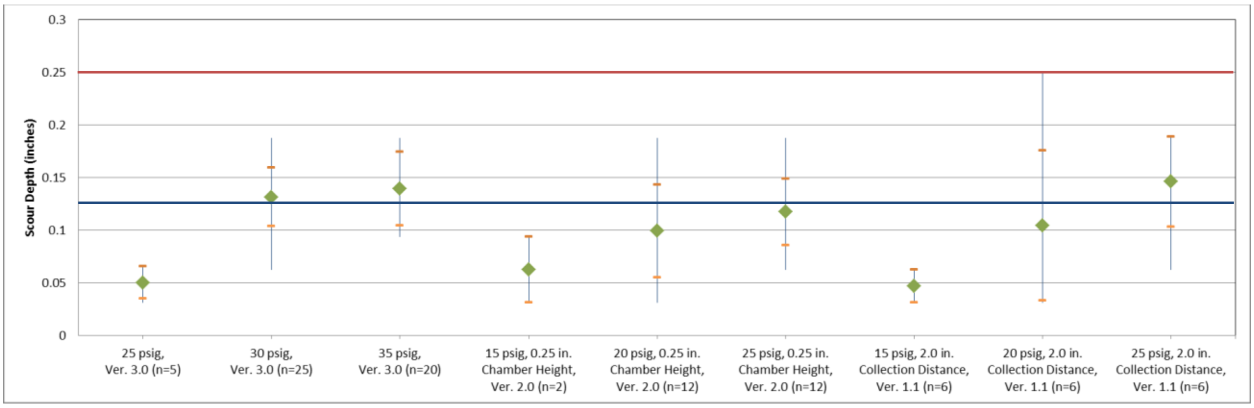

Figure 55. Scour depth results for DSD Version 3.0 at 25, 30 and 35 psig charging pressure. Included are the 15, 20 and 25 psig scour depth results from DSD Version 1.1 at a 2.0 inch collection distance and DSD Version 2.0 at chamber height of 0.25 inch for reference. Black lines indicate ranges of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

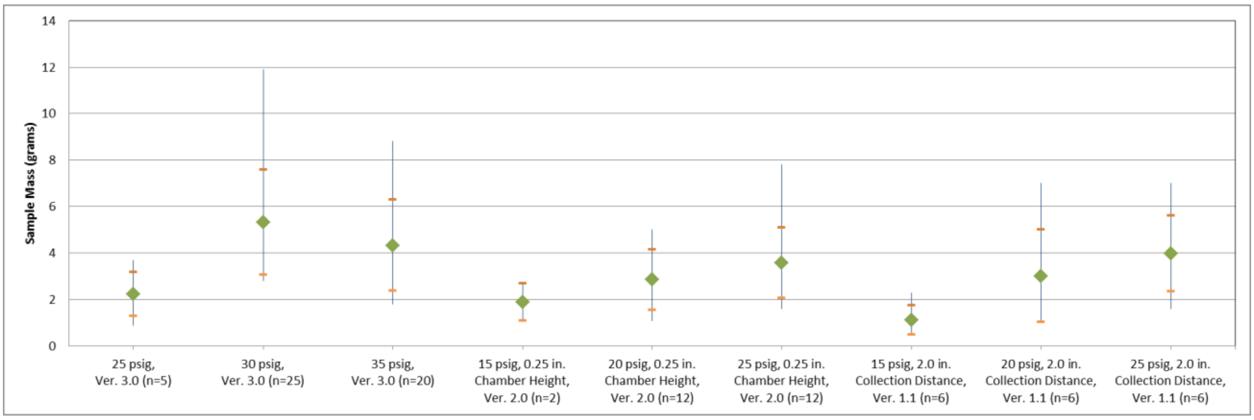

Figure 56. Sample Mass results for DSD Version 3.0 at 25, 30 and 35 psig charging pressure. Included are the 15, 20 and 25 psig scour depth results from DSD Version 1.1 at a 2.0 inch collection distance and DSD Version 2.0 at chamber height of 0.25 inch for reference. Black lines indicate ranges of values, green diamond the average value and orange dashes the standard deviation of the values.

3.6.2 CFD Model Results for DSD Version 3.0

The CFD model accounted for two material phases, air and rock dust, which are both treated as fluids. The density and viscosity used for air and dust are 1.23 kg/m^3, 1.79*10^{-5} kg/m*s. and 2,140 kg/m^3, 1.0*10^{-3} kg/m*s, respectively.

The environment was modeled in two phases with air as the primary and rock dust as the secondary phase. An Eulerian treatment was used, modelling both phases separately, yet interacting. To solve the transient flow of air and dust particles, a viscous model with standard κ-epsilon, standard wall treatment and dispersed turbulent multiphase flow was used. Rock dust was considered as a fluid with granular diameter of 7*10^{-5} m.

The geometry in Figure 57 was created to match the new sample cavity design for Version 3.0. However, the length of the model was increased to allow the flow to fully develop. Figure 58 represents a half-space using symmetry to simplify the CFD modeling process.

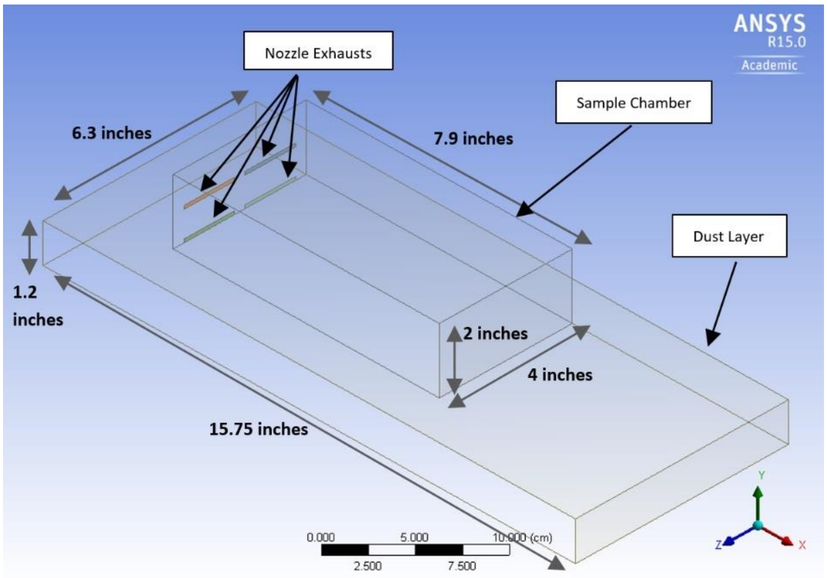

Figure 57. Model space created in Ansys for DSD Version 3.0.

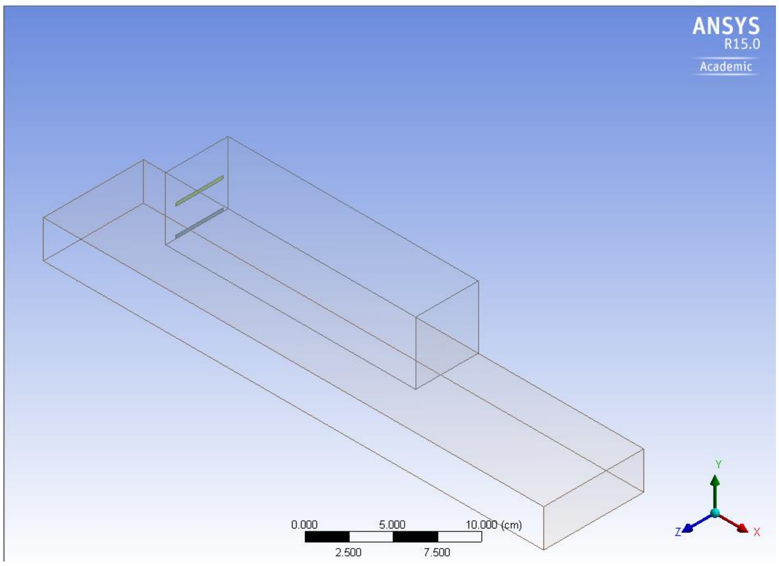

Figure 58. Geometry created in Ansys design modeler considering symmetry.

In order to better visualize the contour plots for the solution, a slice of x-y plane was created between the nozzles, shown in Figure 59.

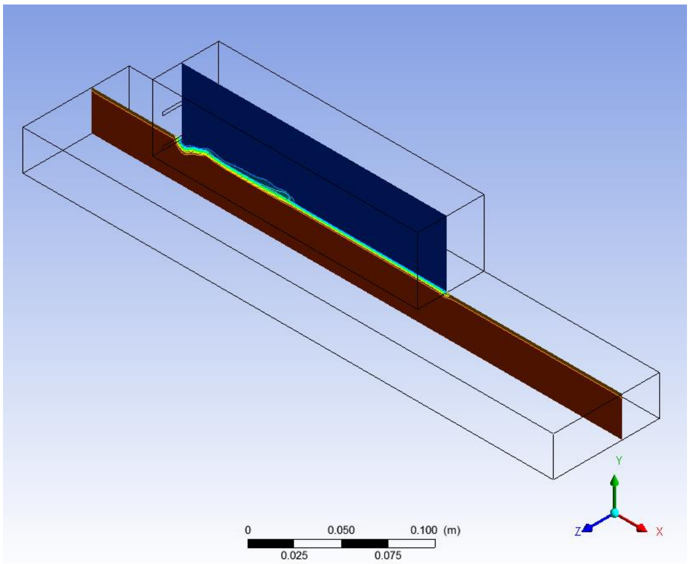

Figure 59. XY Slice Plane used for representation of results.

Figure 60 is a representation of the air flow lines illustrated in a 3D view.

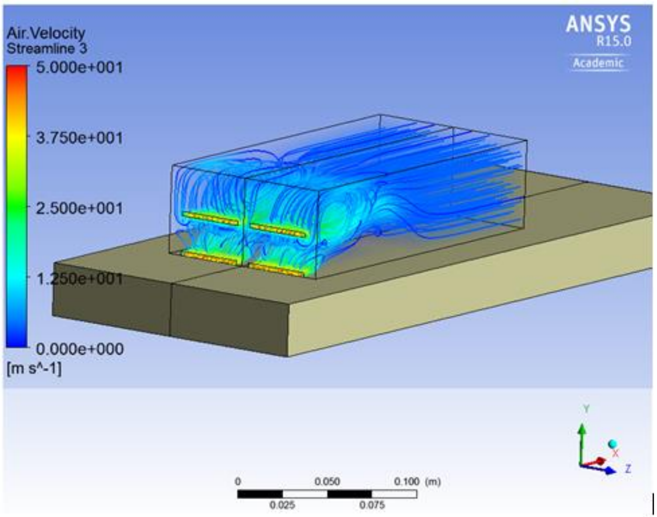

Figure 60. Representation of the puff of air at the end of the solution in a 3D view of the whole device

A plot of the final dust contour after sampling is represented in Figure 61. The black line marks the desired scour depth of 1/8 inch or 3.2 mm. Figure 62 illustrates how researchers determined the volume of the scoured dust with the help of the yellow marker lines.

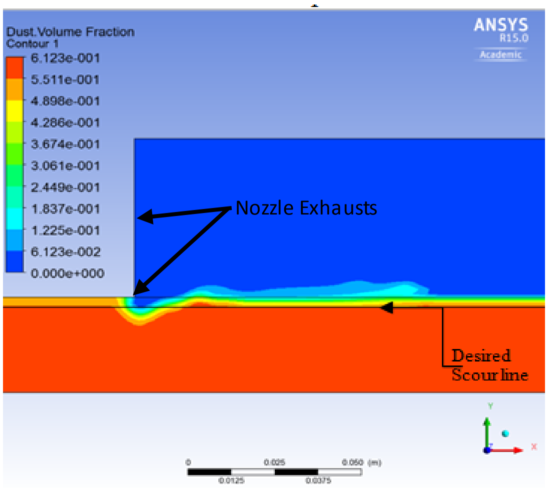

Figure 61. Volume fraction of the dust at time step 0.04 seconds with initial velocity of 50 m/s at nozzle exhausts.

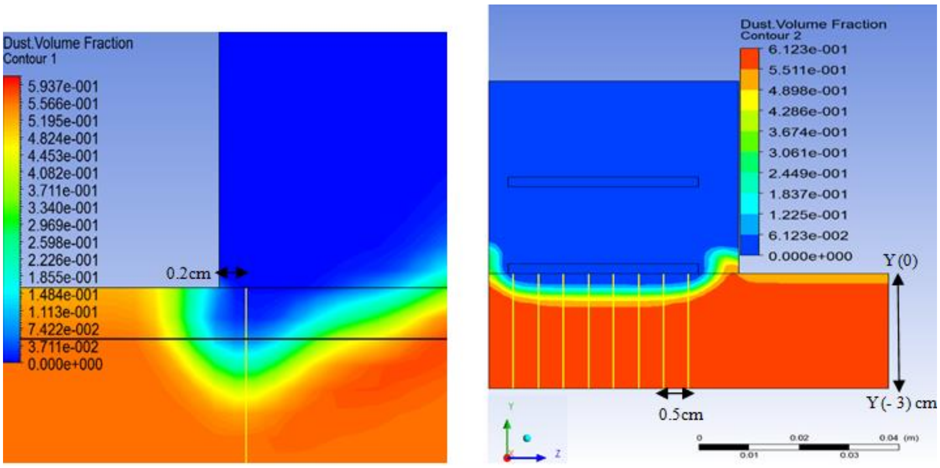

Figure 62. Representation of Lines created to evaluate the scour depth.

Air velocity vectors are plotted in Figure 63. The top nozzles in Version 3.0 attempted to improve efficiency by pushing the flow forward to avoid recirculation. Still, a region of recirculation remained above the bottom nozzles, and given the additional air required for the second pair of nozzles, researchers were not satisfied with Version 3.0.

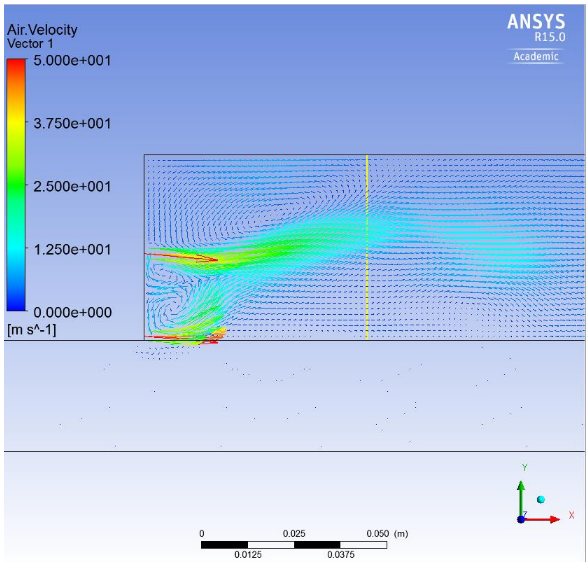

Figure 63. Vector Plots of Air velocity at time step 0.04 seconds with 4 degree nozzle angle and initial velocity of 50 m/s at nozzle exhausts.

3.6.3 Conclusions for DSD Version 3.0

Testing with DSD Version 3.0 showed that the new design was capable of replicating the scour depth results for Version 2.0, while promoting dust movement into the sample collection bag and away from the corners of the sampling chamber where recirculation was occurring. The scour depth results were close to those from Version 2.0, while the sample mass collected increased, which was important for use with the CDEM. Weight did not seem to be an issue for the device, though researchers did pay more attention to placement to ensure an even seal between the dust layer and the DSD. At higher pressures, the sample bags detached from the device, creating unusable samples.

Researchers also had concerns with the increased size of DSD version 3.0 due to its larger sample cavity. The second set of nozzles required additional air and higher charging pressures. This version was more compact than earlier models, yet still too bulky. Ultimately, the sampler needed to become completely portable, along with a small, portable compressed air tank. The increased charging pressure limited the number of tests conducted from a single air tank and restricted the minimum operating pressure for the device. CFD modeling also showed that Version 3.0 did not eliminate all of the recirculation issues previously identified. Researchers redesigned the DSD again to address these issues.

3.7 DSD Version 4.0

Researchers designed and developed a fourth version in response to the recirculation issue identified by the CFD modeling. The new Version 4.0 adopted the same panel mount adjustable regulator and twist activated control valve found in Version 3.0, but only used two 1.5 inch swivel nozzles set at a 5-degree nozzle angle and 0.0 inch nozzle height. Based on CFD modeling, researchers tapered the sampling chamber to address the recirculation issue. Version 4.0 had a wedge shaped chamber that expanded to a height of 0.5 inches at the end of the 2-inch collection distance. As a form factor adjustment to the previous DSD version, researchers designed and built a rectangular steel tank with internal dimensions of 4x4x1.125 inch to use as a new charging vessel that maintained the 18 cubic inch volume of the previous vessels. The dimensions allowed the tank to be situated directly above the sample chamber. The Loc-Line connections between the control valve and nozzles were also changed out for 0.25 inch brass tubing to make the connections less susceptible to damage during in-mine use. Figure 64 shows a diagram of the new sample chamber and nozzle configuration. Figure 65 shows a side and bottom view of DSD Version 4.0. Figure 66 shows a diagram of the combined components of DSD Version 4.0.

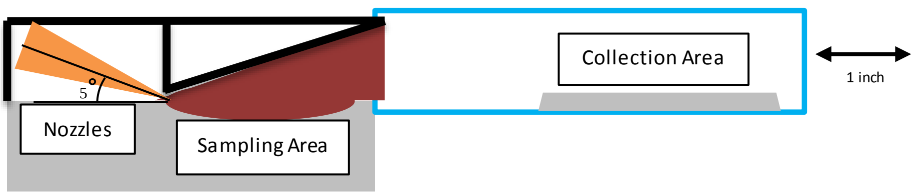

Figure 64. Diagram of nozzles (orange), sample chamber (dark blue) and dust layer (grey) for DSD version 4.0. Blue rectangle shows the sample bag placement.

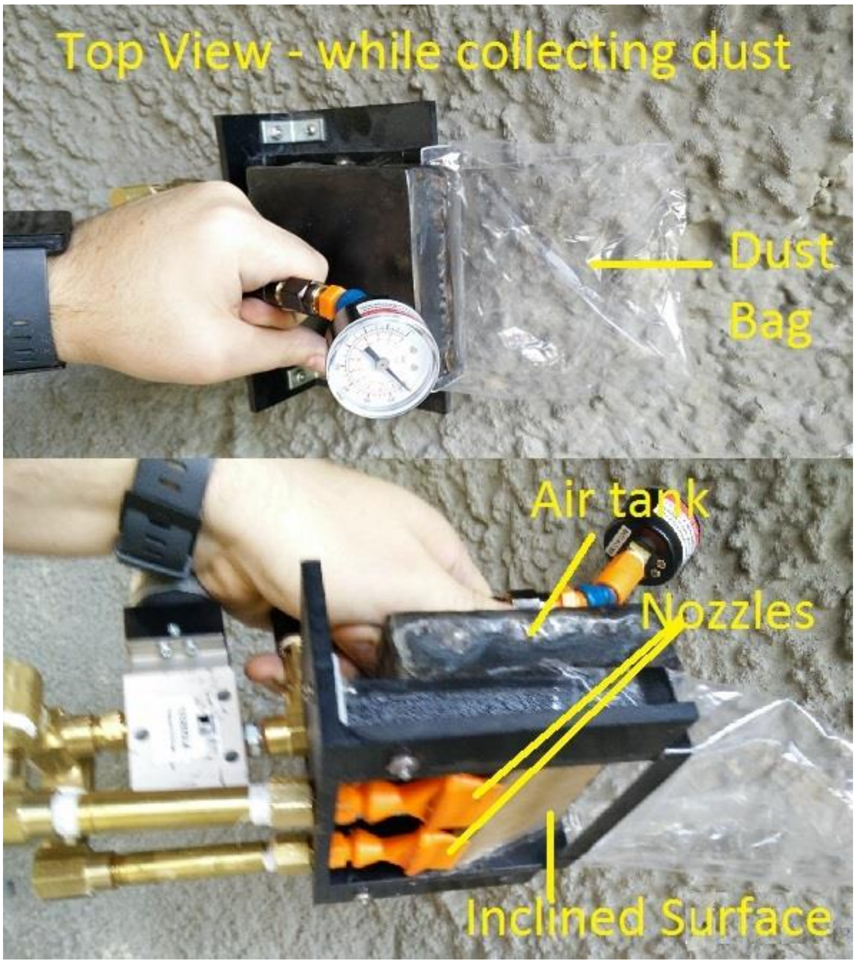

Figure 65. Photo of top (upper) and bottom (lower) of DSD Version 4.0.

