Breathing Easier

With the right ventilation controls and techniques, underground stone operators can create healthier work environments.

by Roy H. Grau III and Robert B. Krog

Increased awareness of a healthy work environment is common to all industries and the stone industry is no exception. The presence of operating diesel equipment, welding, stone production blasting, and silica dust in a working environment all contribute to air quality issues in underground stone mines. Particularly recognized is the exposure of workers to diesel particulate matter (DPM). Recent regulations call for a DPM standard of 160_{TC} ug/m^3 (TC = Total Carbon). The National Institute for Occupational Safety and Health (NIOSH) has conducted research to improve the ventilation of these mines and consequently reduce the exposure of workers to harmful airborne contaminants. The results have shown that the ventilation of underground stone mines can be significantly enhanced using improved ventilation controls and techniques.

Large-opening stone mines present specialized ventilation challenges because their entries are much larger than in other types of mines. Most stone mines have entries about 40 feet wide and up to 30 feet high, with bench areas that may extend even higher. These large entries present the positive opportunity to move large air quantities at relatively low mine fan pressures resulting in lower fan horsepower and reduced operating costs. However, the difficulty in ventilating large-opening mines is that even with large air volumes, the air velocity is often less than 100 feet/minute. Higher ventilation velocities more quickly dilute and remove contaminants from the face areas. Higher ventilation airflow velocities can be achieved by effective ventilation planning and proper choice of ventilation fans.

Good mine planning is essential

Ventilation is improved significantly in underground stone mines by considering future ventilation needs in the mine planning process (Grau and Krog, 2008, Krog et al., 2004). By strategically selecting stopping designs, stopping and auxiliary fan locations, and stopping types, the mine ventilation efficiency (air quantity at face compared to total mine airflow) and, consequently, the air quality will be improved. Although an adequate large-opening mine ventilation system depends on many

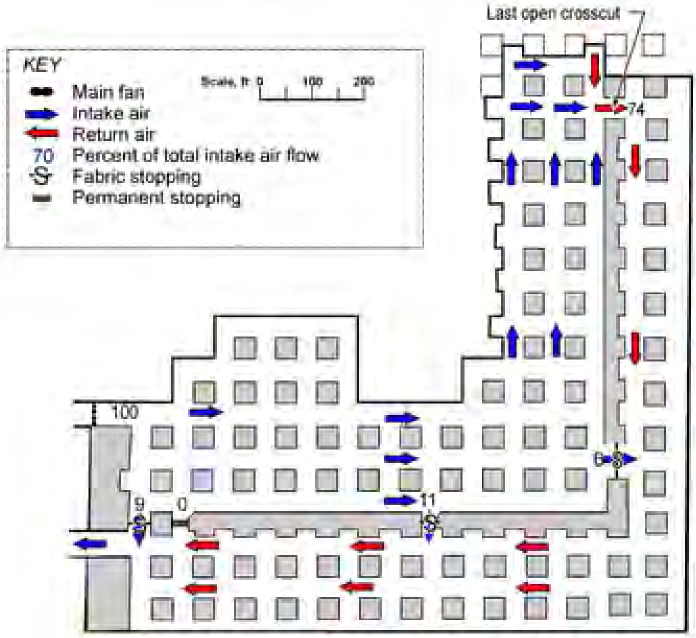

Figure 1. Blowing system using long pillars to direct ventilation air.

factors, preventing leakage between stoppings is a primary consideration. With reduced leakage, more of the airflow generated by the main mine fans reaches the faces to dilute and remove harmful contaminants.

The basic principles of mine ventilation planning include determining the air quantity that is needed to dilute and render harmless all contaminants, how to produce this airflow, and how to direct this airflow to the required mine locations. The necessary airflow quantity is highly dependent on the diesel equipment in use. Cleaner burning engines require less air to dilute diesel emissions and, consequently, require less production from the main mine fan. A mine with less stopping leakage also reduces the needed airflow from the main mine fan because a higher percentage of the airflow from the main fan reaches the face areas. In order to help mine operators determine how much airflow is necessary, NIOSH developed a user-friendly, stand-alone computer program called the "air quantity estimator" (Robertson et al., 2004). The program is available for download on the NIOSH mining Web site (*www.cdc.gov/niosh/mining/products/product4.htm*). The program uses diesel engine information from several sources to provide a starting point to estimate the air quantity required to dilute DPM contaminants to statutory levels in the main return of a mine.

