Ventilating large opening mines

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Abstract

The National Institute for Occupational Safety and Health (NIOSH) has conducted research to improve the ventilation of large-opening mines whose entries are at least 93m^2 (1,000 ft2). The ventilation of large-opening mines is unique compared to other types of mines because (1) it is challenging to keep airflow velocities high enough to effectively remove or dilute airborne contaminants because the entries are so large, (2) large air volumes can be moved through the mines with little static pressure drop, and (3) stoppings that are used to direct ventilation airflows are costly to construct and to maintain. The research results suggest that the ventilation of large-opening mines is improved significantly by incorporating ventilation planning into the mine planning process, using propeller fans to direct airflow, developing new stopping materials and construction methods, and using long pillars to eliminate crosscuts where possible.

Introduction

Some metal/nonmetal mines in the United States have large openings or entries that are at least 93 m^2 (1000 ft^2) in cross-sectional area. Limestone aggregate is the most common type, with 101 of these mines operating in the United States in 2006 (MSHA, 2006). Underground limestone aggregate mines use room-and-pillar mining techniques with entries that are about 12 m (40 ft) wide and 8 m (25 ft) high, often followed by two bench cuts that increase the height to as much as 24 m (80 ft). Other types of large-opening mines include marble, dimension stone, salt, and lead/zinc.

This paper discusses air quality concerns and methods to improve the ventilation of large-opening mines. Due to recent Mine Safety and Health Administration (MSHA) regulations, the primary air quality concern in large-opening mines is diesel particulate matter (DPM). Other contaminants of concern are diesel equipment exhaust gases, welding fumes, silica dust, and nuisance conditions of fog and inert dust. After lengthy litigation, the MSHA rule establishing DPM exposure limits in underground metal/non-metal mines was upheld by the courts. On May 18, 2006, MSHA promulgated a final rule that changed the interim DPM limit to 350 µg/m^{3}EC (elemental carbon) effective on January 20, 2007. On May 20, 2008, the limit was reduced to 160 µg/m^{3}TC (total carbon).

The strategy used by many operators to reduce workers' exposures to these contaminants is to employ engineering controls such as increasing the air quantity entering the mine, using stoppings and auxiliary fans, and developing mine plans that specifically consider ventilation needs (Grau et al., 2004a, 2006a, 2006b; Krog et al., 2004) and methods that direct airflow to the face areas. Previous literature (Head, 2001; Grau, 2004b) has documented that large airflow volumes are required to dilute DPM in order to meet the MSHA regulatory standards.

It is important to consider ventilation requirements while developing mining plans. Until recently, ventilation was not a major part of the underground limestone mine planning processes (Head, 2001; Grau et al., 2002; Krog et al., 2004). The length and orientation of long stone pillars and the principle of dividing the mine into smaller units are vital means to improve ventilation. Mine planning should consider ventilation plans incorporating main mine fans, auxiliary fans, and stoppings and these plans should focus, in particular, on face areas, maintenance shops, crusher areas, and truck haulage routes. Since truck haulage is the largest contributor of DPM in the underground mine environment, effective planning of haulage routes will reduce workers' exposure to DPM. It is generally best for truck haulage to take place in return air, allowing the truck exhaust to exit the mine and thus preventing contamination of the air used to ventilate the face units. Truck operators are usually protected in pressurised and filtered cab systems; however, scaler operators, blasters, drillers, mechanics, and laborers who work outside these cab systems in face areas are exposed to airborne contaminants. Finally, significant decreases in DPM emissions can be realised by using cleaner burning engines, catalytic converters, filters (Schnakenberg et.al., 2002), and alternative fuels.

Understanding the ventilation of large-opening mines

Since many limestone mines operate at shallow depths, drift portals are common at these operations. Operations at depths up to 61 m (200 ft) are ventilated using airshafts or slopes, the latter also providing access. Still deeper large-opening mines such as lead/zinc mines and salt mines use shafts for access and ventilation. The type of opening to the surface largely determines the main mine fan type in large-opening mines. Mines with drift portals have extremely low mine ventilation head loss; therefore, propeller fans are a viable option for whole-mine ventilation in those mines.

