25-084

Study of Breached Gas Mitigation in An Underground Coal Mine Using Network Modeling and Physical Model

Robert Kimutis
National Institute for Occupational Safety and Health, Pittsburgh, PA, USA

Jim Addis
National Institute for Occupational Safety and Health, Pittsburgh, PA, USA

Lihong Zhou
National Institute for Occupational Safety and Health, Pittsburgh, PA, USA

Mark Mazzella
National Institute for Occupational Safety and Health, Pittsburgh, PA, USA

ABSTRACT

Due to the surge in shale gas production, a substantial number of unconventional shale gas wells have been drilled across U.S. coal reserves. Gas breaches resulting from damaged wells pose a considerable safety risk to miners. This paper investigates how a ventilation system can effectively manage breached gas through a network-based numerical model and laboratory-scaled physical model. Several hypothetical gas breach scenarios in a longwall area are simulated, exploring factors influencing gas mitigation. The study establishes correlations between breached gas inflow and gas concentration at critical locations. The findings in this study provide valuable insights for managing mine ventilation systems and enhancing coal miner safety.

Keywords: Gas well; ventilation network; physical model; gas breach

INTRODUCTION

The advancement of horizontal drilling and hydraulic fracturing technologies has made it possible to commercially develop unconventional gas reserves, particularly shale gas reserves. Unconventional shale gas wells have been drilled through current and future coal reserves in Pennsylvania, West Virginia, Tennessee, and Ohio (Su, 2017). The integrity of these wells becomes a concern to the mining company when mining occurs in proximity to the wells. The shale gas wells penetrate the coal seam and an understanding of the impacts to the mining operation from deformed wells due to stresses is paramount to miners' safety.

The National Institute for Occupational Safety and Health (NIOSH) initiated research in 2012 provide scientific evidence to the interaction of shale gas wells and mining based upon modern mining technologies and practices. Previous regulations, such as the 1957 Pennsylvania Gas Well Pillar Regulation formulated by the Pennsylvania Department of Environmental Protection (PADEP), were based upon data considering mining methods at that time, which did not include modern-day longwall mining operations considerations (Commonwealth of Pennsylvania, 1957). NIOSH's research has focused on evaluating the stresses on well casings due to mining-induced ground movements (Su, 2017; Su, et al., 2018, 2019a, 2019b, 2019c, 2021; Zhang, et al., 2020), monitoring permeability changes during mining activities (Ajayi, et al., 2021; Watkins, et al., 2021; Harris, et al., 2023), and predicting potential gas inflow to underground mines (Ajayi and Schatzel, 2020; Ajayi, et al., 2022; Dougherty, et al., 2022).

Preventing gas breaches from gas wells into underground mines is critical for ensuring mine safety. This task requires an integrated approach that combines robust engineering controls, strict regulatory oversight, and continuous monitoring. While best practices and preventive measures have successfully prevented gas well breaches thus far, the worst-case scenario remains a significant concern. In such a case, the primary question is whether the existing ventilation system can rapidly dilute and disperse any gas that enters the mine to prevent any hazardous condition.

To address this concern, simulations using both numerical and physical models are essential. These models allow for the optimization of ventilation systems, assessing their ability to handle potential gas breaches under various controlled conditions. By simulating different breach scenarios, researchers are attempting to identify weaknesses and pinpoint necessary adjustments to the mine ventilation system in the unlikely event of a gas well breach.

In this study, NIOSH researchers utilize a ventilation network model and a scaled physical model to simulate a variety of hypothetical gas breach scenarios in a longwall mine, with the objective of addressing three key questions crucial to mine safety and ventilation efficiency: 1) investigate the dynamics of gas migration within the model if a gas breach were to occur; 2) explore whether there is a quantifiable correlation between gas inflow rates and gas concentration levels at critical locations; 3) simulate the maximum gas inflow rate that the mine's ventilation system can safely handle.

SCALED PHYSICAL MODEL AND NETWORK-BASED VENTSIM MODEL

In this study, both a ventilation network model and a scaled physical model are employed to simulate worst-case scenarios of unconventional gas well breaches in underground coal mines. Since the study relies on hypothetical cases, with no available field data or prior experience, modeling becomes the primary approach. Each method has its own strengths and limitations. The physical model allows for direct observation and measurement of airflow and gas concentrations, but the modifications are cumbersome. Numerical modeling, on the other hand, can simulate complex, large-scale ventilation systems that are challenging to replicate physically. By combining both approaches, the numerical models provide flexibility and efficiency, while the physical models offer validation and practical insight within its limits.

Longwall Instrumented Aerodynamic Model (LIAM)

LIAM is a 1:30 scaled physical model that is constructed to simulate a single longwall panel (as shown in Figure 1). The model design depicts a 3-entry Headgate and 3-entry Tailgate that is typical for longwall section development. The model is scaled for a 720-ft (219-m) face and a 400-ft (122-m) gob area. LIAM can simulate inaccessible gob areas as well as the performance of mine ventilation systems that are easily controlled and monitored. Typical test scenarios incorporate ventilation controls and airflow quantities as supplied by mine cooperators and may be adjusted quickly and easily for various test scenarios. Bleeder fans as well as a main mine fan are utilized for test scenarios. Two gob ventilation boreholes (GVB) are incorporated into the LIAM design.

Sixty hot-wire anemometers are installed throughout the physical model, including the mine entries, longwall face, mined gob areas, GVBs, and bleeder fan location. The data acquisition system records the airflow from the sensors for the duration of each test. A smoke generator and theatrical smoke are used to visually confirm airflow pathways, eddy currents, and gob-to-face interactions in order to confirm that the test scenario parameters conform to the specified ventilation design in place for the test.

