



Evaluation of Post-blast Re-entry Times Based on Gas Monitoring of Return Air

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Abstract

Blasting is the main method of production in many non-coal underground mining operations and produces multiple toxic gases as a result. The Mine Safety and Health Administration (MSHA) requires mine operators to measure the level of toxic gases in mines as frequently as necessary to ensure they are below regulatory safety limits. The current practice uses portable gas monitors to check the concentrations of toxic gases after a fixed post-blast time. This paper studies the application of a gas monitoring system in the return entry of a limestone mine to determine a safe re-entry time. The National Institute for Occupational Safety and Health (NIOSH) conducted such a monitoring program in a limestone mine from September 2016 through May 2018. NIOSH/PMRD (Pittsburgh Mining Research Division) is endeavoring to develop workplace solutions to improve detection of and reduce the risk of hazardous conditions. This study showed that the use of gas monitoring in the return air can be a useful tool at the mine operator's disposal to detect and reduce the risk of hazardous conditions and also to reliably estimate the re-entry time.

Keywords Ventilation · Blasting · Re-entry time · Gas monitoring · Contaminant spread

1 Introduction

Underground miners are at risk of overexposure to toxic gases from various sources. Production blasting operations using explosives in underground mines are a source of multiple toxic gases that could be harmful and even fatal to humans if prolonged exposure occurs beyond the safe limits. According to Code of Federal Regulations, Title 30, Part 57.5002 [1], metal and nonmetal mine operators must conduct gas, mist, and fume measurements as frequently as necessary to determine the adequacy of control measures to protect miners from overexposure to harmful gases. MSHA will inspect mine operators' activities to verify the evidence of such measurements [2, 3]. Continuous gas monitoring in the return air is an effective way to make sure that toxic gas concentrations at the working areas are kept below the regulatory limits before the return of miners.

Toxic gases can enter the mine atmosphere from different operations, such as welding, combustion, and blasting. The main gases produced from blasting are carbon monoxide

(CO), carbon dioxide (CO₂), nitric oxide (NO), and nitrogen dioxide (NO₂). Other gases are produced in small amounts and, therefore, were not considered for this study. Related regulatory and recommended exposure limits of CO, NO, and NO₂ gases are summarized in Table 1 [4].

Researchers have previously developed techniques to model the spread of fumes to determine a safe re-entry time after blasting. Most of the work has focused on the case of development heading or single-entry production stopes. They have not applied these techniques to more complex applications, such as room-and-pillar operations. The computational fluid dynamics (CFD) modeling technique has been used to study the efficiency of gas dilution in small sections of a room-and-pillar operation in detail [5]. Typically, CFD modeling applies to small sections of entries due to the large memory and computing time limitations, for example, blasting gas dilution studies within a small area close to the production face. Mathematical and empirical models, such as the logarithmic dilution model developed by De Souza and Katsabanis [6] or the well-known exponential decay model by Taylor [7], have been used to predict the concentration-time curve by researchers to study the blast fume spread and re-entry time prediction after blasting operations in mines [8–10]. The use of these mathematical models often shows poor correlation with the model input, such as the amount of explosives.

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Table 1 Regulatory and recommended limits of toxic gases produced from blasting

Gas	Regulatory limits*		Recommended limits*	
	OSHA PEL (ppm)	CA/OSHA PEL (ppm)	NIOSH REL (ppm)	ACGIH TLV (ppm)
NO	25	25	25	25
NO ₂	(C) 5	(STEL) 1	(STEL) 1	3
CO ₂	5000	5000	5000	5000
CO	50	25 (C) 200	35 (C) 200	25

*Based on 8-h time-weighted average (TWA), short-term exposure limit (STEL), ceiling (C), permissible exposure limit (PEL), recommended exposure limit (REL), California Division of Occupational Safety and Health (CA/OSHA), Occupational Safety and Health (OSHA), and threshold limit value (TLV)

The poor performance of mathematical methods has been remediated with the use of a calibration method requiring a number of field test measurements to find the best empirical parameters and constants for matching the predicted and measured curves [8–10]. However, the calibrated formula is site specific and, further, only applicable to the similar ventilation and blasting configurations [10]. The poor performance of these mathematical models is attributed to the uncertainty of gas volume, efficiency of fresh air mixing with the contaminated air, non-uniformity of the blasting gases in the face area, and the complex nature of ventilation networks with non-straight entries and multiple entries meeting at junctions [9, 10]. The mathematical models come with simplifying assumptions such as perfect mixing of the blasting gases at the blasting face. These cases are stretching the application of these simple empirical models.

