

VENTILATION PLANNING LAYOUTS FOR LARGE OPENING MINES

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ABSTRACT

Stone mines represent the highest percentage of operating underground nonmetal mines in the United States. With the introduction of stricter Diesel Particulate Matter (DPM) regulations, large-opening underground room-and-pillar stone mine operators are faced with implementing one or more alternative methods to reduce concentration levels including: install and maintain an effective ventilation system; install lower DPM emission diesel engines; the adding of DPM filters. The National Institute for Occupational Safety and Health (NIOSH) is actively researching various aspects of fan and stopping designs in an effort to improve the ventilation of these mines. NIOSH has identified and further developed three alternative ventilation methods for use in large-opening underground mines: split-mine, perimeter, and unit-ventilation. This paper describes the implementation of the three methods with respect to their use in mines of various levels of development.

INTRODUCTION

NIOSH is actively researching ventilation layouts to help the underground stone industry meet and surpass Diesel Particulate Matter (DPM) regulations to protect the health of workers. Large room-and-pillar stone mines in the United States represent a major sector of mines in the noncoal mining industry. Numerous large room-and-pillar mines began as surface quarries, that due to increased stripping ratios or environmental considerations, have become underground mining operations. These stone mines are characterized by massive openings and large expanses that correlate to very low ventilation resistances. Historically, natural ventilation has been their primary means of diluting airborne contaminants. Natural ventilation by itself is no longer regarded as workable in large room-and-pillar mines because it does not guarantee a consistent measurable airflow (Head, 2001a). Without a consistent airflow direction or air coursing, recirculation of contaminants will occur, which could result in unhealthy working environments.

Large room-and-pillar stone mining fundamentals

The value per ton of ore for large room-and-pillar stone mines is typically low, therefore productivity must be high. Typical face areas are 12.2 m wide x 7.6 m high (40 ft wide by 25 ft high) with 4.3 m (14 ft) pulled with each blast (Figure 1). This equates to over 1,000 tons of stone per development/production blast based on standard ore density. Larger face widths up to 18.3 m (60 ft) have been developed. An initial development height in thicker beds of roughly 7.6 m (25 ft) is controlled by equipment limitations (scalpers and roof

bolters). Benching is common in thicker beds with heights of 30.5 m (100 ft) having been recorded in mines after successive benching. Pillars are commonly set on 30.5 m x 30.5 m (100 ft x 100 ft) centers with 75% extraction. Roof control is typically achieved by leaving strong "roof" rock behind where available. Where mechanical rock support is required, mines use various types of rock reinforcement methods.

Mines that have multiple drift (portal) entries with no primary restrictions (exhaust shafts, single ramp) can have remarkably low ventilation resistances, virtually orders of magnitude lower than typical metal and coal mines. For example, a 305 m (1,000 ft) long drift that is 12.2 m (40 ft) wide by 7.6 m (25 ft) high with a k factor of 0.0130 kg/m^3 ($70 \times 10^{-10} \text{ lb-min}^2/\text{ft}^4$) could move $354 \text{ m}^3/\text{s}$ (750,000 cfm) of air at a static pressure loss of 25 Pa (0.0984 in w.g.) (Head, 2001b). The remainder of the workings, which have an even lower resistance in most cases, can be ignored in the calculations. Shock losses, air temperature differences, and wind load can all have a large impact on ventilation patterns because of the low system resistance. The air quantity of $23.6 \text{ m}^3/\text{s}$ (50,000 cfm) of airflow moving in a 92.9 m^2 (1,000-ft²) entry is hard to measure accurately because most flow-recording devices have difficulty reading velocities below 0.25 m/s (50 ft/min). Without an effective ventilation system, airflow reversals and flow inversions in entries are possible and do occur frequently, further complicating accurate airflow measurements.

VENTILATION METHODS FOR LARGE OPENING MINES

Three large opening stone mine ventilation methods have been previously described by NIOSH researchers: perimeter, split-mine, and unit-ventilation (Mucho, 2001) (Grau, 2001b). These three methods are main mine ventilation systems designed to create stable measurable airflow to the last open crosscut by the use of pressurized intakes and returns (Grau, 2002b). These systems should not be mistaken for auxiliary face ventilation of long deadhead drifts or area ventilation that could have high recirculation. The following mine layouts have been designed mainly for ventilation, but ground control issues should also be considered. Standard room-and-pillar mine layouts are used, but can easily be adapted for staggered or elongated pillars.

Split-Mine Ventilation

Of the three ventilation methods, split-mine ventilation is the simplest in terms of layout and design, as the mine is split into separate intake and exhaust sides. Split-mine ventilation is a mine-wide ventilation method designed to deliver the bulk of the main mine fan's airflow to the last open crosscuts near

the active working faces. This is accomplished by the use of a continuous stopping line that is installed from the portals to the active faces. The stopping line is developed parallel to the mining direction and trails the active faces by three or four breaks, thereby locating the stoppings far enough away from the production face shots to reduce damage. Figure 2 shows an early split-mine ventilation system. Bulkheads are more susceptible to blasting pressure damage than stoppings because of their rigid nature and therefore have to be installed further away from blasts. Figure 3 shows a propeller fan blowing into a new mine that uses the split-mine ventilation system. Figures 4 and 5 show how a split-mine is expanded over time. As the mine increases in size, around 10 breaks in, a large-diameter low-pressure fan can be installed in a bulkhead to create a consistent airflow output without damaging the bulkhead from blast pressure (Figure 6) (NIOSH, 2002a).