Several studies performed by NIOSH in mines that produced from 1.0 million to 1.2 million tons of stone per year showed that air quantities of about 750,000 cfm were needed to comply with a 400_{TC} ug/m^3 DPM concentration limit, although the necessary ventilation air quantity is highly dependent upon the diesel equipment in use and resultant ventilation efficiencies (Grau et al., 2002). In order to comply with the current DPM exposure limit of 160_{TC} ug/m^3, the estimated required air flow would be greater.

Since haul trucks are the single highest source of DPM, confining the truck haulage to the return air courses is a good working practice and should be done whenever possible. Truck drivers' exposures to DPM can be minimized by ensuring that truck cabs are equipped with positive filtration systems and the correct filters are used (Noll et al., 2008.)

Use the right fan

Generally, there are two types of fans used in underground stone mines: vane-axial and propeller fans. Vane-axial fans are designed to deliver air volumes at high static pressures. Propeller fans deliver large air quantities, but at much lower pressures. NIOSH observations have found that a total mine fan pressure of less than 0.75 inches (w.g.), not including shock losses, is common in drift portal stone mines and stone mines with slopes or declines operating at depths less than 100 feet or with shaft diameters greater than 15 feet. By comparison, coal mines have higher resistances, which typically range from 2 inches (w.g). to 10 inches (w.g.). The magnitude of the total mine fan pressures is an important factor when choosing what type of fan to use in a stone mine. Propeller fans are often the best choice for ventilating stone mines since these fans generate large air flows at lower static pressures, generally require less capital and lower operating costs, and have lower operating noise levels compared to vane-axial fans (Krog and Grau, 2006). Generally, second-hand vane-axial fans were readily available for sale and thus they are prevalent in many large-opening mines, but propeller fans should be considered in conditions such as those described above.

Ventilation planning factors

The physical layout of a stone mine significantly impacts the mine's ventilation efficiency. NIOSH research has shown that significant improvements in ventilation are achieved by using long stone pillars to direct the ventilation air. Long stone pillars are created by leaving the break-though cut in a crosscut, creating a pillar that is much longer than normal, with some pillars being over 500 feet long compared to a 45-foot width, as shown in Figure 1. Although there is an apparent loss of stone when developing long pillars, the pillars can be mined during

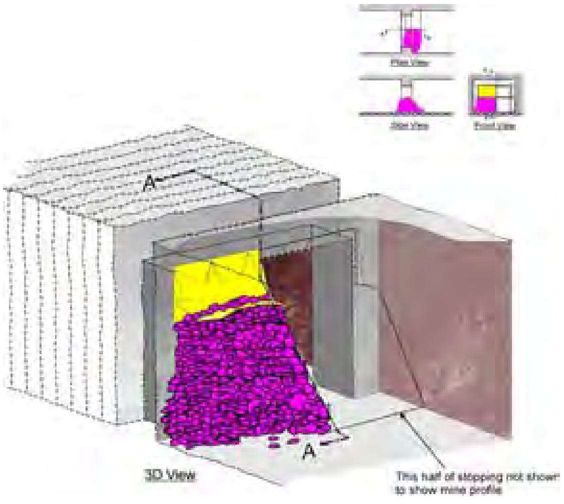

Figure 2. Effective stopping with reduced entry size.

