Raising the Bar of Ventilation for Large-Opening Stone Mines

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ABSTRACT: Due to the difficulties of ventilating large opening stone mines, the effective dilution of diesel particulate matter and noxious gases has often been problematic. Since stone mines have large openings that develop low air resistances, and propeller fans are designed for low pressure-high volume applications, main mine propeller fans may be a feasible option for ventilating underground stone mines. This paper describes the results of a case study where researchers from the National Institute for Occupational Safety and Health have demonstrated that significant increases in total mine airflow can be achieved and the ventilation improved in a large-opening stone mine by replacing an axial-vane mine fan with two 12-ft diameter propeller fans and adding a line of stoppings. In this study, the use of the propeller fans more than doubled the air quantity from 300,000 cfm to 750,000 cfm, while operating at 50 horsepower less than the original axial-vane fan.

1 INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is the primary agency responsible for conducting health and safety research pertaining to the mining industry. A portion of this research is concerned with developing methods and technologies to improve the ventilation technology of large-opening mines. Historically, the ventilation techniques used in large-opening stone mines have often been the result of trial-and-error methodology. In many cases the ventilation system consists of axial-vane fans being used as either auxiliary fans or main mine fans without the use of stoppings to direct the air. The research results presented in this report describe how the ventilation of large-opening drift mines can be dramatically improved by using large-diameter main mine propeller fans in bulkheads in combination with a stopping line. Also discussed are methods for estimating the air quantity requirements for effective dilution of diesel particulate matter (DPM), choosing appropriate fans, air coursing methods, and mine layouts.

2 CONCERNS AND LIMITS FOR WORKER EXPOSURE TO DPM

Legislation was proposed by the Mine Safety and Health Administration (MSHA) to limit DPM concentrations in underground metal/nonmetal mines. Provisions of this health standard are found in “Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Mines” published in the Federal Register on January 19, 2001 and amended on February 27, 2002 (MSHA 2001). An interim DPM standard of 400 µg/m^{3}of total carbon took effect on July 20, 2002 and it’s proposed that the DPM limit be reduced to 160 µg/m^3 of total carbon by July 19, 2006.

To satisfy the requirements of the DPM standard, most operators will find it necessary to employ several engineering controls: increasing the air quantity entering the mine; directing air to the face areas by the use of stoppings and auxiliary fans; and decreasing DPM emissions from engines by using catalytic converters, filters, and cleaner-burning engines (Schnakenberg 2001, Grau et al. 2002a, Grau et al. 2002b). In addition to the general improvements in current ventilation methods, mine planners must also consider ventilation requirements when planning future mine layouts – until now, ventilation has been overlooked in most underground stone mine planning processes (Head 2001, Grau et al. 2002a, Grau et al. 2002b, Mucho et al. 2001).

3 MINE PLANNING CONSIDERATIONS FOR EFFECTIVE VENTILATION

A large-opening stone mine ventilation system must be designed to effectively dilute all airborne contaminants by supplying sufficient ventilation air to locations where it is needed the most, i.e., working faces, worker locations, etc. In order to accomplish that goal, the ventilation plan must include a main mine fan to develop the airflow, stoppings to control the airflow, and auxiliary fans to direct air where equipment and personnel are located. Invariably, all underground stone mines use diesel equipment that emits substantial amounts of DPM and noxious gases such as NOx, SO_2, and CO. In mines that use older diesel engines, the overriding factor for determining ventilation air requirements is probably the dilution of DPM and not the noxious gases. A previous study has shown that significant ventilation air quantities are necessary to meet DPM compliance concentration levels (Grau et al. 2002a). To help determine the ventilation air quantity requirements to dilute DPM concentrations to statutory levels in the main mine air stream, NIOSH has developed an air quantity estimator (AQE) (Robertson 2001, Robertson et al. 2003). The AQE is a user-friendly computer program that comes as a stand-alone package. It will run on most personal computers and is not dependent on the installation of spreadsheet programs.

4 HISTORICAL PHYSICAL CHARACTERISTICS OF UNDERGROUND STONE MINES THAT INFLUENCE VENTILATION

Many underground large-opening stone mines have common physical characteristics that influence ventilation airflow. Multiple portal entries are common, with the portals ranging from fully open to almost completely closed due to highwall rock falls or icing during winter months. Typically, in stone drift mines, the differences in elevation between entries are small in terms of creating natural ventilation. Nevertheless, these mines do have some natural ventilation. In addition, numerous openings, truck movements, outside wind conditions, and freestanding fans provide some ventilation in the mine. Finally, the large mine void volume acts as a sizable sink of available air for diesel exhaust dilution.

