U.S. EPA Coalbed Methane Outreach Program

Coal Mine Methane Recovery:

A Primer

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ABSTRACT

This Coal Mine Methane (CMM) Recovery Primer is an update of the 2009 CMM Primer, which reviewed the major methods of CMM recovery from gassy mines. [USEPA 1999[b], 2000, 2001[a,b,c]] The intended audiences for this Primer are potential investors in CMM projects and project developers seeking an overview of the basic technical details of CMM drainage methods and projects. The report reviews the main pre-mining and post-mining CMM drainage methods with associated costs, water disposal options and in-mine and surface gas collection systems. Updates from previous EPA reports include advances in mining and CMM drainage techniques, directional drilling technologies (from the surface and in-mine), costs of the various drainage methods, and references to the latest research papers and presentations covering CMM drainage issues.

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GLOSSARY OF TERMS

Casing: Sections of steel tubing, slightly smaller than the diameter of the wellbore, placed in the hole and cemented in place to prevent collapse of the wellbore. Casing seals off any water bearing strata that have been drilled through, protecting potential water sources and preventing the wellbore from filling with water. Casing also seals any gas bearing strata, preventing gas flow into the wellbore until it can be produced in a controlled environment.

Coalbed methane (CBM): Methane that resides within coal seams. The equivalent term in Australia is "coal seam gas" and in the United Kingdom is "firedamp". In the U.S., CBM production is defined as methane extracted from coal seams that have not been disturbed by mining. Outside the U.S., methane production from undisturbed coal seams is sometimes referred to as "virgin CBM" or VCBM.

Coal mine methane (CMM): Methane released from coal and surrounding rock strata as a result of mining activity. In some instances, methane that continues to be released from the coal bearing strata once a mine is closed and sealed may also be referred to as coal mine methane because the liberated methane is associated with past coal mining activity. This methane is also known as "abandoned mine methane" (AMM).

Degasification system: A system that facilitates the removal of methane gas from a mine by ventilation and/or by drainage. However, the term is most commonly used to refer to removal of methane by drainage technology.

Drainage system: A system that drains methane from coal seams and/or surrounding rock strata. These systems include vertical and directionally drilled pre-mine wells, gob wells, and in-mine boreholes.

Hydraulic fracturing: (frac, fraccing) In this report, hydraulic fracturing refers to the process of pumping a gas or liquid into a wellbore at high pressure, in an attempt to induce fracture creation in a gas bearing geologic horizon. These fractures provide a conduit for gas flow from the reservoir formation to the wellbore and then to the surface.

Gateroads: Access roadways (tunnels) in an underground coal mine, connecting the longwall working face with the main roadways.

Gob (goaf): The area of unconsolidated rock behind an underground coalface, that forms when overlying strata falls into the void left by mining of the coal seam.

GLOSSARY OF TERMS

Headgate: An access tunnel to the longwall face. It usually contains the conveyor belt that carries mined coal from the longwall face to the main roadways. It is also the intake airway for ventilation air to the longwall face. Can also be termed the "maingate".

Methane drained: The amount of methane removed via a drainage system.

Methane emissions: The total amount of methane that is not used and therefore emitted to the atmosphere. Methane emissions are calculated by subtracting the amount of methane used from the amount of methane liberated (emissions = total methane liberated – methane used or destroyed).

Methane liberated: The total amount of methane that is released, or liberated, from the coal and surrounding rock strata during the mining process. This total is determined by summing the volume of methane emitted from the ventilation system and the volume of methane that is drained.

Methane recovered: The amount of methane that is captured through methane drainage systems.

Methane used: The amount of captured methane put to productive use (e.g., natural gas pipeline injection, fuel for power generation, etc.).

Tailgate: An access tunnel to the longwall face situated on the opposite side of the coal panel to the headgate. The tailgate commonly acts as the return airway from the coal face and as a supply road to the face.

Ventilation system: A system that is used to control the concentration of methane within mine working areas. Ventilation systems consist of powerful fans that move large volumes of air through the mine workings to dilute methane concentrations to “safe” levels.

ABBREVIATIONS

Unit Abbreviations

^oC	degrees Celsius
^oF	degrees Fahrenheit
$	United States Dollar
Bbl	barrel
Bcf	billion (10^9) standard cubic feet
Bcfd	billion (10^9) standard cubic feet per day
Bcm	billion (10^9) cubic meters
Btu	British thermal unit
D (d)	day
ft	feet
in.	inch
km	kilometer
kPa	kilopascal (10^3 Pa)
m	meter
m^3	cubic meter
Mcf	thousand (10^3) standard cubic feet
Mcfd	thousand (10^3) standard cubic feet per day
Mcm	thousand (10^3) cubic meters
Mcmd	thousand (10^3) cubic meters per day
md	millidarcy (10^{-3} D)
mm	millimeter (10^{-3} m)
MMcf	million (10^6) standard cubic feet
MMcfd	million (10^6) standard cubic feet per day
psi	pounds per square inch
scf	standard cubic feet

Other Abbreviations

ARI	Advanced Resources International, Inc.
CBM	Coalbed Methane
CH_4	Methane
CMM	Coal Mine Methane
CO_2	Carbon Dioxide
CO_2eq	CO_2 Equivalent
ECBM	Enhanced Coalbed Methane
HDPE	High Density Polyethylene
ID	Inner Diameter
IPCC	Intergovernmental Panel on Climate Change
MTCO_2e	Million tonnes CO_2 equivalent
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
U.S.	United States of America
USDOE	U.S. Department of Energy
USEPA	U.S. Environmental Protection Agency

1. Introduction

Coal mine methane (CMM) is gas released from coal or surrounding rock strata during and after coal mining. As such, it is considered a mining hazard, a greenhouse gas, and a possible energy source.

CMM as a Mining Hazard.

Methane is explosive in concentrations of 5-15% volume in air and has been the cause of devastating mine explosions around the world throughout the history of coal mining. Modern coal mine operators try to control methane concentrations at the working faces, and throughout the mine, through the implementation of a well-designed ventilation system.

Over the past few decades, emissions of methane from coal mines have increased significantly because of higher mining productivity; the trend towards recovery from deeper, gassier coal seams; and greater pulverization of the coal. When methane emissions into the mine workspace are greater than the ventilation system alone can dilute or remove, methane concentrations may rise above mandated safety levels and production must be halted. Adding additional ventilation capacity is one solution to increase in-mine methane emissions, but eventually, this becomes economically or technically infeasible.

To stay within mandated in-mine methane concentration limits, some coal mines install degasification systems to supplement the ventilation system. Drainage boreholes are drilled from the surface, or from within the mine, to extract as much methane as possible from coal seams and surrounding strata, before, during, and after mining, so as to lower methane concentrations in the mine workings.

CMM as a Greenhouse Gas.

Methane released to the atmosphere is a significant greenhouse gas that contributes to climate change and has a global warming potential 25 times greater than carbon dioxide over 100 years [IPCC, 2007]. The U.S. Environmental Protection Agency (USEPA) estimates that coal mine methane contributes 8% of man-made methane emissions worldwide [USEPA, 2012]. Since 1994, the USEPA has been implementing a voluntary climate change program to promote the profitable recovery and use of CMM (www.epa.gov/cmop).

As of 2014, 15 countries have active mines employing some form of CMM recovery and utilization project [GMI, 2016]. Worldwide, there are more than 200 CMM drainage projects in place resulting in greater than 1.7 Bcm (59.5 Bcf) of methane emissions avoided per year.

China, USA, Russia, Ukraine, Australia and Kazakhstan are the top six emitters of CMM as shown in Exhibit 1.

Country	Methane Emissions			Coal Production		
	Rank	Emissions Volume		Rank	Surface mining %	Underground mining %
		MMTCO$_2$e	Billion m^3			
China	1	295.5	17.4	1	10	90
USA	2	67.5	4.0	3	65	35
Russia	3	48.8	2.9	6	1	99
Ukraine	4	29.7	1.7	14	56	44
Australia	5	27.2	1.6	4	80	20 (NSW 59)
Kazakhstan	6	22.3	1.3	9	85	15

Exhibit 1: Global methane emissions from coal mining (2010)
[USEPA, 2012]

CMM as an Energy Source.

CMM is primarily composed of methane, a valuable, clean energy source. CMM may also contain nitrogen, carbon dioxide, ethane, propane and water in varying quantities. When CMM is diluted by ventilation air, oxygen will also be present. Different CMM recovery methods produce varying concentrations of methane at the surface collection points.

The quality of recovered methane is measured by its calorific (or heating) value, expressed in kilocalories per cubic meter (kcal/m^3) using the metric system, and British thermal units per standard cubic feet (Btu/scf) using the Imperial system. Pure methane has a calorific value of approximately 8900 kcal/m^3 (1000 Btu/scf); while a mixture of 50% methane and 50% air has a calorific value of about 4450 kcal/m^3 (500 Btu/scf).

There are a number of possible end uses for CMM depending on its methane concentration (heating value). High quality gas, with a calorific value normally greater than 8455 kcal/m^3 (950 Btu/scf), is acceptable for injection into natural gas pipelines, where it has many domestic and industrial end uses. Lower quality gas, which is diluted with air, can be used at the mine site in internal combustion engines or gas turbines for electricity production. It can also be used to heat mine buildings or dry coal in a coal processing facility. These applications require a caloric value of only about 2670 kcal/m^3 (300 Btu/scf).

1.1 Coal mining practices

Coal can be mined at the surface (“opencast mining”) or underground, depending on the depth of the seam, or seams, to be extracted. Approximately 60% of world coal production is produced from underground mines (Exhibit 1).

Surface mining is viable when coal is relatively near to the surface, typically less than 100 m (350 ft) deep. The overburden of soil and rock is broken up and removed with large draglines or by shovels and trucks. The exposed coal is drilled, fractured and excavated in a succession of strips and then transported via truck or conveyors to the coal preparation facility. It is possible to extract coal seams as thin as 100 mm (4 in) and recover 90% or more of the coal deposit. Opencast mines can cover an area of many square kilometers.

Underground mining is carried out by two principal methods: longwall mining and room and pillar mining. Almost all modern, high-production mines use a retreat longwall method of mining.

Longwall mining involves the extraction of coal from a large ‘panel’ developed in the target seam. Mining machines, called ‘continuous miners’, develop the sides of the longwall panel by driving parallel tunnels, called ‘entries’ or ‘gates’, into the seam from the mine’s main entries. The outline of the panel is completed with a connecting tunnel between the ‘gates’ which becomes the working face (Exhibit 2). In favorable geologic locations in the U.S, longwall panels have been developed up to ~440 m (1,450 ft) wide and ~3,960 m (13,000 ft) long [Karacan et al., 2007].

A mechanical shearer is mounted on a series of self-advancing, hydraulically powered ceiling supports and shears the coal in repeated passes from the longwall face. The coal falls onto a conveyor belt and is transported to the surface. As the shearer moves forward to cut the next swath of coal, the ceiling supports follow and the roof behind the supports collapses, forming the gob (also known as goaf). Mining back towards the main entries in this way is termed ‘retreat longwall mining’ and over 75% of the coal in the deposit can be extracted using this method.

Room and pillar mining is generally used at shallower depths and where the geology of the coal seam is too complex for longwall mining. Coal is extracted using a continuous miner that cuts a network of rectangular ‘rooms’ in the seam. Up to 60% of the coal can be recovered, with the remaining 40% forming ‘pillars’ which support the mined out rooms. These pillars can be mined as the final stage in the extraction of the section.

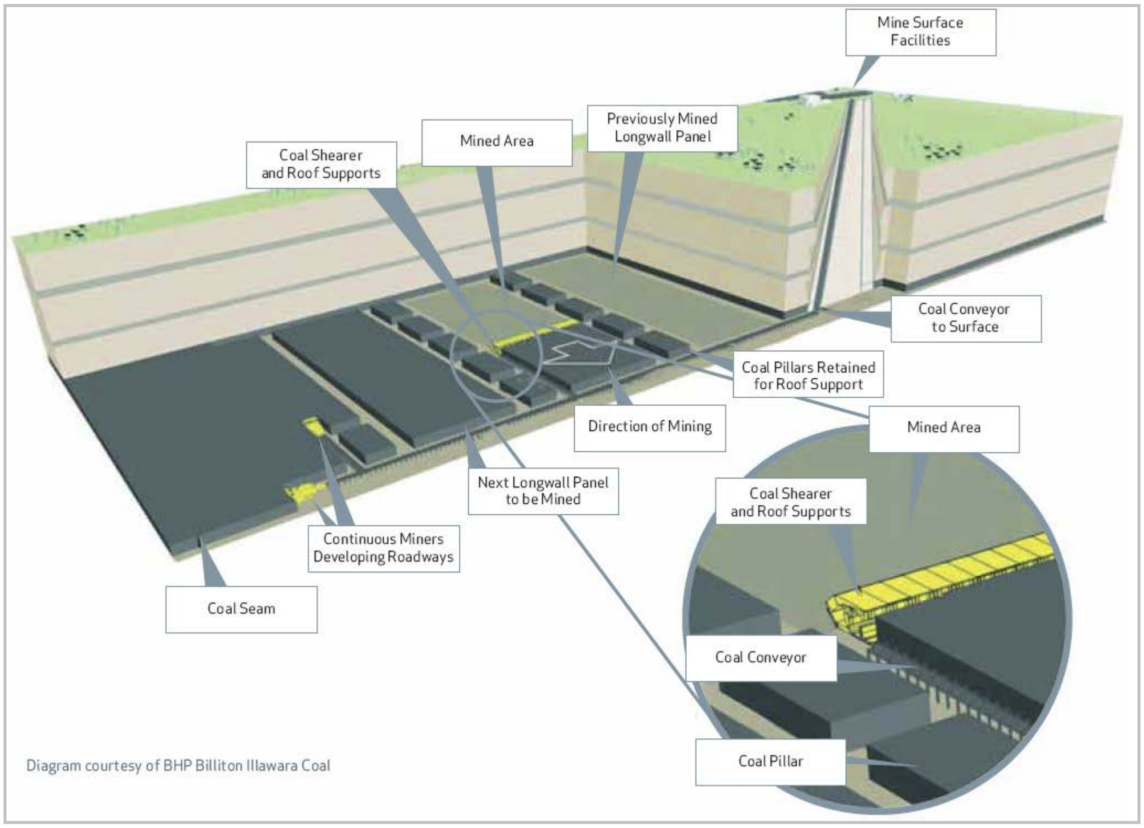

Exhibit 2: Retreat longwall mining
[World Coal Institute, 2005]

1.2 Methane generation, retention and migration in coal

This section briefly summarizes the key factors that influence methane's formation and movement through coal seams.

Coal formation and methane generation

Coal seams form over millions of years from layers of plant material that decay in swamp and marsh-like conditions to form peat. As the peat is covered with sediments and buried more deeply, it is subjected to heat and pressure, which forces water, oxygen, nitrogen, carbon dioxide, and hydrocarbon gases out of the organic matter, increasing its carbon content and forming coal. Large volumes of methane are generated during this coalification process, most of which escapes to the surface at shallow depths, but if the coal is deeply buried, the increased hydrostatic pressure helps the coal to retain the methane.

Coal cleat

Cleat is a coal miners' term for the natural system of vertical fractures generated by local tectonic forces and the shrinkage of the source plant material during the coalification process.

The dominant fracture orientation is called the “face cleat” and the secondary, perpendicular fractures are termed “butt cleats”. Face cleats can be spaced from one tenth of an inch to several inches apart [Steidl, 1996] and are important pathways for methane migration through the coal.

Methane retention

Methane is stored mainly in the matrix of the coal and partly in the fracture spaces (cleat). Matrix porosity largely determines the ability of coal to retain methane [Steidl, 1996]. Methane molecules are packed tightly as a monolayer on the large internal surface area of coal (adsorption) and are held there by hydrostatic pressure. A cubic foot of coal can contain six to seven times the volume of natural gas that exists in a cubic foot of conventional sandstone reservoir.

Methane migration

When the hydrostatic pressure in coal is reduced (i.e., during mining or by a drainage borehole), the methane desorbs from the micropores of the coal matrix, diffuses through the matrix and flows through the cleats (Exhibit 3).

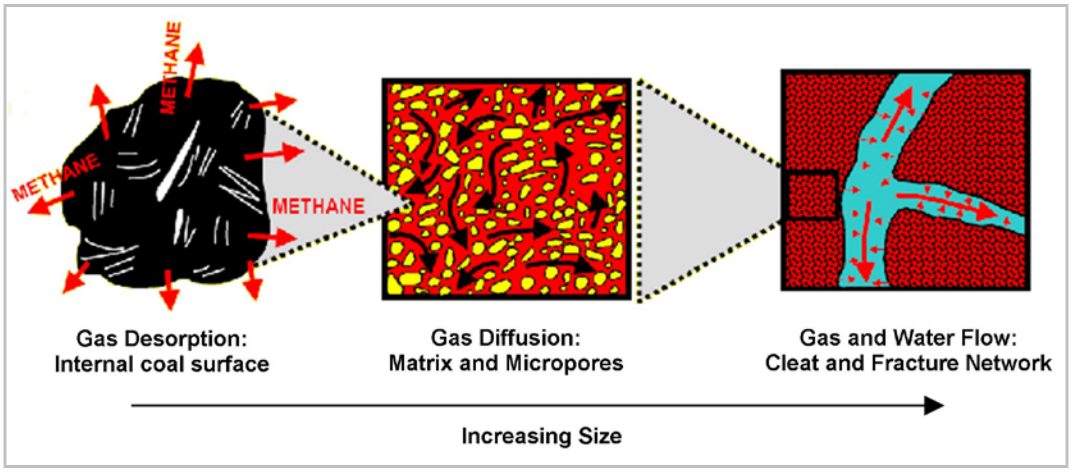

Exhibit 3: Methane migration in coal
[USDOE, 2003]

1.3 Emissions of methane in coal mines

The pattern of methane release from the coal seam and surrounding strata is controlled primarily by the mining method, the location of the gas in the seam and surrounding strata, and the permeability of the relevant strata. During room-and-pillar mining, methane is released from within the coal as the entries and crosscuts are developed. Methane also emanates from the roof and floor during the pillar recovery process as the overlying strata subside and the underlying strata heave. This process also occurs during longwall mining with the geometry of the panels also affecting methane emissions.

