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EVALUATION OF MINE VENTILATION IN LARGE-OPENING UNDERGROUND STONE MINES

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ABSTRACT

Researchers at the National Institute for Occupational Safety and Health (NIOSH) are conducting research to improve the ventilation of large-opening underground stone mines. The mine ventilation in these mines are characterized by: (1) challenges related to keeping airflow velocities high enough to effectively remove or dilute airborne contaminants, (2) low pressure losses needed to move large air volumes of air, and (3) costly stoppings needed to direct ventilation airflows. Each of two field studies was dedicated to specific focus areas.

The first focus area was the characterization of underground mine ventilation airflow. The primary means of airflow control in stone mines is through the use of freestanding booster fans. The primary goal of this study was to identify the effectiveness of various fan types and optimize their placement. Both traverse and grid-based airflow readings were taken at various distances from the fans, ranging from 70 ft to 425 ft away from the fan. The air readings were taken using a vane-anemometer and a handheld hotwire anemometer. The data was used to develop precise computational fluid dynamics models.

The second focus area was to determine diesel particulate matter (DPM) concentrations in the mine. For large-opening underground stone mines, controlling DPM exposures dictates the design of the ventilation system. Therefore, researchers carried out the DPM sampling campaign to identify potential areas of concern within the mine. The samples collected during the campaign were analyzed using NIOSH Method 5040. The sampling was done using the Mine Safety and Health Administration's (MSHA) compliance sampling methodology.

This paper discusses the analysis of ventilation and contaminant sampling data and its various applications for improving underground mine ventilation of large-opening stone mines.

INTRODUCTION

The ventilation systems for large-opening stone operations vary as a function of number of entries, depths of operations, slopes of deposit, use of benching, and use of natural ventilation. During the 2000s, the National Institute for Occupational Safety and Health (NIOSH) conducted extensive research to study large-opening mine ventilation. The research suggested that these mines face three primary ventilation challenges: (1) moving adequate volumes of ventilation air, (2) effectively controlling and directing the airflow, and (3) adequately planning ventilation systems to match production requirements (Grau et al., 2006).

The large entries generate low flow resistance. A well-developed underground stone mine can have a void volume of several million cubic meters and require many hours for a complete air change. Recognizing this fact, NIOSH demonstrated the effectiveness of the use of low-pressure propeller fans for main and auxiliary mine ventilation (Grau et al., 2004; Krog et al., 2004). Mine operators are responsible for meeting any federal guidelines (30 CFR Part 57) regarding placement and installation of fans. NIOSH has since focused on the application of propeller fans for regional and face ventilation applications in large-opening mines.

The continuing and emerging air quality issues in large-opening mines include silica dust, diesel particulate matter (DPM), and noxious gases (from diesel equipment, welding, and production blasts. DPM concentrations are the controlling factor for large-opening underground stone mines and dictate the design of the ventilation system and the air quantities required underground (Bugarski and Potts, 2018; Noll et al., 2008; Harris et al., 2022). The current allowable DPM concentration limit is 160 µg/m^3 (CFR 57.5060(b)(3)). DPM limits still seem to be a prevalent issue and conforming to standard 30 CFR 57.5060(b)(3) can dictate airflow requirements of the entire mine. The utilization of improved Tier 4 diesel engines, exhaust aftertreatment, alternative fuels, environmental enclosures, and administrative controls can reduce DPM concentrations and help underground mine operators meet the MSHA standards covered by code of federal regulations. Improved ventilation plays a vital role in helping mine operators meet the new standards and reduce overexposure in addition to the approaches described above.

EXPERIMENTAL METHODOLOGY

Ventilation Airflow Measurements

A TSI Velocicalc 9535 Air Meter was used for this calculating air velocities (Figure 1). Ventilation airflow was measured using a mechanical anemometer (Davis 6-blade anemometer) and a handheld hotwire anemometer (TSI 9535). The mechanical anemometers are suitable for medium to high air velocities (>50 fpm). The handheld hotwire anemometer was used to take point-based readings at locations characterized by low air velocities. The anemometer reading was taken every 5 seconds. The moving averages were calculated for a 1-minute period. Researchers also utilized smoke tubes for airflow readings and observed the airflow patterns in the areas where there was high recirculation or formation of eddies.