Many of these mines do not utilize stoppings, and thus air moves randomly resulting in unpredictable and haphazard ventilation. It is common for free-standing auxiliary fans to move ventilation air along designated routes and to push the ventilation air to where it is needed. Generally these fan locations are determined by trial-and-error methods. The auxiliary fans, blowing in this manner, provide better ventilation than natural ventilation alone, but bulkheaded main mine fans are superior for providing consistent ventilation.

5 LARGE-OPENING MINE VENTILATION CASE STUDY

At the onset of this research effort, NIOSH engineers visited several underground stone mines to conduct ventilation surveys and observe baseline operating conditions. It was concluded from these initial surveys that the ventilation of many underground stone mines could be greatly improved by using two synchronized approaches: installing main mine propeller fans to produce the air quantity needed to sufficiently dilute the airborne contaminants to statutory levels and constructing stoppings in conjunction with auxiliary fans to direct the ventilation airflow. Propeller fans are used for a variety of circumstances; however, documentation of propeller fans being used in large-opening mines was not available. Therefore, a case study was necessary to determine whether propeller fans are truly applicable for use in underground large-opening mines. The study ran for 21 months and included monitoring the mine ventilation prior to and after the installation of a brattice stopping line and two main mine propeller fans.

The case study mine had a physical extent of approximately 0.75 square miles and entries that are about 1,125 ft^2 in cross-sectional area. However, more than one-half of the mine is benched and those entries are considerably larger, often exceeding 2,200 ft^2 in cross-sectional area. The propeller fans used for this study were selected on the basis of the parameters measured during ventilation surveys made at various stone mines (Grau et al. 2002a). Those surveys suggested that for large-entry drift stone mines, and even for some mines with shallow air shafts, propeller fans would be a good choice for improving ventilation airflow because they are designed to deliver large air quantities at pressures of less than one-inch w.g. (Grau et al. 2002a, Grau et al. 2002b).

6 VENTILATION CHARACTERISTICS PRIOR TO STUDY

Figure 1 shows the ventilation airflow patterns and fan locations before any ventilation improvements were installed. The mine exhibited noticeable air movement at various locations; but recirculation was a predominant factor. In conjunction with the fans, other factors that impacted the ventilation airflow direction included the outside air temperature, the outside wind condition, and the movement of haul trucks in the mine. During this time, one main mine fan and two auxiliary fans were all freestanding and operating without the use of stoppings. The main mine fan was a Pope[1] 250-hp, 1,750-rpm, 350,000-cfm, 72-in-diameter axial-vane fan that was located in the central portion of the mine. The two booster fans were a Joy[1] 100-hp, 1,770-rpm, 150,000-cfm, 60-in-diameter axial-vane fan and a Buffalo[1] 125-hp, 1,770-rpm, 90,000-cfm, 54-in-diameter axial-vane fan.

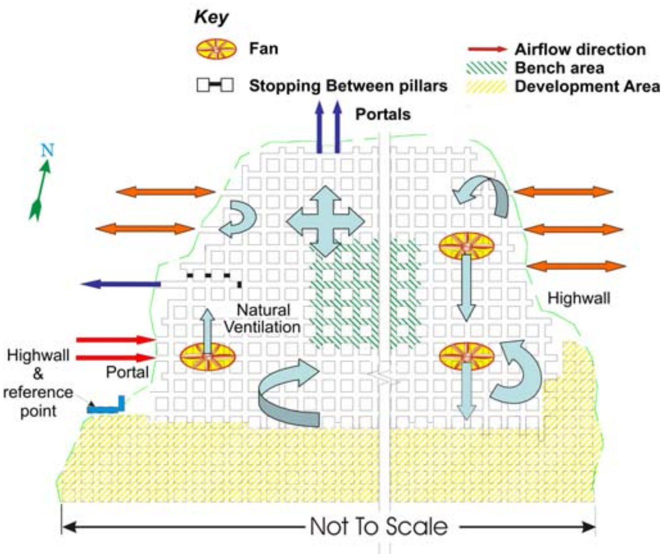

Figure 1. Ventilation airflow patterns prior to modifications.

