# A computer software program that estimates air quantity requirements in large opening stone mines

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ABSTRACT: The National Institute for Occupational Safety and Health (NIOSH) has developed a computer program called the Air Quantity Estimator (AQE). The purpose of the program is to provide a starting point for estimating the air quantity needed to dilute diesel particulate matter (DPM) in an underground large opening mine, albeit taking into account various input assumptions. The AQE estimates the total air quantity needed to dilute DPM emissions that enter the main airstream of the mine to current statutory levels. It helps operators pinpoint vehicles that are high DPM contributors. In addition, it allows the user to make "what if" scenarios by varying the input parameters to achieve the most efficient and practical ventilation system. The AQE is a stand-alone software program that does not require any type of spreadsheet software. Engine data must be known or estimated with some accuracy and assumptions must be made in order to limit the variability of the program output. Program calculations and two case studies, for validation purposes, are included in this report. It should be noted that the program does not ensure adequate face ventilation and personal exposure compliance.

## 1 INTRODUCTION

There has been an increased recognition of worker exposure to DPM as a problem in the mining industry by various health organizations [ACGIH 2001] [NIOSH 1988] [EPA 2000]. Consequently, legislation was recently passed by the Mine Safety and Health Administration (MSHA) to limit DPM concentrations in underground metal/non-metal mines. Provisions of this DPM health standard are found in "Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Mines," published in the Federal Register on January 19, 2001 (66 FR 5706) and amended on February 7, 2002 (67 FR 9180) [MSHA 2001].

Shortly after the standard was published, legal challenges ensued and an interim DPM standard of $400_{TC}$ $\mu g/m^3$ went into effect on July 20, 2002, with that level to be reduced to $160_{TC}$ $\mu g/m^3$ on July 19, 2006.

This paper addresses the ventilation needs of metal/nonmetal mines with large openings in particular, stone mines, although operators of other metal/nonmetal mines may find it useful. A large opening mine generally has entries at least 40 ft–50 ft wide and 20 ft – 30 ft high. Because of the new DPM standards, operators with large opening mines will find it necessary to implement a combination of the following: increase the ventilation airflow in the mine; direct air to working areas by using stoppings or auxiliary fans; decrease DPM emissions from engines by using catalytic converters, filters, low-sulfur fuel, and cleaner burning engines; and employ administrative controls to limit DPM emissions underground. In addition, mine planners must consider ventilation needs when planning future mine layouts [Head 2001] [Grau et al. 2002a] [Grau et al. 2002b] [Mucho 2001].

A critical task for the ventilation planner is to determine the air quantity required to meet the DPM concentration limits when a particular fleet of engines is in operation. To meet this challenge, NIOSH has developed an Air Quantity Estimator (AQE) [Robertson 2001] as a mine planning tool to help underground mine operators determine the air requirements necessary to dilute DPM in the main air stream of their mine to statutory levels. The AQE is a user-friendly computer (PC) program that comes as a stand-alone package – it will run on any computer and is not dependent on the installation of spreadsheet programs, e.g., Microsoft EXCEL. The AQE also provides diesel engine performance test data from both the Environmental Protection Agency (EPA) and MSHA [EPA 2002] [MSHA 2002].

The AQE user must input specific engine data and operating parameters to run the program. The program calculates two different air quantities that will dilute DPM in the main air stream: the first to the current interim limit of $400_{TC}$ $\mu g/m^3$, and the second to $160_{TC}$ $\mu g/m^3$. The user can save the input parameters used in the original calculations, then take these data and theoretically add filters to selected engines, replace engines, or change other input parameters. The program will then calculate new ventilation requirements. Thus, mine planners can experiment with many scenarios until an appropriate ventilation system for the site specific conditions at their mine has been attained for the various DPM standards. This program also displays the amount of DPM each vehicle is emitting into the air stream. With this information, the ventilation planner will be able to identify vehicles that emit high DPM emissions. DPM engineering controls may be considered for these vehicles to reduce emissions. [Schnakenberg 2002].

As stated earlier, the results from this program do not ensure proper working face ventilation or personal exposure compliance. If the ventilation air is not effectively directed to the working faces, high concentrations of DPM can still exist even with extremely large amounts of ventilation air in the main mine current.