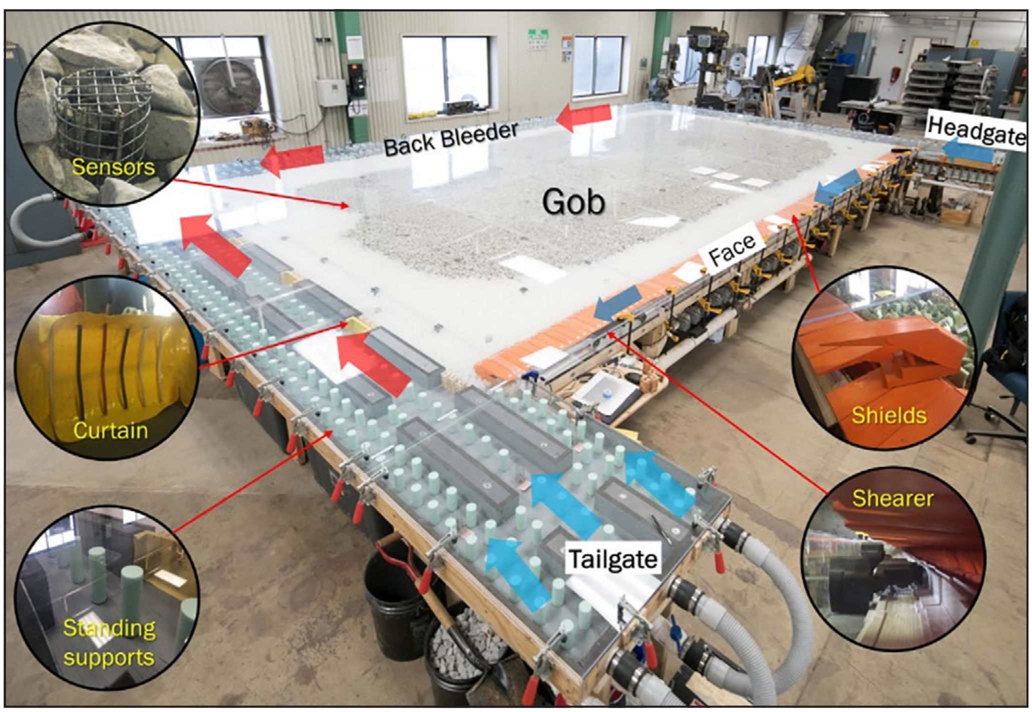

Figure 1. LIAM physical model

Three hypothetical gas breach scenarios were tested using the LIAM model, with inflows of 340 cfm, 500 cfm, and 1,300 cfm. Each scenario included 30 gas insertion locations: 8 positioned in the tailgate corner gob behind the tailgate shields and 22 located inby the longwall tailgate towards the tailgate Bleeder Evaluation Point (BEP), as illustrated in Figure 2. The gas insertion points in the physical model were derived from assumptions made by Discrete Fracture Network (DFN) and Computational Fluid Dynamics (CFD) researchers as part of ongoing NIOSH projects (Watkin et al., 2021; Ajayi et al., 2022). These 30 insertions facilitate gas flow into the gob directly behind the tailgate shields and along the tailgate pillar line. The selected inflow locations reflect a combination of both researchers' assumptions, adapted to align with the LIAM test scenarios.

Table 1 presents the airflows at key locations for each test scenario. The ventilation design air quantities used in the LIAM test scenarios were supplied by cooperators from the Pittsburgh Seam longwall mine. These scenarios incorporated various airflow quantities from the longwall face, bleeder entry, and tailgate entry. Each scenario included the standard MSHA-approved (Mine Safety and Health Administration) T-Split configuration on the tailgate side of the longwall face, with airflow in the tailgate entries designated as an intake air course (MSHA,1996). Belt entry air was not utilized to ventilate the longwall face.

Sulfur hexafluoride gas is used as the tracer gas, inserted into LIAM at a concentration of 25 ppm. Samples are analyzed via Gas Chromatography (GC) using Ultra P5 as a carrier gas (comprising 95% methane and 5% argon), achieving a measurement sensitivity of 1.0 ppb in air. The

