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Practical techniques to improve the air quality in underground stone mines

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ABSTRACT: Researchers working for the National Institute for Occupational Safety and Health (NIOSH) at the Pittsburgh Research Laboratory are developing ways to protect the health of miners. Part of that effort is devoted to improving the air quality in underground stone mines by developing ventilation techniques that can be used in these types of operations. The air quality in these large opening nonmetal mines can be significantly improved by using diesel particulate matter (DPM) controls along with sufficient ventilation quantities to remove contaminants. Practical methods of ventilating these underground stone mines can be accomplished by using mine layouts that course and separate ventilation air through the use of stoppings. The design, construction, and maintenance of effective stoppings in large openings have been a real challenge to mine operators. Several different types of stoppings have and can be used for this application. The choice of stopping design, material used, and construction techniques should be dependent upon a number of factors such as the intended life and effectiveness desired.

1 INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) conducts research into various mining health and safety issues to provide the basis for improvements to U.S. miners' health and safety. As part of this role, researchers at the NIOSH Pittsburgh Research Laboratory (PRL) are developing methods and technologies to improve the air quality for large opening underground metal/nonmetal mines. This paper discusses NIOSH/PRL research dealing with ventilation techniques that will be applicable to large opening mining operations. Furthermore, the paper describes concepts that can be incorporated into the overall ventilation design of these mines. The most common underground large opening mines are underground stone mines followed by underground rock salt mines. Surveillance data from the Mine Safety and Health Administration (MSHA) for the year 2000 shows that there were 162 active nonmetal underground mines in the United States, of which, 117 were stone mines and 13 were rock salt mines.

The continuing and emerging air quality issues in metal/nonmetal mines include silica dust, diesel particulate, fog and fumes. The concentration of these contaminants can be effectively reduced by utilizing various control technologies along with adequate air quantities and proper ventilation methods. A growing concern by various health agencies is the health risks associated with exposure to diesel particulate matter (DPM). It is generally accepted by various regulatory agencies, ACGIH (2001), NIOSH (1988), EPA (2000), and confirmed by the United States Congress, as to the health hazards of exposure to diesel particulate matter. As this concern grows, the mining community is confronted with new DPM regulatory exposure limits. MSHA recently addressed these health concerns by promulgating underground diesel regulations for coal and metal/nonmetal mines, MSHA (2001). The standard was developed to reduce the health risks associated with exposure to DPM. Our view is that the metal/nonmetal DPM exposure limits proposed by the regulations of 400 $_{tc}$ μg/m^3 on July 19, 2002 and a more stringent limit on January 12, 2006 to 160 $_{tc}$ μg/m^3 will impel the use of diesel emissions control technology, and in many cases, some form of ventilation improvement to meet these new air quality standards. The most common ventilation knowledge and techniques that are utilized in coal and some metal mines are not readily adaptable to large opening mines. The large openings in many mines offer little ventilation resistance to air flow. However, this low resistance permits large air quantities to move through the large opening mines at extremely small mine (fan) pressures. From an engineering design prospective, this large air quantity, small pressure scenario should play an integral part in the overall mine ventilation design scheme.

2 FUNDAMENTALS OF IMPROVING VENTILATION IN LARGE OPENING MINES

Previous literature (Head 2001; Grau 2002) has documented the necessity for the large air volumes that are required to effectively dilute DPM concentrations to meet the proposed regulatory standards established by MSHA. In addition to the large air requirements, effective planning for the placement of ventilation equipment and control devices, such as fans and stoppings are necessary to effectively ventilate the large opening mines. Determining the required air quantity throughout the mine is the first and most important elements for planning effective underground mine ventilation. Although many mining activities produce contaminants that enter the mine air, the greatest concern is with the DPM created from the diesel engines used to power the equipment operating in these U.S. mines. Most likely, if the DPM concentrations are reduced or diluted to concentrations that comply with the proposed regulatory standards, the other contaminant concentrations will also be in compliance. The research at NIOSH indicates that there is no single fix or approach to reduce DPM concentrations within these large opening mines, however, providing at least the minimum ventilation quantities to areas with operating diesel equipment plays a crucial role in diluting DPM concentrations. Therefore, we believe, that for the foreseeable future, the eventual DPM regulatory exposure limits will be the dominant parameter driving ventilation requirements for these mines.