Figure 1. TSI Velocicalc 9535 air meter used for low-velocity, point-based measurements.

Diesel Particulate Matter (DPM) Measurement

Various mining activities such as blasting, welding, operating diesel engines, and in some cases emissions from the ground strata, create contaminants that enter the mine atmosphere and need to be diluted. From these activities, a growing concern is with the mine workers' exposure to diesel particulate matter (DPM) emitted from the diesel engines operating in the mine. DPM is a complex mixture of particulate elemental carbon (EC) or soot, particulate and particle-bound organic carbon (OC), sulfates, some metals, and other particles. The DPM sampling and analysis was conducted using the commonly used NIOSH 5040 method.

Diesel particulate matter (DPM) samples from underground mines were collected on quartz fiber filters and analyzed for carbon content using NIOSH Method 5040 (NIOSH, 2003). The SKC DPM cassette were attached to a 10-mm Dorr-Oliver cyclone with tubing extending from the cassette to the SKC Airchek sampling pump operated at 1.7 lpm (Figure 2). The SKC DPM cassette is used for collecting DPM [MSHA, 2001; Noll and Janisko, 2007]. The cassette retrieves particulate, at a 0.8-µm cut point at 1.7 lpm, onto quartz fiber filters to collect DPM in the presence of dust. The samples were analyzed for EC and OC using NIOSH Method 5040 (NIOSH, 2003). The flow rates of all pumps and instruments were checked and recorded.

Figure 2. Pumps for DPM sampling using the NIOSH 5040 method.

RESULTS AND DISCUSSION

Ventilation Airflow Survey

The airflow measurements were conducted at two actively working/producing areas of the mine. The first area had active development on one side of the entry and a long stone pillar in-place on the other side in the ventilation airway (Figure 3). The second area had been developed on both sides, and there were open entries on both sides of the ventilation area (Figure 6). Both these locations had a 6-ft-diameter, freestanding diesel fan (Paul's Fan). The intent behind choosing these two areas of the mine was to compare the airflow patterns, air losses, air recirculation, air entrainment, and air penetration (Watkins and Gangrade, 2022). The data collected from the mine is currently being used to develop computational fluid dynamics (CFD) models to determine the optimal spacing between two booster fans.

The fan shown in Figure 3 moves a large quantity (29.7 m^3/sec, 63,000 CFM) of air through the area, and the air leaving the fan outlet is moving at 11.3 m/sec (2,230 fpm) and expands rapidly to cover the entire cross-section of the drift. The air around the fan gets entrained to increase the overall volume of airflow by seven times. Figure 4 shows the cross-sectional velocity profile 154 ft (47 m) in front of the fan's outlet. The airflow is quickly being dispersed across the entire drift. The peak air velocity was 733 fpm, and the minimum air velocity was 69 fpm, with a very high standard deviation of 1.07 m/sec (211 fpm). All grid sections of the drift had positive airflow down the drift, with no airflow roll back being observed. The velocity was much higher near the floor and progressively decreased towards the roof; this is possibly due to the proximity to the fan where the flow had not yet expanded towards the roof of the section. The velocity is also higher towards the right-hand side (when facing the fan from the cross-section), as the fan was also located on the right-hand side when seen from this location. The average airflow at the location was 210.5 m^3/sec (446 kcfm).

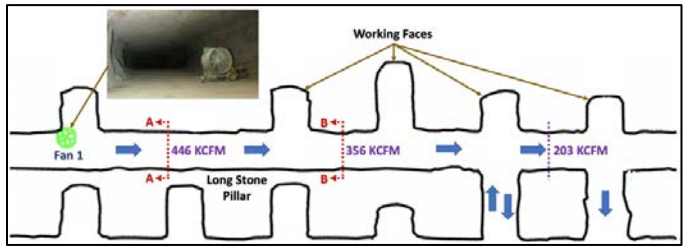

Figure 3. Airflow generated by the 6-ft, freestanding diesel fan in the area with long stone pillar on one side and working faces on the other side.

