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SIMULATING THE IMPACT OF A SHALE GAS WELL BREACH ON LONGWALL MINE VENTILATION UTILIZING A SCALED PHYSICAL MODEL

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ABSTRACT

The recent shale gas revolution in the United States has led to the drilling of hundreds of unconventional shale gas wells in active and future coal reserves in traditional coal-mining regions of Pennsylvania, West Virginia, and Ohio. This paper summarizes the impact of a shale gas well breach on the mine ventilation system of an operating longwall panel. This study utilizes a 1:30 scaled Longwall Instrumented Aerodynamic Model (LIAM) to simulate a single-panel longwall operation. The LIAM will be utilized to identify flow pathways and distribution patterns of gas from breached gas well scenarios in an operating longwall in the Pittsburgh Coal Seam. Sulfur hexafluoride (SF_6) tracer gas is utilized to simulate a breached gas well. Preliminary findings suggest that the breached gas is diluted to regulatory levels and does not accumulate in the mine entries or in the longwall gob when the longwall panel is adequately ventilated. Overall, this study characterizes the potential interaction between shale gas wells and the mine environment in the event of a gas well breach, which provides critical information to the industry and regulatory agencies for improving safety, health, and welfare of miners.

INTRODUCTION

Due to a recent shale gas boom, more than 1,500 unconventional shale gas wells have been drilled through current and future coal reserves in Pennsylvania, West Virginia, and Ohio. These shale gas wells have penetrated many coal seams such as the Pittsburgh, Freeport, and Kittanning seams, and their mechanical integrity may be compromised by longwall-induced deformations and stresses, which may result in dangerous inflow of high-pressure gas into underground mine workings. In 2012, upon recognizing that the 1957 Pennsylvania Gas Well Pillar Regulation was formulated without longwall mining data, the Pennsylvania Department of Environmental Protection (PADEP) initiated a call for research to update the outdated regulation (1). It is important to note that the 1957 Pennsylvania Gas Well Pillar Regulation has been widely used by the Mine Safety and Health Administration (MSHA) and seven other states to govern gas well pillar stability issues over the past 60 years. With a focus on protecting the safety of miners and the public and on contributing towards development of relevant scientific data and engineering guidelines, this paper addresses the impact of a high-pressure shale gas well breach on the ventilation of longwall coal mines.

Researchers with the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Mining Research Division (PMRD) employed a physical modeling approach to study the potential impact of shale gas migration in a longwall mine. The complex and dynamic nature of longwall mining makes it difficult to conduct detailed field experiments for contaminant gas migration in a particular mine. In addition, it is particularly difficult to release and sample gas in the gob regions. As an alternative, physical modeling can be used to simulate areas of a longwall panel, especially those that are inaccessible like the longwall gob. Scaled physical modeling also offers the advantage of simulating the performance of a ventilation system under controlled conditions (2). For this purpose, a 1:30 scale physical model of a portion of a longwall operation was designed and constructed. The Longwall Instrumented Aerodynamic Model (LIAM) is built with critical details of the face and face machinery, including a shearer, shields, pan-line, as well as a portion of the gob, bleeder and gateroad entries, and the barrier pillars (Figure 1, see APPENDIX). The LIAM is constructed to simulate ventilation flow and gas migration in a controlled environment, allowing variables to be systematically modified (3-5)

LIAM DESCRIPTION

The important characteristics of the model are described in the following subsections.

Model Design and Dimensions

The LIAM is configured with airflow quantities and ventilation controls commonly approved by MSHA for operating longwall mines in the Pittsburgh Coal Seam. The LIAM is geometrically designed to represent a single longwall panel with a three-entry headgate and a three-entry tailgate configuration. It also has two-bleeder entries (Figures 1 and 2, see APPENDIX). It has a footprint of 8.94-m (29-ft) in length by 6.1-m (20-ft) in width and is 0.84 m (2.75 ft.) in height from the floor to the surface of the model. The top surface of the LIAM is a transparent acrylic glass that allows a clear view inside the model and visualization of airflow in the model using smoke. Smoke helps in observing and validating the flow paths, eddy currents, turbulence, and gob-face interaction.

Tracer Gas Release, Sampling, and Analysis

Sulfur hexafluoride (SF_6) tracer gas is utilized as a surrogate for methane to simulate breached shale gas in the LIAM. Different concentrations of SF_6 tracer gas (100 parts per billion (ppb) to 25,000 ppb) were tested in the model to determine the optimal concentration for detection during sampling. SF_6 was released at 6.02 standard liter per minute (SLPM) flow rate (equivalent to ~340 cubic feet per minute (cfm) in full-scale) using an Alicat mass flow controller (6). The gas was released at 16 insertion points on the tailgate side of the gob. The release volume and release locations were determined using the complementary research approaches of discrete fracture network modeling and computational fluid dynamics modeling on the project. The SF_6 gas was released continuously and its migration through the model was tracked by sampling at different monitoring stations. The tracer gas was released continuously for 15 minutes.