Figure 1. Typical large-opening mine entry [12.2 m x 8.2 m (40ft x 27ft)]

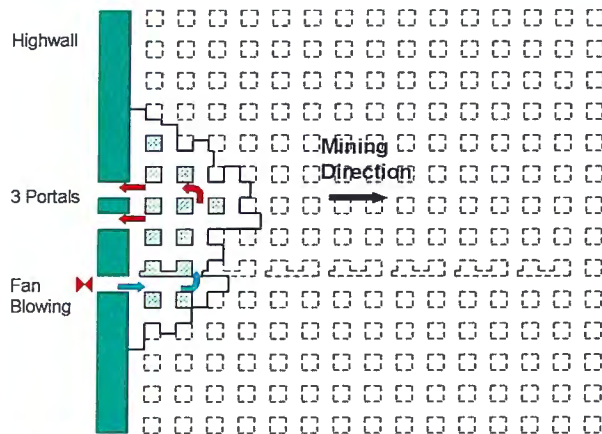


Figure 2. Split-mine ventilation, (phase 1) fan blowing into mine

Stopping line considerations: Stoppings near the production blasts have to be resistant to high blast pressure loading rather than the low static pressure induced by the main fans. As development advances away from the stopping, blast pressure loading decreases, but a tighter seal is required to reduce leakage; thus, the stopping line undergoes different loading conditions throughout its lifetime. As the stopping line increases in length, the initial permanent stoppings encounter

a constant static pressure and have to be sealed completely to reduce repetitive flapping damage (Figure 7).



Figure 3. Propeller fan blowing into a new mine using split-mine ventilation

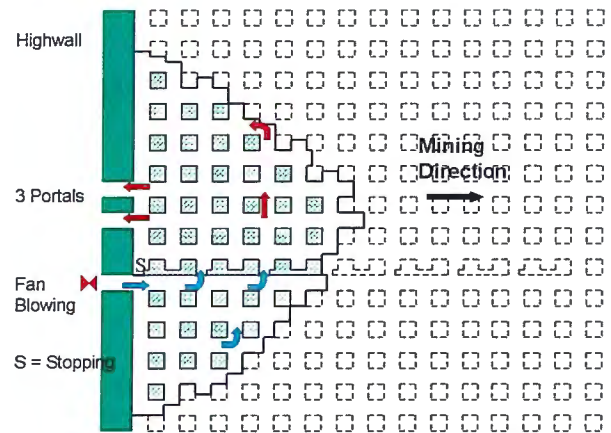


Figure 4. Split-mine ventilation, (phase 2) installation of first brattice stopping, three open crosscuts

The stopping line that separates the two airways could be a combination of brattice stoppings, in-place stone stoppings or permanent stoppings (NIOSH, 2002b). An in-place stone stopping can be defined as stone left un-mined in a room and pillar operation that is used to course airflow by not developing the crosscut or entry completely. Figure 5 shows five in-place stone stoppings running parallel to the mining direction.

Air leakage associated with the stoppings can drastically reduce the overall effectiveness of a ventilation system in any mine. For a split-mine ventilation system, the stoppings closest to the fan, which have the highest static pressure, are the most critical because leakage at the fan does not reach the active workings and is completely lost. Some leakage at the last stoppings, closest to the face, is not a total loss because some dilution will still occur, yet those stoppings have to be able to withstand higher blast pressure. Poor installation or maintenance of a stopping line could quickly result in a large percentage of the total ventilation airflow not reaching the face area. A test case mine was shown to lose 50% of its total ventilation airflow to leakage in the first 12 stoppings (Grau, 2004). Constant inspection and maintenance of the stopping

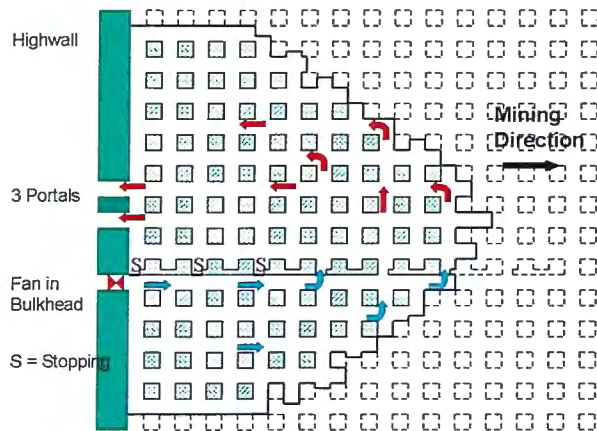


Figure 5. Split-mine ventilation, (phase 3) three stoppings installed with three open crosscuts, high flow fan can be installed in bulkhead