In longwall mining, methane can be emitted directly from the longwall face and from mined coal being taken to the surface. Lower pressures in the mining area, compared to the surrounding strata, causes migration of gas from the surrounding strata into the mine workings. A large source of emissions comes from the gob (or goaf) formed when overlying strata collapses into the void left by longwall mining.

Methane emissions into a mine normally occur at a steady rate, but geologic discontinuities such as faults, clay veins and igneous intrusions, along with other geologic features such as floor feeders, sandstone paleochannels and localized folding, can all be responsible for sudden, potentially dangerous, unusually high emissions [Ulery, 2008].

1.4 Methane control by ventilation

All the major coal-producing countries mandate maximum methane concentrations of 1.0-1.25% at the coal face and within the mine workings [Thakur, 2006]. Coal mine operators try to control methane emissions by using large fans to circulate large volumes of air throughout the mine workings. The ventilation air dilutes methane concentrations and carries the methane to the surface via 'bleeder entries' and ventilation shafts (Exhibit 4).

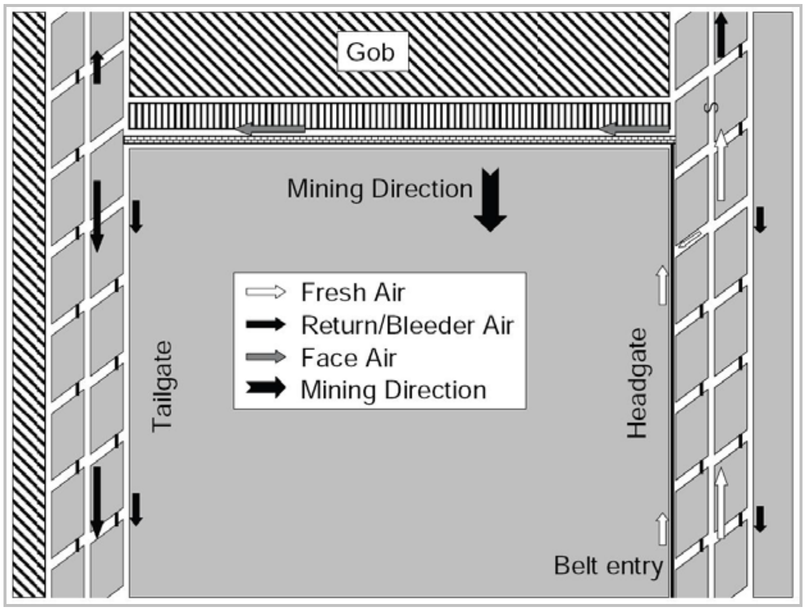

Exhibit 4: Typical ventilation configuration at a U.S. longwall mine [Schatzel et al., 2008]

1.5 Overview of methane drainage practices

In this report, methane drainage techniques are divided into two main groups - techniques that *reduce the gas content of the coal seam* prior to and during mining, and those that *reduce the volume of gob gas entering the mine workings* during and after mining. These groups can be further subdivided into techniques that originate from the surface and those that originate from within the mine workings.

Techniques that reduce coal seam gas content in advance of mining include:

- Vertical boreholes drilled from the surface;
- In-seam boreholes drilled from within the mine – “short hole” and “long hole”;
- Superjacent boreholes drilled directionally from within the mine;
- Horizontal in-seam boreholes drilled directionally from the surface.

Chapter 2 describes each of the above techniques to reduce coal seam gas content.

Techniques for capturing gob gas include:

- Vertical gob wells
- Superjacent boreholes
- Cross-measure boreholes

Chapter 3 summarizes each of the above methods that capture gob gas.

In practice, a combination of these methods is used to degasify coal seams as much as possible before they are mined, and to decrease the amount of emissions from the gob into the ventilation system during mining. The design of the methane drainage system should be governed by the quantity of methane being generated, the geology of the coal seam and surrounding strata, the pattern of emissions, the mining-related costs associated with the methane, and the potential for obtaining revenue from the gas generated. The drainage system design may require adjustment on a continuing basis to ensure that the methane capture system is optimized as the mine develops over time.

2. CMM drainage techniques to reduce in-situ gas content

Decreasing methane flow into mine workings during coal production can be achieved by reducing the gas content of the coal and adjacent gassy strata before mining begins. Where reservoir characteristics are favorable, for example where coal seams have sufficient permeability and rapid diffusion rates, gas can be drained rapidly from large areas. With low permeability coal and/or coal with slower diffusion rates, gas drainage should be started as far in advance of mining as possible.

The main methods of pre-mining degasification are:

- Vertical boreholes drilled from the surface;
- In-seam boreholes drilled from within the mine -“short hole” and “long hole”;
- Superjacent boreholes drilled directionally from within the mine;
- In-seam boreholes drilled directionally from the surface.

2.1 Vertical wells

The term “vertical well” is generally applied to a well drilled from the surface through the target coal seam or seams, which is then cased and hydraulically fractured to pre-drain as much methane as possible prior to mining. Wells are generally placed in operation from 2 to 10 years ahead of mining.

The water in the coal seams must be removed to lower hydrostatic pressure and allow methane to desorb from the coal matrix and flow via the cleat system to the well. This water is separated from the produced gas and then treated and/or disposed of in an environmentally acceptable manner (see Section 2.4). The gas passes through a separator near the well head to remove excess water before being piped to a processing facility to be compressed and dehydrated (Exhibit 5).

Vertical wells offer an advantage over other pre-mining drainage techniques in that they can drain multiple coal seams simultaneously. Under the right conditions, these wells can produce pipeline quality gas with minimal processing and in sufficient quantities to make them economically viable.

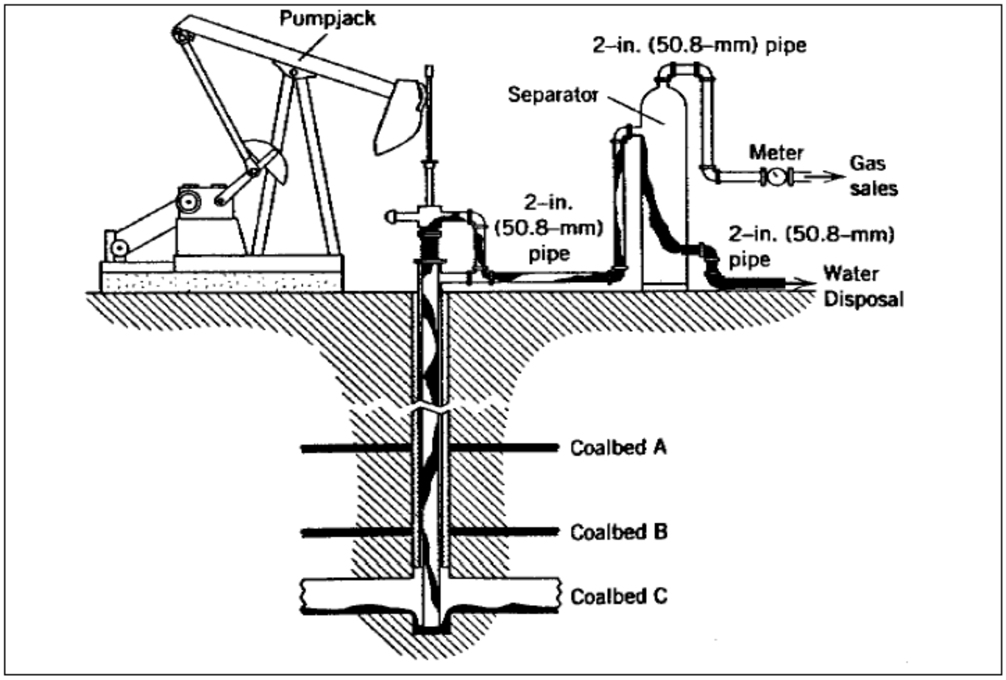

Exhibit 5: Typical vertical well setup[1]

In all of the major U.S. coal bed methane basins (Exhibit 6), vertical wells are used to commercially extract methane from un-mined coalbeds (i.e., in projects that are not associated with coal mining). In the context of coal mining, four of the twenty-five gassiest underground mines in the U.S. use vertical wells at pre-mining degasification projects in Alabama and Virginia (USEPA, 2018[a]).

The use of vertical wells for pre-mine degasification is not as prevalent in the rest of the world, although there is increasing interest in a number of countries, including China and India. High cultural development density makes finding suitable surface drilling locations difficult. Surface constraints, coupled with generally higher drilling costs, are two of the main reasons that vertical well technology has not seen widespread application outside of the U.S.

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[1] Source: Hartman et al., 1997. Copyright 1997, John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.

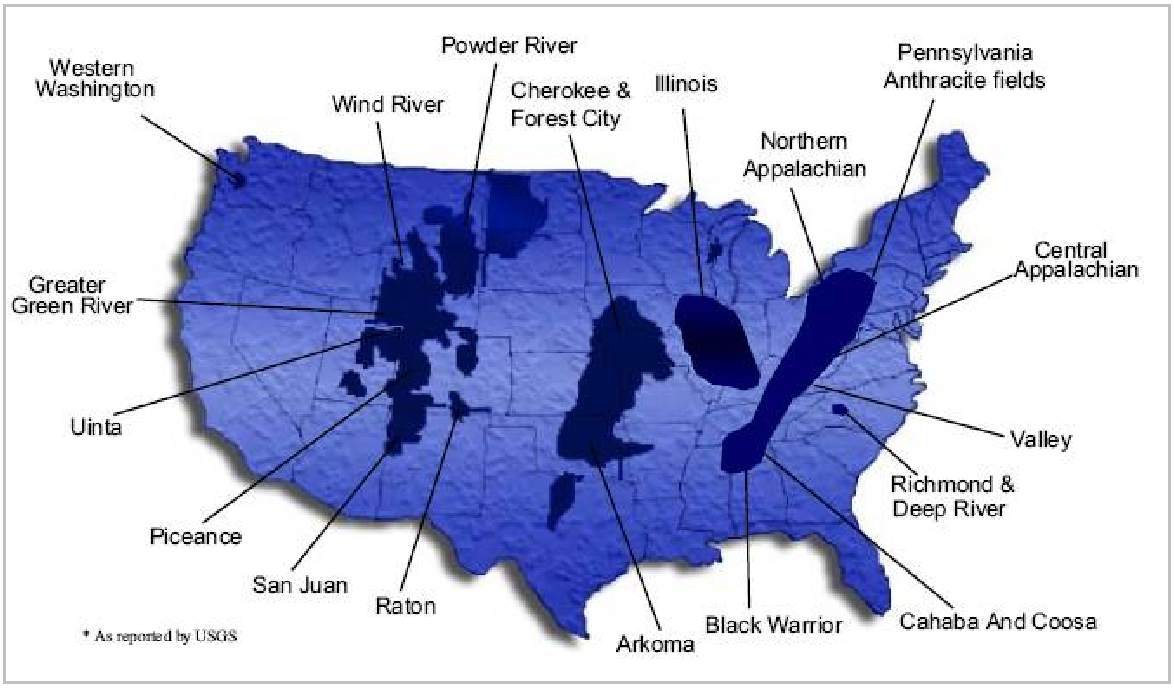


Exhibit 6: Major U.S. CBM basins

[Source: USDOE]

2.1.1 Planning and design

A detailed study of the coal geology of a mine area, created with the use of coal thickness and structure maps, is the first step in planning the location of pre-mining drainage well sites. An optimized well pattern will take into account the mine development plan, the planned time before mining intercepts the well, reservoir characteristics, completion effectiveness, well stimulation effects, and drilling, completion and operating costs [Rodvelt et al., 2008]. The final well pattern will be a compromise between the best theoretical plan and economic and technical realities.

The area of the coal seam drained by a vertical well has been studied by Zuber, Kuuskraa, and Sawyer [1990]. This study examined vertical wells in the Oak Grove field in Alabama, U.S.A. and found that well spacing varying from 40 to 160 acres was optimal under the assumed conditions with closer spacing being optimal for lower permeability areas (below 10.0 md). Typical well spacing in the Alabama coal fields is about 40 acres with 3 to 7 wells placed in each projected longwall panel. Similar results were reported by Richardson, Sparks, and Burdett [1991].

Spacing of vertical wells in CBM projects tends to be larger than spacing for CMM projects. Vertical CBM wells in the San Juan Basin in the U.S. (see Exhibit 6) are typically drilled on a 160-320 acre spacing, with 160 acre spacing being the standard in the Uinta and Raton Basins, and 80 acres the typical spacing of wells in the Arkoma and Powder River Basins. Operators of vertical wells must strike a balance between the economics of the well and the main aim of reducing the methane content of the target coal seam as much as possible in the time available. If time before mining is relatively short, then wells should be spaced closer together to drain gas faster, but this increases the number of wells needed for drainage and the overall cost of the project.

Vertical wells drilled into virgin coal seams often produce large amounts of water and only small amounts of methane during the first several months in operation. As more water is removed, and the hydrostatic pressure in the coal seam is lowered, methane production increases. Vertical wells are usually spaced on a regular grid pattern, such that drainage radii overlap, to efficiently enhance the dewatering process and reduce the coal seam hydrostatic pressure. Adjustments to the grid pattern are made to accommodate any well site location problems caused by surface topography or habitation.

Example

- CNX Gas Corporation has considered the problem of balancing optimum well spacing, time before mining, and costs, at the Buchanan and VP 8 mines formerly owned by Consol Energy, in the Oakwood coal field in Virginia. CNX opted for an advance drainage time frame that adequately balanced the risk of investing in a vertical pre-mine drainage system with that of Consol's mining plans. Thus, a three to five year advance degasification program was used to the extent that it could be feasibly coordinated with overall mining strategies [USEPA, 2008[b]]. CNX drilled wells on 40 acre spacing in the Oakwood field and 60 acre spacing in the Middle Ridge field, and they also evaluated results from drilling 53 wells on 30 acre spacing in 2007 and Investigated the viability of drilling on 20 acre spacing [CNX, 2007].

2.1.2 Well bore completion

Once a well bore has been drilled, the hole is "completed" by lining it with steel casing and cementing it in place. This prevents the well bore from collapsing and seals the well bore from potential water ingress. Completions are broadly classified as either "open hole" or "cased hole".

Open-hole – The most basic type of wellbore completion is to drill through the target coal seam and case to a point just above the seam. This is an "open hole" completion and can only be used when the uncased well bore wall consists of competent geologic formations that are unlikely to collapse.

Cased hole - A typical vertical CMM drainage well is drilled through the target coal seam and cased with steel pipe, with a section (joint) of fiberglass pipe used to case across the seam to be mined. This joint maintains borehole stability in the coal during stimulation, but can be mined through safely when production mining reaches the wellbore. After mine through, the vertical well can, in some cases, continue to drain methane, operating as a gob well.

Final casing sizes and completion type depends on a number of factors including the following:

- Depth of the targeted coal seams;
- Number of seams to be stimulated;
- Maximum water production required to dewater the coals;
- Reservoir pressure of each drained coal seam.

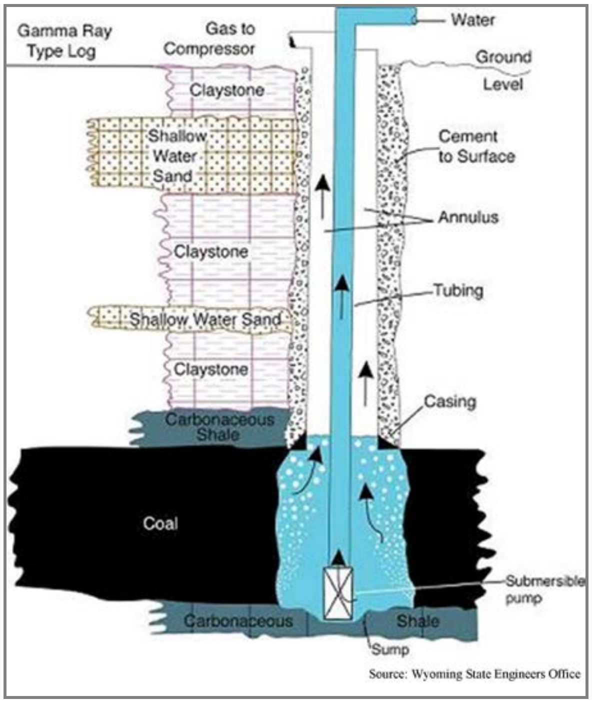
Example

- Successful completions in the Appalachian Basin often cement 18 mm (7 inch) diameter surface casing to depths of 30-90 m (100-300 ft) to protect shallow water sources. 114 mm (4.5 inch) production casing is then set to the bottom of the borehole. The borehole is drilled deeper than the target coal to produce a sump or “rat hole” which allows production equipment to be installed below the target seam.

