IMPLICATIONS OF RECENT NIOSH TRACER GAS STUDIES ON BLEEDER AND GOB GAS VENTILATION DESIGN

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) has been conducting research at a Pittsburgh Coalbed longwall mine to evaluate and optimize bleeder ventilation and gob gas venthole longwall methane control systems. Gas flow into these two methane control systems was investigated using a combination of Sulphur Hexafluoride (SF_6) tracer gas studies and gob venthole pressure monitoring experiments. The insights gained from this research has facilitated the development of a longwall subsided strata methane control system conceptual model. This model provides the basis for design suggestions to increase the efficiency of the gob gas venthole system to permit the bleeder ventilation system to become a "safety net" for methane control.

INTRODUCTION

As part of its Mine Safety and Health research program, the National Institute for Occupational Safety and Health's (NIOSH) Pittsburgh Research Laboratory is investigating methane emissions associated with underground coal mining. The current focus of this research program is to develop a better understanding of the influence of geology, mining and ventilation practices, and methane drainage on the release and migration of methane gas during longwall mining. Papers by Diamond and Garcia (1999), Diamond, et al. (1992, 1994), McCall, et al. (1993), and Schatzel, et al. (1992) document previous research results. The objective of the current phase of the research is to measure gas migration characteristics associated with longwall subsided strata (commonly referred to as gob) using a tracer gas to simulate methane flows. Preliminary results for the current phase of the research can be found in Diamond, et al. (1999) and Schatzel, et al. (1999). The knowledge gained from this research will be used to optimize longwall methane control strategies to intercept a larger portion of the gas associated with the subsided strata over a mined-out longwall panel before it enters the underground workplace.

Research completed to date includes seven SF_6 tracer gas releases into underground ventilation airways between mined-out longwall panels and seven releases into inactive (intaking) gob gas ventholes. This combination of release modes allowed for a comprehensive evaluation of the interaction (or lack thereof) between gob gas ventholes and the ventilation system and between individual gob gas ventholes on the same longwall panel. Implications of the tracer gas study results on the design of longwall methane control systems are the focus of this paper.

The research results reported in this paper are based on work conducted at a longwall mine operating in the Pittsburgh Coalbed. Therefore, some of the conclusions that follow may be specific only to that mine site and perhaps to other mines operating in the Pittsburgh Coalbed under similar mining and geologic conditions. However, it is reasonable to assume that a number of the generalizations and concepts may have at least some degree of application to other mines in other coalbeds.

BACKGROUND

Historically, the retreat mining process at many mines produced high quantities of methane and, therefore, posed a potential risk for a major mine explosion; the most feared and devastating workplace disaster faced by underground coal miners. Bleeder ventilation and methane drainage systems have been developed and refined to move methane away from areas of the mine with high potential for ignition sources through areas or conduits with a very low potential for ignition sources, and finally out of the mine. Bleeder ventilation systems were originally designed to dilute methane liberated from the subsided strata with ventilating air at key points to maintain methane concentrations below statutory limits. The main mine ventilation system and the bleeder ventilation systems had to mesh flawlessly for a mine to operate safely from a methane control perspective. Functionally, the bleeder systems rely on diluting the gas sufficiently below its explosive range, while methane drainage systems typically maintain the gas at high percentages well above the explosive range during transport.

Longwall methane control in the study area includes the bleeder ventilation system and gob gas ventholes. The bleeder ventilation system, as used in this paper, includes the peripheral bleeder entries surrounding the panel series, the former gateroads between the mined-out panels, and the associated bleeder fan shaft(s). Current state-of-the art bleeder ventilation systems are a significant safety and technological improvement over earlier bleeder systems, such as the "wrap-around" systems. The state-of-the-art longwall bleeder ventilation system that has evolved at many mines today now relies on dedicated high pressure bleeder fans to exhaust the air and gases present in the bleeder system. This partial separation of the bleeder system from the main mine ventilation system apparently grew out of difficulties associated with providing sufficient air quantities and pressures with the main mine fans to consistently dilute the methane liberated from the subsided strata. The bleeder fans in the primary study area (BF2 and BF3, Figure 1) are at the top of 1.8-m (6-ft) -diameter air shafts. The shaft for the higher capacity bleeder fan in the new mining area (BF4) is slightly larger [2.1 m (7 ft) diameter].

Beginning in the late 1960's, some coal mines in the eastern United States began experimenting with the use of small-diameter ventholes drilled from the surface and equipped with high pressure centrifugal fans or exhausters to help control the high volumes of methane released from the subsided strata during longwall mining (Diamond, 1994). Removing methane directly from the subsided strata to the surface before it could enter the bleeder system was a major safety innovation. Commonly at this study mine, three ventholes are placed on the tailgate side of each panel in the near-margin configuration developed in earlier research efforts by Diamond et al. (1994), and the exhausters are powered by the produced methane.

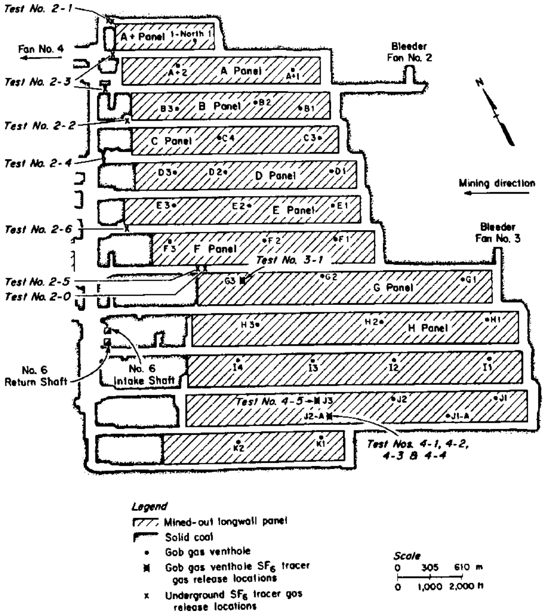

Figure 1. Map of primary study area.

The bleeder ventilation and gob gas venthole methane control systems (if properly designed and maintained) work well together and provide a much higher measure of safety than in the past. While these improved methane control systems represent significant advances over previous practices, analysis of the concepts and insights on the behavior of longwall subsided strata gas resulting from recent NIOSH investigations indicate that their performance from both a safety and efficiency standpoint can be improved even further.

While the study mine rarely experienced methane control problems, some mines using bleeder ventilation and gob gas venthole systems have, on occasion, had problems meeting statutory methane concentration limits at some point(s) underground and/or at the bleeder fans. Assuming that these "out-of-compliance" problems, even if rare, are indicative of a lesser margin of safety, a methane control system that minimizes the risk for such events would undoubtedly lead to a safer underground workplace. Therefore, throughout this paper the concept is advanced that methane flow from the subsided strata into a bleeder system can be minimized by optimizing the performance of the gob gas venthole system. Thus, the bleeder system can function as a "safety net" in the event of unforeseen or unanticipated methane emission/control problems.

Conceptually, the bleeder ventilation system "safety net" would surround the gob gas venthole methane control system which would function as the primary system to control gas emissions from the subsided strata.

Another safety issue behind some of the methane control concepts in this paper is to not only have less methane reaching and being exhausted by the bleeder ventilation system, but also to minimize the aerial extent of the interface zone between the bleeder ventilation system (usually low methane concentration, yet high oxygen), and the gob gas venthole system (high methane). While these interface zones are typically in locations which generally have a low probability for ignition sources, minimizing their aerial extent would obviously result in a safer methane control system. The conceptual model and design suggestions that follow, attempt to advance an overall longwall methane control system that takes into account the following concepts as guidelines (1) the "bleeder ventilation system as a safety net," and (2) "minimizing the aerial extent of the interface between the two methane control systems in the subsided strata" by limiting the interactions between the two systems.

STUDY AREA

The study mine operates in the Pittsburgh Coalbed in Greene County, PA. Longwall panels in the primary study area (Figure 1) were initially 253 m (830 ft) wide and were increased to 305 m (1,000 ft) starting with F Panel. Overburden depths ranged between 152 and 274 m (500 and 900 ft). A new mining area at the mine where the latest gob gas venthole injection experiment was conducted (3 North Panel) is located north-northeast of the area shown in Figure 1. A generalized stratigraphic section of strata above the Pittsburgh Coalbed is shown in Figure 2. Several coalbeds with a combined thickness of almost 2.9 m (10 ft) are present in the 26 m (85 ft) of strata immediately above the Pittsburgh Coalbed, and based on previous research (Diamond, et al., 1992), are most likely the primary source of subsided strata gas at the study mine.