Drift stone mines have some common characteristics that influence the ventilation. Features such as multiple portal openings with small elevation differences between portals are common, creating weak but noticeable natural ventilation. From observation, truck movements and outside wind conditions are factors that appear to create air currents independent of mechanical ventilation that impact air movement in large-opening mines. These air currents may enhance ventilation when the trucks are moving in the direction of the mine ventilation and reduce the mine ventilation when the trucks are moving against the ventilation airflow direction. The large void volume created from benching operations influences the air quality because the void is available for diluting air contaminants, essentially reducing the required ventilation air quantity. In addition, the high roofline in the benching area allows the diesel equipment's hot exhaust gases to rise away from workers, reducing their exposure to DPM.

Ventilating large-opening mines poses some specialised challenges that include providing sufficient airflow to dilute airborne contaminants to statutory levels, while simultaneously using auxiliary fans or stoppings to control and direct the airflow to face areas where diesel equipment is operating. Offsetting these challenges is the extremely low resistance to ventilation airflow because of the large cross-sectional area of the openings. From an engineering design prospective, the large air quantity/low pressure scenario plays an integral part in the overall mine ventilation design of large-opening mines, because large air quantities can be moved through large distances with very small pressure drops.

Estimating air requirements

The first step in designing an effective ventilation system in large-opening mines is determining the total air quantity necessary for effective dilution of DPM and other contaminants. Although there are a number of noxious airborne contaminants, for most mines, the overriding ventilation design parameter is the dilution of DPM. However, the actual air quantity necessary is dependent upon how efficient the air is distributed to the faces using auxiliary fans and stopping lines.

To help operators estimate how much ventilation air quantity is necessary in their mine based upon DPM exposure limits established by MSHA (MSHA, 2001), NIOSH developed an air quantity estimator software programme (Robertson et al., 2004). For the equipment operating in an underground stone mine that annually produced 1.13 million metric tons (1.25 million tons), Grau (2004b) reported that an air quantity of 400 m^3/s (850,000 cfm) was required to dilute DPM to a 400TC $\mu g/m^3$ concentration, and 990 m^3/s (2,100,000 cfm) was required to dilute DPM to a 160 TC $\mu g/m^3$ concentration. However, these conclusions were based on the existing controls and the equipment operating in the mine. In fact, the required air quantity can be reduced significantly by replacing older engines with cleaner-burning engines. Mine operators can dramatically decrease air requirements by selectively replacing older less efficient engines with newer engines that produce less DPM emissions or through the introduction of other controls which reduce DPM emissions.

Ventilation considerations of underground limestone mines

As the mining industry strives to improve the air quality in underground large-opening mines, there is an observable transition from reliance on natural ventilation to an increased use of mechanical ventilation. Mechanical ventilation with stoppings offers a more-controlled ventilation system compared to natural ventilation. Operators of limestone drift mines have often relied on natural ventilation because even with small differences in elevation, natural ventilation can produce large (though uncontrolled) air volume movements and mine air exchanges. Furthermore, natural ventilation is helpful in some large-opening drift limestone mines where larger openings are created during benching. From observation, it appears that even with inadequate ventilation, DPM concentrations develop more gradually in these areas because of the larger available space. During the night shift, when no mining is occurring, the natural ventilation also refreshes the air reserve.

Temperature differences between air pockets in the mine can create barriers preventing effective ventilation. If conditions allow the air to short circuit these areas, inadequate ventilation will result. This is clearly observable as mines often have more difficulty maintaining air quality when the outside temperatures are warmer. Particularly problematic is mining up-grade as shown in Figure 1. In this situation, adequate face ventilation is more difficult because the hot exhaust fumes rise and accumulate in the upper face corner. One way to improve the ventilation in these areas is to ensure auxiliary fans are properly positioned to direct the air to the specific mine areas. As shown, mining down-grade enhances air quality as hot exhaust fumes rise and follow the roofline to the return entry.