Under-reamed - If suitable geologic conditions exist, an additional stage to open-hole completions can be added to widen the borehole where it intersects the target coal. After casing is set and cemented to the top of the coal, a special reaming tool with rotating blades, jets or drill cones, is used to ream out a cavity in the coal. Under-reaming is a technique that can be applied to multiple seams. Once the wellbore has been widened at each seam, slotted casing is inserted across the coal interval and, where needed, gravel is packed between the walls of the cavity and the casing to keep the cavity open.

Examples

- Under-reaming is a common completion method in coal bed methane projects in the Powder River Basin, U.S.A., where boreholes are widened from 158 mm (6.25 in.) in diameter to ~355 mm (~14 in.) [Colmenares and Zoback, 2007]. After under-reaming, the well is cleaned out with a fresh water flush. A down-hole submersible pump produces water up the tubing while the gas that separates from the water is produced up the annulus (Exhibit 7).
- Under-reaming also takes place in the shallow, high permeability coal seams of the Surat Basin, Australia, where the well completion of multiple seams has been demonstrated.



Source: Wyoming State Engineers Office

Exhibit 7: Under-reamed CBM completion

2.1.3 Stimulation technologies

Most vertical wells do not produce gas until the permeability of the coal seam reservoir is enhanced through stimulation treatment. Stimulation can also help remediate any damage to the reservoir caused by drilling and cementing fluids infiltrating the reservoir matrix, coal-cleats and natural fracture system.

Hydraulic fracturing (often referred to as "fraccing" or "frac job") involves the creation of a single, planar, vertical fracture (except in shallow zones where horizontal fractures can be created) which extends in two wings (180 degrees apart) from a wellbore. The well casing is perforated at the coal to be fractured and a frac fluid (such as water, gel, or nitrogen foam) is pumped into the well. If subjected to sufficient pressure, the coal "cracks", forming a fracture that is extended by continued injection of fluid. A solid proppant[2], normally sand, is carried with the fluid. When injection ceases and the fluid flows back to the wellbore, the fracture is held open by the proppant left in-situ. Fractures can extend 60-150m (200-500 feet) from the wellbore and they create highly conductive flow paths for water and gas to migrate to the

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[2] The term “proppant “ refers to sized particles mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment. In addition to naturally occurring sand grains, man-made or specially engineered proppants may also be used. Proppant materials are carefully sorted for size and sphericity to provide an efficient conduit for production of fluid from the reservoir to the wellbore. (Schlumberger Oilfield Glossary – www.glossary.oilfield.slb.com)

wellbore, and be produced to the surface. Multiple layers of coal can be stimulated by isolating each interval and running an individual frac job for each layer (Exhibit 8).

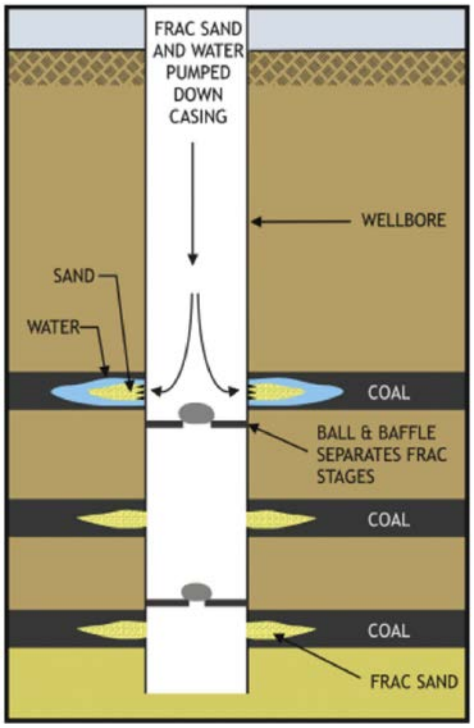

Exhibit 8: Hydraulic fracturing schematic
[Source: AGR Oil & Gas Services]

Cavitation - With this technique, the wellbore is completed using open-hole techniques, and the target coal seam is under-reamed. Using compressed air, the exposed coal is repeatedly pressurized and depressurized. The coal spalls of the face of the wellbore can break off, forming a cavity around the well bore. More expensive than hydraulic fracturing, this method has been used in suitably permeable seams that are overpressured in the San Juan Basin, U.S.A., but has found little application in other U.S. coal basins.

Potential problems - Water based fracturing fluid systems are not suitable for use on all coal seams and in some cases have the potential to create damage to the reservoir, and also introduce extra fluid into a system to be de-watered. Formation damage can take a variety of forms, including gel and chemical residue blocking the cleats and pore spaces of the reservoir or water-induced swelling of formation clays, both of which lead to a reduction in the relative permeability of the coal. Methods to address these problems have been the topic of considerable research, with focus on the use of carbon dioxide and nitrogen as fracturing fluids.

Carbon dioxide (CO_2) fracturing - CO_2 fracturing is discussed in this section, as a viable fracturing method for CBM wells. However, it is not appropriate for use in CMM wells draining active coal mines because high concentrations of CO_2 in the mine workings are a serious hazard to miners.

One approach to avoid formation damage associated with water-based fracturing systems altogether is fracturing with liquid CO_2, which is a non-aqueous, non-damaging fluid. In coal seams, this technique can also provide a small amount of production enhancement through the introduction of CO_2. Liquid CO_2 fracturing has a long track record in Canada.

The principal benefit of liquid CO_2 fracturing in coal reservoirs is identical to that for natural gas production wells - the elimination of formation damage and rapid cleanup. This may be particularly significant since many CBM wells require six to nine months of de-watering after fracture stimulation to clean-up and begin showing significant gas production.

Nitrogen (N_2) fracturing – Like CO_2, gaseous nitrogen is also a non-aqueous, non-damaging fracturing fluid and is also a viable stimulation technique for formations potentially sensitive to aqueous-based fracture fluid systems, such as coal seams. In this case, nitrogen is pumped as a cryogenic liquid and then heated to form a gas prior to being injected into the well. Fracturing mechanics are the same as other hydraulic fracturing techniques, the only difference being that the fracturing fluid is a gas. Pumping nitrogen as a gas normally eliminates the possibility of transporting proppants, and as such, nitrogen fracturing can be classified as a proppantless, nonreactive stimulation technique.

After fracturing using an aqueous-based fluid and proppant technique, the well must be cleaned of excess proppant and fluid that either did not enter the coal, or flows back out of the fractured coal. Many wellbore clean up operations involve using nitrogen to pump excess material from the well, and the process usually takes a minimum of one week and sometimes up to a month. Some CMM/CBM operators have indicated that the time for fluid clean up can be even longer, several months in some cases, and it is in these environments that nitrogen fracturing may be of greatest benefit.

The use of nitrogen as a fracturing fluid may also assist in the production of CMM/CBM through the enhanced production properties the nitrogen has with methane in the coal seam reservoir. The dry coals found in the Alberta Basin in Canada contain very little or no water and nitrogen is used extensively as a fracturing fluid to avoid adding water to the coal reservoir.

Coiled tubing fracturing - Coiled tubing is used in the oil and gas industry for a number of applications, including slimhole drilling, fishing operations, remedial treatments[3] and hydraulic fracturing. In coiled tubing operations, a continuous roll or “coil” of small diameter pipe (19-114 mm, 0.75-4.5 in.) is used in place of drill pipe or tubing strings to conduct the desired operation. Coiled tubing operations offer several advantages over conventional methods of fracturing including portability, a small well site footprint and speed of operations.

In wells with multiple coal seams to be stimulated coiled tubing can be used to isolate a single perforated coal seam, fracture the coal and then move to the next seam. Hydraulic fracturing operations that once required two to three days can now be completed in one day. Rodvelt and others [2008], report that "for shallow CBM wells, as many as 24 intervals in two separate wells have been fracture stimulated in a single day with the same crew and equipment". The ability to complete multiple zones in a single trip mitigates the risk of wellbore damage from the multiple well interventions and down-hole tool runs associated with conventional fracturing operations. Cost savings are realized in several areas, including eliminating the need for work-over rigs and bridge plugs for zonal isolation. Manpower costs are also significantly reduced, as the time required for fracturing operations can be more than halved.

2.1.4 Gas content reduction and production

The use of fractured vertical wells has proven to be an effective method for reducing the methane content of coal seams in advance of mining, thereby ultimately lowering methane emissions to the atmosphere and increasing mine safety and productivity. A study at the Oak Grove mine in the Black Warrior Basin in Alabama [Diamond et al., 1989] documents that twenty-three vertical, hydraulically fractured wells produced 73% of the original gas in place from the Blue Creek coalbed over a ten-year period. Methane reductions of 79% and 75% were achieved in the overlying Mary Lee and New Castle seams, respectively, over the same period.

Four of the twenty-five gassiest mines in the U.S. use vertical, hydraulically fractured wells to reduce coal seam gas content before coal is mined.

One of the main advantages of vertical degasification wells as a methane drainage method is their ability to produce pipeline quality methane without the need for extensive processing. The primary disadvantage to fractured vertical wells is that they are more expensive to drill and

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[3] "Slimhole drilling" refers to drilling wellbores with smaller diameters than conventional wellbores. "Fishing" refers to the process of removing broken or stuck drilling equipment from the wellbore. "Remedial treatments" refer to work done to repair any wellbore problems that occur after the initial completion of the well.

maintain than in-mine boreholes or gob wells. The hydraulic fracturing process can represent one-third to one-half of total well costs.

Example

- Black Warrior Methane, a joint venture between Warrior Met Coal and Atlas Resource Partners, produced about 342,000 m^3/day (12 MMcfd) from 354 vertical wells drilled in advance of mining in 2017.

2.1.5 Costs

The major variables in determining the cost of drilling and completing a vertical well are the drilling depth, the method of completion, the number of coal seams completed, the size and type of the hydraulic fracturing process used and the cost of building the well site infrastructure. Vertical well costs therefore vary widely in the U.S, and around the world, sometimes within the same coal basin, depending on the geology, topography, regulatory constraints of the project area and, in new CMM areas, the availability of service companies and drilling-related raw materials.

2.2 Horizontal in-seam boreholes

Coal seams are deposited as flat beds with a horizontal areal extent much larger than their vertical height (1-10s of meters thick, but 1,000s of meters in areal extent). Therefore, vertical wells intersect only a relatively small section of the coal seam to be drained, and almost always need to be hydraulically fractured to create, or enhance, horizontal permeable pathways in the coal to allow gas to flow to the borehole.

An alternative method of pre-mine drainage is to drill horizontal[4] boreholes, up to 1,600 m (5,250 ft) long, within the coal seam, greatly increasing the volume of coal directly assessed by the drainage borehole and reducing or eliminating the need to hydraulically fracture the well. Boreholes can be drilled directly into the coal seam from within the mine workings or drilled down from the surface, and turned through an arc, to drill horizontally through the coal. When directionally drilled, horizontal boreholes can be positioned to perpendicularly intersect the face cleats of the coal seam for optimum methane drainage.

The main types of in-seam boreholes described in the following sections are as follows:

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[4] In reality, boreholes are never completely horizontal, as coal seams are rarely completely flat, but "dip" (slope) upwards or downwards as local geology dictates

- “Short holes” – typically drilled parallel to the face of a longwall panel;
- “Long holes” – drilled longitudinally through the panel or can be drilled across multiple panels;
- Superjacent boreholes – used to pre-drain methane from over- and under-lying gassy strata adjacent to the target coal seam;
- Directional surface boreholes – start at the surface and turn through varying radii to drill horizontally through the coal.

Of the twenty-five U.S. gassy mines identified by the USEPA as employing methane drainage systems, seven of the mines use horizontal in-seam boreholes for methane drainage prior to mining (USEPA, 2018). In Australian mines, in-seam boreholes are extensively used for methane drainage and about 100km of in-seam holes are drilled each year in the coal basins of New South Wales and Queensland. [Gray, 2002]

2.2.1 Short holes

Short hole horizontal boreholes, drilled parallel to the coal face, drain methane from coal seams shortly before mining, reducing methane flow into the mine workings. Short boreholes less than 305 m (1,000 ft), can be drilled with relatively simple drills without the steerable systems needed for long-hole drilling. Short holes are normally 5-8 mm (2-3 inches) in diameter and spaced 30-122 m (100-400 ft) apart. In longwall panels, they are drilled to within 15 m (50 ft) of the opposite side of the panel. Boreholes are typically drilled from tail gate entries (‘B’ and ‘C’ in Exhibit 9) to maximize drainage time from the future panel and reduce methane flow into adjacent development entries as they are mined [Diamond, 1994].

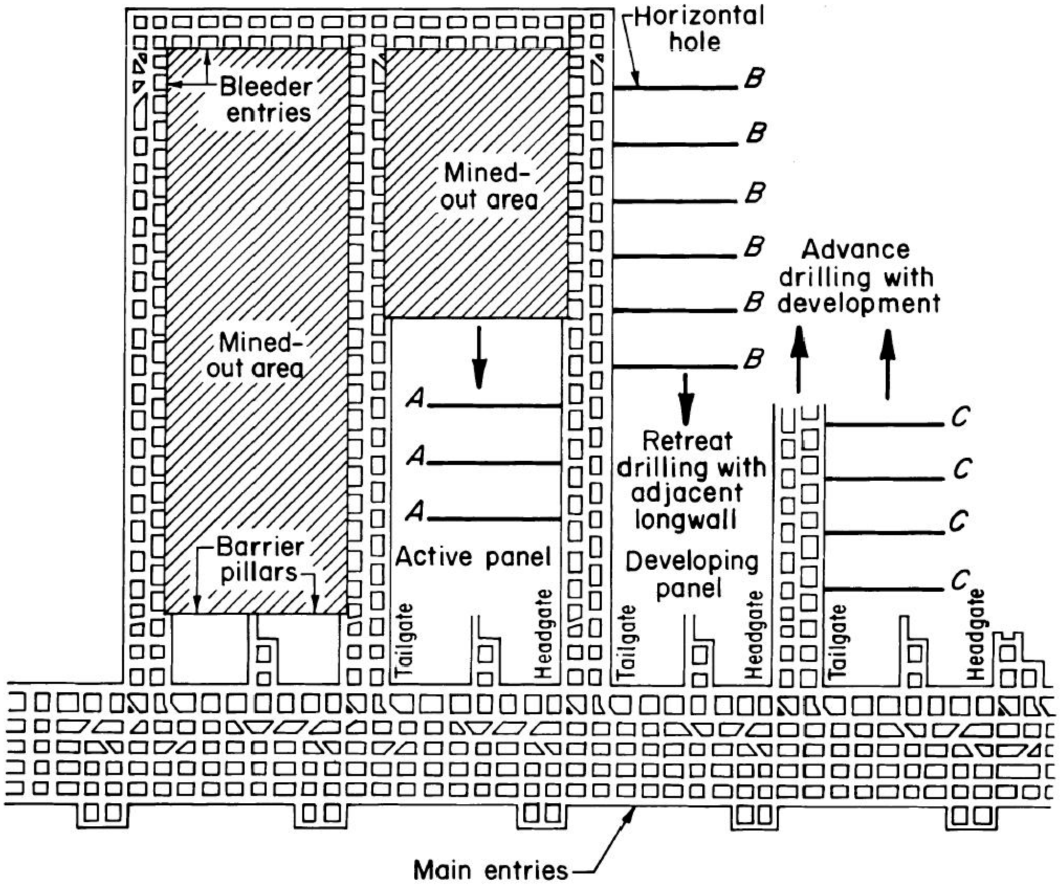

Exhibit 9: Schematic plan view of short horizontal boreholes in longwall panels [Diamond, 1994]

Coal permeability, gas content, time to mining, and drilling economics are important factors in determining borehole spacing. Several factors necessitate closer borehole spacing to adequately degas a longwall panel, such as minimal time before mining, high seam gas content, or low permeability. For example, a study by Aul & Ray [1991] in the Pocahontas #3 seam in Virginia found that 30% of in-situ gas could be removed by shorthole boreholes in less than two months and 80% was removed after ten months, making possible a 79% reduction in ventilation air volume. Produced gas quality from horizontal boreholes is typically high and can be utilized as a pipeline product. Typical costs to drill boreholes using a rotary drill and including utilities and logistical support are $50-65 per meter ($15-20 per foot).

2.2.2 Long holes

Long in-seam boreholes, drilled from existing mine entries into target coal seams (Exhibit 10), can significantly reduce the in-situ gas content of the coal, especially when drilled twelve months or more before mining commences. Long holes can be used to degas longwall panels months to years in advance of mining and can drain methane from coal in the vicinity of development entries as they are being mined. These "shielding" boreholes reduce the volumes of methane entering the development entry.

