Applications of directionally drilled horizontal gob boreholes for methane drainage in Western U.S. Coal Mines

D.J. Brunner
REI Drilling, Inc., Salt Lake City, Utah, USA

F.P. Schumacher
REI Drilling, Inc., Salt Lake City, Utah, USA

ABSTRACT: Directionally drilled horizontal gob boreholes (“HGB”) can be successfully implemented as a means of controlling methane liberated by fracturing roof strata in longwall gobs. Directional drilling has proven to be more effective than traditional drilling techniques because each borehole can be much longer, held at constant elevation above the coal seam, and oriented where the strata are under highest tension during the caving action of the gob.

Between 1999 and 2000 six HGBs were completed to control gob gas emissions at the Willow Creek Mine in Utah. These boreholes were drilled from the gateroads of two longwall panels to a constant elevation above the mining seam and were oriented parallel to the long dimension of the panel. Two of these boreholes were under-mined and measurements of total gob gas flow, well-head vacuum, and gas composition were recorded. Numerical flow correlations performed with this information served as the basis for planning the implementation of HGBs at other western U.S. coal operations.

Between the years of 2001 and 2003, REI assisted in implementing the largest underground gob degasification effort involving directionally drilled horizontal gob boreholes at a longwall mine in the western U.S. Directional drilling was used to develop “modified cross-measure” boreholes from the headgate entries of two longwall panels. Gas monitoring enabled comparisons between performance and as-drilled physical characteristics which allowed optimization of borehole placement for performance.

Since 2003, HGBs have been implemented at several other western U.S. coal operations using lessons learned from the Willow Creek Mine and the modified cross-measure borehole project. Recent implementations include the longest, high-capacity, directionally drilled HGB in the U.S. to date, and directionally drilled modified cross-measure boreholes developed from tailgate entries.

1 Introduction

Longwall gob degasification techniques have evolved throughout the industry to adapt to various mining conditions that operators may face. Operators of gassy coal mines use directional drilling technology from underground to develop horizontal, angled, or parabolic boreholes (all considered horizontal gob boreholes ("HGB”) for the purposes of this paper) in the strata above and below the mining horizon for gob gas recovery. State-of-the art directional drilling and down-hole surveying equipment is used for the development of HGBs as they require accurate and known placement. HGBs have been applied successfully in longwall mines in Japan, China, Germany, Ukraine, and in the U.S., and in many cases, are advantageous over conventional cross-measure and other superjacent (such as entries developed above or below the mining horizon) gob gas drainage methods which are more costly to apply and operate. HGBs are advantageous over vertical or directionally drilled surface gob wells in cases where access is limited or restricted due to terrain, permit, or now more commonly, environmental issues as in some areas of the western U.S.

1.1 Gob Degasification Techniques

In the industry, three primary methods of longwall gob degasification techniques are used, and mine operators often adopt variations of these: (a) surface drilled gob wells, (b) cross-measure boreholes, and (c) superjacent techniques which include boreholes drilled from overlying/underlying galleries and, overlying or underlying directionally drilled HGBs. Figure 1 illustrates these practices.

Surface drilled vertical gob wells are most predominantly used in the U.S., and as at some western mines, directionally steered above the coal seam. Where overlying gas bearing strata of high gas contents are present and where gob permeabilities are enhanced, operators often obtain very high gas production rates and maintain high gas qualities with vertical gob wells operated under high vacuum.

The cross-measure technique of longwall gob degasification is the dominant method used in Europe (east and west) and in the CIS where longwalls mine deep seams (multi-seam mining), sometimes using advancing techniques. Cross-measure boreholes have had limited application in the U.S.; at the Cambria 33 Mine in Pennsylvania (Schwoebel, 1993), and more recently at several western U.S. Mines.

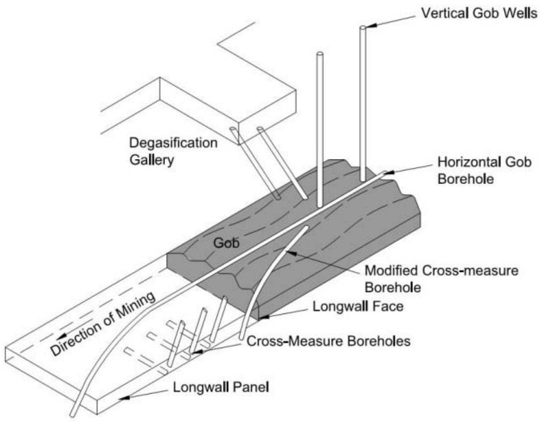

Figure 1. Gob degasification techniques (EPA, 2000).