Knowing the actual amount of explosive gases through the gas concentration measurement will assist the operator in looking for any inconsistencies in terms of a misfire or problem in the ventilation. Gas production and relative density (relative to air density) of commonly produced gases from ANFO (ammonium nitrate/fuel oil) are summarized in Table 2 as reference. The actual amount of gases produced from blasting are found to be largely variable due to a number of in situ factors [8, 11–13]. One approach used to estimate the actual amount of produced gases has been to use optimization of a theoretical model using the measured concentration curve [8]. In addition to the volume of generated gas, other variables of a contaminant transport model in a mine entry such as

average flow velocity and effective dispersion coefficient were estimated using this technique.

It is difficult to predict exactly how long it will take the blasting fumes to clear underground working sections due to the complex nature of mine ventilation networks. The standard procedure of manually checking concentrations by the re-entry crew after at least 30–50 min of continuation or re-establishment of the ventilation has been proposed as the main protocol of re-entry [14].

Real-time monitoring is gaining popularity in post-blasting monitoring and determination of re-entry times. It can also be used to determine the efficiency of the ventilation controls in properly diluting the toxic mine gases. Real-time monitoring of toxic gases has been successfully used in an operating underground metal mine to determine a safe re-entry time [16, 17]. The real-time data is displayed on a computer screen for the mine staff to evaluate any out of the ordinary trends in gas concentration.

In this study, a theoretical advection-dispersion transport model was used to examine the effects of measurement distance from the blasting face and the effective dispersion coefficient on the gas concentrations. Results from a multiple-gas monitoring study were presented and discussed. The collected gas data were used to calibrate the theoretical model and to predict the appropriate re-entry time after blasting.

1.1 Theoretical Considerations

The contaminant concentration prediction, in a straight long pipe at any distance from the source and time, model is originally developed by Taylor [7], known as the one dimensional (1-D) advection-diffusion transport model; it was adapted by other researchers [8, 9, 18] to develop predictive models for the spread of blasting fumes. The adapted model is given as follows:

$$C(x, t) = \frac{V}{2A\sqrt{\pi Dt}} \exp\left(-\frac{(x-\bar{u}t)^2}{4Dt}\right) \quad (1)$$

Table 2 Amount of produced gases from blasting

Substance	Gas yield ¹ (L/kg ANFO)	Relative gas density ²
NO ₂	2.6	1.62
NO	10–40	1.04
CO	5–44	0.97

¹ Source: [14]

² Source: NIOSH Pocket Guide to Chemical Hazards [15]

where x is distance from the source (m), t is time from the release of contaminant (s), D is effective axial dispersion coefficient (m^2/s), $\bar{u}$ is average bulk air velocity (m/s), A is entry cross-sectional area (m^2), and V is volume of gas at the source and beginning of time, $x = 0$ and $t = 0$, (m^3).

Since this 1-D model was developed for the straight flow pipe, it is reasonable to consider the model parameters to be equivalent or effective if applied to complex ventilation networks with multiple entries and junctions. Taylor [7] also developed an empirical relationship for measuring the effective dispersion coefficient in turbulent flow analogous to the laminar flow as follows:

$$D = 10.1R\bar{u}\sqrt{\frac{f}{8}} \quad (2)$$

where R is the radius of a pipe or hydraulic radius of non-circular entries and f is the surface friction factor. The constant multiplier of 10.1 has been obtained by laboratory experiment of saline transport in moving water along a long pipe. It is obvious that this parameter needs to be modified for airflow in underground entries.

The model in Eq. (1) was used to determine the sensitivity of the concentration-time curves to the distance of the measurement station from the contaminant source and to the dispersion coefficient. The identified characteristics will help in understanding the measured concentration data presented in this paper. It can be demonstrated that the peak (maximum) gas concentration decreases while the time at which the peak concentration reaches a given distance from the source (peak arrival time) increases as the distance increases, indicating that locations farther from the source will display smaller peak concentrations. A similar pattern can be observed regarding the effect of the dispersion coefficient on the gas concentration. It can be concluded that the peak arrival time may be used to estimate the average air velocity between the source and the measurement station as it is the least affected by the distance and dispersion coefficients.

1.2 Gas Monitoring After Blasting in a Limestone Mine

NIOSH conducted a monitoring program to measure multiple levels of post-blast toxic gases (CO, NO, and NO_2) of interest as well as the performance of other AMS sensors (smoke, air velocity, oxygen, and CO_2) in a partner limestone mine as part of ongoing research on sensor deployment strategies. A general schematic layout of a production zone in the partner limestone mine is shown in Fig. 1 with the gas monitoring station marked in one of the three-entry return entries. The mine is using the room-and-pillar method to extract the ore using multiple face blasting operation workings on a two 12-h shift schedule. The blasting operation takes place between the shifts to minimize the exposure risk hazard to toxic gases

and to minimize delay by giving more time for the blasting gases to clear the mine. The number of blasting faces varies each day depending on the operations schedule, leading to a variable amount of explosives used. The heights of the mine entries were 17 ft with widths of the main entries being 40 ft and 30 ft for the crosscuts.