Exhibit 10: Longhole drilling from within a mine entry
[JWR, 2008]

Positioning – Advances in drilling technology over the last decade allow long boreholes over 1,600 m (5250 ft) to be accurately, and rapidly, drilled in the coal seam. Stronger, more powerful drilling equipment, coupled with precision, real time, drill bit navigation have resulted in drilling accuracies of +/- 8 m (26 ft) over 915 m (3,000 ft). These advances have led to reduced directional drilling costs and increased the opportunities for the use of this technique in CMM drainage [Brunner and Schwoebel, 2005]

A study of in-seam borehole layouts by the National Institute for Occupational Safety and Health (NIOSH) in the U.S. used a three-dimensional numerical simulator to model the methane drainage of five different borehole layouts (Exhibit 11). NIOSH concluded that dual and trilateral boreholes (layouts A and B) are more effective at decreasing emissions and shielding entries compared to fewer, shorter, cross panel boreholes parallel to the face (layouts C and D). Simulated reductions in methane emissions were 38.6% over 12 months for the tri-lateral pattern, compared to 23% over 12 months for the cross-panel boreholes [Karacan et al., 2007].

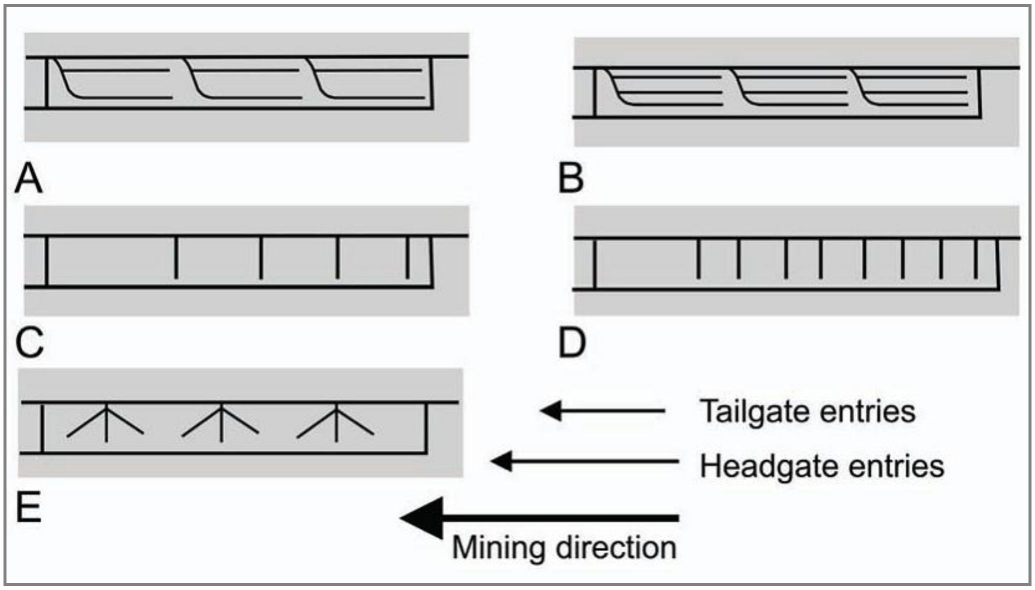

Exhibit 11: Plan view of horizontal methane drainage borehole patterns modeled for degasification of a longwall panel (not to scale)
[Schatzel et al., 2008]

Layout A in Exhibit 11 is a common in-seam borehole layout used in the U.S. As development entries are mined to outline the longwall panel, a borehole is started from the tailgate side of the panel and drilled parallel to the direction of the tailgate entry. A second borehole branches from the first, across the panel and runs parallel to the headgate entry. In this manner, the development entries are shielded at the same time as the panel is being drained [Karacan et al., 2007].

Long, in-seam boreholes can also be drilled into future longwall panels many months before mining commences and, when directionally drilled, can be positioned in coal seams already being degassed by vertical surface wells (Exhibit 12).

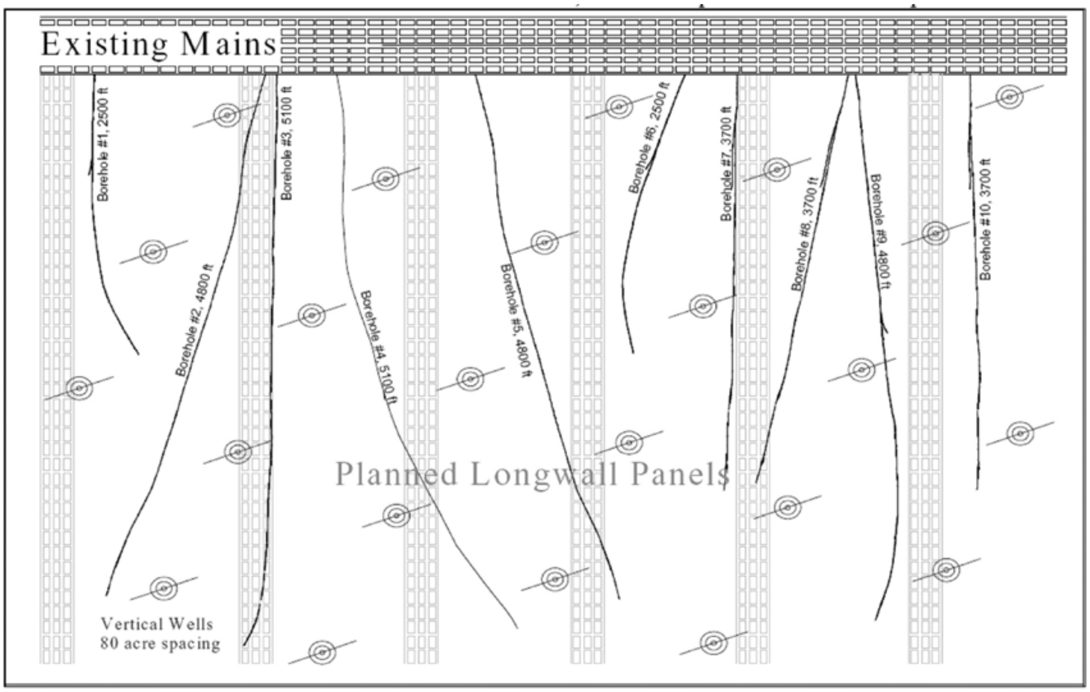

Exhibit 12: Schematic plan view showing in-fill drilling of in-seam boreholes between hydraulically stimulated vertical wells
[Brunner et al., 2005]

Example

- At the Warrior Met No. 7 mine in Alabama, USA long hole directional wells are regularly drilled to lengths of about 1,000 m (3,300 ft.) to degasify the seams in advance of mining. These drilling operations produced about 42,500 m^3/day (1.5 MMcfd) of high quality, 95+%, methane in 2017. This gas is injected directly into a pipeline.

Gas content reduction and production, costs – Long-hole degasification has been shown to facilitate mine production. Brunner and Schwoebel [2005] report that at a mine in northern Mexico, a 885 m (2,900 ft) shielding borehole reduced methane emissions into the adjacent development entry by 30% after 2 months, reducing ventilation requirements by 30% and increasing mining advance rates by 78%.

Up to 50% of in-situ gas can be drained by horizontal in-seam boreholes prior to mining in the high permeability coals in the U.S. Total drainage is limited by the time available for degasification. Shielding boreholes will be mined through once the development entries have been completed and the longwall panel is ready for extraction, typically six months to a year after the longwall mining begins.

Specialist, in-mine drilling contractors report that long, directionally drilled boreholes cost $100-120 per meter ($30-40 per foot). A 1,370 m (4,500 ft) shielding borehole would cost approximately $160,000 including wellhead and mine staff support costs.

2.2.3 Superjacent boreholes

Superjacent boreholes are directionally drilled from mine entries into coal seams, or other gassy strata, above and below the target coal and can be up to 1,000 m (3,300 ft) long (Exhibit 13). Their main purpose is to drain the gob area formed by longwall mining. As such, they are generally considered a post-mining drainage technique, but depending on longwall advance rates, they can drain gassy strata adjacent to the target seam for some time before gob formation. In this case, superjacent boreholes can also be considered a drainage technique that reduces in-situ gas content. More detailed information on superjacent directionally drilled boreholes is provided in section 3.3.2.

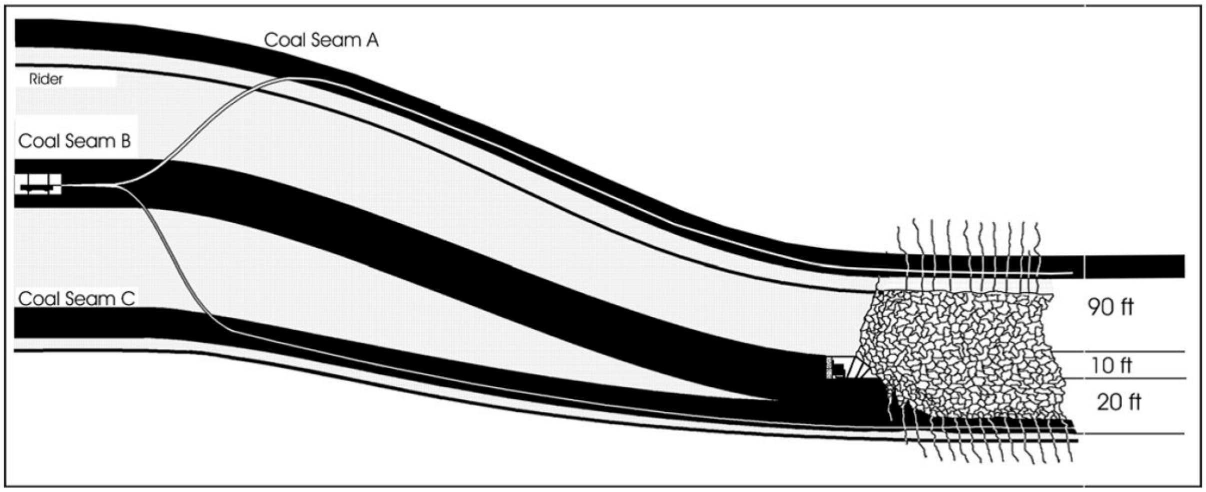

Exhibit 13: Superjacent boreholes reduce in-situ gas content and drain gob gas [Brunner et al., 2005]

2.3 Surface-drilled directional boreholes

Surface-drilled directional boreholes have been used extensively in conventional oil and gas drilling for several decades. Drilling is started in the same manner as a vertical well (see section 2.1) but at a predetermined "kick-off" point (KOP), the well is deviated from the vertical, in an arc, so that the well bore enters the target formation roughly parallel to the bedding plane. Surface-drilled directional holes are defined by the radius of their turn from the vertical (Exhibit 14).

Radius Type	Radius (m/ft)	Achievable Lateral Length (m/ft)	Drilling Method
Zero	0	3 / 10	Telescopic probe with hydraulic jet
Ultra-short	0.3-0.6 / 1-2	60 / 200	Coiled tubing with hydraulic jet
Short	1-12 / 3-40	460 / 1,500	Curved drilling guide with flexible drill pipe; entire drill string rotated from the surface
Medium	60-300 / 200-1000	460-1,525+ / 1,500-5,000+	Steerable mud motor used with compressive drill pipe; conventional drilling technology can also be used
Long	300-850+ / 1000-2,500+	600+ / 2,000+ (Record is over 12,000 m/ 40,000 ft)	Conventional directional drilling equipment used; very long curve length of 850-1,350 m (2,800-4,400 ft) needed to be drilled before achieving horizontal

Exhibit 14: Surface-drilled directional oil & gas well types defined by radius size

[USDOE, 1993]

In the CBM and CMM industries, surface directional drilling was recognized as a way of combining the best elements of vertical well and horizontal in-seam drilling. Drilling from the surface is safer than from in-mine, does not hinder mining operations (for example, there is no in-mine pipeline system), and can be carried out years in advance of mining. A long horizontal borehole intersects a much greater volume of the coal seam than a vertical borehole, negating the need for hydraulic fracturing in most cases and the borehole trajectory can be controlled to take advantage of coal seam directional permeability. In addition, a large area 2.6 km^2 (640 acres), can be drained from a single surface site. This theoretically replaces 16 vertical wells drilled on 0.16 km^2 (40 acres) spacing and greatly reduces the environmental impact of the methane drainage project and results in drilling, infrastructure, and maintenance, cost savings.

2.3.1 Directional borehole drilling techniques

Medium radius boreholes are the most common type of surface directional boreholes currently drilled for methane drainage from coal seams. Over the last 20 years, the technique has been refined and seen increasing use in the CBM and CMM industries mainly in Australia. Early attempts at horizontal drainage boreholes drilled from the surface had problems with the removal of produced water. The curved configuration of the wellbore made conventional pumping techniques difficult, and more complex, and solutions were prohibitively expensive. U.S. and Australian drilling companies introduced new drilling techniques involving the directional drilling of a horizontal well to intersect a standard vertical well that produces the gas and water.

In Australia, a commonly used technique is to directionally drill multiple boreholes to the same vertical well. The technique is referred to as surface to in-seam drilling, or SIS. The boreholes usually drain the same coal seam, but can target multiple coal seams at different depths (Exhibit 15).

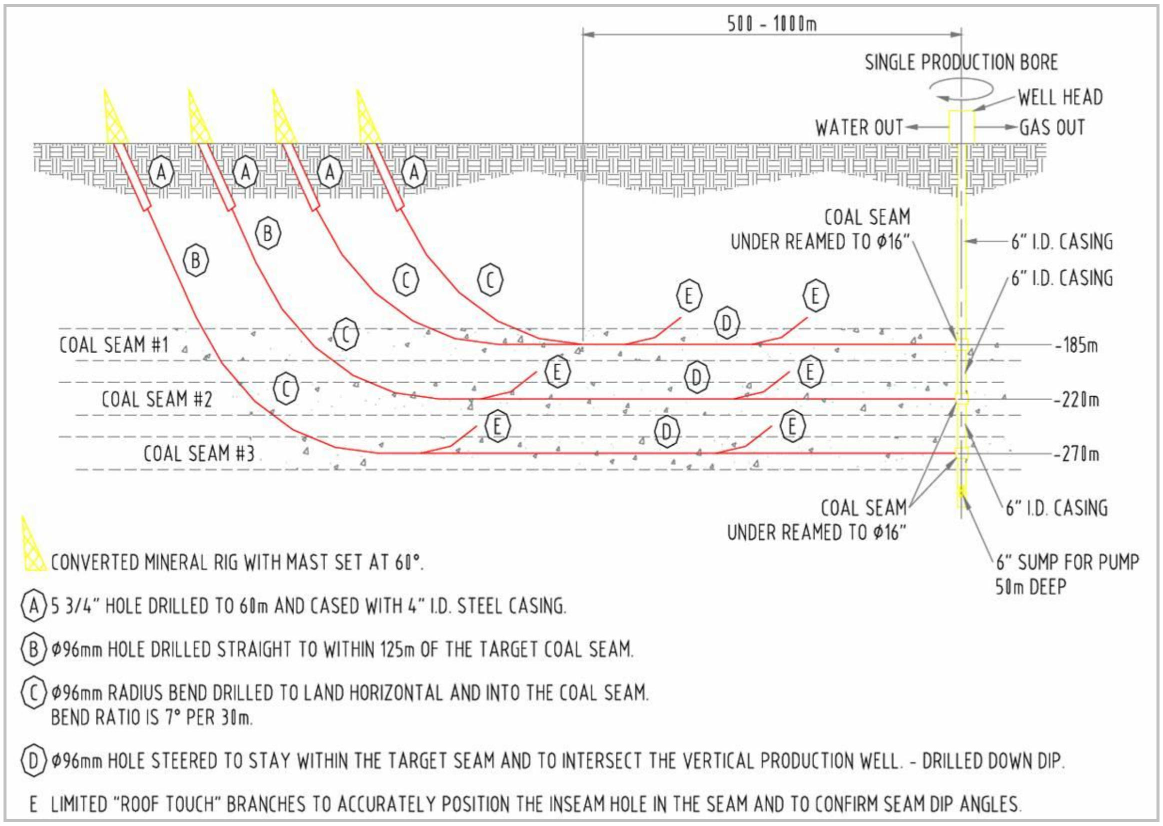

Exhibit 15: Schematic of multiple horizontal wells drilled to a single vertical well
[Mitchell Drilling, 2005]

A magnetic guidance tool, lowered down the vertical well to the target coal seam, helps guide the drillers to intersect the production well [Mitchell Drilling, 2005]. In Australia, directional drilling from the surface using standard oil field equipment proved to be too expensive when applied to shallow, relatively low producing coal seams. This led Australian drilling companies to use small, modified mineral drill rigs to reduce costs, and practice “slant-hole” drilling where the borehole is drilled from the surface starting at angles of 60 degrees to the horizontal (Exhibit 16). Slant hole drilling reduces the angle that needs to be turned through to achieve horizontal drilling and allows the targeting of shallower coals compared to drilling starting vertically and turning through a 90 degree arc.

Exhibit 16: Slant hole drilling
[Mitchell Drilling, 2005]

In the U.S., the vertical production well is situated close to the point where the directional borehole first becomes horizontal. The horizontal borehole intersects the vertical well, or a lateral leading from it, and then continues for lengths up to 1,525 m (5,000 ft) (Exhibit 17). Lateral holes can then be drilled from the first borehole, in various layouts, to increase the areal extent of coal drained. The laterals are drilled such that produced water drains to the vertical well for pumping to the surface.

