Underground Ventilation – Tukkaraja (Ed)

Ventilation research findings for enhanced worker safety when mining near unconventional gas wells in longwall abutment pillars

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ABSTRACT: Unconventional gas wells continue to be drilled through current and future coal reserves in Pennsylvania, West Virginia, and Ohio. The ability for both mining and gas-producing activities to coexist safely is a continuing question for federal and state regulatory entities as well as for industry representatives. A hypothetical, gas well casing failure resulting from mining-induced ground movements could produce unsafe conditions and an explosion hazard in nearby operating mines. The National Institute for Occupational Safety and Health (NIOSH) is conducting research to characterize a hypothetical breach from an unconventional gas well near an operating longwall coal mine and any resulting mine safety consequences for a range of mining conditions. Regional conditions include overburden depths of under 152 m (500 ft), between 152 m (500 ft) and 274 m (900 ft), and overburden depth over 274 m (900 ft). Geologic conditions also include typical southwestern Pennsylvania topography and stream valley environments. Differing ventilation schemes commonly used in Pittsburgh coal bed mines have been considered in assessing the distribution of gas from a hypothetical breach in mine workings. Multiple technical approaches are utilized to address the ventilation research questions. These methods include experimental techniques, analytical methods and interpretations, and numerical and physical modeling tasks. The NIOSH team is providing scientific input to regulatory and industry partners in the development of new recommendations for shale gas wells influenced by longwall mining. A summary of the current findings by the research team, across all tasks, is provided. Although this summary represents years of research by the NIOSH team, refinements to the technical interpretations may continue to be produced over the life of the project as more research data become available.

1 INTRODUCTION

Longwall mining induces surface and subsurface subsidence producing stress changes in the overburden. Gas wells near longwall mining are protected by abutment pillars or barrier pillars. Interested parties have raised some concerns about the possibility that mining conditions could produce excessive stresses that result in deformation and damage to gas well casings and suggested that regulatory guidelines need to be updated (Commonwealth of Pennsylvania, 1957, 2017; John T. Boyd Co., 2016; Mark & Rumbaugh, 2020). NIOSH is providing scientific findings from mining research to improve worker and safety and health (Su et al., 2020; Schatzel & Su, 2020; Zhang & Su 2021).

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2 EXPERIMENTAL METHODS

This research endeavor is a combined ground control and ventilation research effort. To be successful, the two overall research components broadly interact as the movement of ground produces fracturing which is a critical component of the hypothetical inflow hazard. Mining-induced fracturing related to the full extraction mining of the coal seam produces transport pathways for the movement of gas away from the hypothetical breach towards the operating mine resulting in a significant safety risk. This discussion is focused on the ventilation portion of the research with our goal of providing scientific input for the industry and operations associated with the longwall mining of coal near unconventional gas wells.

To conduct research on ventilation objectives, a series of technical approaches were developed Figure 1 shows the technical approaches that continue to progress in this research. They can be broadly categorized as methods to estimate the amount of hypothetical inflow, techniques to produce portrayals of movement through overburden and mine ventilation systems, and a new methodology to distinguish gas sources. A brief summary of each of the technical approaches is included in the subsections that follow.

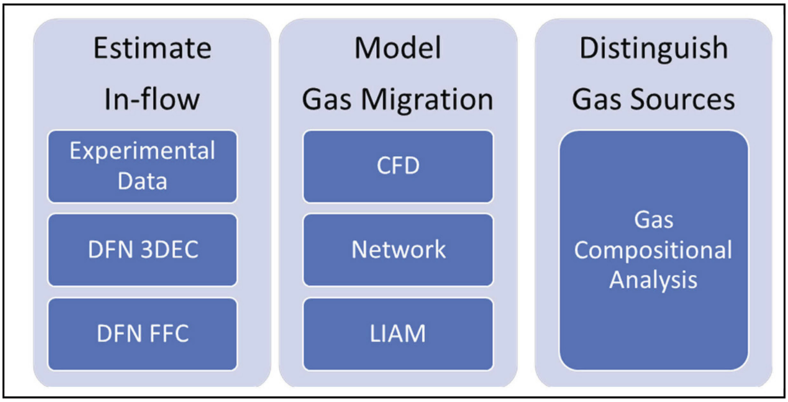

Figure 1. Overview of technical approaches used in the ventilation research component.