3 DESIGNING EFFICIENT VENTILATION SYSTEMS

The fundamental principle of mine ventilation is that air movement is caused by differences in air pressure. The pressure difference results from either natural ventilation pressures or a mechanical fan(s) or a combination of both. There are currently large variations in the methods used by U.S. underground large opening mine operators to develop air movement. The methods vary from reliance on natural ventilation forces to the use of main mine fan(s) or combinations of both. In addition, auxiliary jet fans (free standing) are often used in most of these systems for local areas or to assist and direct the main mine currents. Since natural ventilation is a product of the differences in densities of air columns in and around mine openings, natural ventilation is largely variable and uncontrolled. The direction and magnitude of natural ventilation will change frequently, often several times in a day and certainly seasonally in temperate climates. Therefore, mines that rely solely on natural ventilation as the primary source of ventilation have a highly uncontrolled ventilation system. It should be noted that natural ventilation is better than no ventilation and natural ventilation may provide satisfactory air exchanges in some circumstances or in some parts of the mine. Natural ventilation has been helpful in some large opening drift stone mines with multiple entries and in parts of mines that have been extensively benched. Even with small differences in elevation, natural ventilation alone can promote large volume air movement and mine air exchanges, although in an uncontrolled manner. In areas that have become extensively benched, the large void created may actually create an "air reserve." Although this air reserve can become be gradually contaminated with DPM, the natural ventilation does provide some ventilation relief during working hours and clean out the system during off shift times. Jet fans positioned in proper locations may enhance this exchange process. However, jet fans in other portions of the mine are often positioned working against the natural ventilation flow direction. This results in inadequate air flow and uncontrolled recirculation. In most cases, using natural ventilation as a primary ventilation source is a haphazard affair usually with unknown results.

To effectively improve the air quality in these underground mines, sound ventilation planning needs to be incorporated into the overall mine planning process. For instance, mechanical main mine fans, auxiliary fans, stoppings, and a general ventilation concept should to be integrated into mine layouts and mining sequences. Also, special ventilation considerations, such as production faces, shops, benching areas, and haulage routes should be considered in this mine planning process. Criteria for proper fan selection, installation and operation for both main mine fans and auxiliary fans should be considered. Fan characteristics of pressure and quantity should be matched for the operation. Fan effectiveness is increased dramatically when used in conjunction with stoppings. Utilizing stoppings to build air walls helps control the mine ventilation flow, i.e., efficiently directing the air to where it's needed the most. The air walls also separate the intake and return airways. Stoppings can be made from man-made materials, leaving areas of intact rock to act as stoppings, or by filling an opening with waste material.

Fan and stopping locations need to be an integral part of the mine layout. Stopping and air wall locations will often need to be built, taken down or moved with changes in mining areas and/or in concert with a predetermined sequence of a mining and accompanying ventilation scheme. This would include methods to ventilate the active faces, while providing adequate ventilation to any special needs area noted above. The overall ventilation concepts for these types ventilation concepts are discussed more fully in Grau (2002). Other important factors that reduce DPM at the face area are selecting cleaner burning diesel engines and planning the truck haulage routes. Effective planning of haulage routes will reduce DPM from truck haulage which is the single largest source of DPM in many underground stone mines.

4 DETERMINING SUFFICIENT AIR REQUIREMENTS

The first step to designing an effective ventilation system in underground stone mines is to determine the total air quantity that is needed for effective dilution of DPM and other contaminants. As previously noted, although many different mining activities emit noxious contaminants and require dilution, the result of the new DPM regulations will be that the overriding ventilation design parameter is for the dilution of DPM. In addition, even though the total theoretical air quantity needed to dilute these contaminates can be estimated for adequate dilution, sufficient quantities of air must be distributed to areas where contaminates are being generated. Therefore, certain mining operations may require auxiliary fans to adequately dilute the DPM at the source. Methods to determine the mine air requirements for DPM dilution are described by both Haney (1998); Grau (2002). Grau (2002) reported that the estimated air quantity required for the equipment currently operating in an underground stone mine producing 113 million metric tons (1.25 million tons) is 401 m^3/s (850,000 cfm) to dilute to a 400 $_{tc}$ $\mu g/m^3$ concentration and 990 m^3/s (2,100,000 cfm) to dilute to a 160 $_{tc}$ $\mu g/m^3$ concentration. These conclusions were based on the current equipment, controls, etc being used. The air quantities may be too high for practical mine ventilation, however the required air quantity is highly dependent upon the engines in use and as previously described, the extremely large volume of the bench area may reduce the air flow required. It should be noted that engines of an older vintage are less efficient. As an engine ages, the combustion process degrades, which lowers the fuel economy and promotes higher emissions. Mine operators can dramatically decrease air requirements by selectively replacing the engines with a lower DPM emissions or by adding control measures to engines that emit the most DPM. This significant difference defines why additional research is needed to define more accurate estimates of air requirements.

