The borehole monitoring experiment: field measurements of reservoir conditions and responses in longwall panel overburden during active mining

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ABSTRACT: In order to better understand the effects of longwall mining on the methane reservoir overlying the panel, the National Institute for Occupational Safety and Health/Pittsburgh Research Laboratory (NIOSH/PRL) designed and implemented a vertical borehole monitoring experiment (BME) on an active longwall panel. The mine operates in the Pittsburgh Coalbed in Greene County, Pennsylvania. The BME site was located away from either end of the panel to avoid mechanical influences caused by the draping of overburden in this region and was positioned at the same distance from the tailgate gateroad as the mine's gob gas venthole sites. The borehole drilling depths and monitoring intervals were chosen to address a different stratigraphic zone in each of the three planned holes. The monitoring boreholes were positioned perpendicular to face advance using a close spacing pattern of about 15 m (50 ft) between collars. Boreholes were instrumented downhole and on the surface for various measurements. It was observed from the field data that the gob gas venthole fracture network formed 24-46 m (80-150 ft) ahead of the mining face. Overburden permeability's within the same test zones increased 100 to 500 times following undermining. The borehole test interval within the fractured rock responded to overburden gas pressure while the test interval in the caved zone responded to mine ventilation conditions. Eight months after the boreholes were undermined, slug testing indicated permeabilities had increased further in the fractured rock zone. Measurements of surface movement indicate that the permeability development observed in the boreholes is a product of vertical subsidence without lateral movement within the tensional rock mechanics zone on a supercritical longwall panel. Results from this study suggest that maximum permeability in the longwall panel overburden is achieved 58 to 190 m (190 to 620 ft) behind the longwall following maximum compaction of the overburden.

1 Introduction

Methane control in underground coal mines is an active area of research at NIOSH/PRL. The liberation of methane gas into underground coal mines is impacted by geotechnical variables, as well as those arising from mining method and mine design. A primary goal of NIOSH methane control research is to improve control technology to diminish the potential for an explosive mixture of methane in air which poses a risk to the underground work force. Increased face advance rates, increased productivities, increased panel sizes, and more extensive gateroad developments have challenged existing designs for controlling methane on longwalls.

Studies have shown that methane contributions from the subsided strata (gob) generally account for 80% to 94% of the methane present in the ventilation system of an operating longwall (Curl, 1978; Schatzel et al., 1992). Consequently, controlling methane emissions from longwall gobs is critical to maintaining statutory and safe underground methane concentrations. Methane control in coal mines relies on methane drainage via boreholes. During longwall mining, most US operators utilize vertical boreholes or gob gas ventholes (GGVs) drilled in advance into the panel.

The basic operating principles controlling many aspects of GGV performance are identical to conventional coalbed methane wells. The theoretical basis for coalbed methane well behavior and the key factors influencing production performance have been discussed in the literature (Ertekin et al., 1986; King and Ertekin, 1991; Young et al., 1991; Young et al., 1993; Zuber, 1998). In addition to the parameters controlling coalbed gas wells gas production, the performance of a GGV is influenced by additional borehole design factors (Schatzel et al., 1992; Diamond et al, 1994; Thakur, 1997; Karacan et al., 2005; Karacan et al., 2007). These factors include: the position of the borehole relative to the start and completion of the panel, the position of the borehole relative to the panel margin or gateroad, the height of the borehole completion over the mined coalbed, the diameter of the borehole, the length of open and/or slotted hole, and the surface exhauster configuration. In general, coalbed gas is released during overburden deformation associated with mining and the fractures created from this process become pathways for gas migration. The rate, quantity, concentration and duration of gas movement produced by GGVs are largely controlled by the aforementioned parameters.

2 Description of the Borehole Monitoring Experiment on an Active Longwall Panel

In order to better understand the effects of longwall mining on the methane reservoir overlying a longwall panel, a borehole monitoring experiment (BME) was designed and implemented. The BME provided recommendations to operators for improving methane control measures through field observations and through enhancements of reservoir modeling techniques. The borehole drilling depths and monitoring intervals were chosen to address a different stratigraphic zone in each hole. The experimental design specified that drilling was to be completed two months in advance of undermining the borehole location.

2.1 Borehole Monitoring Test Site

The mine operates in the Pittsburgh Coalbed in Greene County, Pennsylvania. The boreholes were drilled in a new mining district. The drill site was selected based on an active panel and the BME site location was chosen to be away from either end of the panel to avoid mechanical influences caused by the draping of overburden in this region.