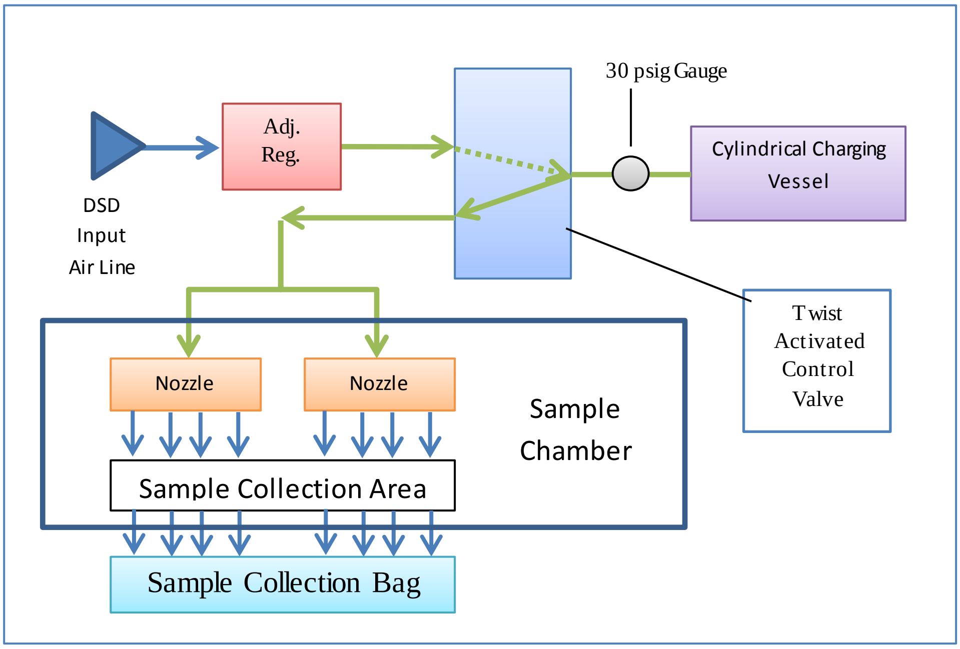

Figure 66. Diagram of combined components for DSD Version 4.0. Dotted line indicates new airflow path when control valve is engaged.

3.7.1 DSD Version 4.0 Testing

Testing with Version 4.0 was conducted at 15, 20 and 25 psig to allow comparison with the results from Versions 2.0 and 1.1. The scour depth and sample mass results for Version 4.0 are presented in Figure 67 and Figure 68, respectively. Test results from Versions 2.0 and 1.1 are included for reference. The scour depth and sample mass results show the wedge-shaped sampling chamber performed much better than the Version 1.1 and Version 2.0 designs. The sample mass collection was noticeably higher with averages between 4 g and 14 g compared to under 4 g for the earlier versions.

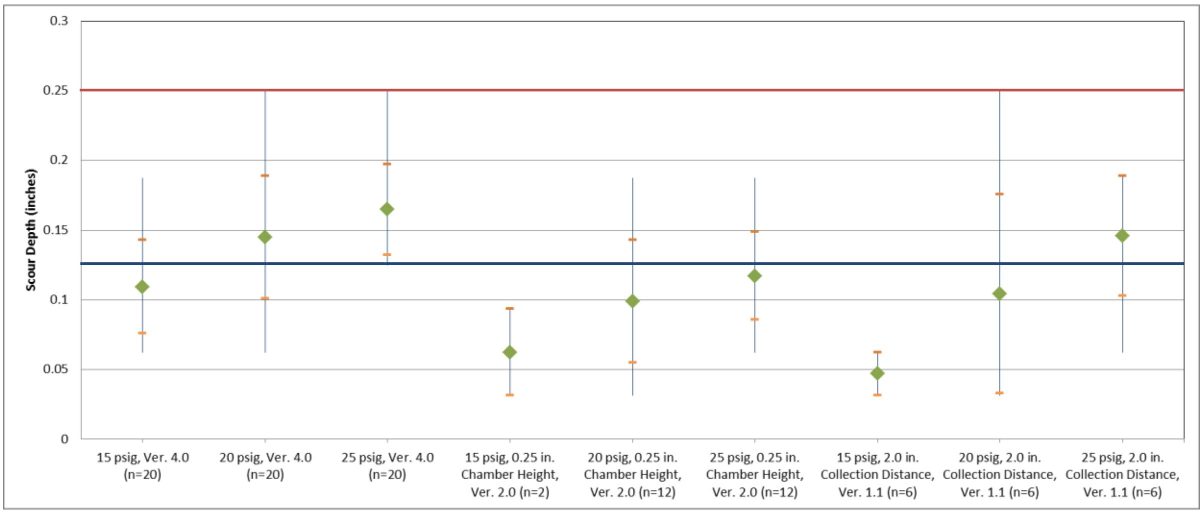

Figure 67. Scour depth results for DSD version 4.0 at 15, 20 and 25 psig charging pressure. Included are the 15, 20 and 25 psig scour depth results from Version 1.1 at a 2.0 inch collection distance and Version 2.0 at chamber height of 0.25 inch for reference. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

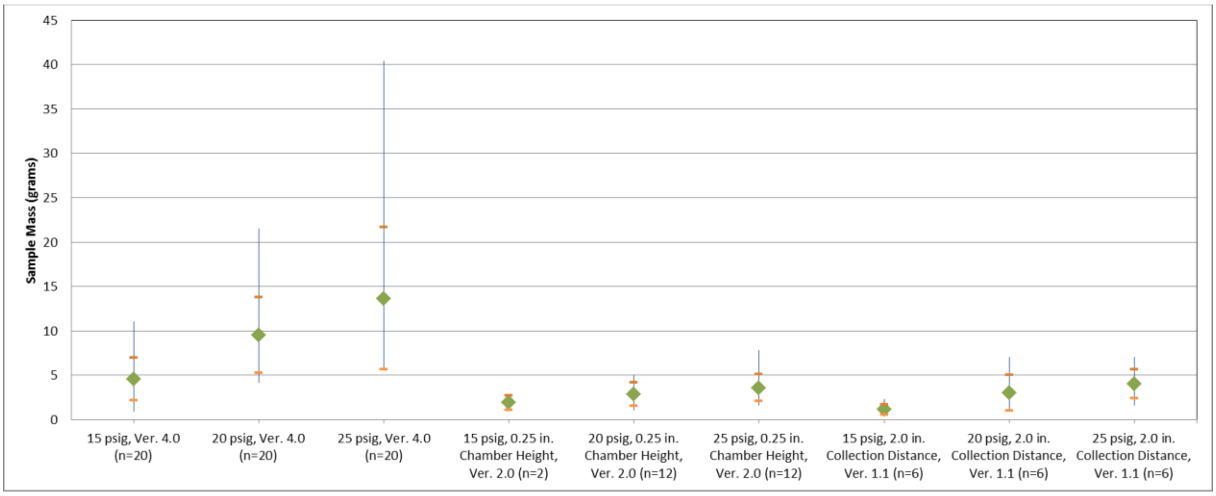

Figure 68. Sample mass results for DSD version 4.0 at 15, 20 and 25 psig charging pressure. Included are the 15, 20 and 25 psig scour depth results from Version 1.1 at a 2.0 inch collection distance and Version 2.0 at chamber height of 0.25 inch for reference. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

3.7.2 DSD Version 4.0 User Comparison Study

Researchers conducted a user comparison study using DSD Version 4.0. Two experienced users (Users A and C) performed the first series of testing with Version 4.0. Both had one year of experience testing with the DSD. Users B and D were less experienced. User B had participated in the first round of testing with Version 1.1, but had no prior experience testing outside Version 4.0. User D had no previous experience testing with any DSD prototypes and was given one day of training with Version 4.0. Each user conducted 5 tests at charging pressures of 15, 20 and 25 psig. The scour depth results for the user comparative study are shown in Figure 69 and the sample mass results in Figure 70.

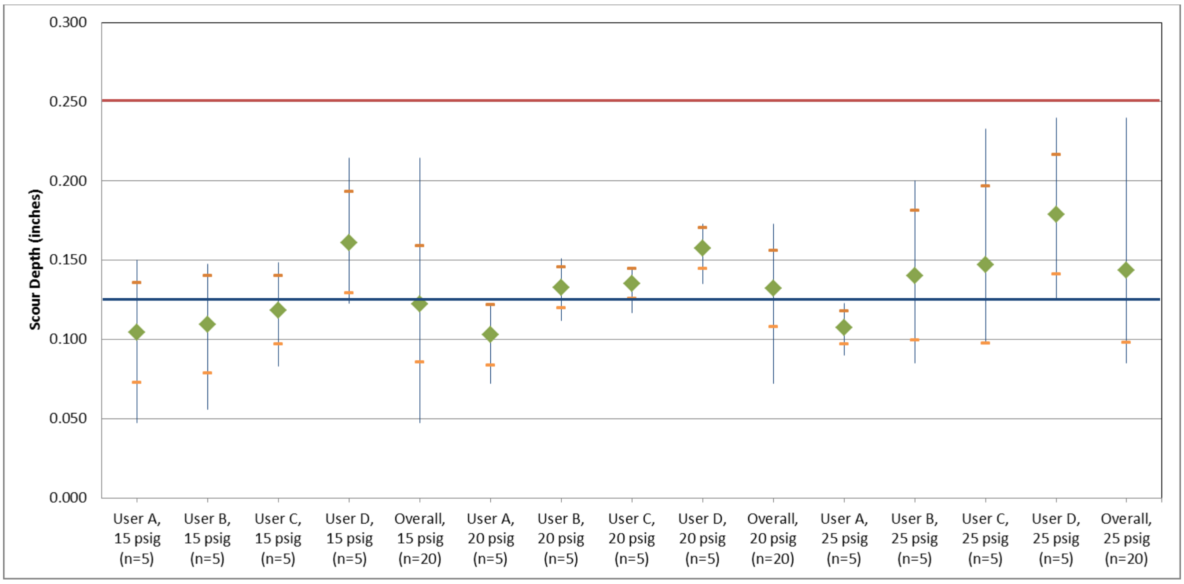

Figure 69. Scour depth results for DSD Version 4.0 at 15, 20 and 25 psig charging pressure with breakdown by user. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

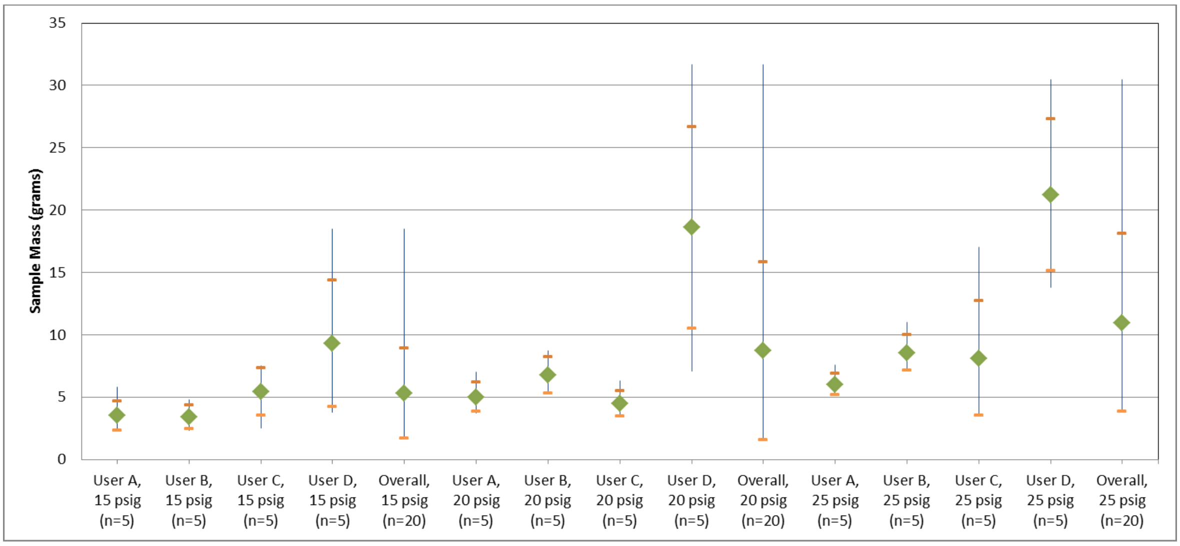

Figure 70. Sample mass results for DSD version 4.0 at 15, 20 and 25 psig charging pressure with breakdown by user. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

User D, with the least experience, showed a higher average scour depth and sample mass at all 3 charging pressures. User A consistently had the lowest average scour depth and sample mass out of the 4 users for each charging pressure. In general, Users A, B and C, who had previous experience testing with the device, had more consistent sets of tests. The sample mass averages in Figure 68 followed a similar trend.

3.7.3 CFD Modeling Results for DSD Version 4.0

Figure **71** shows a wireframe image of Version 4.0. The CFD model used a reference plane 2.4 inches away from the nozzles to measure the quantity of dust collected. Evaluation of this model showed it to be grid independent.

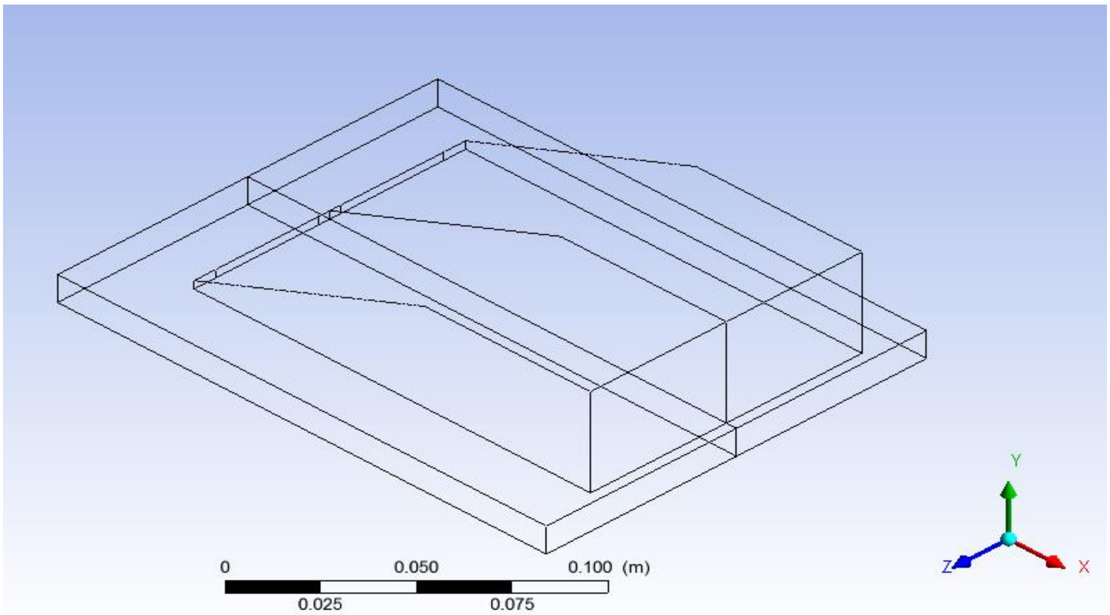

Figure 71. Geometry designed for the CFD model to match the device.

Model Simulation Setup

To better model the actual release of the compressed air through the nozzle exhausts, the ANSYS™ Fluent pressure based solver with a transient case was used. Researchers used a velocity-time transient nozzle velocity curve based on actual pressure measurements at the nozzle. This transient is shown in Figure 72 and was programmed into the CFD model using a user defined function (UDF).

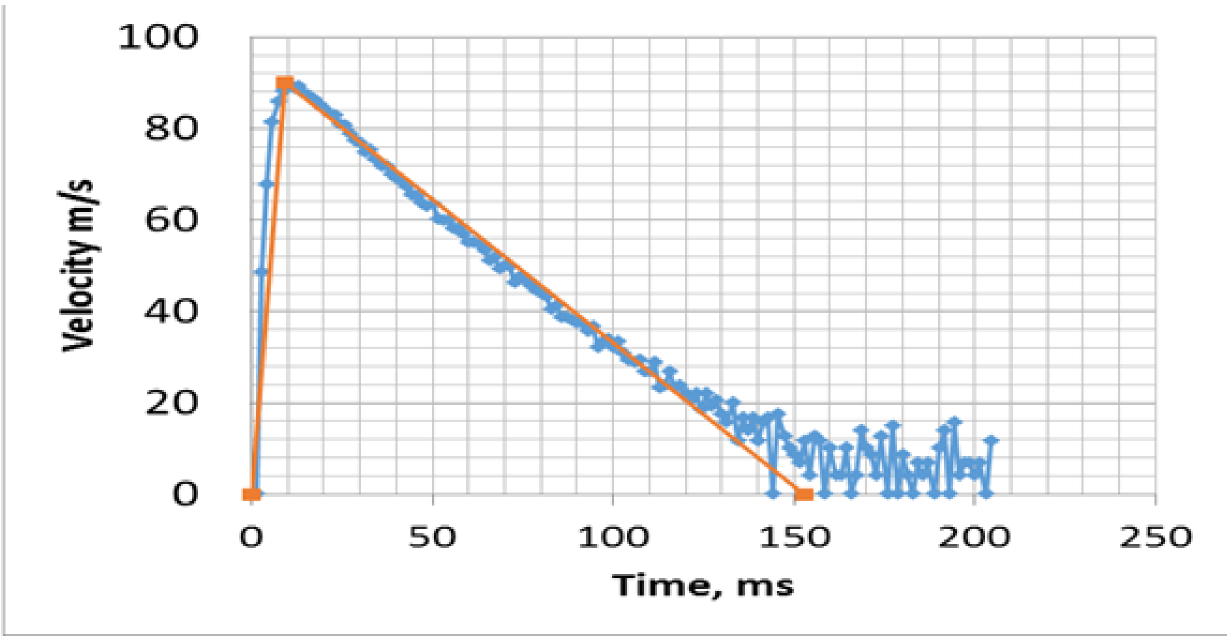

Figure 72. Transient of nozzle velocity vs. time, measured (blue) and UDF function (orange)

Modeling Results

Figure 73 shows the reference planes used for visualization of the dust scouring results. The dust volume fraction is used as reference to measure the depth of the scour. Figure 74 shows the dust volume fraction at time = 40 ms along this reference plane.

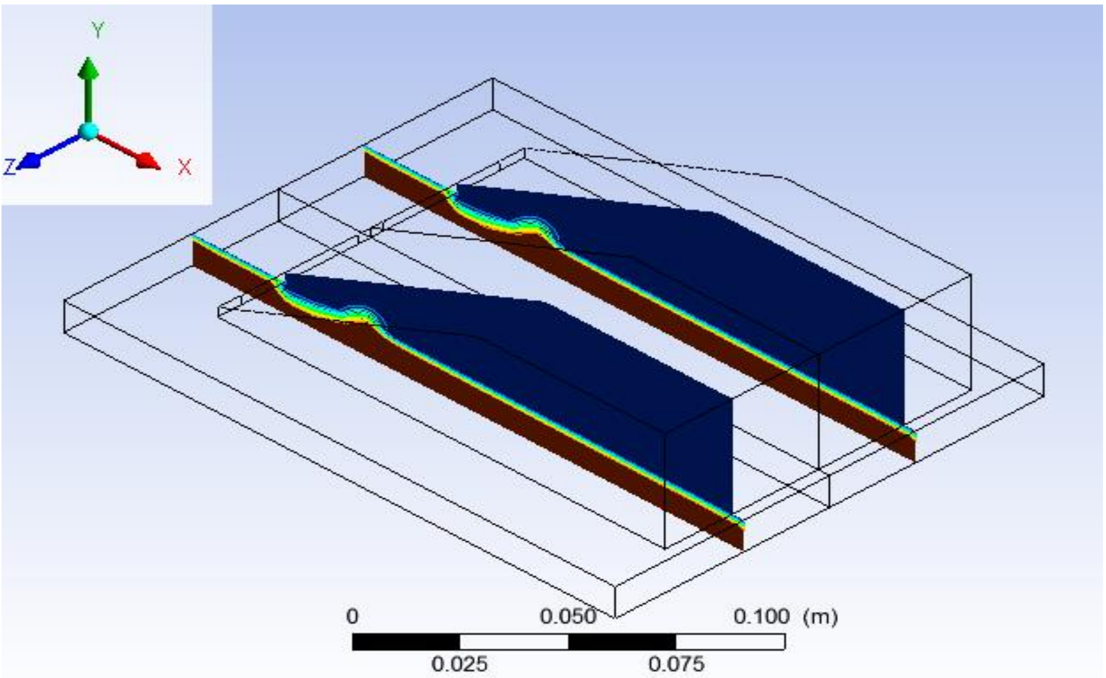

Figure 73. Location of the reference plane used for analysis of results.

To evaluate the scour profile in the model, reference lines were created as shown in Figure 74 and Figure 75. A reference line, represented in black, indicates the desired 1/8th inch scour depth. The yellow line 6 cm downwind from the nozzle represents the reference plane for the measurement of the dust collected. In the models, the depth of the scour profile ranges from 3 mm to 4 mm, meeting the target sampling depth of 0.125 inch (3.2 mm) required by the MSHA (2013).

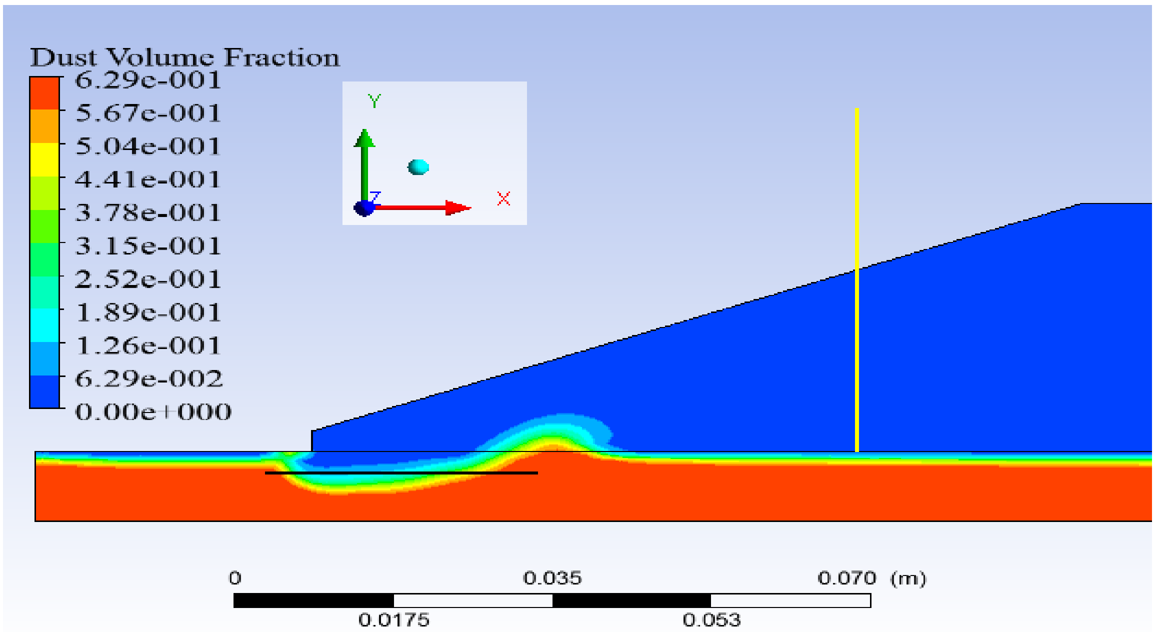

Figure 74. Scour profile along the reference plane at time step 40ms using UDF for velocity and 5 degree nozzle angle.