The goal for many mine operators in the near future will be to have their mine be in compliance with the DPM regulations. We expect that, over time, this will be a process of implementing both DPM control measures and ventilation techniques. Operators are looking at different scenarios in both areas to determine where the most DPM reduction can be achieved in the best practical way. As they move through this iterative process, they will likely make ventilation changes to their mine and also gradually replace the older high DPM emitting engines with new cleaner burning engines. The operators should factor these scenarios into their mine planning process.

5 FAN SELECTION

Many underground limestone mines are drift mines developed from previous quarry operations. Typically, these room and pillar mines have entries that are 6.1 m (20 feet) or higher and at least 12.2 m (40 feet) wide. These large dimensions lead to a very small pressure loss, even when significant air quantities move through the mine. This is especially true of the drift mine operations where our observations found that pressure differences of less than a 24.9 Pa ((0.1 in of water gauge, (w.g.)) are not uncommon, no matter whether these mine are ventilated by natural ventilation, a mechanical fan(s) or combinations of both. Our observations also indicate that the underground stone mines with slope/decline and shaft operations that are less than 70 m (200 ft) in depth, have small mine pressure differences, usually less than 746 Pa (3 in w.g). These differences are or could be much lower if the proper consideration was given to the contribution that the slope/decline and shaft provide to the overall mine resistance.

The low pressure loss present in these large opening mines is actually an advantage compared to other type mines and should be treated as such. The ventilation principles, concepts and techniques used to ventilate these mines are different from the techniques used in mines with larger pressure losses. For example, axial vane fans have predominately been used where higher pressures are required. However, in large opening mines with low pressure requirements, propeller fans offer an alternative. The propeller fans can develop large air volumes under low pressure conditions. Propeller fans can be used as either main mine fans or as free standing auxiliary (jet) fans. Free-standing fans are commonly used to promote air movement as shown in Figure 1.

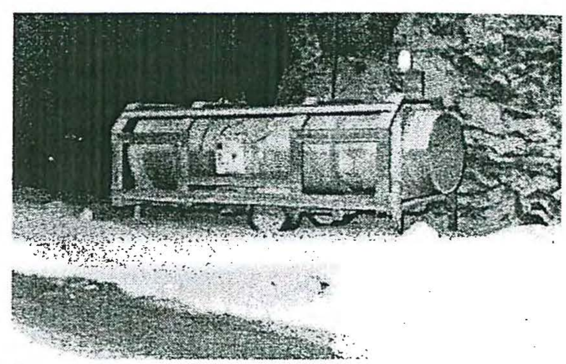

Figure 1. Jet fan.

Ventilation studies by Matt et al. (1978), Agaipito (1985), Goodman (1992) and Foster-Miller (1980) have measured the performance of jet fans (usually axial vane free standing) either in single headings or ventilating portions of the main airways. The research found that the most important aspect for jet fan performance is that the jet fan should be positioned in the intake incoming main air stream so that there is sufficient intake air for the fan. Other important results from these tests showed that the performance of these fans was enhanced by adding a nozzle to the fan. Results were also significantly improved by angling the fan upward and located against a rib when ventilating a dead-ended opening.

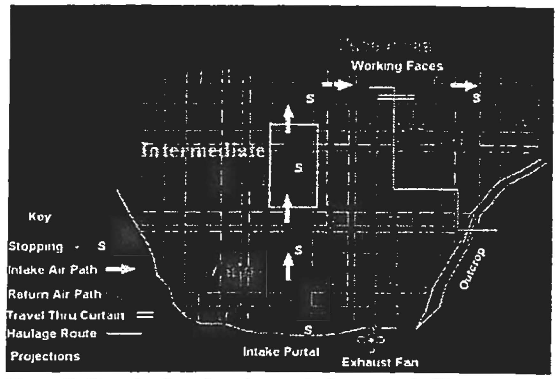

Figure 2. Stopping locations in a typical room and pillar stone mine.