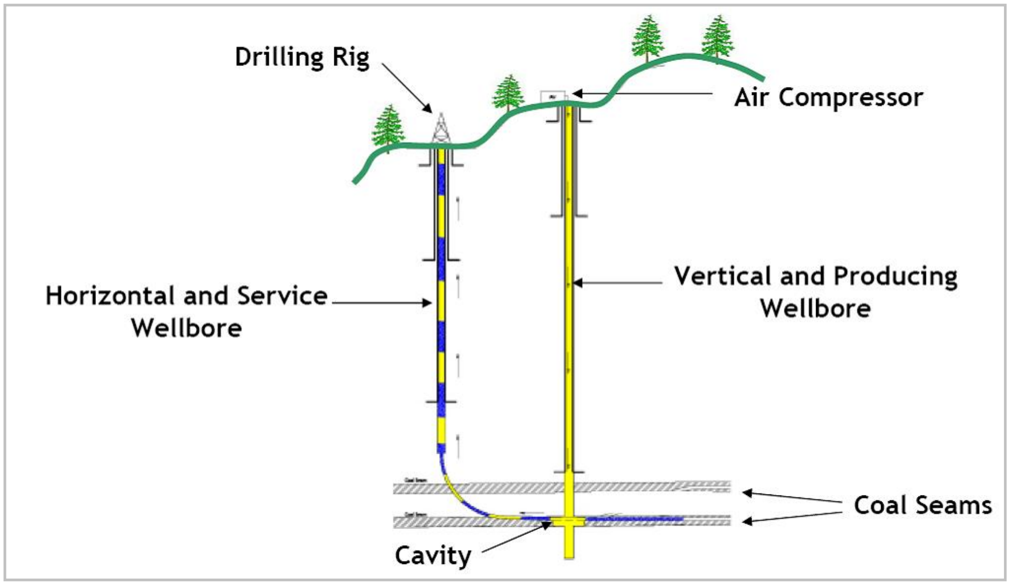

Exhibit 17: Dual well system
[CDX Gas, 2005]

Modeling multi-lateral drainage patterns, Maricic et al. [2005] concluded that the optimum well configuration can be determined by considering the total horizontal wellbore length, the spacing between laterals and the number of laterals. Longer horizontal length increases the contact with the coal seam and increases yields for more gas recovery, but at the same time increases drilling costs and drilling risks. Balancing these factors has led operators to more commonly drill a simple three to four lateral pattern per horizontal well.

Example

- CNX Gas, at its Mountaineer CBM field in southern Pennsylvania and northern West Virginia, targeting the Freeport coal seam, drilled a total of 176 horizontal wells in 2007 and 2008 at average depths of 180-240 m (600-800 ft). The drilling technique was changed from using a simple 3 lateral design draining 2.6 km2 (640 acres), to an asymmetrical quad design ("turkey foot") which resulted in more uniform methane drainage and a decreased well spacing to 1.9 km^2 (480 acres). Consequently, drilling times were reduced from 21 to 15 days, greatly improving well economics. The use of a gamma detector close to the drill bit to more accurately steer the horizontal borehole in the coal, further reduced drilling times to 10 days. One of the first wells produced at 25 Mcmd (900 Mcfd) [CNX, 2008].

The vertical section of the wells, and in some cases the arc of the well, are cased to ensure borehole stability and prevent any potential water ingress from shallow water bearing rock. The main laterals can be lined with slotted pipe to prevent borehole collapse. While directionally drilling the horizontal laterals, if the wellbore intersects the roof or floor of the coal seam, the drill string (pipe) can be pulled back, and drilling continues at an angle away from the coal boundary. This is known as “sidetracking” and ensures that the lateral stays within the coal for its entire length.

Surface-drilled horizontal borehole techniques have seen little application in other countries, often because of lower permeability of the coal seams and more complex geology compared to those found in the U.S. and Australia. One exception is China, where twenty-five multi-branch horizontal wells have been drilled through 2007 [Qiu. 2008].

2.3.2 Gas content reduction and production

Horizontal wells drilled from the surface into relatively high permeability coals, several years before mining takes place, are able to drain over 80% of in-situ methane. This is similar to the drainage efficiencies of vertical wells, but in general, horizontal wells degas coal seams at higher production rates. Gas is drained from virgin coal seams with no dilution by mine ventilation air and, after any necessary processing to remove excess carbon dioxide, nitrogen, or water, is usually of high enough quality for injection into a commercial pipeline.

Production examples

- Target Drilling reports average initial gas production of 18-21 Mcmd (650-750 Mcfd) from 1220+ m (4000+ ft) horizontal wells in relatively high cleat permeability wells in Pennsylvania, with continued production of 11 Mcmd (400 Mcfd) after two years.
- Kreckel [2007] reports that “between 1998 and 2002, six operators drilled 110 horizontal wells in the Hartshorne coal in the Arkoma Basin, Oklahoma. Laterals reached up to 1,615 m (5,300 ft) at depths of 230-915 m (750-3000 ft). Initial production from half of these wells performed at better than twice the average of vertical wells, between 5-11 Mcmd (200-400 Mcfd). Seven wells came in at well over 28 Mcmd (1,000 Mcfd). The highest initial production of 32 Mcmd (1,152 Mcfd), came from a horizontal lateral of 489 m (1,604 feet) length.”

2.3.3 Costs

Drilling costs for surface-drilled horizontal wells are dependent on the depth of the target coal seam or seams, the number of laterals drilled and the length of those laterals. Operators are constantly looking for ways to minimize costs, resulting in innovative drilling methods such as using modified mineral drilling rigs or experimenting with lateral layout patterns.

While drilling horizontal wells tends to be two to three times more expensive than drilling vertical wells in the same area, faster gas recovery times, higher initial gas production and larger ultimate production recoveries can result in lower dollar per produced volume of gas values compared to vertical wells. Horizontal wells have a significant cost advantage because they do not require hydraulic fracturing, which can constitute 30% of the cost of a vertical well completion. Also one horizontal well replaces several vertical wells, with resultant multiple savings in infrastructure capital costs (location and access road construction, gathering pipeline, etc.) and operating costs.

Examples

- Drilling costs for a surface to in-seam horizontal well range from $330-390/meter ($100-120/ft) for a coal seam at a depth of 500m (1,500 ft).

2.4 Water disposal

As is the case with CBM well drilling, pre-mining drainage of CMM usually involves the drainage of water from the coal seam to lower reservoir pressure so that methane will desorb from the coal and flow via the wellbore to the surface. The volumes of water produced vary among coal basins around the world, depending primarily on reservoir thickness, porosity, permeability, well spacing, pump rates, proximity to aquiferous sandstones or intrusions, and proximity to meteoric water recharge.

In the U.S., average daily water production rates from CBM wells vary from 2-5 m^3 (17-42 bbl) per day to over 60 m^3 (500 bbls) per day [Creedy et al., 2001]. Total water production from a CMM drainage project involving a large number of wells can be considerable and must be carefully managed to meet environmental requirements.

The quality of produced coal seam water varies widely among and within coal basins. In some regions, the water is of good enough quality to be used for beneficial purposes such as irrigation, drinking water, or industrial use. In areas that have poor water quality, generally either high total dissolved solids (TDS) or high salinity (up to 5 times that of seawater), the water must be intensively treated before use, or disposed of by reinjection into a suitable aquifer.

2.4.1 Water disposal options

There is no established technology for reducing water production without adversely affecting gas production rates. Consequently, mitigation technologies have focused either on disposing produced water using underground injection or surface evaporation, or by surface treatment of produced water for disposal or utilization.

In the U.S., produced water from CBM/CMM operations is disposed of using several different approaches. The most appropriate method depends on many variables, including water volume, salinity levels and chemical composition, as well as on non-reservoir factors such as local climate, surface drainage, and environmental regulations. Water disposal technology is highly site-specific and must be determined for each individual application.

The most commonly used water disposal options include:

- Surface discharge;
- Impoundments (or evaporation pits);
- Shallow and deep re-injection;
- Active treatment using Reverse Osmosis (RO).

Surface discharge - Surface discharge is the least expensive of the water disposal options. Uses for surface discharged water may include crop irrigation or animal watering, depending on water quality. However, these options will most likely be secondary to any beneficial use at the mine or in other industrial applications where potable water is not required. These applications include ore washing, power plant cooling, drilling/fracturing fluid, and dust suppression. Depending on the end-use, some degree of clean up of the water may be required.

Impoundment / evaporation - Disposal of produced water in evaporation ponds is a simple process, involving constructing and maintaining a shallow, impermeably lined pond with a large surface area, introducing produced water into the pond, and allowing the water to evaporate. Depending on the salinity of the produced water and evaporation rates, the accumulated salt deposits within the pond must be removed. In the San Juan Basin, this accumulation amounts to approximately 5 cm per 20 years of continuous operation.

Exhibit 18: Forced evaporation pond

Evaporation rates can be significantly enhanced in active evaporation ponds through the use of a pump-and-spray system, reducing the required surface area to dispose of a given volume of water, although at higher operating cost (Exhibit 18).

If produced water is of sufficient quality, impoundment ponds can also be used for beneficial uses such as fishponds, livestock and wildlife watering ponds or recreation.

Underground re-injection – In the U.S., water must be re-injected to a depth at which the re-injected water's salinity matches that of the aquifer into which it will be pumped. For example, CBM produced water in the Powder River Basin of Wyoming and Montana is relatively fresh, so shallow re-injection wells are typically only 90-300 m (~300-1,000 ft) in depth.

Downhole gas/water separation - A relatively new method of water disposal is downhole gas/water separation. Downhole gas/water separation requires well boreholes to be drilled deeper than originally designed in order to inject water into a permeable horizon below the coal seams. A pump below the coal seams draws water down, while allowing gas to flow to the surface. Downhole water separation may be economically viable under certain conditions, actually increasing gas flow rates and eliminating water transportation costs. This technique, however, requires an adequately permeable zone located below the coal that can take substantial volumes of fluid.

Reverse Osmosis - Reverse osmosis (RO) of brackish produced water involves the use of a permeable membrane to separate fresh water and waste brine streams. Each pass through the membrane can halve the salinity of the water, thus the performance of an RO system depends on the requirements for the targeted water chemistry. A typical RO system involves processing produced coal seam water to generate fresh water and a small waste stream of highly saline water that can be injected in a conventional underground disposal well or trucked to a permitted disposal location.

3. CMM drainage techniques to recover gob gas

A gob (also known as “goaf”), or gob area, is a region of fractured geologic material from overlying strata that has settled into mined-out areas after coal recovery. The overlying and underlying material relaxes after shortwall or longwall mining operations have passed by (Exhibit 19), or after pillar removal with the room and pillar mining method.

Gas volumes liberated by gob areas into the mine ventilation system depend on the method of mining, the number and proximity of overlying and/or underlying gas-bearing strata, their reservoir characteristics, and other geological factors. The primary motive for gas drainage from the gob is to reduce methane emissions into mine workings and assist the mine’s ventilation system in providing a safe environment for coal mining.

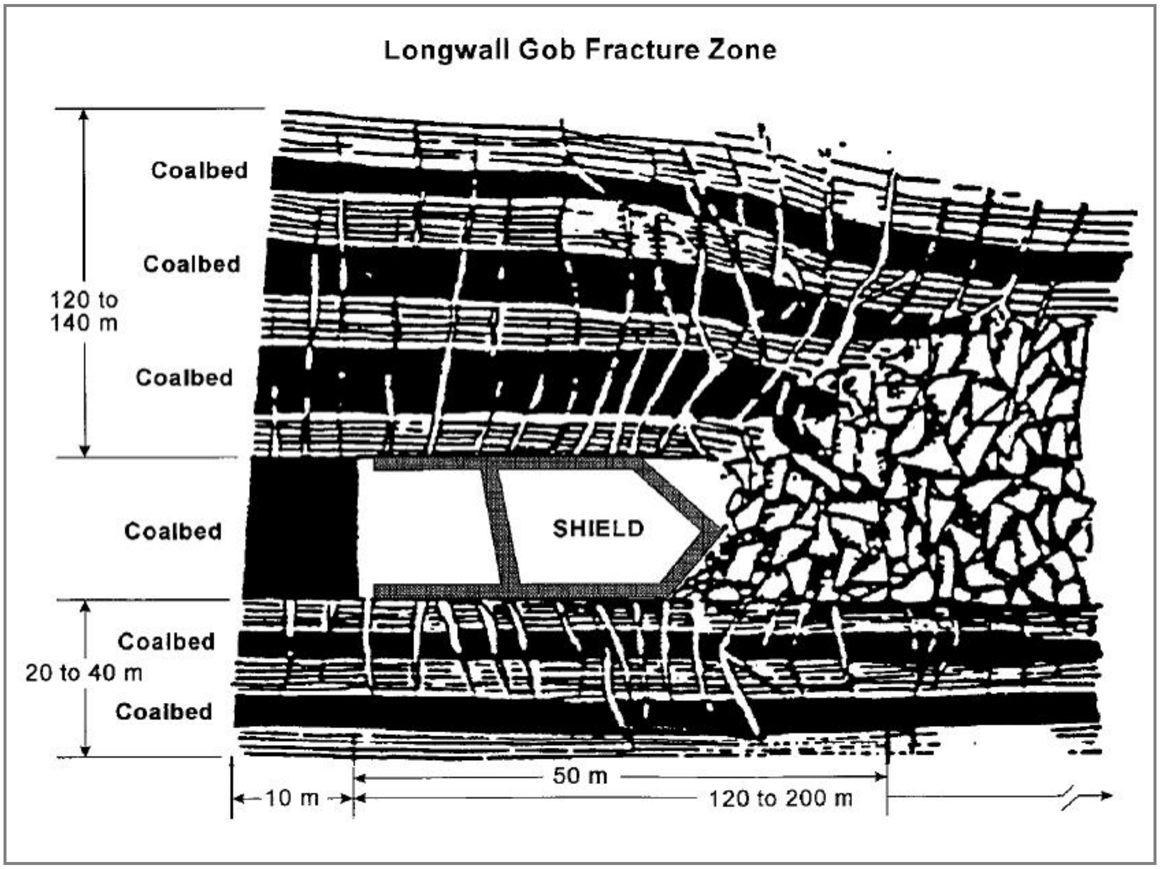

Exhibit 19: Side view of the effects of longwall mining on adjacent strata [Cervik, 1979]

At many coal mining operations, much of the gas emitted from the gob discharges to the atmosphere, either directly from the drainage system or through the ventilation system. Gob gas drainage systems may produce high-quality gas depending on conditions, but generally produce gas with lower heating values between 2,670 and 7,120 kcal/m^3 (300 and 800 Btu/cf) [EPA, 2008[b]]. Poor methane gas recovery may be due to the nature of the resource itself, or may result from focusing attention on minimizing gas emissions into the mine ventilation system, resulting in the dilution of gob gas with ventilation air. However, there is potential at many coal mines to increase gob methane recovery and decrease dilution levels by adopting improved degasification and collection systems and by modifying operating practices.

The three primary methods of longwall gob degasification, used worldwide, are as follows (depicted in Exhibit 20):

- Vertical and deviated gob wells - drilled from the surface;
- Cross-measure boreholes - drilled from mine entries adjacent to the longwall panel;
- Superjacent methods - degasification takes place from overlying or underlying galleries and boreholes.

To maximize gob degasification, CMM drainage systems often use a combination of these techniques.

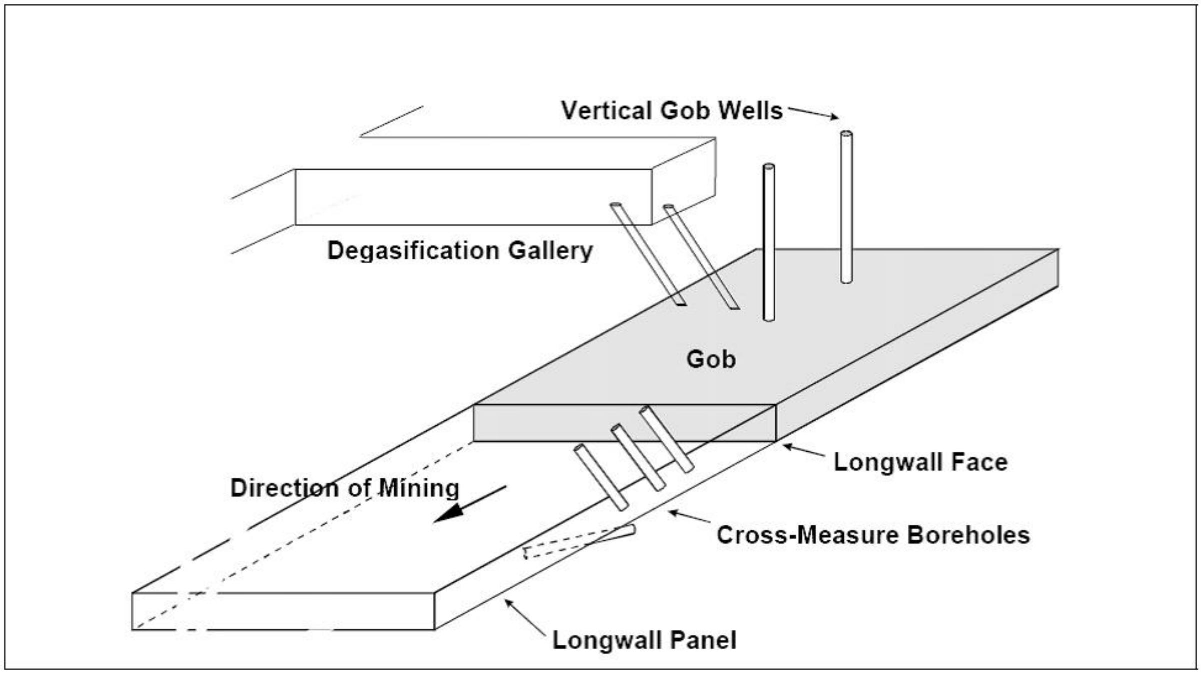

Exhibit 20: Schematic showing vertical and cross-measure boreholes
[Source: REI Drilling]

3.1 Vertical gob wells

Wells drilled from the surface to just above the working coal seam are the predominant gob degasification technique applied in the U.S. Gob wells are normally drilled prior to mining, but are operated only after the longwall face mines past the wellbore and the gob is formed. Methane emitted from fractured strata in and above the gob then flows into the well and up to the surface. Vertical gob wells are the most effective method of reducing methane content in shallow, rapidly moving longwall faces in the U.S. They are less widely used in the rest of the world, where deeper, less permeable coals and greater surface access issues make other gob degasification methods more applicable.