The BME was planned for a panel that was 442 m (1450 ft) in width (Figure 1). The three test boreholes were arranged in a line parallel to the tailgate gateroads. The distance to the tailgate gateroads was 101 m (330 ft), the same distance which the mine used for its GGVs so that they would be in the same mechanical behavior zone and in a similar stress field. One of the operator's GGVs was to be drilled 1930 m (6325 ft) from the completion end of the panel, and was to be included in the BME monitoring activities. The distances between each of the monitoring boreholes was 15 m (50 ft), and the third borehole (BH-3) was 76 m (250 ft) from the nearby GGV.

The three test boreholes were drilled and completed at different depths to monitor initial reservoir and mechanical properties in different strata horizons and subsequent property changes during the mining of the longwall panel. The top of the Pittsburgh Coalbed was 252 m (827 ft) from the surface (Figure 2). According to this plan, the first, or shallowest, borehole (BH-1) was drilled to a total depth of 220 m (721 ft). The second, or middle-range borehole (BH-2), was drilled to a depth of 230 m (755 ft). The deepest borehole (BH-3), which was also closest to the GGV, was drilled to 245 m (803 ft).

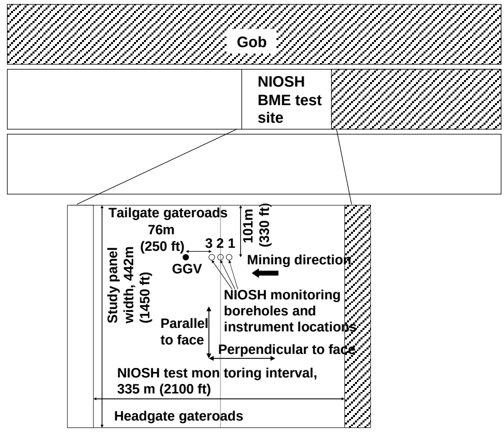

Figure 1. Field site for NIOSH's borehole monitoring experiment (BME) (not to scale).test

Based on the local geology and the depths of the boreholes shown in Figure 2, BH-1 was intended to monitor the Sewickley Coalbed, BH-2 monitored mostly shale sequences below the Sewickley Coalbed and above the Pittsburgh Coalbed, and the deepest (BH-3) monitored the shale and sandstone horizons that would be retained in the gob after undermining. Boreholes were drilled with a 15-cm (6.0-in) diameter bit. After the completion of drilling, the deepest borehole (BH-3) was logged open-hole with density, gamma ray, and sonic tools to identify formations, to refine drilling depths, and to calculate porosity, density, and some of the mechanical properties of the rock. The drilling of the boreholes was started and completed when the longwall face was 760 m (2500 ft) away from the BH-1 location.

The boreholes were cased with 13-cm (5.0-in) steel casing. They were cemented using conventional grout and cement baskets, except for the bottom 6.1 to 9.1 m (20 to 30 ft). These sections were cased with slotted casing and were the primary monitoring zones for each hole. The length of slotted casing was 9.1 m (30 ft) in BH-1 in order to monitor both splits of the Sewickley Coalbed. The slotted section of BH-2 was 6.1 m (20 ft) long. The last 2.4 m (8.0 ft) of the slotted casing of BH-3 was cut and left open-hole in order to keep the casing as high as possible above the gob (Figure 2).

The experimental boreholes were configured to be completed in a manner similar to the mine operator's GGVs. Both borehole designs included flame arrestors, shut-in valves, and long, vertical PVC pipe stacks. However, unlike the experimental boreholes, the GGVs were cased with 61-m (200-ft) slotted casing at the bottom of all boreholes. The operator used a dump grouting procedure on the GGVs instead of the circulating grout method used on the test boreholes. The test boreholes were also different from the operator's GGVs in that the BME boreholes were kept shut-in throughout the mining duration and a powered exhauster was not attached.

Similar to the GGVs, test borehole wellheads were equipped with 15-cm (6.0-in) diameter flange for installation of the flame arrestor and the wellhead valve. Borehole monitoring instrumentation and associated hardware were also attached to the test borehole stack.

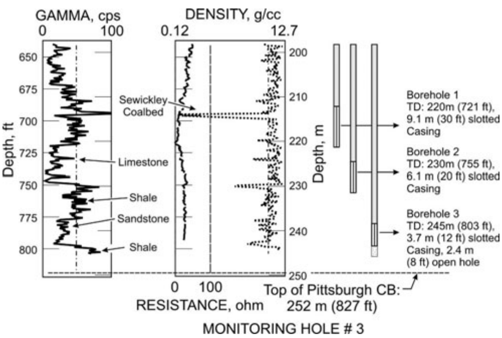

Figure 2. Stratigraphy and downhole configurations for the NIOSH BME.