6 VENTILATION CONTROLS (STOPPINGS)

In order to adequately deliver proper air flows to the face areas, good air controls in the form of stoppings are necessary. Stoppings are physical barriers that separate the intake air from the return air. Since air flows through a mine due to differential pressure between travel points, a pressure difference always exits between the intake and return airways. The stoppings act as a barrier allowing for this pressure differential to exist and circumvent short circuiting of intake air to return air. Currently, in most U.S. large opening mines, stoppings and fans are the only control measures used. Most of these operations are currently using or strive to produce a primary, single mine air current to the active mining faces. However, there are a number of variations, especially for drift operations where natural ventilation and sometimes a number of openings, yields secondary air currents. This single split concept currently eliminates the need for other control measures such as overcasts, regulators and air doors. In many underground mines with large openings, the auxiliary fans are the only control devices used to distribute the air to the face working area.

Stoppings have not been widely used in large opening stone mines. Unfortunately, capital expense, construction, and maintenance problems have impeded this segment of the mining industry from building stoppings. This is particularly problematic in the larger, more established mines. In those mines, stoppings were never incorporated into the mining plan. Retrofitting the mines with stoppings to course the air requires building many stoppings with a corresponding investment in time and construction cost.

Design criteria for stoppings include minimizing the leakage between the intake and return air, withstanding the fan pressure differentials and withstanding or relieving the pressure from face production blasting. Table 1 shows the criteria that are the most important in different parts of the mine. There are three main areas of the mine to consider in determining the type or quality of stopping, the main, intermediate, and the face areas. These areas are shown in Figure 2 for a typical underground stone mine. The stoppings in the main airways will typically have less blast pressure, but since they are usually located near the main mine fan, they are subject to the highest constant pressure differential and thus have the potential for the highest leakage. The stoppings in the main entry will also need to survive the life of the mine, hopefully requiring little maintenance. Minimizing leakage in the main airways prevents a direct short circuit of air to or from the fan. For these reasons, the stoppings located in the main areas of the mine should be substantially constructed. For these stoppings, some form of pressure relief may be needed from production face shots, especially early in their life. This need will often diminish as the active mining advances further away, causing the blast pressures to dissipate with ventilation relief (other openings) and distance.

Table 1 - Stopping criteria for locations in an underground stone mine.

Location in the mine	Fan pressure difference	Blast pressure	Acceptable leakage
Main	Greatest	Little	Low
Intermediate	Significant	Some	Intermediate
Face Area	Lowest	Greatest	Moderate

For underground large opening stone drift mines with multiple entries, the pressure across intake and return air is generally less than 62 Pa (0.25 inch w.g.) as found by Grau (2002). From theoretical ventilation calculations, this pressure differential is greatest near the fan.

Pressures from face production blasts far exceed the ventilation pressure. Tests performed by NIOSH, (Mucho, 2001) found pressures from two different production face shot, ranged from 8.2738 kPA (1.20 psi) to 9.3769 kPA (1.36 psi) at distances of 200-500 ft from the face shot as shown in Figure 3. The face shots were generated with 400 lbs of ANFO, 169 lb of dynamite and 50 lb of Datagel. Research is continuing at NIOSH to further bracket expected blasting pressures that stoppings could be expected to experience in these types of mines and to define the controlling parameters such as distance and the impact of venting to adjacent openings.

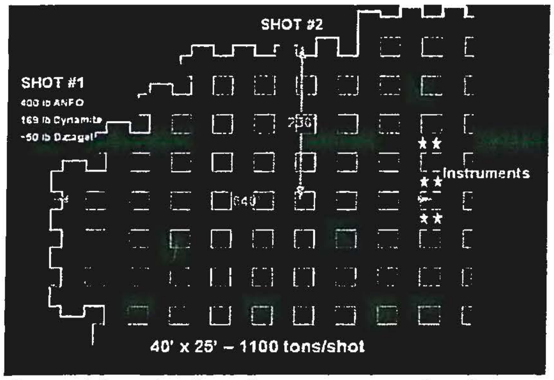

Figure 3. Schematics of tests for measure pressure from face production shots.