Ventilation airflow is needed predominantly where vehicles are most active, i.e., at the active production faces. The active faces in this mine are located in two primary areas: in the bench area located in the central portion of the mine and at the development sections in the south and southeast portion of the mine as shown in Figure 1. From observations and discussions with various mine operators, sufficient ventilation for dilution of noxious gases is often of lesser concern in the bench areas. The large volumetric size of the entries in the bench areas sometimes provides adequate air volume for the dilution of those exhaust gases. In the study mine, as is common with many underground stone mines, the active production faces can generally utilize as much air as the most efficient ventilation system can provide, i.e., for practical purposes, they can never have too much air. Therefore, the ventilation improvements in this case study focused on the southern portion of the mine where the active production faces were located and where the air was most needed.

[1] Product mention does not imply endorsement by NIOSH.

7 OVERHAULING THE VENTILATION SYSTEM

The mine ventilation overhaul for this case study consisted of two phases: constructing a stopping line, and installing and replacing the main mine axial-vane fan with two high-volume, low-pressure, propeller exhausting fans mounted in a bulkhead. The stopping line was oriented perpendicular to the directions of face advance and several breaks outby the working faces. This type of ventilation is typical of a perimeter mining ventilation plan (Grau et al. 2002a). Ventilation surveys were periodically taken during the construction of the stopping line to determine if the stopping line, in combination with auxiliary fans, had sufficient impact to negate the addition of a main mine propeller fan. Before completion, the stopping line which was a series of brattice curtains, initially improved the airflow, but at the end of the brattice line the air movement quickly dissipated as shown in Figure 2. Substantial air recirculation was also present at all times. It was clear that additional ventilation improvements such as completion of the stopping line and the installation of large-volume main mine fans were necessary to effectively ventilate the working faces.

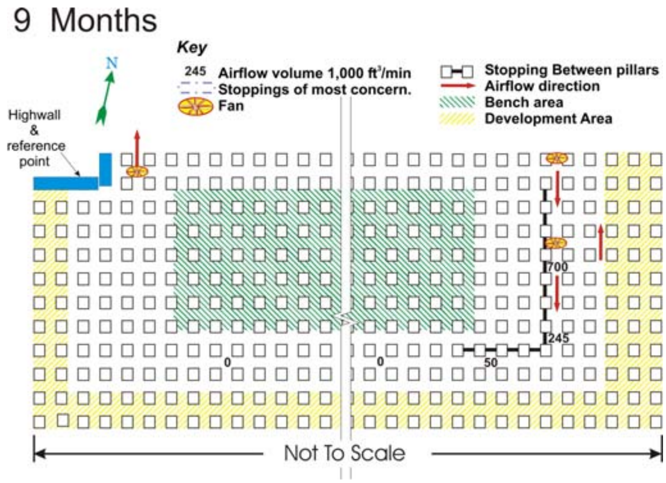

Figure 2. Airflow patterns with partial stopping lines and original fans.

Upon completion of the stopping line, two twelve-foot diameter propeller fans (Figure 3), were installed in the exhausting mode replacing the Pope[1] main mine fan. The propeller fans were Series 10S 12-ft-diameter high-volume, low-pressure fans manufactured by Hartzell Fan Co[1] mounting 100 hp motors each. After the propeller fans were operated for several weeks, it was observed that the standard brattice stoppings would not withstand the pressure and continuous flapping created by the fans, especially at locations near the fans. Brattices were pulled from the roof and rib as shown in Figure 4, or the constant flapping of the brattices near the faces caused them to shred. Other significant forces damaging the brattices were face blast pressures and fly-rock impacts.

Figure 3. Two propeller fans installed for this study.

Figure 4. Typical common example of brattice being pulled from rib.

The brattices used for this study were a one-piece design and were sized for the entries that were 45 ft wide and 25 ft high for a total cross-sectional area of 1,125 ft^2. Metal grommets were spaced every 3 ft on the perimeter of the brattice for added support. A base for attaching the brattice to the rib and roof was made by bolting 2-in x 6-in wood planks to the roof and rib. On the roof, the brattice was wrapped around the wood to make a secure holding for the brattice. Along the rib and roof, the brattice was attached to the wood by 1.5-in common roof nails with a fender washer to account for the grommet hole. Within a few months, many of the roof nails pulled away from the wood, suggesting that some type of a screw would be a better anchor.