2.2 Methodology and Instrumentation

Formation permeability is a key variable influencing coalbed methane borehole production from both coalbed gas wells and GGVs. An important portion of this study performed measurements of insitu permeability in the monitoring boreholes before, during, and after the undermining of the NIOSH drill sites. To make these measurements, an experimental method was designed.

For the initial slug test prior to mining, boreholes were equipped with submersible, downhole transducers which were positioned within the downhole monitoring zones. The boreholes were filled with water so that the change in water head could be observed. The downhole transducers were installed underwater in the boreholes. The water head drop was monitored for about a week on each borehole downhole transducer until the rate of water head change reached a steady state. After the conclusion of the initial slug tests, the downhole pressure transducers were repositioned just above the slotted sections.

Water levels remaining in the boreholes following the initial set of slug tests were monitored to determine the change in formation permeabilities as mining progressed underneath. In order to quantify permeability changes in the overlying strata in response to mining, a slug test model for confined, anisotropic aquifers of infinite or semi-infinite radial extent was utilized (Dawson and Istok, 1991). The model was used for calculating instantaneous permeabilities that are represented by two consecutive data points recorded in 1-minute intervals and also for calculating the average permeabilities during intervals that can be recognized by abrupt changes in the rate of water head drop. The borehole monitoring intervals were selected to provide input on the initiation of strata disturbances and the changing degree of rock damage in terms of fracture permeability with respect to the position of the longwall face. The submersible transducers recorded changes of water head until the water drained completely from the boreholes. A final set of slug tests for determining final permeabilities was to be run after the face had left the test zone and neared completion of the panel.

The wellheads on BME boreholes were equipped with surface pressure transducers for continuous data recording of pressure changes at the surface. Methanometers were also installed to measure methane concentrations at the tops of the three experimental boreholes and to monitor any changes in the wellbores as a result of fracturing of strata.

A total of three tiltmeters were installed on the BME wellhead stacks to define the timing of ground movement (Figure 3). Prior research has shown that GGV production is strongly influenced by the position of the borehole relative to the subsidence trough developed at the surface during undermining of a longwall panel face (Jeran et al., 1986; Adamek et al., 1987; Diamond et al., 1994; Ingram and Trevits, 1995). Conventional positional surveys were scheduled to quantify the vertical and horizontal movement of the surface.

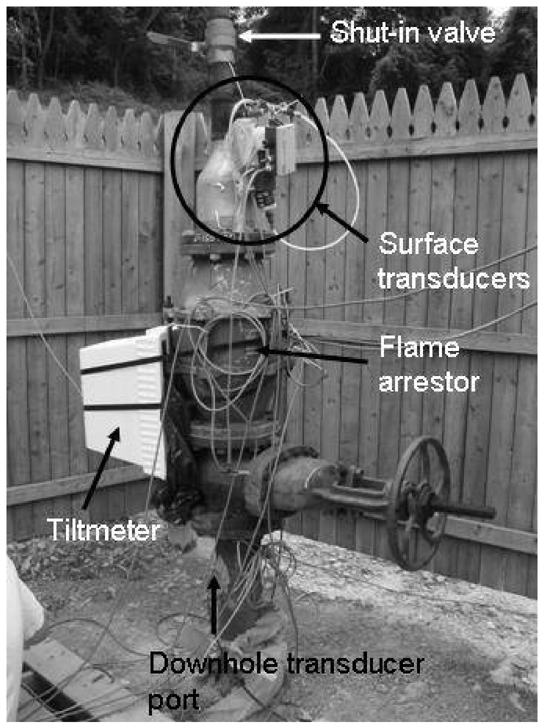

Figure 3. Wellhead arrangement for monitoring boreholes.

The primary experiment test zone extended a distance of 305 m (1000 ft) on either side of BH-1 and BH-3. This distance was chosen based on the overburden depth and typical subsidence profiles for a supercritical panel in the Northern Appalachian Basin. An additional 30.5 m (100 ft) was included in the overall test zone, the distance from BH-1 to BH-3 (Figure 1). All instrumentation was installed, the boreholes shut-in, and monitoring begun while the longwall face was 366 m (1200 ft) away from the first borehole. The longwall face position was recorded daily.