The tracer gas samples were collected in evacuated 15-millileter (ml) glass vials at each monitoring station by manual sampling of ventilation air drawn through a syringe. For each test, 25 samples were collected at each location at varying sampling intervals. The first 10 samples were collected every 30 seconds, the next 10 samples were collected every minute, and concurrent samples were collected at 17.5, 25, 40, 60, and 120 minutes since the time of injection. The varying interval allowed for quantifying the build-up, steady state, and residence time of tracer gas in the model.

Samples collected during the LIAM studies were analyzed for SF_6 concentrations by gas chromatography (GC). Samples were drawn from the bottle samples and analyzed using a modification of NIOSH Method 6602 (7) by a Shimadzu GC8 with an electron capture detector. The limit of detection (LOD) for the GC method is about 1 ppb SF_6 in air.

Ventilation Measurement and Instrumentation

A critical parameter monitored in the LIAM is the mine ventilating air velocity. To measure ventilation flow rates, 42 hotwire anemometers are located in different areas of the model: 8 anemometers on the face, 16 anemometers within the gob, and 18 anemometers in the mine entries. The locations of different sensors are shown in Figure 2 (see APPENDIX). The data acquisition system selected for this study is Measurement Computing/Data Translation Inc.'s MEASURpoint hardware (8). A monitor directly connected to the data acquisition system is installed in the building to show sensor data in real time.

Gob Design

The flow characteristics of a mine gob zone have a significant impact on the relationship between the mine ventilation system and any methane sources in or around the gob area. In order to accurately replicate a longwall coal mine gob area, a representative permeability distribution throughout the gob is required. As shown in Figure 2, four gob permeability zones (#1, #2, #3, #4) were created within the LIAM whose geometry was dictated by a Flac3D model of a Pittsburgh Seam longwall coal mine. Each of the four permeability zones utilized different fill materials to produce a distribution of permeability values equivalent to the past mining research for gob permeabilities (9-10).

To determine if a certain fill sizing or mixture produced a suitable permeability value, pressure drop tests were performed to estimate the Darcy and Forchheimer values for that material. For each pressure drop test, a 0.1016-meter (m) (4-inch (in)) diameter and 0.609-m (2-ft) long PVC pipe containing the fill material was connected to a variable frequency drive fan that induced a range of four different air velocities across the filled section of the pipe. For each air velocity test of the material, a resulting pressure drop was measured across the fill material section of the pipe. An anemometer was used to measure the airflow velocity, and pressure transducers on either side of the fill material measured the pressure drop for each fan flow rate. The four air velocity tests and corresponding pressure drop values formed an exponential pressure-loss versus velocity curve for each gob material as described by the Forchheimer equation (11) described by Equation 1.

$$-\frac{\Delta p}{\Delta x} = \mu D v + \frac{1}{2}\rho F v^2 \quad (1)$$

Where Δp is the pressure drop in Pascals, Δx is the length in meters of the pipe section filled with the gob material, v is the average fluid velocity in meters per second, μ is the dynamic viscosity in Pascal-seconds, ρ is the fluid density in kilograms per meter cubed, D is the Darcy coefficient, and F is the Forchheimer coefficient. The two exponential pressure-loss versus velocity curves estimated through the pressure drop tests are utilized to calculate the Darcy and Forchheimer coefficients that describe the viscous and inertial resistances that represent the permeabilities of each material. Table 1 shows the results of the pressure drop tests for the gob fill materials selected.

Table 1. Pressure drop test results for selected gob zone fill materials.

Gob Zone	Material Type	D (1/m^2)	F (1/m)	Darcy
Zone 1	Mixed Gravel	8.454E+06	356.9	119,858
Zone 2	½" to ¾" Sized Gravel	4.286E+06	478.7	236,426
Zone 3	¾" to 1" Sized Gravel	1.077E+06	287.6	940,808
Zone 4	Foam	2.14E+05	99.1	4,730,198

SCALING RELATIONSHIPS

The concept of physical modeling has been applied widely in industrial and environmental fluid flow studies, especially in the aeronautics, automobile, and construction industries (12). In mining, however, the complex and dynamic nature of underground mines has made modeling studies more complicated and difficult when studying ventilation problems. Two particular challenges in developing a physical model include geometric and aerodynamic scaling. To ensure good geometric scaling, all internal components in the LIAM such as the standing supports, shields, cribs, 3D printed shearer, regulators, and curtains are built to specific detail. For aerodynamic scaling, a set of similarity relationships were developed between the important physical properties of the flow in the model compared to the flow in full scale. More detail on the scaling factors can be found in a previously published peer-reviewed journal paper (5). Table 2 below summarizes the scaling factors.

