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# REDUCING COAL MINE GHG EMISSIONS THROUGH EFFECTIVE GAS DRAINAGE AND UTILISATION

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## ABSTRACT

Gas emission from Australian coal mining is estimated to account for 4-5% of the nation's 559 million tonnes of $CO_2$ equivalent ($MtCO_{2-e}$) annual greenhouse gas (GHG) emissions. With the intense focus on global GHG management and reduction, to slow the rate of climate change, significant community and political pressure is mounting to reduce gas emission from coal mining. This paper discusses the various sources of gas emission from an operating underground coal mine, with particular focus on longwall mining which accounts for the majority of Australian underground coal production. A variety of gas drainage techniques, both from surface and from within operating underground mines, are described along with a range of commonly encountered problems that exist within coal mine gas drainage system that prevent optimum drainage system performance being achieved. Two variations of a new surface based gas drainage system for the removal of goaf/gob gas emissions to improve longwall mine productivity and safety are described. This proposed new technique aims to cost effectively increase the total gas volume extracted from the goaf (gob) whilst maintaining a relatively consistent gas production rate throughout the operating life of the well. Various methods of coal mine methane gas utilisation are examined, including the capture and utilisation of low concentration methane present in mine ventilation air.


## INTRODUCTION

In December 2007 Australia committed to join the Kyoto Protocol, and in doing so committed to implement strategies to manage the country's GHG emissions to achieve an emissions target of not more than 108% of 1990 levels by the end of the 2012 commitment period. From early 2008 the Australian Government has been developing an emissions reduction scheme, to continue beyond the end of Kyoto. The scheme, known as the Carbon Pollution Reduction Scheme (CPRS), which is planned to be implemented by the end of 2010, prescribes emissions targets for Australian industry. The proposed CPRS, which incorporates a cap-and-trade emissions trading scheme, will require coal mining companies to surrender a number of emissions permits equal to the total emission of greenhouse gases. Companies will be able to acquire emissions permits either directly from the government at a quarterly public auction, or by way of trade with other holders of emissions permits. Companies that fail to surrender sufficient emission permits to cover their greenhouse gas emissions will be liable to a penalty.

In the case of the Australian coal industry, which is estimated to emit some 22.5 $MtCO_{2-e}$ per annum (Somers, 2008), the introduction of the CPRS will add in the order of half a billion dollars to the

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cost of operations (based on a carbon unit cost of \$20/t$CO_{2\text{-}e}$). Faced with the prospect of incurring such a significant additional cost it can be expected that increased attention and support will be directed toward technologies to improve gas capture and emissions reduction. It is therefore essential that operators and planners understand the principles of gas generation, storage and the ability to drain gas from the coal seam in order to effectively manage the safety and productivity of the mine. This knowledge will also underpin the company's ability to effectively respond to the requirements of new environmental legislation and to achieve an optimised economic outcome.

Gas is generated during the coalification process and the amount of gas present within a particular coal seam is dependent upon a range of factors, which include; seam thickness, depth of burial, surrounding strata type, coal geology, coal structure, coal strength, igneous activity and/or igneous sources, secondary biogenic activity and the ground stress regime. Given the large number of factors that impact gas generation, storage and movement it should be no surprise that there is such a high degree of variability in gas content and composition as well as the ability to drain gas from coal seams throughout Australia.

During the ten years from 1998 to 2008, there has been a drop in the number of operating longwall mines from 35 to 29. However, as shown in Figure 1, the production capacity has increased substantially with total annual production increasing from 67.2 Mt (1998) to 99.4 Mt (2008), an increase of 47.9% (Cram, 1998-2009). During this period the average longwall mine production has increased approximately 80%, from 1.9 Mtpa to 3.4 Mtpa.