3 Discussion of Results

3.1 Fracture Permeability

The calculated initial permeabilities determined by the slug tests for BH-1, BH-2 and BH-3 were 2.8 md (millidarcies), 0.1 md, and 0.2 md for the Sewickley Coalbed, shale and limestone, and for the shales, respectively. These data were measured immediately after the borehole stacks were assembled and prior to the formation of mining-induced fractures in the BME test zone.

During mining, fracture permeabilities were calculated using the data recorded by the downhole transducers as water-head dropped during undermining of all three boreholes. However, soon after starting to record data from the deepest borehole, communication with the downhole pressure transducer was lost. Thus, none of the figures include downhole pressure data from BH-3. Water head data suggest that mining-induced disturbances forming the GGV fracture network can occur 24-46 m (80-150 ft) ahead of the mining face. In monitoring water levels in the boreholes, the loss of water can be rapid up to about 32 m (100 ft) above the mined coalbed, limiting the duration of monitoring. The rate of water loss was not related to the depth of the borehole. Shearing and deformation in the overburden is typically severe in near margin GGVs where much of the annulus is generally modified.

Figure 4 shows water head and permeability evolution averaged for some distinctive segments in BH-1. The data show that as soon as the strata are affected from mining disturbances, an initial permeability increase response. The averaged value of this initial permeability increase is ~400 md. After this initial increase, permeability decreases to 100 md. This permeability change behavior may indicate that initial reservoir disturbance is due to shearing and fracturing of the strata or bedding planes. After the borehole is undermined, averaged permeability increases to larger values (~400 md) due to larger-scale fractures. The highest instantaneous permeabilities measured in the borehole occur just after disturbances first affect the coalbed (over 800 md), during initial ground movement, and during the undermining of the borehole location. The highest averaged fracture permeability for any of the segments in the Sewickley horizon occurred after the face had passed the BH-1 location as last of the water was leaving the borehole (Figure 4). Borehole 2, designed to monitor a 6.1-m (20-ft) section in the shale and limestone zone between Sewickley and Pittsburgh Coalbeds, was analyzed using the same approach.

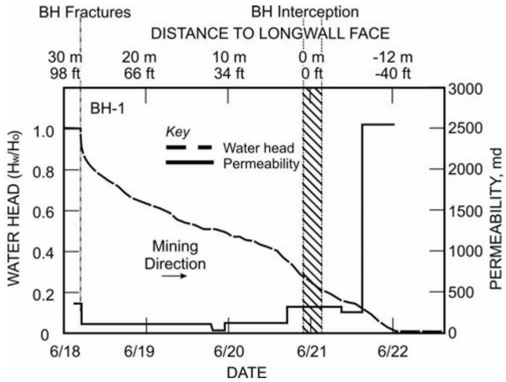

Figure 4. BH-1 average permeabilities and water head drop rate (height of water/original water height).

Figure 5 presents average permeabilities (utilizing short-term, rapid instrument response data) within different segments based on the changes in the rate of water head drop for BH-2. Although this borehole is deeper and closer to mining than BH-1, this interval did not show the sudden water head loss as observed in BH-1 when mining influence reached the borehole location. This behavior may be due to the combination of different structural and mechanical properties of this horizon compared to the BH-1 test horizon which included the Sewickley Coalbed.

The data in Figure 5 show that permeabilities in BH-2 gradually increased to the 100-200 md range, possibly due to bedding plane movements. A sudden drop in water head occurred with an associated permeability increase occurred on 6/21 where the segment averaged about 400 md. This increase coincides with the approach of the longwall face (15 m (50 ft) away) and may suggest communication between these two wells. Figure 5 shows that permeability starts increasing as the mining face advances towards the BH-2 location until it is undermined. Shortly after undermining, large-scale horizontal and vertical fractures are created and the permeability increased to about ~1600 md. Permeabilities measured prior to undermining were in the ~1 md range. Permeability increases following undermining were dramatic with increases of about 100 to 500 times and instantaneous increases of up to about 1000 times. Formation and fracture permeabilities gradually increase as mining-induced disturbances progress to the borehole locations. However, the biggest average change occurs following the interception of borehole locations. The advantage of the test method applied is to allow monitoring of water-head changes as mining progresses. However, the disadvantage is the data can be collected only as long as water is present in the borehole.