Table 2. Geometrical and aerodynamic scaling factors for the LIAM.

Model	Specification	Characteristic
Scale for geometry	x 1/30th	7.62-cm-high face in the LIAM represents 2.28-m face in full scale. 7.31-m face length in the LIAM represents 219 m in full scale.
Scale for velocity	x 0.56	0.56 m/s (110 fpm) in the LIAM represents 1 m/s (197 fpm) in full scale.
Scale for flow	x 6.20E-04	5.85E-02 m^3/s (124 cfm) in the LIAM represents 94.4 m^3/s (200 kcfm) in full scale.
Turbulent dispersion	Reynolds number > 6000.00	Similitude for turbulent dispersion. Reynolds number ~12,000 in headgate entry.
Layer formation	Conservation of the Richardson number	Similitude for layering.

EXPERIMENTAL DESIGN

Two sets of experimental tests were conducted in the LIAM to achieve two different goals. The first goal of the experimental testing was to simulate the longwall mine ventilation as observed at the underground longwall coal mines in the Pittsburgh Seam. To determine the key ventilation parameters such as face airflow, T-split, bleeder ventilation, etc., mine maps were studied from Pittsburgh seam mines. The ventilation in the LIAM does not necessarily simulate any particular mine but rather represents the typical ventilation in Pittsburgh Coal Seam mines. This set of experiments did not involve tracer gas, and only ventilation airflow data were recorded in the simulated mine entries and gob.

The second set of experiments were designed to simulate the injection of methane gas from a breached shale gas well drilled through the coal mine in the Pittsburgh Seam. Experiments were conducted utilizing a range of SF_6 tracer gas concentrations (100 ppb to 25,000 ppb). These tests were conducted in the LIAM to determine the mixing of tracer gas in ventilation airflow. For the release volume tested in the LIAM and tracer gas concentrations below 25,000 ppb, the gas was diluted below GC LOD (1 ppb) at the monitoring locations near the bleeder evaluation points. Therefore, experiments were conducted using the 25,000 ppb gas concentration and all the experiments described in this paper were conducted using this tracer gas concentration.

The release volume and injection locations within the LIAM were determined using complementary research approaches of discrete fracture network (DFN) modeling and computational fluid dynamics (CFD) modeling. The input for these numerical models was determined using field permeability data from a drilling project at a Pittsburgh Coal Seam longwall mine (13-17). Simulated gas flow to the mine from 10 gas well breaches at the Sewickley horizon using a shale gas well shut-in pressure of 3,000 psi produced a representative value of 340 cfm.

The experiments determine the impact of the breached shale gas well on a longwall mine in terms of migration characteristics of the gas (qualitative) and increase in gas concentrations at critical locations in the mine environment (quantitative).

RESULTS AND DISCUSSION

Shale Gas Well Breach based on DFN Modeling

Gas inflow into the LIAM from breached gas well scenarios utilized the following DFN modeling assumptions (18). Gas was released at the mine roof (340 cfm inflow) at location A in the LIAM at 8 and 16 insertion points under separate testing scenarios (Figure 3, see APPENDIX). Scenario (1) gas was released at 8 insertion points inby the longwall face off the tailgate pillar in the tailgate corner gob. Scenario (2) gas was released at 8 insertion points inby the longwall face off the tailgate pillar in the tailgate corner gob and 8 insertion points at the tailgate pillar line (1" in model and 30" in full-scale) in the gob adjacent to the tailgate entry. Thirteen tests were performed with samples taken (Figure 3, see APPENDIX) on the longwall face, tailgate entries outby the face, tailgate bleeder near the fan, tailgate bleeder (BEP) inby the face in the tailgate entries, tailgate corner gob, mid-gob tailgate side, back-end gob near the bleeder entries, mid-gob face side of panel, mid-gob bleeder side of panel, gob ventilation borehole (GVP) mid-panel, and the bleeder entries at the back side of the panel. The test results reveal that although gas is present in the gob sample locations near the scenario insertion points, ventilation airflow pathways that exist in the mine ventilation system are capable of coursing, diluting, and rendering harmless any gas outflow into the accessible areas of the mine. None of the tests resulted in any gas detectable on the longwall face or tailgate drive areas (>1 ppb). Minor amounts of gas were detected in samples taken at the inby the tailgate BEP (0.131%). Gas detected from samples taken outby the tailgate BEP location was 1.08%. This amount was detected prior to the bleeder entry "sweetening" effect and is located at a normal MSHA-approved mine plan examination point.