Conventional cross-measure boreholes are typically smaller diameter boreholes (75 to 100 mm in diameter) that are rotary drilled at high angles from gate-road entries up into overlying or down into underlying strata ("crossing the measures"), in advance of the longwall face. Directional drilling is now used to develop "modified cross-measure boreholes" (also considered HGBs for the purposes of this paper) that are steered to target certain strata, or extend horizontally at specified elevations over the mining seam, and at longer lengths than conventional rotary drilled cross-measure boreholes. In very gassy conditions, operators will apply cross-measure boreholes from the head-gate entries as well as the tail-gate entries.

Superjacent techniques involve the use of adjacent entries or boreholes developed above or below the mining seam. The use of drainage galleries developed in advance of mining in overlying or underlying strata is common at some of the deeper and gassier mining operations in Eastern Europe, the CIS, and China. These operations typically drill smaller diameter, short boreholes, into overlying/underlying strata from the drainage galleries, and/or they seal the drainage galleries and connect the seals to a gas collection system operating under high vacuum.

1.2 Long Horizontal Gob Boreholes

Superjacent gob degasification techniques involving long in-mine directionally drilled HGBs placed over or under the mining seam in advance of longwall operations were first implemented in Japan and are now commonly applied in China, and more recently in the western U.S.

Mine operators drill HGBs between 75 mm and 150 mm in diameter to lengths of up to 1,200 m, into the strata overlying or underlying longwall panels from gate-roads, or the panel ends. Overlying HGBs are strategically placed: (a) into or below the lowest producing source seam depending on elevation (into the seam for purposes of pre-mine drainage and subsequent gob degasification (dual purpose)), (b) to intersect the fracture zone above the rubble zone after the gob forms, (c) over the tension zones near the edges of the panel, (d) over the low pressure or high elevation side of the gob, and (e) to remain intact following undermining with the intent to produce gob gas over the entire length of the borehole.

The advantages of this technique are: (a) the boreholes are developed from underground, in advance of and away from mining activity for either advancing or retreating longwall systems, (b) fewer, longer boreholes produce an effective low pressure zone over the gob, (c) strategic placement may allow borehole collars to remain intact (protected from the effects of local stress redistribution) and allow boreholes to remain productive after longwall mining is completed.

2 HGBs Developed for the Willow Creek Mine

In-mine directionally drilled HGBs were developed from gate entries over two longwall panels at the gassy Willow Creek Mine in Utah, USA. Five HGBs, generally 95 mm in diameter, between 500 and 640 m in length were developed at different defined elevations over the mining seam. As shown on Figure 2, only two of these boreholes, D2R1 and D2R2, were under-mined prior to mine closure, and only two gas production measurements were collected, including gas samples for laboratory analysis, at two different times during mining.

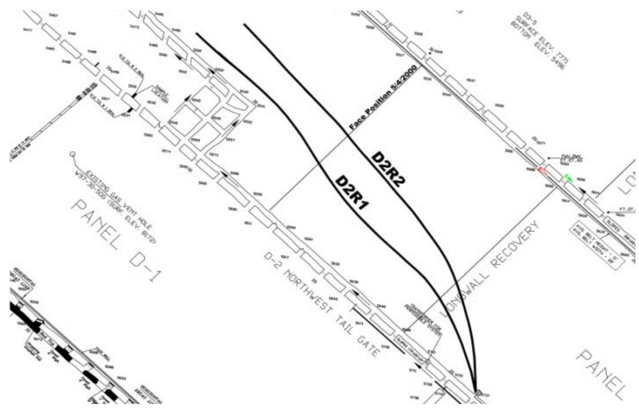

Figure 2. HGBs drilled over the D2 longwall panel at the Willow Creek Mine, Utah, USA.

2.1 HGBs drilled over the D2 Panel

The two HGBs were drilled over the D2 Panel from the tailgate entry at elevation targets of between 18 and 23 m above the mining seam. D2R1 was drilled to 549 m in length at 89 mm diameter and placed generally 60 m from the panel abutment along the tailgate entry (then 15 m inby where the panel reduces in width) at an elevation target of 18 m above the top of the mining seam. D2R2 was drilled to 534 m in length at 95mm in diameter and placed initially near mid-panel, and then 60 m from the panel abutment inby where the panel reduces in width. D2R2 was drilled to a target elevation of 29 m above the top of the coal seam.