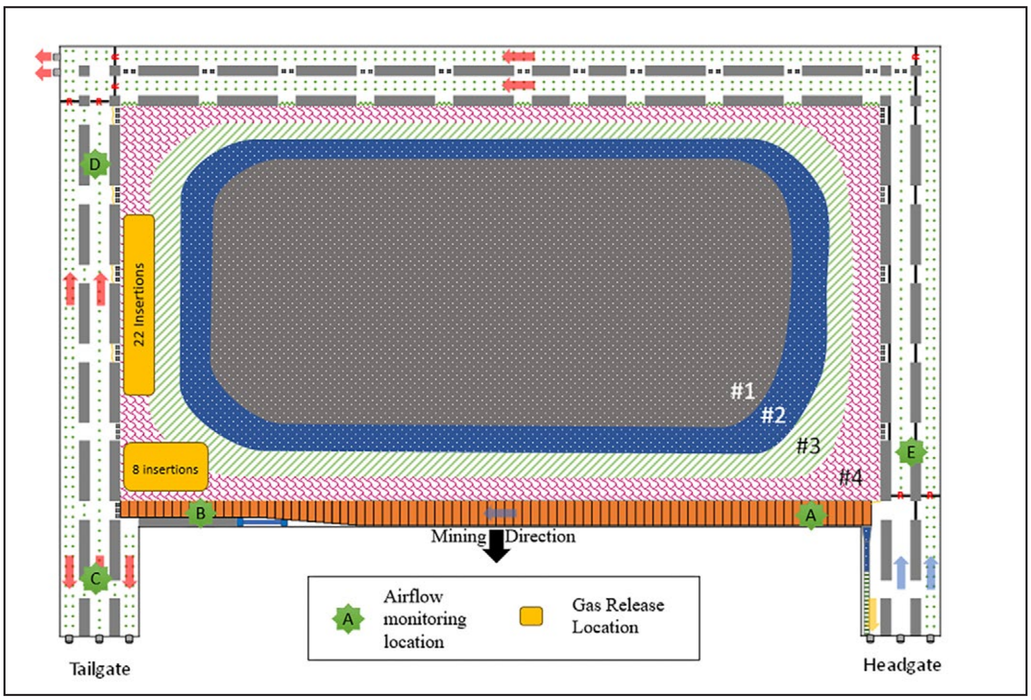

Figure 2. Tracer gas release locations and airflow monitoring locations in LIAM

Table 1. Airflows at some locations for each test scenario

Test Scenario	**Gas Inflow Rate CFM**	**Headgate Shield #17 CFM**	**Tailgate Shield #115 CFM**	**Tailgate Entries (3) Outby Face CFM**	**Tailgate Entry Outby BEP CFM**	**Bleeder Entries from Headgate CFM**
Location indicator in Figure 2	in	A	B	C	D	E
A	340	78996	42199	55004	50882	69303
B	500	80833	43546	55544	52318	69883
C	1300	83542	43929	55947	52520	69858

sampling protocol and test duration are designed to collect samples throughout each test scenario until no gas is detected in any of the samples.

Ventsim Model for a Typical Longwall Mine with Gob Grids

Ventilation network models have become an indispensable tool in mine operations, aiding in not only the planning and management of ventilation systems but also in simulating gas migration, assessing potential hazards, and formulating responses to emergencies such as fires or gas leaks. VentSim, a mine ventilation simulation software from Howden, is used in this study to conduct the ventilation and gas simulation.

A well-established longwall mine ventilation network from a partner coal mine located in the Pittsburgh coal seam is selected for this case study. Figure 3 displays the layout and ventilation of the studied longwall panels, which includes two mined-out panels and one active longwall face. A bleeder ventilation is applied to the longwall face, which is intended to draw explosive methane accumulations directly towards a dedicated bleeder fan (located in the upright corner in Figure 3), and a gas well pad, including ten gas wells, is located in the coal pillar between the active longwall panel and the adjacent gob with the face just mine by.

In typical ventilation simulations for mine design and planning using network-based mine ventilation software, the gob area is often excluded from consideration because its airflow typically impacts only localized regions without significantly influencing the overall mine ventilation system. However, in this study, the gob area plays a critical role in gas migration and ventilation dynamics, making it impossible to overlook. To accurately simulate the airflow and gas distribution in and around the gob, we introduced gob grids to the gob areas of the active and adjacent longwall panels. The gob grids were created using a grid with branches of 33 ft by 33 ft (10 m by 10 m). The permeability of the gob is simulated by assigning varying levels of resistance: lower resistance in the outer layers, indicating higher permeability, and the highest resistance at the center, reflecting lower permeability.

In this study case, the gas wells are in the abutment coal pillar at the tailgate side of the active longwall panel with the longwall just mined by (as shown in Figure 4). In the worst-case scenario, if longwall-induced stress deforms the gas well casing and causes breaches, the leaked gas will enter the mine and be carried into the ventilation system. In the VentSim model, the breached gas was added into the mine with ten short branches connecting the surface. The branches were set as fixed flow with 100% methane introduced into the mine surrounding the gas wells. The combined flow from the 10 short branches represents the total gas inflow from the breached well.

RESULTS FROM LIAM PHYSICAL MODEL

Samples for GC analysis were collected from critical locations, including the longwall face, tailgate entries, tailgate corner gob, tailgate mid gob, BEP, and bleeder entries. These locations were chosen because they are where power is energized at the longwall face, at approved monitoring points in the ventilation plan, and areas where miners are

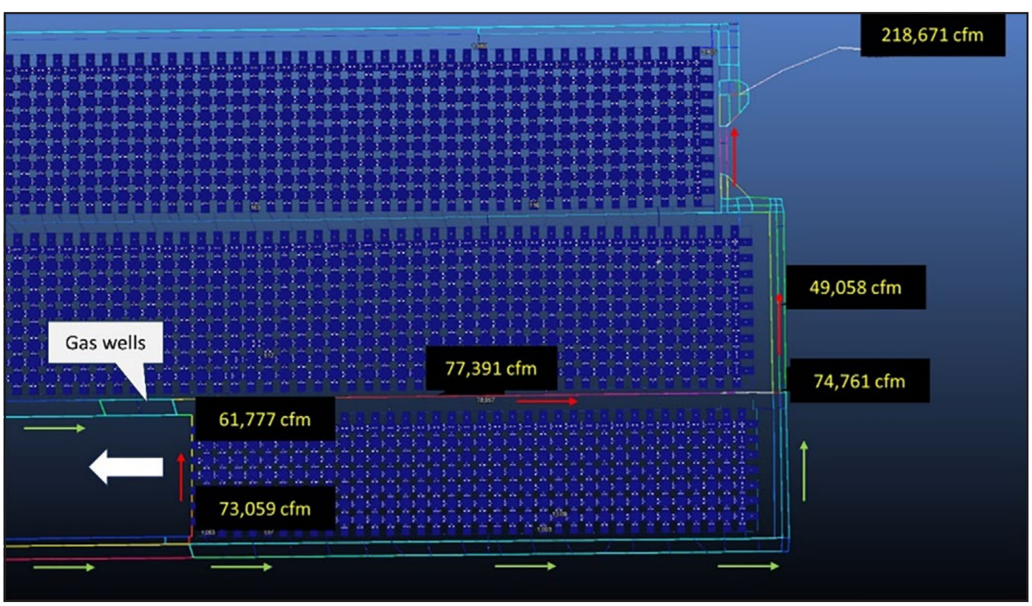

Figure 3. Layout of longwall face, gobs, and gas wells

likely to be working. During each test, twenty 60-second samples were taken, along with additional samples at the 17.5, 20, and 25-minute marks. The gas inflow timeline for each test scenario ranged from 15.5 to 16.5 minutes.