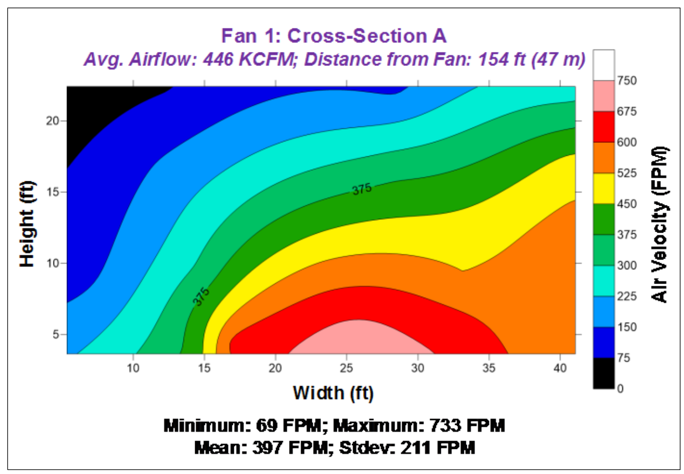

Figure 4. Cross-section A-A, the airflow at 154 ft (47 m) in front of 6-ft-diameter fan, and flow out of page.

Figure 5 shows the airflow 128 m (421 ft) in front of the fan. The air stream completely enveloped the drift, with a peak air velocity of 1.67 m/sec (329 fpm) and minimum air velocity of 1.20 m/sec (237 fpm). The velocity profile is much closer to uniform (i.e. being more evenly distributed across the drift) than was observed in Figure 4. The average airflow recorded at this location is 162.82 m^3/sec (345 kcfm) and the standard deviation is 0.14 m/sec (27 fpm) compared to 1.07 m/sec (211 fpm) for cross-section A, signifying that the flow is more uniform at this location further away from the fan. Part of the airflow goes straight after the intersection; however, there is some recirculation in the crosscut of the first intersection with air trying to leave and air entrainment bringing some air back.

Figure 6 shows the airflow characteristics for a fan in an area with open entries on both sides of the main ventilation airway. Similar to fan 1, air entrainment also takes place near fan 2. The high-velocity air moving down the main entry would catch the corners of the pillars and be directed perpendicularly down the crosscuts. An eddy formed behind the pillars of the crosscuts, pulling air into the main ventilation drift. The net result was a comparatively small change in the total airflow moving down the main entry for the first few intersections, downstream from the fan (Figure 6). However, because of the expanding airflow and open entries with low resistance around the main entry, there was recirculation with the surrounding air, especially in the first couple of crosscuts. Some crosscuts down the entry had airflow going in both directions within the same crosscut.

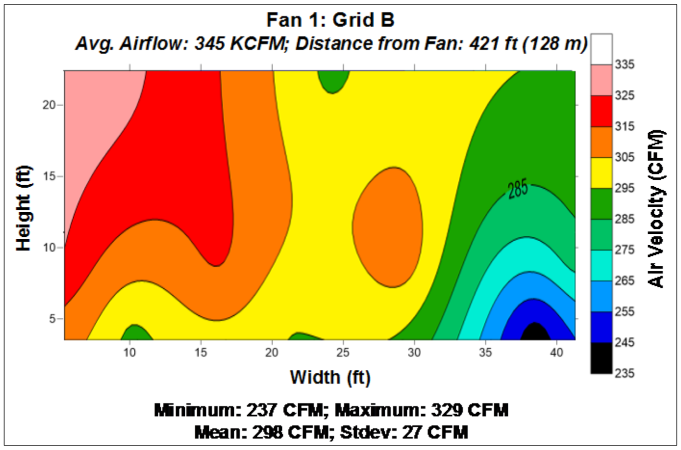

Figure 5. Cross-section B-B, airflow at 421 ft (128 m) in front of 6-ft-diameter fan, flow out of page.

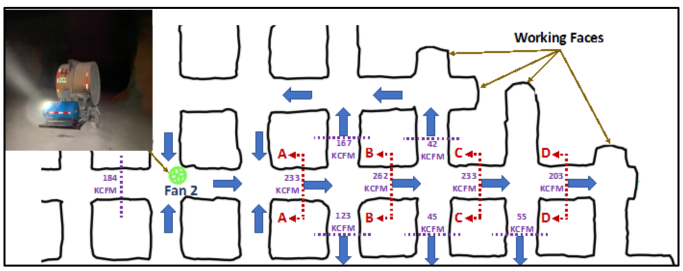

Figure 6. Airflow characteristics for a 6-ft, freestanding diesel fan in an area with open entries on both sides in the drift. Open entries lead to recirculation of air.