GAS ASSOCIATED WITH LONGWALL MINING

As will be further developed, the bleeder ventilation and gob gas venthole systems are treated as separate but related components of the overall longwall methane control system. To understand the development of the longwall subsided strata methane control conceptual model in this paper, it is important to review the source and pathways of gas movement associated with longwall mining.

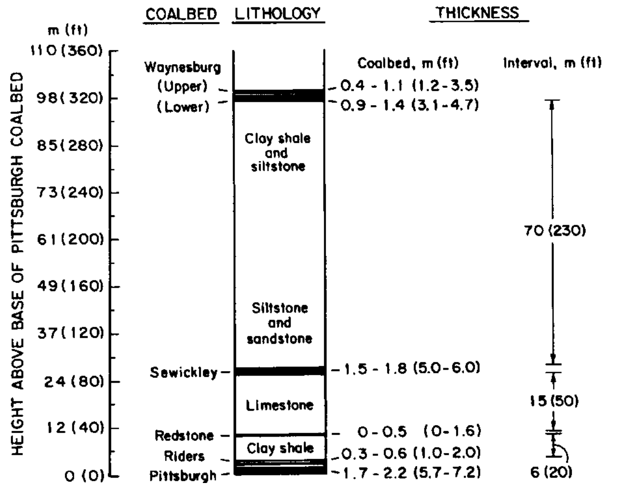

Figure 2. Generalized stratigraphic section for study area.

Gas Emissions from the Ribs Surrounding the Bleeder Ventilation System

This methane source originates from the unmined coalbed gas reservoir adjacent to the development entries of the bleeder system and is emitted from the solid coal ribs. Emissions from a specific rib area generally decline with time after development mining. However, the continual addition of freshly mined coal surface area as new panels are progressively developed makes the cumulative effects of these emissions at some mines (including the study mine), a significant contributor of gas to the bleeder ventilation system. Other than utilizing vertical methane drainage boreholes in advance of mining or horizontal holes during mining, there is little that can be done about this methane emission source. Therefore, it is considered "residual" bleeder system gas in the longwall methane control conceptual model.

Gas Emissions from the Active Longwall Face

Mining of the longwall face is another obvious potential source for methane entering the bleeder ventilation system. Methane from the face area includes both the gas in the mined coal itself as well as methane being emitted from the fresh face on the longwall (Diamond and Garcia, 1999). If, during the early phases of mining on the longwall panel, the face ventilation airflow is directed inby to the bleeder fan (as the study mine does), then gas associated with mining on the face will report to the bleeder system until the face ventilation is switched to outby, and is directed to the main mine ventilation system. Other than using methane drainage in advance of mining, there is little that can be done to reduce this volume of methane reporting to the bleeder ventilation system. The inby ventilation mode is sometimes used due to the high ventilation resistance of today's long tailgate entries which is often exacerbated by the high resistance of current tailgate support configurations (Barczak, et al., 1999).

Gas Emissions from Subsided Strata

The final source for methane associated with longwall mining is that which originates or accumulates in the subsided strata above the mined out longwall panel (Figure 3). This gas includes (1) methane released from the strata in the caved zone, in particular coalbeds, boney coal, and coaly shales, and (2) methane that migrates via mining induced fractures from gas bearing strata adjacent to the caved zone (both vertically and horizontally). Gas in the strata adjacent to the caved zone will migrate to one or the other longwall methane control system, depending on the relative magnitude of the pressure sinks associated with each system at a particular time and location.

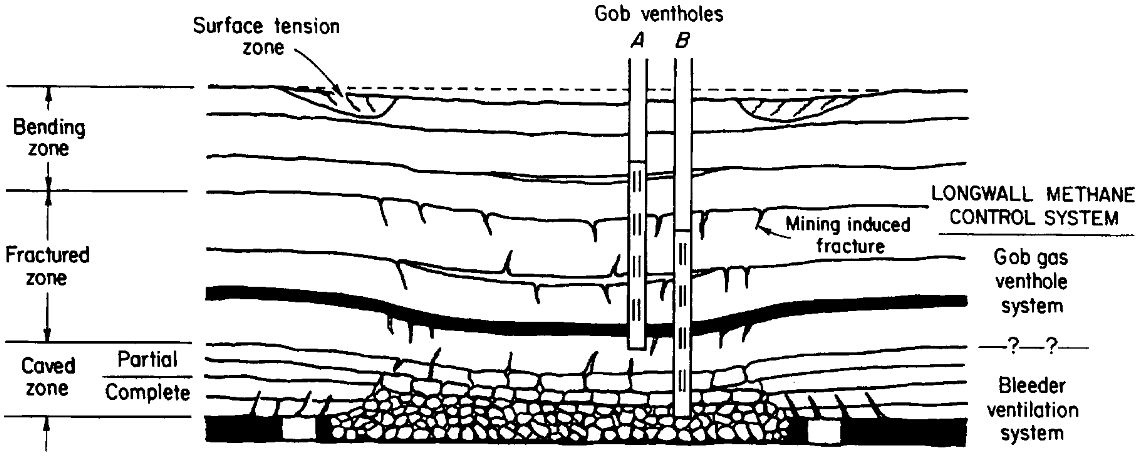

Figure 3. Schematic cross-section view of subsided strata zones and methane control system influence zones above mined-out longwall panel (modified from Peng and Chiang, 1984 and Singh and Kendorski, 1981).

Methane Production Distribution Between Longwall Methane Control Systems

All active gob gas ventholes in the primary study area collectively produced an average of 3.94 x 10^6 m^3 (139.0 MMcf) of methane per quarter during 1996 (the only extended time period with complete data sets available) (Figure 4). By comparison, methane production from the two bleeder fan shafts averaged 7.6 x 10^6 m^3/qtr (268.5 MMcf/qtr), or nearly double that of the gob gas ventholes. There is some evidence to suggest that methane reporting to the bleeder ventilation system was influenced by production variations in the gob gas venthole system, i.e., an increase or decrease in methane production from the gob gas ventholes was reflected in a corresponding decrease or increase, respectively, in methane production from the bleeder fan shafts.

Analysis of Historic Gob Gas Venthole Production Trends

One aspect of the gob gas venthole system at the study mine that can be exploited to increase its efficiency is understanding the areas of high and sustained gas inflows into the longwall subsided area. Inspection of the methane production curves for individual gob gas ventholes on individual panels in the study area suggests that ventholes on the start-up ends of the panels generally performed the best (Figure 5). To quantify this observation, the average gob gas venthole cumulative methane production by location on the panel (start-up end, center, and completion end) was plotted (Figure 6). It is quite evident that the average cumulative methane production from gob gas ventholes on the start-up end of the panels is by far the highest of the three general hole locations.

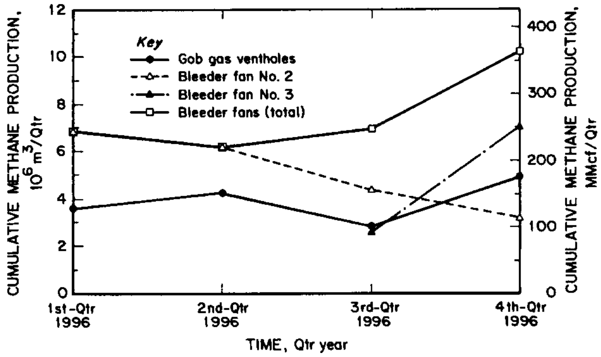

Figure 4. Methane production from both bleeder fans and active gob gas ventholes in primary study area.

In the sequence of panels at the study mine, the ventholes on the start-up end of the panels are also the ones adjacent to extensive virgin strata beyond the subsided strata zone. However, ventholes on the completion end of the panels are across the mains from previously mined panels (Figure 1), where subsided strata gas has already been exhausted. Typically, holes on the start-up end of the panels produce enough methane to operate the methane fueled engines running the exhausters for a long time, even well after the panel has been completed. After the methane concentration in the produced gas becomes insufficient to operate the exhausters efficiently (~45 to 55%), these same holes continue to free flow methane for an even longer time, unlike the outby holes on the same panels.