Figure 5 illustrates the gas flow paths for a 340-cfm inflow test scenario. The inserted gas flows directly towards the tailgate entries, moving inby the longwall face towards the BEP and the mine bleeder fan. In this scenario, minimal gas flows toward the GVB, and the longwall face remains

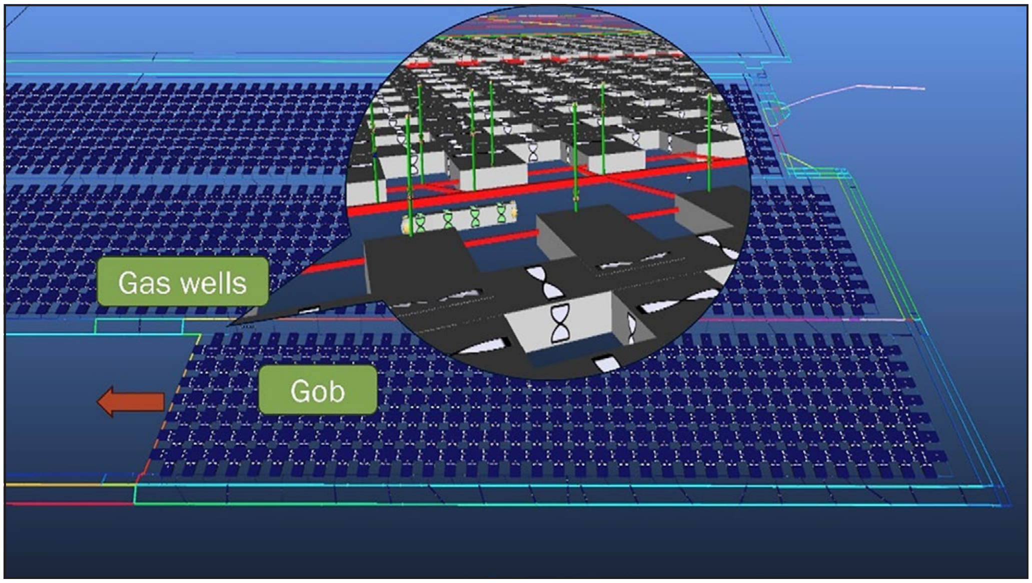

Figure 4. Breached gas inlets to the mine

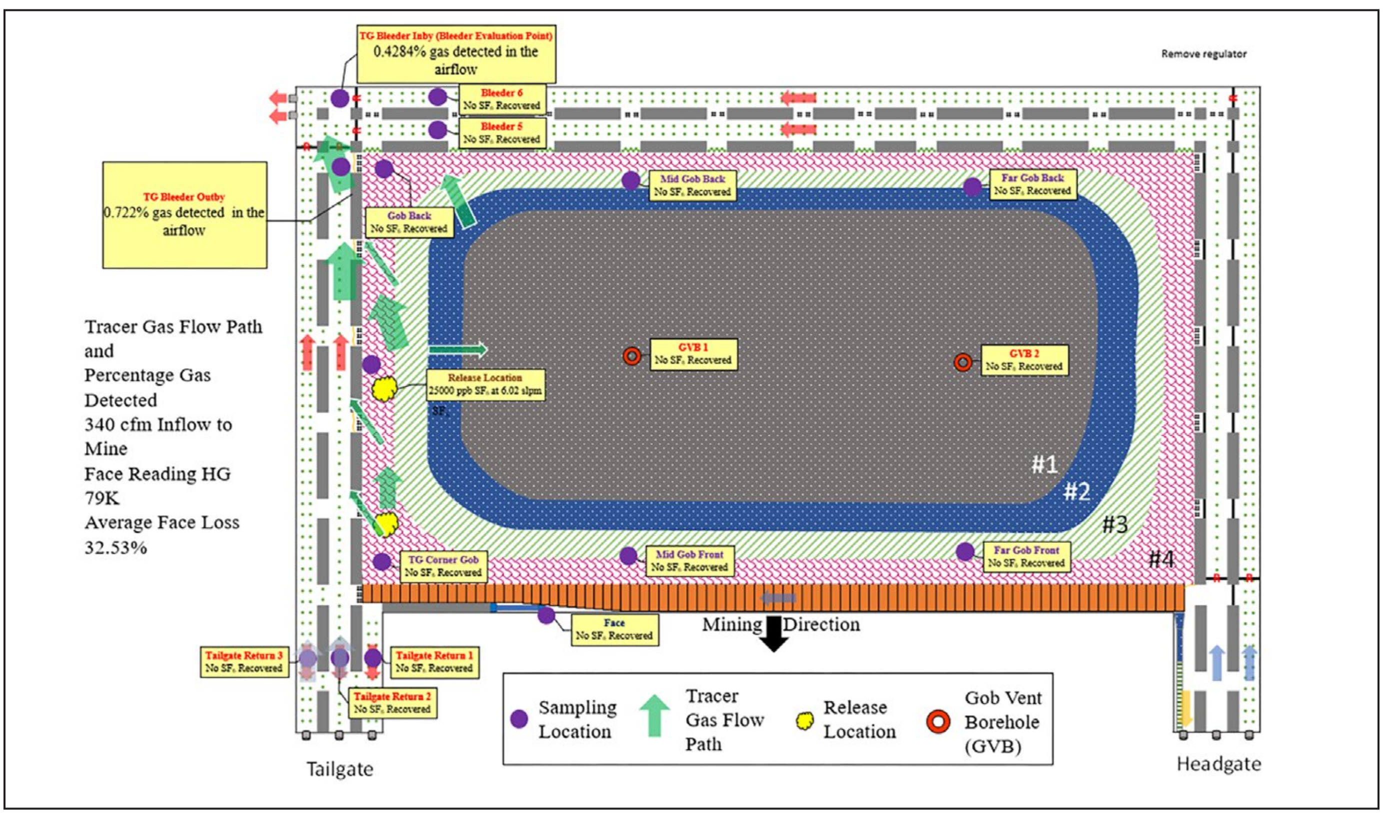

Figure 5. Gas flow path and GC sample results at the sampling locations

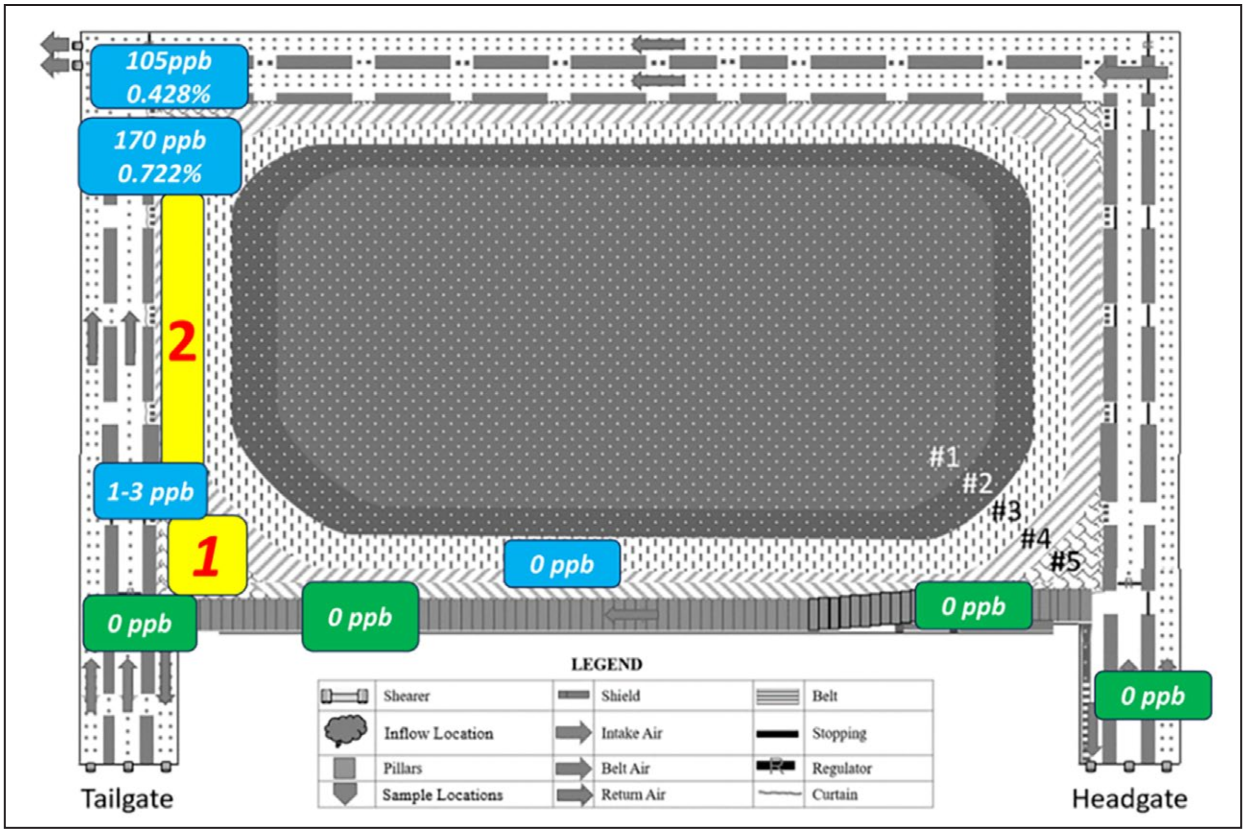

Figure 6. Sampled gas concentration at selected sampling locations for 340-cfm test case

unaffected by the inserted gas. Out of the 5 sampling locations, tracer gas SF6 was detected only at the tailgate side bleeder entry inby the face, the BEP, and the gob near the 22 gas insertion points on the tailgate side.

Figure 6 indicates the ability of the LIAM ventilation system to dilute and render harmless breach gas from a 340-CFM gas inflow that enters the mine at the roof level in 30 locations as shown in yellow (identified as 1 and 2). No gas is detected on the longwall face. In this test scenario, 0.7221% gas is detected at the Bleeder Evaluation Point (BEP), and the 0.4284% detected in the bleeder entries inby are within acceptable limits (1%) as identified in approved mine ventilation plans.

For the test cases with 500-cfm and 1,300-cfm gas inflow, the gas flow paths are very similar with what the 340-cfm case obtained illustrated in Figure 6, which flow from the release locations to the tailgate side bleeder entry toward the BEP. The longwall face remains unaffected by released gas in the 500-cfm and 1,300-cfm case as well. Table 2 shows the gas concentrations at selected sample locations for all three test scenarios in the LIAM test. The data indicate that gas concentration increases with the rise in gas inflow. For example, at the BEP, the measured gas concentrations are 0.72% for 340 cfm inflow, 0.87% for 500 cfm, and 1.10% for 1,300 cfm.