Shale Gas Well Breach based on CFD Modeling

Gas inflow into the LIAM from hypothetical breached gas well scenarios utilized the following CFD modeling assumptions. Gas was released at the mine roof (340 cfm inflow) at location B in the LIAM at 8 and 16 insertion points under separate testing scenarios (Figure 4). In Scenario (1) gas was released at 8 insertion points inby the Tailgate pillar line (1" model) in the gob (30" scale) at the mid center of the gob area adjacent to the tailgate entry. In Scenario (2) gas was released 16 points inby the Tailgate pillar line (1" model) in the gob (30" scale) at the mid-center of the gob area adjacent to the tailgate entry. Thirteen tests were performed with samples taken (Figure 4, see APPENDIX) on the longwall face, tailgate entries outby the face, tailgate bleeder near the fan, tailgate bleeder (BEP) inby the face in the tailgate entries, tailgate corner gob, mid-gob tailgate side, back-end gob near the bleeder entries, mid-gob face side of panel, mid-gob bleeder side of panel, gob ventilation borehole (GVB) mid-panel, and the bleeder entries at the back side of the panel. The results of the test reveal that although gas is present in the gob sample locations near the scenario insertion points, ventilation airflow paths that exist in the mine ventilation system are capable of coursing, diluting, and rendering harmless any gas outflow into the accessible areas of the mine. As shown in Figure 5, the tracer gas builds up in gob sampling locations and fluctuates near the steady state level and then goes back to zero when the gas injection is shut-off. The gas does not reside in the gob for an extended period of time after the injection is shut off, meaning the residence time is little to nonexistent, and the ventilation system of the mine is moving the gob gas towards the bleeders and it is not accumulating in the gob. Data are shown for the "gob back" location. None of the tests resulted in any gas detectable on the longwall face or tailgate drive areas. Minor amounts of gas were detected in samples taken at the Tailgate Bleeder inby the BEP (0.134%) and Bleeder entry #5 location (0.05%). Minor amounts of gas were detected in Tailgate entry #2 (0.049%) outby flow and Tailgate entry #3 (0.064%) outby flow. Gas detected from samples taken at the Tailgate Bleeder (BEP) location was (1.014%). This amount was detected prior to the bleeder entry "sweetening" effect and is at a location that is normally an MSHA-approved mine plan examination point.

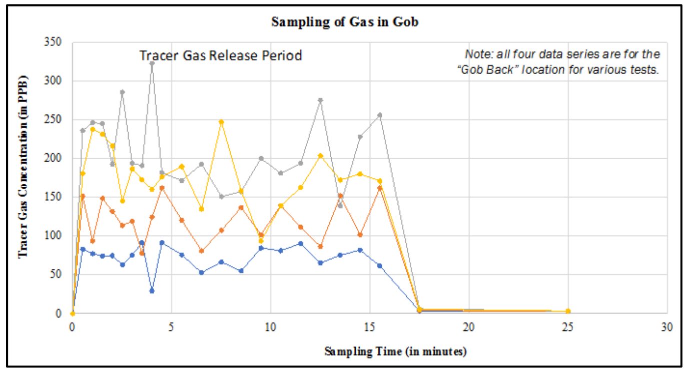

Figure 5. Graph showing little to no residence time of tracer gas in the gob after the injection is shut off. All four data series shown are from the "Gob Back" location for various tests.

Table 3. Average tracer gas percentage detected at various sampling locations.

Location	Insertion Location A (DFN based)	Insertion Location B (CFD based)
	Tracer gas percentage detected	Tracer gas percentage detected
Tailgate Bleeder Inby BEP	0.131	0.134
Outby BEP	1.080	1.014
Tailgate #1	Below LOD*	Below LOD
Tailgate #2	Below LOD	0.049
Tailgate #3	Below LOD	0.064
Face	Below LOD	Below LOD
Back Bleeder #5	Below LOD	Below LOD
Back Bleeder #6	Below LOD	0.050
GVB #1	Below LOD	0.007
GVB #2	Below LOD	Below LOD