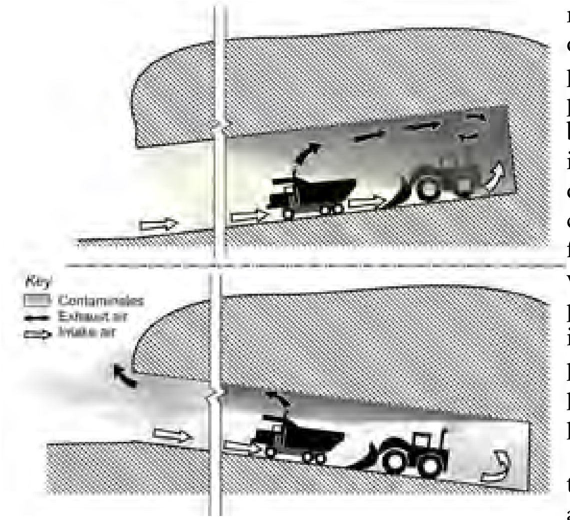

Figure 3. Air movement when mining up and down slope.

the last days of the mine. Long stone pillars eliminate the leakage that occurs when using fabric stoppings and substantially increase the ventilation airflow to the face. Notice that the mine in Figure 1 delivered 74 percent of the air produced by the main mine fan to the face. By observation, it was apparent an even higher percentage could have been achieved by reducing the leakage at three of the four crosscuts. In comparison tests, a different mine using conventional fabric stoppings at every crosscut, instead of long stone pillars, moved only 33 percent of the total air produced to the face.

Although conventional fabric stoppings are difficult to properly construct and maintain and are prone to leakage, they are a necessity in some locations. Where stoppings are required, a good construction technique is to use "cut-downs." Cut-downs involve cutting the roof and rib of the entry smaller than normal, as shown in Figure 2. This allows for a solid stone backing along the rib and roof against which the material can be attached to permit a better seal. Cut-downs are helpful in any entries where stoppings are to be built. One more effective method to reduce leakage is to use piled rock in the crosscut entry and top it with a fabric stopping, as shown in Figure 2. The smaller area created by the piled stone reduces the quantity of fabric material and the opportunity for rips or tears.

Although stone mines are generally shallow operations, their natural ventilation is apparent, but it is uncontrollable in direction. In many mines, the natural ventilation changes direction several times within a day. In most cases, the main mine fan should overcome all natural ventilation. However, there are conditions that make a mine or sections of a mine much more difficult to ventilate. Mining up slope creates contaminated air pockets of warm diesel exhaust, as shown in Figure 3. NIOSH has observed large production areas being difficult to ventilate because the sections were developed up slope. In the summer months, fresh air that has been cooled by the mine ground temperature is required to move up slope to push out warm air that is collecting in the upper reaches. Mines that are developed down slope are easier to ventilate as the warm, contaminated air naturally rises away from the face.

Many mines use a slope for access from the surface or from one mining level to another. When developing the slope or the mine workings, advancement can be slow. If a single slope is used, tubing attached to an exhaust or blowing fan is necessary for ventilation. In such cases, operators may be tempted to develop a mine airshaft as soon as possible once the mining level is reached. In fact, NIOSH has observed some operations where the slope bottom is just a few breaks away from the bottom of an airshaft with no stoppings between. As the mine expands, this creates a ventilation problem, as most of the airflow will short circuit directly to the exhaust shaft rather than move past the shaft to the mine workings. This results in serious contamination problems in the mine workings due to minimum inflow of fresh air.

An alternative approach is to continue to use the blowing tubing to construct the shaft a further distance from the slope bottom and orient long stonewalls to force the air to the production faces, as shown in Figure 4. Later, the cut-downs "A" can be permanently sealed to prevent short-circuit leakage from the slope to the shaft. It is a tradeoff, as using tubing is considered a necessary nuisance while trying to locate the shaft some distance from the slope. Notice that once underground development to the shaft begins, at least two entries must be available for an escapeway, as shown by "A." Once the mine is expanded, future mine plans may eventually call for abandoning the shaft and relocating the shaft to a location beneficial to a larger mine.