8 PROPELLER FAN INSTALLATION

Fan installation techniques vary and depend upon the physical attributes at the fan site. The fans for this case study were installed in entries that were 25 ft high and 45 ft wide. The two 12-ft-diameter fans displace a combined area of 226 ft^2. Therefore, for practical purposes, a difference of about 900 ft^2 needed to be bulkheaded. The most convenient way to create the bulkhead was to first construct a ramp from waste rock across the entry to set the fan on as shown in Figure 5. This tactic effectively reduced the size of the bulkheaded area from 900 ft^2 to about 630 ft^2 (not including fan area). The ramp consisted of large boulders which were covered with smaller 2A modified gravel. The bulkhead was secured by 4-ft long split set bolts into the boulders.

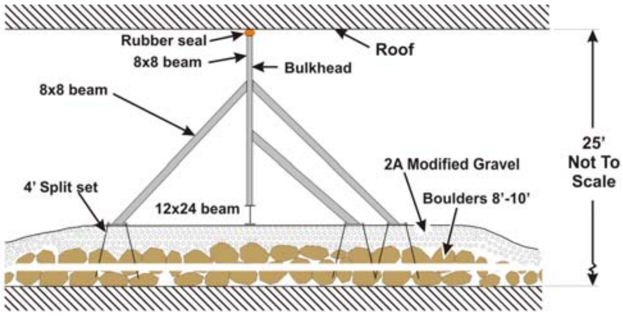

Figure 5. Cross-sectional view of propeller fan installation.

Because of stresses from blast pressures, the fan bulkhead and associated framework needed to be designed carefully. Incidents have occurred where face blast pressures have blown out bulkheads or damaged fans. However, over design of bulkheads can be costly. The entire framework for the fan bulkhead used in this case study sits atop a 12-in x 24-in I beam. The framework consists of 8-in x 8-in beams as shown in Figure 6. The beams were oriented in a square/triangle pattern to enhance the strength of the bulkhead. The fan was bolted to the bulkhead frame through tabs available on the fan's exterior shell. Smaller sections of I-beam were positioned to increase the bearing support of the circular fans that were positioned in the square box frame. The entire frame, excluding the opening for the fan, was covered with a 3/8-in steel plate to act as a barrier to prevent short-circuiting of air. To further minimize leakage, a U-shaped rubber seal was positioned between the fan frame and the mine roof. The bulkhead framework was prefabricated in a machine shop and shipped to the mine in two sections; the bottom half with beams only, and the top half with beams and plate attached. After securing the base half, the top half was simply set on top of the base half, as shown in figure 7, and welded in place. The final step was welding the bottom plate in place.

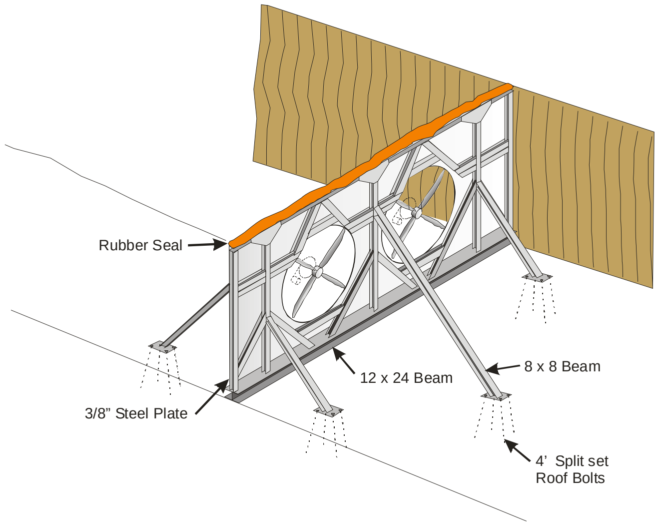

Figure 6. Plan view of propeller installation.

Figure 7. Installation of prefabricated fan bulkhead

Mine fans are required to have a guarding grid that is less than 1 in^2. The manufacturer reports that the pressure loss on the flat fan guarding that is normally used in these applications ranges from one-eighth to one-quarter of an inch of w.g., not including the resistance caused by the build up of soot deposits on the grid (Atkinson 2002). This resistance could be detrimental to the performance of a low pressure propeller fan. One alternative to flat fan guarding is area guarding. Area guarding is a fence enclosure installed several feet from the fan, and was utilized for the fan in this study. The fan area guarding consisted of a 10-ft high chain link fence with locked access doors, as shown in Figure 8. MSHA required that the guards used for this fan be at least 5 ft away from the fan. This distance not only satisfied the necessary safety requirements but also prevented any air-flow resistance.