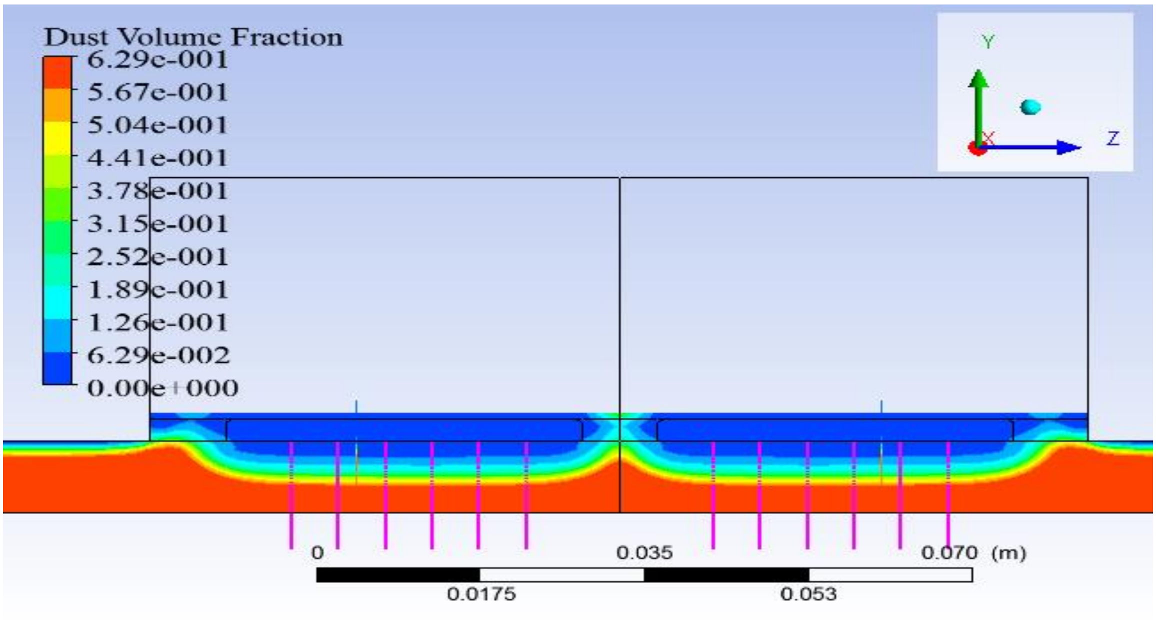

Figure 75. Reference lines along Y-axis to evaluate the depth of the scour profile using UDF for velocity and 5 degree nozzle angle.

In developing the optimal chamber geometry, researchers aimed to avoid eddies and recirculation of air above the nozzles that resulted from the rapid expansion of the air. The velocity vectors of the expanding air inside the device, as shown in Figure 76, demonstrate that that the inclined surface is effective in removing the recirculation above the nozzles.

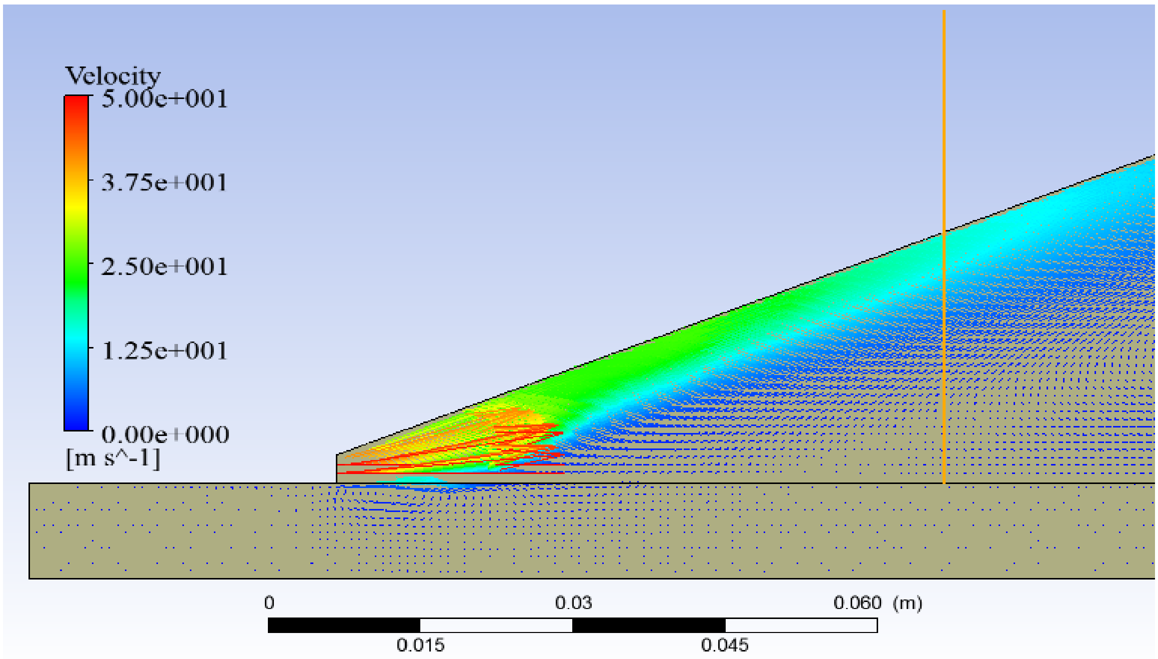

Figure 76. Velocity vectors of air in the XY plane using UDF for velocity and 5 degree nozzle angle.

3.7.4 Initial Conclusions for DSD Version 4.0

The results from the initial testing with DSD Version 4.0 showed that the new sample chamber design promoted a deeper scour and significant increase to the sample mass collected. Researchers believe the wedge design eliminates the recirculation observed in the CFD analysis of Versions 2.0 and 3.0. Additionally, the Version 4.0 could be operated at lower charging pressures to provide results close to the target 1/8th inch depth. The improved sample masses were consistently above the 5 gram minimum that researchers required for CDEM testing.

The CFD modeling confirmed that the new sample chamber design utilized for Version 4.0 eliminated the recirculation problem that was present in Versions 2.0 and 3.0. All of the dust entrained by the DSD is pushed forward towards the sample collection bag. Version 4.0 also maintained a more compact design that was lighter and easier to operate. With Version 4.0 running at a lower charging pressure, researchers switched to a portable air tank as the compressed-air source for future testing. This meant that the device was fully portable and researchers now felt confident introducing the DSD to field testing conditions. With the successful testing and design of a fully-portable DSD prototype unit, researchers completed Task 1 of Design and Development, and were ready to begin comprehensive lab testing with the DSD against the Brush and Pan method to meet Tasks 3 and 4. Researchers also made progress towards the completion of Task 2 CFD Analysis.

3.8 Comparative Testing with Brush and Pan Method

With the DSD Version 4.0 verified by the CFD modeling, researchers began Task 4 and comparative laboratory testing between DSD Version 4.0 and the Brush-and-Pan (BaP) method prescribed by MSHA (2013). This comparative testing consisted of specially prepared test beds that included a layer of coal dust sifted on top of the rock dust, with a ratio of rock dust and coal dust in the scour profile that would produce a total incombustible (TIC or ASH%) reading between 70% and 85% on the CDEM. Researchers prepared a sample of crushed coal and pulverized it to a custom size distribution. This custom distribution was based on a survey of average of coal dust particle sizes conducted by NIOSH and MSHA (Sapko et al., 2007). Sapko et al. found that the average coal size distribution for all MSHA districts was “31% minus 200 mesh, 65% minus 70 mesh, and a mass median of ~150 µm”. Researchers attempted to size the coal as closely as possible to this distribution and obtained a distribution of 30% minus 200 mesh, 82% minus 65 mesh, and a mass median of 136 µm. Researchers believed their actual distribution was an acceptable substitution for the measured distribution from the survey.

3.8.1 BaP and CDEM Procedures

Researchers conducted testing with the BaP method in compliance with the outlined procedures in the Coal Mine Safety and Health General Inspection Procedures Handbook (MSHA, 2013). Researchers were trained on the proper collection technique and scour depth evaluation with the BaP method. During recorded and controlled testing, DSD and BaP method tests were conducted in pairs on the same dust bed to ensure comparable results between the two methods of collection. If a variance in the prepared dust bed was present, it would affect both results in a similar way, thus reducing bias between the two methods. The scour profiles from both methods were now traced using a notecard and sharpie pen. Researchers placed the notecard perpendicularly through the center of the scour profile and traced the outline of the scour pattern to measure its length and depth. This was a more reliable method for determining scour depth and length as the caliper method was reliant on flat, even testing surfaces to provide an accurate scour depth.

For lab testing with the CDEM, the custom sized coal dust was sifted on top of the rock dust layer in a thickness of 0.05 inches to target the 70% to 85% range on the CDEM. After testing was completed with either the DSD or BaP method and the sample mass was weighed, the dust sample was evaluated with the CDEM sampling procedure outlined in the CDEM User Manual. Prior to testing, the CDEM was calibrated using samples of the rock dust and coal dust used for testing in the lab.

3.8.2 Verification of CDEM Results with MSHA Method MH-102

As laid out in Task 4, a set of 50 dust samples were sent to an independent testing laboratory to verify the incombustible content against the CDEM output. Forty-two of these samples were taken from previous DSD and BaP tests to verify the results at specific TIC outputs, while 8 samples were manually prepared mixtures of rock and coal dust at specific ratios to verify the independent laboratory testing results. The samples were run through the Gravimetric Method for Determining Incombustible Content for Dust Samples as outlined by MSHA as Method 102. This method provided both ASH% and TIC. For comparison purposes with the CDEM results, researchers used the ASH% results since that is closer to the value the CDEM outputs when the sample is dried using the provided molecular sieves.

For the manually prepared mixtures, researchers assumed that the custom sized coal had a base ASH % of 5%. As shown in Figure 77, the expected ASH % matched closely to the measured ASH % of the prepared samples. This verified that the lab results were accurate across the full range of coal and rock dust mixtures and were a viable comparison to verify the CDEM results. Figure 78 shows the measured results from the first 17 samples of the laboratory tests against their CDEM results obtained during controlled testing with both DSD and BaP methods.

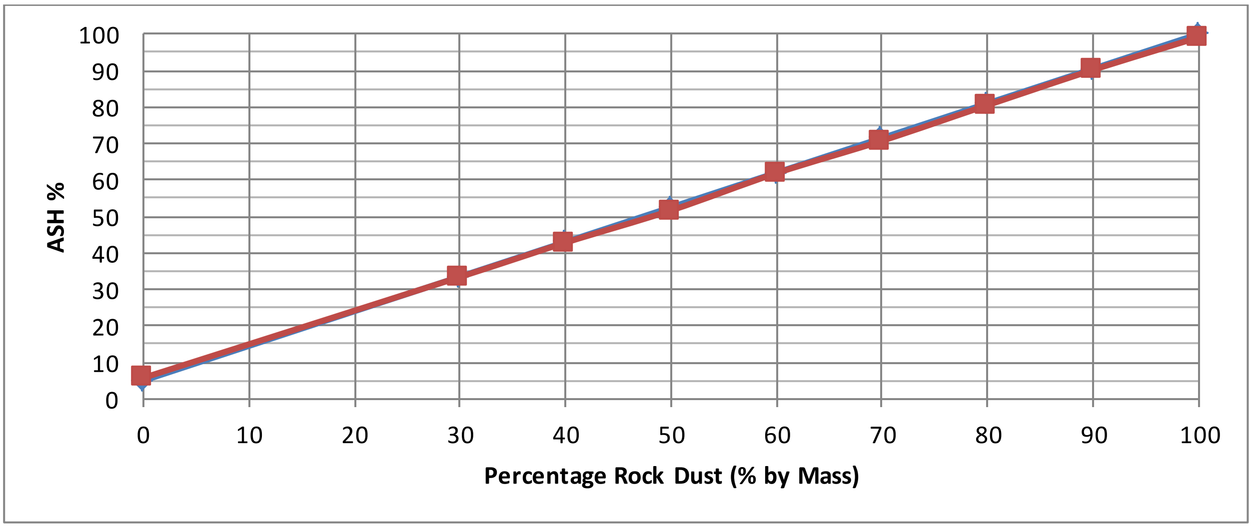

Figure 77. Comparison of expected ASH % (blue) and measured ASH % (red) from laboratory verification manual samples.

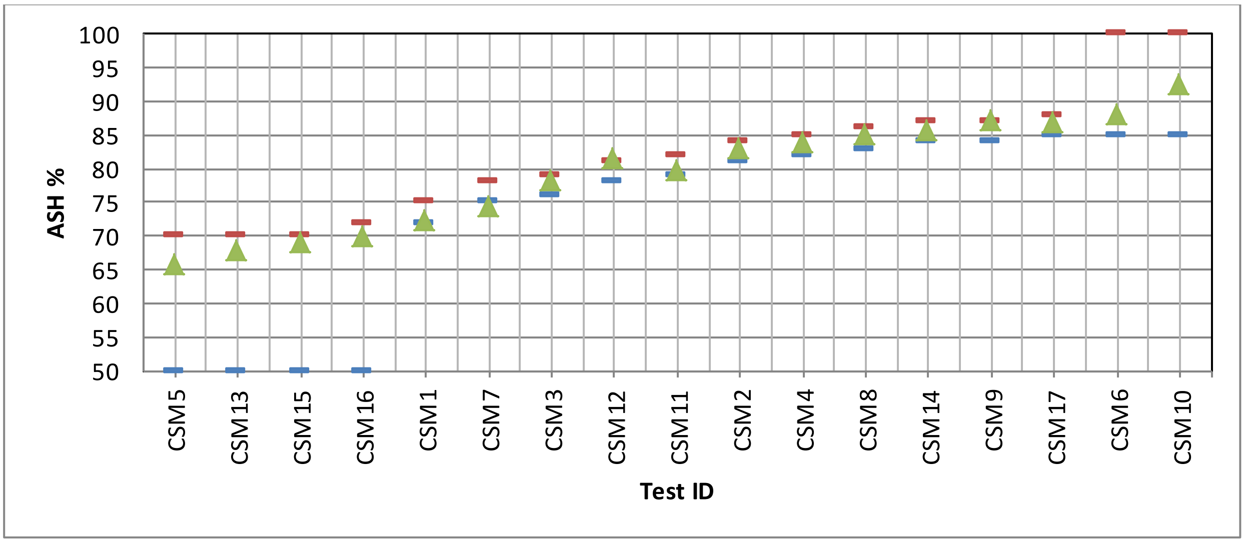

Figure 78. Results from first 17 Test ID samples showing measured ASH % against the CDEM TIC ranges for the samples. Red dashes indicate CDEM upper readout, blue dashes indicate CDEM lower readout and green triangles indicate measured ASH %.

3.9 DSD Version 4.0 Comprehensive Testing with BaP Method

Testing with DSD Version 4.0 was conducted at 15 psig charging pressure. The scour depth and sample mass results for Version 4.0 are shown in Figure 79 and Figure 80 respectively. The scour depth results show that the average depth increased along with the maximum depth compared to previous testing with DSD Version 4.0 using only rock dust. The BaP method scour depth average was lower than Version 4.0. The maximum scour depth for the BaP method testing reached the maximum scour limit described in the Coal Mine Safety and Health General Inspection Procedures Handbook (MSHA, 2013), while DSD Version 4.0 exceeded the scour limit.

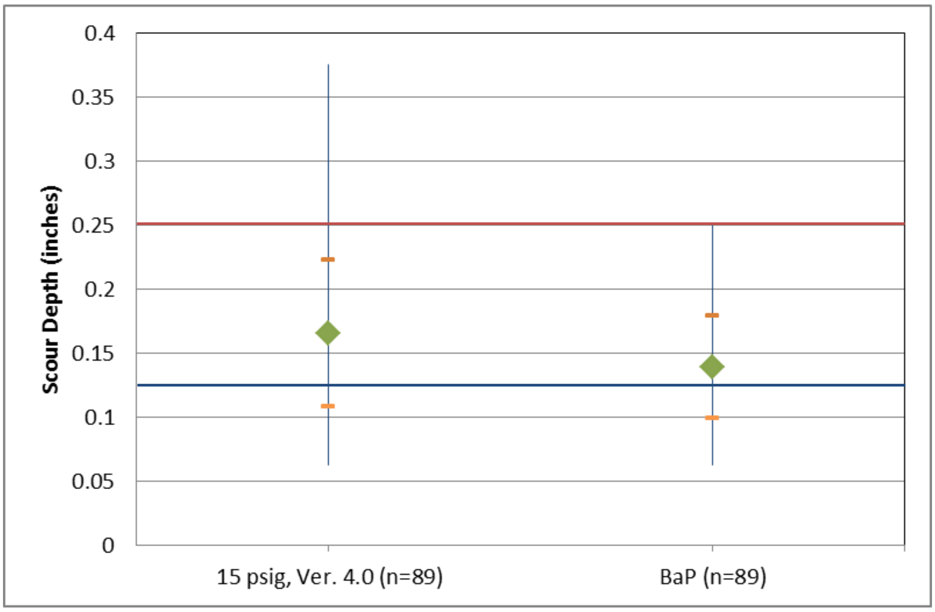

Figure 79. Scour depth results for DSD Version 4.0 at 15 psig charging pressure and BaP method. Black line indicates range of values, green diamonds the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

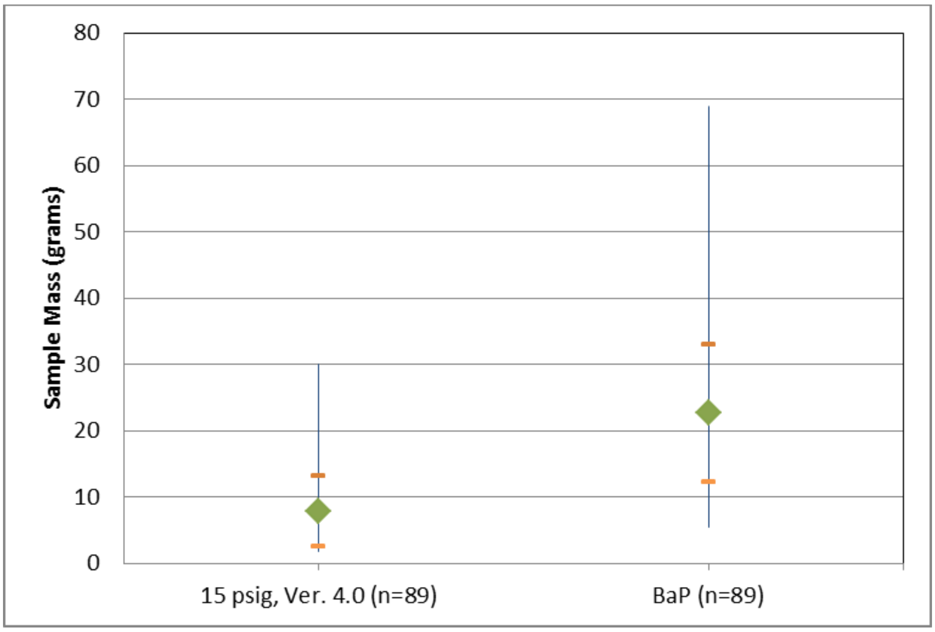

Figure 80. Sample mass results for DSD Version 4.0 at 15 psig charging pressure and BaP method. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

The CDEM outputs 3 ranges of explosibility results: Green (inert, 85 to 100% TIC), Red (marginal, 70-85% TIC) and Below 70% TIC. To compare the CDEM results between the DSD and BaP methods, researchers compared the TIC results from both methods that were within the marginal range of 70% to 85% TIC on the CDEM. Since the CDEM only provides a range of TIC, the minimum and maximum values were averaged to create a single result for each of the tests. The tests were then subdivided based on the scour depth result measured by the researchers. Since the coal dust layer was on top of the rock dust, an increase in the scour depth produced an increase in the TIC as the ratio of coal dust to rock dust decreased. The TIC results for Version 4.0 and BaP method are shown in Figure 81. The CDEM results for Version 4.0 aligned with the expected trend with the exception of the 0.125 inch depth average. As expected, CDEM results from BaP sampling did not provide consistent, repeatable values.