Figure 7 shows the cross-sectional velocity profile 69 ft (21 m) in front of the fan's outlet (cross-section A). The airflow is concentrated right side of the opening as the high-speed air starts to expand (when facing towards the fan in the cross-section). The peak air velocity was 3.76 m/sec (741 fpm) near the bottom corner, and the air velocity was less than 0.15 m/sec (30 fpm) in the left-hand side of the cross section. Airflow near the left-hand side rib was below recordable levels. The reasoning behind this is the proximity to the fan and the airflow not fully developing. The mean velocity in this cross-section was 1.17 m/sec (231 fpm), and the average airflow was 110 m^3/sec (233 kcfm). The standard deviation was very high, with a value of 1.12 m/sec (220 fpm).

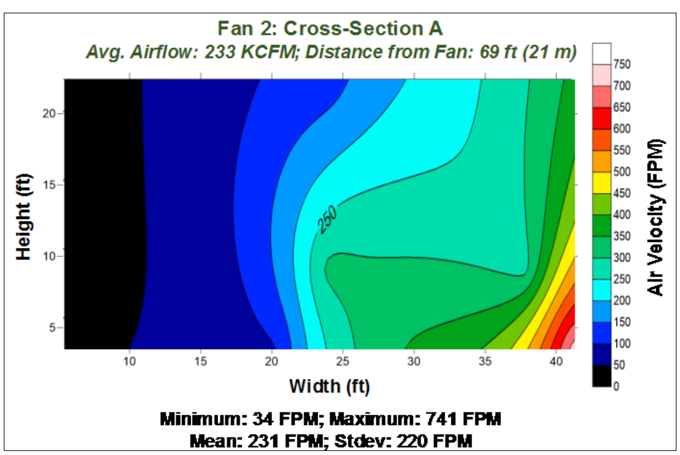

Figure 7. Cross-section A-A, airflow at 69 ft (21 m) in front of 6-ft-diameter fan, flow out of page.

Figure 8 shows a similar air profile (cross-section B) further down the drift at a distance of 180 ft (55 m) from the fan. The air stream is predominantly flowing 3/4th of the entry and higher near the ground then at the roof, and very little airflow was recorded in the upper left portion of the drift. The peak velocity was 1.16 m/sec (229 fpm), and the minimum velocity was 0.47 m/sec (93 fpm). The mean velocity was 1.09 m/sec (215 fpm), and the standard deviation was 0.2 m/sec (40 fpm). As the air expands further, the air flows into the open entries and recirculates, forming a loop around the pillars as shown in Figure 6.

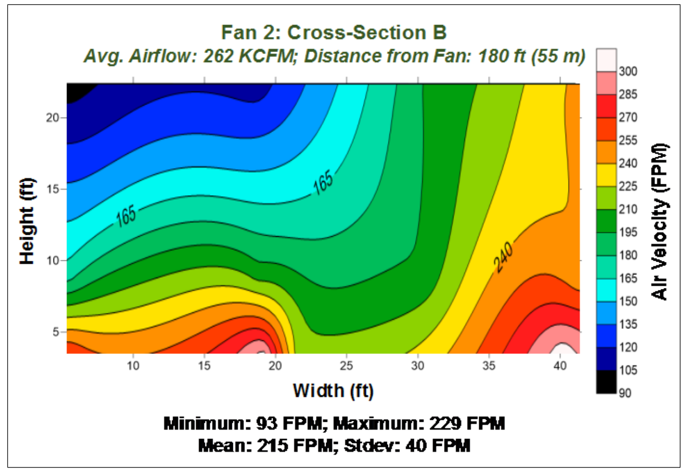

Figure 8. Cross-section B-B, airflow at 180 ft (55 m) in front of 6-ft-diameter fan, flow out of page.

Figures 9 and 10 show the vertical cross-sections C-C and D-D further down the drift. The air stream completely enveloped the drift, with a peak air velocity of 1.58 m/sec (311 fpm) in cross-section C-C and a mere 1 m/sec (195 fpm) in cross-section D-D. The minimum air velocity is 0.5 m/sec (98 fpm) for cross-section C-C and 0.71 m/sec (139 fpm) for cross-section D-D. The velocity profile is much closer to uniform (i.e. being more evenly distributed across the drift) than was observed at cross-sections A-A and B-B. The low standard deviations for these locations show that as well. The airflow quantity progressively diminishes after each intersection. Recirculation is observed in the first and second intersection.