The appropriate selection of auxiliary fans and main mine fans should be based upon their operating parameters and the mine characteristics. Low-pressure propeller fans move large airflow volumes efficiently in

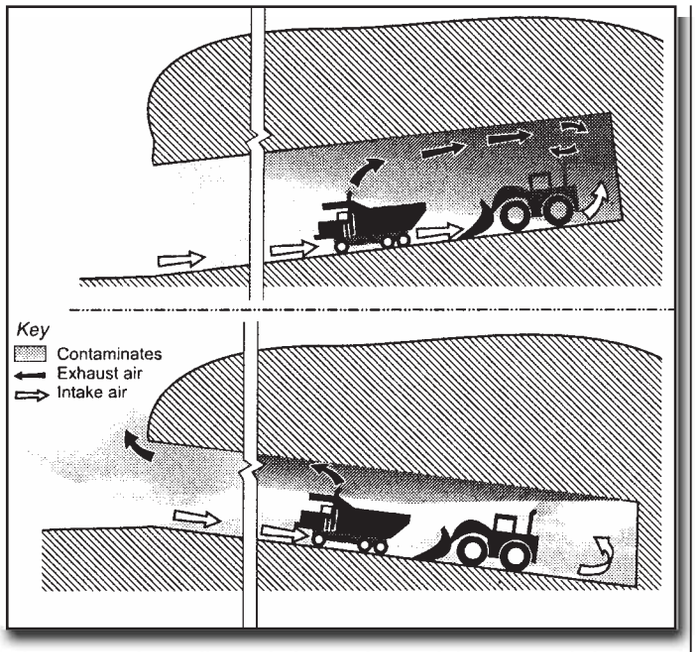

Figure 1: Air quality variations when mining up and down dip.

large-opening drift mines and in some shallow slope or shaft mines (Grau et al., 2004b; Krog et al., 2004). Further, mine ventilation effectiveness is substantially increased when used in conjunction with directional control devices such as stoppings or rectangular pillars. The rectangular stone pillars are named "long pillars" because their length is over ten times their width. The long pillars are oriented to create continuous walls, often called "air walls," that separate intake airways from return airways and, with stoppings, direct the air to desired locations. Other methods to separate airways permanently are stoppings constructed of fly ash block or piled waste stone. Alternatively, fabric stoppings can be moved in concert with mining advances to create needed ventilation changes.

From NIOSH observations, it appears that most U.S. large-opening limestone mining operations use a primary single mine air split to ventilate the active mining faces. This single split concept eliminates the need for other control measures such as overcasts, regulators, and air doors. Ventilation techniques in underground limestone mines have evolved from using auxiliary fans alone to auxiliary fans with stoppings to direct air to the faces. It appears that the combination of auxiliary fans and stoppings is becoming more frequently used to direct the ventilation airflow. Many operators of older mines that do not have long pillars directing the ventilation air are now faced with installing stoppings, requiring a considerable investment in time and construction costs.

Using long stone pillars to increase ventilation efficiency

Reducing DPM concentrations requires that a high percentage of air generated by the main mine fan be used to ventilate the faces where much of the diesel powered equipment operates. This percentage of air is represented by the mine ventilation efficiency, which equals the airflow at the face divided by the total mine ventilation airflow. Ventilation airflow must be directed to the faces using stopping lines that separate intakes from returns. Using long pillars, rather than leakage-prone constructed stoppings, dramatically increases ventilation efficiency. It is clear that long stone pillars reduce the building and maintenance of constructed stoppings, reduce leakage, and increase the percentage of total mine ventilation air reaching the working faces. Unfortunately, due to mine layout and vehicle movement, directing ventilation air using only long stone pillars is not always practical. Constructed stoppings are often necessary, even though they are difficult and costly to construct and maintain in large openings. Poor installation techniques and inferior construction materials lead to stopping failure, resulting in large air quantity leakage.

Grau (2006a) demonstrated the dramatic differences in mine ventilation efficiencies found between an older mine retrofitted with fabric stoppings and a newer mine that used long stone pillars from mine start. In the former case, controlling leakage was difficult due to tears in the brattice material from repetitive motion and blast damage. Due to this leakage, only about 33% of the ventilation air from the fan was available for the faces at 800 m (2,625 ft) from the main mine fans. In comparison to the older mine with the brattice stopping wall, the newer mine using the longer stone pillars to direct the air delivered 77 pct of air at the main mine fan to the last open crosscut located 680 m (2,230 ft) from the fan. Mines using fabric stoppings to run long air walls will find that as the mine expands, requiring additional stoppings, the ventilation system may be incapable of delivering adequate fresh air quantities to the working areas. This will necessitate the addition of a ventilation shaft or portal located closer to the workings to deliver the needed ventilation air. These results suggest that newer mines can benefit from using long stone pillars instead of brattice curtain stoppings to maintain adequate airflow to the face.