The review of these approaches follows the path and chronological order of gas migrating away from a damaged well in the event of a hypothetical casing breach. Gas is transported away from the well through the fractured overburden for different sites, overburden depths and stratigraphic units. The fractures in the overburden are characterized in terms of the fracture aperture and permeability in the strata and then an estimated inflow quantity to the nearby mine is given. Gas movement from the hypothetical breach is simulated moving through the ventilation system and concentrations of added gas are quantified in key areas of the mine. Findings from NIOSH's proposed methodology for distinguishing gas sources as contributors to the gas emissions underground are reviewed.

2.1 *Field measurements of pressure for monitoring*

Field measurements for permeability monitoring are done in experimental boreholes as part of the ventilation research component. These boreholes are configured by NIOSH to monitor changing permeabilities at specific stratigraphic horizons of interest (Watkins et al., 2021). These units are chosen based on previous experiments or ground movement data as being sites of likely high-magnitude, horizontal movement. It is these positions that are considered the most probable locations for a hypothetical breach. Boreholes are configured with one section open to the stratigraphic unit of interest. Communication between the inner casing annulus and surrounding strata occurs through slotted casing matching the thickness of the stratigraphic unit. Falling head slug tests are performed with the addition of incremental amounts of water and head loss rates are measured with a downhole piezometer.

2.2 *Discrete Fracture Network (DFN) 3DEC simulations*

Simulations are made using commercial DFN 3DEC code which incorporates geomechanical changes in the rockmass. It describes fractured rocks as a population of individual fractures. A pseudo-2D, two-panel longwall model is constructed for analyzing the fracture permeability induced by the mining deformation. All fluid transport is assumed to move through the fracture system. Lithologic descriptions from the study site are used to describe strata and fracture locations in longwall gobs. Rockmass permeability can be estimated through calculating the fracture permeability, which is a function of the fracture hydraulic aperture and fracture geometry. The model assumes a constant starting aperture width. Changes in overburden rock stresses as the face advances modify the aperture width (Khademian et al., 2022). Permeability data are used to produce inflow simulations using a second DFN technology described below.

2.3 *Discrete Fracture Network (DFN) Fracture Flow Code (FFC) simulations*

The DFN FFC analysis simulates fluid transport through a stochastic representation of fracture systems. This technology is used to map fracture apertures in longwall gobs following a log normal distribution. This study develops a stochastic DFN model for the site using fracture parameters obtained from the site core log data and geomechanical analysis. Flow from a breached gas well casing is modeled through the strata's fracture network using cubic law. Fracture position data is produced from lithologic input based on information from field sites and from DFN 3DEC results to generate 100 two-dimensional realizations (Ajayi & Schatzel, 2020).

2.4 *Computational Fluid Dynamics (CFD) simulations-Ansys Fluent*

CFD is a type of fluid mechanics simulation that uses numerical analysis to analyze and solve problems that involve fluid flows. A finite volume model was created, using Ansys Fluent, to simulate gas transport from the hypothetical breach through fractured rock. into the mine. and through the ventilation network. This technique provides a numerical analysis of fluid flow showing interactions of fluids (air-methane species). This Ansys Fluent model incorporates field site permeability and mine ventilation data to estimate methane inflow in a worst-case scenario of a ruptured shale gas wall drilled through a longwall abutment pillar. The caved and, fractured and zones that represent the overburden of the CFD model are described as three-dimensional porous zones, each with a prescribed permeability value that is constant and isotropic. The volumes of flow are based on DFN results and defined by boundary conditions (Ren et al., 2011; Watkins & Gangrade, 2022). The resulting simulation is a full-scale, two panel longwall model.

2.5 *Network Simulations, VentSim*

Simulations of gas from hypothetical breaches into a longwall mine's ventilation system were done using VentSim commercial software. Ventilation air transport rates in Pittsburgh seam mines were used in this and all ventilation-based tasks. This technology is a circuit-based approach with airflow through branches. The mine model data were used as input to the VentSim software and a section of gob was added. The gob consisted of an approximately 10 m by 10 m grid. The gob in the model consists of 4 different resistances similar to the permeability zones in the LIAM model. Quantified inflows from the DFN simulations were included to add gases at nodes in the network with guidance from CFD simulations on the transport pathways (Dougherty et al., 2022). The VentSim simulations provide a strong visual representation of gases moving through the ventilation network.