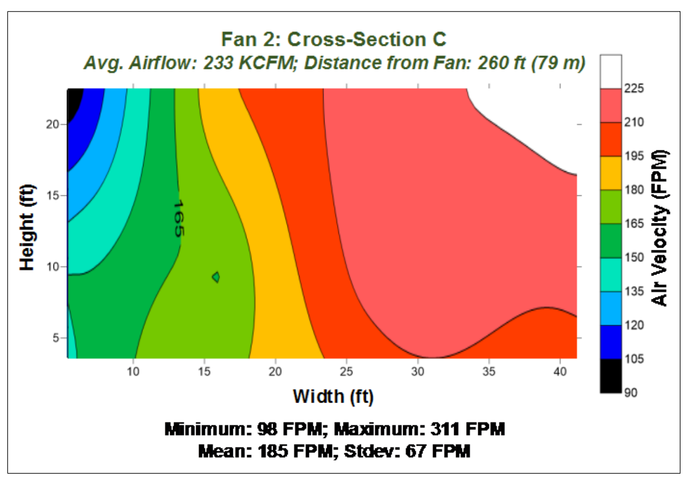

Figure 9. Cross-section C-C, airflow at 260 ft (79 m) in front of 6-ft-diameter fan, flow out of page.

DPM Contaminant Sampling

There were six areas chosen in the mine that were distinct from each other in characteristics. Some areas had machines such as drills, scalars, man lifts, haul trucks, etc. actively working in them, and others had no machines or haul trucks moving in the entries. Table 1 (see APPENDIX) describes the various locations where samples were collected. Due to logistical and operational challenges, the samples could not be collected for 8 hours. In this study, the sampling time ranged from 3-4 hours at each location. As shown in Figure 11, the SKC cassettes placed in a special holder were connected to a portable battery-operated pump. The setup was installed using wooden sticks in the areas of interest. The main goal behind this sampling was to understand the background levels of DPM in these areas of interest when the machines are operating, and production is going on. At the location with the drill, three samples were taken at various heights in the bottom 20%, mid-height, and top 20% of the roof (percentage of entry height). It should be noted that the sampling was not an average of the entire shift and was only representative when the machines were actively working in the area of sampling or haul trucks were running in the entries.

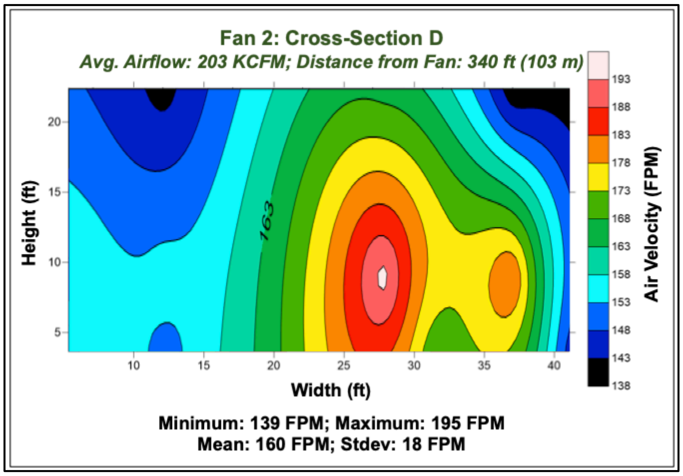

Figure 10. Cross-section D-D, airflow at 340 ft (103 m) in front of 6-ft-diameter fan, flow out of page.

Figure 11. DPM sampling underground.

At the location with the scalar machine, the average total carbon (TC) concentration was 153.5 µg/m^3 which is slightly below the 160 µg/m^3 PEL. Similarly, the TC concentration at the haul truck route was 145.94 µg/m^3. At the bottom of the ramp, the TC concentration was 101.22 µg/m^3. There was very little TC near the blaster. The mine had a small ventilation raise, and one of the sampling locations was located near the bottom of the raise where contaminated air was coming from working faces and was exhausted outside the mine. The TC concentrations at that location were as high as 164.02 µg/m^3. The TC concentrations were highest at the drill location. Those were attributed to the relatively large diesel engines installed in the drilling machines underground. The DPM data will be used to validate CFD models.

