Maximizing the ventilation of 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. Large-opening mine ventilation is unique for the following reasons: (1) it is challenging to keep airflow velocities high enough to effectively remove or dilute airborne contaminants, (2) large air volumes can be moved through the mines with little static pressure drop, and (3) stoppings to direct ventilation airflows are costly to construct and maintain. The research results suggest that by incorporating ventilation planning into the mine planning process, using propeller fans, developing new stopping materials and construction methods, and using long pillars to eliminate crosscuts where possible, the ventilation of large-opening mines can be significantly improved. The ventilation improvements created by incorporating these various techniques into the ventilation plan will help reduce the exposure of mine workers to airborne contaminants in underground large-opening mines.

1 INTRODUCTION

Large-opening, room-and-pillar mines (i.e., those with openings larger than about 92.9 m^2 (1000 ft^2), or 12.2 m (40 ft) wide and 7.6 m (25 ft) high) accounted for 135 of the 230 metal/nonmetal mines operating in the United States in 2004, and they employed about 2600 underground workers (MSHA 2004). The commodities produced from these large-opening mines and the corresponding number of mines include: limestone for aggregate (103), lead/zinc (15), salt (14), marble (7), lime (6), stone (4), and sandstone (1) (MSHA 2004). Virtually all large-opening mining operations use a fleet of diesel-powered equipment that typically includes several large haulage trucks, one or more front-end loaders, drills, scalers, dozers, and various utility vehicles. A typical diesel-powered fleet frequently approaches 3730 kW (5000 hp), necessitating ventilation airflows of more than 354 m^3/s (750,000 ft^3/min) to dilute diesel particulate matter (DPM) and diesel exhaust gases. A stone production blast will commonly use 454 kg (1000 lb) or more of high explosives and will liberate about 425 m^3 (15,000 ft^3) of blasting gases and fumes, thereby imposing additional ventilation airflow requirements.

2 VENTILATION CHALLENGES IN LARGE-OPENING MINES

Large-opening mines face ventilation challenges in the following areas:

- moving adequate ventilation airflow volumes to dilute airborne contaminants to statutory levels
- controlling and directing the airflow to where it is needed the most
- planning ventilation systems to integrate with production requirements

2.1 *Moving adequate ventilation airflow volumes*

Large-opening mines pose unique ventilation challenges simply to move sufficient air quantities for dilution of all airborne contaminants. In mature stone mines, the total open-space volume can reach 7,079,200 m^3 (250 $MMft^3$). With these large open-space volumes, even fans capable of moving 472 m^3/s (1.0 $MMft^3/min$), take hours to complete a total air change. Therefore, ventilation air should be directed and coursed to the production face areas to concentrate and minimize the ventilation airflow volumes necessary to provide sufficient fresh air to the active working areas.

2.2 *Controlling and directing the airflow*

The size of large-opening underground stone mines creates problems for controlling and directing ventilation airflows. Stopping designs and techniques suitable for use in coal mines generally cannot be applied in stone mines because of the entry sizes and the associated cost of construction. Ventilation curtain materials, such as mine brattice, can be problematic because of significant air leakage due to its deterioration caused by repetitive flapping (especially near the main mine fan) and blast pressures.

2.3 *Planning ventilation systems*

Stone production from most large-opening, room-and-pillar underground stone mines comes from multiple working faces located on the perimeter of the mine. In the initial mine development stages when few operating faces are present, it is relatively simple to provide adequate ventilation airflow across the production faces. Natural ventilation and an auxiliary fan may be sufficient to reduce airborne contaminants to acceptable levels at this stage of mine development. However, as a mine expands, ventilating all the working areas becomes more difficult as the number of working faces and the distances between the main mine fan and the working faces increase.