Some mines have had success in developing stoppings designed to provide relief from blast pressure. Techniques such as leaving the brattice loose at the floor (and sometimes ribs), using tear away VELCRO strips (Timko 1987), creating openings in the stoppings prior to blasting, and using a combination of used mine belt and brattice have been used. The brattice left loose at the floor simply allows the brattice to fly up when the face shot pressure passes by and returns to the floor when the pressure is through. This technique has been used in some mines near face areas where leakage is not as critical and pressure differentials are lower. Brattice stoppings sealed with VELCRO strips have been developed and used on brattice stoppings in oil shale mines (Timko 1987) and in the NIOSH Lake Lynn Laboratory (Mayercheck 2002). The VELCRO strips separate during the impact of the face shot but they immediately reseal. If sealing is not immediately accomplished, the VELCRO strip seals are manually reconnected after the mine blast. Although they exhibited good success in the Lake Lynn conditions, at least one mine has discontinued their use because of mud and dirt filling the VELCRO and reducing the sealing effectiveness.

7 TYPES OF LARGE OPENING STOPPINGS

Stoppings are built from a variety of construction materials. The construction materials are chosen based upon the desired performance, construction time and ease, and material cost. Construction materials that have typically been used in these mines for stoppings include steel sheeting, cementious-covered fiber matting, mine brattice cloth, used mine belting and piled waste stone.

Used conveyor belting that is no longer useful for material transport can be used to make stoppings. The combination of used belting and brattice have been used effectively in stoppings for both sealing, production face shot relief, and flyrock or other physical damage protection. It has been successfully used as blast relief in a main mine fan bulkhead. Prior to utilizing the mine belt as shown in Figure 4, the mine had several stoppings blown over during production face shots. The mine belt weight and strength allow it to be strong enough to withstand the pressure wave from the face shot but flexible enough to give and act as a pressure relief. Belting hung in this manner should be hung in an overlapping concave pattern to promote interlocking of belting. This technique will minimize air leakage. Figure 5 shows used mine conveyor belt supplementing conventional mine brattice in a stopping. This combination minimizes leakage while providing protection, blast relief, and a more substantial stopping. Conveyor belts could also be used to shield conventional brattice stoppings from the fly rock damage shown in Figure 6.

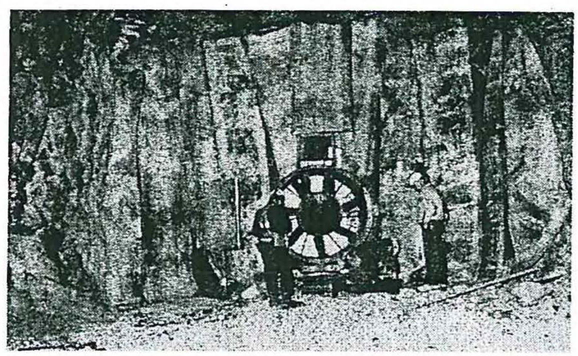
Figure 4. Used mine belt used pressure relief.

Certainly one of the most durable, but also the most costly, for both construction and materials are the corrugated steel panels reinforced with a steel frame as shown in Figure 7. This is the most durable stopping and can be effectively sealed on roof and rib by making a template of the rib and cutting the corrugated sheet to match. The remaining spaces can be filled with expanding foam. One advantage of this stopping is that a swing door can be incorporated into it. This allows for personnel and equipment passage, as well as for blast relief. Besides the cost and time required to install, a disadvantage of this door is that leakage can occur at the door bottom. This might be corrected by adding some type of door sweep.

Figure 5. Used mine conveyor belt supplementing conventional mine brattice in a stopping.

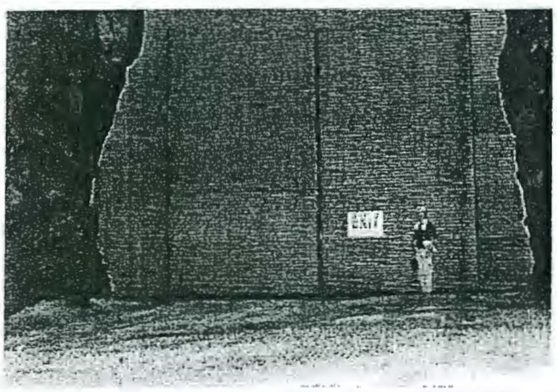

Figure 7. Stopping made for corrugated steel panels reinforced with a steel frame.