## 2 OVERVIEW OF HISTORICAL STONE MINE VENTILATION TECHNIQUES

Recent case studies conducted by NIOSH showed that, historically, natural ventilation has been their primary means of diluting airborne contaminates in large opening stone mines [Grau et al. 2002a]. But natural ventilation, by itself, did not guarantee a consistent measurable airflow [Head, 2001]. It provided some air exchange in specific portions of a mine, but the air quantities were generally insufficient and uncontrolled, i.e., not directed to the areas where it was needed. Some mines used fans to increase ventilation airflow, but ineffectively. Commonly, the main mine fans were not installed in a bulk head making them very inefficient. In many cases, the main mine fan and auxiliary fans were improperly sized and/or not placed at the strategic locations throughout the mine. There was modest mine planning in relation with future ventilation techniques. Also, there was minimal use of stoppings to control the direction of air movement. Without consistent ventilation airflow coursing, recirculation of ventilation air and high concentrations of contaminates could potentially be found.

## 3 PROPER VENTILATION PLANNING IS CRITICAL

As a consequence of the DPM legislation, ventilation practices are changing in the metal/non metal industry, in particular, the stone industry. To effectively improve the air quality in these underground mines, bulk headed fans with stopping lines need to be incorporated into the overall mine planning process. This air coursing scenario includes an entire array of ventilation considerations and requirements. Mechanical main mine fans, auxiliary fans, stoppings, and a general ventilation concept must be integrated into mine layouts and mining sequences. Also, areas with special air requirements, such as production faces, shops, benching areas, and haulage routes need to be included in the ventilation planning process.

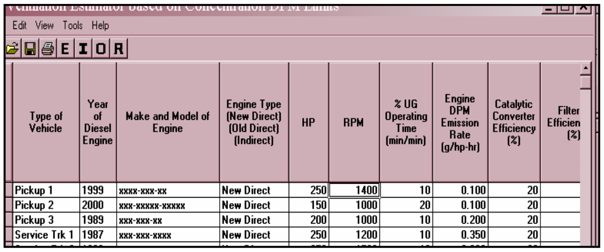
Criteria for proper fan selection, installation, and operation for both main mine fans and auxiliary fans must also be considered. Fan pressure and quantity characteristics should be matched to the specific operation. Utilizing stoppings as air walls helps control the mine ventilation air flow, i.e., the stoppings efficiently direct the air to where it is needed the most. The air walls also separate the intake and return airways. Stoppings can be constructed from man-made materials, by filling an opening with waste material, or by leaving areas of rock intact to direct ventilation airflow [Timko and Thimons 1987]. Furthermore, fan effectiveness is increased dramatically when used in conjunction with stoppings.

Finally, fan and stopping locations need to be an integral part of the mine layout. Stoppings will need to be built, taken down, or moved with face advances and/or changes in the direction of mining. These measures will help to ventilate the active faces while providing adequate ventilation to any special-needs area noted above. These overall ventilation concepts are discussed more fully in Grau et al. [2002a].

## 4 USING THE AIR QUANTITY ESTIMATOR

### 4.1 *Assumptions Inherent with the Air Quantity Estimator*

The AQE does not ensure adequate face ventilation, but it provides a starting point as to how much air quantity is needed to dilute DPM contaminates to statutory levels in the main airstream of the mine. There are a number of factors and assumptions that affect the accuracy of the air quantity estimate. The program assumes there are sufficient amounts and thorough mixing of ventilation air where equipment is operating. It assumes that the contaminates from all the working faces or areas where equipment is operating are eventually dumped into the main air stream of the mine and then exhausted out of the mine through one portal. Also, the program assumes that a ventilation system is in place where there is little to no air recirculation in the mine and no air leakage across the main mine fans or stoppings. Finally, it assumes that the ventilation air is free from DPM contaminates before it enters the mine. An equally important factor is that the air quantity estimates are affected by the user's presumptions for some of the input data, namely the engine DPM emission rate and the percent underground operating time.



| Type of Vehicle | Year of Diesel Engine | Make and Model of Engine | Engine Type (New Direct) (Old Direct) (Indirect) | HP | RPM | % UG Operating Time (min/min) | Engine DPM Emission Rate (g/hp-hr) | Catalytic Converter Efficiency (%) | Filter Efficien (%) |
|---|---|---|---|---|---|---|---|---|---|
| Pickup 1 | 1999 | xxxx-xxx-xx | New Direct | 250 | 1400 | 10 | 0.100 | 20 | |
| Pickup 2 | 2000 | xxx-xxxxx-xxxxx | New Direct | 150 | 1000 | 20 | 0.100 | 20 | |
| Pickup 3 | 1989 | xxx-xxx-xx | New Direct | 200 | 1000 | 10 | 0.200 | 20 | |
| Service Trk 1 | 1987 | xxx-xxx-xxxx | New Direct | 250 | 1200 | 10 | 0.350 | 20 | |

Figure 1. Sample sheet of input data for the AQE.