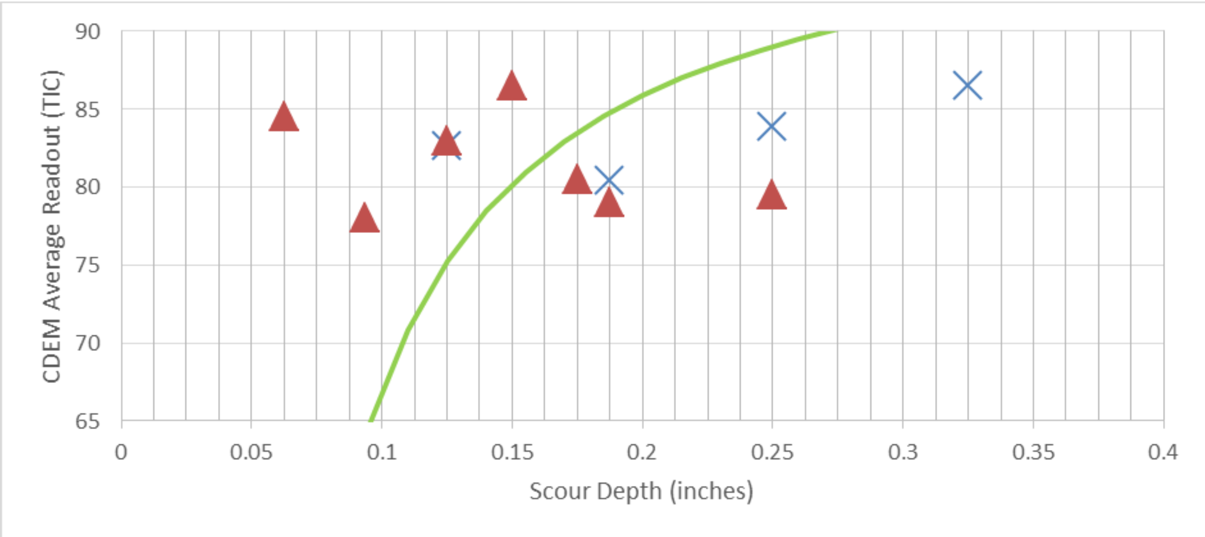

Figure 81. Comparison of CDEM Average Readout for Various Scour Depths with Version 4.0 and BaP method. Blue X's denote average CDEM readout from DSD Version 4.0 tests (n=39) and red triangles denote average from BaP method tests (n=41). Green line shows expected TIC based on ratio of coal and rock dust at given depth.

3.9.1 Conclusions for Version 4.0 Comprehensive Testing with BaP Method

Researchers found that the BaP method seemed to compress the dust downward, rather than scooping the top 1/8th inch sample as intended. This downward compression caused excessive fluctuations in the CDEM results, confirming that the BaP method may not be reliable. Researchers confirmed with CDEM results that the DSD Version 4.0 was doing a better job at collecting the full profile of the depth scoured than the BaP method, and provided a more representative sample of what is entrained from the dust surface during a coal dust explosion.

3.10 DSD Version 4.1

Researchers wanted to refine the DSD design for improved performance, decreased weight, and greater usability. In version 4.1, the sampler body was machined from a single piece of aluminum rather glued together from pieces of ABS plastic. The steel pressure vessel was also replaced with machined aluminum, combining pressure vessel and sampler in a unibody structure with an overall reduced weight. The new design also allowed for the mounting of the pressure vessel on top of the unibody part to ensure a tight fit of all components. The unibody design helped eliminate leakage from the sampler cavity and ensured a flat, even surface for contact with the dust sample location. The design of the new DSD body is shown in Figure 831.

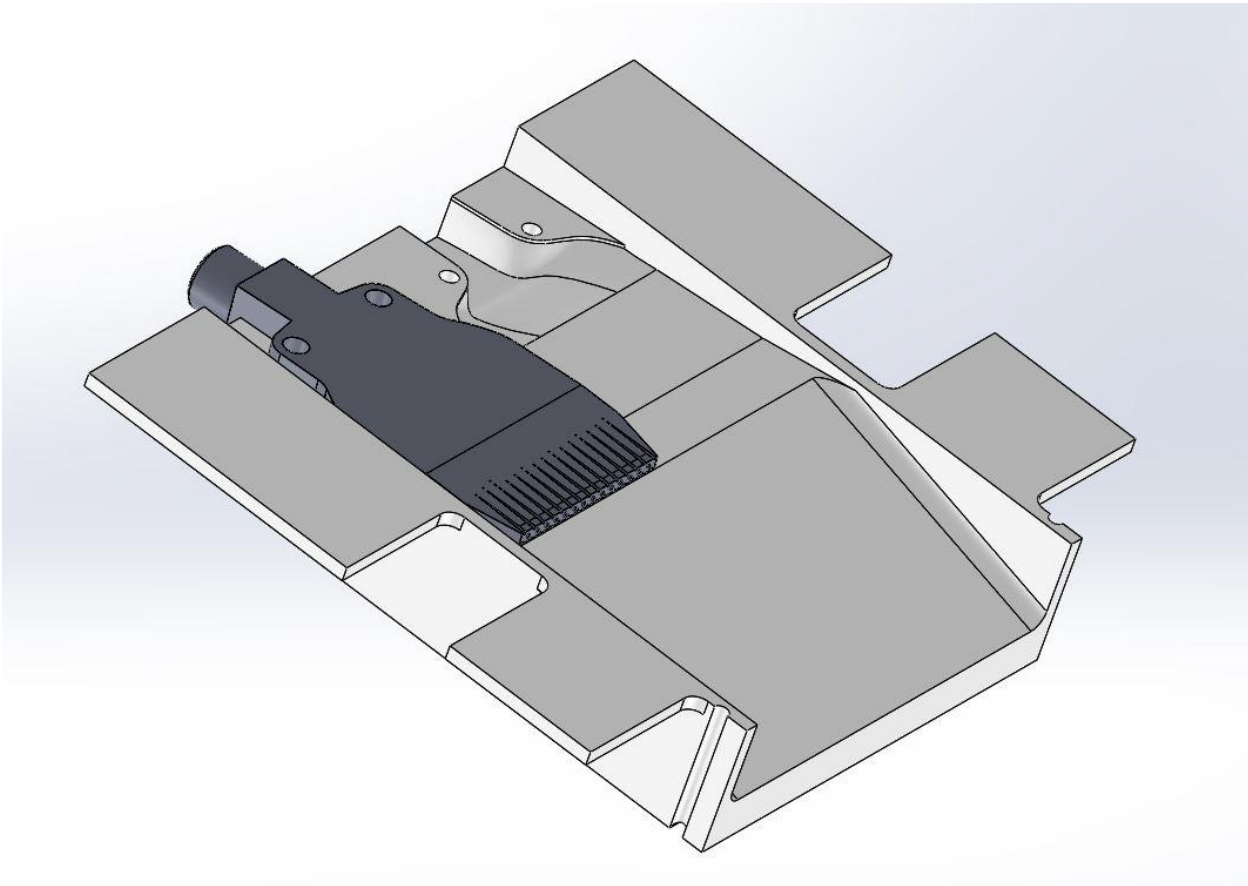

Figure 82. Isometric view of bottom design of sample cavity body with one nozzle in configuration for DSD Version 4.1. The device carries two nozzles and the collection cavity is at bottom right.

Improvements were made in the attachment of sample collection bag as well. In the previous design, the sample bag placement took extended time due to the use of the elastic band on a narrow edge as the securement mechanism. In the new version, the addition of a bottom lip created a flat surface for collection bag attachment, which reduced setup and placement time in the sampling process. The new cross section for the DSD Version 4.1 is shown in Figure 83. Figure 84 shows two photos of the side and front of DSD Version 4.1.

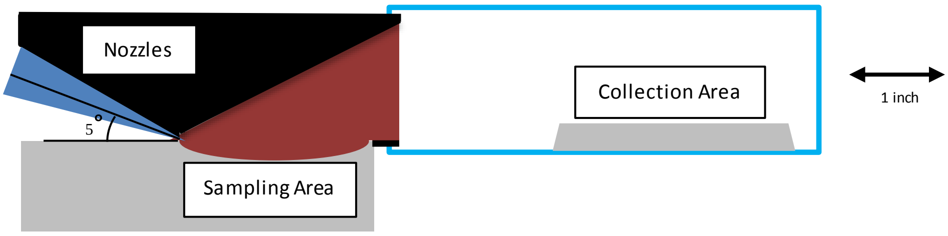

Figure 83. Diagram of new nozzles (blue), sample chamber (dark red) and dust layer (grey) for DSD Version 4.1. Blue rectangle shows the sample bag placement.

Figure 84. Photo of back (left) and front (right) views of DSD Version 4.1.

3.10.1 Field Testing of DSD Version 4.1 at the Edgar Experimental Mine

To continue progress towards the completion of Task 4, the research team coordinated an in-mine field experiment to conduct comparative testing between the DSD and traditional PaB sampling techniques in an underground environment. A series of tests were conducted at the Colorado School of Mines' Edgar Experiential Mine in Idaho Springs, Colorado. The goal for these experiments was to comparatively test the DSD Version 4.1 and BaP methods on various rock-dusted surfaces and configurations, and to discover what operational challenges might exist with the design of the sampling instrument. Figure 85 shows the sampler during testing. The data collected from these experiments aided in determining the variability in scour profile dimensions and sample mass, along with user descriptions of ease of testing for both sampling methods. Table 3 displays the collected data from this round of in-mine testing.

Figure 85. Testing DSD Version 4.1 on a horizontal dust surface.

Table 3. DSD Version 4.1 and BAP data from Edgar Mine testing.

Test	Type	Location	Hum	Dry B	Wet B	depth	length	mass	comments
1	DSD	A- Right, floor	57%	45.1	38.8	0.125	1	4.9	
2	BAP	A- Right, floor	57%	45.1	38.8	0.1875	2	20.4	
3	DSD	A- Right, floor	57%	45.1	38.8	0.125	0.875	2.1	
4	BAP	A- Right, floor	57%	45.1	38.8	0.15625	1.5	19.9	
5	DSD	A- Right, floor	57%	45.1	38.8	0.09375	0.875	2.5	side blowout
6	BAP	A- Right, floor	57%	45.1	38.8	0.125	2.375	16.5	
7	DSD	B-Right 1st, floor	36.50%	57.8	45.5	0.125	1.4375	1.2	
8	BAP	B-Right 1st, floor	36.50%	57.8	45.5	0.1875	1.625	23	
9	DSD	B-Right 1st, floor	36.50%	57.8	45.5	0.09375	0.875	0.09	poor contact 2 points
10	BAP	B-Right 1st, floor	36.50%	57.8	45.5	0.0625	1.875	20.6	
11	DSD	B-Right 1st, floor	36.50%	57.8	45.5	0.3125	1.875	15.5	incline, deep
12	BAP	B-Right 1st, horizontal rib	36.50%	57.8	45.5	0.15625	0.875	3	
12	DSD	B-Right 1st, floor	36.50%	57.8	45.5	0.125	0.875	16.1	
14	BAP	B-Right 1st, horizontal rib	36.50%	57.8	45.5	0.15625	1.375	11.5	
15	DSD	B-Left, vent tube	47.40%	56.1	46.4	0.0625	0.75	3.6	
16	BAP	B-Left, vent tube	47.40%	56.1	46.4	0	0	0	Unable to make proper contact
17	DSD	B-Left, inverted surface	47.40%	56.1	46.4	0	0	9	could not determine depth
18	BAP	B-Left, inverted surface	47.40%	56.1	46.4	0	0	0	could not determine depth
19	DSD	B-Left, over-shot mucker	36.90%	54.6	43.1	0.125	0.875	2.7	
20	BAP	B-Left, over-shot mucker	36.90%	54.6	43.1	0.1875	1.5	10.2	
21	DSD	B-Left, over-shot mucker	36.90%	54.6	43.1	0.3125	1.375	10.3	deep
22	BAP	B-Left, over-shot mucker	36.90%	54.6	43.1	0.1875	1.1875	10.1	
23	DSD	B-Left, wet floor	36.90%	54.6	43.1	0.0625	0.4375	0.8	minimal loose dust
24	BAP	B-Left, wet floor	36.90%	54.6	43.1	0.1875	1.875	2.6	minimal loose dust
25	DSD	B-Left, wet floor	36.90%	54.6	43.1	0	0	0	no loose dust
26	BAP	B-Left, wet floor	36.90%	54.6	43.1	0	0	0	no loose dust

Horizontal Testing

Comparative testing on the mine floor in a horizontal configuration was the basic test conducted at numerous locations throughout the mine. Horizontal testing was also conducted on sections of host-rock ribs, mining equipment, and ventilation tubing with a diameter of 2 feet, as shown in Figure 86. When comparing the data between the DSD and BAP, the BAP method maintained a tighter grouping of scour depths and sample masses and did not scour deeper than the upper threshold of 0.25 inches. The DSD had two scour depth results above the 0.25 inch threshold limit. Researchers determined that, in these two cases the users had improperly placed the sampler on the surface during testing. The average scour depth for the DSD was 0.128 inches and 0.113 inches for the BAP method which showed that both methods were close to the target 0.125 inch depth. There were no visible differences between testing on the horizontal section of the rib and on the mining equipment compared to the floor testing conducted. Due to the curvature of the circular ventilation tubing, the support wings of the DSD Version 4.1 did not make full contact to the testing surface, which created the potential for leakage out the side of the cavity. There was no observable leakage from those edges by the user, but researchers noted it as a potential concern for any tests on round or curved surfaces.

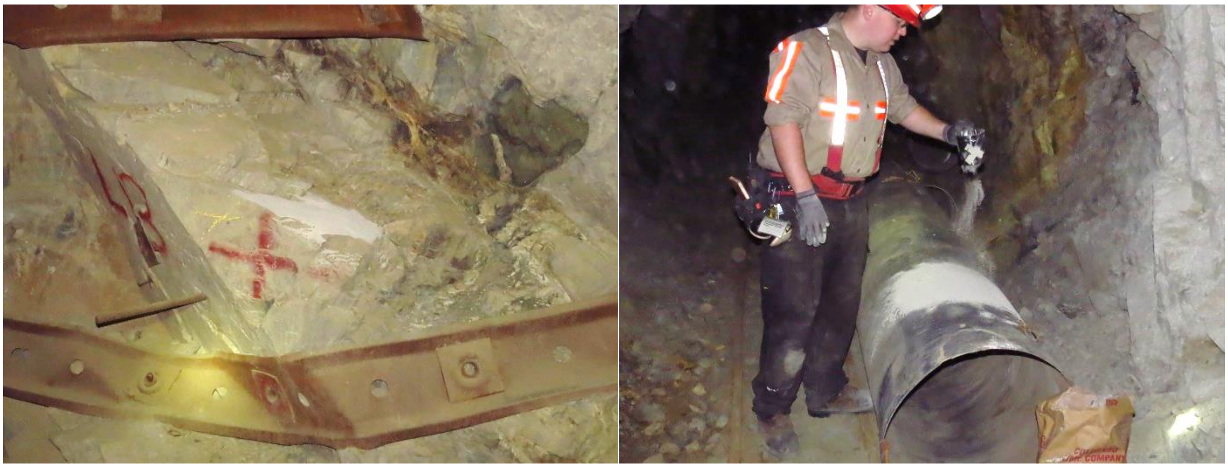

Figure 86. Horizontal dust testing on rib (left) and typical mine object (right). Image on left taken directly facing rib section (roof up and floor down).

Vertical and Inverted Testing

Testing was conducted with both the DSD and PaB methods on two vertical rib locations and one inverted roof location, see Figure 87. For these tests, rock dust was pitched onto the clean, dry rock to create a sampling surface for both methods. Through the vertical rib testing, it was discovered that placement of the DSD did not disturb the wall sample or cause initial liberation of dust from the surface as researchers hypothesized. When sampling was initiated, small amounts of dust were dislodged and collected in the sample bags. Similar observations were made during the inverted roof tests. As expected, the collected mass of these samples was low compared to the floor samples. Researchers concluded that the DSD would need to be applied to multiple locations on the roof or ribs to collect a sufficient sample mass for the CDEM. PaB sampling resulted in equally small samples, requiring the user to collect dust from a larger area. Where a thicker rock dust layer was placed, the mass collected increased. Researchers noted that dust accumulations on the surfaces of mining equipment may also be thin so that multiple samples may need to be combined to accumulate a sample size that can be tested using the CDEM.

Figure 87. Rock dust testing on vertical and inverted surfaces with DSD.

There were no traditional scour patterns visible on the surface during the vertical and inverted tests, only minor disturbances showing where the surface had loose dust that was scoured. This is a critical difference between the DSD and PaB method: the MSHA inspection procedures (MSHA 2013) for non-floor band samples are held to the same depth requirement of ⅛ to ¼ inch depth even though it may not be possible to attain the required sampling depth. Here again, researchers consider the pneumatic sampling process of the DSD superior since it will dislodge only the entrainable dust from all mine surfaces, while the BaP method may dislodge dust particles from cracks, etc. that would not normally participate in a coal dust explosion.

Wet Surface Testing

Researchers also created wet dust test beds using two methods that simulated wet mine conditions: wetting the mine surface with water prior to rock dusting, and wetting the dust after it has been applied. For the pre-dust watering, 8 oz. of water were sprinkled onto a 1-foot by 2-foot dry, clean rock surface before a ½ inch thick layer of rock dust was sifted on top. This set up simulates a typical scenario where ribs and roof are wet before rock dusting, or where water seeps from the coal or rock into the dust to moisten and bind the dust into clumps. For the second series of tests, a ½ inch thick layer of dry rock dust was sifted onto a dry, clean rock surface, and then 8 oz. of water was sprinkled over the test area. This method created clumps of rock dust at the surface, with dry dust underneath. Water was sprinkled over the area to allow patches of clumped and unclumped dust in the similar sampling locations for the DSD and PaB methods. Figure 88 shows the wet test bed with the DSD collecting a dust sample.

Figure 88. Wet dust testing with DSD on horizontal surface.

Results showed the DSD is capable of collecting the dry samples of dust that lay between the clumped and wet sections. This ability demonstrates again the key benefit of pneumatic sampling compared to PaB: the DSD replicates dust entrainment during a mine dust explosion. Only dust dry enough to be entrained during an explosion was sampled with the DSD, leaving behind dust that was too wet to be entrained. Using the PaB method, researchers could not collect a viable sample on either the wet dust surface due to the pan making poor contact with the rigid wet dust clumps, which allowed loose coal dust to be swept underneath the collection pan. The DSD proved superior to the PaB method on wet dust surfaces. However, collected sample quantities from partially wet surfaces were generally smaller in mass, so sampling in wet areas might require multiple tests to create sufficient mass for CDEM testing.

3.10.2 Field Testing of DSD Version 4.1 at Operational Coal Mine

Another key component of completing Task 4 was to conduct testing with the DSD in an operational underground coal mine. A team of 4 new researchers, Users A, B, C and D, traveled to one such mine in the USA. The researchers had varying degrees of experience testing with the DSD and BaP methods, which provided insights for test result variations based on user experience. User A had 10 months of experience with the DSD and BaP throughout the project. User B had 4 months experience with the DSD and BaP. User C had experience with Version 4.1 from the Edgar Experimental Mine testing and was trained on the BaP method for a week. User D was an untrained person and was trained a week before the on-site testing to use both the DSD and BaP methods of sample collection. Researchers also had the mine employee and on-site escort (User E) take a small number of samples using the DSD. User E had no prior experience with the DSD and was given a brief on-site training. It was important to the research group to have a range of experiences on the site visit to identify how the experience level might impact sampling results.

The researchers conducted in-mine testing for 2 days. Researchers tested both methods through a variety of locations, rock dusting conditions, environmental conditions, and surface orientations. The DSD Version 4.1 was in the same configuration as was tested at the Edgar Experimental Mine. Testing with the device was predominantly conducted at the 15 psig pressure setting with a small set of samples conducted at 20 psig. Samples were bagged, marked, and zip-tied closed on-site. Samples were weighed and tested for TIC with the CDEM later at the Colorado School of Mines (CSM) campus. A sample of pure crushed coal and a sample of pure rock dust furnished by the cooperating mine were used to calibrate the CDEM. The coal was crushed at CSM's Mineral Processing Lab to 100% passing 200 mesh to represent float coal dust.

Horizontal Testing on Mine Floor

The majority of the in-mine tests conducted were on horizontal surfaces with low dust compaction (loose, almost fluffy dusting) and in the working mine entries and crosscuts. Researchers took 23 DSD samples at 15 psig, 9 DSD samples taken at 20 psig, and 21 BaP tests. Twenty-four tests were conducted where foot and equipment traffic had compressed the dust. Dust on these surfaces still contained loose particles entrainable in air. Twelve tests under this criterion were taken with the DSD and 12 with the BaP method. The scour depth results are shown in Figure 89 and sample mass results in Figure 90.