The explosive agent is ANFO with 6% fuel oil. On average, 3200 kg (7000 lb) of ANFO is used for about nine production faces. Clearing the production faces from the blast fumes in this mine is based on zone ventilation provided by the main exhaust ventilation by two box-type axial main fans, augmented by portable regional axial fans and stoppings to direct the fresh air toward the production zone. Most of the produced fume is thrown into the ventilated airway near each blasting face by the blasting. The entrainment of fresh air into the production faces helps in removing the remaining toxic gases. However, this process is significantly slower than clearing a single heading by an auxiliary fan pushing the fresh air into each face. Therefore, the application of conventional air exchange methods to determine the clearing time may not be accurate.

A set of multi-gas sensors (Conspec Control, Inc.) used in the monitoring program included CO (0–50 ppm), oxygen (0–25%), NO_2 (0–20 ppm), NO (0–50 ppm), and CO_2 (0–5%). Additionally, air velocity and smoke sensors were included to measure air velocity and smoke concentration as part of the gas monitoring system. The oxygen and smoke sensors were included mainly for performance evaluation of the sensors. Four battery-powered AEMC data loggers were used to store data on 30-s intervals. All the sensors are assembled on a metal plate and hung from nearly the middle of the return entry at about 1 ft from the roof (shown in Fig. 2).

During the first few months of data collection, no air velocity measurements were available. The daily explosives usage data was available only during the last 45 days of blasting out of 265 days.

2 Results and Discussion

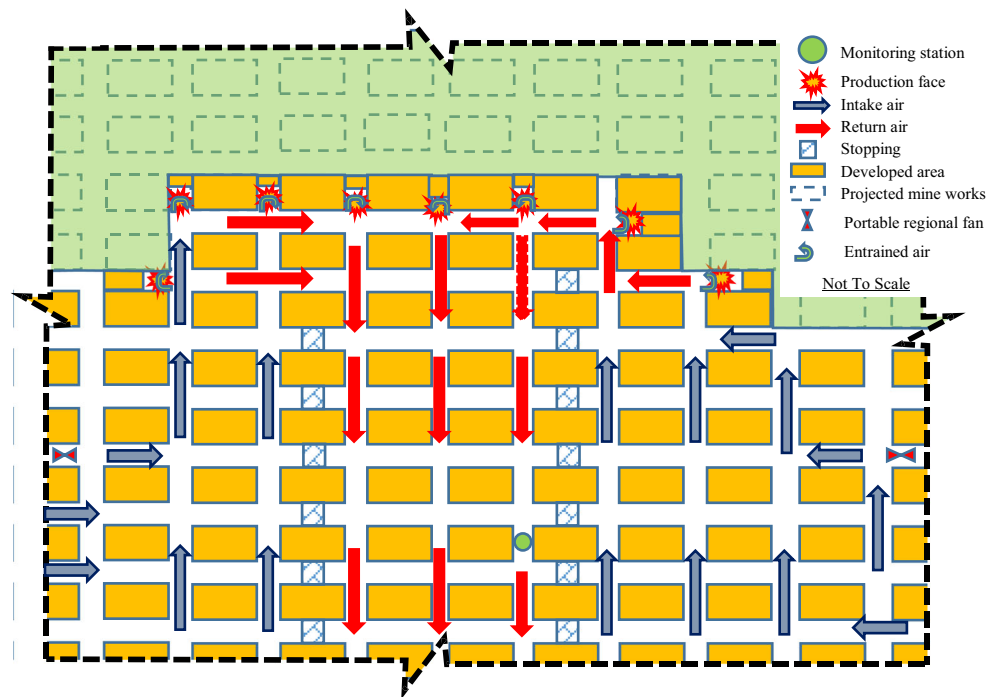
2.1 Gas Concentration Curves

Data were collected between September 2016 and May 2018 covering a total of 265 days of blasting (Fig. 3).

Figure 3a shows the CO concentration-time curves over a 6-h time period after each blast for a few selected days of blasting. The gas concentration curves vary widely depending on the ventilation flow rate, distance from the blasting faces, and the amounts of explosive.

Gas concentration curves are capped at a maximum level specific to the selected CO sensor. The 25-ppm threshold limit value (TLV) level of CO is also shown in Fig. 3a and used to determine the re-entry time. It can be seen that the safe re-entry time can vary to well over 2 h for certain days of

Fig. 1 General main airflow pathways and blasting faces in the limestone mine



blasting. CO concentration curves from all days of blasting were averaged and shown in Fig. 3.

It must be noted that the limitation of the CO sensor to 50 ppm has skewed the average curve (Fig. 3b). It can be inferred that the peak area of the average curve would be most affected if the untrimmed data were used. The shaded area represents one standard deviation and shows the average re-entry time is about 1.3 h. However, one standard deviation puts the re-entry time at about 2.7 h after each blast as shown in Fig. 3.