After longwall mining had neared completion of the study panel, the final slug tests were performed on BH-1 and BH-2. When adding known amounts of water to the boreholes, the rate of water head loss was rapid and the interval above the transducers was emptied in a matter of minutes. In both holes, a second slug of water was added to retest borehole permeability. Borehole 1 measured 63 and 65 Darcys in the two tests. Consequently, the increase in permeability for BH-1 compared to the maximum measured immediately following undermining increased by a factor of about 40 to 60 times. When performing the slug test in BH-2, no water head build-up was achieved due to water leaving the borehole at such a rapid rate that a permeability value could not be determined. The final permeability level for BH-2 was apparently far above what was measured in BH-1.

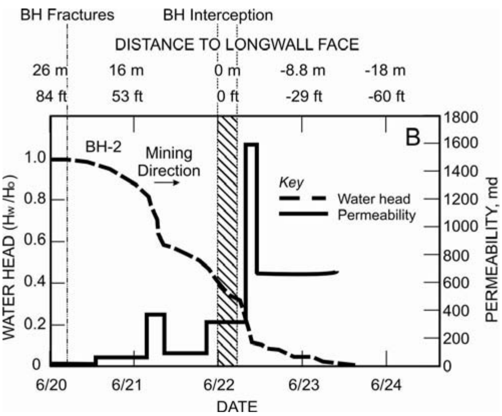

Figure 5. Average permeabilities and water head drop rate (height of water/original water height).

3.2 Borehole Gas Pressures and Concentrations

The changes in methane concentrations and static pressures in the boreholes were monitored at the surface after the boreholes were shut-in. These concentration and pressure measurements are shown in Figures 6A and 6B, respectively, during the monitoring period. The vertical shaded area in these figures shows the dates for miners' vacation. All three boreholes were intercepted during the week just before vacation, during which time the longwall did not operate. The nearby GGV was intercepted after longwall mining resumed. The coal production delay associated with miners' vacation and the date when the nearest GGV began gob gas production is also marked on Figure 6.

The monitoring of shut-in pressures began before mining disturbances reached the borehole locations. This period (until the shaded area) is characterized by almost consistent changes in methane levels near about June 12 (Figure 6A) and static borehole pressures (Figure 6B) in BH-1 until the mining-related disturbances reach the borehole locations. The data show that until shearing occurred, resulting in an initial water head drop, methane concentration was 75% in BH-1. Gas concentration then increased to 85% methane within a few days and pressure increased to 20 cm (8.0 in) of water gauge in the borehole. These increases suggest that the coalbed was producing methane that was migrating into the borehole. However, when mining disturbances reached the BH-1 borehole location, methane concentrations decreased to 40% and borehole pressure dropped to 10 cm (4.0 in) of water gauge. Interception by mining resulted in a further decrease. However, after this borehole location was intercepted by the longwall face and all the water was drained out, methane concentrations started to increase to 90%-100% due to coalbed fracturing.

The interception of BH-2, which monitored shale and limestone layers, showed a different behavior. Initial methane readings in this borehole before undermining were around 10% and the shut-in pressures were low, indicating that there was not significant methane flow into the borehole, probably due to low permeabilities and the presence of water in the borehole. However, after it was undermined and the water drained out, methane concentrations increased to 90%-100% in the borehole with a sudden pressure fluctuation. This borehole response may be the result of new horizontal and vertical fractures associated with the permeability increase in the monitoring zone.

It is also interesting to note the similar behavior of methane concentration change in BH-1 and BH-2 after undermining. This behavior suggests that these two boreholes started to communicate through horizontal and vertical fractures even though they monitored two different horizons about an 11 m (35 ft) vertical distance from each other. This observation shows that the layers within 24 m (80 ft) of the top of the coalbed being mined are sufficiently fractured or there is enough shearing or opening of natural fractures so that the formations can interact with each other. However, the fact that the mine ventilation pressures (-8 to -10 cm water gauge (-3 to -4 in)) have not been continuously recorded at these boreholes suggests that there was either no direct communication with the mine or that the positive gas pressure into the boreholes from the monitored zones was high enough to compensate the negative pressure influence of mine ventilation.

The behavior of pressure and concentration data produced by BH-3, 6.1 m (20 ft) above the Pittsburgh Coalbed, is completely different from the other two boreholes. In BH-3, the decrease in methane concentrations and shut-in pressures after undermining showed that this borehole started to communicate with the mine atmosphere. After undermining, the shut-in pressure decreased to mine ventilation pressures and stayed as such for the rest of the monitoring. Methane concentrations were in the 40% to 50% range before undermining then decreased to about 5% methane during and immediately following undermining. Concentrations remained close to 5% methane after undermining. Then the GGV exhauster, 76 m (250 ft) away, began to operate with a high flow rate following undermining. This resulted in an initial decrease in borehole methane concentration followed by a concentration rise in the gob, as recorded in BH-3, to about 35% (Figure 6A).