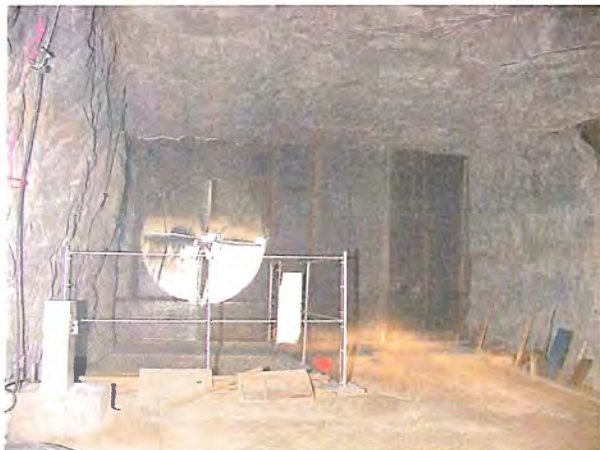


Figure 6. Large propeller fan mounted in bulkhead



Figure 7. Typical repetitive flapping damage caused by static pressure across stopping (not blast damage)

line is essential for a split-mine ventilation system to work properly and effectively.

The stoppings installed near the active workings are categorized as check curtains, damage resistance is a priority over leakage at this stage so the stoppings are hung loosely

from the roof. Leakage is minor as there is very little static pressure generated across the stopping due to the large unobstructed openings located nearby. As the mine expands and the stopping line is extended with the development faces, a permanent, better sealing stopping is warranted due to the increase in static pressure and at this point, i.e. leakage, not blast damage, becomes the priority (Figure 8).



Figure 8. Tightly installed brattice stopping in a large-opening mine [16.8 m x 8.5 m (55 ft x 28 ft)]

Because the stopping line is developed parallel to the mining direction, production disruptions are minimal due to the lack of mining faces or excessive restrictions on travelways. In-place stone stoppings can play a dominate role in reducing leakage and stopping maintenance. Most of an in-place stone stopping's internal crosscut can be mined except for the last round. Stone stoppings should not be considered lost production. Only if no other faces are available can the material left in place for the stopping be considered lost production. Also, the material can be recovered at a later date. With the low value of the material, the profit incurred by mining the last part of the crosscut should be compared to the cost of constructing a stopping to seal the crosscut later, the required maintenance on that stopping, and the lower effectiveness of the stopping.

Split-mine ventilation is very effective for new mines because permanent stoppings can be designed and installed during the initial development. The effectiveness of this system is based on the number of main entries, number of open crosscuts, stopping leakage, mine development shape, and stopping line location.

Numerical modeling of ventilation airflows:

Numerical modeling is one method to estimate the flow rates in various entries. A numerical model of various ventilation scenarios shows that the number of main entries determines the effectiveness of the ventilation system. For this research on numerical modeling of large opening room-and-pillar mines, Ohio Automation's ICAMPS MineVent program¹ was used and it should be noted that resistance had to be entered at 100 times the actual value because the model does not work well with such low values. A key simplification in numerical modeling ignores the airflow momentum, which plays a large role in determining flow patterns in large-opening mines. Unlike deeper, higher pressure metal mines, airflow that reaches an intersection does not split according to resistance (pressure drop) of the next branch, but tends to be controlled by momentum. This is because the shock loss of changing

¹ Product mention does not imply endorsement by NIOSH

directions even with a low velocity pressure is significantly higher than the static pressure drop of the next branch.

The model reveals that an 8-main mining system with a stopping line running down the middle can effectively ventilate the two outermost entries. However, a 16-main system with a stopping line running down the middle does not effectively ventilate the two outermost entries. Using the numerical model as a guide with 236 m³/s (500,000 cfm) as the base airflow rate, airflow at the outermost entries was determined to be 12.7% [30.0 m³/s / 236 m³/s (63,300 cfm/500,000 cfm)] of total flow in an 8-main system (Figure 9). Results of 10.2% [24.1 m³/s / 236 m³/s (50,900 cfm/500,000 cfm)] of total flow in a 12-main system (Figure 10) and only 7.2% [17.0 m³/s / 236 m³/s (36,100 cfm/500,000 cfm)] in a 16-main system (Figure 11) were determined. Even with double the airflow, mines using a 16-main system will find it very difficult to get an equivalent airflow to the outer entries without using auxiliary ventilation.

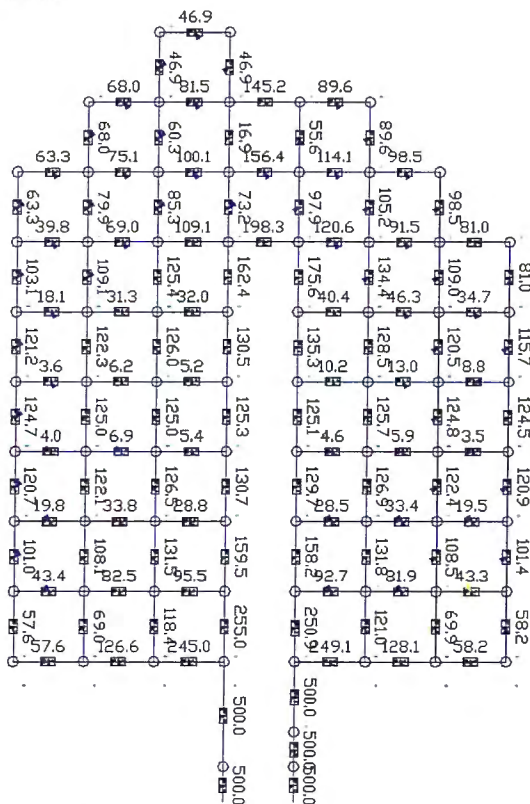


Figure 9. Numerical model ventilation airflow simulation of an eight-entry split mine with three open crosscuts (flow in 1,000 cfm, divide by 2.118 to get m³/s)