2.6 *Longwall Instrumented Aerodynamic Model (LIAM)*

A 1:30 scale physical model of a longwall panel that replicates a cooperating Pittsburgh coal bed mine was built. The ventilation and reservoir properties have a high degree of similitude with full-scale mines operating in the study area. To ensure good geometric scaling, the LIAM is built with a very high attention to detail, including shields, cribs, 3D printed shearer, regulators, standing supports, gob vent boreholes, and curtains. To simulate the reservoir properties of the gob for the Pittsburgh seam, five types of materials having of different permeabilities are used. The model was adapted to incorporate known quantities of dilute sulfur hexafluoride tracer gas as a proxy for hypothetical breached gas mixed in mine air. Flow paths can be defined, and the increase in methane (CH_4) concentrations can be quantified in the LIAM using this technology (Gangrade et al. 2019, 2022).

2.7 *Gas compositional analysis, distinguishing gas sources*

Other sources of gas, primarily hydrocarbons not produced from coal seams, are present near longwall mines in southwestern PA and potentially other mines in U.S. locations and international sites. Additions of gas from these sources could produce hazards for operating longwall mines, particularly when combined with conventional coalbed gas emissions. There is a possibility that underground storage facilities or shale gas wells could be contributors in hypothetical, unplanned mine emissions. A methodology to distinguish potential gas contributions from these sources was developed based on interpretations of gas chromatography (GC) results (Schatzel & Su, 2020; Schatzel et al., 2022). The overall composition of these gases is primarily related to the type of organic matter that produced them and to the thermal maturity, or rank, of the organic material generating the gas, forming a theoretical basis for distinguishing these sources.

3 RESULTS AND DISCUSSION

In NIOSH's efforts to protect miners throughout the range of scenarios that may present themselves during longwall mining near unconventional gas wells, several key, impactful variables were identified as most influential. The described technical approaches were utilized to provide scientific input for safety enhancements in the event of a hypothetical well breach. These variables and the current technical findings are discussed below.

3.1 *Modification of overburden permeability due to mining-induced fracturing*

Overburden depth is very impactful in the creation of mining-induced fracturing permeability. For first panel mining, there is a significant increase in permeability in going from deep (>274 m, 900 ft) to shallow cover overburden (<152 m, 500 ft), measuring two orders of magnitude greater for the maximum value in the shallow case (Figure 2 and Figure 3). These are the regional depth categories used in the study region. Fracture permeability, produced by longwall mining, substantially increases the overburden fracture permeability over in-situ values and changes with longwall face position (Figure 3). Second panel mining under shallow cover (<152 m, 500 ft) increases maximum permeability by about 1.5 to 3 times the maximum from the first panel mine-by according to the experimental data set. Regionally the Sewickley and Uniontown coal beds can be very important for methane control and ground control in Pittsburgh coal bed longwall mines.

3.2 *Impact of topography on fracture network behavior*

Another parameter found to be very important in the magnitude and character of mining-induced fracture permeability is surface topography. Sites showing more typical topographic features for southwestern PA such as rolling hills and plateaus, show different permeability

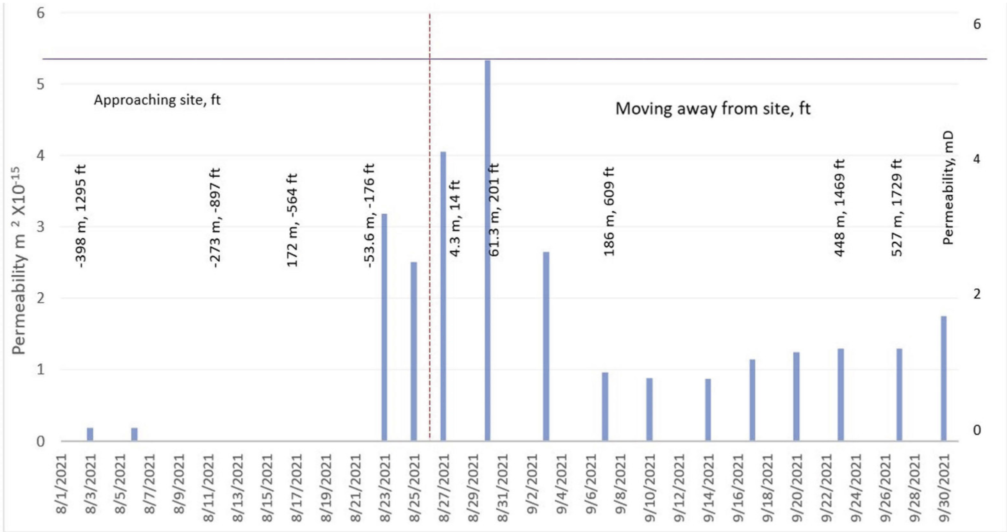

Figure 2. Panel 1 mining under deep cover, Uniontown horizon. Mine-by shown by vertical, dotted red line. Maximum permeability during monitoring reached about 5.4 mD, purple line shortly after the face passed the monitoring site. The undisturbed rock permeabilities are shown by the initial readings. Maximum permeabilities are two orders lower at the deep cover site compared to the shallow cover site.