2.2 HGB Performance and Analysis

From the measurements obtained, each of the two overlying HGBs produced between 104 and 166 l/s of gob gas at standard conditions under wellhead vacuum pressures ranging from -25 to -30 kPa at high gob gas density due to the presence of significant concentrations of CO_2. The gas flow and quality data measured for the HGBs is presented in Table 1 with face activity during measurement. The two readings/samples were obtained approximately 1 month apart and both boreholes were generally under-mined the same distance from collar. At the time of the measurement during idle longwall activity, the longwall face had been down for approximately 1 week and the HGBs produced significant ventilation air.

Table 1. Results of Flow Measurements for D2 HGBs.

HGB	LW Activity	WH Vacuum (kPa)	CH_4 (%)	CO_2 (%)	Air (%)	Total Flow (l/s)
D2R1	Idle	-30	13	6	81	136
D2R2	Idle	-30	23	12	64	144
D2R1	Mining	-25	51	23	24	104
D2R2	Mining	-25	54	22	22	166

The measurements obtained during active longwall mining indicate that both HGBs produced gob gas at similar high concentrations (approximately 77 percent by volume) but that D2R2 produced gas at higher volume flow rates than D2R1. Although slightly larger in diameter (6 mm), D2R2 was placed further inby the longwall abutment, closer to the zone of re-compaction, and at a higher elevation in the fracture zone than D2R1. Because of its lateral and vertical placement, D2R2 should have produced gob gas at higher concentrations than D2R1, and at potentially lower gob gas flow rates. The results suggest that D2R1 was not as well connected to the gob gas resource and may have not remained intact over the gob. The higher concentration of ventilating air produced by D2R1 when the longwall was idle also suggests this possibility.

2.3 Correlating Measured with Calculated Gob Gas Flow Rates

Prediction of gob gas flow rates from HGBs is difficult because gas flow rate is not steady state; gas flow varies with borehole length and time. Gas emissions from the gob flow into the borehole through fractures along its under-mined length, while desorbed/free gas migrates into the borehole along it un-mined length. Under-mined length and un-mined length change with time (mining).

Assuming that the gob gas flow measured at the HGB collar originates from the end of the hole, an approximation of performance can be determined with the fundamental flow equation by adjusting the friction factor to match the collected data. Menon (2005) recommends that for steady-state isothermal flow in a gas pipeline, the basic equation for relating the pressure drop with flow rate can be written as:

$$Q = 1.3303\,(10)^{-5} \left(\frac{T_b}{P_b}\right) \left[\frac{(P_1^2 - P_2^2)}{G T_f L Z f}\right]^{0.5} D^{2.5} \qquad (1)$$

Where:
Q = gas flow rate, measured at standard conditions, l/s
f = coefficient of friction, dimensionless
P_b = base (standard) pressure, kPa
T_b = base (standard) temperature, K
P_1 = upstream pressure, kPa
P_2 = downstream pressure, kPa
G = gas gravity (air = 1.0)
T_f = average gas flowing temperature, K
L = pipe length, km
Z = gas compressibility factor, dimensionless
D = pipe inside diameter, mm

For the correlation analyses, the base temperature (T_b) and the gas temperature (T_f) were considered standard ambient (293.15 K). Gas compressibility and gas gravity were obtained from the lab analyses performed with the gas samples collected. The pressure contribution (P_1), the static pressure at the end of the borehole, was assumed to be the static pressure at the collar (less vacuum pressure) with no additional pressure contribution from the gob gas reservoir. Figure 3 shows a summary of the correlation performed between measured and predicted gob gas flows for D2R1 and D2R2.