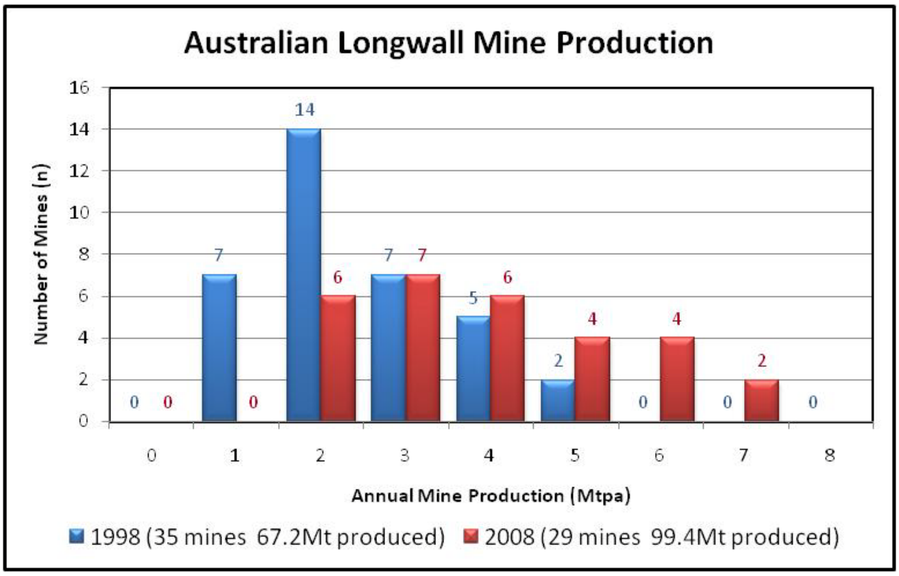


**Figure 1: Comparison of Australian longwall mine production 1998-2008 (Cram, 1998-2009)**

Of the 29 mines operating in 2008 it is estimated that 12 mines employ gas drainage, of varying degrees of complexity and effectiveness, to reduce gas content prior to and during mining. It is generally accepted in Australian underground coal mines that a gas content above 6-8 $m^3$/t signals the need for gas drainage to reduce the content of the seam to a level where the risk of initiating an outburst is significantly reduced and the volume of gas liberated from the coal during mining is able to be diluted by the mine ventilation air to a level which complies with mine safety regulations. The complexity and effectiveness of the drainage systems varies significantly, ranging from boreholes that discharge into the mine return airways through to mines whose drainage boreholes are connected to surface drainage plant via complex reticulation networks with subsequent downstream utilisation of the drainage gas.

In those mines considered to be less gassy and therefore not requiring gas drainage for operational control the gas emitted from the coal during operations is cleared from the working areas by the mine ventilation system where it is removed from the mine and discharged to atmosphere via the mines ventilation fans.

There are many sources of gas emission throughout an operating underground coal mine, shown in Figure 2, which include:

**A.** Rib emission into both intake and return airways;
**B.** Emission from coal cutting – both development and longwall production;
**C.** Emission into longwall goaf from adjacent gas bearing coal seams and strata;
**D.** Emission from longwall goaf into connecting airways; and
**E.** Emission from coal being removed from the mine via the coal clearance system

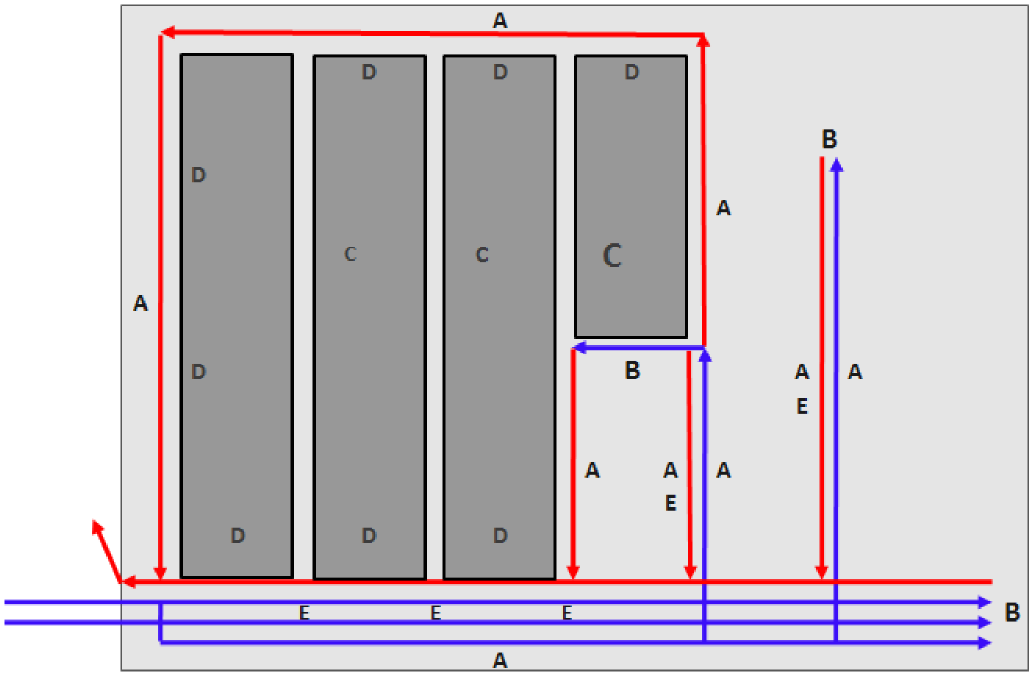


**Figure 2: Conceptual mine layout illustrating the location of potential gas emission sources**

Given the many sources of gas emission associated with underground coal mining it is possible for certain operations to produce significant volumes of methane along with smaller amounts of other gases, such as carbon dioxide.