Effective use of the split-mine ventilation method requires that the number of open crosscuts be kept as low as possible to bring the highest volume of air to the apex of the mining front. The optimum number of open crosscuts is determined by blast damage, ventilation requirements, and haulage constraints. Figure 12 shows the relationship between the number of open crosscuts to airflow and truck travel directions. Limited observations have suggested that three to four open crosscuts is the preferred arrangement. With five or more open crosscuts, little ventilation airflow reaches the mining equipment at the active faces (Figure 13).

The locations of the open crosscuts are assumed to be at the end of the stopping line.

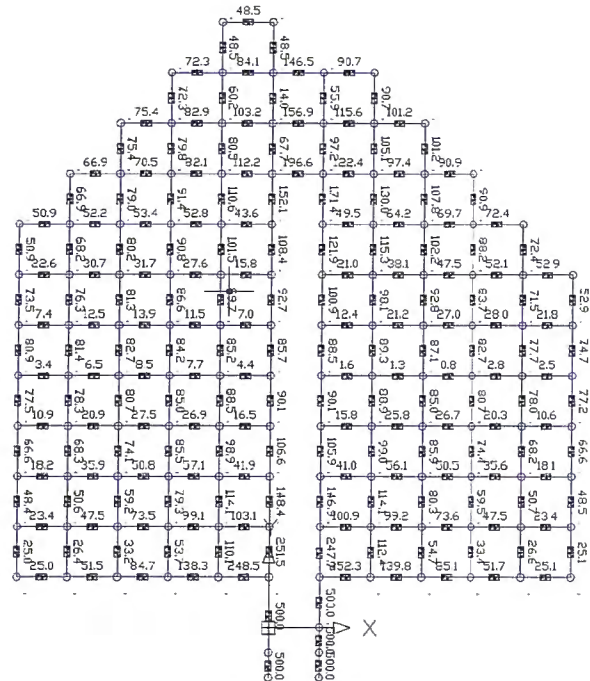


Figure 10. Numerical model ventilation airflow simulation of a twelve-entry split mine with three open crosscuts (flow in 1,000 cfm, divide by 2.118 to get m³/s)

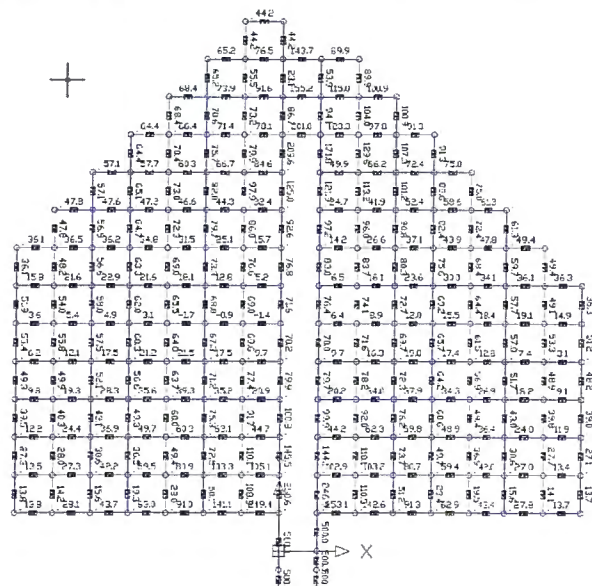


Figure 11. Numerical model ventilation airflow simulation of a sixteen-entry split mine with three open crosscuts (flow in 1,000 cfm, divide by 2.118 to get m³/s)

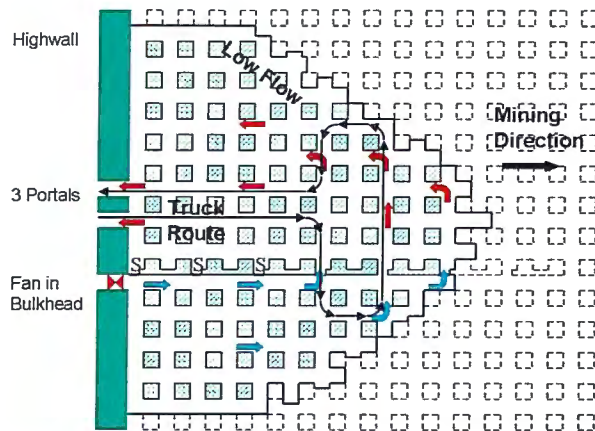


Figure 12. Possible main truck route to get to most areas of the mine with little disruption in travel