It should be noted that one standard deviation covers only 68% of the data, and it is possible to have a much longer re-entry time in some cases Fig. 3b.

Figure 4 depicts the NO concentration-time curves for the same selected days of blasting. The spread of NO concentration curves is visibly smaller than the one for CO concentration curves in Fig. 3. The average NO concentration curve together with one standard deviation for all available days

blasting is shown in Fig. 4b. The results suggest that the NO concentration is primarily below the TLV limit and returns to pre-blasting background level about 2 to 3 h after blasting.

Similar observations and conclusions can be made from the NO₂ concentration curves shown in Fig. 5a and the average curve together with one standard deviation shown in Fig. 5b. It can be observed that NO₂ measurement-based re-entry times are somewhat smaller (1.0 and 1.8 h) compared with the ones of CO gas. The NO gas tends to clear faster than the NO₂, partially due to the continuous oxidization and conversion to NO₂. CO gas concentration curves demonstrate a slower decline, which is believed to be attributed primarily to the larger volume of CO gas and also possibly by the gradual generation of CO from diesel-powered equipment as well as the liberation of blasting fumes trapped in the muck pile, that enter into the return air. The data shows that the CO is indeed the most critical gas, as it takes the longest time to clear the mine.

The small increase in the CO and NO concentration seen at around 3 h after blasting may be due to the return of the diesel-powered equipment to the work areas. Any out of the ordinary trend in the gas concentrations can also raise a flag warranting further investigation of the underground environment for blasting or ventilation problems, which can be a useful tool for safety personnel and mine managers.

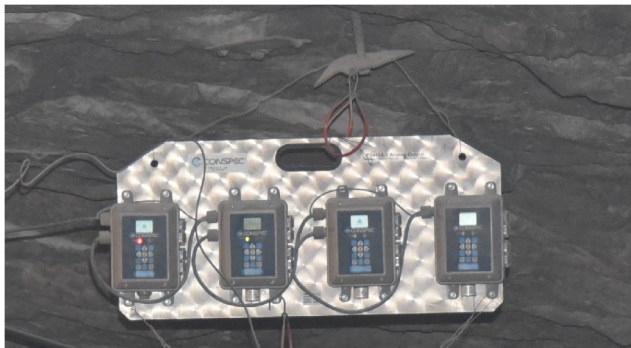


Fig. 2 Installed gas sensors near the roof

2.2 Calibration of the Theoretical Model

Researchers [8, 9] applied Taylor's formula in laboratory and field experiments to obtain effective dispersion coefficients. They demonstrated that the effective turbulent dispersion

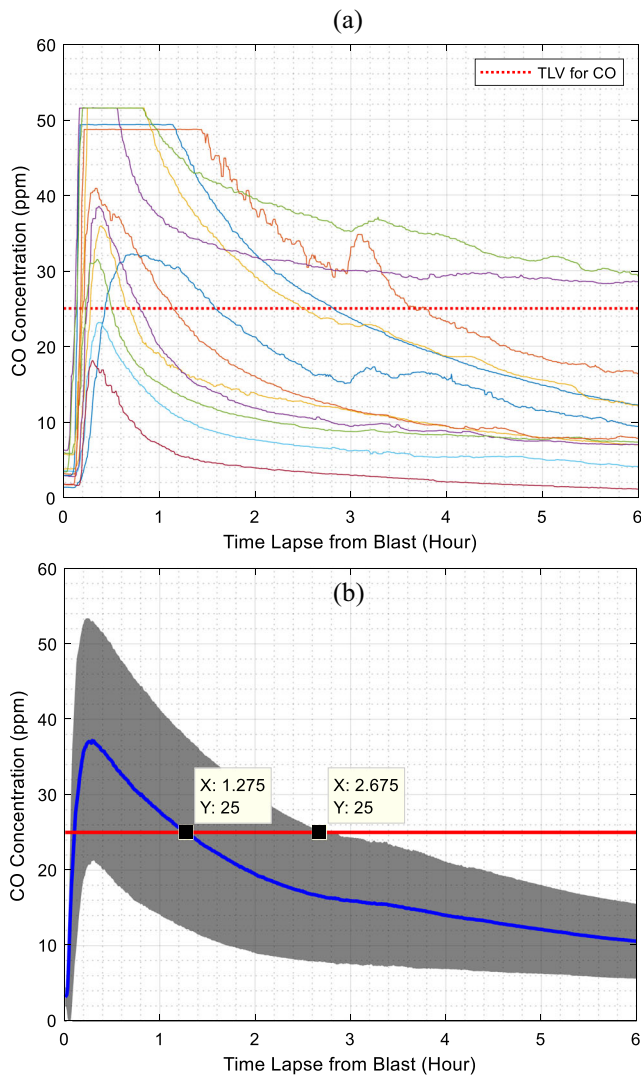


Fig. 3 CO concentration curves for **a** selected days of blasting and **b** average of all days of blasting

coefficient of a curved entry is widely variable, 1.5 to 32 times the value obtained from the Taylor Eq. (2). In addition to curved entries, there are many junctions causing the airflow to merge or split, adding even more turbulent mixing and, consequently, leading to a larger effective dispersion coefficient.