The start of the nearby GGV operation is also noticeable in the other two BME boreholes (Figure 6). Although this venthole did not operate continuously and successfully due to mechanical problems after an initial high production rate, the data confirms that the venthole was communicating with the monitoring boreholes through fractures and bedding plane separations (Mucho et al., 2000). The explanation for the methane concentration increase in the gob (or in BH-3) may be due to an increase in methane height in the gob as a result of the negative pressure generated by the venthole blower. This rise may also be due to drawing gas from other horizons into a more permeable gob following undermining. This may also explain the decrease in BH-1 and BH-2 shut-in pressures and the decrease in measured methane concentrations associated with a concentration increase in BH-3, before the recovery again to 70% methane. Downhole pressure and methane concentration data suggest that BH-1 and BH-2 interact and behave similarly to overburden conditions. BH-3 responds to mine ventilation pressure and later to gob pressure conditions.

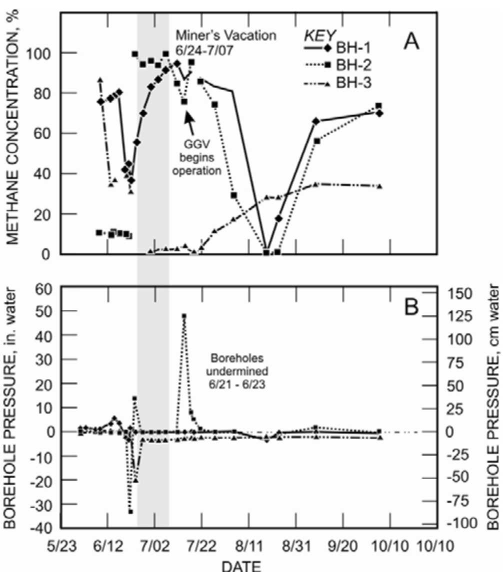

Figure 6. Methane concentration (A) and static shut-in pressures (B) measured in the boreholes during progress of mining.

3.3 Survey Measurements for Evaluation of Subsidence During Mining

Figure 7 illustrates the ground elevation survey information and the data collected by the three surface-mounted tiltmeters. The plot shows there was an instrument adjustment on about June 12, which is usually performed when the instrument is bumped or reaches its range limit. By June 13, all instruments were recording tilt perpendicular to the longwall face, well before undermining occurred (Figure 1). This tilt response appears to precede rock fracturing recorded by the slug tests (Figures 4 and 5) but corresponds to gas concentration and pressure changes in the boreholes (Figure 6). These data show an interval of strata bending preceding fracture formation. On June 21, the longwall undermined BH-1. Major fracturing in BH-1 on June 18 (Figure 4) is represented by slight tilting with fracturing at BH-2 occurring on June 21 during continued tilting perpendicular to the longwall face. From June 24 through July 8, operations on the longwall stopped for miners' vacation. The gob stopped collapsing during this period but began again after longwall mining resumed. A much larger tilt response perpendicular to the longwall face occurred on about July 8 at all three boreholes after the resumption of mining. Tilt perpendicular to the face reached a maximum on July 11 to 13 at all three boreholes and then returned close to the original position.

Tilt parallel to the face (Figure 1) began at BH-1 and BH-2 from June 13 to 15 and very slight movement was seen at BH-3. A period of movement was indicated at BH-3 parallel to the face during the non-mining period from June 30 to July 8 (Figure 7). The instrument measured off-scale on the axis corresponding to the parallel to the face direction during this time. Since no other surface movement was recorded by the tilt meters and due the lack of induced surface movement during the period of non-mining, these data are likely instrumentation problems. Instrument data from BH-3 is back within scale on July 9 and appears to be responding to surface movement for the remainder of the monitoring period.

Maximum movement parallel to the face was reached from July 18 to July 21 at all boreholes. This period of movement may correspond to the formation of higher fracture permeabilities measured in the final series of slug tests months later. This time corresponds to a face position about 160 to 190 m (520 to 620 ft) past the borehole locations. Tilt parallel to the longwall face did not return to level (pre-mining position).