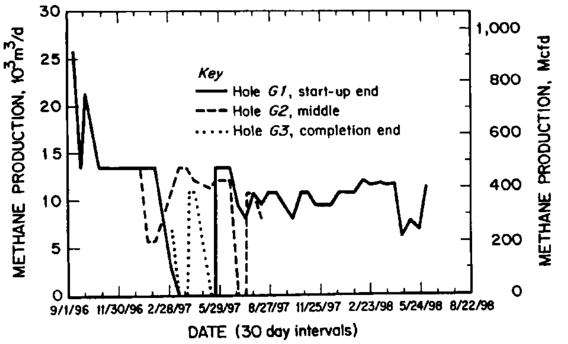

Figure 5. Methane production from G Panel gob gas ventholes.

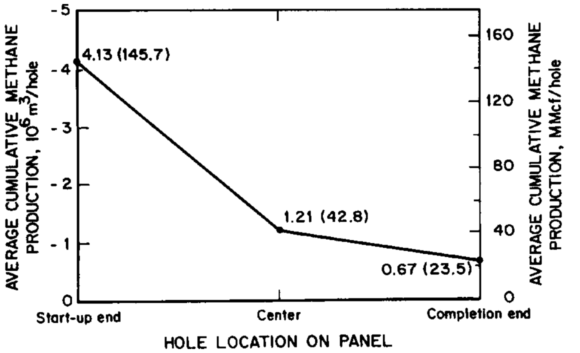

Figure 6. Average Cumulative gob gas venthole methane production by location on longwall panel.

The high initial and sustained methane flow rates for the first venthole on the start-up end of an active panel are easy to understand, given their location relative to the virgin (non subsided) strata gas reservoir. The early caving action of the overburden on a new longwall panel fractures into the strata beyond the start-up end and the headgate side of the panel. These mining induced fractures connect to the naturally occurring permeability of the surrounding virgin strata gas reservoirs. These strata gas reservoirs should be at a higher pressure than the strata immediately above and inby the face area as it progressively moves away from the start-up end of the panel, thereby providing a mechanism for additional gas flow to the pressure sink of the first gob gas venthole. Additional factors contributing to the high level of methane production from holes on the start-up end of the panels at the study mine include (1) ventholes on the start-up end of the panels are the first holes to come on production; therefore, they have a time advantage for longer term production, which generally results in higher cumulative gas production, and (2) a general flow direction for gas in the gob and ventilation airflow towards the startup end of the panels is established early by the presence of the first gob gas venthole on this end of the panels, as well as the bleeder fan shafts located at the back end of the panels.

In contrast to the gob gas production trends established at this study site, studies by Diamond et al. (1994) at the Cambria 33 Mine operating in the Lower Kittanning Coalbed, Cambria County, PA, showed that gob gas ventholes on both ends of the panels produced at the highest rates. The Cambria 33 Mine study demonstrated that given enough time, cumulative gob gas production from the holes on the completion end of the panels eventually caught up to that of holes on the start-up end of the panels. The primary difference between these two mine sites is that the Cambria 33 Mine did not use bleeder fan shafts on the back ends of the panels, but relied on the main mine fans for bleeder ventilation.

TRACER GAS STUDY RESULTS

Underground Releases

To properly design and operate a longwall methane control system, the action and interaction between the two main components, the bleeder ventilation system, and the gob gas venthole system must be understood. The first step towards characterizing this interaction was to conduct seven underground SF_6 tracer gas releases. The purpose of these releases was to assess a complete geographic distribution of the flow of air-gas mixtures within the bleeder ventilation system, including determining if any substantial portion of this airflow interacts directly with the gob gas venthole system. The tracer gas was released into the bleeder ventilation system airflow at the completion end of the panels (Figure 1), into or near the inlet evaluation points (IEP's). Ventilation airflow for this part of the mine was directed towards the back (start-up) ends of the panels where the two bleeder fan shafts are located.

The details of these releases have been reported elsewhere (Schatzel et al., 1999), however, the key findings from the underground tracer gas releases were:

- *-Paths of the tracer gas in the bleeder ventilation system were along the peripheral bleeder entries surrounding the panel series or* *apparently along the gateroads between panels.*

- *-Tracer gas injected into the ventilation airflow in the bleeder system generally stayed in the bleeder system and reported to the associated bleeder fan.*
- *-Only minor amounts of tracer gas were detected at operating gob gas ventholes on three occasions (maximum recovery was 0.7% of released volume).*

Venthole Injections

A series of seven tracer gas injections were performed into selected gob gas ventholes on G, J and 3 North Panels to further characterize the interaction between the bleeder ventilation system and the gob gas venthole system. Another goal of the venthole injection tests was to characterize the factors influencing the flow of gas within the subsided strata area itself.

Gob gas ventholes at this mine site are generally drilled to within 12 m (40 ft) of the top of the Pittsburgh Coalbed and 17.8-cm (7-in) casing, with 61 m (200 ft) of slotted pipe on the bottom is installed, as shown in Figure 7. For the venthole injection tests, the SF_6 tracer gas is released through tubing extended some distance down the venthole. The venthole, which must intake for the injection test, is open to the atmosphere during the injection to facilitate the mixing and dilution of the tracer gas to a sufficiently low concentration to simulate the flow of the host air stream (Timko et al., 1986). The monitoring strategy for the venthole injection tests included collecting periodic gas samples at all outlet points for the most likely migration path(s) for the tracer gas. The samples were analyzed with a gas chromatograph for the presence and concentration of SF_6. The monitored outlet points generally included the bleeder fans and producing gob gas ventholes associated with each injection test. Surface shut-in pressures and methane flow rates for key ventholes associated with the injections were also monitored to further evaluate the ventilation mechanics of the subsided strata gas reservoir.

The details of the G Panel gob gas venthole injection test have been published previously by Diamond et al. (1999), and the details of the six additional tests will be reported in a forthcoming NIOSH publication. A summary of the venthole SF_6 injection tests follows.

G Panel Venthole Injection, Test 3-1: The injection venthole G3 is located on the tailgate side of the panel near the completion end (Figure 8). At the time of the test, venthole G3 was off production, but the two inby ventholes G2 and G1 were online.

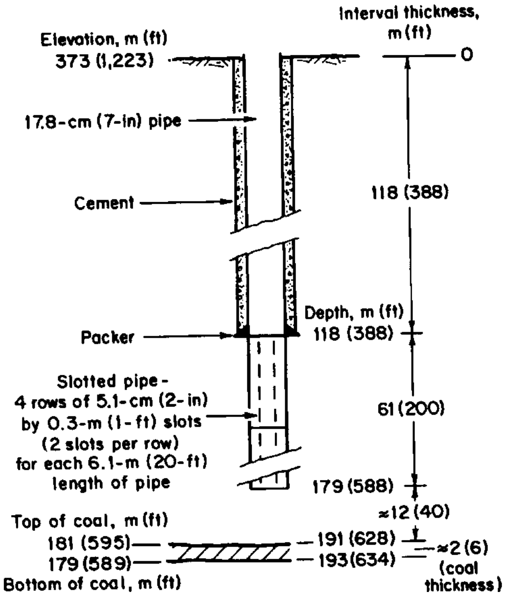

Figure 7. Schematic of gob gas venthole G3 configuration.

TRACER GAS RESULTS: Data relative to the tracer gas first arrival and peak concentration at the monitored locations, as well as the calculated velocity between the injection venthole and the recovery points, are shown in Table 1. Tracer gas from the G3 injection was recovered sequentially from the two inby producing ventholes on the panel (Figure 9). Tracer gas was first detected at G2, 1.1 days (27 h) after the release [velocity of 0.008 m/s (1.5 ft/min)], and was detected next at G1, 15.3 days after the release [the velocity of 0.002 m/s (0.3 ft/min) was influenced by G1 being off production for 8 days prior to the SF_6 arrival]. The only other confirmed location to which tracer gas migrated from the G3 venthole injection experiment was at the associated bleeder fan shaft (Figure 1). The arrival of tracer gas at BF2 on day 30 after the release is probably directly related to gob gas venthole G2 going off production on day 25 of the test (Figure 9).