Increasing face ventilation

Although the preceding example shows that it is possible to deliver large airflows to the last open crosscut, the airflow must also be effectively distributed within the face. Total mine ventilation efficiency includes delivery of the air toward the face and then properly distributing this air to the face using an auxiliary fan. Generally, in large opening mines, air is distributed to the face using auxiliary fans as shown in Figures 2. The fan used in these analyses was a freestanding vane-axial fan with a diameter of 0.91m (36 in), powered by a 19kW (25 hp) motor, and mounted with a reducer at the outlet with a discharge diameter of 0.58 m (23 in).

The location of the auxiliary fan makes a big difference in the ventilation efficiency. Figure 3 shows the improper location of an auxiliary fan inby the last open crosscut. A fan located inby the last open crosscut increases air

Figure 2: uxiliary Fan type used near face.

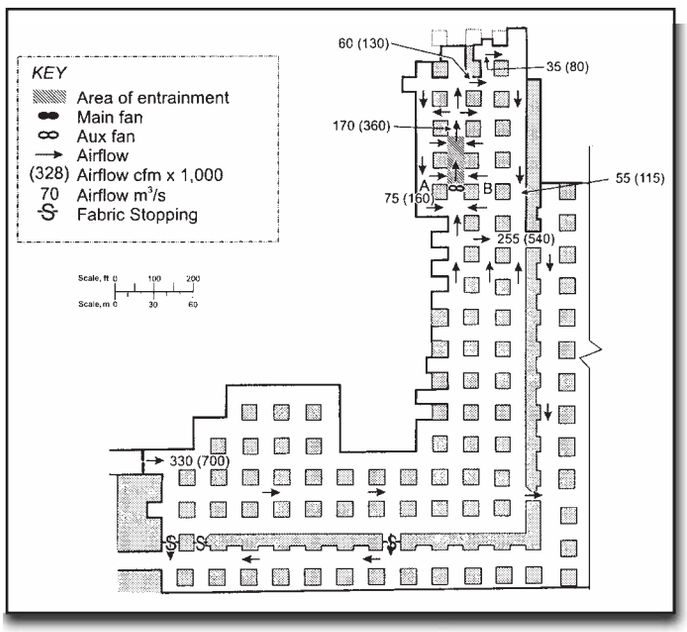

Figure 3: Incorrect Auxiliary Fan Placement

recirculation at the face thereby reducing total mine ventilation efficiency. Fans must be positioned in the intake airflow to ensure that a substantial quantity of fresh intake air is moved and directed to the face. Figure 4 shows the proper placement of the auxiliary fan, positioned in the intake air stream, outby the last open crosscut. The proper placement of the auxiliary fan inby the last open crosscut makes a significant ventilation improvement by increasing the percentage of fresh air delivered to the face thus significantly increasing the total mine ventilation efficiency.

Figure 5 shows the ventilation efficiency of a large-opening stone mine along the stone pillar air wall to the last open crosscut and through the face where the highest efficiency drop occurs. The positioning of the auxiliary fan makes little difference in mine ventilation efficiency up to the last open crosscut. The differences to total mine ventilation efficiency and face ventilation efficiency is found by the placement of an auxiliary fan or fans near the last open crosscut. Without the auxiliary fan, the air naturally follows the path of least resistance and bypasses the face