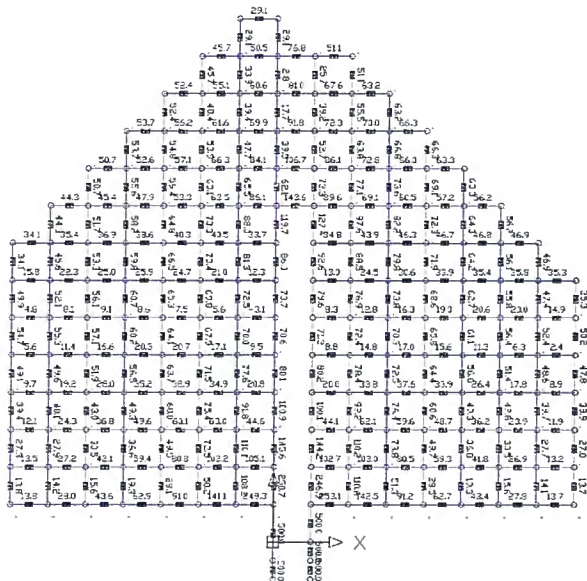


Figure 13. Numerical model ventilation airflow simulation of a sixteen-entry split mine with five open crosscuts (flow in 1,000 cfm, divide by 2.118 to get m³/s)

Figure 14 represents the ventilation airflows determined by numerical models for different entry and crosscut conditions. The entries are labeled "1 to 8 Right" or "1 to 8 Left" starting with the middle two entries called "1 Right" and "1 Left" and moving outward to "8 Right" and "8 Left", respectively. The airflow distribution for the middle entries is very similar for an 8- or 16-entry system with three open crosscuts. The outer entries that are farther away from the stopping line have progressively larger reductions in ventilation airflow. The leading central entries also have low flow, but are located near an intersection with high flow rates, so dilution should not be a problem. Compared to the 16-entry system with three open crosscuts, the 16-entry system with five open crosscuts has a significant reduction of total ventilation airflow reaching the last open crosscut. This shows the importance of maintaining a minimum number of open crosscuts.

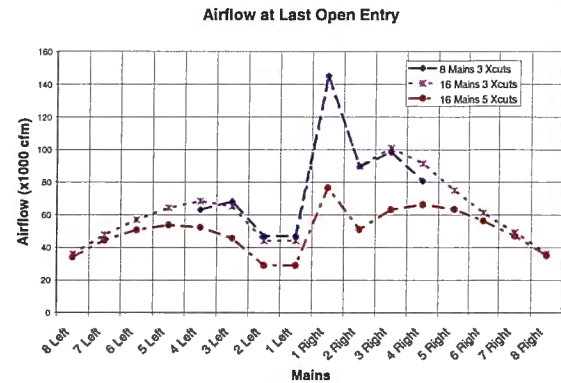


Figure 14. Flow rate distribution at the last open crosscuts from three numerical model ventilation airflow simulations

Development front shapes considerations: The shape of the development front can also play a role in determining the effectiveness of the split-mine ventilation system. Common mining shapes are the "arrow head," "wedge," "flat wall," and "expanding mushroom" (Figure 15). The arrow head and wedge development fronts are usually high-intensity mining where all faces are developed at the same time. The intent of the flat wall mining front is to keep all main entries at the same depth. The expanding mushroom shape represents an older mine with an abundant number of faces that are mined infrequently.

Mining Front Shapes

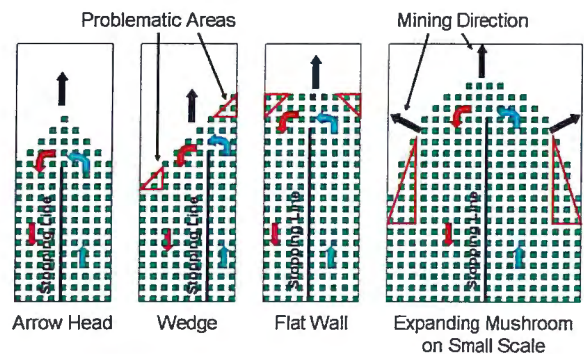


Figure 15. Common mining front shapes for large room-and-pillar stone mines

For an equivalent number of entries, the arrow head shape with a centrally located stopping line has the best flow distribution to the active faces. Flow will be best at the midpoints of both sides of the arrow and lower at the tip and corners (Figure 15). With the wedge shape, which is just one side of an arrow head, it will be hard to ventilate both the leading and trailing corners at the same time regardless of the location of the stopping line. The problematic areas in Figure 15 have been outlined by triangles. The preferred location of the stopping line for the wedge front is closer to the leading corner. If the stopping line is located centrally, the leading corner will require a dedicated auxiliary fan.

The flat-wall shape with a centrally located stopping line will have good central ventilation, but poor ventilation at the corners. The expanding mushroom mining shape is a poor

candidate for split-mine ventilation because only the central section will be well ventilated, whereas both long flanks will have problems meeting minimum ventilation airflow requirements. With multiple mining directions, the expanding mushroom would require that multiple stopping lines be installed to all the active fronts. Multiple stopping lines would adversely affect the haulage system by restricting and lengthening possible truck routes.