General ventilation considerations

A common question is whether to use blowing or exhaust ventilation in a stone mine. Due to the low fan exit losses, equal amounts of energy are used with either method. If a mine uses drift portals for ventilation, one disadvantage of an exhaust system is the need for check curtains on the portal where the trucks leave the mine. A mine operating an exhaust system needs two

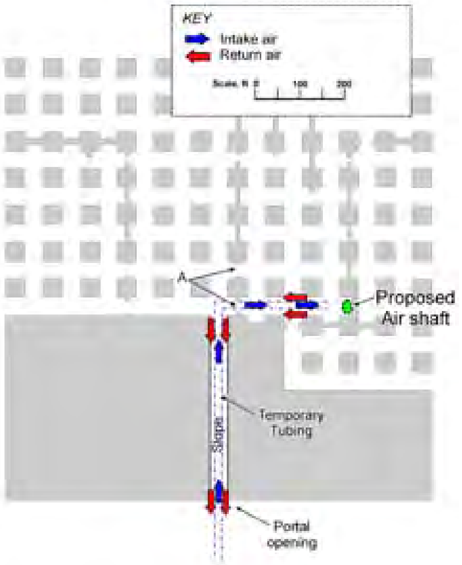

Figure 4. Using blowing tube down slope while driving to shaft.

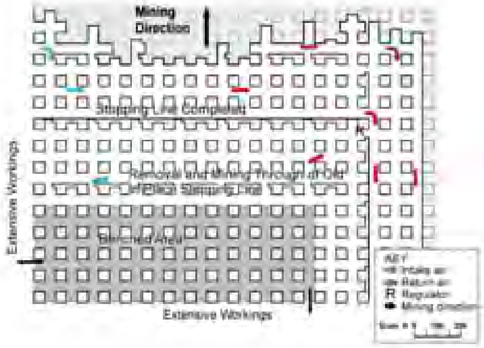

Figure 5. Perimeter ventilation with bench mining following development of in-place stone stoppings.

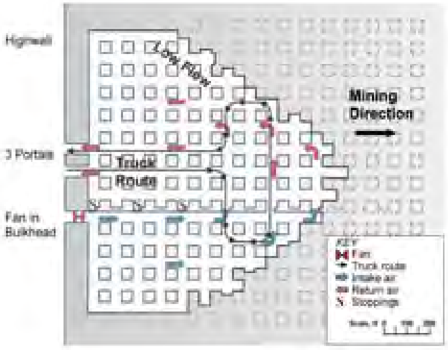

Figure 6. Split mining blowing system with truck haulage.

return portal exits, one for the truck haulage and one for the fan. Without check curtains, the exhaust fan would pull air from the truck portal, short circuiting airflow to the active face area. For a mine operating a blowing system, truck haulage using the returns and exhaust portals do not need check curtains. This is a distinct advantage for a blowing system in these types of instances.

Potentially hazardous circumstances can develop on a seasonal basis depending upon how and where the ventilation air enters the mine. If a mine has an exhaust shaft with an intake slope, cold air that enters the slope may create icy roadways and hazardous travel conditions during the winter months. In the summer months, warm moist intake air being cooled in the mine causes condensation on the roof and ribs, which, in turn, can promote ground control problems. This is likely less of a problem near the shaft, which is normally away from common travel areas. Therefore, local conditions may dictate the choice of an exhaust or blowing system. For a mine with only portals and no air shaft, blowing ventilation has a distinct advantage of not requiring the check curtains. Also, it has been observed that the fans can be reversed during different times of the year. In some cases, this reversal could be beneficial, although a detailed investigation into changes in traffic pattern would be required. Considerations must also be given to keeping haul trucks from traveling in the return airways until blast fumes from stone production have left the mine. This can usually be accomplished by blasting at the end of the last shift of the day (assuming the mine doesn't work all night). This schedule allows the mine ventilation to clear out blast fumes. To determine the time required, velocity rates for intake air can be checked in the return using an anemometer. Chekan et al. (2004) found that velocities in one stone mine ranged from 60 feet/minute to 75 feet/minute by monitoring dust and exhaust clouds traveling through the mine after a production shot.