G3 SHUT-IN PRESSURE MONITORING RESULTS: As can be seen in the G3 shut-in pressure monitoring data (Figure 10), variations in gas production at G1 and/or G2 influenced the shut-in pressure at G3. The venthole exhausters at this mine typically operate at between 3.733 and 9.954 kPa (15 and 40 in w.g.), as measured at the top of the venthole. It is evident from Figure 10 that gas production variations at G1 were reflected in the gas production rates at G2 and the shut-in pressure at G3, i.e., when G1 was offline, the gas production at G2 increased and the shut-in pressure at G3 rose (became less negative). Similar influences are evident when G2 was offline, i.e., a slight increase in gas production at G1, and the shut-in pressure at G3 rose.

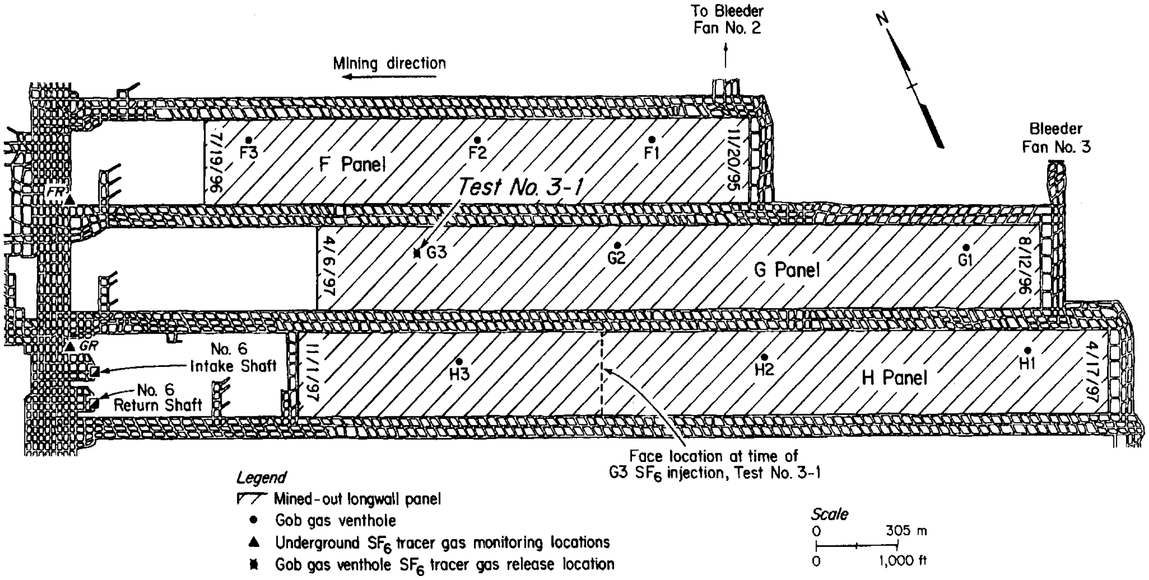

Figure 8. Detailed map of F, G, and H longwall panel area at time of the G3 gob gas venthole tracer gas injection test.

Table 1. Borehole to borehole tracer gas velocities (first arrival) and tracer gas peak data

Test no.	Flow path (time since gob hole mine-through)	Horizontal distance, m (ft)	1st arrival time, min	Velocity, m/s (ft/min)	Peak		
					Conc. ppb	Test day	Days after 1st arrival
3-1	G3 (5mo) - G2 (6 mo)	2,500	1,621	0.008 (1.5)	1.3	7.1	6.0
	G3 (5mo) - G1 (8 mo)	6,800	22,399	0.002 (0.3)	43.7	25.1	9.8
	G3 (5mo) - G1 (8 mo)	6,800	10,436[1]	0.004 (0.7)	43.7	25.1	9.8
	G3 (5mo) - BF2	NA	30 days	NA	0.25	35.0	5.0
4-1	J2A (1.5 mo) - J2 (2.5 mo)	2,000	677	0.015 (3.0)	119	2.0	1.5
	J2A (1.5 mo) - J1 (4.8 mo)	5,100	1,423	0.018 (3.6)	267	3.0	2.0
4-2	J2A (2.9 mo) - J2 (3.8 mo)	2,000	748	0.014 (2.7)	223	2.2	1.7
	J2A (2.9 mo) - J1 (6.2 mo)	5,100	2,068	0.013 (2.5)	558	4.0	2.6
4-3	J2A (6.4 mo) - J1 (9.7 mo)	5,100	1,568	0.017 (3.3)	1,390	4.1	3.0
	J2A (6.4 mo) - J1A (8.8 mo)	3,600	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]
4-4	J2A (7.1 mo) - J1A (9.4 mo)	3,600	1,213	0.015 (3.0)	2,423	3.1	2.3
4-5	J3 (7.2 mo) - J1A (10.9 mo)	5,450	3,958	0.007 (1.4)	759	6.0	3.2
4-6	2NE-1A (2.2 mo) - BF4	270[3]	43[4]	0.032 (6.3)	186	3 hr 22 min	2 hr 34 min
	2NE-1A (2.2 mo) - 2NE-4 (1.9 mo)	1,845	669	0.014 (2.8)	198	2.0[5]	1.5[5]

NA = Not applicable

[1] Subtacting time J1 off production before arrival.

[2] Hole J1A started on day 5.9 of test.

[3] Distance from gob hole to tailgate entries.

[4] Estimated time to reach tailgate entry (5 min subtracted from actual 48 min travel time to BF4).

[5] Gob hole off production for ~14 hrs (~day 1.014 to day 1.597).

The 0.622 kPa (2.5 in w.g.) shut-in pressure differential observed at G3 when G1 was offline and G2 stayed on production is an estimate of the contribution the exhauster on G1 had on the -2.488 kPa (- 10.0 in w. g.) of shut-in pressure when both G1 and G2 were producing gob gas (Figure 10). The resulting pressure differential of 1.493 kPa (6.0 in w.g.) when G2 is offline and G1 was operating is then a measure of the contribution the exhauster on G2 had on the -2.488 kPa (10.0 in w.g.) of shut-in pressure at G3. The larger contribution of the exhauster on hole G2, as compared to G1, to the observed shut-in pressure at G3 is due to G2 being 1,311 m (4,300 ft) closer to G3 than is G1 and the higher total gas production from venthole G2 at the time of the test. Venthole G2 was permanently off production on day 26, resulting in a sustained rise in shut-in pressure at G3 to an average of about -0.995 kPa (-4.0 in w.g.), which represents the combined influence of the exhauster on G1 and the bleeder fans. Since the influence of G1 was calculated to be 0.622 kPa (2.5 in w.g.), the contribution from the bleeder fans is then only 0.373 kPa (1.5 in w.g.) of the -0.995 kPa (-4.0 in w.g.) of shut-in pressure at G3. BF2 and BF3 were operating at approximately 4.230 and 3.235 kPa (17 and 13 in w.g.), respectively.

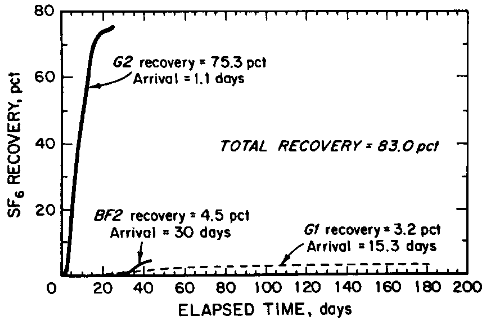

Figure 9. SF_6 tracer gas cumulative recoveries from gob gas venthole injection Test 3-1.

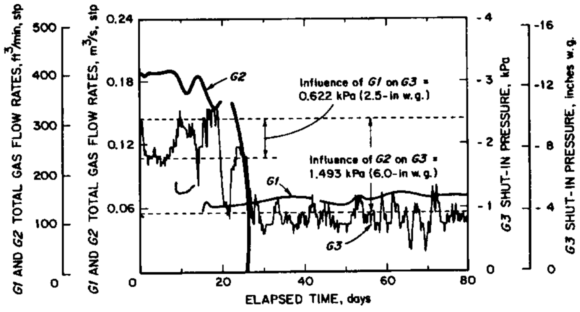

Figure 10. Influence of gob gas venthole production on G3 shut-in pressure.