Maximum tilt movement may indicate the onset of maximum subsidence at the surface and an increase in permeability underground in the monitored borehole interval. The permeability increase was evident in BH-1 and BH-2 but can only be assumed in BH-3 due to the downhole instrumentation failure in this borehole. In directions both parallel and perpendicular to the face, surface tiltmeters indicated movement had ceased 1 to 2 weeks after undermining, not including work stoppages.

Two mechanisms are recognized as potentially contributing to the increase in fracture permeability during overburden compaction. The first is the draping effect in the tensional zone of the overburden. As the final phase of overburden compaction over a longwall panel came to an end, the adjacent overburden over the gateroads experienced very limited surface movement. The overburden connecting the compacted zone over the longwall panel to the largely uncompacted zone over the gateroads is in tension and achieves maximum fracture permeability during maximum compaction of the gob.

The compaction-related increase in permeability may be partly produced by a loss of coal volume between the coal cleats as coalbed gas migrates out of the coal matrix in response to the decrease in gas pressure within the coal fracture system. In other words, the data indicate swelling of the coal matrix due to coalbed gas retention and shrinkage of the matrix during the loss of that gas. Diamond et al. (1992) measured gas content in longwall panel overburden before and after undermining to determine the primary sources of gas in the zone of emission. Diamond et al. estimated that the coalbed sequences contributed 91% of the overburden gas released during undermining. It is considered likely that both tensional strata fractures and coal matrix shrinkage mechanisms are contributing to the permeability increase measured in the near-margin GGV monitoring intervals.

Five conventional surface surveys were conducted at different dates during the monitoring period. These surveys registered the positions of a bolt at the wellhead and ground locations for each borehole to define the lateral and vertical movements. A portion of the subsidence data is also shown in Figure 7. The full set of vertical movement data at the borehole sites is shown in Figure 8. Three surveys were conducted within the primary test zone. These surveys were conducted just before, during, and just after the borehole locations were intercepted by the longwall face. The other two surveys were conducted outside the primary test zone as the longwall face approached the boreholes and after it passed beneath them.

Elevation measurements of the landmarks during these surveys revealed the amount of subsidence at the borehole locations. The magnitude of the subsidence was 0.99 m (3.25 ft) at BH-1, 0.93 m (3.05 ft), at BH-2, and 0.86 m (2.82 ft) at BH-3. These values are within the range of expected subsidence values observed in Northern Appalachian basin due to longwall mining. The measurements show that there was no appreciable lateral movement of either the ground or the wellhead. Permeability development observed in the boreholes is product of vertical subsidence without any component of lateral movement.

Figure 8 shows that as of July 13, surface subsidence had ceased. The tilt meter data shows that by this date, most borehole movement parallel to the longwall face had already occurred on boreholes 1 and 2 and some movement was still occurring on borehole 3. Perpendicular to the longwall face, maximum movement had already been achieved by July 13 although the surface contour was in the process of returning to the pre-mining configuration. These results suggest that although the bulk of the surface subsidence had occurred by July 13, surface movement and tilting associated with subsidence trough formation was not complete. Maximum tilt movement parallel to the face from July 18 to July 21 did not produce a significant component of vertical movement. The high permeability's measured or indicated in the final series of slug tests were

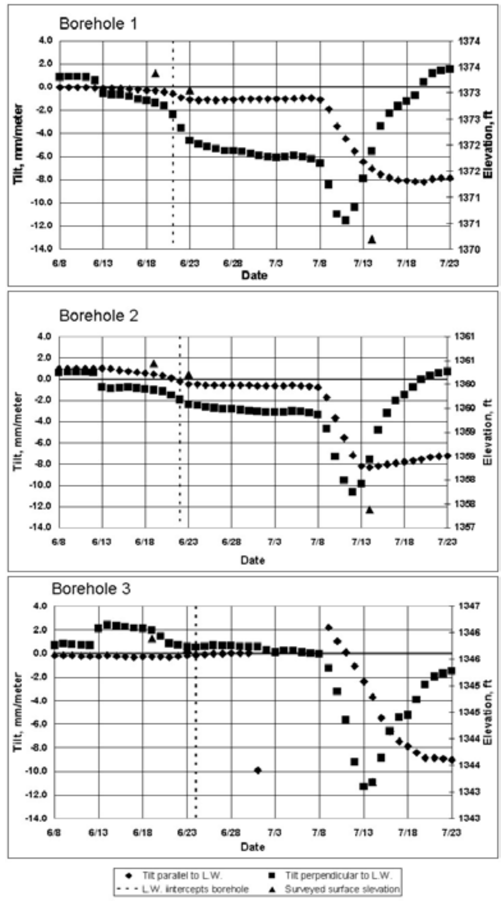

Figure 7. Surface movement over longwall panel study site during undermining as measured by tilt meters.