Perimeter Ventilation

The second ventilation method identified by NIOSH is perimeter ventilation. This method is strategically different from split-mine because it uses a stopping line developed perpendicular to the mining direction. The main advantage of this system is that it could be installed in a large, mature mine that has been extensively benched. The goal of perimeter ventilation is to create continuous ventilation airflow across all of the active faces, bypassing the bulk of the old mine workings. Figure 16 shows a section of a large mine using perimeter ventilation. The continued development of in-place stone stoppings is required at all times to minimize their impact on production and to ensure that they are in-place when required for directing ventilation airflow. If in-place stone stoppings are not consistently developed, then a great number of stoppings have to be installed in a very short timeframe. Figures 16 and 17 show how the mining face is developed over time. The main concerns with perimeter ventilation are road haulage restrictions, maintaining a continuous stopping line (brattice and in-place stone) at an appropriate distance from the active faces, and reducing blast damage.

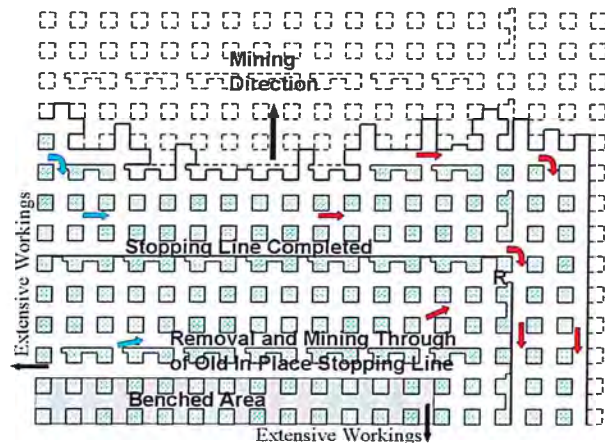


Figure 16. Perimeter ventilation, (phase 1) developing upwards with benching following development of half of new in-place stone stoppings, new stopping line completed, removal of old stopping line (R = regulator or accumulated leakage through stoppings)

Stopping line considerations: The use of a continuous stopping line to limit air short circuiting requires that the haulage road be located entirely in the active face areas. This can cause restrictions to haulage efficiency by having longer routes. An alternative is to have doors or drive through check curtains (both of which greatly increase leakage) to allow trucks to travel through the stopping line for a shorter truck route. The effectiveness of doors and drive through check curtains is very mine-specific and must be determined on an individual basis. Doors should be located nearest the face as possible to position the leakage where the pressure differential is least.

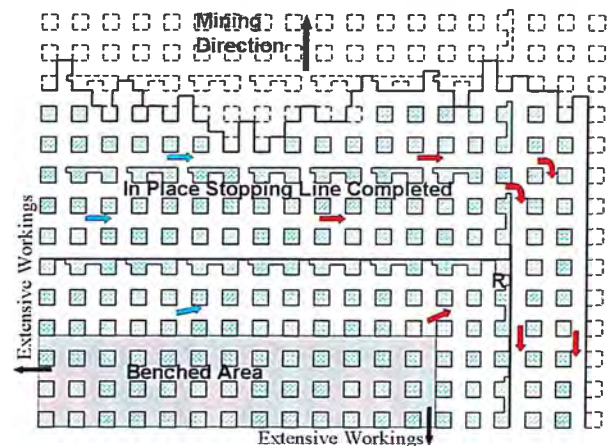


Figure 17. Perimeter ventilation, (phase 2) new in-place stopping line completed, mined through old in-place stone stopping line, benching advanced (R = regulator or accumulated leakage through stoppings)

Maintaining an appropriate distance between the active faces and the stopping line can be a challenge. If the active faces are too close, there will be excessive blast damage to the stoppings resulting in high corresponding leakages. If they are too far away, only a small fraction of the ventilation airflow will sweep the active faces. Installing and maintaining continuous stopping lines four to eight entries away from the active face is challenging because a lot of work has to be done in short order to remove the old stopping line and install the next one. Developing in-place stone stoppings perpendicular to development can adversely affect production because longer dead-head entries are created. Figure 16 shows how dead-end drifts are mined to create the in-place stoppings. The reduction in the number of available working faces during development of the in-place stone stoppings requires that all of the in-place stoppings cannot be created at the same time.

Influence of blast pressure: Another concern with the perimeter ventilation method is that the stoppings are located at right angles to a majority of the development blasts. Blast pressures are assumed to be higher against stoppings that are located across an entry than those located parallel to the blast. Stoppings that are perpendicular with a blast will bear the full force of the explosion, whereas those located around a pillar will see only a fraction of the force.

Influence of Benching: Benching operations can influence the choice of ventilation method. If a mature mine has extensively benched the central area of the mine, placing a split-mine stopping line could be difficult because of the height and size number of the stoppings required. Since benching is a primary supply of production for some stone mines, it is desirable to implement a ventilation system that accommodates benching into its design.