### 4.2 *Getting Started*

The AQE is a 32-bit computer program that runs under all Microsoft Windows operating systems of Version 95 or later. The program is distributed by NIOSH on CD-ROM and can be installed by clicking on the setup file located in the program's main directory. After installation, the program can be opened the same way as any other Microsoft Windows program, i.e., by clicking on an icon, etc. The AQE is a stand-alone program, i.e., no commercial spreadsheet program is required for its use.

When the program launches, there is an option either to open the AQE User's Guide or to continue with the program. If you choose not to open the User's Guide, the next screen is the input sheet for entering data. This screen resembles that shown in Figure 1 except that no data will be present. Data must be entered into the rows and columns of the data table (spreadsheet). Although the data can be entered by either row or column, after a data value is entered into a cell or box, the enter button on the keyboard must be pressed. The next active cell will automatically be displayed to the right of the cell where data was last entered until the end of the row is reached. Therefore, entering data by rows is the easiest method which is also the organizational principle for describing vehicles. A sample sheet of input data, shown in Figure 1, is provided in the program. There are numerous file, editing, and sorting functions in the program to assist the user in entering and handling data. In addition, there is a help menu that includes engine DPM emission data, links to the MSHA and EPA websites, and the AQE User's Guide.

## 5 REQUIRED INPUT DATA

Before entering input data into the program, one should first obtain all the necessary site specific performance and operating data required to run the AQE. The following input data, as shown in Figure 1, are required to be entered into the AQE program. Column headings correspond to speific input variables and are defined as follows:

*Type of Vehicle:* For example, Pickup 1, Water Truck, or Drill 1. This information is for the users benefit only to distinguish between vehicles/engines.

*Year of Diesel Engine:* The manufactured year of the engine, for example, 2002.

*Make/Model of Engine:* The make/model of the diesel engine, e.g., CUMMINS QSK19-C.

*Engine Type:* There are three choices for this item. The engine is either a New Direct, Old Direct, or Indirect Injection engine. Most engines manufactured prior to 1988 are either Old Direct Injection or Indirect Injection engines. Old Direct Injection engines lack the features found on New Direct Injection engines such as electronic controls, turbo chargers, or after-coolers. Recent Indirect Injection engines are engines have less than 100 horsepower. The Engine Type parameter will help the user determine the DPM emission rate of the engine described below [Haney 2001].

*HP:* This is the rated horsepower of the engine. For example, 300 hp, entered as "300."

*RPM:* This is the revolutions per minute of the engine at the specified horsepower. For example, 1,200 rpm would be entered as "1200."

*% UG Operating Time:* This is the percentage of the time for which the equipment is contributing DPM into the main underground air stream of the mine during a full shift. For example, if a haul truck is operating in the mine 450 out of 600 minutes (10-hr shift), the percentage should be 75 percent (450/600), entered as "75." Time studies can help determine these percentages.

*Engine DPM Emission Rate:* This is the average DPM emission rate that the engine contributes to the air stream. It is represented in grams per horsepower-hour (g/hp-hr). Because there is such little test information about the DPM emissions from diesel engines, especially for older models, the user will have to make the best estimate possible with the information available. Since there is no set method to arrive at an exact emission rate, we have provided the following steps to help guide the user in estimating an engine DPM Emission Rate:

*Step 1*: Check if the engine is MSHA approved under Part 7. Engines approved by MSHA will have a nameplate on the engine with an MSHA approval number on it. If the engine is an MSHA-approved engine or you believe that it is, go to step 2. If the engine is not an MSHA-approved engine, go to step 3.

*Step 2*: Locate the engine on the MSHA-Approved Engine Emissions list by consulting the HELP menu under "EPA and MSHA Information." You can find the engine by looking for the MSHA Approval Number. The DPM emission rate, located in the last column, is given in g/hp-hr. There is a possibility that not all MSHA-approved engines are on this list because the engine may have been approved after this program was developed. Therefore, if you have an approved engine, but it is not on this list, find the engine on the MSHA website at www.msha.gov/TECHSUPP/ACC/lists/07npdeng.pdf. Note that the DPM emission rate on the MSHA website is given as a Particulate Index and must be converted to g/hp-hr. To calculate the rate in g/hp-hr, multiply the Particulate Index of the engine by 0.0017, and then divide by the engine horsepower.