**LOD: Limit of Detection is 1 ppb (0.004%) for the 25,000 PPB injection*

SUMMARY

The LIAM is configured with representative airflow quantities and ventilation controls commonly approved by MSHA for operating longwall mines in the Pittsburgh coal seam. Breached gas well inflow (340 cfm) was tested and sampled in multiple scenarios utilizing 8 and 16 insertion points based upon assumptions generated by CFD and DFN models. The results reveal that a properly managed and ventilated longwall panel and bleeder system can dilute and render harmless any gas outflow from a breached gas well scenario involving a 340-cfm inflow into the simulated underground mine. Confidence in the ability to dilute 340-cfm of gas inflow is provided by the multiple ranges of longwall intake air and face air used to ventilate the LIAM during the testing scenarios. Additional confidence is provided by test results from various Tailgate T-split arrangements during the LIAM tests. At no time was gas from a breached gas well scenario recorded from samples taken on the longwall face or at the Tailgate drive location. Minor amounts of gas were present in samples taken in the Tailgate entries (0.064% max.) and the Tailgate Bleeder locations (0.134% max.). At the mine-specific MSHA-approved Mine Ventilation Plan Bleeder Evaluation Point (BEP), commonly approved and in service for Longwall Operations in the Pittsburgh Coal Seam, a maximum concentration of gas was recorded measuring 1.08%. The gas released from the breached gas well scenarios enter the LIAM ventilation system at the mine roof level through the 8 and 16 insertion points. Gas is present in samples taken in longwall mined gob areas: Tailgate corner gob, mid-gob Tailgate side, Backend gob Tailgate side, gob mid-backend panel, and gob mid-frontend panel. At no time during the tests did gas released into the LIAM gob from a breached gas well scenario enter the mine ventilation system where powered equipment is in operation (longwall face or tailgate drive) in measurable quantities. The limit of detection for the testing method was 0.004% or 1 ppb of SF_6. Gas released into the LIAM gob from a breached gas well scenario into the mine ventilation system (Tailgate entries, Bleeder entries, or mine fan) recorded some measurable quantities greater at 0.134% or less. The maximum percentage recorded was 1.08% at the bleeder evaluation point (BEP) prior to mixing with fresh air supplied from the mine bleeder system. LIAM testing confirms that a prudent mine operator utilizing a properly managed and properly designed ventilation system for an operating longwall face can course ventilation air pathways, dilute, and render harmless any gas outflow entering the mine ventilation system (in the gob) from a 340-cfm inflow breached gas well scenario.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

1. Gas Well Pillar Study (1957). Joint Coal and Gas Committee: Commonwealth of Pennsylvania, Department of Mines and Mineral Industries, Oil and Gas Division. Harrisburg, Pennsylvania: 28 pp.

2. Gangrade, V., Calizaya, F. and Nelson, M.G. (2013) Use of a CO_2 gas injection system in a laboratory model to study controlled recirculation. In Proceedings of International Association for Automation and Robotics in Construction (IAARC). August 10-14, Montreal, Canada. Preprint No. 321

3. Gangrade V., Harteis S.P., Addis J.D. (2017) Development and applications of a scaled aerodynamic model for simulations of airflows in a longwall panel. In: Proceedings of 16th North American Mine Ventilation Symposium. Golden, CO: Colorado School of Mines. pp. 6-17 to 6-24.

4. Gangrade V., Harteis S.P., Addis J.D. (2018) Studying longwall ventilation with physical modeling. Coal Age, Volume 123, Issue 6, July-August 2018, pages 38-39.

5. Gangrade, V., Schatzel, S.J., Harteis, S.P., Addis, J.D. (2019) Investigating the Impact of Caving on Longwall Mine Ventilation Using Scaled Physical Modeling. Springer Mining, Metallurgy & Exploration. 2019 Aug;36(4):729-740. https://doi.org/10.1007/s42461-019-0065-7, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6556897/

6. Alicat (2021). Mass flow controllers. https://www.alicat.com/product/mass-flow-controllers/#g_mass-flow-controllers.

7. NIOSH (1994) Sulfur hexafluoride by portable GC, NIOSH method 6602. NIOSH Manual of Analytical Methods, 2003-154, third supplement. http://www.cdc.gov/niosh/docs/2003-154/pdfs/6602.pdf

8. Data Translation (2021). QuickDAQ, Data logging and FFT analysis software. https://www.mccdaq.com/Products/Data-Acquisition-Software/QuickDAQ.

9. Marts, J., Gilmore, R., Brune, J., Bogin, G. (2014) Dynamic gob response and reservoir properties for active longwall coal mines. In: Mining Engineering, 2014, Vol. 66, No. 12, pp. 59–66.

10. Ren, T., Balusu, R., Claassen, C. (2011) Computational Fluid Dynamics Modelling of Gas Flow Dynamics in Large Longwall Goaf Areas. In: 35th APCOM Symposium, Application of Computers and Operations Research in the Minerals Industry, pp. 603–613.

11. Forchheimer, P. (1901) Wasserbewegung durch boden. In: Zeitschrift des Vereines deutscher Ingenieure, Dusseldorf, 45(50), 1781–8.