Mine plan layouts should be developed with considerations given to future ventilation needs as the mine expands in size. Three methods to ventilate a large, underground limestone mine have been documented and tested by NIOSH: perimeter, split, and unit ventilation (Grau et al., 2002). These methods are designed to create stable and measurable airflows at the working faces. Older large-opening mines that have limited preplanned ventilation systems often attempt to ventilate using the perimeter ventilation system. This system is designed to keep the active faces continuously supplied with intake air, which is accomplished by separating the active mining areas from the rest of the operation using air walls of stoppings or rectangular pillars, as shown in Figure 5. The disadvantage of this system is that all sections are on one ventilation circuit, creating possible air quality issues with multiple faces. Since the mining front continually expands, a second air wall is developed at least four entries beyond and parallel to the first air wall. In an older developed mine that is trying for the first time to establish a ventilation system, the first air wall needs to be developed by erecting fabric stoppings. However, the second air wall could be developed by minimizing crosscut development through the use of long stone pillars. As mining progresses beyond the second air wall and a third air wall is developed, crosscuts in the second air wall can be fully developed and the stone recovered. Expanding the perimeter in this way allows for better ventilation to the faces. Split mine ventilation is designed to split the mine into two parcels, intake and return, separated by an air wall (Figures 1 and 6). Face ventilation with this system is similar to the perimeter ventilation method, in that air is coursed by air walls. However, this system can be used during mine start-up and allows the ventilation air to be divided into multiple splits, if desired. Also shown in Figure 6 is a projected truck route situated in return air.

Unit mining is generally used in combination with other ventilation plans such as split ventilation systems (Krog et al, 2004). The unit ventilation method is a series of "units" or "sections" which make up the active mining areas, as shown in Figure 7. The units described in this method are pre-planned mining blocks of several pillars that contain the working faces and that are surrounded on four sides by long air walls incorporating stone stoppings. The air walls have only a few openings or check curtains, which allow for ventilation control and haulage. One advantage of this method is that it allows for these units to be at least partially removed from the main mine ventilation circuit when mining is completed.

Using auxiliary fans

Auxiliary propeller fans are becoming more popular in underground limestone mines. NIOSH studies have found that auxiliary, free-standing vane-axial and propeller fans have different airflow patterns which affect the positioning of fans for effective face ventilation (Krog et al., 2006). The study found that, due to momentum transfer, both types of fans entrain and move considerably more air than the rated capacity of the fan, as shown in Figure 8. The 8-foot-diameter propeller fan was rated at 115,000 cfm and was powered by a 30-horsepower motor. The vane-axial fan was rated at 22,000 cfm, it was equipped with a 23-inch-diameter discharge reducer, and was powered by a 25-horsepower motor. The propeller fan generated airflow of 536,000 cfm. However, this was a slower-moving air mass that interacted differently with the surrounding air as compared to the airflow developed by the vane-axial fan. The air exited the propeller fan outlet at 2,500 feet/minute and expanded rapidly to cover the entire cross-section of the drift.

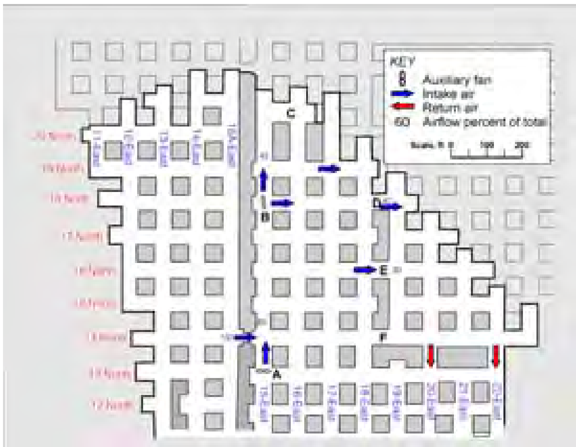

Figure 7. Transitioning from split ventilation to unit ventilation.

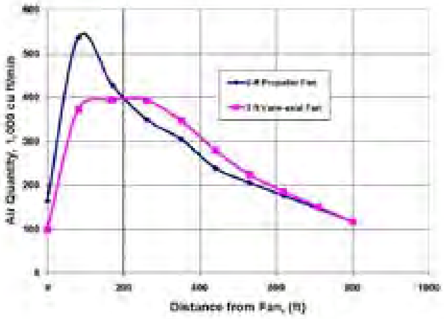

Figure 8. Velocity profiles for propeller fan and vane-axial fan.