3 NIOSH LARGE-OPENING MINE VENTILATION RESEARCH

NIOSH is conducting a research effort to improve the ventilation airflow quantity and quality in large-opening underground mines. Investigations have focused on a four-point approach:

- Developing techniques to estimate the required air quantity to dilute airborne contaminants.
- Identifying alternative fans capable of efficiently moving the required air quantity to dilute airborne contaminants to statutory levels
- Developing improved stoppings to direct and control the ventilation airflow to the production faces
- Evaluating improved mine designs to deliver and distribute the required ventilation airflows without interfering with production requirements

3.1 *The Air Quantity Estimator*

Mine ventilation planners must determine the air quantity needed to meet the statutory DPM concentration limits by taking into account the emissions characteristics of the site-specific fleet of engines at their operation. To meet this challenge, NIOSH developed the Air Quantity Estimator (AQE) to assist mine operators with ventilation planning (Robertson et al. 2004). The AQE provides an initial estimate of the required air quantity needed to dilute DPM contaminates to statutory levels in the main air stream of the mine. The AQE is a user-friendly, stand-alone computer program that uses diesel engine performance test data from both the Environmental Protection Agency (EPA 2002) and the Mine Safety and Health Administration (MSHA 2002). The AQE is available upon request to NIOSH at: http://www.cdc.gov/niosh/mining/products/analysissoftware.htm#AQE.

3.2 *Improving ventilation airflow volumes with propeller fans*

Due to the opening size, the resistance to flow in large-opening drift mines is minimal. Low-pressure propeller fans can efficiently move large airflow volumes in such mines as demonstrated by NIOSH (Grau et al. 2002, 2004, Krog et al. 2004). Grau (2002, 2004) found that historically, large-opening drift mines almost exclusively used vane-axial fans for main mine fans, where in most cases, a better choice would have been propeller fans. The difference in the air quantity-pressure loss relationship between a large-opening mine and a typical coal mine is significant, as shown in Figure 1. In both cases, the mine resistance pressure increases as the square of the ventilation airflow volume. The required ventilation pressure for an underground stone drift mine rarely exceeds 249 Pa (1 in w.g.) (Grau et al. 2004a) since the resistance is so small.

Figure 1 also shows the fan curves for a typical high-pressure, vane-axial fan commonly used to ventilate a coal mine and the fan curve for a typical 3.66-m (12-ft) propeller fan. The operating point for the coal mine (Point A, Fig. 1), occurs at a flow volume of 118 m^3/s (250,000 ft^3/min) and a static pressure of 1.77 kPa (7.1 in w.g.). The same coal mine vane-axial fan used in a large-opening mine would operate at 153 m^3/s (325,000 ft^3/min) and 52 Pa (0.21 in w.g.) (Point B, Fig. 1). However, at that operating point, the static fan efficiency is less than 6%, well outside the manufacturer's normal operating envelope.

The operating point for the 3.66-m (12-ft) propeller fan (Point C, Fig. 1) occurs at 175 m^3/s (370,000 ft^3/min) and 67 Pa (0.27 in w.g.) however, the static fan efficiency is much higher at 14%. Although this efficiency is low for the propeller fan, it is 2.3 times more effective than the axial-axial fan used in the same mine.