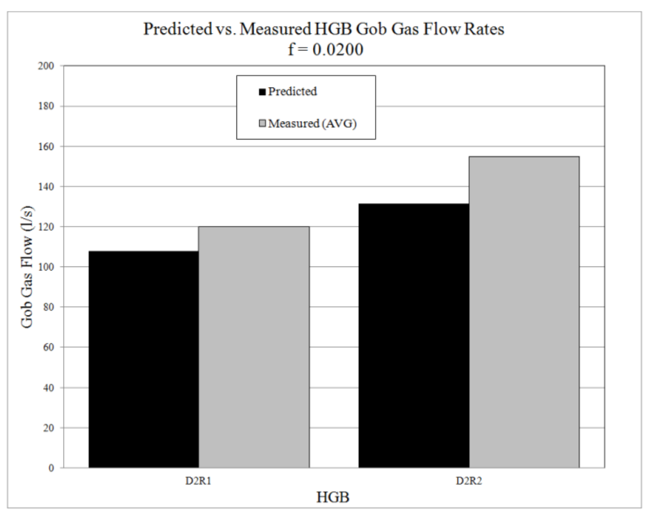

Figure 3. Measured vs. predicted gas flow for boreholes D2R1 and DR2.

The measured data was matched for each borehole by adjusting the coefficient of friction starting with values recommended for unlined shafts (McPherson (1993), coefficient of friction for a circular, unlined shaft varies from 0.0167 to 0.0230). The derived coefficient of friction values for each of the two HGBs and the two data sets were averaged and then plotted versus average measured flow at standard conditions. The average coefficient of friction derived from this analysis is 0.0200.

3 Modified Cross-Measure HGBs

An underground gob gas drainage system was implemented (with mine assistance) that comprised of rotary drilled traditional cross-measure boreholes, and directionally drilled modified cross-measure boreholes for a longwall mining district comprised of four panels at a western mine ("WLM1"). As shown on Figure 4, the conventional cross-measure boreholes were drilled from the tailgate entries for Panels 1 and 4, and due to mining considerations, the dip of the coal seam (down from headgate to tailgate), including ventilation requirements for drilling and the gas collection pipeline, the modified cross-measure boreholes were drilled from the headgate entries for Panels 2 and 3.

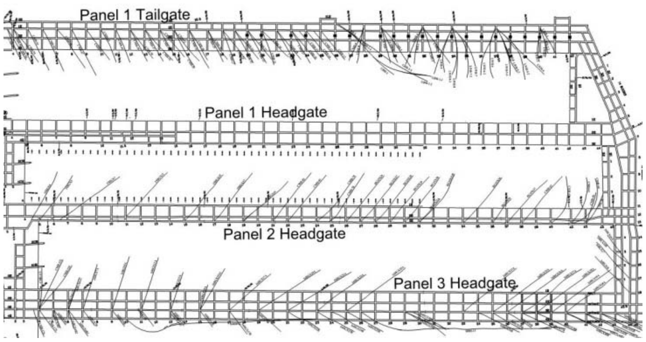

Figure 4. Conventional cross-measure and modified cross-measure HGBs at WLM1.

In order to optimize performance of the modified cross-measure boreholes and improve implementation from panel to panel, detailed physical data were collected from borehole surveys and drilling and completion logs, and measurements of wellhead vacuum pressures, gas flow rates, gas composition (indirectly by measuring oxygen and correlating oxygen with other gases based on gas sample analyses), and duration of production (time on line) were obtained for each borehole. This information served to improve implementation of the modified cross-measure borehole configurations developed at the Mine.

3.1 Modified Cross-Measure Borehole Characteristics

A cross-section of a typical modified cross-measure borehole implemented at WLM1 is illustrated on Figure 5a and Figure 5b, in profile and plan view, respectively. As shown on Figure 5a all of the HGBs were developed over protective pillars, and were lined with perforated steel casing from the end of the borehole to near the longwall abutment and solid steel casing, grouted in place, from this point to the borehole collar. Figures 5a and 5b identify the characteristics of the modified cross-measure boreholes that affect performance.

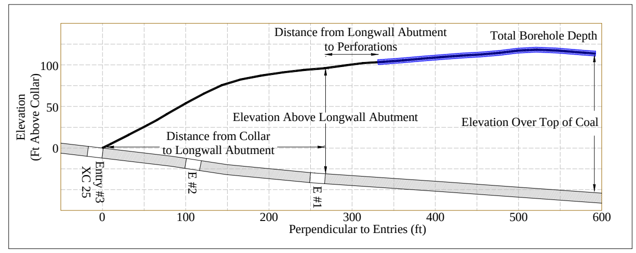

Figure 5a: Parameters that affect modified cross-measure borehole performance.