3.1.1 Planning and design

The number of vertical gob wells above a longwall panel varies considerably, with the number being a function of the rate of mining, the length of the longwall panel and the gas content of the caved strata. The first borehole is typically sited 50-170 m (150-500 ft) from the longwall face and, during mining of a typical 3,000 m (10,000 ft) longwall, between 3-30 gob wells may be needed for adequate degasification [Thakur, 2006]. A higher density of wells at the beginning of the longwall is often used to drain the higher methane emissions encountered in the initial stages of the longwall caving operation.

Examples

- Warrior Met Coal in Alabama typically drills 5-6 gob holes per 3,660 m (12,000 ft) longwall panel.

Studies by the U.S. Bureau of Mines [Diamond, Jeran, and Trevits, 1994; Diamond, 1995] indicate that wells located in the zone of tension along the margin of the longwall panel[5], produced 77 percent more gas than wells drilled on the traditional centerline location, which is in compression. Often, operators select a location for the first gob well on a panel and evaluate its production record to help locate the subsequent wells.

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[5] When a coal seam is mined, the overlying strata subside into the void left behind forming the gob (Exhibit 19). Maximum subsidence occurs along the centerline of the gob, where gob material is "pushed" together in compression. At the edges of the gob, the overlying strata are partially supported by unmined rock below it and are "stretched" over this support and into the gob. This zone of "stretched" strata is in tension, which is surmised to enhance fracture permeability and gas production [Diamond et al., 1994].

3.1.2 Gob well completion

Vertical gob wells are drilled in advance of mining to a depth 6-28 m (20-90 ft) above the working coal seam. Gob wells are normally cased and cemented to a point just above the uppermost coal seam or gas-bearing stratum believed capable of liberating gas as a result of longwall mining. The lower portion of the well is either left uncased as an open hole completion (see section 2.1.2), or is lined with slotted casing to maintain borehole integrity while allowing gas flow to the well, as shown in Exhibit 21.

The slotted liner is not cemented in place, but hung from the bottom of the casing. Gob well completions in the different coal basins in the U.S. vary depending on depth, anticipated gas and water flows, and geomechanical characteristics of the overlying strata.

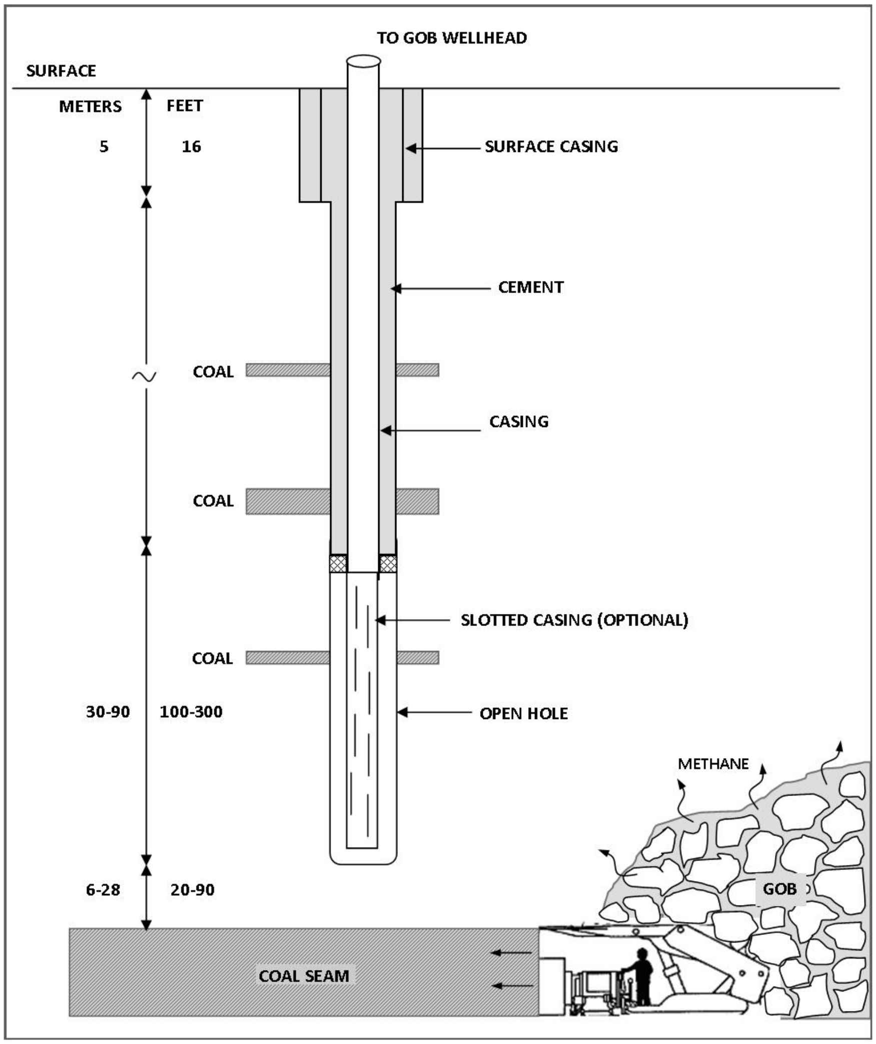

Exhibit 21: Profile of a typical U.S. vertical gob well

A number of aspects of gob well completion must be carefully considered, including vertical placement of the well within the gob, maintaining well integrity and productivity after undermining, ensuring connectivity with the fracture zone to enable gas flow, and isolating shallow, water-bearing strata from the well and mine workings by proper well-casing cementation practices. In some cases, significant water inflow is unavoidable and may worsen after mining because of increased conductivity exhibited by fractured strata [Diamond, 1995].

Completion examples

- At the West Elk Mine in Colorado, USA a borehole 311 mm (12 1/4 inch) in diameter was drilled to a casing point depth of 610 m (2,000 ft) [Peacock, 2006]. The hole was cased from the surface with 244 mm (9 5/8 inch) steel casing and then a 222 mm (8 3/4 inch) diameter hole drilled for another 91 m (300 ft), stopping 8 m (25 feet) above the seam to be mined. 178 mm (7 inch) slotted steel casing was hung in the hole to maintain borehole integrity, but not cemented in place, so as to allow gas to flow from the gob and surrounding fracture zone into the wellbore.
- In the Pittsburgh coalbed in Pennsylvania, USA, where average overburden depths range from 152-274 m (500-890 ft), gob wells were drilled to 9-14 m (30-46 ft) of the top of the coal and completed with 178 mm (7 inch) casing and 61 m (200 ft) of slotted pipe [Karacan et al., 2007].
- Gob wells 311 mm (12 1/4 inch) in diameter have been drilled as deep as 915 m (3000 ft) in Virginia, USA, [Atlas Copco, 2007].

Some non-U.S. coal operators have had little success with gob well degasification due primarily to their completion practices. Wells that are completed mostly “open hole” and extend into the rubble zone may encounter water problems or shear after undermining, which limits the productive life of the well. Proper casing of the well above the gob area, to isolate surface water-bearing zones avoids water accumulation. At the same time, protecting the borehole in the gob area with slotted casing minimizes the potential of well bore instability, which can lead to collapse and shorten the well production life.

3.1.3 Gob gas production and quality

As with all gob degasification techniques, the methane quality and quantity produced from vertical gob wells vary depending upon many factors including:

- Site-specific geological and reservoir characteristics;
- Mining characteristics;
- Well siting;
- Completion practices;

- Wellhead operations; and
- Degasification and ventilation practices at the mine.

Intrusion of mine ventilation air is common because of connectivity in the gob between the borehole and ventilation system. Typical U.S. gob well capture efficiencies[6] are in the 30-70% range [USEPA, 1999[b]], depending on geologic conditions and the number of gob wells within the panel. Some operators who use vertical gob wells in favorable geologic and reservoir settings have claimed methane capture efficiencies up to 80%.

The flow rates of gas from the gob to the well are controlled by the permeability of the fracture zone, the natural pressure differential created by low-density methane gas rising in air, and the amount of suction applied by vacuum pumps (exhausters) at the surface. Vertical gob operators have attained significant increases in gas production, and methane reductions in the mine ventilation system, by applying slight vacuum pressures at the surface. In some cases, operators have noted a three-fold increase in production rate with application of 6.9 kPa (1 psi) suction pressure [Mazza and Mlinar, 1977] to gob wellheads.

Vertical gob well performance records indicate that well productivity is also linked to the dynamic creation of the gob and is dependent on the volume of coal extracted. At many U.S. operations, gob gas production rates depend on the longwall face advance rate. Operators have reported a two- to three-fold increase in gob gas production rate with increased longwall face productivity.

In a vertical gob well system, wellhead operations on the surface, ventilation controls situated in the mine offices, and mining operations underground are widely separated. Therefore, it is important to have effective tools to manage the impacts of each system on the others. Because of the gob wells' effect on the mine ventilation system (particularly if gob ventilation is required, as in the U.S.), operators must closely coordinate these systems with continuous monitoring. Continuous monitoring is particularly important to maintain gob gas quality for projects that use the recovered gas. At some mining operations, excellent production rates and high gas qualities are maintained with suction and proper monitoring and control.

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[6] Methane capture efficiency is defined as the ratio of the gas captured by the degasification system to the sum of (the gas emitted into the ventilation system plus that captured).

Example

- At the Warrior Met mines in Alabama, methane production and mining activities are closely coordinated and a system has been implemented to carefully monitor gob gas collection and process it for pipeline injection. The company reports that their gob wells produced approximately 107,600 m^3/day (3.8 MMcfd) of about 60 percent quality methane. The gas from the gob well system is sent to a gas processing plant where it is upgraded to 96 percent methane and then sent to an interstate gas pipeline.

Data from 2015 show that out of twenty U.S. mines employing a methane drainage system, twelve of them use surface vertical gob wells as part of their methane control plan [USEPA, 2018[a]]. Nine of the mines are selling the recovered gob gas into pipelines, with three mines using the recovered gas for medium-quality applications such as on-site electrical power generation and heating applications. The rest of the mines are venting the gob gas to the atmosphere because of a lack of an identified economic use for the gas.

Some U.S. operators recover large volumes of gob gas (up to a half of a gob well's cumulative production) after they complete longwall mining. These operators seal the mined gob areas from main mine ventilation air courses to minimize leakage and to increase ventilation system efficiency. Effective sealing of gob regions from the active portion of the mine can improve recovered gas quality.

3.2 Cross-measure techniques

The cross-measure technique of longwall gob degasification is the primary technique employed in Europe and Russia, where operators practice longwall mining in multiple dipping coal seams, normally deeper than 610 meters (2000 feet). Several U.S. mines have tested cross-measure boreholes [Cervik and King, 1983] and found them effective. However, the general ease of using vertical gob holes in the U.S., and their relative cost effectiveness when compared to cross-measure boreholes, has resulted in minimal use of cross-measure boreholes in U.S. mines. Cross-measure systems may be more attractive in the U.S. in deeper, gassier mines and where the siting of vertical gob wells at the surface is difficult.

Example

The West Elk Mine in Colorado compared methane drainage from cross-measure (CM) holes and large diameter surface gob wells [Peacock, 2006]. Both methods were used to degas a longwall in a heavily faulted area, where, even with new, larger airshafts, the ventilation system could not adequately dilute in-mine methane concentrations to safe levels, resulting in production slowdowns. After an initial learning process in drilling both types of drainage boreholes, the gob wells were found to be much more effective at methane drainage than CM boreholes.

- CM holes were more prone to be affected by air ingress from the mine ventilation system decreasing the amount of methane captured by the system.
- Gob wells were able to drain up to 10 times the amount of methane per hole compared to CM holes at a cost approximately that of 5 times a CM hole.
- Gob wells were effective over a wider range of panel than the CM holes and the decrease in gas concentrations around the longwall face was immediately noticeable, with a subsequent increase in mining production levels.

3.2.1 Planning and design

Borehole positioning

Cross-measure boreholes are drilled in advance of the longwall face, at varying angles into the roof or floor from the gateroad entries (Exhibit 22). Their purpose is to pre-drain over- and under-lying strata, and then capture gas from the gob area once the longwall face has passed. Boreholes are normally placed in the return entry, but in extremely gassy conditions, boreholes can be sited in both the intake and return entries surrounding the coal panel. The angle, length, and spacing of the boreholes are all dependent on site-specific conditions such as the width of the longwall panel, depth below the surface, thickness of the mined seam, geomechanical properties of adjacent strata, available drilling space and drilling equipment limitations.

In retreating longwall mining, keeping the cross-measure boreholes and their gas gathering pipelines intact is complicated by the gateroad entries adjacent to the gob collapsing upon retreat. For single entry retreat mining (performed outside the U.S.), boreholes are drilled from an extra gateroad, developed along one side of the panel (Exhibit 22), which provides access to the degasification boreholes and a protective environment for the gas gathering system.

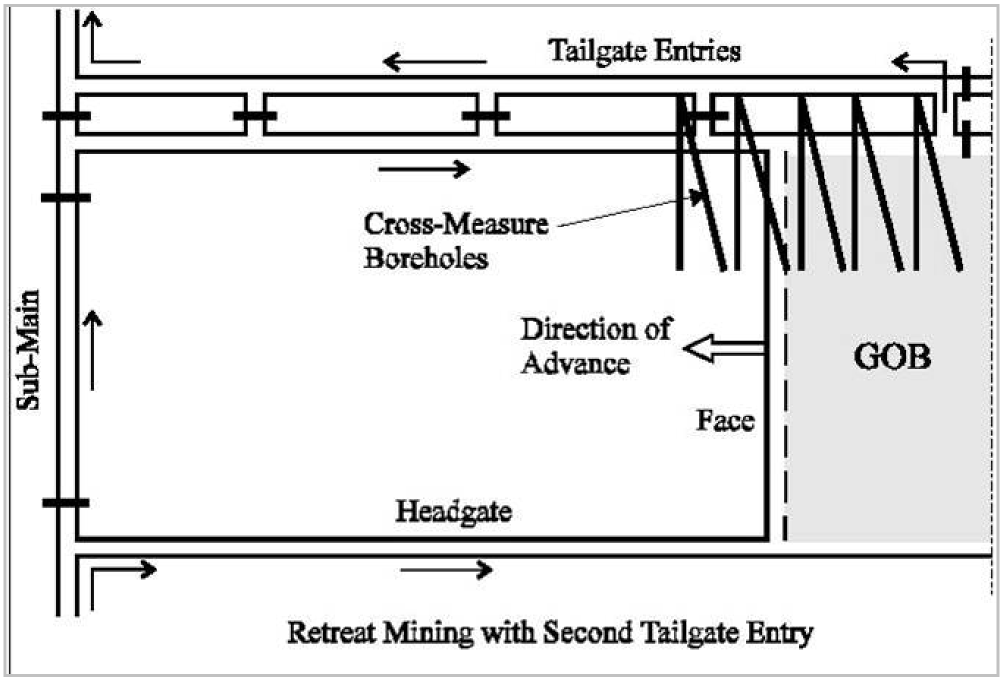

Exhibit 22: Cross-measure boreholes developed from a second entry for longwall gob gas recovery for retreating operations
[Wisniewski and Majewski, 1994]

Borehole sizing and spacing

Cross-measure boreholes are small in diameter, between 50 to 100 mm (2-4 inches) and are drilled at angles varying from 20-50 degrees from horizontal. U.S. studies and European experience indicate that boreholes at higher vertical angles have a longer productive life and tend to produce higher quality methane. However, each gob has an optimum drilling angle and exceeding it will impair the borehole's performance.