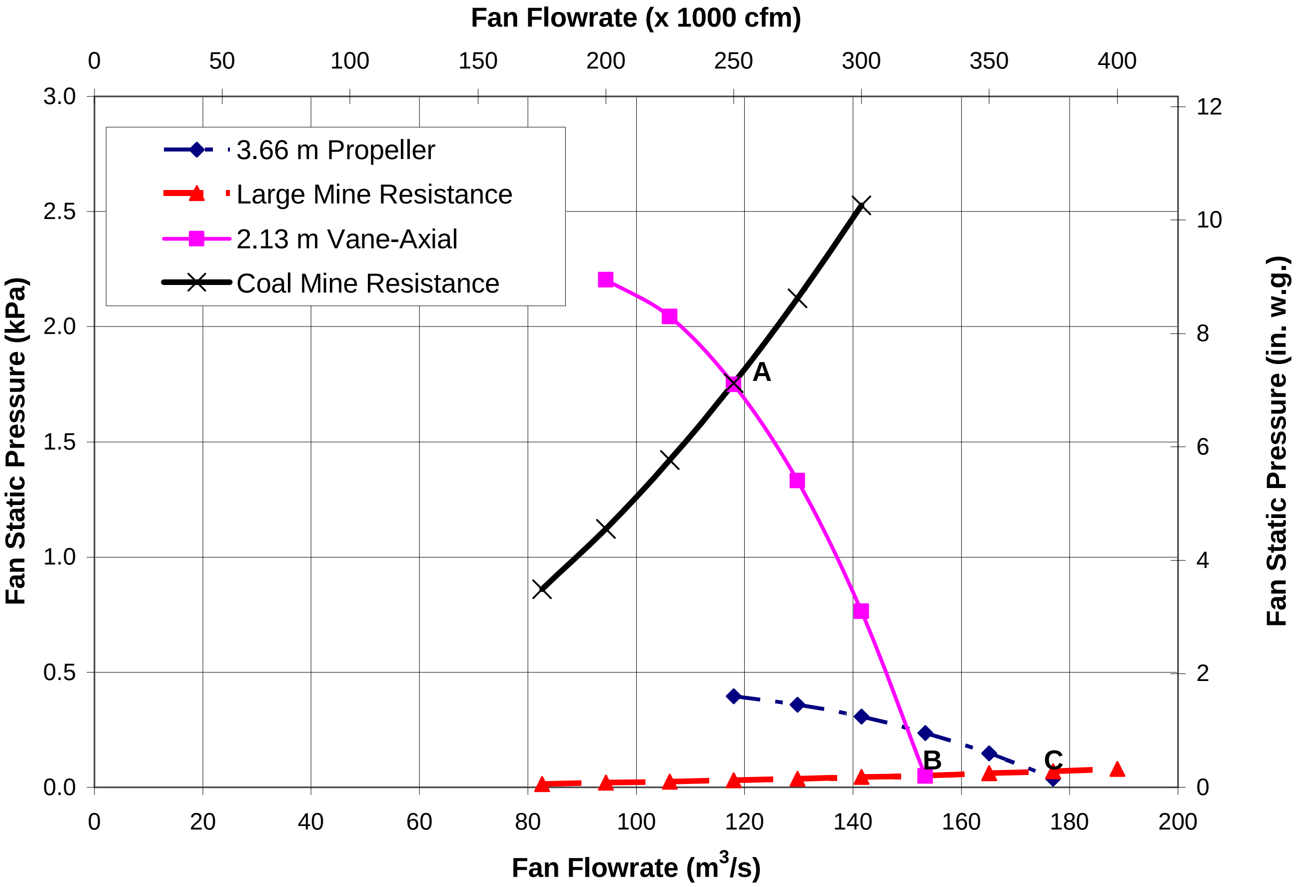

Figure 1. Pressure and quantity curves for two fans and corresponding resistance curves.

3.3 *Improving stoppings for directing ventilation airflows*

Using stoppings to direct ventilation airflows in large-opening mines has been limited due to their high capital cost and construction and maintenance difficulty. The most challenging problems exist in older, extensive mines that have never incorporated stoppings into the mining plan. Retrofitting an older mine with stoppings requires considerable labor, material, and maintenance costs (Grau 2004). Major design criteria for stoppings are:

- withstanding fan pressure differentials
- withstanding production blast pressures
- minimizing leakage between the intake and return air courses
- having high durability and requiring minimal maintenance