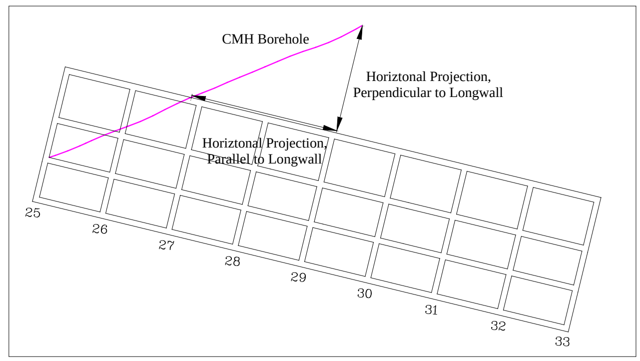

Figure 5b: Parameters that affect modified cross-measure borehole performance.

3.2 HGBs Developed for Panel 2 and 3 at WLM1

A total of 50 modified cross-measure boreholes were directionally drilled from the No. 3 Entry in 2 Headgate (across Entries 2 and 1) over Panel 2, and from the No.3 Entry in 3 Headgate (also across Entries 2 and 1) over Panel 3, as shown on Figure 4. The modified cross-measure boreholes, generally 245 m in length, were placed at approximately 50 Degree angles relative to Panel 2, while those inby for Panel 3 were placed at more acute angles (generally 38 Degrees). HGBs were drilled to a target elevation of between 24 to 39 m above the top of the coal at 145 mm in diameter and lined with steel pipe 100 mm in internal diameter. The steel liner was perforated starting inby the longwall abutment to the end of each borehole.

After development of the Panel 2 modified cross-measure boreholes, REI and WLM1 made significant changes to the configuration of the modified cross-measure boreholes drilled for Panel 3 based on borehole performance data. Table 2 compares the average physical characteristics and performance data of the Panel 2 modified cross-measure boreholes with the Panel 3 boreholes. Table 2 indicates that the Panel 3 modified cross-measure boreholes recovered 50 percent more methane from the longwall gob than those employed in Panel 2.

REI attributes the improved performance of the Panel 3 modified cross-measure boreholes to practices observed in European and U.S. Studies of the application of conventional cross-measure boreholes (US EPA, 2000).

Table 2: Comparison of Panel 2 and Panel 3 modified cross-measure boreholes.

Modified Cross-Measure Borehole Physical Characteristics	P-2	P-3	Difference
Horizontal Projection, Perpendicular (m)	120	87	(33)
Horizontal Projection, Parallel (m)	103	103	(0)
Peak Elevation Relative to Top of Coal (m)	29	39	10
Elevation over Longwall Abutment (m)	16	25	9
Orthoginal Distance between Abutment and Perforations (m)	6	12	6
Headgate HGB Borehole Performance Characteristics			
Gob Gas Flow Rate (l/s)	87.3	51.4	(35.9)
Oxygen Concentration (%)	6.7	2.3	(4.4)
Methane Flow Rate (l/s)	59.5	45.8	(13.7)
Time on Line (days)	24	47	22
Total Methane (m^3)	123,379	185,985	62,606

For example, it was determined that: (a) modified cross-measure boreholes placed higher in the gob have a longer productive life and tend to produce less ventilation air. The average target elevation is approximately 10 m higher for the Panel 3 modified cross-measure boreholes; (b) adjacent pillars better protect the integrity of the modified cross-measure boreholes and collars, and improve access to the wellheads, resulting in improved recovered gas quality and increased production life. The distance between the collar and the longwall abutment was 15 m greater for the Panel 3 modified cross-measure boreholes and the Panel 3 headgate was comprised of four entries; (c) perforations placed further inby the longwall abutment minimizes ventilation air leakage to the modified cross-measure boreholes, increasing recovered gas quality and borehole life. The average distance between the abutment and the perforations is 6 m greater for the Panel 3 modified cross-measure boreholes; (d) modified cross-measure boreholes with longer parallel horizontal projections (at more acute angles relative to the longwall panel) produce for longer periods than boreholes with shorter projections. Although the average parallel horizontal projections are similar for the modified cross-measure boreholes in both headgates, the average parallel horizontal projection is 41 m greater for the top performing Panel 3 boreholes, and; (e) modified cross-measure boreholes with shorter perpendicular horizontal projections over the longwall gob are as effective as boreholes with longer projections. The average horizontal perpendicular projection is 33 m less for the Panel 3 modified cross-measure boreholes than the Panel 2 boreholes.