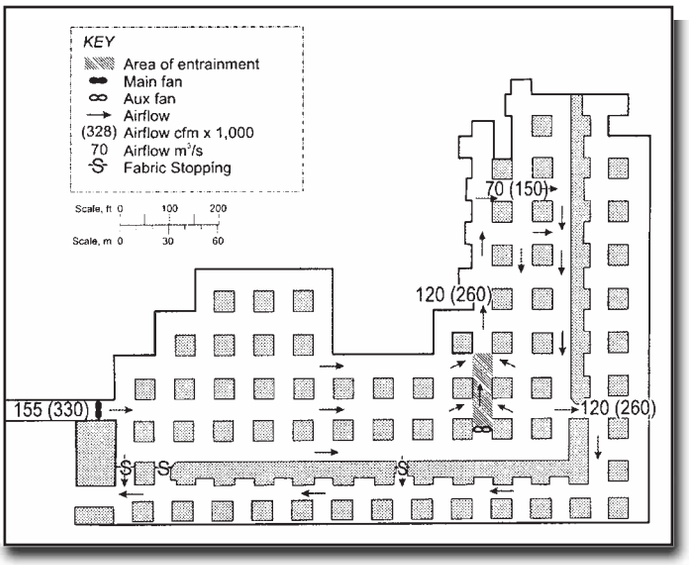

Figure 4: A Properly Positioned Auxiliary Fan

through the last open crosscut. This resulted in a mine ventilation efficiency of 5 percent at only 73 m (240 ft) from the last open crosscut. Similar poor efficiency but at a slightly further distance is obtained with the fan being located inby the last open crosscut. The authors have frequently observed auxiliary fans improperly positioned inby the last open crosscut in large-opening mines. Tests showed that an auxiliary fan positioned in by the last open crosscut provided a mine ventilation efficiency of 5 percent at 122 m (400 ft) inby the last open crosscut. Contrasting with this, an auxiliary fan properly positioned in the intake air, significantly increases the fresh air quantity that moves to the face. Correct positioning of the fan led a mine ventilation efficiency of 45 pct 122 m (400 ft) inby the last open crosscut. As DPM regulations are becoming more stringent, the use of all available air will be necessary to meet the regulatory mandates.

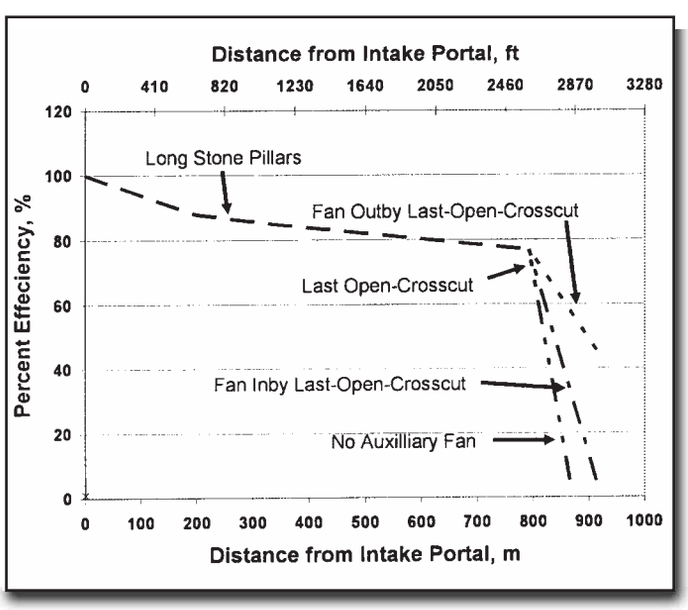

Figure 5: Comparison of ventilation airflow efficiencies for new and 15-yyr old mine.

Ventilating unit mining operations

Unit mining is a recognised form of mining in large-opening mines (Grau et al, Krog et al) and is generally used in combination with other ventilation plans such as split ventilation systems. Unit mining consists of sectioning off specific zones for development using rectangular pillars arranged in sections that permit a controlled ventilation system. Ventilation air enters and exits the units in a few entries allowing auxiliary fans to be strategically positioned at air entrance locations. This type of face ventilation configuration permits better face ventilation and reduces ventilation recirculation than mining situations where there are wide mine expanses where many faces are present. Also, at some time in the mine's life, these units can be sealed and separated from the main ventilation flow of the mine, thus reducing demands on the main ventilation circuit.