KEY FINDINGS, G PANEL VENTHOLE INJECTION TEST:

- *-Most of the tracer gas injected into the gob gas venthole system at G3 stayed in the subside strata and was recovered at the inby producing ventholes.*
- *-The recovery of tracer gas at the bleeder fan is probably directly associated with venthole G2 going off production 5 days before the arrival of tracer gas at BF2.*
- *-All three ventholes on G panel were in communication with each other as evidenced by the tracer gas arriving sequentially at the two inby producing ventholes. This was also substantiated by fluctuations in the shut-in pressure measurements at G3 in response to production variations at the two inby ventholes.*
- *-The G3 shut-in pressure monitoring data indicate that the producing gob gas ventholes on G Panel had a greater influence on the shut-in pressure than did the bleeder ventilation system.*
- *-Based on venthole injection Test 3-1 it can be concluded that the portion of the subsided strata gas primarily influenced by the gob gas venthole system tended to report to that system, and not to the bleeder ventilation system, as long as the gob gas ventholes that were capable of producing methane at concentrations sufficient to run the methane fueled engines were operating.*

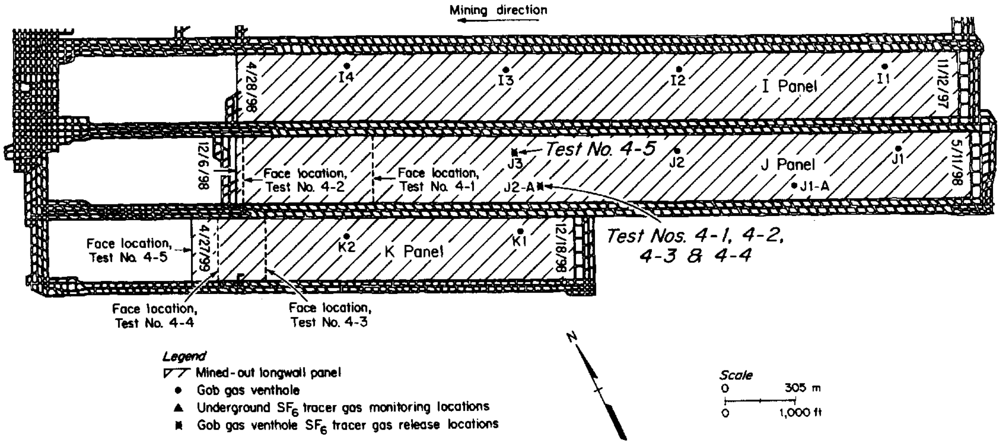

Figure 11. Detailed map of I, J, and K longwall panel area at time of the J Panel gob gas venthole tracer gas injection tests.

J Panel Venthole Injections: Five venthole tracer gas injection tests were conducted on J Panel (Figure 11) over a six month period. The placement of the five gob gas ventholes on J Panel presented a unique opportunity to investigate several aspects of gas flow in longwall subsided strata. Three of the holes were placed in the traditional configuration on the tailgate side of the panel, and the other two holes were placed on the headgate side of the panel. The first two venthole injection tests on J Panel were designed to test the ability for gas to migrate across the centerline of this super critical panel. A super critical panel, as used here, is one in which the panel width is greater than the height of the overburden, which results in a more complete caving of the overburden strata into the mine void (Figure 12). The remaining three venthole injection tests on J Panel were designed to characterize other potential gob gas flow paths, including those along the tailgate and headgate sides of the panel. Summary data for the J Panel venthole injection tests is given in Table 1.

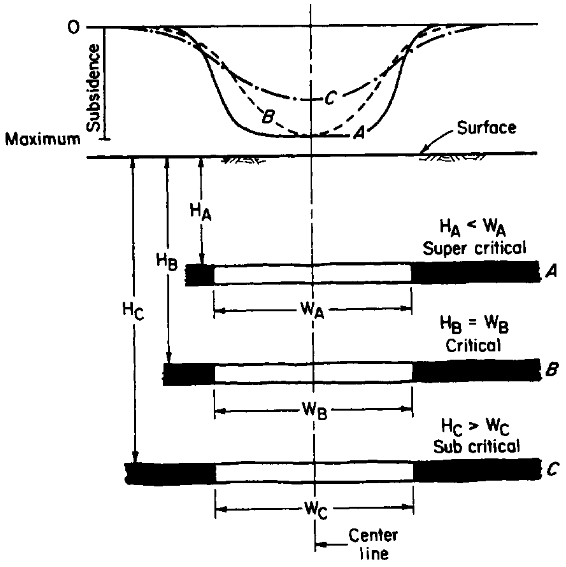

Figure 12. Schematic cross-section view of super critical, critical, and sub critical longwall panels (modified from Jeran and Barton, 1985).

TEST 4-1 AND 4-2 RESULTS: Many longwall mines have adopted the near-margin gob gas venthole placement concept reported by Diamond, et al. (1994). However, as longwall panels have steadily increased in size, the ability for gas to efficiently flow from the headgate side of a panel to gob gas ventholes placed on the tailgate side of a super critical longwall panel came into question. Gob gas venthole tracer gas injection Tests 4-1 and 4-2 were designed to investigate this concern. Tracer gas was injected into venthole J2-A on the headgate side of J Panel, with only two ventholes (J2 and J1) on the tailgate side of the panel operating (Figure 11). Tracer gas was recovered sequentially at the two inby producing gob gas ventholes on the tailgate side of the panel during both Test 4-1 and Test 4-2, conducted 41 days apart (Figures 13 and 14). The migration time for tracer gas to reach the two inby producing ventholes increased only moderately (by 1.2 hours to J2 and 10.8 hours to J1) from the first to second test. These results suggest that there is little, if any, impediment to gas flow across the super critical panels at the study mine.

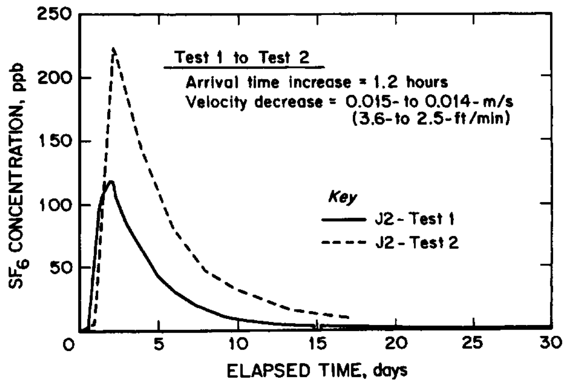

Figure 13. SF_6 tracer gas concentration curves at gob gas venthole J2, Tests 4-1 and 4-2.

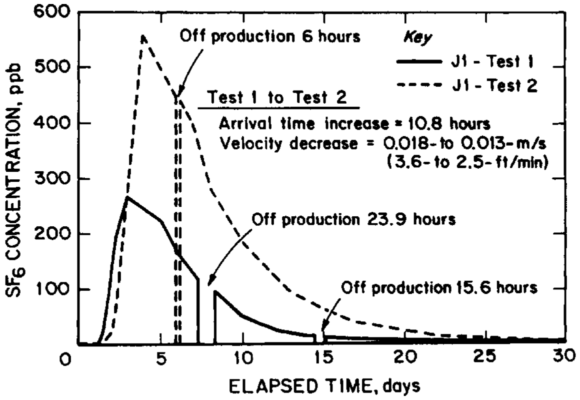

Figure 14. SF_6 tracer gas concentration curves at gob gas venthole J1, Tests 4-1 and 4-2.

The only other monitored location where tracer gas was detected was at BF3. Tracer gas reached the BF3 location on day 7.8 of Test 4-1, just 12 hours after venthole J1 went off production for approximately 1 day. As was the case with tracer gas being detected at BF2 during the G Panel venthole injection test, the presence of tracer gas in the ventilation system during the first J Panel venthole injection is believed to be directly related to one of the producing gob gas ventholes (J1) going off production.

One additional experiment of note conducted at the end of Test 4-2 was to start venthole J1A, 1,097 m (3,600 ft) inby the J2A injection hole on the headgate side of J Panel to determine if tracer gas was present at this location, even though the recovery points for the test indicated a general gas flow direction across the panel to the tailgate side. Tracer gas was detected immediately after venthole J1A was started on day 22 of Test 4-2.