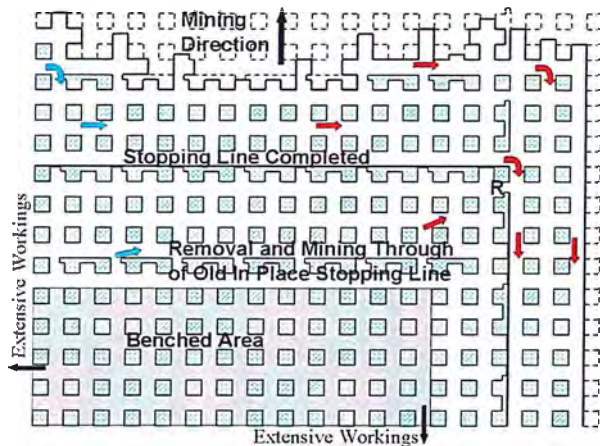


Figure 18. Perimeter ventilation, (phase 3) development of half of new in-place stone stoppings, new stopping line completed, benching advanced (R = regulator or accumulated leakage through stoppings)

Unit Ventilation

The third ventilation method identified by NIOSH is unit ventilation. Unit ventilation is not a stand-alone system, but requires that a preexisting ventilation system is already installed. Unit ventilation works off of a preexisting airflow system to block off an area for development (Figure 19). Units of pillars are created that are surrounded by in-place stone stoppings. The unit is mined using a dedicated auxiliary fan for ventilation (Figure 20) (Dunn, 1983). To reduce recirculation, the fan is located in the fresh airstream of the already completed ventilation system. The block of pillars is developed diagonally as a wedge shape (Figure 21). During development of the block, check curtains may need to be installed to guide the airflow to the active heading.

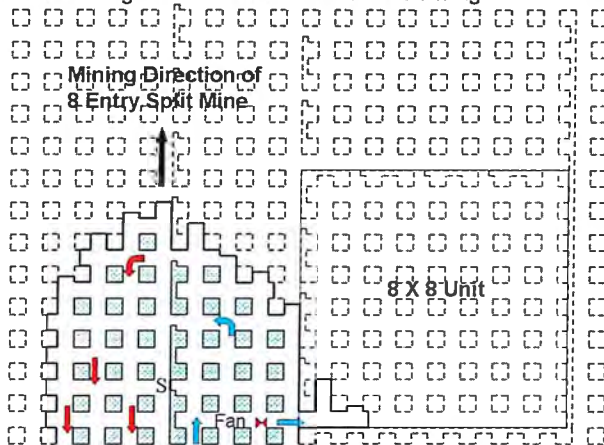


Figure 19. Unit ventilation, (phase 1) split mine develops airflow pattern, using an auxiliary fan for unit development (shaded area is an 8 by 8 unit block)

If a split-mine ventilation system is used to develop the mine's initial ventilation airflow, the split-mine can be developed faster than the unit block, which has to be mined in a diagonal direction. Therefore more than one unit can be in production at the same time (Figure 22). As the unit block is finished, it can either become the fresh air supply for the next unit or it can be sealed off (Figure 23).



Figure 20. Axial vane auxiliary fan (note that the fan has a reducer that increases airflow momentum with a corresponding increase in entrainment and total airflow)

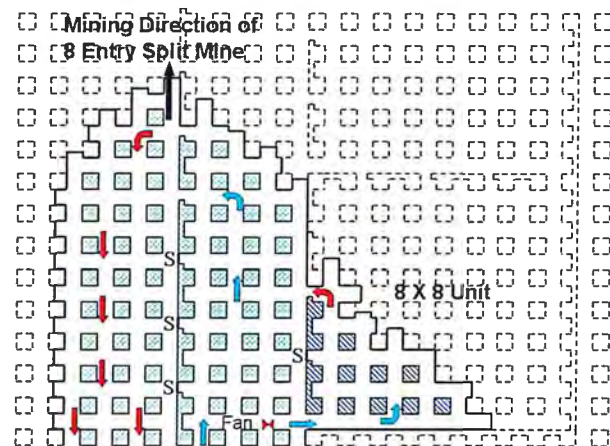


Figure 21. Unit ventilation, (phase 2) first stopping installed, blue diagonal pillars are unit ventilation, green brick pillars are split-mine

Benching can occur after development is completed. Once the block is finished, it can be completely sealed off. The advantage to this is that the mine does not have to exchange this unit's air so the main mine air is exchanged faster, thereby reducing worker exposure to airborne contaminants. The unit block shown in Figure 19 was developed on the fresh-air side of a split-mine mining system that uses trucks in the fresh air side. A unit could be developed on the return side of the split mine, but because the auxiliary fan should be on the upstream side of the ventilation system to reduce recirculation, the unit has to be developed backward relative to the direction of the split mine. This backward development could raise ground control concerns. Unit mining can also be used in perimeter ventilation.