3.3 Best Performing HGBs at WLM1

The best performing modified cross-measure boreholes developed from the headgate of Panel 3 were directionally drilled as presented in profile on Figure 6a, and in plan view on Figure 6b. The best performing HGBs produced at an average gob gas flow rate of 64.2 l/s at an average concentration of less than 2 percent oxygen at a wellhead vacuum of 6.8 kPa for an average time on line of 42 days.

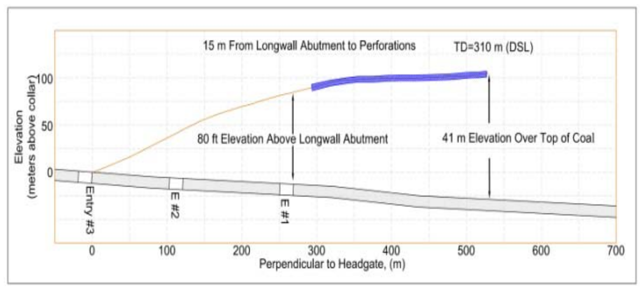

Figure 6a: Cross-section of the best performing headgate modified cross-measure boreholes at WLM1.

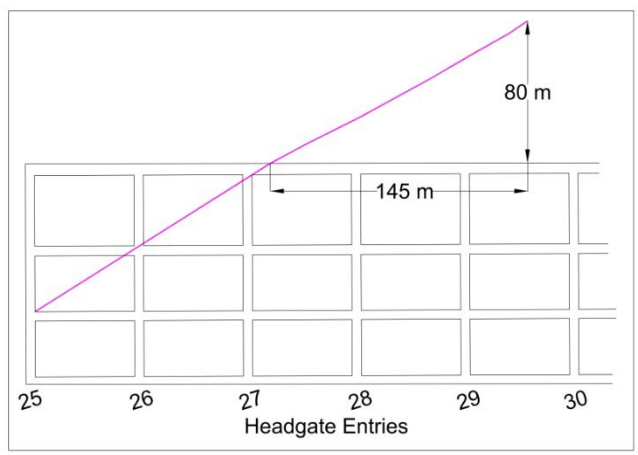

Figure 6b: Plan view of the best performing headgate modified cross-measure borehole at WLM1.

3.4 Correlating Measured with Calculated Gob Gas Flow Rates

Equation 1 was used to correlate calculated gob gas flow rates with measured rates for the best performing modified cross-measure holes at the WLM1. The measured data was matched for each best performing modified cross-measure borehole during peak flow conditions. Calculations were performed assuming no reservoir pressure contribution on the gob side of the borehole, 101.6 mm borehole diameters (internal diameter of the perforated steel pipe in the 146 mm diameter boreholes), and by adjusting the friction factor to match calculated flow with measured flow. The average friction factor calculated for the best performing modified cross-measure boreholes is 0.0543. This friction factor was used to compare the calculated gob gas flow rates with the average of the measured gob gas flows as shown on Figure 7.

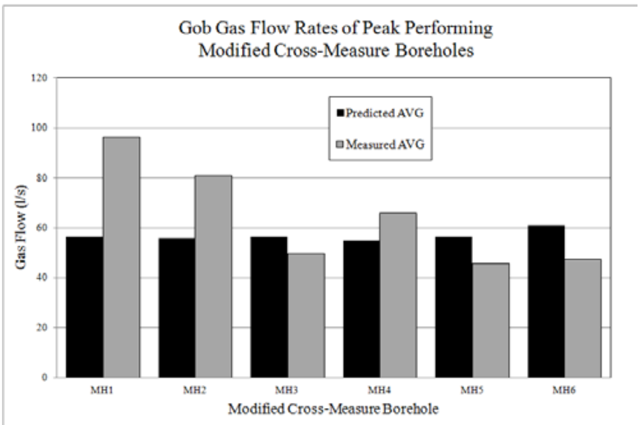

Figure 7. Measured vs. predicted average gob gas flow for best performing modified cross-measure boreholes.

The average friction factor derived for the modified cross-measure boreholes (0.0543) is significantly greater than the friction factor obtained from the Willow Creek analyses for the HGBs placed along the longitudinal length of the panels (0.0200). This difference is attributed to using the internal diameter of the steel liner (102 mm) as the diameter of the entire borehole in the gas flow calculations, rather than an effective diameter to account for the perforated steel liner installed inby the longwall abutment in a 146 mm diameter borehole. The friction factor derived is essentially an "effective" friction factor for the perforated liner configuration employed at the WLM1.