TEST 4-3 RESULTS: The next J2A venthole injection (Test 4-3) was conducted 3.5 months after the Test 4-2 SF_6 injection. Only venthole J1 was running at the start of Test 4-3. Venthole J2 had gone off production permanently on day 19 of Test 4-2, and was never restarted. Tracer gas was detected at venthole J1, 26. 1 hours after the release, or 8.4 hours sooner than during Test 4-2, when ventholes J2 and J1 were both running. The velocity of 0.017 m/s (3.3 ft/min) falls between the 0.018 m/s (3.6 ft/min) and 0.0 13 m/s (2.5 ft/min) values calculated for Tests 4-1 and 4-2, respectively (Table 1). Potential explanations for the observed faster migration time to J1 during Test 4-3 would include (1) a more direct physical "connection" between J2A and J1 than between J2A and J2, (2) a more efficient (higher permeability) tracer gas flow path along the headgate side of the panel, around the startup end of the panel to J1 on the tailgate side, (3) the operating vacuum pressure on J1 had been sufficiently greater than that on J2 [9.954 kPa vs 3.981 kPa (- 40 in w.g. vs. -16 in w.g.)] so that the dominant gas flow path was towards J1, and when J2 was running, it only exerted enough influence to slow the velocity towards J1, and (4) some combination of the first three explanations.

One additional experiment of note conducted during Test 4-3 was the restarting of venthole J1A on day 5.9 to determine if tracer gas was present in that area on the headgate side of the panel. As was seen in the earlier experiment at the end of Test 4-2, tracer gas was detected in the produced gas immediately after starting venthole J1A. These data (and the headgate gas flow velocity for the subsequent Test 4-4) would seem to support the potential for a higher permeability gas flow path along the headgate side of J Panel to the producing venthole J1 on the tailgate. Alternatively, it could indicate a very wide flow path through the gob.

TEST 4-4 RESULTS: Test 4-4 was designed to determine the velocity for gob gas flow along the headgate side of J Panel. This SF_6 injection into venthole J2A was conducted with only venthole J1A operating. Tracer gas reached venthole J1A in 20.2 hours for a velocity of 0.0 15 m/s (3.0 ft/min). This velocity for gas flow along the headgate of J Panel was double the velocity along the tailgate of G Panel [(.007 m/s (1.5 ft/min)].

TEST 4-5 RESULTS: This test was designed to determine the velocity for gob gas flow along the tailgate side of J Panel. For this test scenario, tracer gas was injected into venthole J3 for the first time, with only venthole J1 operating (Figure 11). The tracer gas arrival at venthole J1 was at 2.7 days for a velocity of 0.007 m/s (1.4 ft/min). This is a value almost identical to that for the G Panel tailgate velocity test [0.007 m/s (1.5 ft/min)].

KEY FINDINGS, J PANEL VENTHOLE INJECTION TESTS: The key findings from the G Panel venthole injection test were reconfirmed and in some cases amplified.

- *-Tracer gas injected into the subsided strata on J Panel was produced by the J Panel gob gas venthole system, and only migrated to the bleeder ventilation system in response to a producing gob gas venthole going offline.*
- *-Tracer gas injected into the subsided strata on the headgate side of this super critical panel migrated to producing gob gas ventholes on the tailgate side of the panel.*
- *-Tracer gas flow velocity along the tailgate side of J Panel was essentially the same as that of G Panel. Tracer gas flow velocity along the headgate side of J Panel was double that of the tailgate side.*
- *-Tracer gas appeared to move freely through the J Panel subsided strata to the most negative pressure sinks, indicating an effective mining induced fracture system with relatively high permeability to gas flow.*

3 North Panel Venthole Injection: The final gob gas venthole injection experiment was conducted on the first longwall panel in a new mining area at the study mine (Figure 15). The new panel (3 North) is approximately 6 km (3.7 mi) north-northeast of J panel (Figure 1). Test 4-6 was prompted by reports from the mine that the performance of the gob gas ventholes on this new panel was substandard, and the holes were not on production. One possible explanation to be investigated was that with such a small mining area to act on, the high capacity fan [4.479 kPa (18 in w.g.)] installed on the bleeder fan (BF4) was actually overwhelming the gob gas venthole methane control system, and pulling gob gas away from the ventholes. A production test on the first venthole on the panel (2NE-4) yielded a typical methane concentration approaching 75% when the hole was started with propane. Based on the production test results, it did not appear that the bleeder fan was overwhelming the gob gas venthole methane control system, as originally speculated, and the reported production problems were mechanical in nature. Evaluation of the conditions at the second hole on the panel (2NE-1A) revealed that it was capable of intaking when opened. A tracer gas injection test into hole 2NE-IA was designed to further evaluate the gas flow characteristics of this first panel in the new mining area.

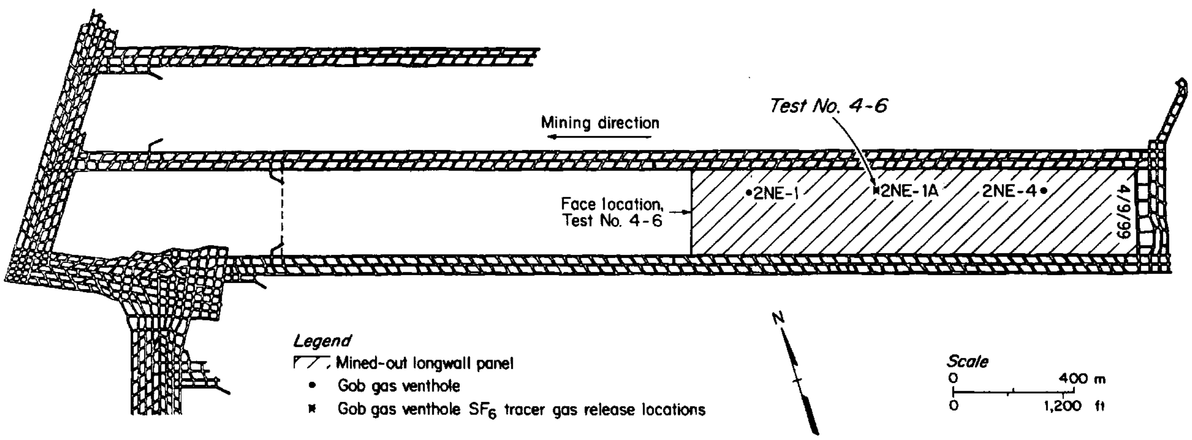

Figure 15. Detailed mine map of 3 North Panel at time of the 2NE-1A gob gas venthole tracer gas injection test.

TEST 4-6 RESULTS: This test was an SF_6 injection into venthole 2NE-1A, with only the inby venthole 2NE-4 operating. The first place tracer gas was detected after the 2NE-1A injection was at BF4 (Figure 16). Tracer gas reached this location in only 48 minutes. The calculated velocity for gas to flow the 82 m (270 ft) from the injection hole to the bleeder ventilation system is then 0.032 m/sec (6.3 ft/min) (Table 1). This velocity is higher than that of any other venthole injection test. This was also the only test where tracer gas from a venthole injection reached the bleeder system before being detected at a producing venthole on the test panel.

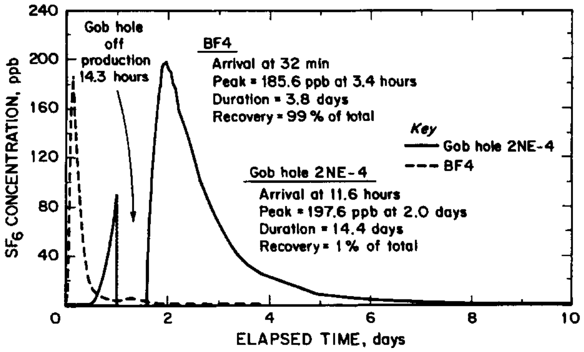

Figure 16. SF_6 tracer gas concentration curves, Test 4-6.