Exhibit 23: Cross-measure drilling

Studies by the U.S. Bureau of Mines (USBM) have shown that up to 75 percent of the gob gas emits from the newly fractured strata and stress relaxation zone directly behind the face [Garcia and Cervik, 1985]. Cross-measure boreholes in European mines are typically angled toward, and above, the longwall face, to intercept this zone (Exhibit 23). This orientation is especially important for single-entry gateroads used with retreat mining because of the need to maximize production within the borehole's finite life span. Once the longwall face passes the wellhead, the access to the borehole is lost, and the well is normally shut-in. Boreholes are typically inclined to the longwall axis at 15-30 degrees [Thakur, 2006].

In order to produce a continuous low-pressure zone over the gob using the cross-measure system, the boreholes must be spaced such that their drainage areas overlap slightly. If boreholes are too far apart, then the accumulated methane between boreholes will tend to migrate toward the nearest mine entry. If the boreholes are spaced too close together, they may promote migration of mine ventilation air into the gob, reducing the quality of recovered methane.

Borehole spacing can vary from 25-60 meters (80-200 ft) apart and is dependent on available suction pressure at the wellhead and the gob permeability. Spacing may be decreased near the start and end of new coal panels, to capture increased gas flows generated in these tension zones, which are more fractured and have higher permeability than in the rest of the panel [Garcia and Cervik, 1985; Diamond, 1995].

USBM tests of cross-measure systems along return gateroads show that a borehole's horizontal projection over the longwall rib does not need to be very long. In fact, 30 m horizontal projections were sufficient to obtain capture efficiencies of 71 percent with this system [Garcia and Cervik, 1985], and data indicated that shorter holes would have been as effective.

Horizontal and vertical placement considerations

The point where a borehole is drilled into the mine roof, or floor, is called the "collar location" and is critical to the borehole's performance and to recovered gas quality. The collar location is normally situated close to existing pillars or other roof supports, in an attempt to minimize fracturing near the initial length of the borehole as the longwall face passes. In order to maximize connectivity with the gob, minimize inflow of mine air into the degasification system, and prevent the borehole from closing, a steel or plastic standpipe, up to 10 m (33 ft) long, can be inserted and sealed into the initial borehole length.

3.2.2 Recovered gas quality and production

Monitoring

Because the degasification system operates in conjunction with the ventilation system and mining operations, it is important to provide coordinated management (using measuring instruments, monitoring, controls, and good communications) to optimize each of the three functions.

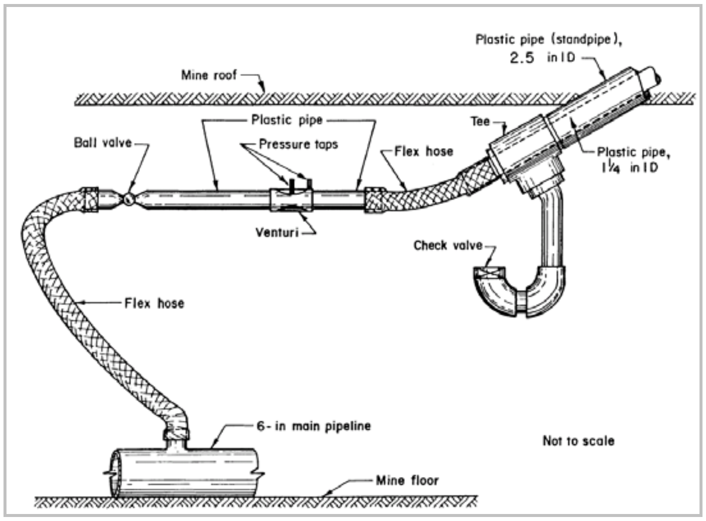

Exhibit 24: Cross-measure borehole wellhead configuration with monitoring provisions [Garcia & Cervik, 1985]

Modern wellhead configurations enable measurement of gas quality, gas flow rate, and pressure. Good monitoring practices ensure that the quality of recovered gas is above the limiting value for the mine. Exhibit 24 provides an example of a system for suction control, pressure and flow monitoring, and water separation for a cross-measure wellhead.

Gas quality

Cross-measure boreholes connect to a gas collection manifold that is normally under suction induced by a vacuum pump. Suction (negative pressure) is the primary means of controlling the gas flow rate from cross-measure boreholes. Maintaining standpipe integrity is crucial to borehole productivity and recovered gas quality because system suction will promote intrusion of mine ventilation air through inadequate standpipe seals.

Methane capture efficiencies[6] range from 20 percent to 70 percent using the cross-measure borehole technique [McPherson, 1993]. Lower gas purities are typical with this system because of the number of boreholes drilled, and the connectivity between the boreholes and the ventilation system. A typical flow from an individual borehole is 815 m^3/day (28 Mcfd), but can occasionally reach over 4000 m^3/day (141 Mcfd) for deeper holes [Thakur, 2006].

3.3 Superjacent techniques

Superjacent techniques involve the creation of low pressure zones in strata immediately above (and occasionally below[7]) the rubble zone of the gob, into which gob gas migrates instead of into mine workings. The low-pressure zones can be formed by using an existing mined gallery (roadway), driving a new one, or by directionally drilling a series of boreholes. The zone is sealed and subjected to vacuum pressure.

Superjacent drainage systems have the advantage of being initiated away from production mining operations, which facilitates placement of boreholes in advance of the mining face for both advancing and retreating longwall systems. Gob degasification with superjacent techniques is applicable in mines that cannot implement surface drilled gob wells, or effectively control gob gas emissions using only these wells, and as a cost effective alternative (implementation and operation) to cross-measure boreholes [Brunner and Schwoebel, 2001].

3.3.1 Overlying or underlying galleries

Superjacent techniques involve the use of drainage galleries (roadways) developed in advance of mining in overlying or underlying strata, and are used at some of the deeper and gassier mining operations in Eastern Europe, Russia, and China. This method was developed in highly gassy coal seams in French and German mines in the late 1940’s.

In these techniques, a gallery is developed 20-35 meters (65-120 ft) above the seam to be mined. Development costs can be partially offset if the gallery is driven in a coal seam. It is sealed and connected directly to a gas collection system operating under high vacuum, forming a low pressure sink into which gob gas migrates. Short, small diameter boreholes, can be drilled into surrounding gassy strata from the gallery to improve gas migration (Exhibit 25).

Using pre-existing galleries makes this technique more economically viable. Generally, operators using superjacent methods claim methane capture efficiencies of up to 80 percent (efficiencies as high as 90 percent have been reported [Liu and Bai, 1997] with superjacent galleries). Thakur [2006] reports methane flow rates averaging 28-40 Mcmd (1-1.4 MMcfd) from superjacent galleries.

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[7] Although the term “superjacent” literally means “lying above”, drainage galleries and boreholes developed under the working seam are also included as superjacent techniques.

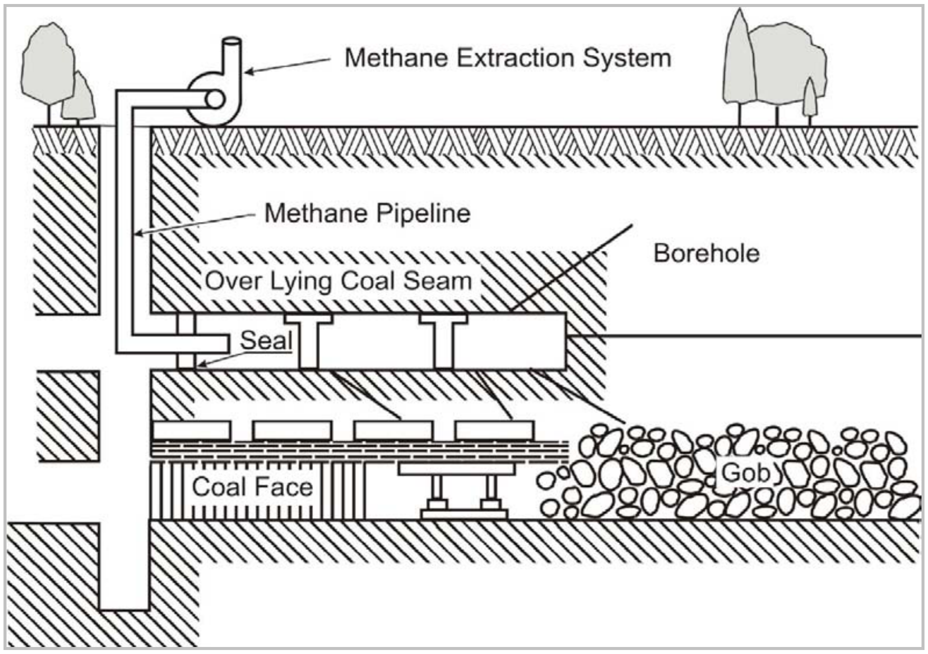

Exhibit 25: A sealed superjacent gallery with drainage boreholes [Thakur, 2006]

Exhibit 26 shows two superjacent gob drainage techniques used in eastern European mines.

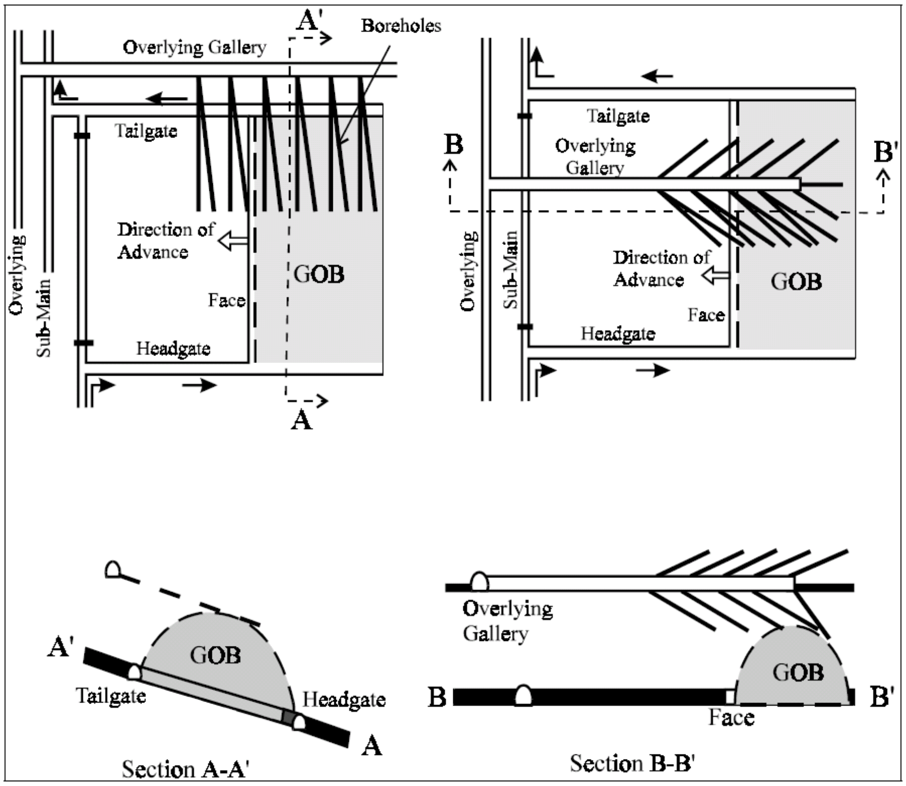

Exhibit 26: Degasification of gob areas using the superjacent method in Eastern Europe [Wisniewski, 1994]

3.3.2 Directionally drilled gob boreholes

Over the past two decades, superjacent techniques involving in-mine directionally drilled boreholes, placed over or under the mining seam in advance of longwall operations, have been applied in Japan, China, Australia, Germany, and in the U.S. This technique uses state-of-the-art, in-mine directional drilling equipment normally used to develop long in-seam methane drainage or exploration boreholes.

In-mine gob boreholes, 76-152 mm (3-6 inches) in diameter, are drilled into the strata overlying or underlying un-mined panels, to lengths up to 1,500 m (5,000 ft) as previously shown in Exhibit 13.

Positioning

Ideally, overlying boreholes should be positioned taking into account as many of the following factors as possible:

- To be in or below the lowest producing source seam;
- To intersect the fracture zone above and below the rubble zone after the gob forms;
- To be over the tension zones near the edges of the panel;
- To take advantage of gob gas migration patterns caused by the mine's ventilation system and geometry of the gob – gob gas will accumulate toward the low pressure side of the gob and higher elevations;
- To consider water accumulation – either slope upwards from the collar to allow water to drain back to the wellhead for separation, or, once the target horizon has been reached, drill downgrade so that water drains down the borehole and back into the gob;
- To remain intact following undermining and produce gob gas over the entire length of the borehole.

The optimal vertical placement of the borehole is typically determined by trial and error and requires properly monitoring gas flow and quality, monitoring longwall face production and controlling vacuum at the well heads.

Superjacent directionally drilled boreholes have several advantages over the cross-measure method, namely:

- The boreholes can be developed in advance of mining, away from mining activity for either advancing or retreating longwall systems;
- Fewer, longer boreholes can produce an effective low pressure zone over the gob;
- 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;
- The system may be more effective and less costly to implement and easier to operate than a system of cross-measure boreholes.

Relative to a system employing galleries, horizontal gob boreholes will be less costly to implement, particularly if the galleries are developed specifically for degasification purposes and mined in rock or uneconomic coal seams.

Borehole diameter and spacing

The volume of gob gas emissions determines the number of boreholes required per panel. At least three boreholes per panel appear to be necessary for adequate gas capture and to provide redundancy in the case of borehole failure. Long boreholes, in excess of 500 m (1640 ft), 100 mm (4 inches) in diameter and subject to a high vacuum (100 mm Hg) can recover approximately 15 Mcmd (530 Mcfd) of gob gas. Short deviated boreholes can be drilled from the main borehole to enlarge the zone of reduced pressure over the gob.

As is the case with cross-measure boreholes, developing a continuous low-pressure zone over the gob requires borehole influence zones to overlap slightly. If boreholes are insufficiently sized and spaced too far apart, gob gas will tend to migrate to the mine entry. If boreholes are over-designed and too close together, they may promote migration of mine ventilation air into the gob. Fewer, farther-spaced, larger-diameter (150 mm or 6 inch) boreholes may recover more gas at lower pressure losses than smaller-diameter, closely-spaced holes. This would result in less drilling, fewer wellhead connections and minimized leakage, leading to improvement in gas production rate and quality, increasing the system efficiency and ease of maintenance. The extra cost incurred in drilling larger-diameter holes, which might even require different equipment and/or larger galleries, needs to be weighed against the incremental benefit of increased gas production and improved gas quality.

Recovered gas quality and production

Gob gas drainage efficiency and gas purity for superjacent systems are affected by geologic and reservoir conditions, orientation of the galleries and/or boreholes, borehole size and spacing, gallery and borehole integrity, suction control, water accumulation, and mine ventilation.

Superjacent borehole drilling is technically more complicated than in-seam drilling, and this is reflected in higher drilling costs of $100-130 per meter ($30-40 per foot).

Example

- Test studies developed by REI Drilling, Inc., in mines in the U.S., Japan, China and Germany resulted in average borehole production figures ranging from 8,300 mcm/d to 15,000 mcm/d (293-530 Mcfd). Boreholes were 500-800 m (1640-2624 ft) in length. Gob gas quality varied between 35-90 percent and was directly affected by longwall face advance rates, requiring constant monitoring and vacuum control [Brunner and Schwoebel, 2001]. REI Drilling tested the effects of drilling larger (150 mm, 6 in.) diameter boreholes for high capacity gob gas recovery in very gassy conditions; lining the borehole with perforated steel casing to improve borehole integrity; and the development of parabolic boreholes to simulate effective surface-drilled angled gob wells.

4. Gas gathering and collection

An integral component of a mine degasification system is the gas collection and transport system. Underground, this infrastructure serves to move coal mine methane collected from degasification boreholes up to the mine surface. On the surface, gathering infrastructure can include gob wells, pipelines, compression and processing facilities (if the methane is to be used commercially), flare stacks, and exhausters.

4.1 Underground gas collection systems

Underground gob gas collection systems are typically more difficult to control and maintain than surface systems because of mining activity and the complex subsurface environment. Gas collected from underground degasification boreholes is brought to the surface via a network of pipes fitted with safety devices, water separators, monitors and controls, and vacuum pumps (Exhibit 27).