Although it is possible to encounter gas stratification in areas of the mine with very low velocities due to differences in air and gas densities, especially for NO_2 with a relative density of 1.6, this effect was not included in this study. Additionally, the air velocity of the return air is fully turbulent at near 1 m/s, reducing the likelihood of any gas stratification. This is further supported by the fact that measured NO_2 concentration near the roof can reach high values, indicating a well-mixed flow of air and NO_2 .

Therefore, a similar calibration technique was applied to the measured gas concentration data using Taylor's formula in Eq. (1) to investigate its applicability to the blasting gas transport in the room-and-pillar operation used in the current study.

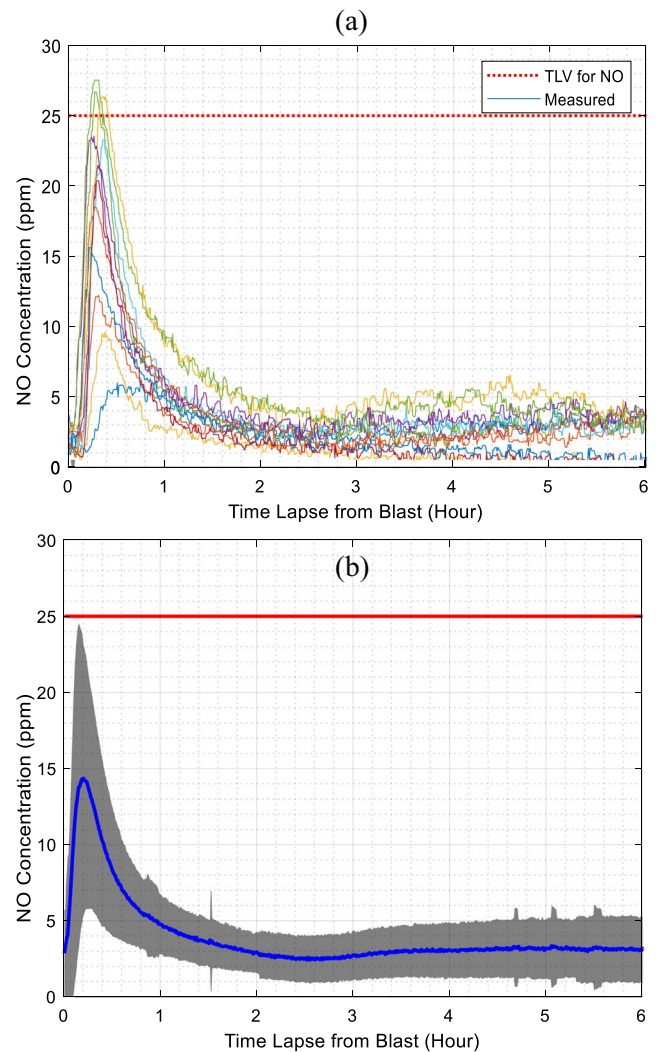


Fig. 4 NO concentration curves for **a** selected days of blasting and **b** average of all days of blasting

In most cases, the measured concentration curves for CO were reasonably smooth, indicating a well-mixed mixture of CO and air, and consequently appropriate to achieve a calibrated model for each blasting operation. A calibrated model was then used as a predictive tool to estimate the re-entry time based on the CO concentration data.

2.2.1 Model Parameters

There are only three independent model parameters in Eq. (1) that can be calibrated: (1) effective dispersion coefficient, (2) gas volume or effective flow cross-section area, and (3) average velocity or distance from the source. The 1-D model of Eq. (1) assumes that the contaminant transport is in a straight entry between the source and the measurement station. As a result, the calibrated parameters are considered as effective, considering the complexity of the flow pathways.