The tracer gas from Test 4-6 also reached the inby producing venthole 2NE-4. Based on the arrival time of 11.2 hours (Table 1), the velocity along the tailgate side of this panel is 0.014 m/sec (2.8 ft/min), almost double the velocities calculated for G and J panel tailgates. The 0.014 m/sec (2.8 ft/min) velocity for the tailgate on the 3 North Panel is similar to that calculated for the J Panel headgate (Test 4-4, Table 1). It is postulated that the similar gas flow velocity results from these two tests (Tests 4-4 and 4-6) are due to the gas flow paths being in an area of enhanced mining induced fracture permeability due to their proximity to unmined adjacent areas (Figures 12 and 16), even though the tests were conducted on different sides of their respective panels. As can be seen on Figure 16, venthole 2NE-4 went off production for 0.6 days due to mechanical reasons at day 1 of the test. During this down time the SF_6 concentration, which previously had been steadily declining at BF4, rose slightly indicating an interaction between the two methane control systems.

As a result of the atypical findings from the venthole injection test on 3 North Panel, a production test was conducted on venthole 2 NE-1A to determine its capability for producing methane. Methane concentrations never reached 20%, in fact they declined slightly over the time of the test. The reason for this low methane concentration was an inadvertent error in the drilling and completion of venthole 2NE-1A to a depth approximately 14.6 m (47.8 ft) below the bottom of the Pittsburgh Coalbed. Once the section of slotted casing placed across the mined coalbed interval had been removed, approximately 43 m (140 ft) of slotted casing remained in the overlying roof strata, including the caved zone, as shown in Figure 3 (venthole B). Therefore, the 2NE-1A venthole configuration provided a direct link to the bleeder ventilation system which resulted in the atypical test results discussed above. Based on the caving height formula of Peng (1984) and bulking factors for the area provided by Chen (1999), a maximum mining height of 2.1 m (7 ft) would yield a maximum caving height (and estimate for the functional top of the bleeder ventilation system gas production zone) of 10.7 m (35 ft). The 10.7 m (35 ft) estimated caving height is a point below the typical bottom hole depth of the gob gas ventholes at the study mine (venthole A, Figure 3), thus supporting the conceptual model that the "typical" ventholes are generally producing gas from a subsided strata zone separate from the bleeder ventilation system.

KEY FINDINGS, 3 NORTH PANEL VENTHOLE INJECTION TEST:

- *-The venthole inadvertently drilled into the mined coalbed produced methane at low concentrations due to a reduced length of slotted casing in the fractured zone, and a greater influence of the bleeder system on the gas in the caved zone adjacent to the lower section of the slotted casing.*
- *-The venthole completed to a depth 12.2 m (40 ft) above the top of the mined coalbed produced methane at high concentrations indicating it was producing gas primarily from the subsided strata zone influenced by the gob gas venthole system.*
- *-The height of the caved zone (and the interface between the bleeder ventilation system and the gob gas venthole system) is below the typical completion depth of ventholes at the study mine site.*
- *-The two methane control systems are operating and extracting gas at two different levels in the subsided strata, with the bleeder ventilation system operating at the level of the mined out coalbed and the lower part of the caved zone, and the gob gas venthole system generally operating in the fractured zone and at the top of the caved zone.*

IMPLICATIONS OF TRACER GAS STUDIES FOR BLEEDER AND GOB GAS VENTHOLE SYSTEM DESIGN

The tracer gas study results presented in the previous discussions have been used to develop a conceptual longwall subsided strata methane control model. The insights for gas flow inherent in the conceptual model can be incorporated into the current state-of-the-art design practices for longwall methane control systems to produce a more efficient optimized system which would provide an increased margin of safety for the underground workforce.

Longwall Subsided Strata Methane Control Conceptual Model

The conceptual longwall subsided strata methane control model is as follows:

- *-The bleeder ventilation and gob gas venthole longwall methane control systems exhaust methane from different subsided strata zones.*
- *-In addition to the "residual" methane emissions from the ribs and active face area, the bleeder ventilation system exhausts methane primarily from the lower part of the caved strata zone in direct contact with the bleeder ventilation system around the periphery of the mined out panel.*
- *-The gob gas venthole system exhausts methane primarily from the upper caved and fractured strata zone, due in part to the layering effect of methane and the primary source of long term methane flow being in and adjacent to this zone.*
- *-An interface for methane/air mixtures exists between the two longwall methane control systems, but as long as both systems are operating efficiently, they are essentially operating independently.*
- *-Disruptions in methane production from the gob gas venthole system may move the interface between the two systems, i. e., gas previously exhausted by the gob gas venthole system will then flow to the bleeder ventilation system.*
- *-It may be possible to optimize gas production from the gob gas venthole system sufficiently by minimizing the interaction between the two methane control systems. Thus, the aerial extent of the interface between the two methane control systems is reduced and the bleeder ventilation system can then junction as a "safety net" for the longwall methane control system.*

Design Considerations for Optimized Longwall Methane Control Systems

Bleeder System: The design of the bleeder ventilation system envisioned for the longwall subsided strata methane control model is fairly straightforward using standard ventilation design principals and methods. Key aspects of the conceptual model are briefly summarized here, but the overall design of the bleeder ventilation system will be discussed in a forthcoming NIOSH publication. An important result of the tracer gas studies on bleeder system design is that for all panels in the bleeder system series, the bleeder fans must be capable of generating sufficient ventilating pressures at the front of the panels to induce flow to the back of the panels, as was the case at the study mine.

The studies also indicate that given the minimal interaction of the bleeder ventilation and gob gas venthole systems at the study mine, ventilation quantities along old gateroads can diminish, over time and with panel age, without deleterious effects. This assumes that the gob gas venthole system is adequate to handle the gas inflows into the upper subsided strata zone. It also assumes that the bleeder ventilation system would be capable of delivering the required air flow quantity and, therefore, ventilating pressures, at the desired points in the system where most needed, e.g. near or at the active panel where higher levels of emissions are occurring (Figure 17). Obviously, under sizing of the bleeder ventilation system from a ventilation air flow quantity and pressure standpoint can negatively impact compliance with statutory methane concentration levels in the bleeder entries or at the bleeder fan.

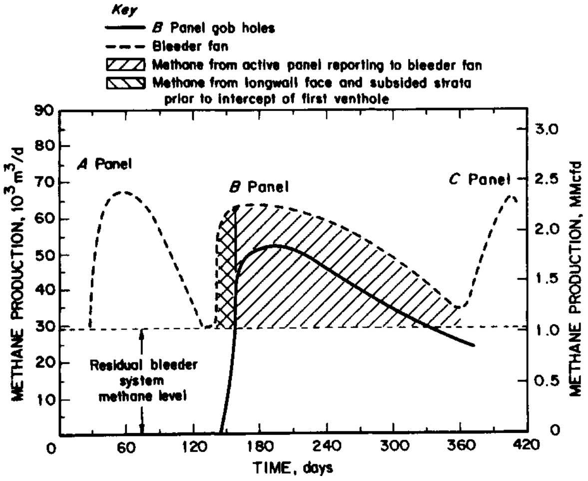

Figure 17. Conceptualized methane production curves for gob gas ventholes and bleeder fan associated with active longwall panel.

Gob Gas Ventholes: Design of gob gas venthole systems are not as straightforward as bleeder ventilation systems, which has provided the basic impetus for the present direction of NIOSH longwall methane control research. Most of the current gob gas venthole systems at individual mines have resulted from a trial-and-error design practice. Until the reservoir mechanics of longwall subsided strata and the interaction of the bleeder ventilation system and the gob gas venthole system are more completely understood, the trial-and-error approach will probably continue, aided by the type of research described in this paper.

One example of gob gas venthole design practice highlighted in the work at the study mine (3 North Panel venthole injection test) is that the completion depth of the gob gas ventholes should be at or above the height of the caving zone. It was determined that the typical completion depth for gob gas ventholes approximately 40 ft above the Pittsburgh coalbed accomplished two goals, (1) it protected the slotted casing from damage, and (2) it was high enough in the subsided strata to minimize the interaction between the two longwall methane control systems.

Changes in other design practices at the study mine might increase the overall efficiency of the gob gas venthole system. Typically at the study mine, gob gas ventholes at the start-up end of the panel initially run at a high volume with a fairly low head, and gradually shift to a lower volume at a relatively high head. Since a reasonably consistent flow velocity (permeability) in the gob gas venthole-influenced subsided strata zone on the tailgate side of longwall panels is indicated by the current study, it is assumed that the change in production characteristics with time is due to changes in the volume of methane available in the subsided strata. Coordinating gob gas venthole system production capacity with the volume of available gas is critical to minimize the interaction between the longwall methane control systems. Designing the gob gas venthole system for the expected range of production capacities is then the objective to be met to make the system operate more efficiently.