9 MEASURED VENTILATION IMPROVEMENTS

The combination of a stopping line and propeller fans resulted in dramatic ventilation improvements at the case study mine, as shown in Table 1 and Figure 9. The most important improvement was the more than doubling of the quantity of fresh airflow into the mine; from 300,000 cfm to 750,000 cfm. After the addition of the two propeller fans, the total number of fans increased from three fans to four fans, while the total rated horsepower of the fans decreased from 475 hp to 425 hp.

Figure 8. Fan installation with perimeter guarding during maintenance.

Table 1. Ventilation fan criteria before and after ventilation changes

Ventilation Stage	Number of Fans	Available Total Horsepower	Air Volume; 1,000 cfm
Original Ventilation	3	475	300
Improved Ventilation	4	425	750
Difference	+1	-50	+450

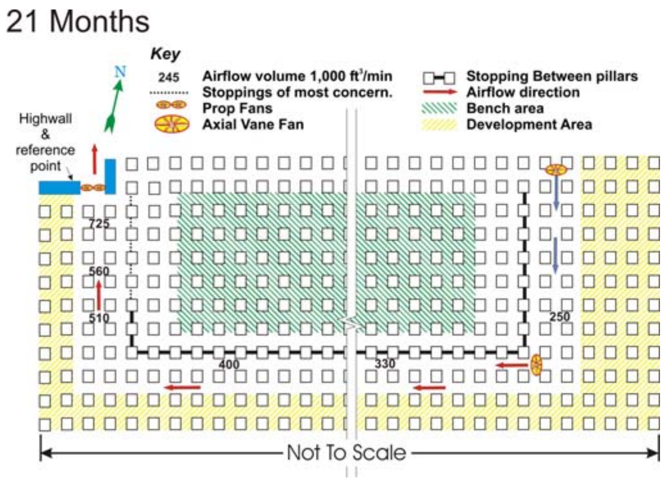

Figure 9. Airflow patterns after installation of stopping line and propeller fans.

A graphical representation of the airflow measured along the stopping line after the propeller fans were installed is shown in Figure 10. The first airflow measurement was made after the first stopping closest to the fans and was 725,000 cfm (an estimated 25,000 cfm had already been lost); the last measurement was taken 3,200 ft from the fan and was only 250,000 cfm. The 475,000 cfm loss of ventilation airflow was due to air leakage across the stopping line. The air quantity reaching the working faces, when compared to the air exhausted by the fans represents the mine ventilation efficiency. The ventilation efficiency calculated for the mine after the propeller fan and brattice installation was about 34 pct (Scenario 1, Table 2). The ventilation efficiency could have been further improved by two means; using stone pillars or permanent stoppings and/or upgrading the remaining stoppings as will be discussed latter.

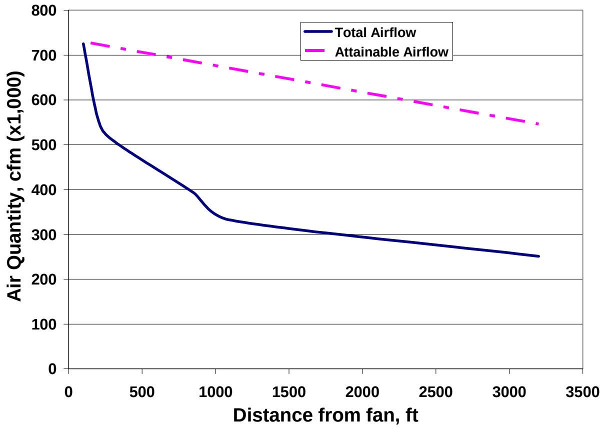

Figure 10. Airflow along stopping line.