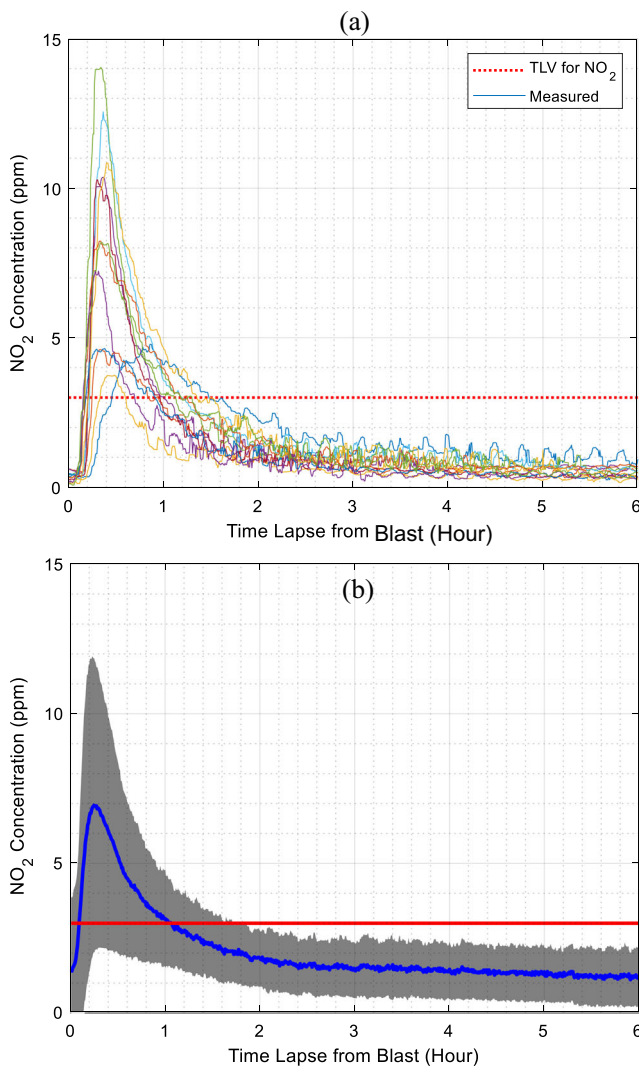


Fig. 5 NO₂ concentration curves for **a** selected days of blasting and **b** average of all days of blasting

With the assumption of a reasonable effective velocity between the blasting faces and the measurement station, an effective distance can be found through the model calibration assuming a known effective flow velocity is available. The effective flow velocity in the model can be set to the estimated flow velocity based on the number of blasting faces and the measured air velocity at the measurement station. The average number of faces being blasted every day is about nine. This will translate to about three faces per each return entry since there are three entries at the measurement station. The measured velocity is a point velocity of the airflow at 0.3 m near the roof. It is assumed that this velocity is about the same as the average cross-sectional air velocity. No verification through ventilation survey has been done in these large cross sections. However, previous experimental work [19] shows that the correction coefficient factor for the same airflow sensor is site specific. This correction factor was found to range from 0.92 to 1.6 with an average of 1.09 for small cross

sections [19]. For the present analysis, a factor of 1.0 is used for simplicity due to the lack of any field verification at this mine. The average and median measured post-blasting velocities in the return air were about 1.2 m/s and 0.9 m/s, respectively. Therefore, 1 m/s was used in the model.

The effective flow cross-sectional area between the blasting faces and the measurement station in the return entry can be determined as part of the model calibration against the estimated blasting gas volume. The gas volume is estimated using the measured velocity and CO concentration at the measurement station and applying an integral/summation of the area under the concentration curve:

$$V_m = \sum_{i=1}^n 10^6 C_i A_m u_m \Delta t \quad (3)$$

where C_i is the gas concentration based on the calibrated parameters, A_m is the total entry cross-sectional area of the return entries, u_m is the measured air velocity, Δt is the measurement time interval, and i is the time index and n is the number of time steps in a time window, e.g., 6 h. In order to avoid the interference of the diesel-powered equipment as well as the trimmed segments above the sensor maximum, the predicted concentration from the model is used instead of the measured values in Eq. (3) to determine the gas volume. It must be noted that the process of finding the effective cross-sectional area based on the gas volume will not affect the predicted concentration curve.

2.2.2 Model Performance

In order to verify the model calibration performance, CO concentration curves of a few blast days were selected from the measured data at the beginning of the gas monitoring program with a known distance from the source (shown in Fig. 6). The

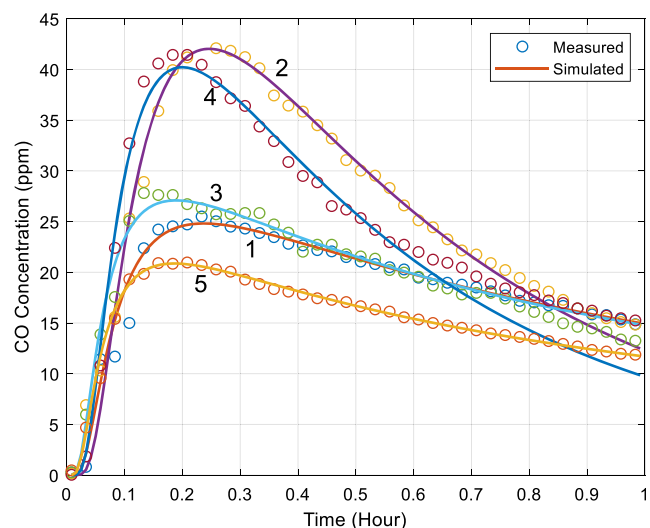


Fig. 6 Comparison between measured and simulated CO concentration curves over a 1-h time period after blasting for the selected blast days

results show an excellent agreement between the model fit and the measured CO concentrations for the selected days of blasting.