It is generally understood that if the gob gas venthole system capacity is operating at a production volume level higher than the methane inflow rate, then mine ventilation air is pulled into the gob gas venthole system, thereby reducing the methane concentration at the venthole. The methane concentration then becomes a gauge of this interaction, as was seen during Test 4-6. Conversely, if the volume of methane available in the subsided strata zone influenced by the gob gas venthole system is greater than the gob gas venthole system capacity, then more of this gas will enter the bleeder ventilation system. A number of the gob gas venthole tracer gas injection tests at this mine have verified these kinds of interactions. This rationale then provides additional guidelines for the design of gob gas venthole systems (1) the gob gas venthole system capacity must nearly equal or be adjustable to the volume of gas inflows into the system, and (2) sufficient monitoring and maintenance of the producing ventholes is critical to ensure that production of subsided strata methane is uninterrupted.

Figure 17 shows conceptualized methane production curves for a bleeder system and associated active panel gob gas venthole system based on data from the current study and previous work (Diamond, 1994, Diamond et al., 1994, and Diamond and Garcia, 1999). The major longwall methane control system design concerns are the rather sudden and large increase in methane production at the bleeder fan early in the life of the panel, and the sustained high level of methane inflow from the subsided strata during most of the life of the active panel. The initial high level of methane production from the bleeder ventilation system comes primarily from two sources (1) longwall face ventilation airflow reporting to the bleeder fan, and (2) newly subsided strata gas prior to intercept of the first gob gas venthole. Additional volumes of methane may report to the bleeder ventilation system after the first gob gas venthole is intercepted due to subsided strata gas inflows above the capacity of the gob gas venthole system. Optimizing the gob gas venthole system should reduce the volume of methane reporting to the bleeder ventilation system, i.e., an overall lowering of the bleeder fan methane production curve shown in Figure 17.

At the study mine, the longwall face air usually reports to the bleeder fan shaft for a relatively short period of time before the face ventilation is switched to outby, generally accounting for a relatively small portion of the total panel methane volume at the bleeder fan shaft. The subsided strata gas that reports to the bleeder fan shaft prior to interception of the first venthole is a significant source of gas. Typically at the study mine the first venthole is located 305 to 366 m (1,000 to 1,200 ft) from the start-up end of the panel. One way of decreasing the volume of subsided strata methane that reports to the bleeder fan shaft is to move the location of the first venthole closer to the start-up end of the panel. However, there is a practical limit as to how close to start-up the first gob gas venthole can be placed without being detrimental, i.e., it can't be so close to the start-up end that it is within the zone of influence of the bleeder ventilation system. Some mines operating in the Pocahontas No. 3 Coalbed in Virginia place ventholes as close as 30 to 46 m (100 to 150 ft) to the start-up end of the panel, however, they do experience high O_2 concentrations (R.E. Ray, Jr., Pers. Commun., 1999). The Mine Safety and Health Administration (1996) reports that the first gob gas venthole on a panel is generally drilled within 152 m (500 ft) of the start-up end. Some mines operating in the Pittsburgh Coalbed have successfully drilled their first ventholes as close as 76 m (250 ft) to panel start-up, so placing the first gob gas venthole closer to the start-up end of the panel is probably a viable option for the study mine.

Reducing the volume of methane entering the bleeder ventilation system due to an under capacity of the gob gas venthole system can probably be successfully addressed. A key design factor to achieve optimized performance from the ventholes is to allow for the variability in methane volumes available in the subsided strata as a function of time, and to some extent, position on the panel, as discussed above. A consideration for the study mine to evaluate is to increase the production capacity of the first hole on the panel by increasing the size and/or capacity of the gob gas venthole exhausters. The exhausters at the study mine are four stage centrifugal fans powered by diesel engines converted to operate on methane/propane mixtures. Quantities and pressures generated by the exhausters are quite variable and are a function of engine rpm, air/methane mixture percentages, air temperature and humidity, elevation above sea level (particularly at the higher elevations of some mines in the western United States), and system resistance. System resistance is mainly a function of the external plumbing, venthole diameter and depth, condition of the casing and surface piping, fracture permeability, and volume of gas inflow from the subsided strata. The current 17.8 cm (7 in) borehole diameter casing used at the study mine contributes little head losses to the system, however, this may not be true for deeper mines and/or mines producing higher volumes of gas.

A potential option for increasing the gas production capacity from the first venthole on the panel is to run two exhausters of the current design in parallel during the early stages of longwall panel coal production when gas inflows are generally higher. This configuration of the exhausters should give ample capacity for any conceivable level of gas inflows at the study mine site, and has been successfully implemented at some mines operating in the Pocahontas No. 3 Coalbed in Virginia (R.E. Ray, Jr., Pers. Commun., 1999).

A companion suggestion for optimizing the performance of the gob gas venthole system at the study mine is to consider eliminating the third (completion end) venthole on panels, since they have historically been poor producers (Figure 6). Based on the results of the tracer gas venthole injection tests and associated shut-in pressure monitoring experiments, eliminating the third venthole may be possible. Along with the elimination of the ventholes on the completion end of panels, the two exhausters on the first venthole may have to be reconfigured from the parallel arrangement into a series alignment (easily accomplished with minor surface plumbing changes). This would be implemented later in the panel's life to provide a greater pressure sink in the gob gas venthole system as the face progressively moves towards the completion end of the panel and the level of subsided strata gas inflow decreases.

The final consideration for optimizing the performance of the gob gas venthole system is related to monitoring and maintenance of the system. Earlier it was noted that the gob gas venthole and bleeder ventilation systems tended to not interact as long as the gob gas venthole system was operational, i.e., that all ventholes capable of producing methane at concentrations sufficient to run the methane fueled engines powering the exhausters were online.

One operational issue is associated with the use of the produced methane to run the methane fueled engines. In addition to the variability of the fuel source and associated carburetor problems that must be dealt with, problems with other mechanical components such as self-oilers, provide ample opportunity for these engines to cease operation. An associated problem is that when an exhauster is found offline, the question of whether the methane fueled engine stopped due to a mechanical malfunction or methane depletion must be addressed. This distinction may be difficult to determine without considerable effort. While electricity would be a more reliable power source to run the exhausters, providing electricity to the remote locations at this site and at other mine sites can be prohibitively expensive. Also, due to the often remote locations for the ventholes and the frequency of visits by maintenance personnel, it may be several days before it is discovered that a venthole is not online. The worst case scenario is that an under performance of the gob gas venthole system is discovered because of increased methane concentrations in the bleeder ventilation system.

Recent advancements in monitoring technology may help address these operational problems, thereby minimizing the interactions between the gob gas venthole and bleeder ventilation systems. Remote data transmission systems that use solar powered cellular phone technology are currently available. It should be possible to combine this remote data transmission capability with the data acquisition and storage system developed by NIOSH for use at the study site. Integration of the two systems will then permit the transmission of real time performance data directly to the mine office. System operational problems can thus be identified and corrected before they lead to additional methane flow into the bleeder ventilation system. An integrated system of this type is scheduled for demonstration at the study mine in the near future.

SUMMARY

Tracer gas studies can be a valuable tool to study ventilation airflows associated with longwall gobs, bleeders, and gob gas ventholes. The analysis of data obtained from the tracer gas experiments and ancillary investigations at the study mine have been used to develop a conceptual longwall subsided strata methane control model. The gas flow insights inherent in the conceptual model can be incorporated into the current state-of-the-art design practices for longwall methane control systems to produce a more efficient optimized system which would provide an increased margin of safety for the underground workforce.

ACKNOWLEDGMENTS

The interest and assistance of the management and engineering staff of the cooperating mine that provided access and data for the successful completion of this study is gratefully acknowledged. It is through cooperative research efforts of this kind that important mine safety and health innovations can be made readily available to the industry as a whole. The following NIOSH personnel are acknowledged for their contributions to the successful completion of this research effort: C. S. Compton, D. L Dwyer, P. W. Jeran, J. C. LaScola, J. K. Marshall, F. E. McCall, G. F. Persetic, S. J. Schatzel, and J. P. Ulery.

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