RESULTS FROM VENTSIM MODEL

Breached Gas Migration in the Mine

Various gas inflows ranging from 340 cfm to 1,500 cfm from the breached gas were simulated in this longwall layout with the same ventilation configuration. Figure 7 displays the breached gas migration in this study case for the inflow of 340 cfm. According to the VentSim simulation, once gas enters the ventilation system, a portion is transported by the airflow to the bleeder entry and subsequently exits through the bleeder shaft. At the same time, another fraction of the gas flows into the adjacent gob area. Fortunately, the active face and its gob remain unaffected by the breached gas. In the other simulation cases with larger gas inflows, the same pattern was observed, although the levels of gas concentrations were elevated.

Relationship Between Gas Inflow and Gas Concentration at Some Key Locations

To evaluate the ventilation system's capacity, NIOSH researchers performed simulations with varying gas inflows

Table 2. Gas concentrations at selected sample locations for all test scenarios from LIAM

Test Scenario	LW Face Headgate (%)	LW Face Tailgate (%)	Tailgate Entry #1 (%)	Tailgate Entry #2 (%)	Tailgate Entry #3 (%)	Tailgate Corner Gob (%)	Tailgate Mid Gob (%)	Tailgate BEP (%)	Tailgate Bleeder Inby BEP (%)
A	0	0	0	0	0	0	0.6	0.72	0.43
B	0	0	0	0	0	0	0.63	0.87	0.43
C	0	0	0	0	0	0 .1	0.65	1.10	0.67

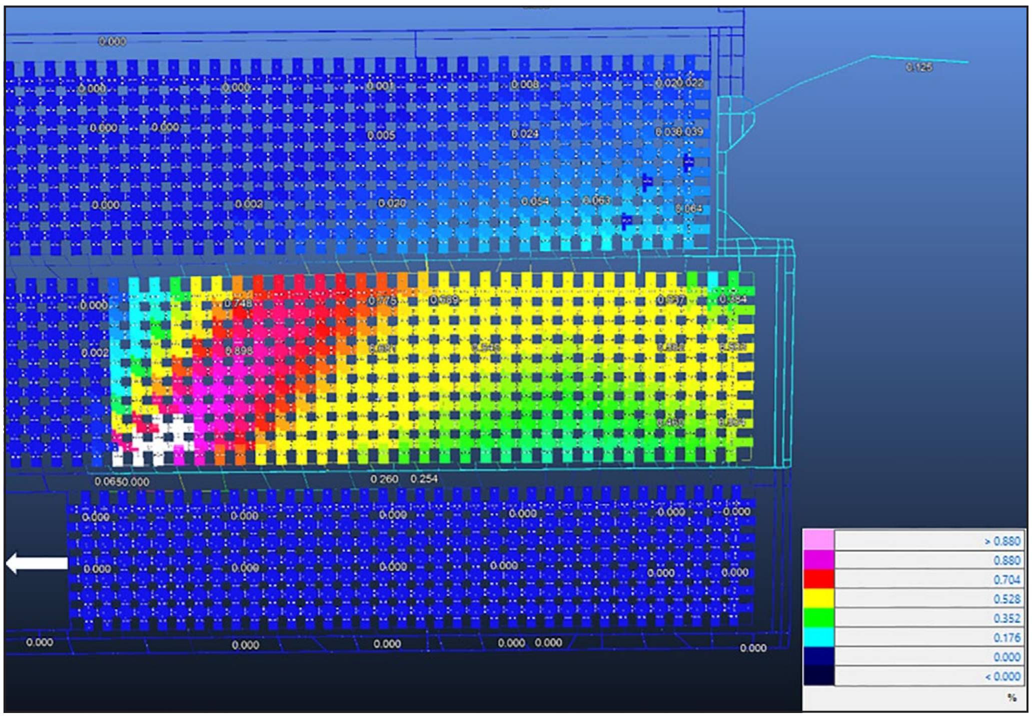

Figure 7. Breached gas migration for an inflow of 340 cfm

of 340 cfm, 500 cfm, 1,000 cfm, 1,300 cfm, and 1,500 cfm. In each test scenario, NIOSH researchers monitored gas concentrations at three key evaluation points along the tailgate side entry and bleeders (as shown in Figure 8). The first monitoring location is on the tailgate side of the longwall face, a few blocks inby. The second is at the Belt Evaluation Point (BEP) on the longwall face, and the third is in the bleeder shaft.

The gas concentration at each monitoring location for each gas inflow are displayed in Table 3. Based on the analysis, results indicate a high coefficient of determination in the relationship between increasing gas inflow and gas concentration. For example, at the BEP, which is denoted as the #2 monitoring point, gas concentration rose from 0.20% at 340 cfm to 0.30% at 500 cfm, and further to 0.88% at 1,500 cfm. Similar patterns were observed at other monitoring locations, confirming that higher gas inflows result in higher gas concentrations throughout the system.

A positive correlation between gas inflow and gas concentration can be seen clearly from Figure 9, when we applied mathematical analysis to determine the relationship between the two variables. Focusing on the BEP (Location 2) as an example, we used five data sets, which are listed in Table 3. The linear equation derived from this analysis characterizes the relationship between gas inflow and gas concentration at the BEP. With this established equation, the concentration of breached gas at the BEP for a given gas inflow can be predicted. The established relationship between gas concentration at key locations and gas inflows can help mine operators better understand their ventilation system's capacity to manage breached gas from gas wells.