Table 3 summarizes the calibrated model parameters. The model parameters were obtained with two assumptions of (1) known average or bulk air velocity and (2) known distance between the source and the measurement station. The model parameters based on the known average velocity between the source and measurement station are listed in parentheses.

Since there is no verification method available for monitoring velocity, a qualitative verification is considered. Two velocity values were calculated from each measured or predicted concentration curve. One was based on the arrival time of a fix concentration value of 5 ppm for CO concentration and the other one was based on the concentration peak arrival time. The bulk air velocity estimated by the 5 ppm arrival time can be significantly overestimated by a factor of two or more with large values of dispersion coefficients (as shown in Table 3). However, the peak arrival velocity (determined as the ratio of the distance from blasting face to the peak concentration arrival time) is the closest to the bulk air velocity providing an upper limit. The calibrated model velocity values seem to be in reasonable agreement with the peak arrival velocities (as evidenced in Table 3).

A cross-sectional ratio is defined as A/A_m , where A is the effective calibrated cross-sectional area in Eq. (1) and A_m is the total entry cross-sectional area of the return entries. This ratio is an indication of the total cross-sectional area of airways leading to the measurement stations. The cross-sectional ratio, given in Table 3, is roughly equal to the ratio of velocity at the measurement station, 1 m/s in this case, to the bulk air velocity, 0.2 m/s, between blasting faces and the measurement station, which agrees with the nine entry pathways from nine blasting faces leading to the measurement section. The effective flow cross-sectional area may also be affected by the number of cross cuts and junctions along the entries due to the increased mixing, air entrainment, and delay of contaminant gas transport. The calibrated model distances assuming a constant bulk air velocity of 0.2 m/s were found to be close to the value of 335 m (1100 ft) for the initial setup at the beginning of the monitoring program.

The calibrated effective dispersion coefficients vary from 30 to 75 m^2/s with assumed distance and 23 to 132 m^2/s with the assumption of fixed air velocity. These values are significantly larger than the 2.0 m^2/s value predicted by Taylor's formula in Eq. (2) using a typical value for entry friction factor. Taylor's formula was found only applicable to straight entries [7, 8]. These large values have been reported by other researchers for large and complex underground ventilation networks [20].

The large value for the dispersion coefficient may be attributed to the complexity of the ventilation network. Every bend, every cross-sectional change, and every junction (merging or splitting) adds more turbulent mixing to the contaminant flow and, consequently, adds more spread to the concentration-time curve. It has been reported that a curved entry can increase the effective dispersion up to 32 times than the one obtained by the Taylor Eq. (2) for a straight entry [9]. Also, the presence of dead end along the mine entries influences the contaminant gas transport significantly [21] by entraining the contaminant into the dead-end spaces.

Regardless of which assumption is used to obtain the calibrated model parameters for each blasting event concentration curve, either the known distance or the average velocity, they both yield the same concentration-time curve, which will be used to predict the re-entry time. The reason that the solution to a model calibration is not unique is that these two parameters are not independent of each other. Since the focus of the study is not about the specific parameters but about the model fit, the use of either assumption is valid.

2.3 Evaluation of Re-entry Time

The calibrated model of each concentration curve and a corresponding TLV value, 25 ppm for CO, can now be used to estimate the re-entry time for each corresponding blasting operation. The re-entry time values, for all 182 useful CO concentration curves out of 265 blasting events exceeding the TLV value of 25 ppm, were determined from both measured and predicted concentration curves (shown in Fig. 7) referred to as measured and predicted re-entry time, respectively. Comparing the two re-entry time values shows an excellent agreement and

Table 3 Model parameters for the initial setup at 335 m (1100 ft) distance from the working faces and model parameters (in parentheses) for 0.2 m/s effective velocity

Blast day	Dispersion coefficient (m^2/s)	Gas volume (m^3)	Velocity (m/s)			Distance (m)	Cross-sectional ratio (A/A_m)
			Model	Peak arrival	5-ppm arrival		
1	57.69 (122.10)	23.43	0.14 (0.20)	0.39	2.12	335.28 (487.78)	6.63 (4.56)
2	35.47 (22.56)	16.58	0.25 (0.20)	0.38	1.74	335.28 (267.42)	3.99 (5.00)
3	74.79 (131.62)	24.06	0.15 (0.20)	0.49	2.82	335.28 (444.78)	5.99 (4.51)
4	47.67 (22.63)	14.52	0.29 (0.20)	0.47	2.24	335.28 (230.97)	3.44 (5.00)
5	29.58 (74.12)	14.36	0.13 (0.20)	0.24	0.93	335.28 (530.83)	7.67 (4.84)