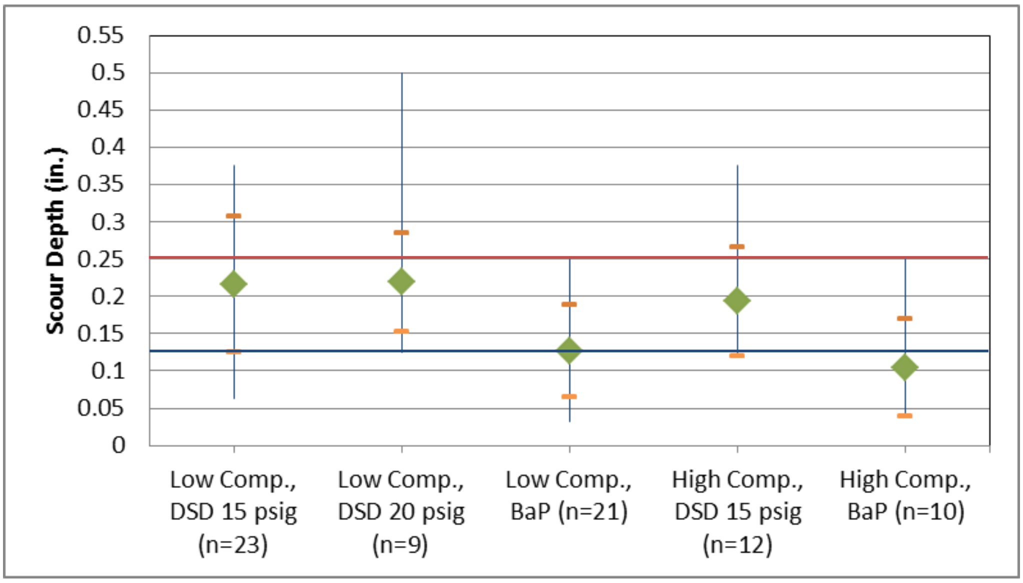

Figure 89. Scour depth results for low and high compaction horizontal tests at operational underground coal mine. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicated the 0.125 inch scour target.

Comparing the DSD results to the BaP results showed that the BaP results were closer to the target scour depth. The average scour depth decreased in the compacted areas, as researchers expected. In the high compaction areas, the DSD sample mass was low, indicating that less dust could be entrained by the DSD or by an explosion. It was determined that in cases where insufficient sample mass can be collected, additional sampling would be required to obtain at least 5 g of sample mass for CDEM testing.

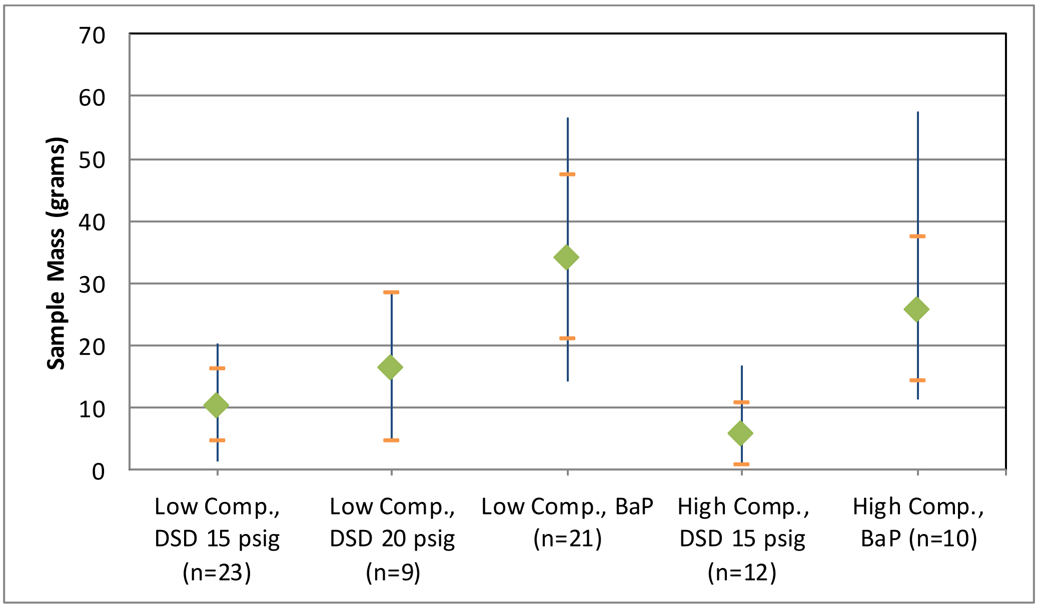

Figure 90. Sample mass results for low and high compaction horizontal tests at operational underground coal mine. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

User Variation with DSD on Low Dust Compaction Surfaces

A comparative user analysis was conducted using the horizontal, low compaction dust surface tests conducted with the DSD at 15 psig. The scour depth analysis for each user is shown in Figure 91. Researchers A and C, who had the most experience with the DSD, showed a tighter range of scour depth variation than the other users. Novice users B and D had wider ranges of scour depths. The data shows that user variation can cause significant variation in scour depth.

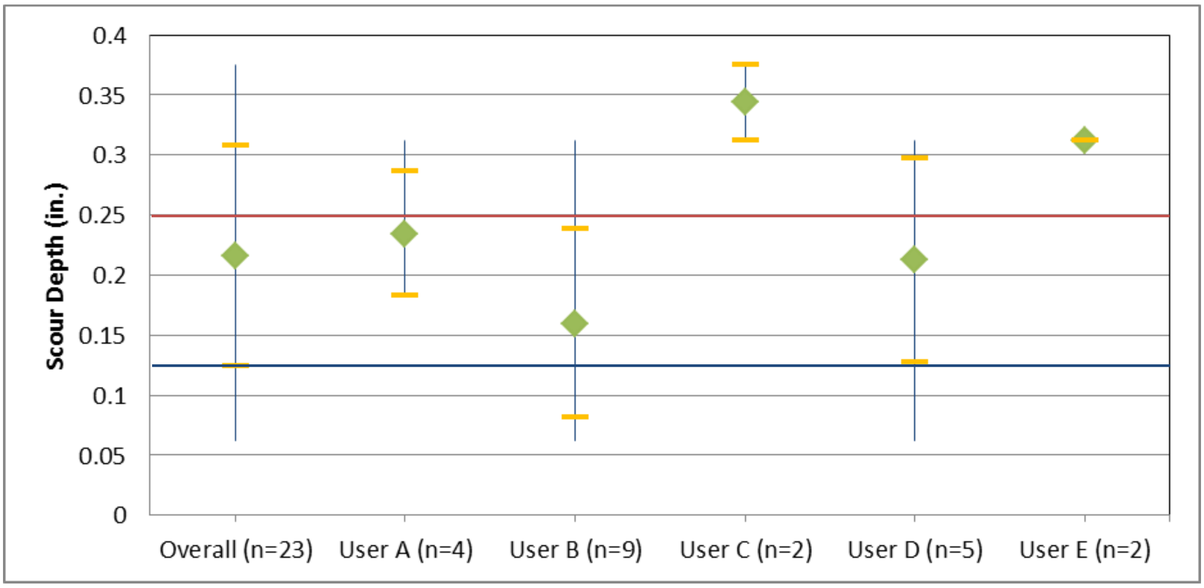

Figure 91. User analysis for DSD Version 4.1 at 15 psig on horizontal, low compaction surfaces. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values.

Testing in High Humidity and Wet Surface Conditions

Researchers collected 10 floor samples in a belt entry where the relative humidity was near 100%. Five tests were taken using each method of sample collection, DSD and BaP. Two tests each were taken on loose dust surfaces and 3 tests each were taken on compacted dust surfaces. One of the loose dust tests and 2 of the compact dust surface tests for each method were identified as visibly wet surfaces. Current inspection regulations (MSHA 2013) do not require dust sample in locations that are deemed too wet. Researchers compared DSD and BaP methods on wet surfaces to understand if either method could collect a representative sample that could be tested with the CDEM. The scour depth and sample mass data for these tests are show in Table 4. It was difficult to collect a sample off the wet surfaces with either method, which was consistent with the wet dust testing conducted at the Edgar Experimental Mine. Researchers believe the high humidity also made it difficult to obtain a consistent scour in the "dry" dust tests in the area due to dust particles clumping together in irregular patterns. The scour profiles for the DSD were uneven and no typical, symmetrical profile was formed in front of the two nozzles. With the BaP method, sampling was at irregular depths along the scour cross section due to dust clumping and the mechanical action of the brush bristles. Measuring the scour profiles was difficult as the dust was at times too wet and clumped to insert the notecard into the scour profile and trace a representative outline.

Table 4. Results from high humidity horizontal testing on both low and high compaction dust.

Method	Compaction	Dust Condition	Scour Depth (inch)	Sample Mass (grams)
DSD	Low	dry dust	0.13	3.10
DSD	Low	wet dust	not measurable	0.05
DSD	High	dry dust	not measurable	0.20
DSD	High	wet dust	0.06	1.00
DSD	High	wet dust	0.13	3.80
BaP	Low	dry dust	0.06	19.5
BaP	Low	wet dust	0.13	26.7
BaP	High	dry dust	not measurable	18.2
BaP	High	wet dust	0.06	7.50
BaP	High	wet dust	0.06	14.6

Non-Horizontal Testing in Various Mine Conditions

Since inspection regulations (MSHA, 2013) allow for band sampled material to be taken from the roof and ribs of an airway, researchers took additional tests on these surfaces to compare the DSD and BaP methods. A total of 8 tests were conducted on non-horizontal surfaces. Two tests were conducted on a timber surface at 45 degrees to horizontal. The timber had a loose layer of dust with a thickness of 0.5 inches evenly settled on the surface. Six tests were conducted on vertical surfaces of the rib. These vertical tests were conducted in both normal atmosphere and in the near 100% humidity beltway. All of the vertical tests had an even layer of rock dust settled on the surface. Tests were evenly split between DSD and BaP method tests. The only test of the 8 to have a visible scour pattern was the DSD test on the 45-degree timber with a scour depth of 0.125 inch and sample mass of 27.2 g. One of the BaP vertical tests had a mass of 22.6 g and another a mass of 6.8 g, while the remaining 5 tests had little mass collected. The researchers concluded that vertical testing on the rib may be difficult due to the thin, compacted layer that is formed as the dust is pneumatically blown to adhere to the coal surface. When a sample could be collected, it was layered and clumped together.

Conclusions from Operational Coal Mine Testing

The CDEM results from the in-mine tests showed that all samples collected were above the 80% TIC requirement. The mine used extensive rock dusting through its entries and cross-cuts, which resulted in both DSD and BaP sampling methods agreeing on TIC. The scour profile results between the various users showed that the DSD requires more user training to get consistent scour depth results. Researchers had similar experiences when conducting in-lab testing on campus.

Testing on vertical surfaces confirmed that a valid sample could be collected from the ribs for both methods, but the sample mass collected was significantly less due to the lower amount of entrainable dust on these surfaces. Insufficient research is available to say if the sample collected by either method on vertical and inverted surfaces is representative of dust that would be entrained during an explosive event. Testing on horizontal equipment surfaces, pipes, and belt structure showed no difficulty with either test method. Researchers concluded that, with the completion of the on-site coal mine testing, minor adjustments remained to finalize the DSD prototype and conduct final, controlled laboratory testing to complete Task 4.

3.10.3 Controlled Lab Testing for DSD Version 4.1

Based on the results of the coal mine tests, researchers wanted to test the effect that the thickness of the dust layer had on the operation of the DSD and to see if there were noticeable differences to the scour depth. The researchers also made an adjustment to their scour profile recording procedure for this and future lab tests. Instead of tracing the scour profile directly from the dust surface using a marker, a thin layer of glue was applied to the notecard on the portion that was placed into the dust layer. When the card was removed, the scour profile was visible on the notecard due to the dust sticking to the glue. The scour profile could then be traced separately and more accurately than with the previous procedure. Tests were conducted at 15, 20 and 25 psig reservoir pressures with a dust thickness of 0.31 inch and 0.5 inch split evenly between the pressures. The scour depth results from these tests are shown in Figure 92.

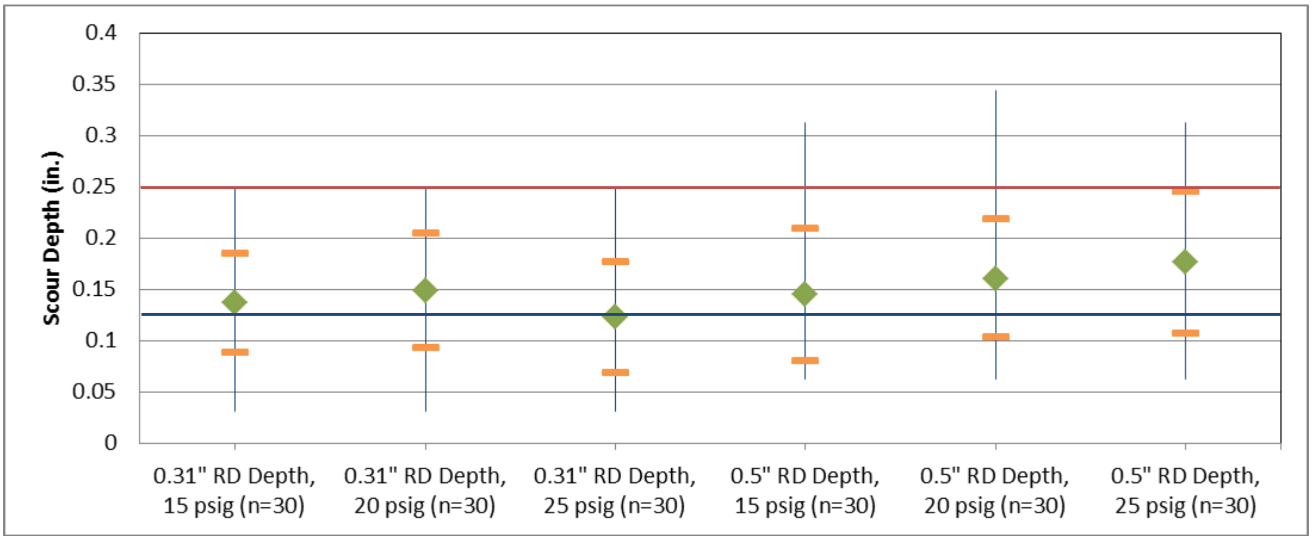

Figure 92. Scour depth variation based on rock dust layer thickness (RD) and charging pressure. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

There is a noticeable change between the 0.3 and the 0.5 inch dust thickness tests, showing an increase in the scour depth at all pressures. Researchers believe that, due to the weight of the DSD and the packing properties of the rock dust, the DSD sinks deeper into the dust layer with increases to the thickness of the dust layer. The weight of the DSD was reduced in the next version. The change in dust thickness should not have an impact on the BaP method, and variation in scour depth with the BaP method resulted from the inconsistency of the user brush pressure.

3.10.4 Conclusions for DSD Version 4.1

DSD Version 4.1 was the first version researchers considered field ready. Researchers were able to make a number of observations on the use of the DSD in various mine conditions. The in-mine testing done both at the Edgar Experimental Mine and the operational coal mine brought forward the effect of dust layer thickness on sampling performance. The impact of DSD weight was most noticeable with Version 4.1 and its steel charging vessel, and its aluminum mount and sampling chamber. Controlled testing demonstrated that DSD weight and the control valve operation were a factor in obtaining a representative and repeatable sample.

The field experience and feedback from users and observers at the Edgar Experimental Mine and operational underground coal mine provided insight towards the initial writing of the User Manual for the DSD needed for the completion of Task 5 and acted as milestones towards the completion of Task 4.

3.11 DSD Version 4.2

Based on feedback from users, researchers determined that the physical action of operating the DSD control valve could cause the DSD to shift and possibly disturb the test. Users reported that the current twist-knob for the air directional control valve was sometimes difficult to use. To address these issues, researchers replaced the twist-knob valve with a remote-controlled, pneumatically operated control valve. The new push-button trigger was connected to the device by flexible vinyl tubing. The button control valve and pneumatic control valve setup are mechanically similar to the manual control valve in switching the connection from the charging vessel to the incoming air-line and the nozzles. A diagram of the new mechanical design of DSD Version 4.2 is shown in Figure 93. Figure 94 shows a side and bottom photo of DSD version 4.2.

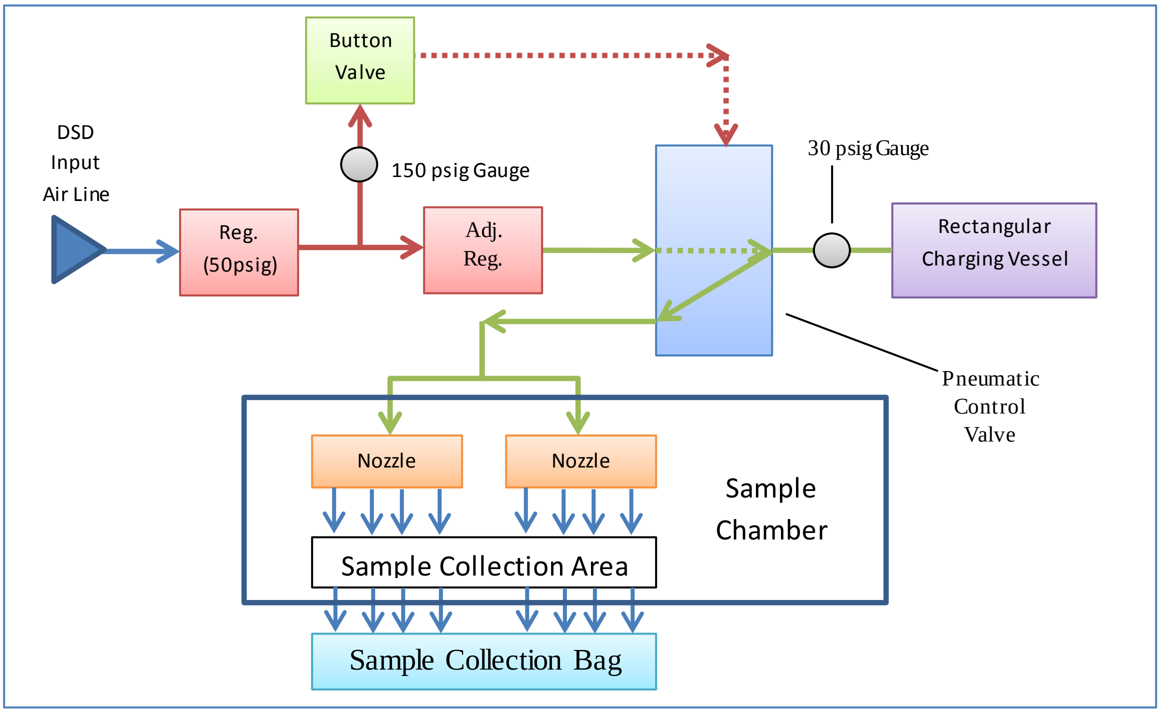

Figure 93. Diagram of combined components for DSD Version 4.2. Dotted lines indicate new airflow path when button valve is engaged.

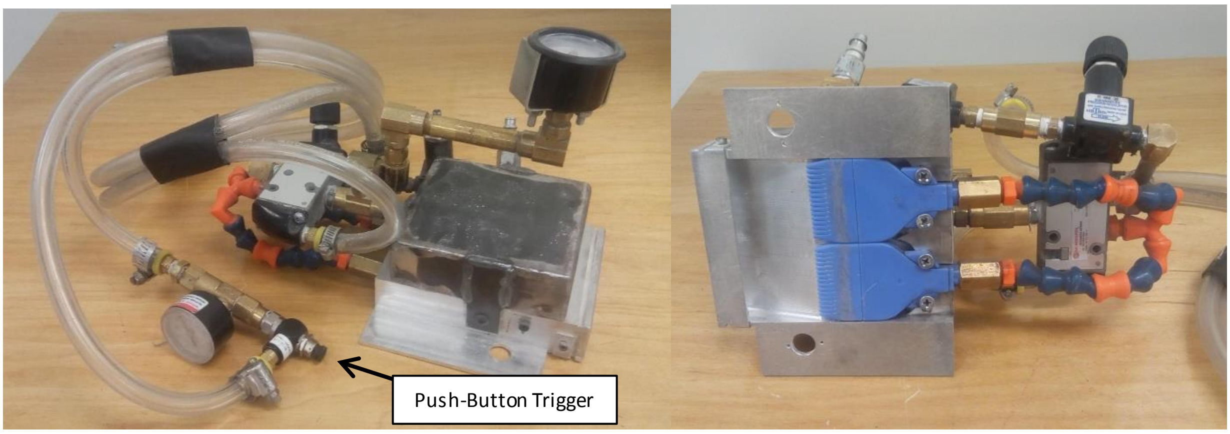

Figure 94. Photo of side (left) and bottom (right) view of DSD Version 4.2.

3.11.1 Version 4.2 Testing

The new control valve was tested following the previous testing procedures. The scour results for 360 tests conducted with Versions 4.1 and 4.2 are shown in Figure 95. The average scour depths at the 0.31 inch dust layer thickness with Version 4.2 showed improvement from Version 4.1 data, while there was a slight, but consistent increase in sampling depths at the 0.5 inch dust layer thickness. With the new trigger, the average sampling depths did not vary with different charging pressures. Feedback from users was positive for the Version 4.2 in terms of ease of use and consistent placement of the DSD.