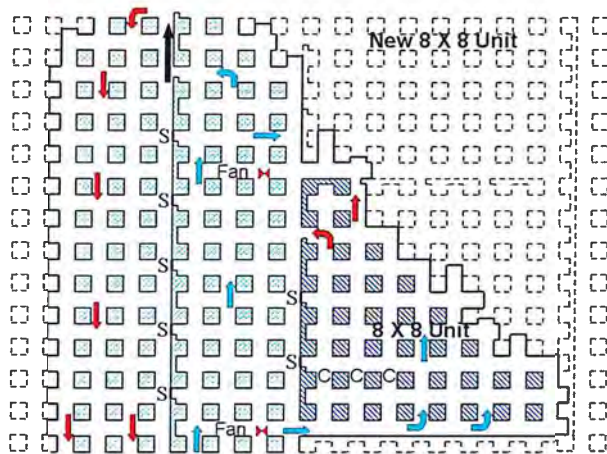


Figure 22. Unit ventilation, (phase 3) connection with next unit block created (C = check curtain used to course the air to the active faces)

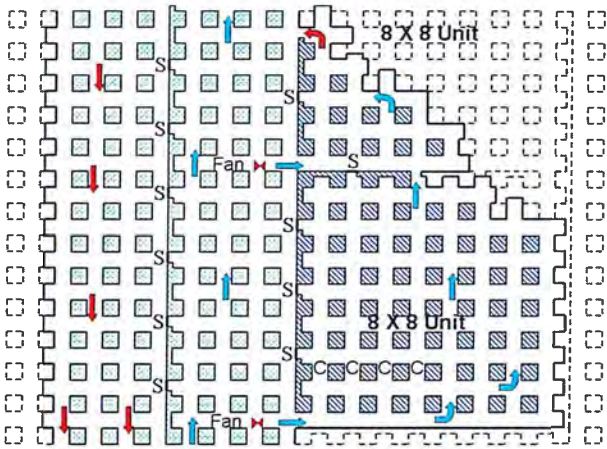


Figure 23. Unit ventilation, (phase 4) unit almost completed, unit can be sealed off or benched as required

THE VENTILATION QUESTION: "PUSH OR PULL"?

The two decisions that need to be made for ventilating a large opening mine are: (1) should a push (blowing) or pull (exhausting) ventilation system be used, and (2) should truck routes be located in fresh or exhaust air? These two choices are not independent from a production viewpoint, as two of the four possible combinations require that doors be installed for the ventilation system to work appropriately, assuming that the primary crusher is located outside the mine. Trucks running in the exhaust returns of a pull ventilation system require that a door be installed to stop short-circuiting. Trucks running in fresh air of a push ventilation system have the same concern. These doors are not more than access doors that trucks have to drive through to get to the active section of the mine at the start of the shift; the trucks would need to drive through the doors with each trip in and out of the mine.

The requirement of having to drive through a door twice for each truck load of stone cannot be understated. A typical mine could have four trucks running, which equates to 40 round trips each per shift. This would require that the door be opened 320 times during a shift. Each time the door opens, the ventilation system will be short-circuited for the time that it remains open. From a practical standpoint, ventilation doors

on the main production route quickly get damaged, and repair work can get delayed because it interferes with production. Therefore, for simplicity only, pull (exhaust) ventilation with trucks running in fresh air and push (blowing) ventilation with trucks running in exhaust air should be considered.

Another question remains: is it more advantageous to bring fresh air to the active faces of the mine or to quickly remove contaminants from the mine? From an airborne contaminants viewpoint, a pull (exhaust) system gets rid of blast gases and DPM quickly from the mine, therefore, most of the mine is in clean fresh air. The main disadvantage to the pull system is that the air reaching the active faces is not pure. Thus, a higher total ventilation airflow has to reach the active faces to adequately control airborne contaminants. A push (blowing) system does get rid of blast gases and DPM quickly from the face, but not from the mine as a whole, therefore, most of the mine is in contaminant-laden air. The main advantage to the push (blowing) system is that clean uncontaminated air reaches the active faces.

To decide between a push or pull ventilation system, the following mine dependant questions have to be answered: (1) where are most of the workers located and (2) which workers are at the greatest risk from exposure to airborne contaminants? Most of the workers are at the active faces and along the haulage routes, so providing the cleanest air to the face is important. Powder men and shop workers are particularly vulnerable to airborne contaminants because they spend a large amount of their time outside of vehicle cabs.

Diluting a continuous, stationary contaminant source (power loader, driller) is the trickiest part of any ventilation system. Ventilation airflow has to be consistent and at a high enough volume to dilute and transport the contaminants away from the stationary source. Having just a face ventilation system without a mine-wide or regional system can cause excessive recirculation. Any recirculation at this point has a detrimental effect on ventilation efficiency. Diluting a mobile contaminant source (trucks, load-haul-dump) is not as difficult because the contaminants are deposited over a large area and these employees are normally in environmental cabs. Having an effective mine-wide and regional ventilation system should help maintain airborne contaminants below statutory levels.

CONCLUSION

NIOSH has shown that both split-mine and perimeter ventilation can be effectively installed in large-opening mines. Split-mine ventilation has worked well as the primary ventilation system in a new high-intensity mine. Maintaining the integrity of the stopping line is the most important factor for efficiency of this ventilation method. Perimeter ventilation has worked well as a retrofit to a large mature mine that was extensively benched before installation. Maintaining the existing stopping line while developing a new continuous stopping line is a primary factor for determining efficiency of the perimeter ventilation method. Use of the unit ventilation method has not yet been adequately documented by NIOSH, but shows promise for future mines.

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