The relative importance of these design criteria is associated with three distinct areas of a mine, the main entries, intermediate entries, and the face areas. The stoppings in the main entries will typically see low blast pressures. However, due to their close proximity to the main mine fan, they experience the highest pressure differential and thus have the greatest potential for leakage. The stoppings in the main entries must last throughout the life of the mine with little maintenance, and thus have the highest durability requirement. If curtain stoppings are installed close to the main fan, they must have sufficient durability to withstand repetitive flapping (Krog et al. 2004). Grau et al. (2002) measured pressure differentials generally less than 62 Pa (0.25 in w.g.) at the main mine fan in large-opening stone drift mines with multiple entries. Pressures from face production blasts can far exceed these ventilation pressures and from observation, depending on the mine layout, stoppings may be located near face blasts for several years. Mucho et al. (2001) measured blast pressures from two different production-face shots, ranging from 8.27 kPa (1.20 psi) to 9.38 kPa (1.36 psi) at distances of 61 m (200 ft) to 152 m (500 ft) from the shot. Both test shots were similar to typical production blasts in underground stone mines, and they each consisted of 181 kg (400 lb) of ANFO, 77 kg (169 lb) of dynamite, and 23 kg (50 lb) of Detagel.

Stoppings located close to face areas or even in intermediate areas may require a blast pressure relief mechanism to prevent damage from production blasts. Timko and Thimons (1987) discussed a method to provide blast relief using VELCRO^{TM} fasteners on typical brattice stoppings. NIOSH recently performed tests where twelve 23-kg (50-lb) sandbags were placed on the bottom of a curtain stopping that was laying on the mine floor. It was found that this method held the stopping in place for lower pressure shots, but allowed for pressure relief during higher pressure shots by allowing the curtain to slip out from under the sandbags. Experimentation on a site-specific basis may be necessary to determine the appropriate sandbag pressure relief weight for stoppings in intermediate areas of the mine.

The most efficient ventilation barrier separating intake from return air is a long stone pillar. These barriers are created by eliminating at least the last face shot that would normally break through two adjoining entries, thus keeping a natural connection between the pillars. A series of these connected pillars creates a long stone air wall that is an effective and practical method for directing ventilation air. This technique reduces maintenance and the expense of building stoppings. The pillars can eventually be mined when the barrier is no longer needed, such as just prior to mine closure.

Since stone stoppings cannot always be used, NIOSH has developed and tested two new stopping types, the “Super Stopping” and the “EZ-Up Stopping” (Figures 2 and 3) for use in large-opening mines (Grau et al. 2006). The Super Stopping is a long-term or permanent ventilation control structure, and is constructed from low density, composite cement and fly ash blocks measuring 1.22 m (48 in) wide by 1.22 m (48 in) high by 0.81 m (32 in) thick, and weighing approximately 544 kg (1200 lb) each. The blocks are laid and positioned using an extended reach fork lift. The EZ-Up stopping is a temporary, portable, curtain stopping which is raised to the mine roof using a winch system. In-mine tests at NIOSH’s Lake Lynn Laboratory have demonstrated the viability of the proposed construction methods and materials.

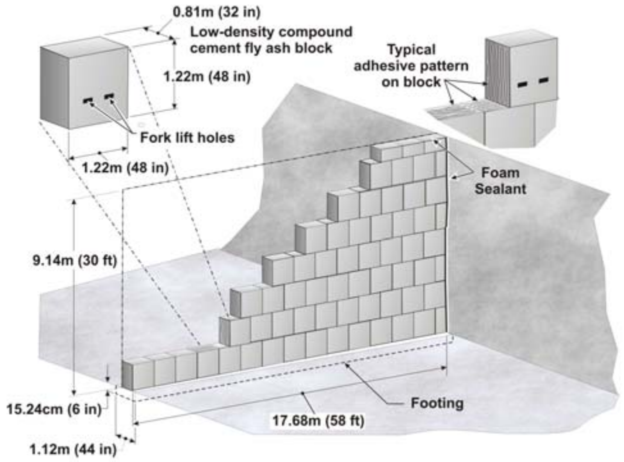

Figure 2. Schematic of Super Stopping.