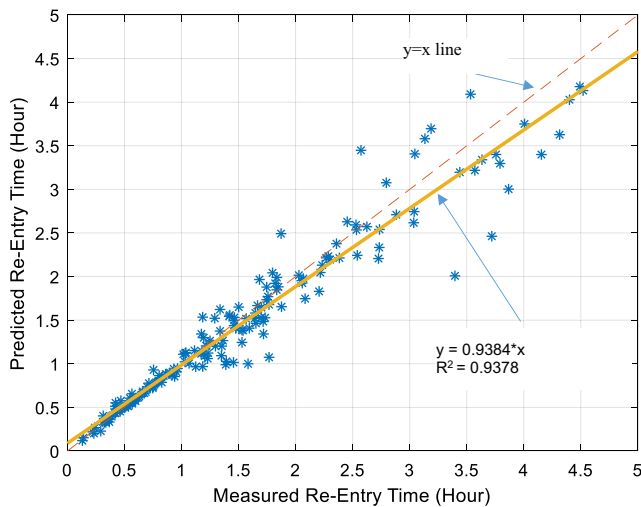


Fig. 7 Comparison between the predicted and measured re-entry times

correlation between the measurement and model-based re-entry time values. The offset of the linear fit to the data indicates an underestimation tendency as the re-entry time increases. The number of points under the 45-degree line represents 100 out of 189 points, indicating a nearly balanced distribution with an almost normal distribution of the relative difference between the two re-entry time values. The correlation also shows that as the re-entry time increases the absolute difference increases. It should be pointed out that after about 2–3 h the diesel equipment activity usually causes significant disturbances in the CO concentration. The standard deviation is about 2 min for the first hour after blasting, 8.5 min for 1 to 2.5 h, and 19 min beyond 3 h. Therefore, the predicted re-entry time based on this model must be used with caution.

The predicted re-entry time values were based on CO, being the most critical of the three toxic gases to clear the mine. Even though the re-entry time based on NO₂ and/or NO concentration curves was not included for the sake of brevity, it is possible to apply the same model calibration technique to these gases. It is expected that a combination of real-time monitoring and a model-based prediction algorithm can lead to the prediction of the re-entry time with increased accuracy. The process starts with running the calibration algorithm after blasting and as soon as the monitored gas concentration exceeds the corresponding TLV value. At this stage, the predictive algorithm starts reporting the predicted re-entry time together with an error of fit. Once the calibration R-squared value exceeds a predefined value considered as a good fit, the predicted re-entry time could be used as a general guide. The predicted re-entry time is continually updated as more concentration data becomes available. The mine operator could use the predicted re-entry time. On some occasions, if the predicted re-entry time is unusually longer than normal, it could indicate an unusual and unsafe circumstance possibly warranting additional inspection of the mine entries or the ventilation system.

3 Conclusions

This work supports NIOSH/PMRD efforts to develop workplace solutions to improve detection of hazardous conditions. A monitoring system of selected multi-gas sensors was applied to an operating limestone mine to study the spread of toxic gases after blasting and to evaluate re-entry times. The measurement of blasting gases proved to be reliable and effective for real-time monitoring purposes in an operating mine with a complex ventilation network in a room-and-pillar mining operation.

The collected gas data shows that it takes the longest time for CO to clear the mine compared to NO and NO₂. The average re-entry time based on CO measurement was found to be 1.3 h, 2.7 h for one standard deviation, and well over 3 h on some occasions.

The collected data was used to calibrate a theoretical 1-D advection-dispersion contaminant transport model. Excellent agreement between the calibrated model and measured CO concentration data confirms the validity of the simple 1-D model and its successful application to a complex ventilation network. The calibrated model was successfully used to predict the re-entry times with reasonable confidence. The results of this study demonstrate that the monitoring of toxic gases in the return may indicate the time at which re-entry can be conducted safely.

The developed model in this study helps the underground mine operators minimize the health hazard to the miners by predicting a safe re-entry time using real-time gas monitoring. However, the model should be used with caution by adding 10% or more to the predicted re-entry time values. This model is not meant to replace the current practice of manual checking during re-entry procedure.

Although the value of effective distance or velocity parameters does not affect the 1-D contaminant transport model fit, it influences the calibrated model parameters, namely, dispersion coefficient and cross-sectional area. These model parameters are specific to the selected site and further research will be needed to examine the applicability of the predictive model and improve the understanding of contaminant gas transport in underground mines with complex networks and large cross sections.

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Compliance with Ethical Standards

Disclaimer The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Conflict of Interest The authors declare that they have no conflict of interest.

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