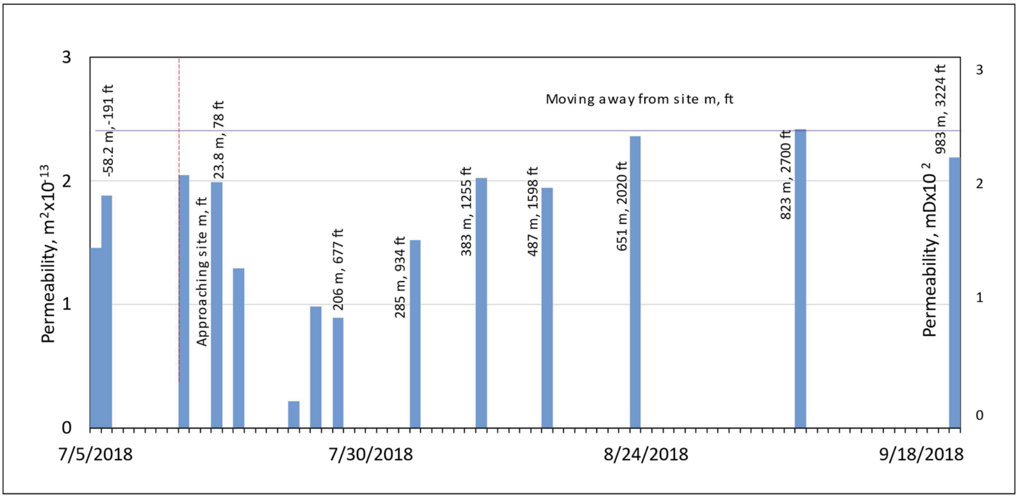

Figure 3. Panel 1 mining under shallow cover, Uniontown horizon. Mine-by shown by vertical, dotted red line. Maximum permeability of about 246 mD, purple line. Permeabilities increased as the face approached but reached a maximum almost two months after the face passed, possibly effected by the stream valley location of the monitoring site.

behavior than sites near stream valleys. For more typical topography away from stream valleys, the first panels mine-by showed permeability dropping to about 10% to 20% of the maximum value achieved for about 610 m (2000 ft) after mine-by (Figure 4). For sites near stream valleys, first panel mine-bys show the permeability remains in the range of 90% of the maximum value achieved for about 610 m (2000 ft) after mine-by (Figure 5). Note there is also a significant difference in overburden depth between the two sites which may contribute to these findings.

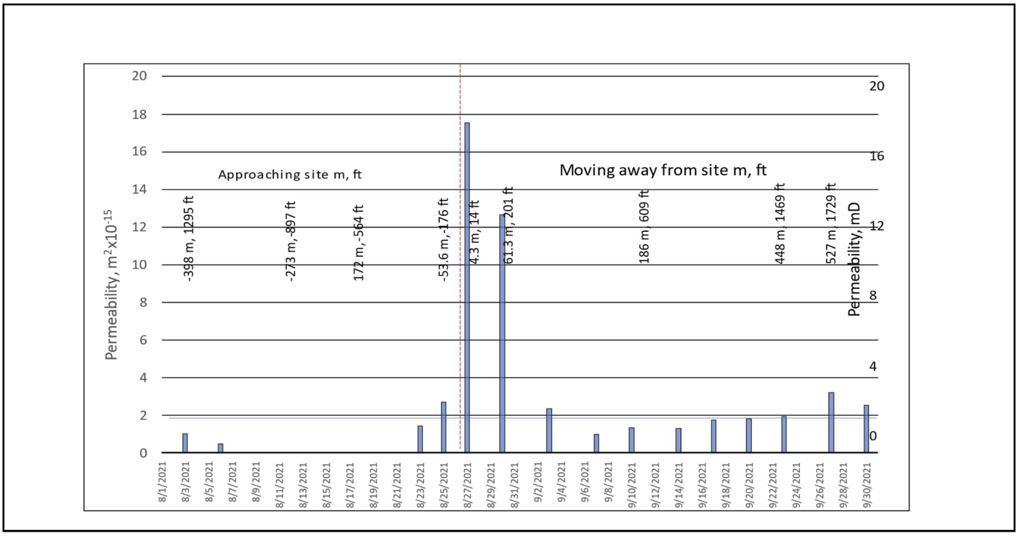

Figure 4. Panel 1, typical regional topography, Sewickley horizon. Mine-by of longwall face shown by vertical, dotted, red line. Green, horizontal line shows 20% of maximum permeability value, which is close to the post mining values during this time interval. Maximum permeability was achieved shortly after face passed.