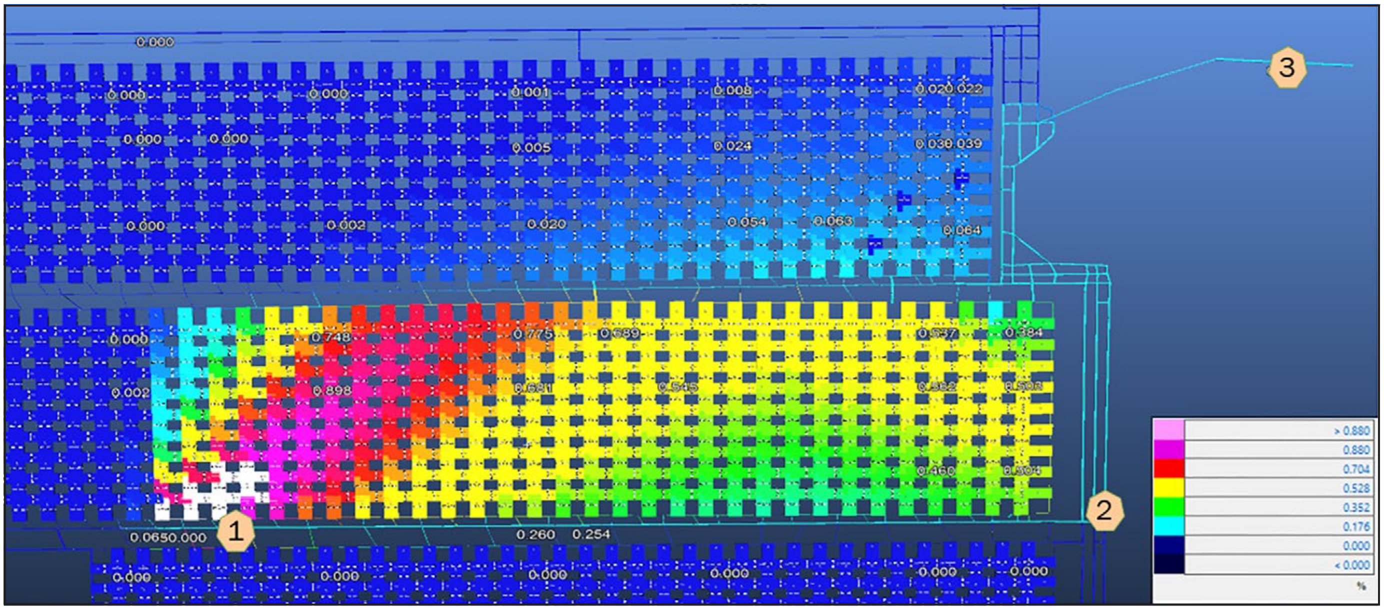

Figure 8. The three key monitoring locations for gas concentrations

Table 3. Gas concentration at the monitoring locations for various gas inflows

Gas Inflow (cfm)	340	500	1000	1300	1500
Location 1	0.26%	0.39%	0.76%	1.00%	1.14%
Location 2	0.20%	0.30%	0.59%	0.78%	0.88%
Location 3	0.13%	0.19%	0.37%	0.49%	0.55%

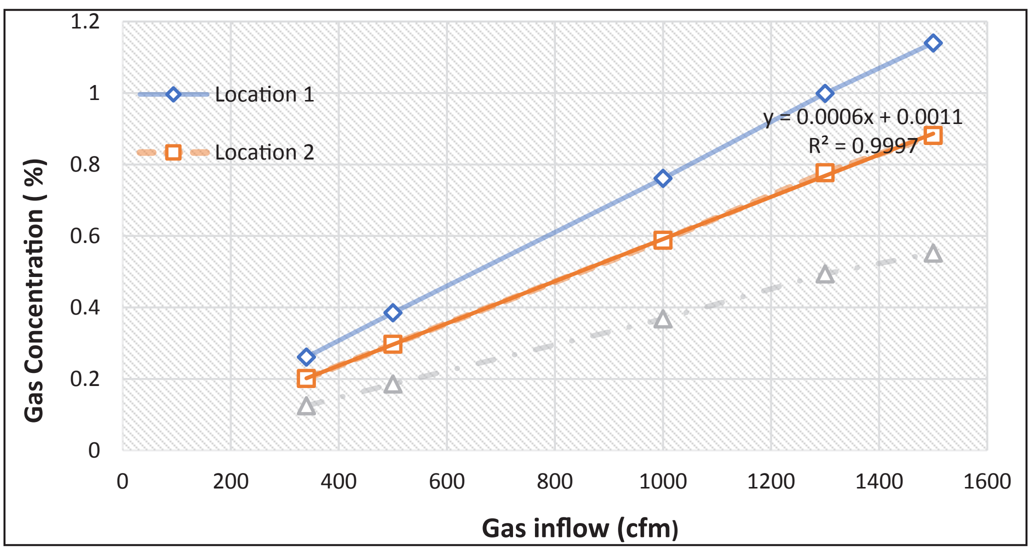

Figure 9. Gas concentrations at each monitoring location for each gas inflow

CONCLUSION

Several hypothetical gas well breach scenarios were investigated using both a network-based VentSim model and a scaled physical model, the LIAM. This study offers mine operators insights into the expected migration of breached gas within the ventilation system and enhances their understanding of how to address potential gas breach hazards effectively.