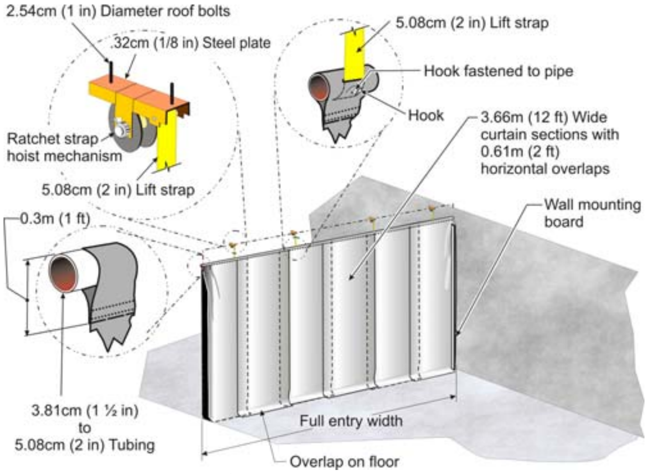

Figure 3. Schematic of EZ-Up Stopping.

3.4 *Mine design considerations for improving ventilation airflows*

Three improved mine designs and associated ventilation plans have been identified for large-opening mines: perimeter, unit, and split. Selecting the appropriate mine design and associated ventilation plan is a factor of mine size. Grau et al. (2002, 2004), Mucho et al. (2001), and Krog et al. (2004) discuss the applications of these proposed mine designs for improving the ventilation of large-opening mines. Perimeter ventilation is best suited for older mines with little previous ventilation planning. New mines are generally more readily adaptable to split and unit mine ventilation practices. Achieving an optimal ventilation system layout that works well with production is relatively easy for a newer operation. However, retrofitting the new concepts into extensive existing operations may present unique challenges. NIOSH research has identified key considerations for selecting the best mine design for optimal ventilation while meeting basic production requirements (Krog et al. 2004). These considerations include:

- maximizing ventilation system efficiencies
- determine the maximum distance between the face area and a fresh air source while still providing adequate ventilation
- locating truck haulage routes underground to minimize contamination of the fresh air supply
- direct fresh air to the faces along the shortest path possible

A mine ventilation system can be rated by calculating ventilation efficiency. Ventilation efficiency is the percent of useful ventilation air quantity passing a specific point compared to the total possible air quantity available. When evaluating different designs for large-opening, room-and-pillar mines, three related ventilation efficiency measures have been used by NIOSH:

(1) $E_d = Q_{lop} \div Q_m$

(2) $E_f = Q_f \div Q_{lop}$

(3) $E_t = Q_f \div Q_m = E_d \times E_f$

Where:

- E_d = delivery efficiency, air delivered to the working area
- E_f = face ventilation efficiency, air available at the face
- E_t = total mine efficiency;
- Q_m = air quantity entering the mine
- Q_{lop} = air quantity exiting the face area at last opening at a pillar
- Q_f = air quantity at face.

An example of increasing ventilation efficiency by incorporating long stone pillars in the design of a new mine is shown in figures 4 and 5. This example is a variant of a split-mining ventilation system where a propeller fan blows 143 m^3/s (303,000 ft^3/min) into three dedicated intake airways located in the northwest portion of the mine.

A long stone pillar separates these intake airways from the working areas. Two crosscuts within this pillar line have been sealed with permanent stoppings as the mine was developed. Of the 143 m^3/s (303,000 ft^3/min) entering the mine, about 122 m^3/s (258,000 ft^3/min) ventilated the working area and was measured passing through the last opening in the stone pillar, giving a ventilation delivery efficiency of 85% (see Equation 1).