3.3 *Importance of the location of maximum horizontal movement of strata in gas transport*

There is a high degree of importance regarding the location of maximum horizontal movement of strata in gas transport and the amount of predicted inflow quantities associated with a hypothetical well breach. The zone of maximum horizontal movement or unconventional subsidence was assumed to be the most likely position for the hypothetical well breach. From our ground control research partners, it is understood that zones of maximum unconventional subsidence are positioned where large contrasts in bending strength occur in adjacent strata. Multiple stratigraphic zones of these high contrasts in bending strength were identified at the study sites by monitoring ground movement, and through ground movement simulations using numerical modeling software FLAC 3D. This software can be used to solve complex geotechnical problems for three-dimensional analyses of rock.

These factors contributing to overburden deformation are incorporated in the overburden fracture characterizations completed by DFN modeling. The two simulation methods portray the changes to vertical fracture in response to ground movement (3DEC) and to fluid transport through fractured rock, or FFC. The combination of these DFN simulations produce a simulation of inflow to an active mine in the event of a hypothetical casing breach. The summation of these results to date has shown that, for flow simulations under intermediate cover (between 152 m, 500 ft and 274 m, 900 feet) and deep cover (>274 m, 900 ft) where the zone of maximum movement was above the mining-induced fracture zone (more than about 300 ft above the Pittsburgh seam), no hypothetical breached gas reached the mine (Table 1).

When the horizon of maximum horizontal displacement occurs above the zone of mining-induced fracturing (typically more than 91 m, 300 ft above the Pittsburgh seam in the region), the likelihood of hypothetical breached gas reaching the mine is low. Research has shown the dominant means of gas transport is through the induced fracture network formed by longwall mining. When the induced fracture network is not in contact with the location of maximum horizontal movement, the opportunity for appreciable gas migration from a hypothetical well breach is limited. For simulations under intermediate cover (between 152 m, 500 ft) and deep cover (>274 m, 900 feet) where the zone of maximum movement was above the mining-induced fracture zone, no gas from a hypothetical well breach reached the mine (Table 2).

Table 1. A short summary of inflow simulations for intermediate depth (between 152 m, 500 ft and 274 m, 900 ft) at 20,700 kPa (3000 psi).

Sites	Hypothetical breach location	1 borehole	10 boreholes
Tunnel Ridge	51.2 m (168 ft) below surface	0 m^3/s (0 cfm)	0 m^3/s (0 cfm)
NV35	120 m, 395 ft below surface	<5^{-4} m^3/s, <1 cfm	Not determined