This case study provides scientific evidence indicating a good correlation between the network model and the LIAM model in predicting the impact of gas breaches. Both models indicate that the active longwall face and its gob will remain unaffected by gas released from wells located on the tailgate side. However, for a given ventilation layout, increasing gas inflows from breached wells will lead to higher gas concentrations at key monitoring locations. A linear positive correlation between gas inflows and gas concentrations at each monitoring location has been established using the VentSim model. This will assist mine operators in understanding the capacity of their ventilation system in the event of a gas well breach.

LIMITATIONS

The findings and conclusions of this study are based on hypothetical gas breach scenarios, and no known gas well breach has occurred to date. One key limitation is that the gas simulation in the network model has not been validated using field data, which may introduce some inaccuracies in the results. Additionally, in-situ gas in the mine was not considered, as the primary focus of this study was on the impact of breached gas. The gas concentrations obtained at each location represent the added gas, on top of any in-situ gas present.

It is worth nothing that the linear equation is specific to this particular ventilation system and is not generalizable. If the ventilation system or gas source model changes, the equation would need to be recalibrated. In addition, the gas concentrations discussed here are exclusively from the breached gas; our simulations did not account for in-situ gas as those from the face or other mine areas.

REFERENCES

Ajayi, K.M., Z. Khademian, S.J. Schatzel, E. Watkins, and V. Gangrade (2021). Numerical modeling of longwall-induced permeability under shallow cover. Tukkaraja (Ed.), Mine Ventilation, 2021: p. 389–397.

Ajayi, K.M. and S.J. Schatzel (2020). Transport model for shale gas well leakage through the surrounding fractured zones of a longwall mine. International Journal of Mining Science and Technology, 2020. 30(5): p. 635–641.

Ajayi, K.M., Z. Khademian, and S.J. Schatzel (2022). Evaluation of parameters influencing potential gas flow to the mine in the event of a nearby unconventional shale gas well casing breach. Mining, Metallurgy & Exploration, 2022. 39(6): p. 2333–2341.

Commonwealth of Pennsylvania, Department of mines and mineral industries, oil and gas division. Joint coal and gas committee, gas well pillar study. Harrisburg, Pennsylvania; 1957.

Dougherty, H., E. Watkins, R. Kimutis (2022). A network model analysis of an unconventional gas well breach above an underground coal mine, Pre-print of SME Annual Meeting, Feb.27-Mar.02, 2022, Salt Lake City, UT.

Gangrade, V., S. Harteis, and J. Addis. Development and applications of a scaled aerodynamic model for simulations of airflows in a longwall panel. in Proceedings of the Sixteen North American Mine Ventilation Symposium. Golden, CO. 2017.

Harris, M., S.J. Schatzel, K.M. Ajayi, M. Van Dyke, P. Zhang, V. Gangrade, J.D. Addis, H. Dougherty, E. Watkins (2023). Permeability determination for potential interaction between shale gas wells and the coal mine environment due to longwall-induced deformations under deep cover; Underground Ventilation. 2023, CRC Press. p. 499–506.

Kimutis, R.A., Harris, M.J., Schatzel,S.J., Addis, J.D., Mazzella, M.M., Guitard, M., Ganagrade, V. Mine Ventilation Pathway Simulation on a Hypothetical Shale Gas Well Breach Utilizing the Longwall Instrumented Aerodynamic Model (LIAM). Society for Mining, Metallurgy and Exploration Inc. 2023.

Mine Safety and Health Administration, MSHA (1996) Bleeder and Gob Ventilation Systems. Ventilation Specialist Training Course. Revised 2002.

Su, D. W. (2017). "Effects of Longwall-Induced Stress and Deformation on the Stability and Mechanical Integrity of Shale Gas Wells Drilled Through a Longwall Abutment Pillar." International Journal of Mining Science and Technology 27(1): 115–120.

Su, D. W., P. Zhang, M. Van Dyke and T. Minoski (2018). "Effect of Cover Depth on Longwall-Induced Subsurface Deformations and Shale Gas Well Casing Stability." 52nd U.S. Rock Mechanics/Geomechanics Symposium, OnePetro.

Su, D., P. Zhang, H. Dougherty, M. Van Dyke, T. Minoski, S. Schatzel, V. Gangrade, E. Watkins, J. Addis and C. Hollerich (2019a). "Effects of Longwall-Induced Subsurface Deformations and Permeability Changes on Shale Gas Well Integrity and Safety Under Shallow Cover." 53rd U.S. Rock Mechanics/Geomechanics Symposium, OnePetro.

Su, D., P. Zhang, S. Schatzel, V. Gangrade and E. Watkins (2019b). "Longwall-Induced Subsurface Deformations and Permeability Changes—Shale Gas Well Casing Integrity Implication." Proceedings of the 38th international conference on ground control in mining.

Su, D. W., P. Zhang, M. Van Dyke and T. Minoski (2019c). "Effect of Longwall-Induced Subsurface Deformations on Shale Gas Well Casing Stability Under Deep

Covers." International Journal of Mining Science and Technology 29(1): 3–8.
Su, W., P. Zhang, H. Dougherty and M. VanDyke (2021). "Acquisition and Interpretation of Critical Scientific Data for Shale Gas Wells Influenced by Longwall Mining." 40th International Conference on Ground Control in Mining, Virtual, SME.
Watkins, E., C.Ö. Karacan, V. Gangrade, and S. Schatzel, Assessing Gas Leakage Potential into Coal Mines from Shale Gas Well Failures: Inference from Field Determination of Strata Permeability Responses to Longwall-Induced Deformations. Natural Resources Research, 2021. 30(3): p. 2347–2360.
Zhang, P., H. Dougherty, D. Su, J. Trackemas and B. Tulu (2020). "Influence of Longwall Mining on the Stability of Gas Wells in Chain Pillars." International Journal of Mining Science and Technology 30(1): 3–9.