4 High Capacity HGBs at Western U.S. Mines

Improvements in downhole directional drilling technology allow for development of high capacity HGBs at larger diameters. HGBs up to 150 mm diameter can be developed to 1,100 m and completed with slotted casing if necessary. Since the WLM1 underground gob degasification effort, REI implemented HGBs at three other western longwall mines. Applications include installation of the longest high capacity HGB in the U.S. to date (146 mm diameter, lined with slotted lining to 920 m, 121 mm diameter un-lined to a final depth of 1009 m, and placed along the longitudinal axis of a longwall panel), a dual purpose HGB, 96 mm diameter drilled to 432 m in an overlying coal seam 24 m above the mining seam, also developed along the longitudinal axis of a longwall panel, and numerous 96 mm un-lined modified cross-measure boreholes developed from tailgate entries.

4.1 High Capacity HGB Gob Gas Flow Projections

The parameters that have the most impact on HGB gob gas flow rates are borehole diameter, length, and wellhead vacuum (and reservoir pressure contribution), while the parameters that have the most impact on HGB effectiveness, are vertical placement above the longwall panel, lateral placement relative to tension zones along the gob, and wellhead/stand-pipe integrity.

Using the gob gas flow calculations and friction factors derived from correlations performed with actual data, gob gas flow estimates were derived for high capacity HGBs at currently achievable diameter and length configurations for varying wellhead vacuum pressure assuming a gob gas concentration of 70 percent methane in air. Figure 8 illustrates the incremental increase in gob gas flow capacity as a function of wellhead vacuum and diameter for a 1,000 m HGB at 96 mm (standard configuration), and for two high capacity (or enhanced) HGBs at diameters of 121 mm, and 146 mm. These are un-lined configurations. Figure 9 presents the estimated capacity of 300 m modified cross-measure boreholes at 96 mm (standard) diameter, 127 mm (high capacity) diameter, and 152 mm (high capacity) diameter. These are all lined (perforated steel) configurations. The high capacity options for both the HGBs placed along the longitudinal axis of longwall panels, and the modified cross-measure boreholes, increase gob gas recovery rates at up to 3 times that of standard configurations.

4.2 Applying High Capacity HGBs in the West

Western U.S. coal mine operators should consider the following guidelines when considering HGBs for gob degasification:

Longitudinal HGBs: To determine the most efficient means of gob degasification relative to other means, or to determine the required number of HGBs per panel (longitudinal to the longwall panel) consider that high capacity HGBs, approximately 1,000 m in length, recover approximately 15,000 m^3 of gob gas per day under high vacuum.

Modified Cross-Measure Boreholes: Layout modified cross-measure boreholes to overlap so that the end of a subsequent borehole is undermined prior to complete under-mining of the previous borehole. In considering the modified cross-measure borehole technique, assume that an enhanced cross-measure borehole will recover approximately 10,000 m^3 of gob gas per day. Depending on collar integrity, typically several modified cross-measure boreholes will be in operation at any one time.

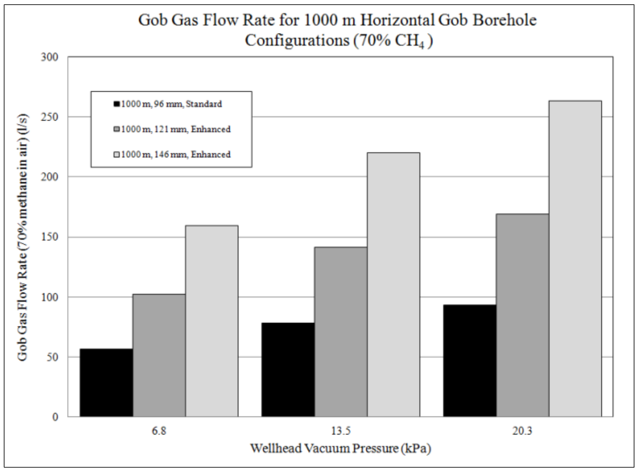

Figure 8. Gob gas flow rate projections for high capacity HGB configurations at varying wellhead vacuum.