12. Science Direct (2021) Physical Modelling. https://www.sciencedirect.com/topics/engineering/physical-modelling.

13. Watkins, E., Karacan, C.O., Gangrade, V., Schatzel, S.J. (2021) 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, NARR-D-20-01102R1 https://pubs.er.usgs.gov/publication/70219064.

14. Watkins, E., Gangrade, V., Schatzel, S.J. (2020) Permeability Determination for Potential Interaction between Shale Gas Wells and the Coal Mine Environment due to Longwall-induced Deformations. In proceedings of the Society of Mining, Metallurgy & Exploration Annual Conference. Phoenix, AZ: Feb 24-27, Pre-print 20-108

15. Schatzel, S.J., Su, D.W.H., Gangrade, V., Zhang, P. (2020) Evaluation of permeability and transport characteristics formed by the induced fracture network around gas wells drilled through longwall abutment pillars. In proceedings of the Society of Mining, Metallurgy & Exploration Annual Conference. Phoenix, AZ: Feb 24-27, Pre-print 20-118

16. Su, D.W.H., Schatzel, S.J., Gangrade, V., Zhang, P. (2019) Longwall-Induced Subsurface Deformations and Permeability Changes-Shale Gas Well Casing Integrity Implication. In Proceedings of the 38th International Conference for Ground Control in Mining, Morgantown, WV, July 23–25.

17. Su, D.W.H., Schatzel, S.J., Gangrade, V., Zhang, P. (2019) Effects of Longwall-Induced Subsurface Deformations and Permeability Changes on Shale Gas Well Integrity and Safety Under Shallow Cover. In Proceedings of the 53rd US Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association, New York, NY, June 23–26. https://www.onepetro.org/conference-paper/ARMA-2019-0013

18. Ajayi, K.M., Khademian, Z., Schatzel, S.J., Watkins, E., and Gangrade, V. [2021] Numerical modeling of longwall-induced permeability under shallow cover. Mine Ventilation, Book Chapter, 389-397 https://doi.org/10.1201/9781003188476.