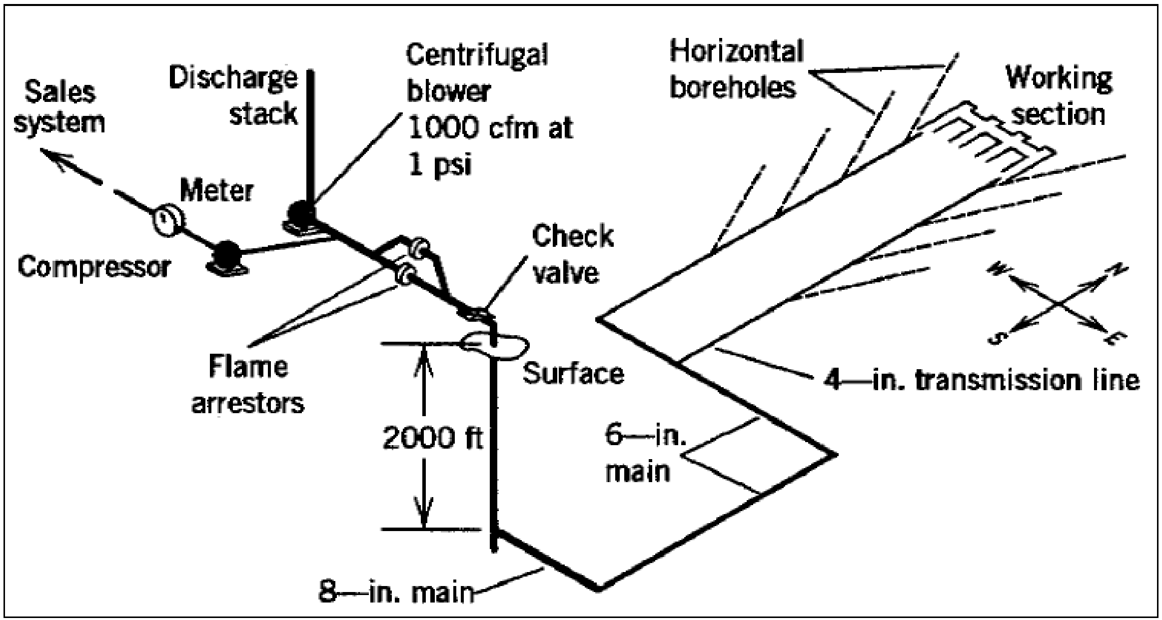

Exhibit 27: Layout of a horizontal borehole methane drainage system showing both in-mine and surface facilities [Hartman et al., 1997]

4.1.1 Pipelines

In-mine methane drainage boreholes normally connect to a collection line via flexible piping. Collection lines are either suspended or laid on the mine floor (Exhibit 28), and transport drained methane to a main gas line, which leads to a vertical collection well that may be freestanding or affixed to the lining of an exhaust shaft. In the U.S., guidelines stipulate that a methane drainage pipe should be in return airways, visible along its entire length, not submerged at any location, and pressure tested during installation.

Air leakage into a negative pressure gas collection system affects recovered gas quality and system performance. Fewer leaks at pipe joints and fittings lead to less dilution of drained methane and allow for greater system suction pressures, resulting in higher gas quality and volumes gathered at the surface.

Pipelines are steel or, where permitted, high-density polyethylene (HDPE). Steel lines are preferred for mechanical strength, especially for the underground to surface connections, but HDPE is easier to work with and is non-corrosive.

Steel pipes are joined by threaded connections or by gasketed, flanged connections, although both types can corrode and leak over time, particularly if frequent pipeline moves are necessary. HDPE pipe sections are non-corrosive and can be fused together, greatly reducing mine air leakage into the pipeline system. HDPE pipe is lighter and easier to handle than steel pipe, reducing installation and maintenance costs. Depending on conditions, increases in recovered gas quality as high as 50 percent may be realized with HDPE systems versus flanged steel pipe networks.

Exhibit 28: HDPE gas collection piping

Steel pipe		High-density polyethylene pipe	
Advantages	Disadvantages	Advantages	Disadvantages
Superior mechanical strength	Connections can corrode and leak over time Heavy and difficult to move	Non-corrosive - resistant to H_2S, does not rust Lighter and easier to handle than steel, reducing installation and maintenance costs Connections can be fused together minimizing leaks	Less mechanical strength than steel Some concern about static electricity issues

Exhibit 29: Summary of gas collection pipe properties

4.1.2 Safety devices

Safety devices installed along the pipeline network serve to protect the infrastructure from leakage during pipe ruptures. Operators typically install automatically activated safety shut-off valves at each borehole and at regular intervals along the pipeline network. This sectionalizes the system and minimizes methane liberation into the mine ventilation system should a breach in the pipeline occur. The valves are activated pneumatically or electrically by means of methane sensors in the airway, pressure sensors, or, most commonly in the US, protective monitoring tubing devices.

4.1.3 Water separation

Water traps, or separation devices, installed at low elevations along a methane drainage network, prevent the accumulation of water (condensate, or formation water) which would otherwise impede gas production. Large separators are placed at wellheads and the base of vertical collection wells (Exhibit 30). These devices subject drained methane to a sudden expansion that reduces its velocity, dropping any entrained water.

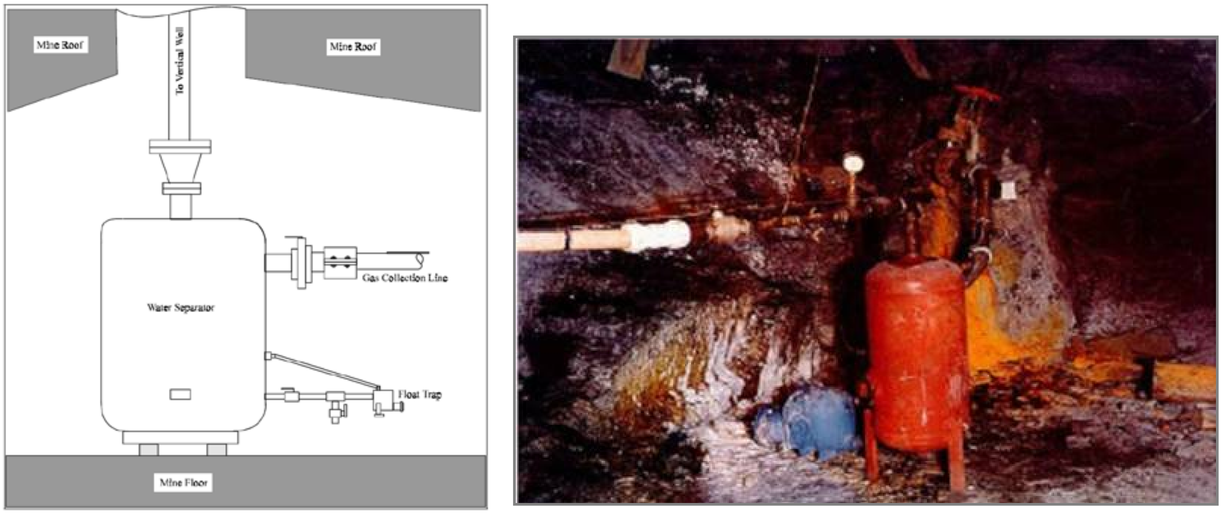

Exhibit 30: Separation system at the base of a vertical collection well

4.1.4 Monitoring and control

Gas collection system monitors sense three parameters: pressure, flow rate, and concentration of gas constituents. Valves comprise the control system. They are activated either manually or remotely by pressure, gas quality, or flow sensors. Negative pressure applied at the wellhead affects gas production and quality. High suction pressures tend to introduce mine ventilation air, while insufficient suction may impair production and increase methane emissions into the ventilation system. Proper pressure control in the drainage system is achieved through strategic placement of control valves within the system, employing sufficient wellhead monitors, and properly designing the vacuum pump and gathering system. Pressure responses are specific for each drainage borehole. Frequent monitoring at critical junctions underground can optimize system performance and provide warning of increased system demands. Benefits are improved system performance and increased recovered gas quality.

4.1.5 Underground gas movers

There are three types of extractor pump systems that are most prevalent for supplying negative line pressures to a degasification pipe network: water seal extractors; centrifugal blower/exhausters; and rotating pumps. Water seal extractors are preferred for installations underground because of the inherent safety features of producing a vacuum, since these do not significantly increase gas temperature and do not require contact between stationary and moving parts [McPherson, 1993].

4.2 Surface gas collection systems

At the surface, gas is collected from vertical fractured wells, surface-drilled horizontal wells, gob wells and centralized vacuum stations, which collect the gas produced by in-mine boreholes. Ideally, all CMM collected at the surface is used commercially either at the mine or off site. Depending on produced gas quality and volumes, CMM can be used for a number of purposes:

- Fed in to a natural gas pipeline;
- Used to power electric generators for the mine or local region;
- Used as an energy source – co-firing in boilers, district heating, coal drying, use as a vehicle fuel, and manufacturing or industrial uses such as ammonia production.

In many CMM drainage projects worldwide, commercial CMM use is currently not technically or economically viable. As a result, the drained gas is vented directly to the atmosphere, via an exhauster/well head blower. One option to reduce the environmental impact of direct venting is to burn the vented methane in a controlled flare system [USEPA, 1999^{a}]. While the byproduct of burning methane is carbon dioxide, itself a greenhouse gas, the global warming potential is still reduced since carbon dioxide is 23 times less potent than methane. CMM flaring has been used successfully in the U.K. and Australia, but has yet to gain widespread acceptance in the U.S. coal mining industry.

The main components of a surface gas collection system include the well head equipment, gathering pipelines, gas processing equipment, and compressors.

4.2.1 Pipelines

Gas is transported from individual wells via an in-field gathering system to a central processing facility where the gas is treated and compressed to meet transmission pipeline specifications. The pipeline gathering system requires various diameters of pipe at different intervals to be efficient.

A system of relatively small diameter, low pressure pipelines, referred to as "flowlines", is designed to move gas or water from the wellhead to a larger diameter pipe that moves the fluid from the field to a central treatment facility. Flowlines are typically made of high-density polyethylene and are 100-200 mm (4-8 inches) in diameter (water flowlines can be as small as 50 mm (2 inches) in diameter).

The larger diameter pipe, made of steel, is known as a "trunkline". Intermediate lines between the trunk and flowlines, are sometimes referred to as “gathering lines”, are necessary as the system grows with field development. Once processed and compressed, a large, high-pressure steel pipeline, operating at 4,480-8,620 kPa (650-1250 psi) and referred to as a transmission pipeline moves the gas from the project area to the market.

4.2.2 Compression

CMM is collected from the wellbore at relatively low pressures and is compressed to attain the necessary pressure requirements for injection to a transmission pipeline. The number of stages needed for compression will depend on the suction and discharge pressures needed to produce the wells and compress the gas into the transmission line, and the compression ratios of the equipment. Three to four stages of compression are common in CBM/CMM projects in the U.S. due to the low suction pressures required to maintain gas production and the high pressures (see above) required for interstate transmission lines. A low suction pressure of between 70-210 kPa (10-30 psi) is typical for the network of flowlines taking gas from the well sites to the central treatment facility. Depending on engineering requirements, some operators will locate compressors at each well site, while others will situate compressors at a central facility.

4.2.3 Gas processing

Gas drained from vertical wells, horizontal wells and in-seam boreholes is usually of sufficient quality (greater than 90% methane) for injection into natural gas pipelines with minimal processing. Gas from gob wells and cross-measure boreholes is more variable in quality (30-80% methane), depending on the amount of dilution caused by air infiltration into the gob and boreholes. An integrated processing plant can be installed at a central facility to remove contaminants and increase the quality of the gas to pipeline specifications. The CMM is treated in a series of connected processes, which first removes any hydrogen sulfide present, followed by excess oxygen, carbon dioxide, water vapor, and nitrogen. In the U.S., pipeline quality gas must contain less than 0.2% oxygen, less than 3% nitrogen, less than 2% carbon dioxide and less than 112 kg/MMcm (7lbs/MMcf) of water vapor, while having a heating value of greater than 967 Btu/scf [USEPA, 2008[c]].

5. Summary

There are significant benefits to the mining operation and to the environment by optimizing methane drainage systems at coal mines.

5.1 Benefits of CMM drainage for coal mines

Many benefits can accrue to the mine owner from installing a methane drainage system. An efficient methane drainage system can help achieve the following:

- Improved mine safety resulting from lower methane concentrations at the face, returns, gobs and bleeders;
- Enhanced coal productivity because of less frequent downtime or production slowdowns caused by high methane concentrations in the mine;
- Decreased fan operating costs because of reduced ventilation air requirements for methane dilution;
- Reduced shaft sizes and number of entries required in the mains;
- Increased tonnage extracted from a fixed-size reserve as a result of shifts of tonnage from development sections to production sections;
- Decreased dust concentrations and improved worker comfort through reduction of ventilation air velocities at the working face; and
- Reduced mining problems caused by water.

Each of these benefits is described below.

Improved mine safety

The effect of a methane drainage system on the safety of a mining system will result in positive benefits [Ely and Bethard, 1989]. A mine operation with high methane levels will experience a higher level of hazardous operating conditions than an equivalent mine with a methane drainage system in place.

Increased coal production

Enhanced coal productivity is a significant benefit realized from the installation of methane drainage systems. The economic value of such a benefit can be very large when one considers that the value of coal that comes off a longwall in a shift can average between $100,000 to $200,000 for an average modern longwall. Any lost production caused by excessive methane levels in the mine workings results in a sizable cost - around $200 to $400 per minute of downtime in this case. The significance of this cost can be realized when considering that downtime of up to 11,000 minutes per month for a single longwall have been reported in the literature [Aul and Ray, 1991] and that many longwalls will experience slowdowns in production as well as times where the longwall is completely down due to high methane concentrations.

A similar economic advantage will occur in room-and-pillar operations that have the possibility of production interruptions due to methane emissions in the working sections. With continuous miner productivities continually rising, the economic benefit can be in the range of $50 - $100 per minute of downtime averted by a well-designed gas drainage system.

Ventilation power cost savings

Several papers have outlined costs associated with ventilating mines with high levels of methane emissions [Mills and Stevenson, 1989; Kim and Mutmansky, 1990; Aul and Ray, 1991]. Aul and Ray [1991] and cite situations where a methane drainage system reduced the ventilation requirements for methane dilution to about half, thus greatly reducing the ventilation power costs. Cost savings are dependent on mine size, the ventilation plan, electrical power costs, and the actual air quantities saved in a particular mine ventilation network. Wang [1997] has verified the significant nature of ventilation power cost savings, especially if gas released during mining is 10 m^3/tonne (400 ft^3/ton) or more. The study by Wang also concluded that potential power cost savings in continuous mining operations were even more significant than they are in longwall operations.

Reduced development costs and increased reserves

The installation of a methane drainage system can significantly reduce mine ventilation requirements and allow for the extraction of wider longwall panels. Reduced ventilation requirements may make possible a reduction in the size and number of shafts and other development openings connecting the mine workings to the surface. Extracting wider longwall panels also reduces the number of development entries in a mine.

Longwall mining can extract 85-95% of the coal under optimal conditions, while in development sections only about 50% of the coal is recovered. The coal produced from development sections is generally more costly to extract, on a dollars per ton basis, than the coal produced on a longwall panel. Therefore, increasing panel width and decreasing the number of development entries not only leads to an increase in mineable coal reserves, but also lowers the extraction cost per ton of those reserves. These cost differences can be significant as shown in previous studies [Kim and Mutmansky, 1990].

Reduced dust problems and increased worker comfort

The comfort level of the work environment in the mine deteriorates if high air velocities are required to keep methane concentrations below the regulatory limits. Air velocities above 180 meters per min (600 ft/min) can generate more dust and ordinary tasks become more difficult. In some longwall sections, for example, the high velocities downward of the shearer result in the transported dust creating a “sand blasting” effect on the exposed skin of workers that is both unpleasant and hazardous to their eyes. While the number of personnel working downwind of the shearer is generally small, the hazards involved are both significant and avoidable.

Reduced water problems

The presence of water in coalmine roof strata can be a costly source of delays in some underground mining operations. Generally, the most sizeable delays will be encountered in the development sections of the mine and will be quite variable depending upon the geologic conditions of the roof strata. The water in the roof, when occurring in conjunction with high methane contents, can be removed by a methane drainage system. The statistics of downtime reductions in such mines vary, but the reduction in downtimes from water can produce significant economic value. Reese and Reilly [1997] have outlined the benefits for a longwall mine in Pennsylvania. In this operation, the use of gas drainage wells achieved a 63% reduction in water downtimes and a 16% reduction in methane downtimes.

5.2 Environmental benefits of CMM drainage

The major environmental benefit of CMM drainage and utilization is a reduction in the amount of methane entering the atmosphere and contributing to anthropogenic greenhouse gas emissions. When methane is captured and either flared or used as an energy source, the combustion process destroys the methane and produces CO_2, which is twenty-five times less potent as a greenhouse gas than methane [IPCC, 2007].

GMI [2016] estimates that there are more than 200 CMM projects worldwide, which through draining, capturing and utilizing methane, reduce emissions to the atmosphere by more than 1.7 Bcm (59.5 Bcf) methane a year, equivalent to 28.6 $MTCO_2e$.

USEPA [2018[a]] profiled twenty-five of the gassiest mines in the United States in 2015 that are possible candidates for development of CMM recovery and use projects. Methane from mine drainage systems peaked at 1.67 Bcm (59 Bcf) in 2010 and declined to 1.16 Bcm (41 Bcf) in 2015. Methane recovered and used increased from 1.27 Bcm (45 Bcf) in 2006 to 1.38 Bcm (49 Bcf) in 2010 but has since decreased to 0.93 Bcm (33 Bcf) in 2015. Declines in both were due to natural fluctuations in methane production, mine closures, decreased underground coal production, low natural gas prices, and low carbon prices for CMM projects prior to 2015. Simultaneously, the number of mines with gas drainage systems increased from 23 in 2006 to 26 in 2015, and the number of mines with active methane recovery and use projects increased from 14 in 2006 to 17 in 2015. There are other encouraging developments that may increase methane capture and use in the future: two commercial VAM projects were implemented at U.S. mines, which successfully demonstrated both the technical and commercial viability of these project types, and the California Air Resources Board adopted the Mine Methane Capture Protocol allowing CMM projects to qualify for offsets in California's Cap-and-Trade Program.

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