Table 2. Potential improvements in air distribution by upgrading stoppings

Scenario	Total Number of Brattice Stoppings	Total Leakage, 1,000 cfm	Available Airflow at 3,200 ft, 1,000 cfm	Ventilation Efficiency, Pct.
1. Initial Conditions	28	475	250	34
2. Improving first 8 Stoppings (4 Stone Stoppings)	24	267	458	63
3. Improving all stoppings (14 stone stoppings)	14	179	546	75

One noteworthy observation from the case study was that when two parallel entries were available for ventilation airflow, about 60 pct of the total airflow traveled in the entry immediately adjacent to the stopping line. This percentage was slightly lower when more entries were present. In areas with four entries; the distribution of air from the first entry to the fourth entry was 43 pct, 29 pct, 20 pct, and 8 pct, respectfully. This indicates that when using the perimeter mining method, fresh air is being delivered near the working areas, but auxiliary fans become necessary to push the air to the active faces. This becomes increasingly important as the production faces advance more than four entries away from the stopping line as described above.

10 POTENTIAL ADDITIONAL VENTILATION IMPROVEMENTS

NIOSH is researching methods to improve the performance of both permanent and flexible stoppings (i.e. brattice). The mine in the case study utilized brattice stoppings and from observations it appears that brattice stoppings can be improved by backing with cabling or geotechnical grid and by attaching the brattice to the roof and rib in a manner to minimize high stress points. During the case study, there were 28 stoppings along the 3,200 ft brattice line perimeter (Figure 9); however, 70 pct (333,000 cfm) of the air loss occurred in the first 1,200 ft (8 stoppings) from the fan. A significant decrease in air short circuiting could have been achieved if half of the first eight brattice stoppings would have been stone stoppings or permanent stoppings of some type. If the remaining four brattice stoppings were improved to reduce losses by a conservative 25 pct, the total air loss in the first 1,200 ft of stopping line could be reduced to 125,000 cfm. The remaining 2,000 ft of stopping line had a loss of about 143,000 cfm through 20 stoppings for a total leakage of 267,000 cfm and a ventilation efficiency of 63 pct for the first potential improvement, as shown in Scenario 2, Table 2.

If all stoppings were improved, i.e., if half of the remaining 20 brattice stoppings from the previous scenario were stone pillars and the remaining 10 brattice stoppings were improved to reduce leakage by 25 pct, the total air loss in the remaining 2,000 ft would be reduced to about 54,000 cfm from 143,000 cfm. This would represent a total air loss of only 179,000 cfm (75 pct efficiency) at the end of the brattice stopping line (Scenario 3, Table 2). The available air at 3,200 ft would increase to 546,000 cfm from the initial conditions of 250,000 cfm, and is shown as the attainable airflow in Figure 10. Repairing the brattice stoppings to reduce short circuiting by 25 pct is a conservative estimate since the observed stoppings had large gaps present as shown in Figure 11.

11 OTHER BENEFITS OF PROPELLER FANS

Improving ventilation is not the only benefit to using propeller fans. The two 12-ft-diameter propeller fans used in this case study are capable of producing about 750,000 cfm under loads that are less

Figure 11. Leakage through brattice stopping

than one-quarter of an inch of w.g. with an actual 130 combined total operating horsepower. As a feasibility comparison to using traditional axial-vane fans, three 84-in diameter fans would have been required in this study with each fan producing 250,000 cfm to move a total air quantity of 750,000 cfm. Each of these axial-vane fans would require an outlet cone and a 200-hp motor that would operate at 130-hp for a total of 390-hp, as compared to the 130 hp of the two propeller fans.

The capital cost for the two propeller fans is about $25,000, as compared to about $90,000 for three axial-vane fans with outlet cones. Both sets of capital costs exclude the necessary starter motors. Annual operating costs are dependent upon the number of hours operated and the electrical unit cost. However, assuming an electrical cost of $0.08/kWh with the fans operating for 50 hrs per week for 50 weeks, the annual operating cost for the two propeller fans would be about $20,000, while the operating cost for three axial-vane fans would be about $59,000.

12 SUMMARY

The results of this case study demonstrate that dramatic improvements in ventilation airflow in underground large-opening mines can be achieved by the addition of large-diameter propeller fans. This increase in ventilation airflow should be an effective, practical, and cost-saving answer for improving the air quality in many underground large-opening mines, particularly large-opening drift mines. Not only do propeller fans produce large air quantities, they do so with relatively low initial capital cost, low operating cost, and at a higher mechanical efficiency than axial-vane fans under the typical low-pressure conditions. Additionally, a method to bulkhead propeller fans was documented and serves as an installation guide for other mine operators. The study also showed that a brattice stopping line and auxiliary fans used in conjunction with the propeller fans was an important aspect of improving the ventilation efficiency in the mine.

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