*Step 3*: The EPA has tested a number of diesel engines starting in 1998 until the present. A list is provided in the program HELP Menu of EPA-approved, nonroad engines manufactured from the years 1998 to 2003. A specific engine can be located by looking for the Make/Model, manufactured year, engine hp/rpm and then finding the corresponding DPM. The last column in the list provides the emission rate for the engine. The emissions lists for both MSHA and the EPA are based on evaluations performed on the engines during an 8-cycle test where the emission rate is based on the weighted average of all eight cycles. Therefore, there is not a direct relationship between the cycle time of the engine in an underground environment and the cycle time of the engine during the testing cycle. If information is needed on an engine that is not on the EPA list in the Help File (newer than 2003) or you would like additional information, go to step 4.

*Step 4*: For years not available in the help file, EPA approved engines can be found on the EPA website at www.epa.gov/otaq/certdata.htm. Make sure the DPM emission rate (Particulate Matter Rate on website) is given in g/hp-hr. If not, convert g/kW-hr to g/hp-hr by dividing by 1.34.

*Step 5*: If information is not available from MSHA or EPA for the particular engine of interest, check with engine manufacturers for engine DPM emission rates. If engine information is not available from the manufacturer, go to step 6.

*Step 6*: If information is not available for a particular engine, an estimate on the DPM emission needs to be made. The estimate is dependent on whether the engine is a New Direct, Old Direct, or Indirect Injectionengine. Below is the range of DPM emission rates for each engine type [Haney et al. 2001].

| | |
|---|---|
| NEW DIRECT | 0.1 to 0.4 g/hp-hr |
| INDIRECT | 0.3 to 0.5 g/hp-hr |
| OLD DIRECT | 0.5 to 0.9 g/hp-hr |

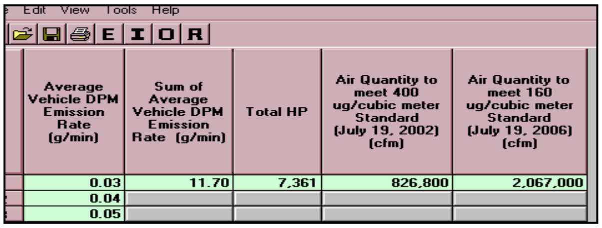
Estimating the DPM emission is subjective and depends on its age and how well the engine has been maintained. For example, 0.1 g/hp-hr would be an estimate for a newer, well-maintained New Direct Injection engine. A rate of 0.5 g/hp-hr would be an estimate for an Indirect Injection engine that is fairly old and not well maintained. A well maintained Old Direct Injection engine may have a DPM emission rate of 0.6 g/hp-hr.

*Catalytic Converter Efficiency: If t*he engine has a catalytic converter, the efficiency is generally 20%. Make sure the percentage is entered as "20" on the spreadsheet.

*Filter Efficiency: Th*is is the efficiency of any filter system used in combination with a particular engine. The efficiencies will vary depending on the filter system and these data may be available from the manufacturers. If information is not available, 85% is a conservative filter efficiency estimate which should be entered as "85."

## 6 PROGRAM OUTPUT

As previously detailed, the AQE program output is highly dependent upon the accuracy of the input information. The program provides calculated results and displays five output values on the right side of the spread sheet, as shown in Figure 2. The first three values, "Average Vehicle DPM Emission Rate," "Sum of Average Vehicle DPM Emission Rate," and "Total HP" are general information that provides the user with a better understanding of the relationship between a particular vehicle and DPM emissions in the mine. The last two values, "Air Quantity to Meet $400_{TC}$ µg/$m^3$ DPM Standard" and "Air Quantity to Meet $160_{TC}$ µ/$m^3$ DPM Standard," are calculated air quantities that provide the mine operator with an estimate of the total air quantity needed to reduce DPM to each respective concentration level. There is an assumption in the calculations that, for these air quantity values, the total carbon is approximately 80% of the raw DPM. A description of the calculated output values are as follows:



| Average Vehicle DPM Emission Rate (g/min) | Sum of Average Vehicle DPM Emission Rate (g/min) | Total HP | Air Quantity to meet 400 ug/cubic meter Standard (July 19, 2002) (cfm) | Air Quantity to meet 160 ug/cubic meter Standard (July 19, 2006) (cfm) |
|---|---|---|---|---|
| 0.03 | 11.70 | 7,361 | 826,800 | 2,067,000 |
| 0.04 | | | | |
| 0.05 | | | | |

Figure 2. Sample program output for the AQE.