Alternative stopping designs

Even when using long stone pillars, constructed stoppings are a necessity in some locations. However, they should be designed and constructed to minimise air quantity leakage. NIOSH designed, constructed and blast tested (Grau, 2006b) two novel stoppings at its Lake Lynn Laboratory (LLL): the Super Stopping and the EZ-Up Curtain Stopping (Grau et al., 2006b; NIOSH, 2006a, 2006b). These stoppings are a means to control and direct ventilation airflows throughout large-opening mines. The Super Stopping was designed as a permanent stopping for use in the main entries of the mine, while the EZ-Up Curtain Stopping was portable, more economical, and easier to install.

The Super Stopping (Figure 6) was constructed from oversized Omega Blocks1, which are low-density, composite cement and fly ash blocks manufactured by Burrell Mining Products, Inc. The individual blocks are 1.22 m (48 in) long by 1.22 m (48 in high) by 0.81 m (32 in) wide and weigh approximately 544 kg (1,200 lbs) each. The Super Stopping constructed at LLL was 17.4 m (57 ft) wide by 9.1 m (30 ft) high.

After a footing was built, the Super Stopping was constructed using an extended reach forklift to lift and position the blocks in the standard masonry pattern of staggered blocks on successive layers. Two factory cast holes are in place on one side of each block to receive forklift tines. In order to maintain stability and vertical trueness, a forklift with an articulating head is necessary to align the blocks in the structure. Since the stopping will be subjected to blast pressures, securing each block with a high-grade polyurethane construction adhesive strengthens the stopping. Gaps present between the stopping and roof were sealed using an expansion foam product that was applied using a handheld apparatus. The expansion foam acted to conform to the shape of both the cut blocks and surfaces of the mine opening, thus increasing structure stability.

Ventilation curtain stoppings in large-opening mines are cumbersome to construct and they often deteriorate from blast pressures or from repetitive flap damage. NIOSH researchers have investigated new techniques to construct stoppings and alternative fabric materials for use in underground large-opening mines. A variety of fabrics can be used for the EZ-Up Curtain Stopping (Figure 7). The most common type of fabric observed in underground stone mines is brattice cloth. However, other materials that are lighter in weight are available and offer viable alternatives to brattice cloth. Evaluations were performed on EZ-Up Curtain Stoppings that were composed of two different fabrics: NOVA-Shield RU88XFR-6, a high-density polyethylene woven fabric, manufactured by Intertape Polymer Group, Inc., and Dura-Skrim D15CFB, which is composed of two layers of film laminated with polyethylene that sandwiches a scrim reinforcement, manufactured by Raven Industries, Inc. The sewn-in loop allowed the tubing to be easily laced into the curtain while it was laid out on the ground. The tubing and curtain were then hoisted to the mine roof with a strap and ratchet mechanism system. The stopping was attached to the mine roof with four ratchet assemblies, each anchored by a roof bolt.

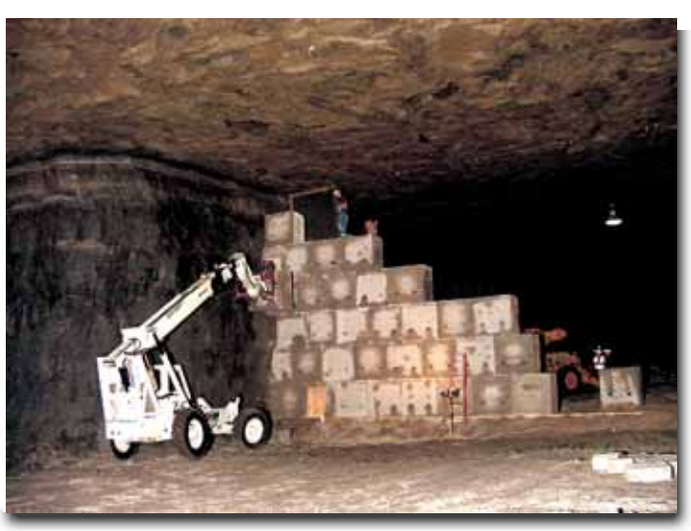

Figure 6: Placing Blocks in Place for Super Stopping.

Figure 7: Raising the EZ-Up Stopping.