Figure 9. Face ventilation with improperly positioned auxiliary fan.

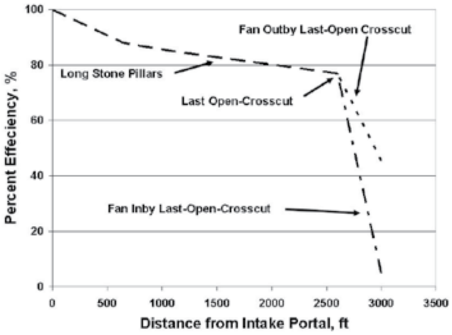

Figure 10. Ventilation efficiencies found using long pillars and auxiliary fans.

The velocity profile was much closer to uniform (i.e., being more evenly distributed across the drift) than was observed with the vane-axial fan. The vane-axial fan had an exit velocity of 7,600 feet/minute and entrained air as far as 260 feet downstream from the fan, whereas the propeller fan entrained air only for about 100 feet. Both fans showed similar reductions in airflow quantity with distance.

These test results verified those by Dunn et al. (1983), who found that a free-standing vane-axial fan entrained nine to 15 times the rated capacity of the fan. Due to these different entrainment levels, propeller and vane-axial fans have different placement criteria when used as auxiliary fans. Kissell (2007) reported several studies showing that ventilation efficiencies in dead-end entries were improved when free-standing vane-axial fans were equipped with a reducing nozzle and were tilted slightly towards the roof.

Placing auxiliary fans

Although a long pillar air wall can assist in delivering large air quantities to the last open crosscut, the correct placement of auxiliary fans plays a vital role in moving the air from the last open crosscut to the face. To better understand this concept, NIOSH performed a series of in-mine tests to determine the impact that auxiliary fan positioning has on the percentage of intake air at the last opening of the long pillar that is delivered to the face (Grau and Krog, 2008).

Figure 9 shows an auxiliary fan improperly positioned because it is inby the last pillar opening. A fan at this location provides only marginal improvement in ventilation. In this scenario, 74 percent of the air produced by the main mine fan reached the last open crosscut, while only 5 percent of the air was measured 400 feet from the last open crosscut. A small amount of face ventilation is achieved because the air mass moving down the intake entries carries momentum which pushes it a short distance into the face area. Also, a small amount of ventilation arises from the motion of both the loader and trucks at the face. However, even with the fan and the equipment movement, the face ventilation in this scenario is minimal.

The fan being positioned inby the main ventilation air stream increases recirculation while providing minimal fresh intake air to the face. Furthermore, the position of the fan in the middle entry tends to promote excessive recirculation as the air reverses both in entry “A” and is non-directional in the entry at “B,” with the recirculated air acting as a substitute for fresh air. It should be noted that not all recirculation is detrimental, with previous studies showing that recirculation is a problem only when it replaces the quantity of fresh air moving to the face (Kissell and Bielicki, 1975).

Figure 10 shows the ventilation efficiencies measured along the stone pillar air wall to the last open crosscut and to the face where the highest efficiency drop occurs. The total efficiency is highly dependent upon the placement of an auxiliary fan or fans near the last open crosscut. An auxiliary fan improperly positioned inby the last open crosscut provided a ventilation efficiency of 5 percent measured at a location 3,000 feet from the intake portal or 400 feet inby the last open crosscut.

The correct auxiliary fan location, as shown in Figure 11, is outby the last open crosscut where it can entrain and blow fresh air into the face area. The fan should also be positioned in the furthest upstream entry (in this case, the left) to create air movement that is traveling in the same general direction as the air being moved by the main mine fan. Being in the left-most entry, recirculation is reduced and the air sweeps the face. Using this configuration, virtually all of the air that was moved by the auxiliary fan was intake air, and 57 percent of the air at the last open cross-cut was pushed 400 feet to the face area. Figure 10 shows that the proper positioning of the auxiliary fan in the intake air significantly increases the fresh air quantity that moves to the face. Correct positioning of the fan yielded a mine ventilation efficiency of 45 percent when measured 400 feet inby the last open crosscut.