SUMMARY

The researchers conducted detailed mine ventilation and contaminant surveys at two large-opening underground stone mines. The results were used to study the ventilation airflow rates and DPM concentrations. The data improves the overall understanding of the ventilation system and characteristics in these types of mines.

The survey was conducted at two actively working/producing areas of the mine that were selected for the study. The first area had active development on one side of the entry and a natural long stone pillar in-place on the other side in the ventilation airway. The second area had been developed on both sides and there were open entries on both sides of the ventilation area. Both of these locations had a 6-ft-diameter, freestanding diesel fan. Statistical data for the velocity profiles of the cross-sections in front of the fans (Figs. 4-5 and 7-10) are given in Table 2. It was observed that the level of possible entrainment is a function of the nonuniformity in the velocity profiles across the drift. A uniform distribution of velocities across the drift may not induce entrainment, but nonuniform velocity distributions can. As can be seen in Table 2, the standard deviation is high when compared to the mean velocity for both cross-sectional locations, indicating that entrainment may occur down the drift and work against the natural decay of airflow quantities. For cross-sections that have a much lower standard deviation, additional airflows may not be entrained beyond the initial crosscuts.

Table 2. Mean velocity and standard deviation of cross-sectional airflow in front of the fans.

	Fan 1		Fan 2			
Distance to fan (ft)	154	421	69	180	260	340
Mean Velocity (fpm)	397	298	231	215	185	160
Standard Deviation (fpm)	211	27	220	40	67	18

The DPM results showed that there are multiple areas of concern in the stone mine where the TC concentrations are high due to the extensive use of diesel engines. Past and current research from NIOSH in this area indicates that a multiprong approach is needed to reduce DPM exposures of miners in the large-opening mines.

The NIOSH researchers are currently utilizing the ventilation and contaminant data discussed in this paper to develop complex CFD models as shown in Figure 12 to answer multiple research questions pertaining to improvement of ventilation and reduction of contaminant exposure underground. One of the most important research questions that the researchers are currently working on is the determination of optimal spacing between two booster fans underground. The data is also being used to simulate the drill, scalar, haul trucks, and other mining equipment underground using the CFD analysis.

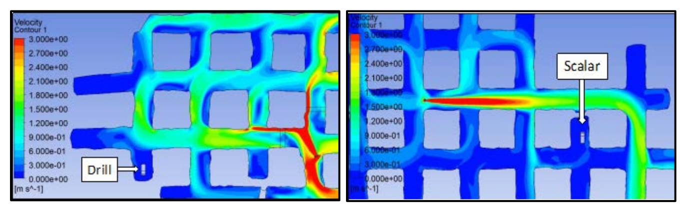

Figure 12. CFD model development using field data from underground stone mines.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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APPENDIX

Table 1. DPM sampling analysis using the NIOSH 5040 method.

Location	**Organic Carbon ($\mu g/cm^2$)**			**Elemental Carbon ($\mu g/cm^2$)**			**Total Carbon ($\mu g/cm^2$)**	**Sampling Time (min)**	**TC Concentration ($\mu g/m^3$)**
	Primary	Secondary	Net	Primary	Secondary	Net	OC+EC		
Scalar	3.07	1.66	1.41	5.60	0.00	5.60	7.01	216	**153.50**
Haul Truck Route	3.63	1.42	2.21	3.26	0.00	3.26	5.46	177	**145.94**
Ventilation Raise	3.70	1.28	2.43	5.13	0.00	5.13	7.56	218	**164.02**
Bottom of the Ramp	4.67	3.35	1.33	2.61	0.00	2.61	3.94	184	**101.22**
Blaster	1.72	1.56	0.16	1.86	0.00	1.86	2.02	226	**42.18**
Drill (Bottom)	12.86	1.73	11.12	0.19	0.00	0.19	11.32	197	**271.69**
Drill (Middle)	10.38	1.35	9.03	2.45	0.00	2.45	11.48	197	**275.63**
Drill (Top)	5.28	1.75	3.53	12.44	0.00	12.44	15.97	197	**383.29**