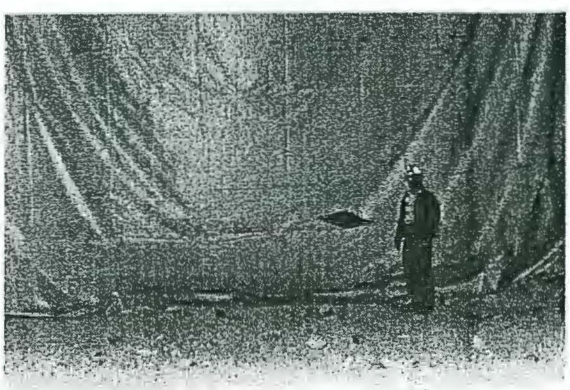

Figure 6. Fly rock damage in brattice cloth.

A less elaborate, but still rigid, stopping is a fiber/mesh covered with cementious grout as shown in Figure 8. This type of stopping is currently being evaluated in an operating underground limestone mine. This stopping is installed by hanging fabric backed by grid and then sealed by spraying with a water-based cementious grout on both sides using high pressure grout pumps. Stoppings of this type are still being evaluated for effectiveness by NIOSH researchers.

A prototype stopping being researched by NIOSH is a tension brattice stopping. The stopping is similar to the tension membrane construction methods used to create various fabric covered, large dome stadiums throughout the country. In this stopping, currently being installed and tested at NIOSH's Lake Lynn Laboratory, a brattice material is tensioned and attached to the various steel framework supports, thereby increasing the strength of the structure.

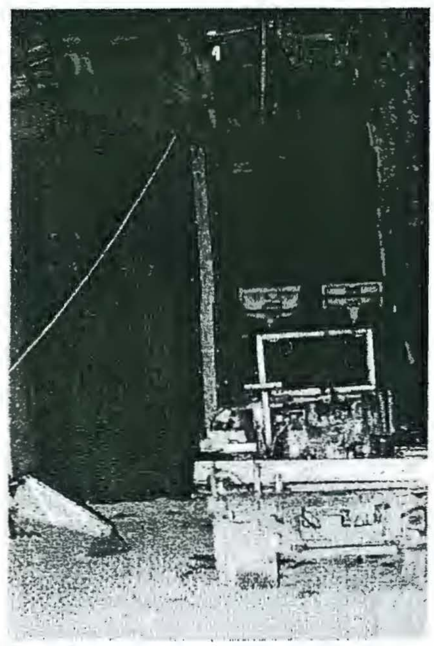

Figure 8. Fabric-grid material sprayed with cementious material.

8 NATURAL ROCK STOPPINGS

Leaving rock in place to form natural rock stoppings has several advantages. By using the natural rock stopping, leakage, construction, and maintenance costs are eliminated. The rock stoppings are created by leaving at least the last face shot that would normally break through two adjoining openings. This keeps a natural rock integrity between the two adjoining pillars. Similar to constructed stoppings, natural rock stoppings between future independent pillars can be strategically oriented to direct the ventilation air. In strategically oriented to direct the ventilation air. In order to direct the air, the rock stoppings are oriented parallel to the ventilation flow. Stone production may be temporarily compromised because the stone in the rock stopping is not immediately mined. However, the rock stoppings can be pre-drilled and mined through at a later time for stone recovery, or for other reasons when the particular stopping line is no longer required to course the air.

When using lines of rock stoppings to separate and course the air, openings need to be created every few crosscuts to meet practical mining needs. However, often the natural rock can be left in place along the ribs and back of the final cut that creates these long pillars to serve as a natural framework for the stoppings and to minimize the size of the stoppings. These too can be pre-drilled for future enlargement to normal opening size when the stopping line is no longer needed and/or the area is to be benched. A caution when using this method is the mining horizon for the top or back rock must be carefully chosen so that a ground control problem is not created.

9 CONCLUSIONS

NIOSH is researching various ways to improve ventilation in large opening mines in an effort to assist with methods and techniques to improve the air quality in these mines and therefore the health of miners. NIOSH is currently focusing on fan applications, air coursing, intake and return airway separation using stoppings, and implementing mine ventilation techniques and concepts into the mine planning to accomplish this goal.

Many U.S. underground stone mines are large opening mines that generally feature small ventilation head losses compared to other types of underground mining. Propeller fans are generally well suited to efficiently produce large air quantities under low pressure requirements. Stoppings are necessary to direct and control the mine air. A variety of stopping choices exist for these types of applications and depend upon the quality of the stopping needed. Different portions of the mine may be better suited to different types of stoppings. The use of stone stoppings is being investigated, especially as it relates to their deployment in various stages of the mine layout. Operators of all underground stone mines should find that this information will improve their ventilation in the underground workings.

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