The stopping was secured to the walls using two sets of vertical boards with dimensions of 3.8 cm (1.5 in) by 8.9 cm (3.5 in) by 3 m (10 ft). The first set of boards was bolted to the ribs from the floor to the roof in line with the edge of the curtain. The excess fabric on the curtain sides was then wrapped onto the second set of boards. This wrapping prepares the curtain for attachment to the existing wall-mounted boards to create a sandwich effect. The wrapped curtain boards on the LLL prototype stopping were attached to the wallboards using 0.6-cm (0.25-in) diameter by 10-cm (4-in) long lag screws.

The curtain stopping was secured to the floor by laying sand bags on the excess curtain material that was draped on the floor. The sand bags seal the stopping from excessive leakage and provide pressure relief to reduce stopping damage in the case of a face blast that produces excessive pressures against the stopping. In an over pressure scenario, the curtain will be blown free from the sand bags, thus preventing damage; however, the sandbags need to be replaced to re-establish the seal. Another option for holding the curtain down is jugs filled with water or sand that are attached to the curtain and would move with the curtain during excessive over pressures from blasting but still hold the curtain down during non-blasting conditions.

A brief overview of costs in 2006 U.S. dollars of the two stoppings is shown in Table 1. The stopping size for the EZ-Up Stopping was 17 m (55 ft) wide by 9 m (28 ft) high. The Super Stopping was 13 m (44 ft) wide and 9 m (30 ft) high. The total cost in 2006 was US$1,325 for the EZ-Up Stopping and US$23,750 for the Super Stopping. Super Stopping costs did not include the rental price for an extended forklift, which many mines already have. The rental cost for an extended forklift was $200/day for 2 days plus $150 for combined pickup and delivery charge. The overwhelming cost for the Super Stopping was for the blocks and labour. A reduction in labor time will be realised as the workers gain experience in building the stopping, thus significantly reducing the stopping costs.

Table 1- Estimated costs for EZ-Up Stopping and Super Stopping.

Estimated Capital Investment and Labor Costs for EZ-Up Stopping	**$**
Ratchet Winch, weld-on storage, bottom mount, 4 @ $33.51 ea	134
Yellow polyester webbing, 4 @ $23.81 ea	95
Flag Bolts, 1 box	27
Washers, 1 box	13
10 ft x 1.5 in rigid conduit, 6 @ $36.00 ea	216
0.25 in x 1.5 in lag screws, 50 @ $0.33 ea	17
0.25 in x 1 in fender washers, 50 @ $0.12 ea	6
Fabric, 57 ft x 30 ft @ $1.35/yd2	257
Labor, 20 hrs @ $28.00/hr	560
Total estimated cost for EZ-Up Stopping	**1,325**
Estimated Capital Investment and Labor Costs for Super Stopping	**$**
Footer, 44 ft wide x 32 in depth x 6 in thick, @ $74.5/yd3	162
Omega Blocks 443, 48x48x32 in, 110 @ $78.00 each	8,580
Omega Block 384, 24x8x16 in, 418 @ $4.50 ea	1,881
Block Delivery	515
Wood framing (reusable)	112
Glue, 8 @ $14.20 each	114
Mine Seal foam, 4 @ $199 each	796
Miscellaneous items	110
Labor, 410 hrs @ $28.00/hr	11,480
Total estimated cost for Super Stopping	**23,750**

Summary

Due to recent MSHA regulations, the primary air quality concern in large-opening mines is DPM. Some strategies available to operators to reduce workers' exposure to DPM are to increase the air quantity entering the mine, use long stone pillars, stoppings, and auxiliary fans to direct the air, consider ventilation in the mine planning process, and replace high-emitting DPM engines with cleaner-burning engines. An important step in reducing DPM concentrations is to direct a high percentage of air provided by the main mine fan to the faces. This paper demonstrates that the percentage of air reaching the face is increased by using long pillars that reduce crosscuts between intake and return airways and by building stoppings that are constructed to allow for low leakage amounts. Long stone pillars reduce the building and maintenance of constructed stoppings, reduce leakage, and dramatically increase the percentage of total mine ventilation air reaching the working faces. Building and maintaining stoppings are costly and persistent issues in large-opening mines. In response, NIOSH has developed several stoppings that provide mine operators with alternatives for efficiently installing stoppings and reducing stopping maintenance.

Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH. Mention of any product or company name does not constitute endorsement by NIOSH.

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