*Average Vehicle DPM Emission Rate:* This is the average amount of DPM per shift that each vehicle contributes in grams per minute (g/min) into the main airstream. By examining the values in this column, a mine operator can pinpoint the vehicles that contribute higher amounts of DPM during the shift. These vehicles are leading candidates for engine replacement or DPM controls.

*Sum of Average Vehicle DPM Emission Rates:* This is the sum of the average DPM emission rates for all vehicles given in grams per minute (g/min).

*Total HP:* This is the sum of the rated horsepower of vehicles operated underground.

*Air Quantity to Meet $400_{TC}$ μg/$m^3$ DPM Standard:* This is the estimated air quantity, given in cubic feet per minute (cfm), to dilute the sum of average vehicle DPM emission rates to a DPM concentration limit of $400_{TC}$ μg/$m^3$.

*Air Quantity to Meet $160_{TC}$ μg/$m^3$ DPM Standard:* This is the estimated air quantity, given in cfm, needed to dilute the sum of average vehicle DPM emission rates to a DPM concentration limit of $160_{TC}$ μg/$m^3$.

## 7 PROGRAM CALCULATIONS

Below are the input and output variable abbreviations along with the AQE program calculations:

- Horsepower = HP (*hp*)
- % Underground Operating Time = % UG Op (*%*)
- Engine DPM Emission Rate (raw DPM) = EDER (*g/hp-hr*)
- Catalytic Converter Efficiency = CCE (*%*)
- Filter Efficiency = FE (*%*)
- Average Vehicle DPM Emission Rate (raw DPM) = AVDER (*g/min*)
- Sum of Average Vehicle DPM Emission Rate (raw DPM) = SAVDER (*g/min*)
- Total Horsepower = Total HP (*hp*)
- Air Quantity to Meet $400_{TC}$ μg/$m^3$ Standard = AQ $400_{TC}$ (*cfm*)
- Air Quantity to Meet $160_{TC}$ μg/$m^3$ Standard = AQ $160_{TC}$ (*cfm*)

AVDER *g/min* = (hp *hp*) [(0.01)(% UgOp)] (EDER *g/hp-hr*) [0.01(100-CCE)] [0.01(100 – FE)] (8 *hr/shift*) (0.00208 *shift/min*)

SAVDER *g/min* = Σ AVDER *g/min*

Total HP *hp* = Σ HP *hp*

AQ $400_{TC}$ *cfm* = 1 / [($400_{TC}$ μg/$m^3$)($1^{-6}$ *g/μg*) (1/SAVDER $_{\text{raw DPM}}$ *min/g*) (1.25 *raw DPM/ TC*)(.0283 $m^3/ft^3$)]

AQ $160_{TC}$ *cfm* = 1 / [($160_{TC}$ μg/$m^3$)($1^{-6}$ *g/μg*) (1/SAVDER $_{\text{raw DPM}}$ *min/g*) (1.25 *raw DPM/ TC*)(.0283 $m^3/ft^3$)]

## 8 VALIDATION OF THE AQE

Two separate case studies were conducted by NIOSH at an underground limestone mine in southwestern PA. The objective was to verify the accuracy of the AQE by comparing the AQE estimated output results to actual air quantity measurements and DPM area sampling concentrations taken in the field.

The mine chosen for both studies utilized a perimeter mine ventilation system where all the DPM from the mine vehicles eventually flowed into the main airstream of the mine and then exhausted out of the mine through a bulkheaded fan assembly (two, 12-ft propeller fans). Stopping lines and auxiliary fans were used to direct ventilation air to the working faces. Air readings were taken in the main airstream near the sampling locations periodically throughout the shift with vane anemometers.