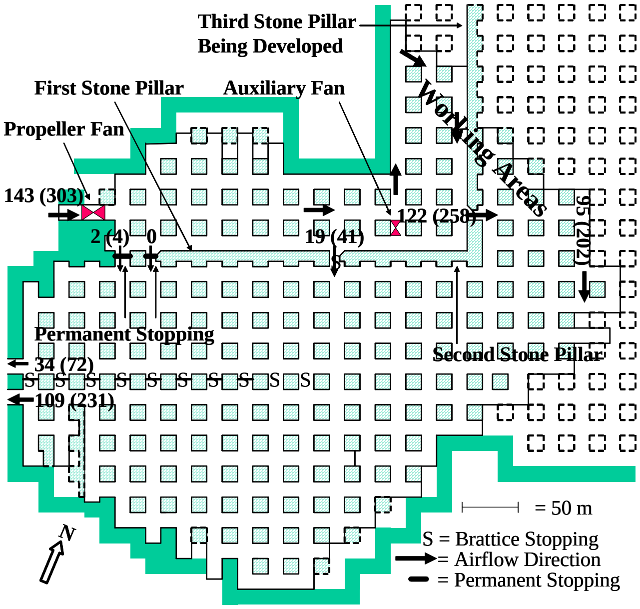

Figure 4. Ventilation airflows of new mine with long stone pillars. (Bold numbers are ventilation airflow volumes, m^3/s, (x 1000 cfm).