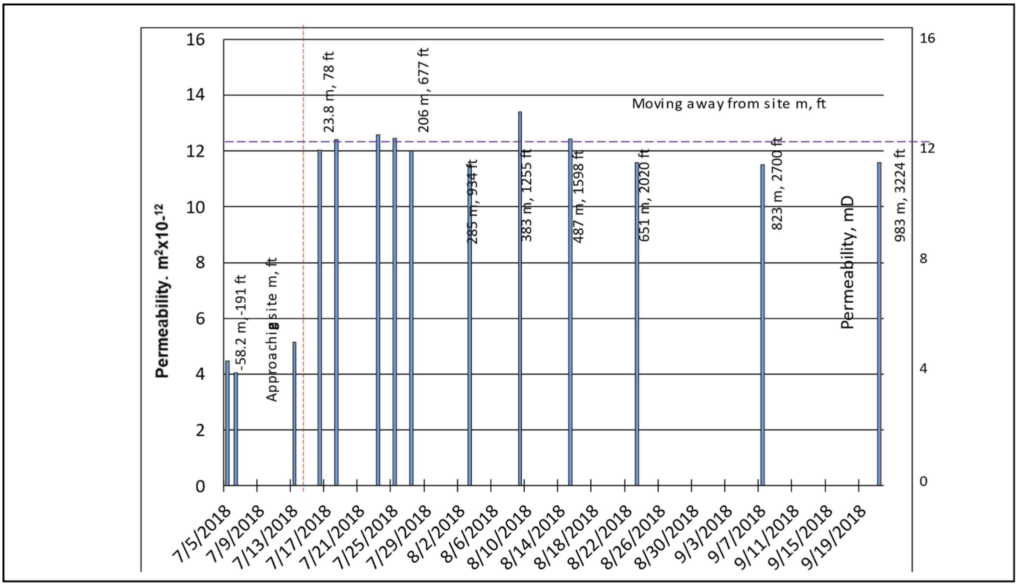

Figure 5. Sewickley horizon monitoring borehole at the, shallow, stream valley monitoring site. Mine-by of longwall face shown by solid, red line. Dashed purple line shows 90% of maximum permeability value, which is close to the post mining permeability values.

An additional consideration for these unconventional well pads is the number of wells drilled from a site. For the locations adjacent to mining, the well pads can contain different numbers of wells. As part of this study, hypothetical well breach inflows were assessed for different numbers of wells on a pad, both at flowing and shut-in pressures. Increasing from 1 to 10 boreholes typically increases inflow prediction quantity about 2 to 3 times the single well rate at 20,700 kPa (3000 psi).

3.4 *Summary of hypothetical inflow findings*

A series of simulations of the transport of hypothetical breached gas were made based on the inflow estimates for Pittsburgh coal bed mine ventilation systems. These simulations for mines under shallow cover (<152 m, 500 ft) with a hypothetical breach at the Sewickley horizon showed relatively high inflow rates at shut-in pressures of 20,700 kPa (3000 psi) (Table 2). If the zone of maximum movement is very shallow—above the mining-induced fracture zone more than 91 m (300 ft) above the Pittsburgh seam—the site would experience a much-reduced likelihood of inflow or reduced inflow quantities.

Simulations of the transport from the hypothetical breached gas for mines under intermediate cover show no hypothetical inflow to the mine when maximum ground movement is above the mining-induced fracture zone for the regions Pittsburgh coal bed mines under 20,700 kPa (3000 psi) of pressure. If a hypothetical breach occurs under intermediate cover within the mining-induced fracturing and at 20,700 kPa (3000 psi) shut-in pressures, some limited gas inflow to the mine may occur (Table 2).

Table 2. Summary of hypothetical inflow findings for differing depths.

Overburden depth	20,700 kPa (3000 psi) 1 casing	20,700 kPa (3000 psi) 10 casing	Comments
Shallow cover sites (under 152 m, 500 ft, depth of overburden cover at well site)	0.347 m^3/s, (736 cfm)[1]	0.672 m^3/s, (1420 cfm)[1]	Maximum movement within fractured zone[2]
Intermediate cover sites (between 152m, 500 ft and 274 m, 900 ft, depth of overburden cover at well site)	0 m^3/s, (0 cfm) inflow	0-0.00656 m^3/s, (0–13.9 cfm) inflow	Maximum movement above fractured zone
Deep cover sites (over 274 m, 900 ft depth of overburden cover at well site)	0–0.035 m^3/s, (74 cfm) inflow	0–0.0854 m^3/s, (181 cfm) inflow	Maximum movement above and within fractured zone[2]

[1] Inflow data for shallow cover site in stream valley at 2410 kPa (350 psi)
[2] Inflow data with hypothetical breach above fractured zone expected to produce different behavior

Under deep cover, quantities of inflow from a hypothetical breach are anticipated to be low under shut-in pressures—20,700 kPa (3000 psi). No inflow quantities were predicted from a hypothetical breach under deep cover above the mining-induced fractured zone under shut-in pressures.

3.5 *Behavior of gas transport in underground mine ventilation systems and possible input for monitoring or mitigation*

Different inflow scenarios were simulated using the model gas migration methods shown in Figure 1. Two fundamentally different ventilation schemes were used in these simulations and are described in Dougherty et al., 2022. If estimated inflow quantities from a hypothetical well breach do not exceed about 0.19 m^3/s (400 cfm), mitigation by the mine's standard ventilation system may be possible. Ventilation systems using conventional Pittsburgh coal mine strategies showed good potential for controlling this level of additional inflow.