Both vane-axial and propeller fans should be positioned in such a way that they entrain, and then

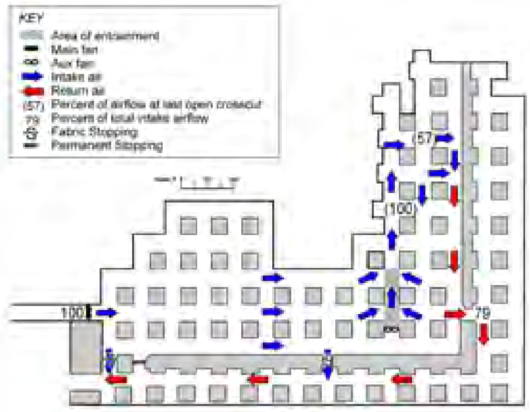

Figure 11. Face ventilation with properly positioned auxiliary fan.

move, the maximum quantity of fresh intake air to the face. Generally, this is outby the last opening in the pillar. Both vane-axial fans and propeller fans should be positioned to entrain as much intake air as possible, keeping in mind that vane-axial fans entrain for up to 260 feet after the fan (Krog and Grau, 2006). The propeller fans should also be located in the intake air where entrainment takes place within 100 feet downstream from the fan. It should be noted that moving the fan further from the face, outby the last open crosscut in the long pillar, does not increase the airflow to the face, but increases the percentage of fresh air available at the last open cross-cut that is moved to the face.

Concerning the application of these fans, propeller fans work best in regional ventilation applications where they can move large slugs of air. Vane-axial fans work best in face and dead-end ventilation applications (due to better penetration and greater mobility) (Krog et al., 2006).

Unit ventilation systems

Figure 7 shows the transitioning of a split mining system to a unit mining system where the unit section is to the right of entries “D,” “E,” and “F.” In this scenario, the ventilation of the unit section was significantly affected by the positioning of two auxiliary fans. The fan situated at “A” is needed to push the air from the last open crosscut toward the face at “C” and to prevent short circuiting of airflow to the bottom of the figure. The second fan is situated near “B” between the last open crosscut and the “C” face. This fan, when directed to ventilate “C” face, allows only about 10 percent of the available air at “A” to reach the unit section through entries “D” and “E.” However, when the fan is positioned in the same location, but directed toward the unit section, the total ventilation air through “D” and “E” amounts to about 70 percent of the air coming through the last open crosscut near “A.”

Two important considerations are noteworthy when transitioning to unit ventilation. First, it is necessary that a mobile fan can be quickly adjusted, depending upon whether workers are in the uppermost “C” face or in the unit section. Portable diesel-powered fans are becoming popular in underground limestone mines and are best suited for such conditions. Second, as shown in Figure 7, a fan is necessary at “A” in all situations to ensure that fresh air passing through the last open crosscut is directed to the active faces.

Conclusions

These methods to improve ventilation airflows and ventilation efficiencies in large-opening mines include the use of the NIOSH Estimator to estimate the airflow required for proper DPM dilution, use of propeller fans where possible, and utilization of mine planning layouts that incorporate long stone pillars, stoppings, and auxiliary fans to direct airflow to active face areas. The use of long stone pillars is particularly effective in reducing leakage between intake airways and return airways, thus allowing the maximum amount of air produced by the main mine fan to reach the face area. Although various factors can impact face ventilation effectiveness, the best method to ventilate the face is to position an auxiliary fan outby the last open crosscut and in the furthest upstream entry, such that it blows through the intake entry. It is shown that auxiliary fans entrain and generate considerably more air quantity than the actual fan rating. Therefore, although actual conditions will dictate the proper position of the auxiliary fans, as a general rule, they should be located in the intake air, outby the last opening in the long pillar, entraining as much intake air as possible. This will lead to increased fresh air quantities moving toward the face. To reduce recirculation, the fan should also be located in the furthest upstream entry to create air movement that is traveling in the same general direction as the air being moved by the main mine fan.

Authors’ note: The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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