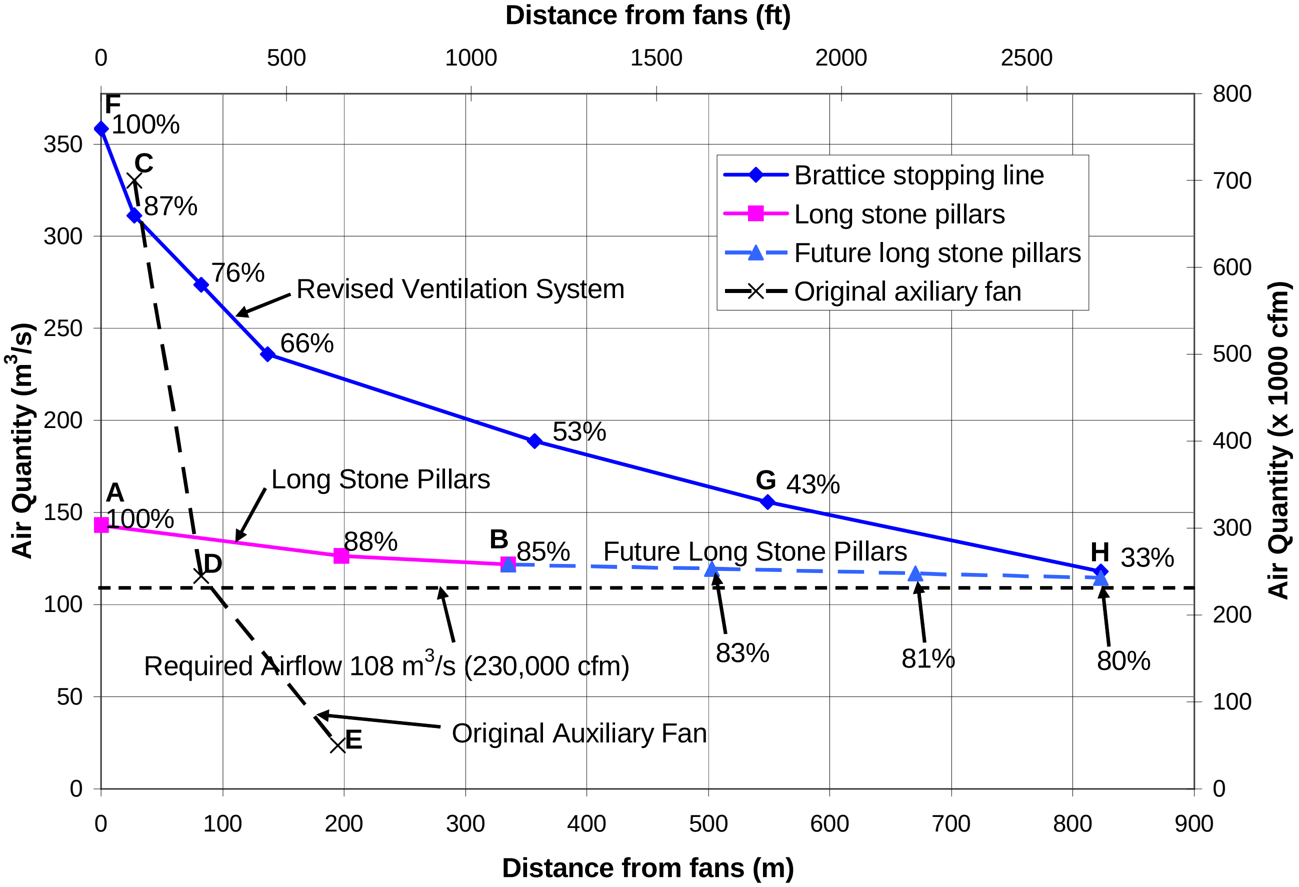

Figure 5. Ventilation delivery efficiencies of new mine using long stone pillars, and 15-year-old mine before and after ventilation improvements.

About 95 m^3/s (202,000 ft^3/min) of the ventilation airflow entering the working area was measured at the working faces, resulting in a calculated face efficiency of 78% (see Equation 2). Total mine efficiency (see Equation 3), is the working face ventilation airflow divided by the mine intake volume, or 67% for this case. Alternatively, total mine efficiency is the product of delivery efficiency multiplied by the face ventilation efficiency (85% × 78% for this example), or again, 67%.

Separating ventilation efficiency into its component parts provides a useful way to compare and evaluate alternative mine ventilation systems layouts for large-opening underground stone mines. Recent work by Grau et al. (2004) illustrates the utility of the ventilation efficiency concept for planning a ventilation system that delivers more air to the working faces.

Figure 6 shows a 15-year-old mine that relied primarily on natural ventilation supplemented with three auxiliary fans. The working faces required an air quantity of about 109 m^3/s (230,000 ft^3/min) to dilute the expected DPM. An air quantity of 330 m^3/s (700,000 ft^3/min) was measured downwind of the second auxiliary fan. Unfortunately, only 116 m^3/s (245,000 ft^3/min) flowed to the turn in the stopping line (Location D), giving a ventilation efficiency of less than 35% (116/330) to that location. Less than 24 m^3/s (50,000 ft^3/min) is available at the last stopping (Location E), implying a delivery efficiency of less than 7% (24/330), and a very low total mine efficiency, as evidenced by air velocities that were too low to measure at the production faces.

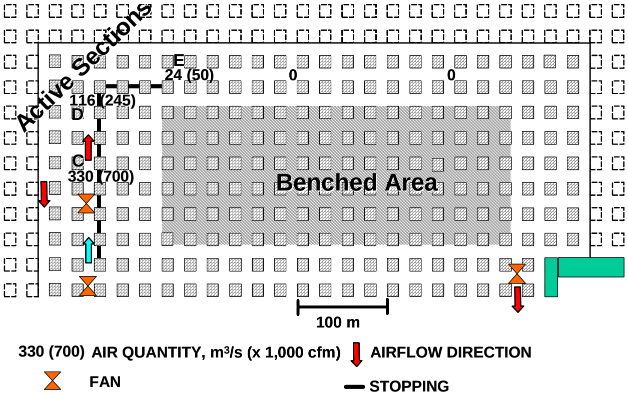

Figure 6. Initial ventilation airflows for a 15-year-old mine with partial brattice curtain stopping line and auxiliary fans.