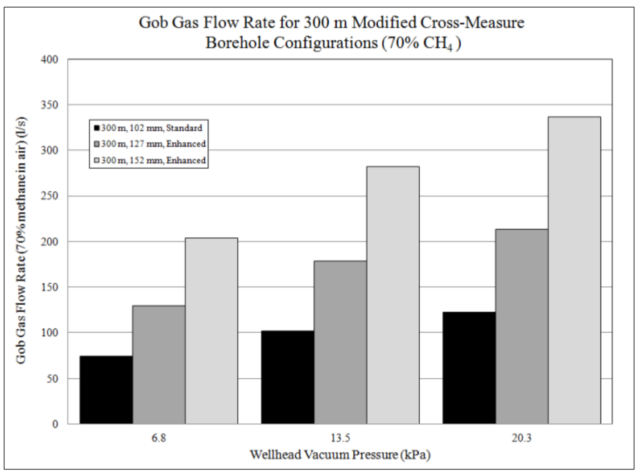

Figure 8. Gob gas flow rate for high capacity modified cross-measure borehole configurations at varying wellhead vacuum.

Optimal vertical placement of the boreholes: This will require trial and error and more than one panel and more than one HGB or modified cross-measure borehole to optimize. At most western U.S. mines, the rubble zone extends between 3 to 4.5 times the mining height, and the fracture zone potentially up to 35 times the mining height, depending on geomechanical conditions, mining plans (panel dimensions), and depth to surface. At most western U.S. mines HGBs remain intact over the gob at an elevation of over 25 m above the mining seam.

Drilling locations: These are often dictated by mine plans, however, proposed locations must consider handling of gas emissions during drilling (diffusion zone or gas collection system), the gas collection route (will need to be a return air course), and timing of mine developments. Proposed drilling locations should consider the ability to directionally steer over adjacent entries and achieve high elevation targets over the longwall abutment, particularly for HGBs drilled from gate-roads, and for modified cross-measure boreholes.

Dual purpose HGBs: Depending on elevation with respect to the mining seam, western U.S. operators should consider HGBs placed in overlying seams to reduce the in-situ gas content of these gob gas contributing source seams in advance of longwall mining, and then subsequently use these boreholes to recover gob gas during under-mining.

Borehole lining: Improves the viability of overlying HGBs. Larger diameter HGBs can accommodate perforated steel casing and remain intact even when placed too low over the mined panel. HGBs should be lined for single hole implementations, e.g. where drilling multiple HGBs at varying elevations for optimization is not feasible. Modified cross-measure boreholes, or HGBs drilled from gate entries should be lined with solid steel casing to inby the longwall abutment, approximately 15 m (perpendicular distance from abutment).

Target strata tension zones: HGBs and modified cross-measure boreholes should target strata that will be under tension after longwall mining, particularly the start, sides, and ends of longwall panels. Geomechancical characteristics, mining plans (panel widths), depth, and coal structure (dipping seams), determine the extent of these zones in the horizontal plane. At western U.S. mines, generally operators should place long longitudinal HGBs starting at 1/5th of the panel width along the up-dip tailgate side. The horizontal projection of modified cross-measure boreholes perpendicular to the longwall does not need to extend more than 1/3rd of the panel width depending on conditions (dip, panel width, drilling location relative to ventilation system (headgate or tailgate)).

Monitoring: HGBs need to be connected to a pipeline system under vacuum. Every borehole collar should provide for monitoring of shut-in pressure, vacuum pressure, gas velocity, and gas quality (obtain gas samples and measure gas concentration indirectly (oxygen, for example)) in order to optimize future installations. At some western U.S. mines shut-in pressures prior to under-mining can be very high and care should be taken to insure use of properly rated fittings. These Boreholes should be connected to the collection system to produce free gas or desorbed gas prior to under-mining as feasible.

5 Summary and Conclusion

In-mine directional drilling techniques provide western U.S. coal mine operators an alternative approach to gob degasification. In many cases HGBs can displace conventional techniques and provide a lower overall cost approach. Applying HGBs requires careful consideration as borehole placement, including collar location, in particular for HGBs implemented from gate entries, or as modified cross-measure boreholes, can significantly impact effectiveness. The ability to increase diameter with advances in directional drilling technology increases the capacity of HGBs. Lining HGBs with solid and perforated steel casing improves their use for post-mining gas recovery, and improves the success of the technique.

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