APPENDIX

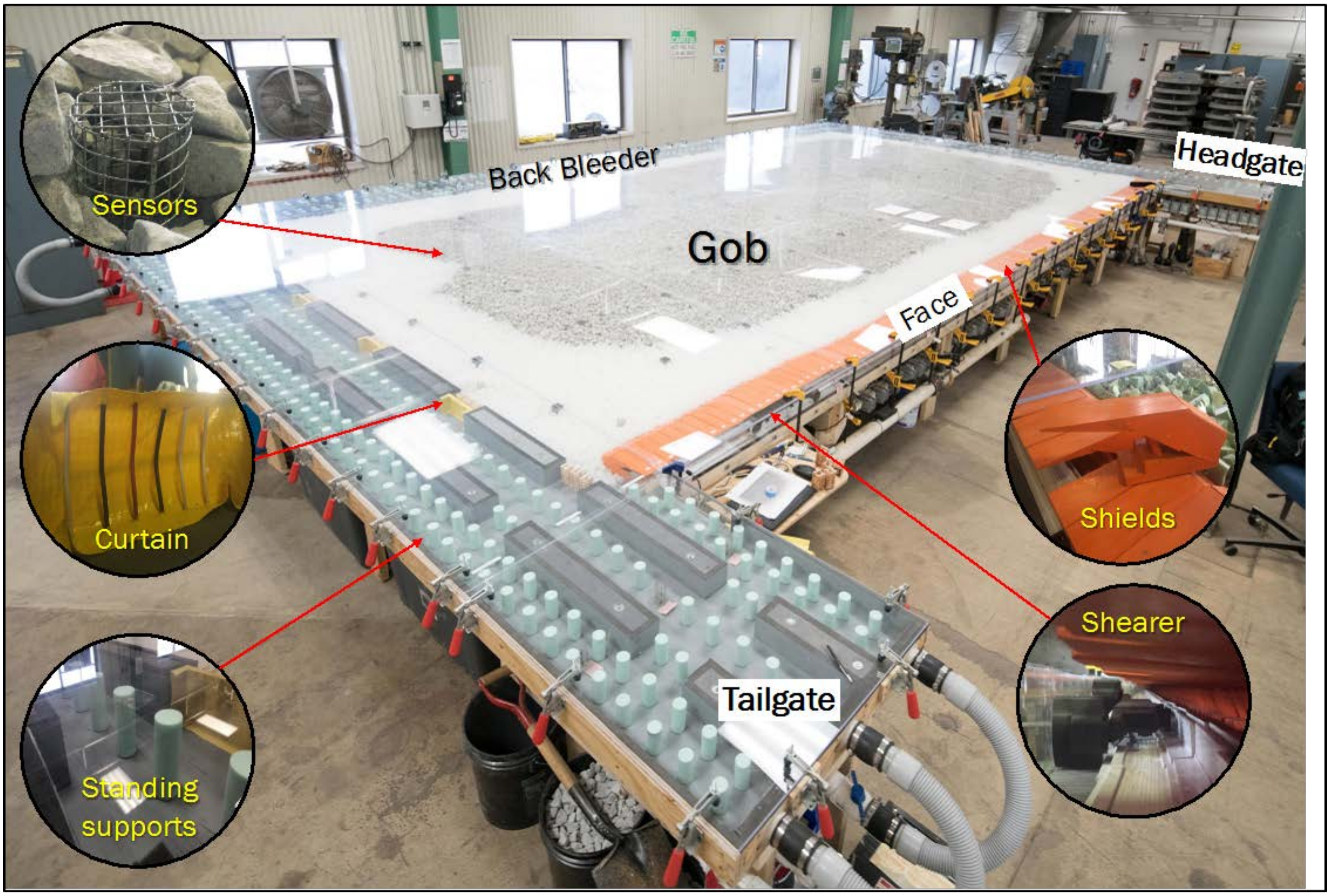

Figure 1. Illustration of the LIAM with some key features shown in circles.

APPENDIX (cont'd)

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Figure 2. Schematic showing longwall features, gob, ventilation airflow and controls, and locations of gas release, sampling, and sensors.

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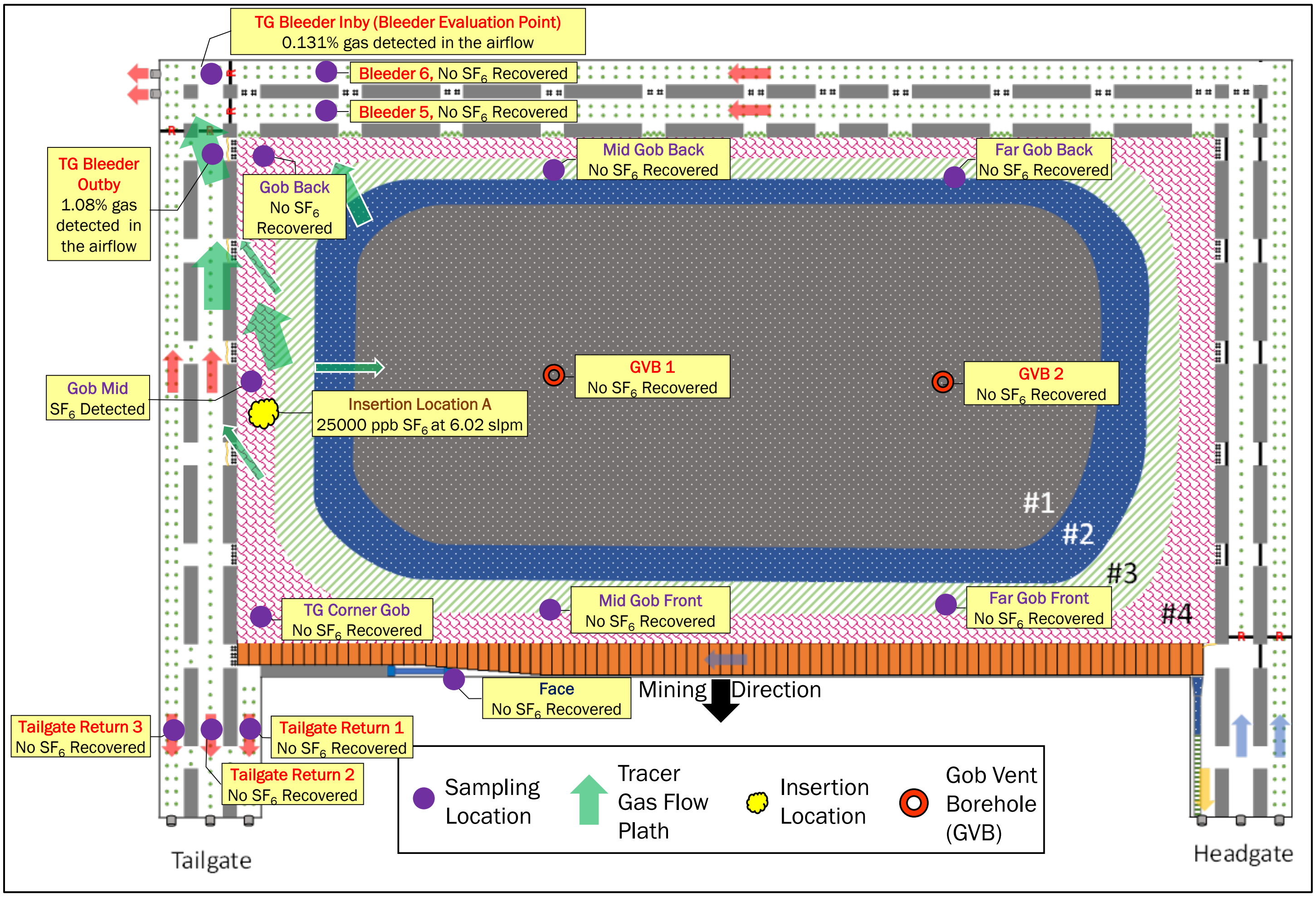

Figure 3. Schematic showing flow pattern of breached shale gas and sampling locations for breach based on DFN modeling.