In the Pittsburgh ventilation systems studied, gas from a hypothetical well breach of 0.19 m^3/s (400 cfm) was primarily concentrated at the bleeder evaluation points (BEPs) and bleeders but below statutory limits, with some limited amounts of the hypothetical breached gas in the gob and no gas on the active longwall face (Table 3). The lower simulated inflow quantity of 0.16 m^3/s (340 cfm) showed identical distribution patterns regarding of where the hypothetical breached gas accumulated, was absent.

A second, higher level of hypothetical breach inflow was considered. These simulations showed 0.99 m^3/s (2100 cfm) of gas entering the mine through roof fractures. Ventilation airflow simulations for a conventional Pittsburgh coal mine and a hypothetical breach of 0.99 m^3/s (2100 cfm) showed methane concentrations at elevated levels, above or near statutory limits in the BEPs and the bleeders. Hypothetical inflows of this magnitude or greater will likely require mitigation to re-establish safe conditions underground.

3.6 *Potential mitigation methods and monitoring guidance*

As NIOSH research has progressed, the focus of the interested parties has changed in the event of any potential for a hypothetical well breach, however unlikely towards monitoring and detection and away from mitigation or rehabilitation activities. Consequently, the simulations for any gas from a hypothetical well breach can be used as characterizations of transport within the underground ventilation system as a guide to detect this unplanned gas underground.

The locations for accumulations and higher concentrations of methane shown in Table 3 have been consistent across different inflow quantities, simulation methods and the two general ventilation schemes. The ventilation simulations include CFD, the LIAM and VentSim network modeling (Figure 1). The plan for monitoring gas underground could benefit from this guidance on where hypothetical breached gas will accumulate. The simulations can show

Table 3. The Table shows results from the LIAM physical model for ventilation testing using tracer gas mixture as a proxy for introduced gas from a hypothetical well breach through roof fractures. Results are in close agreement with other simulation methods for transport in the ventilation network. Multiple tailgate, bleeder, and gob vent borehole/gab gas venthole locations are standardized test locations in entries or the gob.

Monitoring location	0.16 m^3/s, 340 cfm hypothetical inflow	0.19 m^3/s, 400 cfm hypothetical inflow
	Increased CH_4 concentration due to hypothetical well breach, % CH_4	
Tailgate Bleeder Inby BEP Evaluation Point	0.131	0.301
Tailgate Bleeder outby BEP Evaluation Point	1.080	1.328
Tailgate #1	0.000	0.000
Tailgate #2	0.033	0.049
Tailgate #3	0.047	0.064
Longwall Face	0.000	0.000
Back Bleeder #5	0.000	0.000
Back Bleeder #6	0.016	0.019
GVB #1	0.002	0.004
GVB #2	0.000	0.000

how the gas moves through the mine and the magnitude of concentration change due to the added gas from the hypothetical breach.

3.7 *Methodology for distinguishing gas sources near well sites or within mines*

A GC-based methodology was developed to discriminate coalbed gas, unconventional (shale) gas, and underground storage field gas. The anticipated need to retrieve and analyze samples with a relatively short turnaround time makes GC methods attractive for this application. Gas analysis for stable isotopes of carbon and hydrogen have been used to discriminate gas sources (Coleman, 1991). These analyses can have limitations for routine, frequent sampling and analysis in this application where short turnaround times for results and lower analytical costs for multiple samples are desirable. Bivariate plots using the hydrocarbon index and carbon dioxide (CO_2) concentration show coalbed gas plotting above 2% CO_2 with shale gas and storage field gas below this value and below 80 on the hydrocarbon index (Figure 6).

Plots of the hydrocarbon index and CH_4/CO_2 ratio show coalbed gas below 80 for the CH_4 $/CO_2$ ratio with shale gas and storage field gas over 110 for the CH_4/CO_2 ratio and below 80 on the hydrocarbon index. A strategy for implementing this technique uses small diameter boreholes to collect samples that can be analyzed by GC to identify incursions of non-coal gas (Schatzel et al., 2022).

The limitations of this methodology have not been completely established. In southwestern PA, differences in both organic matter type and rank for coal and non-coal sources create a good theoretical basis for discrimination of the produced gases. The accumulation of more data is in progress and will better define performance parameters for the methodology.

4 CONCLUSIONS AND SUMMARY

Overburden depth is very impactful in the creation of mining-induced fracturing permeability. For first panel mining, there is a significant increase in permeability in going from deep (>274 m, 900 ft) to shallow cover overburden (<152 m, 500 feet), measuring two orders of magnitude greater for the maximum value in the shallow case.