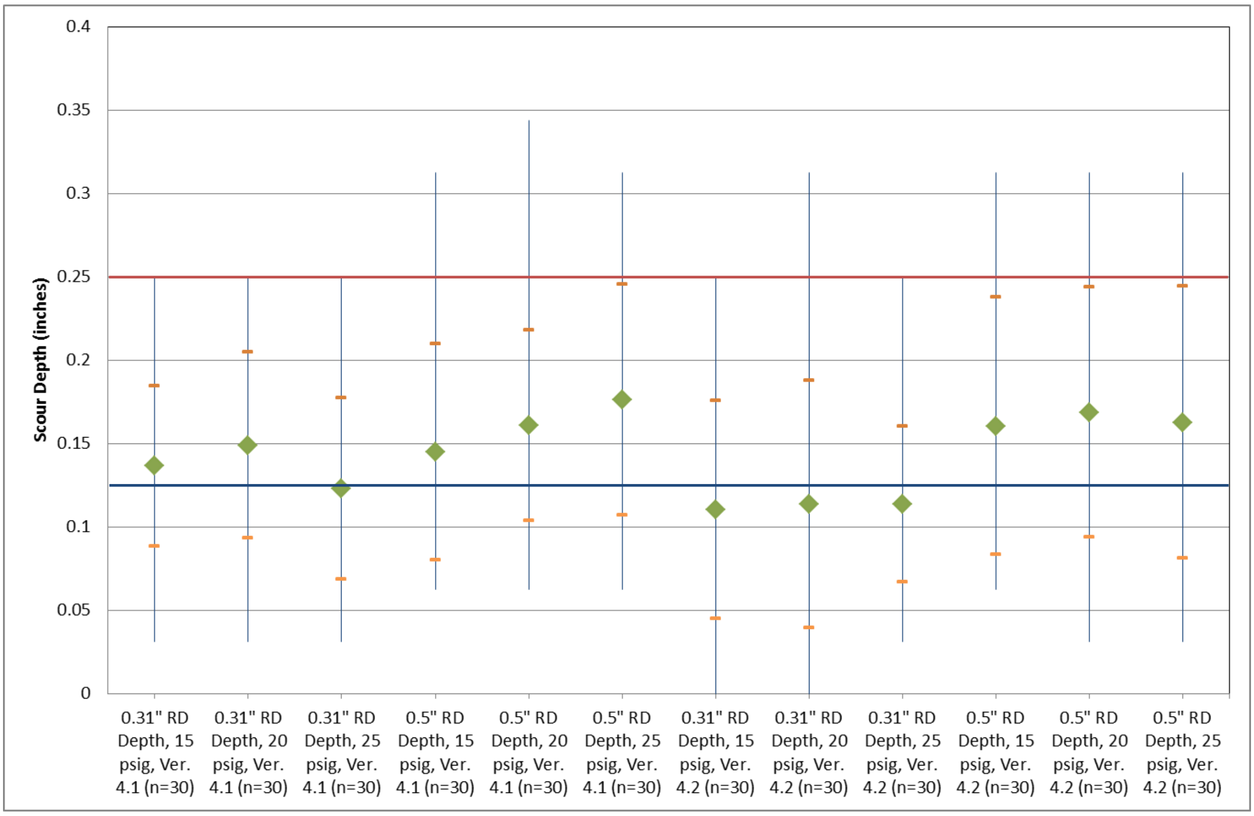

Figure 95. Scour depth variation DSD Version 4.1 and 4.2 based on rock dust layer thickness (RD) and charging pressure. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicated the 0.125 inch scour target and the red line the 0.25 inch upper threshold.

3.11.2 Version 4.2 Comparative Testing with BaP Method

Accordingly, researchers decided to continue testing with the pneumatic control valve and run comparison tests with the BaP method. These comparison tests consisted of a 0.31 or 0.5 inch layer of rock dust covered with a 0.05 inch coal dust layer designed to produce an average of 70 to 85% TIC. The scour depth results for these comparison tests are shown in Figure 96.

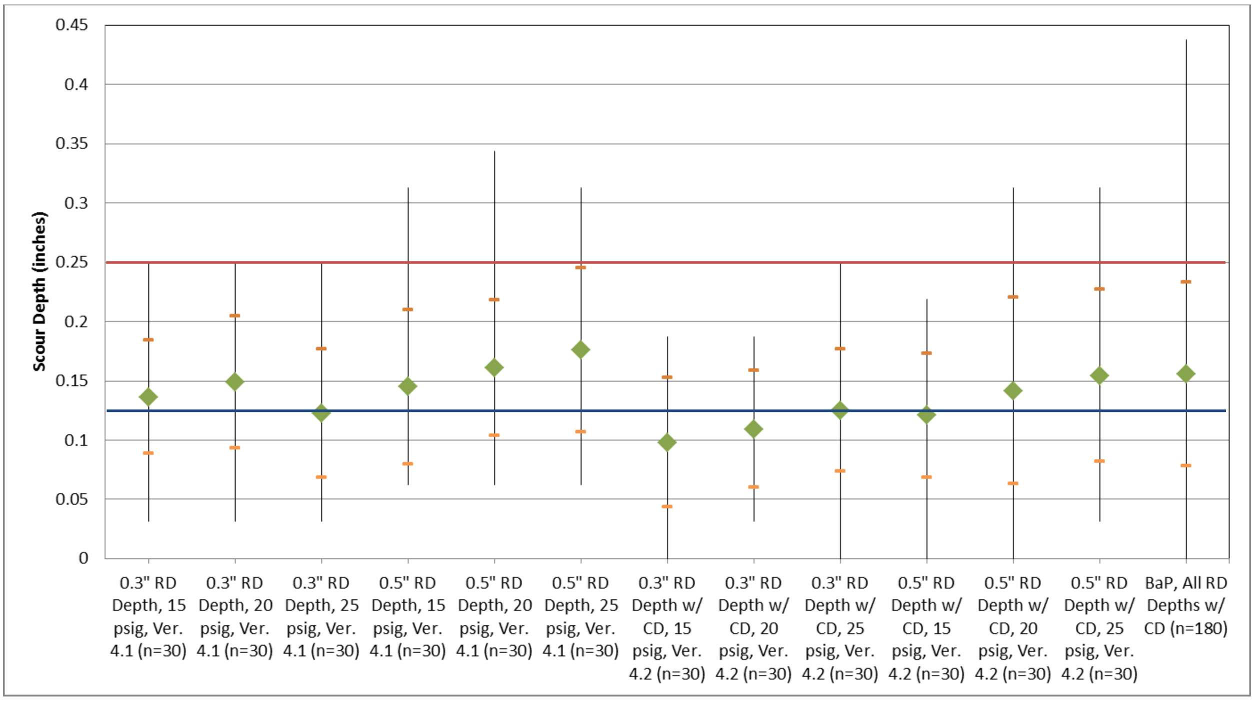

Figure 96. Scour depth results for DSD versions 4.1, 4.2 and BaP method with rock dust thickness (RD) and 0.05 inch coal dust test bed (CD, Ver. 4.2 and BaP only). Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

The results of the comparative testing with the coal dust layer showed an improvement between the 0.31 and 0.5 inch rock dust layer scour depth average, range, and standard deviation. The 15 psig results consistently stayed below the 0.25 inch scour depth upper limit with an average near 0.1 inch for the 0.31 inch rock layer and slightly below 0.125 inch for the 0.5 inch rock dust layer. At 20 psig, the 0.31 and 0.5 inch layer tests are close to the 0.125 inch target. The standard deviation of the BaP method is close to that of the 0.5 inch rock dust layer results for 20 and 25 psig. From the scour depth results, researchers determined that the optimal DSD operating pressure is 15 psig.

3.11.3 Comparative CDEM Results for DSD Version 4.2 and BaP Method

The results of the CDEM results for the 0.31 inch rock dust layer are shown in Figure 97. Looking at the trends between the DSD and BaP methods, it can be seen that the DSD Version 4.2 results follow the expected trend of increasing average readout with increasing scour depth. The BaP results do not follow the expected trend, which may be due to the mechanical mixing that occurs with the movement of the brush during collection. The results showed again that the DSD performed better at collecting the full profile of the depth scoured than the BaP method, and provided a more representative sample of what is entrained from the dust surface during an explosion.

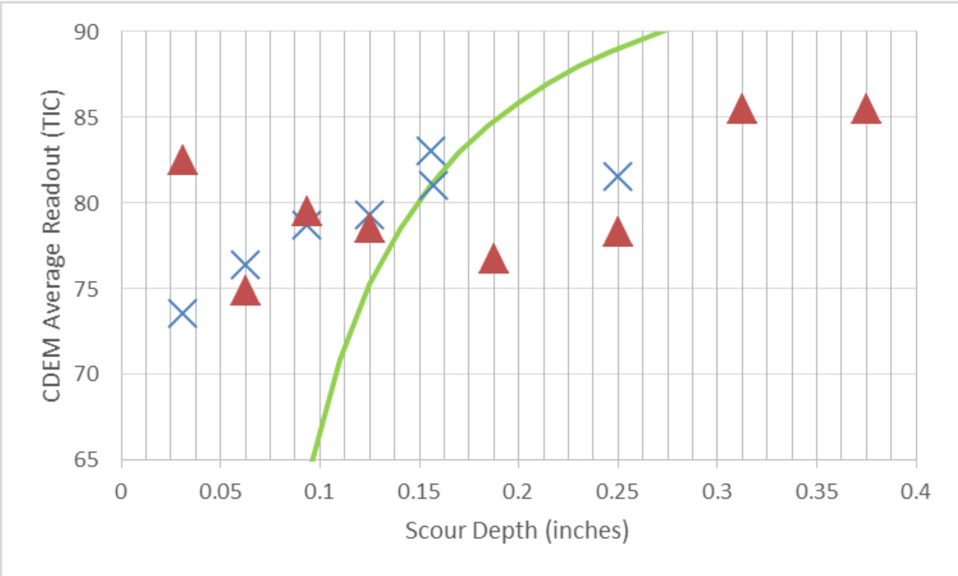

Figure 97. Comparison of CDEM Average Readout for various scour depth with DSD Version 4.2 and BaP methods at 0.31 inch rock dust thickness with 0.05 inch coal dust layer on top. Blue X's denote average CDEM readout from DSD Version 4.2 tests (n=39) and red triangles denote average from BaP method tests (n=40). Green line shows expected TIC based on ratio of coal and rock dust at given depth.

3.11.4 CFD Modeling Results for DSD Version 4.2

The focus for the CFD during this timeframe was to test the sensitivity of the simulation model against the results of Version 4.2. Parameters observed for this sensitivity testing were density, frictional viscosity, angle of airflow, and packing limit. These parameters were important to monitor as they impact how the dust interacts with the airstream. The parameters were controlled to help the verification of the CFD results and to create an accurate model for further analysis of different dust configurations. The results from the model show that the trends from the CFD and the DSD testing are similar and accurate.

Figure 98 and Figure 99 show the collected mass and scour depth results from the CFD model and the controlled DSD testing with the pneumatic control valve. In Figure 98, the mass results are similar and fall within the mass standard deviation, showing that the model can be used as a predictor of the amount of sample mass the DSD will collect. Figure 99 shows that the scour depth results for the CFD fall within the standard deviation of the controlled lab tests for the new DSD Version 4.2.

The controlled lab testing was imperative for the confirmation that the CFD results were representative of the DSD function. Compared with the lab tests, the CFD model can be used to predict further environmental differences and conditions that the device would encounter in mines with different altitudes, humidity, and packing limit. With this work, researchers completed Task 2 CFD Analysis.

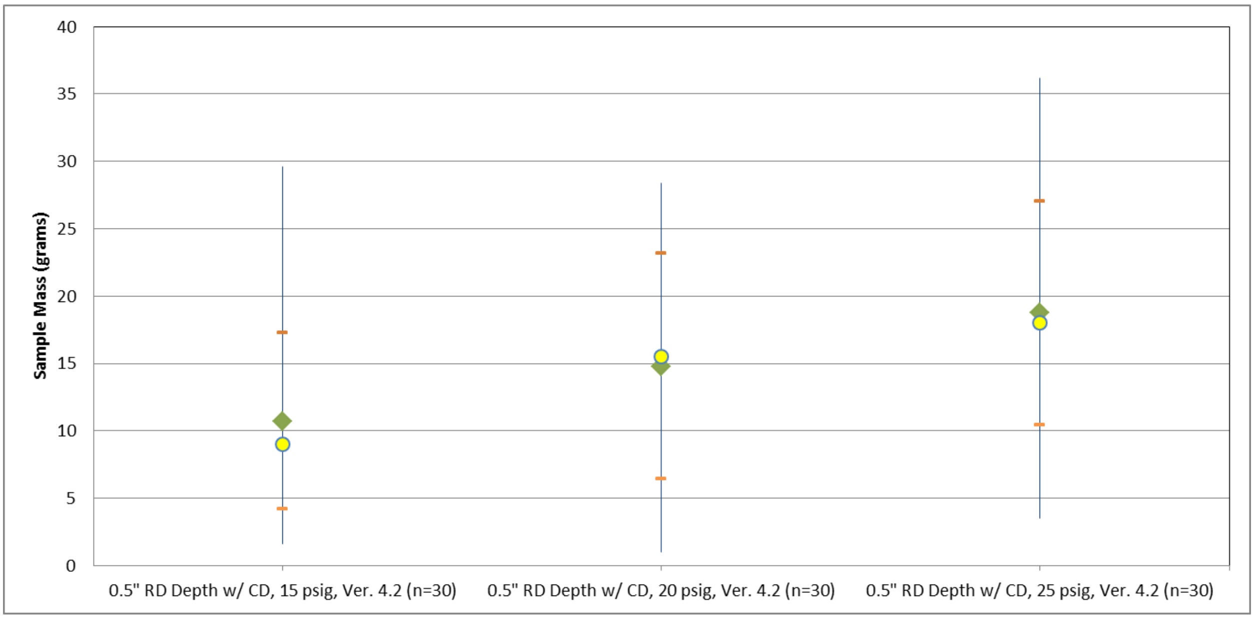

Figure 98. Collected sample mass results for CFD and DSD Version 4.2 with 0.5 inch rock dust (RD) test bed. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The Yellow circle indicated the CFD result.

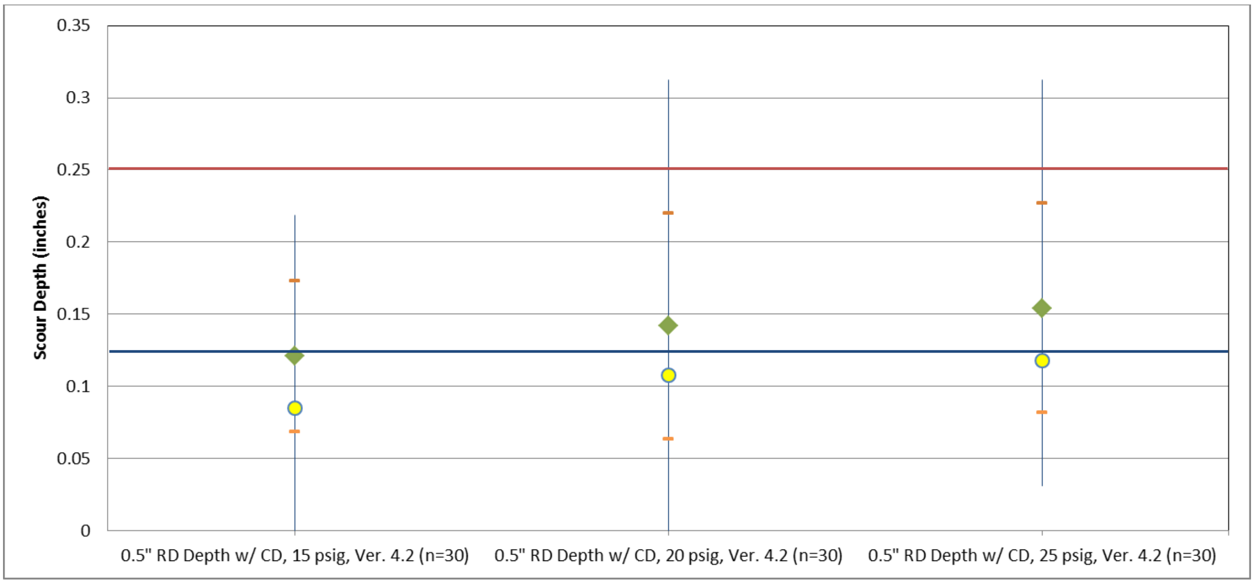

Figure 99. Scour depth results for CFD and DSD Version 4.2 with 0.5 inch rock dust (RD) test bed. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold. The yellow circle indicates the CFD result.

3.11.5 Conclusions for DSD Version 4.2

DSD version 4.2 with the pneumatic control valve reduced the variation researchers experienced with the manual control valve. The new design also performed better than the BaP method when comparing the scour depth targets and limits along with the expected results for the CDEM readouts. The CFD model of Version 4.2 was verified by controlled lab testing and demonstrated that Version 4.2 scours to the desired sample depth within reasonable accuracy. CFD modeling also confirmed that Version 4.2 has no recirculation issues and uses the full energy of the airstream from the nozzles to entrain the top layer of dust and move the sample into the collection bag. Researchers concluded that there was sufficient testing to construct the final DSD version, and that Tasks 1, 3 and 4 were complete. During this process, researchers also worked toward the completion of the Final Report and associated User Manual (available in Appendix A) that would constitute the fulfillment of Task 5.

3.12 Final DSD Version 5.0 Design

Researchers worked towards completion of Task 1 with final adjustments to the DSD. Figure 100 shows a picture of the DSD Version 5.0. This version of the DSD had no mechanical or functional design changes. Changes made from Version 4.2 were merely cosmetic. Researchers adjusted the placement of the device's control valves, pressure reducers, lines and other components and added a more practical handle for the user. The following section goes into details about the design of DSD Version 5.0, with a diagram provided in Figure 101.

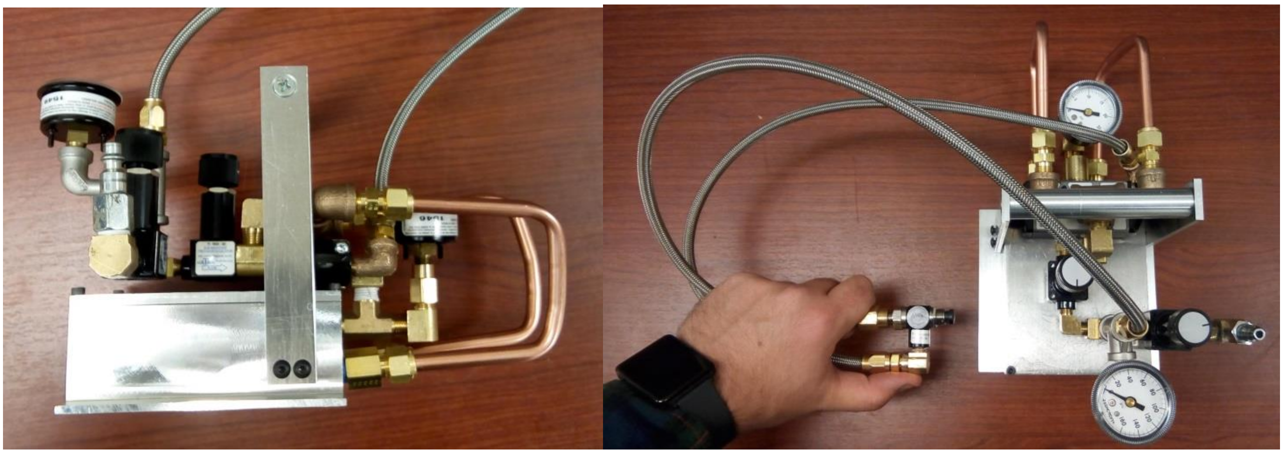

Figure 100. Photos of side (left) and top (right) views of the DSD Version 5.0.

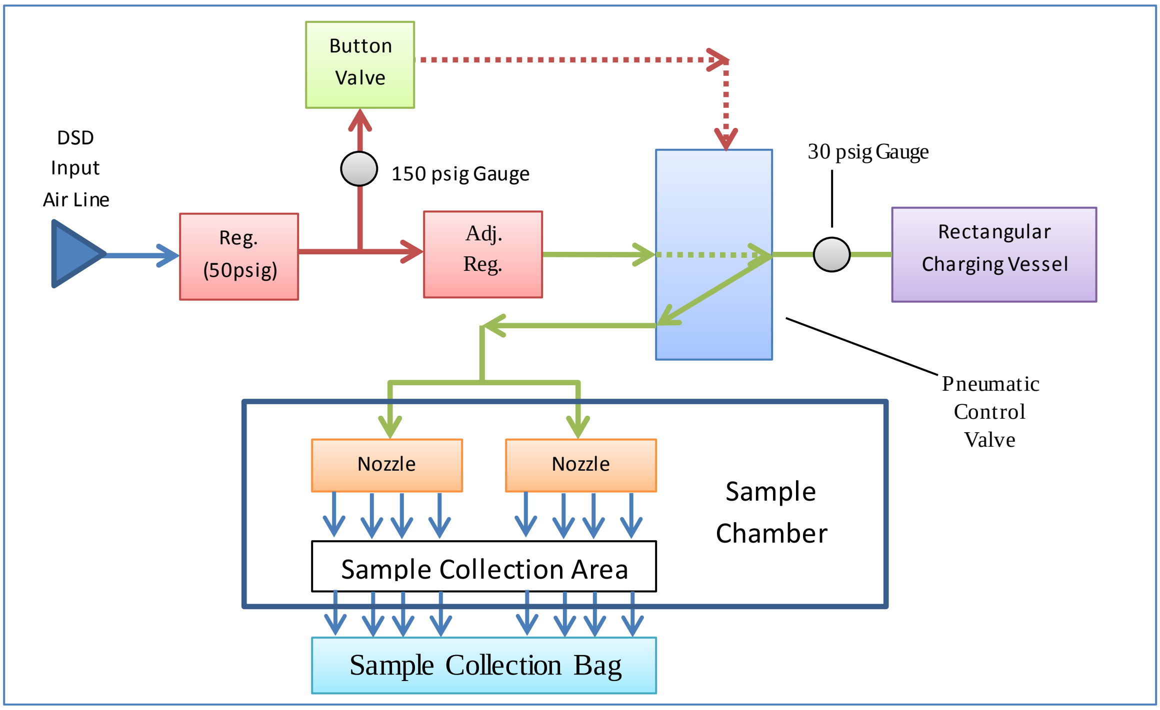

Figure 101. Diagram of final DSD version 5.0 components. Arrows indicate flow of compressed-air through DSD. Dotted lines indicate new airflow path when button valve is engaged.