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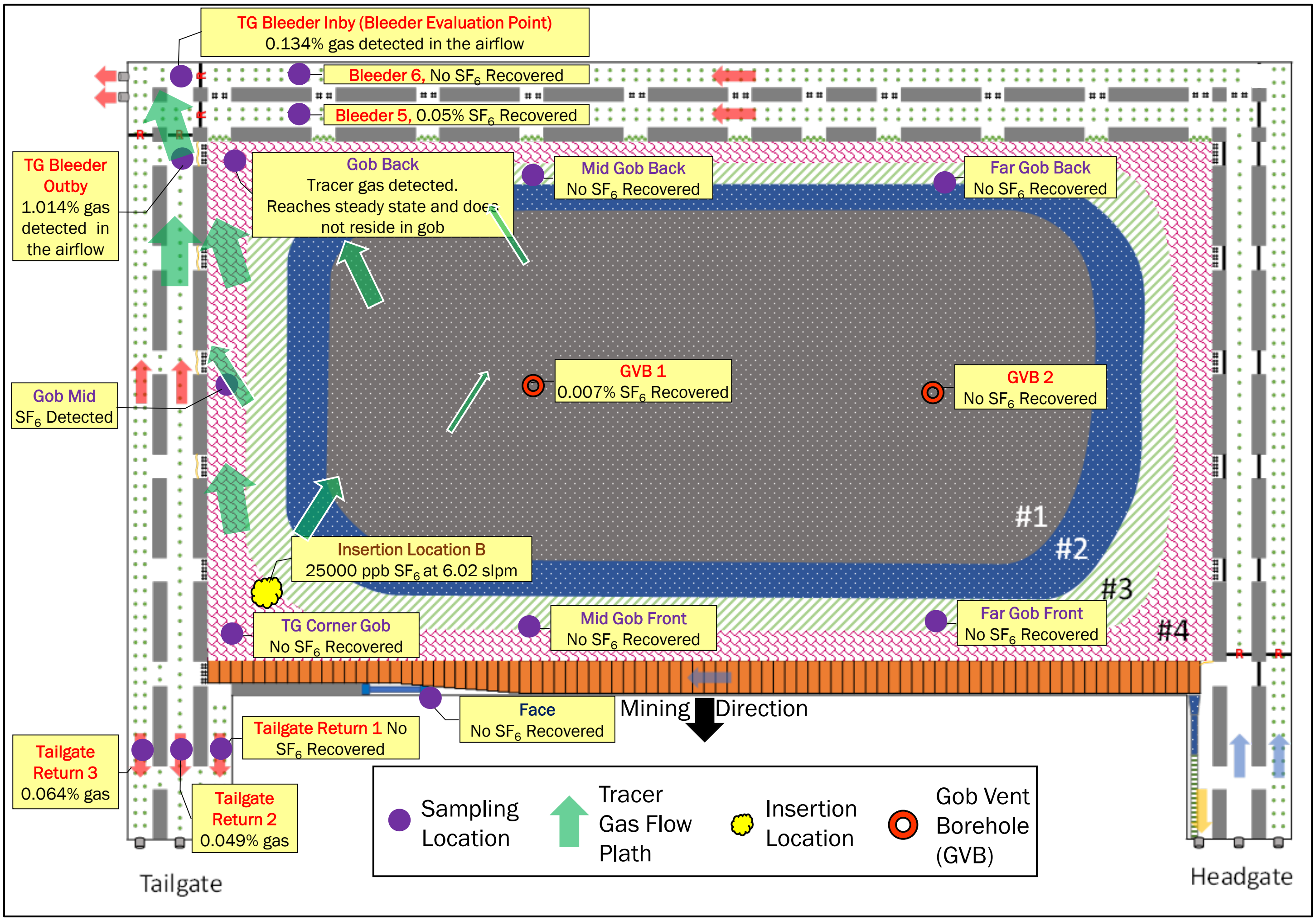

Figure 4. Schematic showing flow pattern of breached shale gas and sampling locations for breach based on CFD modeling.