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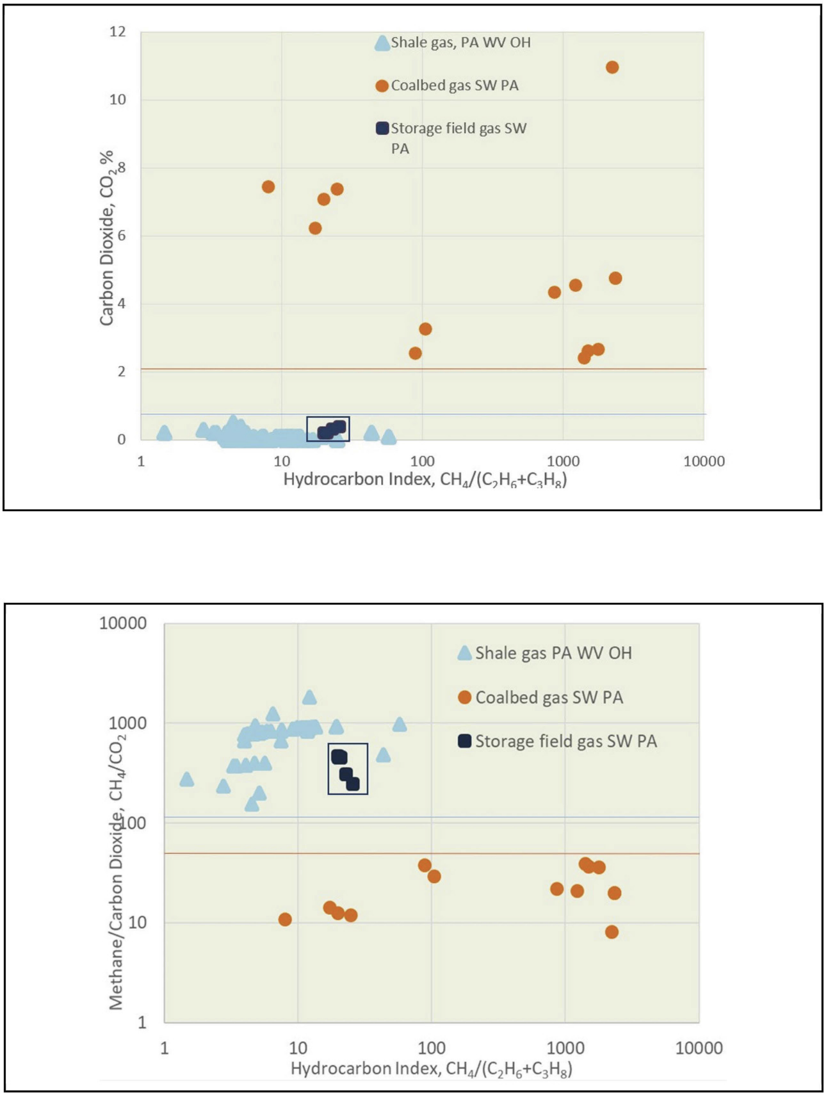

Figure 6. Graphical methods of discriminating gas sources using gas chromatography and graphical, interpretive methods. Plots of the hydrocarbon index and CO_2 concentrations (a) and CH_4/CO_2 ratio (b) with potential gas sources occupying different portions of the plot.

Differences in topography at the monitoring sites were also very influential for mining-induced fracture permeability. Where topography near the monitoring site included a stream valley, the site retained much of the increase in permeability after the face passed, up to 90% of the maximum value. In more typical western PA topography, away from stream channels, induced permeability dropped to 10 to 20% of the maximum value in the time frame of monitoring presented.

The position of maximum horizontal movement has a great effect on the amount of hypothetical breached gas that can reach the mine workings. Enhanced inflows were estimated at the shallow cover, stream valley site, within the fractured zone. The intermediate and deep cover sites showed essentially no inflows when the hypothetical breach location is above the fracture zone.

Gas transport in the ventilation system for a hypothetical 0.19 m^3/s (400 cfm) gas breach showed a good possibility for managing gas within statutory limits. If a hypothetical breach of 0.99 m^3/s (2100 cfm) were to occur, this quantity would be excessive and require mitigation to comply with statutory limits for the mine.

A methodology for distinguishing gas sources near well sites or within mines was reviewed. A GC-based method was developed to distinguish coalbed methane, shale gas, and storage field gas sources. The proposed method successfully distinguished the gas sources in the data set. The goal of the ventilation research is to allow for the intersection of these two industries to co-exist with science-based recommendations forming a framework for worker safety.

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