Compressed Air Line Input

The final DSD Version 5.0 is configured to run off of any compressed-air line with a minimum pressure of 50 psig, which can come from a separate air reservoir, such as a 5-gallon portable air tank. The tank and hose can be disconnected from the sampler by means of a quick-disconnect fitting. Researchers determined that a 5-gallon tank charged to 100 psig is sufficient to take about 50 dust samples.

Pneumatic Control Valve, Remote-Button Press 1-1 Line Valve, 1 In-Line Regulator and 150 psig Gauge

A pneumatic 2-1 control valve allows the DSD to pressurize its internal charging vessel and release that compressed-air to the nozzles when the user is ready to take a sample. The line air of up to 150 psig passes through the first regulator to reduce the pressure to 50 psig. The pneumatic control valve has a minimum operating pressure of 45 psig, requiring a minimum of 50 psig in the air tank to operate the sampler. The pneumatic valve button is pushed to charge the vessel, and then released to take a sample.

15 psig In-Line Adjustable Regulator, Compressed-Air Charging Vessel, 30 psig Gauge and two, 1.875 inch Length Compressed-Air Blowoff Nozzles

A second adjustable regulator reduces the line pressure to 15 psig to fill the charging vessel. A 30 psig gauge allows the user to verify the correct charging pressure. The charging vessel has a volume of 18 cubic inches and is designed for pressures up to 150 psig.

When the pneumatic control valve is in the discharge or idle position, the high pressure line is closed and the connection between the charging vessel and the blowoff nozzles is open. When the trigger is pushed to the charge position, line pressure is connected to the charging vessel and the line to the nozzles is closed. After charging the DSD to 15 psig, the user releases the button valve to discharge the DSD vessel to the nozzles to collect a sample.

Component Housing and Sample Chamber, Collection Bag Attachment and Sample Collection Bag

The control components of DSD Version 5.0 are mounted directly to the aluminum housing. The footprint of the sample chamber is 3.75 inches by 1.75 inches. The sample bag is secured to the open end of the chamber using a mechanical attachment. The bag attachment allows the user to secure the sample collection bag to the bag attachment and then clip the attachment to the component housing and sample chamber. The attachment creates an effective seal between the collection bag and the sample chamber, which prevents air and dust sample leakage and allows for easy removal of the sample once the test is complete. The current sample collection bags are sandwich bags available at most grocery stores.

4 *Summary of Accomplishments*

The objective for this research project was to develop a handheld, pneumatic mine dust sampling device (DSD) for underground coal mines that collects a dust sample from the mine floor, roof, or ribs by mimicking the dust entrainment process during a mine explosion. Researchers designed, built and tested the DSD to deliver a controlled, repeatable, light puff of air over a mine dust surface. This puff of air entrains a representative and repeatable dust sample that is captures for subsequent analysis of total incombustible content (TIC) using the coal dust explosibility meter (CDEM). In the project proposal, researchers listed the following tasks necessary to design and build a fully operational DSD. Those tasks included:

1) Design and Development of a DSD prototype
2) Analysis and improvement of the DSD with computational fluid dynamics (CFD) models
3) Laboratory testing of the DSD prototype
4) Controlled laboratory and in-mine tests to compare a DSD dust sample to those obtained with the traditional Brush-and-Pan (BaP) method, backed up with laboratory inert content analysis applied to a portion of the samples for comparison
5) Documentation of the design, testing and operation of the DSD with reports and a User's Manual.

Researchers designed and developed a DSD prototype that meets the research objective as stated. Figure 102 and Figure 103 show the top and bottom views of the DSD.

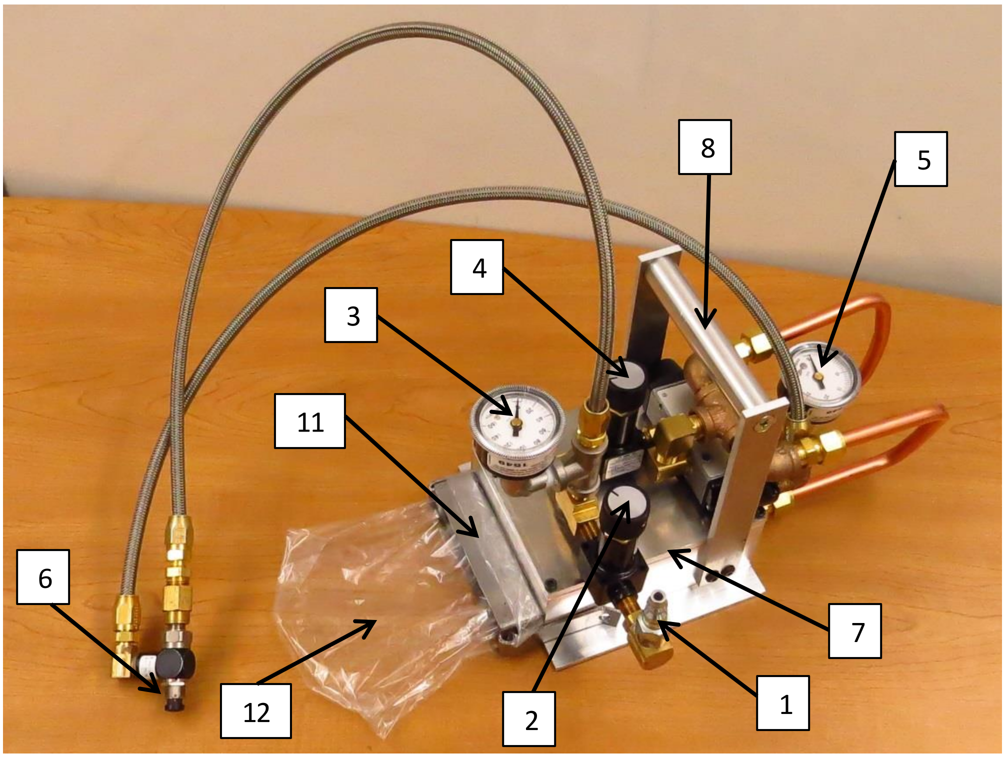

Figure 102. Top view of DSD prototype.

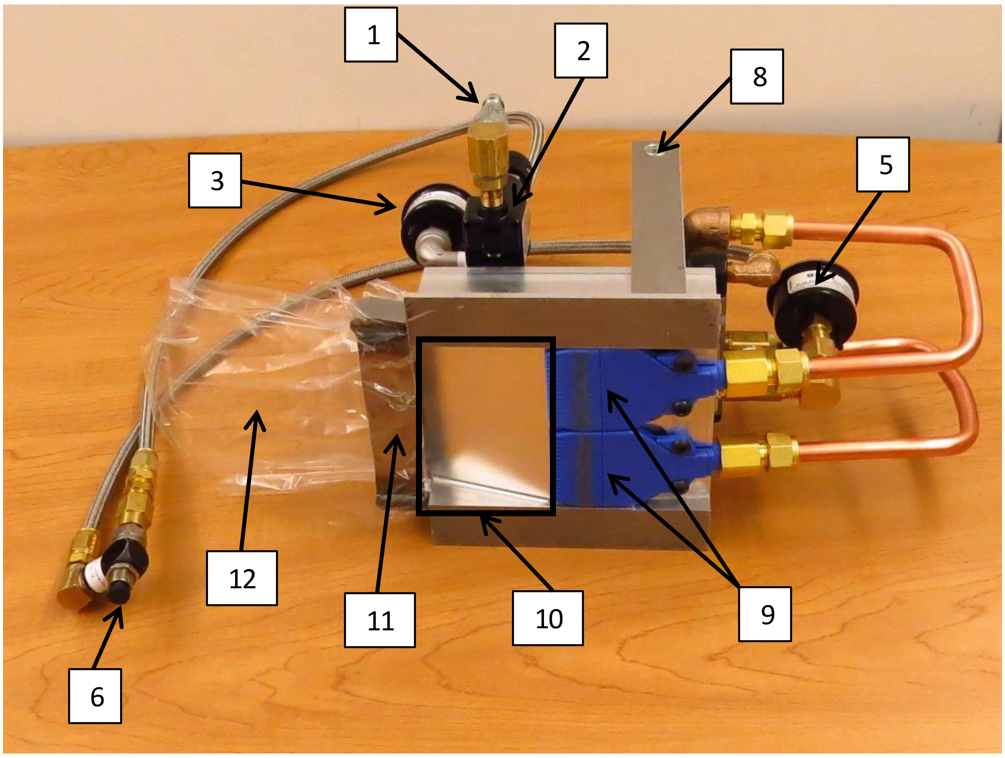

Figure 103. Bottom view of DSD prototype.

The components of the DSD are as follows:
1 – Air-line Connection (interchangable)
2 – Device Regulator
3 – Operating Pressure Gauge
4 – Charging Regulator
5 – Charging Pressure Gauge
6 – Push Button Trigger
7 – Charging Vessel
8 – Handle
9 – Air Nozzles
10 – Sample Chamber
11 – Sample Bag Clip
12 – Sample Bag

Both DSD and traditional brush-and-pan (BaP) methods were tested in the Edgar Experimental Mine owned by CSM and at an active, underground coal mine. In-mine tests confirmed that the DSD can sample mine dust in the full range of configurations outlined in the primary objective. Researchers performed controlled lab testing and compared the DSD to the BaP method prescribed by MSHA. Researchers confirmed that DSD sampling is more consistent at targeting the 1/8th inch sample depth while staying under the current upper threshold of 1/4 inch. Figure 104 shows a comparison of DSD Version 4.2 at varying dust layer thicknesses against the BaP method.

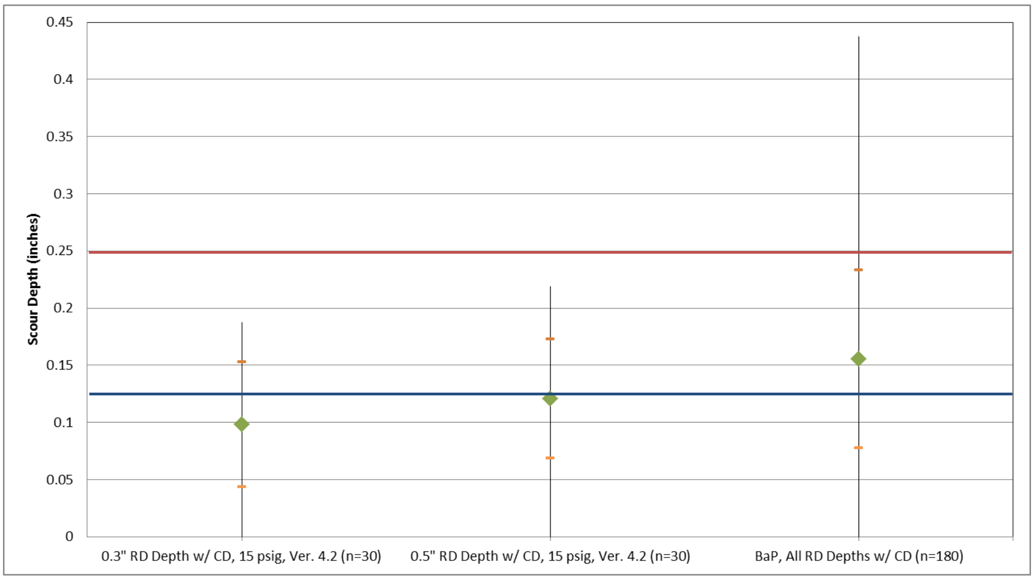

Figure 104. Scour depth results for DSD versions 4.2 at 15 psig and BaP method with rock dust thickness (RD) and 0.05 inch coal dust test bed. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold.

The DSD also provided a more accurate sample when comparing the TIC from the CDEM to the BaP method as shown in Figure 105. The results from the DSD at the shown scour depths are closer to the expected TIC than the BaP results. This indicates the DSD is collecting a sample which better represents the top layer of the dust surface.

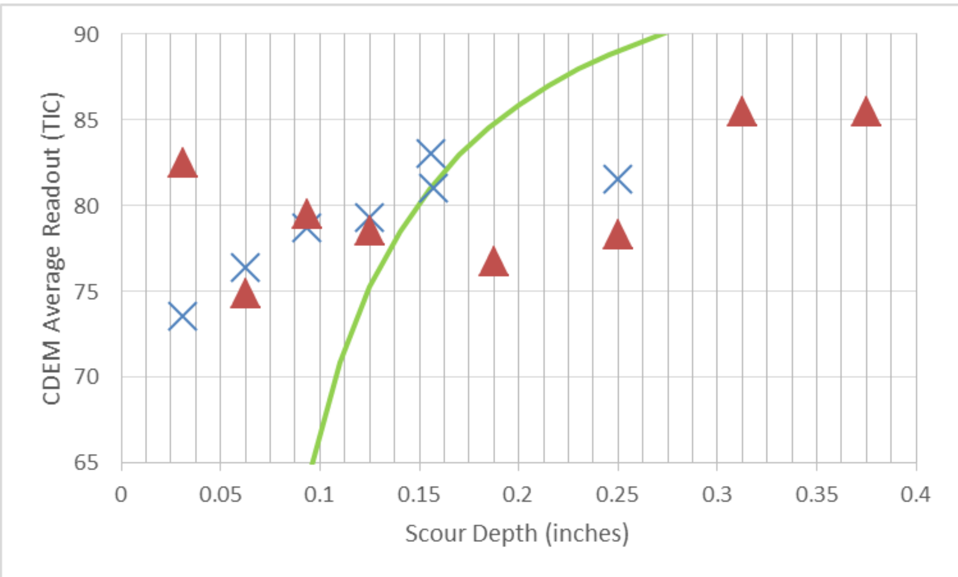

Figure 105. Comparison of CDEM Average Readout for various scour depth with DSD Version 4.2 and BaP methods at 0.31 inch rock dust thickness with 0.05 inch coal dust layer on top. Blue X's denote average CDEM readout from DSD Version 4.2 tests (n=39) and red triangles denote average from BaP method tests (n=40). Green line shows expected TIC based on ratio of coal and rock dust at given depth.

The DSD design was improved and verified throughout the project with a CFD model detailing the interaction between the pneumatic air and dust layer inside of the DSD. Figure 106 and Figure 107 show the final results of the CFD model to the results measured during the controlled lab testing. The CFD results trended with the actual results from the DSD and were within standard deviation indicating the model is predictive of the DSD results and can be used for verifying the DSD in alternate testing conditions.

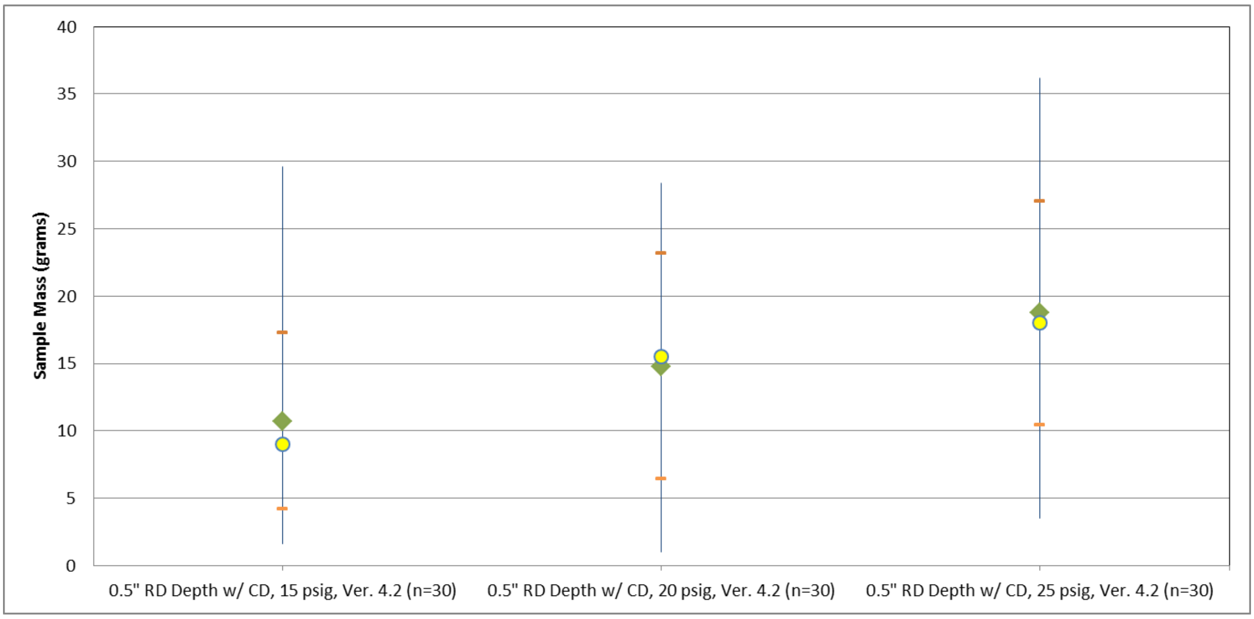

Figure 106. Collected sample mass results for CFD and DSD Version 4.2. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The Yellow circle indicated the CFD result.

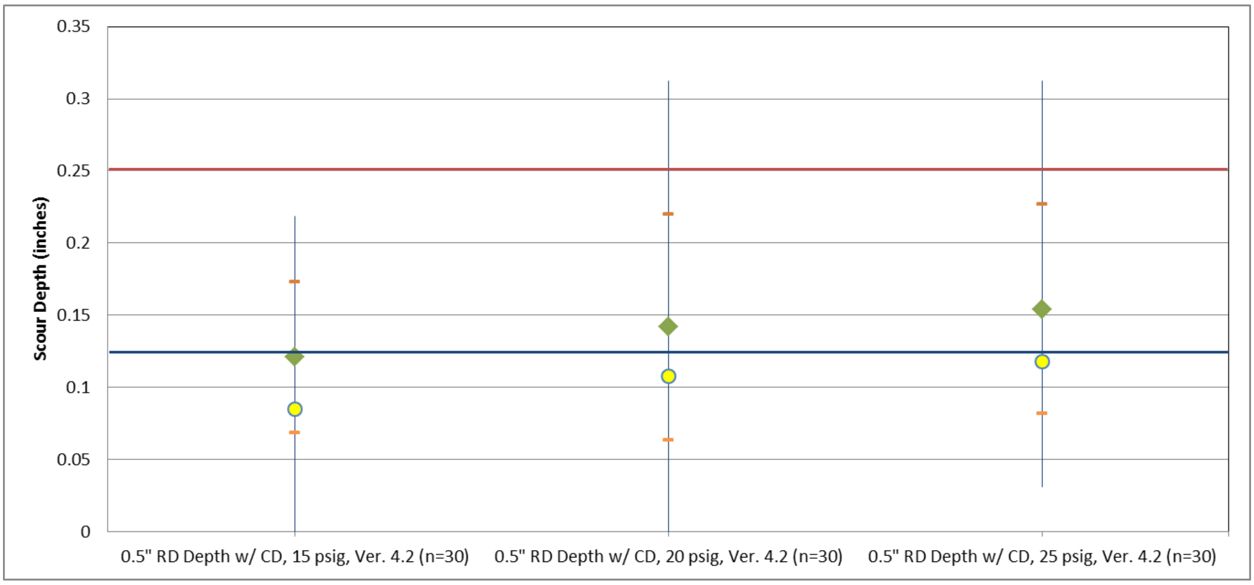

Figure 107. Scour depth results for CFD and DSD Version 4.2. Black line indicates range of values, green diamond the average value and orange dashes the standard deviation of the values. The blue horizontal line indicates the 0.125 inch scour target and the red horizontal line indicates the 0.25 inch upper threshold. The yellow circle indicates the CFD result.

Researchers have provided documentation of the life of the project along with a User's Manual found in Appendix A.

5 Dissemination Efforts and Highlights

The main dissemination efforts for the project were through major conferences and symposiums related to the mining and ventilation fields. Researchers submitted the following manuscripts and gave presentations at the events:

- Goertz, B; Brune, JF; Bakhsh, KJ; McDaniel, S; Rockley, T [2015]: Development of a Dust Sample Collection Prototype for Use in Underground Coal Mines, preprint no. 15-104, SME 2015 Annual Meeting, Denver
- Goertz, B; Brune, JF; Parmar, A; McDaniel, S, Rockley, T; Soares*, F [2015]: Development of a Mine Dust Sampling Instrument for use in Underground Coal Mines, 15th North American Mine Ventilation Symposium, Blacksburg, VA; June 2015
- Duddempudi, V; Goertz, B; Soares Barreto, F; Bogin, GE; Jr.,; Brune, J [2016]: Development of a Computational Fluid Dynamics Model for the Design of Pneumatic Dust Sampling Device. Preprint no. 16-148, SME 2016 Annual Meeting, Phoenix AZ February 2016.

Researchers will submit an abstract and manuscript for the 16th North American Mine Ventilation Symposium.

An Impact Spotlight was written for the Alpha Foundation website and can be found by going to http://www.alpha-foundation.org/outputs-and-impact/. Researchers also submitted a patent for the design and functionality of the DSD through CSM's Office of Technology Transfer on October 24, 2016.