Probably reached once these tilting and vertical movement events were completed and subsequent surface movement had diminished (Figures 7 and 8). If the end of vertical surface movement indicates essentially the end of permeability increases, then maximum permeability was achieved 58 to 88 m (190 to 290 ft) behind the longwall face. If permeability increases were still being realized during surface tilting without vertical movement, then the increases occurred 160 to 190 m (520 to 620 ft) past the borehole locations. Distances are approximate due to the limited quantity of conventional survey measurements and the termination of tilt meter monitoring outside the primary test zone.

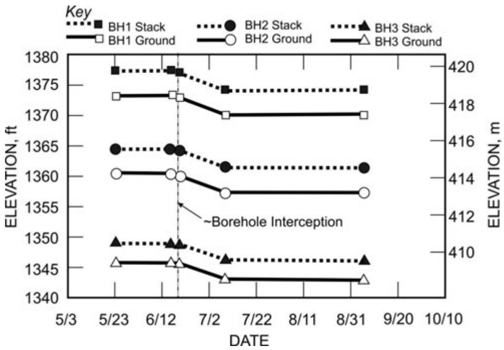

Figure 8.Vertical movements of the survey points of the monitoring boreholes during mining.

4 Summary

A primary goal of NIOSH methane control research is to improve control technology to diminish the potential for an explosive mixture of methane in air which poses a risk to the underground work force. Researchers at NIOSH/PRL designed and implemented a borehole monitoring experiment (BME) on an active longwall panel to measure changing reservoir conditions in the overburden. The BME provided recommendations to operators for improving methane control measures through field observations and through enhancements of reservoir modeling techniques. The GGV fracture network can form 24-46 m (80-150 ft) ahead of the longwall mining face on a Northern Appalachian Basin supercritical panel. This distance may vary when conventional GGV slotted pipe configurations are used. Much shorter lengths were used during monitoring.

The loss of water from GGVs was rapid from 32 m (100 ft) to 22 m (72 ft) above the mined coalbed. The rate of water loss was not related to borehole depth. Overburden permeabilities within the same overburden test zones ranged from about ~1 md range prior to undermining and increased 100 to 500 times following undermining with higher instantaneous peaks. This increase in permeability occurred when the longwall face reached the monitoring locations

About 7 months after undermining had occurred, additional borehole permeability tests showed the fracture permeability had increased again since undermining. Borehole 1 (the shallowest in the Sewickley Coalbed horizon) had a permeability of 63 to 65 Darcys. Borehole 2 (limestone and shale interval) had a higher permeability but the water loss in the hole was so rapid it could not be accurately be measured. Borehole 3 was expected to have an extremely high permeability (Pittsburgh Coalbed caved zone) but no plans were made to measure this interval after mine through. The borehole test intervals within the fractured rock responded to overburden gas pressure and the test interval in the caved zone responded to mine ventilation conditions.

Surface tilting appears to precede rock fracturing in the monitored borehole interval but corresponds to gas concentration and pressure changes in the boreholes. Additional surface tilting measured 1 to 2 weeks after undermining (not including work stoppages) may correspond to the onset of maximum permeability measured in the boreholes in the final series of slug test months later. Permeability development observed in the boreholes is product of vertical subsidence without any component of lateral movement.

The period of overburden compaction and tilting occurring 58 to 190 m (190 to 620 ft) behind the longwall face is assumed to create the final phase of fracture permeability measured in the near-margin GGV monitoring intervals. Two mechanisms are recognized as potentially contributing to the increase in fracture permeability during overburden compaction. The first is the draping effect in the tensional zone of the overburden. The overburden connecting the compacted zone over the longwall panel to the largely un-compacted zone over the gateroads is in tension and achieves maximum fracture permeability during maximum compaction of the gob.

A second mechanism which may contribute to the onset of the final fracture permeability levels in the overburden is coal matrix shrinkage. A loss of coal volume within the matrix occurs when coalbed gas migrates out of the coal matrix in response to the decrease in gas pressure within the coal fracture system. In this scenario, there is swelling of the coal matrix due to coalbed gas retention and shrinkage of the matrix during the loss of that gas. It is considered likely that both mechanisms are contributing to the permeability increase measured in the near-margin GGV monitoring intervals.

5 Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute of Occupational Safety and Health.

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