The primary location of the DPM area sampling was in the main airstream of the mine near the exhaust fan. Sampling was also conducted near the working areas to detect whether sufficient ventilation air was effectively being directed to the working faces. For each study, DPM sampling began at the start of the shift and generally lasted the entire shift. The sampling apparatus used for both studies were respirable dust samplers with pumps that ran at 1.7 liters/minute that were configured with a two step process to eliminate the larger particles. First, A DORR Oliver cyclone was utilized to remove the largest particles. The remaining particles are separated by a sub-micrometer impactor which had a cut off point of 0.9 micrometers at a flow rate of 1.7 liters/min. Particles less than 0.9 micrometers are deposited on a sampling cassette. These sample cassettes were analyzed in the lab at the Pittsburgh Research Laboratory for total carbon using the NIOSH Analytical 5040 Method and given as an eight-hour weighted average equivalent. All the pump flow rates were checked prior to, throughout, and at the end of the shift and were found to have functioned properly.

As part of collecting input data for the AQE, time studies of the haul trucks were conducted to calculate an accurate percentage of the underground operating time. The average percent of the time underground for the trucks was found to be 59%. The remaining 41% of their time was spent outside of the mine hauling stone to the crusher and stopping for maintenance.

For each case study, researchers entered the collected input data into the AQE program. An estimated ventilation air quantity was then calculated that could dilute DPM contaminates from all the vehicles contributing DPM underground down to a $400_{TC}$ μg/$m^3$ concentration. This value would be compared to field study results.

### 8.1 *Case Study 1*

The average airflow reading near the exhaust fans in the main airstream of the mine was 752,000 cfm and the DPM concentration near the same location was $361_{TC}$ μg/$m^3$ as shown in Table 1. The average

Table 1. Ventilation Results from 2 Case Studies

| Case study | Field measurements and sampling at mine outlet | | | AQE | %Difference in AQE air quality estimation |
|---|---|---|---|---|---|
| | Measure air quality (CFM) | Sampled DPM concentration ($_{TC}$µg/m$^3$) | Normalized air quality for a 400 $_{TC}$µg/m$^3$DPM concentration (cfm) | Estimated air quality for a 400 $_{TC}$µg/m$^3$DPM concentration (cfm) | |
| Case 1 | 752,000 | 361 | 678,700 | 794,000 | +15% |
| Case 2 | 760,000 | 285 | 541,000 | 586,000 | +9% |

sampling time was 487 minutes. The AQE provided air quantities to meet a higher DPM concentration of 400$_{TC}$ µg/m$^3$, so the measured air quantity had to be normalized in order to compare the measured air quantity with the AQE estimated quantity. The normalized air quantity was 679,000 cfm. DPM sampling from locations near the working faces showed somewhat higher DPM concentrations than at the exhaust location indicating that improvements could be made directing more airflow to the working faces. The calculated result from the AQE was an estimated air quantity of 794,000 cfm to dilute DPM down to a 400$_{TC}$ µg/m$^3$ concentration. After comparison to the normalized measured air quantity, it was concluded that by using the AQE, the air quantity was overestimated by 17% (Table 1).

### 8.2 *Case Study 2*

During this case study, the equipment underground was the same as Case Study 1 except for there was 1 fewer haul truck, drill, and service truck operating. In addition, a new loader was being used that had a much lower emission rate than the loader that it replaced. The average air reading near the exhaust fan in the main airstream of the mine was 760,000 cfm and the DPM concentration near the same location was 285$_{TC}$ µg/m$^3$ (Table 1). The average sampling time was 567 minutes. The normalized air quantity was 541,000 cfm. DPM sampling from locations near the working faces showed fairly low DPM concentrations indicating that the ventilation air was being effectively directed to the working faces. The calculated result from the AQE was an estimated air quantity of 586,000 cfm to dilute DPM down to a 400$_{TC}$ µg/m$^3$ concentration. Again, after comparison, it was concluded that by using the AQE, the air quantity was overestimated by 8% (Table 1).

## 9 SUMMARY

DPM legislation and a growing concern for miner health in underground metal/nonmetal mines has led to an increased awareness of the need to include ventilation planning in mining plans. With this in mind, the AQE is a valuable tool for estimating the total air quantity required in a mine for dilution of DPM to specified or statutory concentration levels. This estimate of required total air quantity gives the mine operator a starting point from which to plan a DPM control strategy. This user-friendly AQE program will not only provide air quantity estimates, but it will allow the user to interactively make theoretical changes to the input parameters leading to a more efficient and effective ventilation system. Results from case studies show favorable results towards the accuracy of the AQE.

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