6 Conclusions and Impact Assessment

The research team designed and built a portable, non-electric DSD prototype that collects dust samples from underground coal mine surfaces that performs better than the current BaP method. The DSD prototype was designed to scour mine dust to a depth of 1/8th inch to meet MSHA dust sampling guidelines. The DSD prototype is operated using a compressed air tank or direct line with a minimum line operating pressure of 50 psig. Controlled lab testing of the DSD against the BaP method showed that the DSD produces a tighter range of scouring depths than the BaP method. Testing with coal dust and rock dust mixtures showed that samples taken by the DSD prototype better captured the profile of the scour depth than the mechanical bristle sampling of the Brush and Pan method, as verified by the Coal Dust Explosibility Meter (CDEM) readouts.

In-mine testing of the DSD prototype proved that the prototype is easy to use in underground coal mine conditions. Comparing in-mine testing with the BaP method showed that the DSD prototype provided a more representative sample of what would be entrained during an actual explosive event, including samples of wet mine dust.

Computational Fluid Dynamic modeling was utilized to create a DSD model that predicts the scour depth and sample mass with reasonable accuracy. The CFD model verified the controlled lab tests of the DSD and helped improve the DSD prototype design for pneumatic efficiency. CFD modeling can be used to assist in future DSD refinement.

The final DSD version can be used to collect mine dust samples that are more representative than the BaP method. Researchers recommend that mine inspectors, mine examiners, ventilation engineers, and rock dusting crews use the DSD to sample dust in underground coal mines to verify sufficient rock dusting and to identify areas that require additional rock dusting. Researchers believe that sampling with the DSD can flag areas with insufficient rock dust that might propagate a coal dust explosion. The DSD, in conjunction with the CDEM, provides near instantaneous TIC data to guide explosion prevention efforts, and may help reduce costs related to excessive rock dusting practices due to imprecise BaP testing methods currently available.

Researchers have filed a patent for the design of the DSD and are in negotiations with a manufacturer to further the development and manufacturing of DSDs. These DSDs would be distributed to underground coal mines to acquire user feedback for further refinement of the design. Researchers expect commercialization of the DSD for the underground coal mine market.

7 Recommendations for Future Work

USBM and NIOSH research of dust entrainment during coal dust explosions has focused on flat, horizontal, non-compacted dust surfaces. Importantly, these testing scenarios do not represent the conditions in actual underground coal mines, where the dust surface is undulating similar to sand on a beach. The MSHA (2013) prescribed sampling depth of 1/8th inch was established based on USBM and NIOSH research, while the actual depth of dust entrained by an explosion may actually be deeper along the peaks and shallower in the valleys of the undulating dust surface covering the mine floor. Researchers propose examining a dust surface with an undulating profile using CFD modeling along with laboratory and in-mine DSD sampling. Additionally, dust compaction and density are also not considered in the MSHA (2013) guidelines. Researchers found that compaction may likely affect dust entrainment in an explosion. Researchers recommend further investigations to improve the scientific understanding of the mine dust entrainment process on various types of surfaces and dusts during coal dust explosions. This would lead to further refinement of the DSD design and recommendations for more representative mine dust sampling for the industry.

8 References

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9 Appendices

Appendix A: User's Manual

Dust Sampling Device (DSD) Prototype User Manual

Section 1. Introduction

The Mine Dust Sampling Device (DSD) is a safety instrument used for the prevention of coal dust explosions in underground coal mines. It is a handheld, pneumatic mine dust sampling device for underground coal mines that collects a coal-rock dust sample from the mine floor, roof or ribs with air-entrained dust, i.e., by mimicking the dust entrainment process that occurs during a mine explosion. The DSD works by blowing a puff of air of defined pressure and duration over deposited coal and rock dust, entraining the dust sample in air as in a mine explosion, and then trapping the sample for subsequent analysis of its explosibility properties with a Coal Dust Explosibility Meter (CDEM). The use of dust entrainment by the device is superior to the traditional Brush and Pan sampling method, which was shown in mine testing to not properly mimic the explosion process.

Current 2013 MSHA inspector guidelines (MSHA, 2013, pp. 5-12) require mine dust sampling with a brush and dust pan, removing the “uppermost 1/8th inch (approximate depth)” of the mine dust layer. This method is systemically flawed: First, it is difficult to consistently maintain the required sampling depth of 1/8 or 0.125 inches with the brush and pan (BaP). Second, sampling to a given target depth creates a mixing problem: Per the findings by Sapko et al. (1987) and Edwards and Ford (1988), 0.120 inch (3 mm) of rock dust overlaid by 0.005 inch (0.13 mm) of pure coal dust would still be explosive, even though a 0.125-inch-deep sample taken at this location would yield 96% inert content. Furthermore, the brush action is questionable since the bristles may be able to dislodge dust particles with much greater directional force compared to those forces generating entrainment in an explosion.

Section 2. Safety Information

Read and follow information in the User Manual for safe operation of the device.

The Mine Dust Sampling Device (DSD) works with compressed air. Users should wear eye protection while using the DSD.

When using compressed air, all necessary precautions shall be taken to protect persons from injury. The nozzle exhausts of the DSD should never be pointed toward anyone.

The DSD is designed to operate with a compressed air supply between 50 psig and 125 psig.

Operating the DSD at a pressure lower than 50 psig may lead to changes in the sampling duration and charging pressure and may affect the sample depth.

Operating the DSD at a pressure higher than 125 psig may damage components or cause the sudden depressurization of the DSD due to air line connections breaking or components cracking. If the operator of the DSD notices signs of air leakage from the device, immediately cease operation, disconnect the air supply, and contact the manufacturer for repair options.

Section 3. Specifications of the DSD

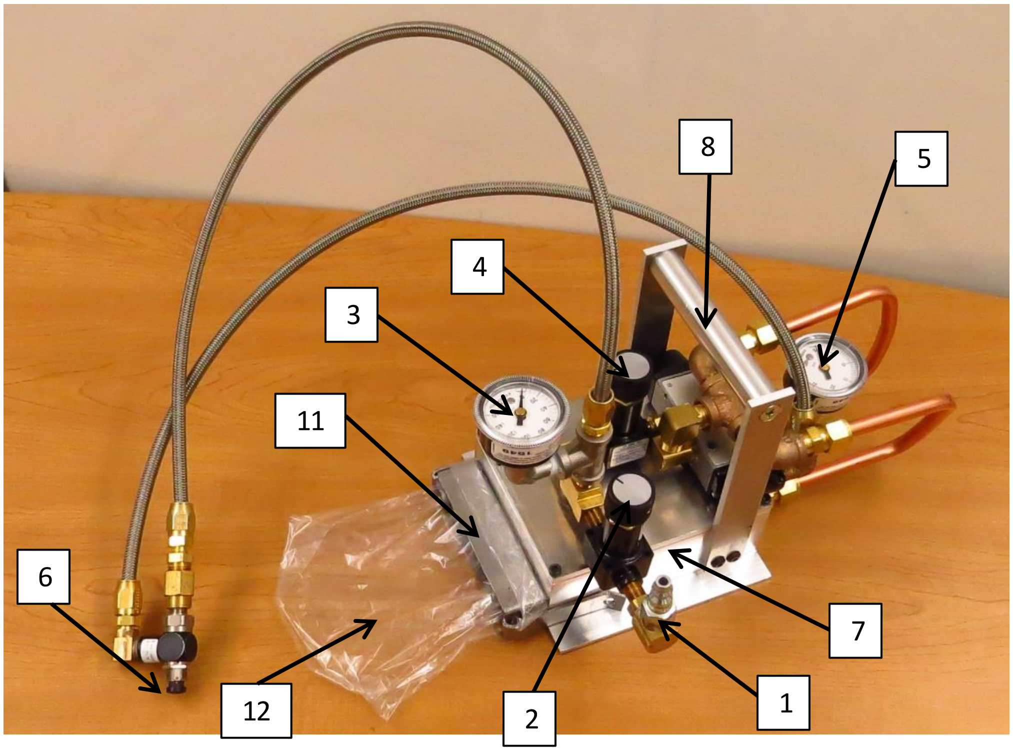

Figure 1. Top view of DSD Version 5.0.

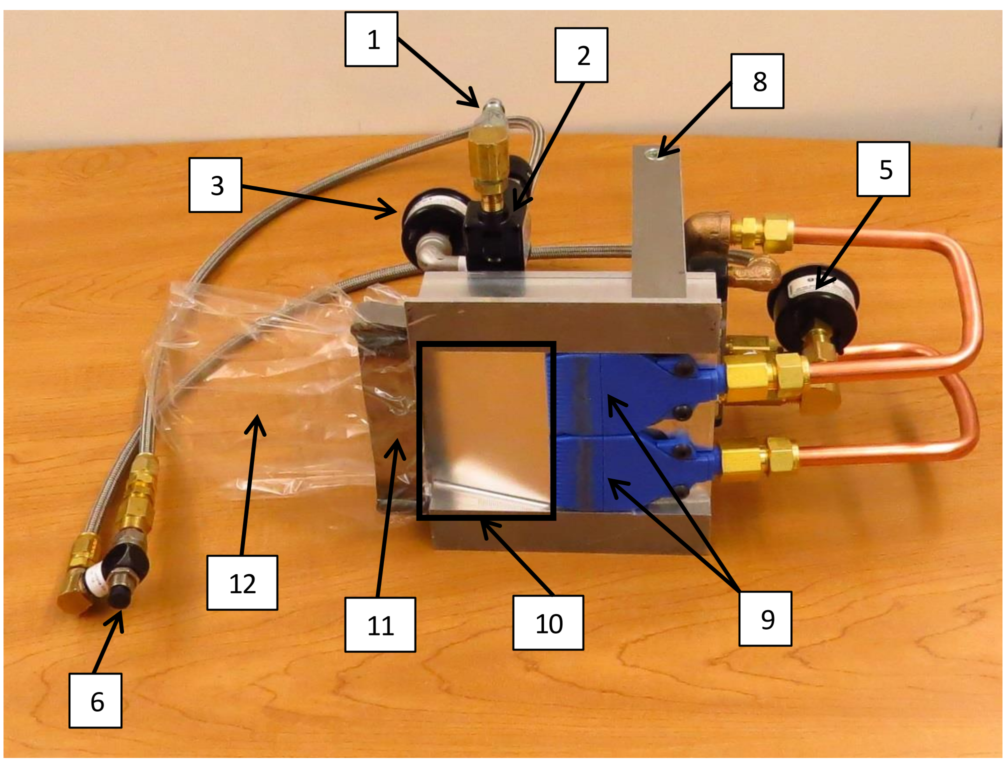

Figure 2. Bottom view of DSD Version 5.0.

1 – Air-line Connection (interchangable)

2 – Device Regulator

3 – Operating Pressure Gauge

4 – Charging Regulator

5 – Charging Pressure Gauge

6 – Push Button Trigger

7 – Charging Vessel

8 – Handle

9 – Air Nozzles

10 – Sample Chamber

11 – Sample Bag Clip

12 – Sample Bag

Section 4. Calibration of DSD

Ensure the DSD is properly calibrated for operation whenever a new compressed air supply is used. Improper calibration may lead to an inaccurate sample.

To calibrate the DSD, follow these steps:

1) Connect the input air-line to the *Air-line Connection* on the DSD. The *Operating Pressure Gauge* will increase from zero psig to either the pressure currently set on the *Charging Regulator*, or the pressure of the input air-line. If the *Operating Pressure Gauge* does not increase, ensure the input air-line is properly connected and charged.
2) Adjust the *Operating Regulator* until the *Operating Pressure Gauge* indicates 50 psig.
3) Place the DSD down on a flat surface and with one hand, hold down the *Push Button Trigger*. The operator should hear the *Charging Vessel* getting up to pressure. Once the *Charging Vessel* pressure normalizes, continue to Step 4.
4) While still holding down the *Push Button Trigger*, use your other hand to adjust the *Charging Regulator* until the *Charging Pressure Gauge* reads 15 psig.
5) Release the *Push Button Trigger*. You will hear the *Charging Vessel* discharge.
6) Repeat Step 3. If the *Charging Pressure Gauge* normalizes to 15 psig, then release the *Push Button Trigger* and the DSD is ready for operation. If the *Charging Pressure Gauge* does not normalize to 15 psig, repeat Steps 4 through 6 until the *Charging Pressure Gauge* normalizes to 15 psig.

Check the calibration of the DSD before each sample collection to ensure the device is operating within its intended parameters.

Section 5. Operation of DSD

Directions for operating the DSD follow the sampling location requirements as stated in the Coal Mine Safety and Health General Inspection Procedures Handbook (MSHA 2013).

1. Ensure the DSD is connected to an input air-line and that the device has been calibrated. (If DSD has not been calibrated, refer to section 3 Calibration of DSD)
2. Attach a *Sample Bag* by placing it through the clip and folding the open end around the edge of the *Sample Bag Clip* (similar to placing a trash bag on a container).

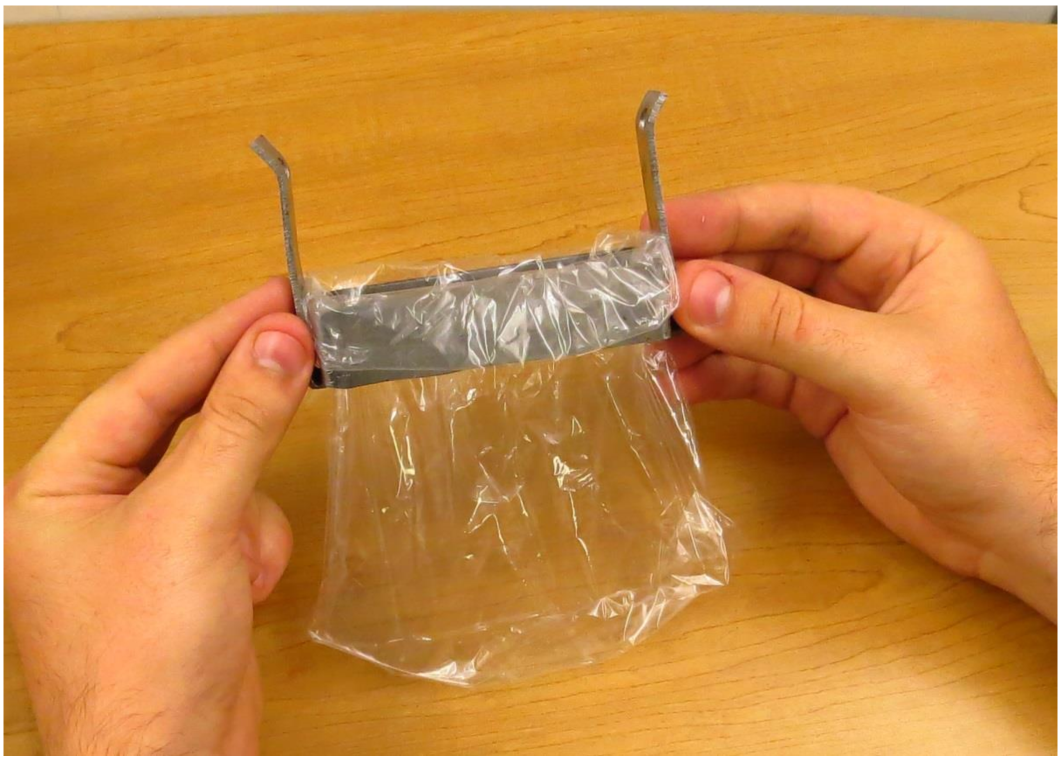

Figure 3. *Sample Bag* properly placed in *Sample Bag Clip.*

3. Slide the *Sample Bag Clip* onto the DSD so the extended arms of the clip snap securely to the rivets on the device.
4. Ensure the portion of the *Sample Bag Clip* with the *Sample Bag* has a tight seal around the entire edge. If the seal is not tight, remove the *Sample Bag Clip* by lightly pulling the extended arms from the rivets of the DSD.
5. Once the *Sample Bag* is secured, take the DSD by the handle in one hand and the *Push Button Triger* in the other hand.
6. Carefully place the device so the bottom of the sampling chamber and leveling wings are level with the surface to be sampled.
7. While continuing to hold the DSD by the handle, hold down the *Push Button Trigger* until the *Charging Pressure Gauge* normalizes to 15 psig.
8. When 15 psig is achieved, release the *Push Button Trigger* to discharge the DSD and collect a dust sample.

9. After the sample has been collected, lift the DSD from the sampled surface and tilt the device so the *Sample Bag* is hanging straight towards the floor.
10. Using the brush, lightly dislodge any of the dust sample still in the sample chamber so that it falls into the *Sample Bag*.
11. Remove the *Sample Bag Clip* by lightly pulling the extended arms from the rivets of the DSD, ensuring not to tilt the bag in an orientation that may cause portions of the dust sample to fall out.
12. Remove the *Sample Bag* from the *Sample Bag Clip*. The collected sample can be stored for later testing or used with a CDEM to provide TIC information at the sample location.

If there was poor contact with the sampling surface, or the DSD was pressed too deeply onto the sampling surface, reset the test by recharging the DSD. If an inadequate sample is identified after Step 8, restart from step 1. If an inadequate sample is identified before step 8, place the DSD in a new area of the sample surface and continue from the current Step.

Section 6. Maintenance and Cleaning of DSD

Ensure the DSD is discharged and disconnected from any air-supply before performing maintenance. The DSD can be wiped down with a cloth or paper towel using general purpose cleaner or water when it becomes dirty. Do not submerge the device or use excessive cleaner near the *air nozzle* exhausts and the *air-line connection*. Allow the DSD to fully dry before operation.

Section 7. Sample Bag Replacement Information

The DSD is designed to work with any standard fold-top sandwich bag with similar dimensions of 6.5x5.5x1 inch. Bags of this size are readily available at online retailers or local household goods stores.

Section 8. References

MSHA [2013]: Coal Mine Safety and Health General Inspection Procedures Handbook, Mine Safety and Health Administration, Handbook Number: PH13-V-1, February 2013, p. 276.

Appendix B: Cylindrical Dust Sampler Concept

Before the design of DSD Version 1.0, researchers considered an entirely different sampler design with a collection system that used a vertical nozzle to entrain dust and blow it radially away from the nozzle onto a collection plate. The initial design for this prototype used a 6 inch long piece of 0.25 inch inner diameter steel pipe inside of a 4 inch inner diameter piece of PVC pipe. The top section was sealed with a screw cap and the steel pipe fixed in position through a center hole made in the cap at 1 inch above the dust layer. The bottom section that contacted the dust surface used a 6x6 inch PVC plate. Two plates were constructed, one with a 1 inch diameter hole cut through the center and the other with a 2 inch diameter hole in the center. These plates were the location on which the scoured dust would be collected and weighed. To allow for easy collection of the dust sample, the PVC plates were kept separate from the main unit. A diagram of the cylindrical sampler is shown in Figure 108.

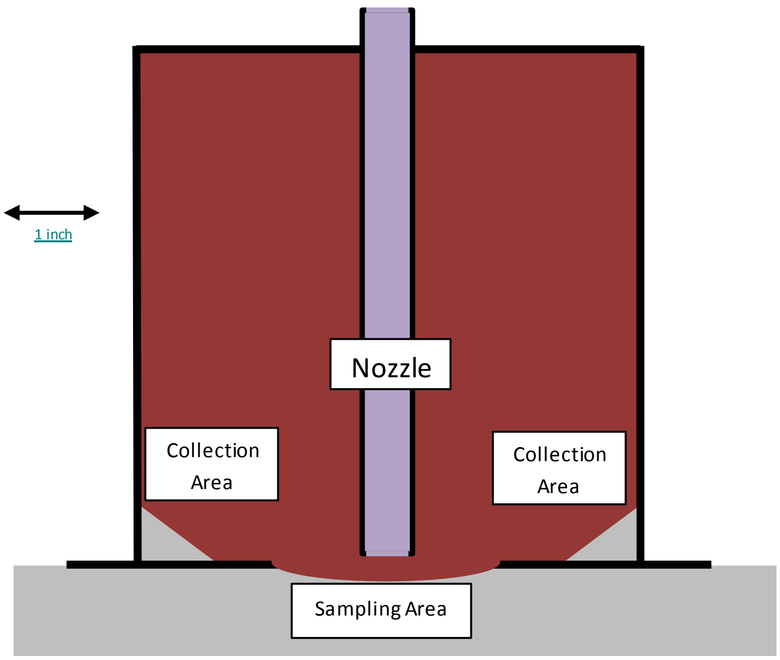

Figure 108. Diagram of cylindrical DSD prototype with air pipe (purple) and sample chamber (dark red) on top of dust surface (grey).

Test Results and Conclusions

Tests were conducted at 15, 20 and 35 psig using the plates with 1 inch and 2 inch diameter holes. The steel pipe nozzle was connected to a control valve and 18 cubic inch charging vessel. Test results in Table 5 showed that that this vertical nozzle arrangement created either too deep of a scour or did not collect a sufficient sample mass. Additionally, the force from the nozzle airstream caused compaction rather than entrainment. This made it difficult for researchers to accurately determine if the sample mass being collected was representative of the top 0.125 inch of the dust layer. Researchers decided that a vertical nozzle setup could not properly collect the top layer of dust as intended for the DSD and decided to design a DSD prototype that built upon the nozzle testing conducted previous to the cylindrical sampler.

Table 5. Scour and depth results from tests with cylindrical DSD prototype.

Plate Hole Diameter (inch)	Pressure (psig)	Scour Depth (inch)	Sample Mass (g)
1	15	0.22	1
1	20	0.72	2.8
1	35	0.97	3.8
2	15	0.41	4.8
2	20	0.97	8.7
2	35	0.97	11.8

10 Acknowledgement/Disclaimer

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