Figure 7 shows the measured ventilation airflows for the same 15-year-old mine that is shown in Figure 6 after it has been upgraded with two exhausting propeller fans (Location F) and 23 additional brattice curtain stoppings. Figure 5 shows the calculated ventilation efficiencies for both the old auxiliary fan ventilation system and the improved revised ventilation systems in the 15-year-old mine, as well as the results of using long stone pillars in the new mine shown in Figure 4. At distances greater than 91 m (300 ft) from the fan, the original auxiliary fan ventilation system could not deliver the required air quantity of 108 m^3/s (230,000 ft^3/min) to dilute the expected DPM in the 15-year-old mine, and the total efficiency decreased rapidly with increasing distances from the fan. As indicated on Figures 5 and 7, measured airflows for the upgraded ventilation system exceed the required airflow at the working faces, and uses less fan energy (Grau et al. 2004). However, total efficiency beyond about 305 m (1,000 ft) (Location G) from the propeller fans falls to less than 50% due to stopping leakage. This upgraded ventilation system was a significant improvement from the original auxiliary fan ventilation system, but as the mine expands, the loss of ventilation airflow due to leakage will result in inadequate fresh air being supplied to the working area.

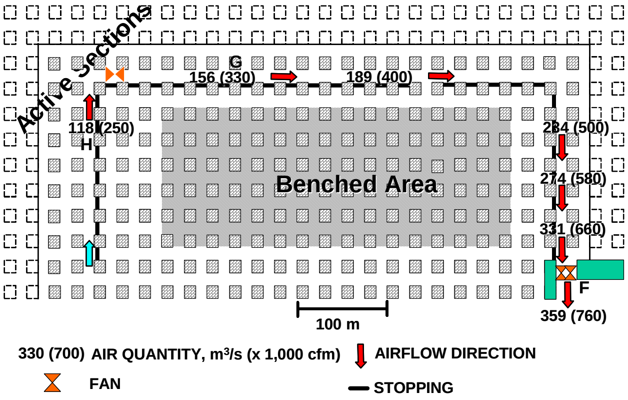

Figure 7. Improved ventilation airflows for a 15-year-old mine after installation of brattice curtain stopping line and propeller fans.

Preliminary research by NIOSH suggests that using long stone pillars instead of brattice curtain stoppings will maintain the total efficiency over 60% at distances greater than 305 m (1000 ft) from the propeller fans in similar mining situations as shown in Figures 4, 6, and 7. Long stone pillars eliminate the construction and maintenance costs associated with brattice curtain stoppings. Long stone pillars also eliminate leakage, resulting in both an increase in total mine, and delivery ventilation efficiencies, as illustrated for the new mine in Figure 5 by the long stone pillar curve. Using long stone pillars can be a key factor in maintaining adequate ventilation airflows at increasing distances from the fan to the active production faces where it is most critical.

4 SUMMARY

Improvements in ventilation efficiencies can be achieved in underground large-opening mines by utilizing a systematic four point approach to the problem. First, it is imperative to estimate the air quantity required for adequate dilution of airborne contaminants. A thorough understanding of the airborne contaminant sources such as DPM and fumes from diesel equipment and blasting is necessary for the selection of the appropriate fan for the site-specific conditions. An air quantity estimator has been developed by NIOSH to perform that task.

Second, appropriate fan selections should be based upon the most effective method to move the required ventilation air quantity for proper dilution. Propeller fans produce large air quantities at a higher mechanical efficiency than vane-axial fans for the typical low-pressure conditions of large-opening drift mines, and with relatively low initial capital and operating cost.

The third component is the use of improved stopping designs to direct and control the ventilation airflow to where it is needed the most. Long stone pillars are recommended to reduce air leakage, and they also eliminate the stopping maintenance issue. In situations where long stone pillars are not feasible, proper stopping construction techniques are vital for the delivery of a high percentage of the ventilation airflow to the desired location.

Fourth, improved mine designs should be used to deliver and distribute the required ventilation airflows without interfering with production requirements.

When properly addressed, these four key ventilation factors will ultimately result in effective, practical, and cost effective increases in the ventilation airflows to improve the air quality in large-opening mines.

5 DISCLAIMERS

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

Mention of any company or product does not constitute endorsement by NIOSH.

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