The scale of emissions will however vary between mines and is primarily controlled by the gas content ($m^3/t$) of the coal seam, or the specific gas emission ($m^3/t$) from all gas sources impacted by mining, and the rate at which coal is produced (tonnes).

Table 1 shows the volume of methane gas that would be liberated from a particular mine given a range of both annual coal production and gas content / specific gas emission (SGE). For example, a mine producing 4.0 million tonnes per annum that has a specific gas emission of 20 $m^3/t$ would liberate 80 million cubic metres of methane annually.

As methane is a greenhouse gas, with a global warming potential 21 times greater than carbon dioxide, the potential mine gas emission can also be considered in terms of tonnes carbon dioxide equivalent ($tCO_{2\text{-}e}$). Table 2 shows the volume greenhouse gas emitted annually from a mine given a range of coal production and specific gas emission. Using the same example of a mine producing 4.0 million tonnes per annum, with an SGE of 20 $m^3/t$, the annual gas emission would be equivalent to 1.14 million tonnes of carbon dioxide.

**Table 1: Total annual gas production based on gas content and annual coal production rate**

| Specific Gas Emission ($m^3$/t) Gas Content | Total Annual Gas Emission (million $m^3$ - $CH_4$) | | | | | | |
|---|---|---|---|---|---|---|---|
| **35** | 35.0 | 70.0 | 105.0 | 140.0 | 175.0 | 210.0 | 245.0 |
| **30** | 30.0 | 60.0 | 90.0 | 120.0 | 150.0 | 180.0 | 210.0 |
| **25** | 25.0 | 50.0 | 75.0 | 100.0 | 125.0 | 150.0 | 175.0 |
| **20** | 20.0 | 40.0 | 60.0 | 80.0 | 100.0 | 120.0 | 140.0 |
| **15** | 15.0 | 30.0 | 45.0 | 60.0 | 75.0 | 90.0 | 105.0 |
| **10** | 10.0 | 20.0 | 30.0 | 40.0 | 50.0 | 60.0 | 70.0 |
| **5** | 5.0 | 10.0 | 15.0 | 20.0 | 25.0 | 30.0 | 35.0 |
| | **1.00** | **2.00** | **3.00** | **4.00** | **5.00** | **6.00** | **7.00** |

**Annual Coal Production (million tonnes)**

**Table 2: Annual GHG emission based on gas content and annual coal production rate**

| Specific Gas Emission ($m^3$/t) Gas Content | Annual Coal Mine Gas Emission (tonnes $CO_{2\text{-}e}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| **35** | 497,595 | 995,190 | 1,492,785 | 1,990,380 | 2,487,975 | 2,985,570 | 3,483,165 |
| **30** | 426,510 | 853,020 | 1,279,530 | 1,706,040 | 2,132,550 | 2,559,060 | 2,985,570 |
| **25** | 355,425 | 710,850 | 1,066,275 | 1,421,700 | 1,777,125 | 2,132,550 | 2,487,975 |
| **20** | 284,340 | 568,680 | 853,020 | 1,137,360 | 1,421,700 | 1,706,040 | 1,990,380 |
| **15** | 213,255 | 426,510 | 639,765 | 853,020 | 1,066,275 | 1,279,530 | 1,492,785 |
| **10** | 142,170 | 284,340 | 426,510 | 568,680 | 710,850 | 853,020 | 995,190 |
| **5** | 71,085 | 142,170 | 213,255 | 284,340 | 355,425 | 426,510 | 497,595 |
| | **1,000,000** | **2,000,000** | **3,000,000** | **4,000,000** | **5,000,000** | **6,000,000** | **7,000,000** |

**Annual Coal Production (tonnes)**

Note: The global warming potential (GWP) of methane is 21 times greater than carbon dioxide.

With the introduction of the cap-and-trade system for GHG emissions permits, to be implemented as part of the Australian government's CPRS, mining companies will be required to surrender to the government one emissions permit for every tonne of 'carbon dioxide equivalent' emitted. With the total number of emissions permits in circulation expected to be equivalent to the government-determined 'cap' on greenhouse gases it can be expected that insufficient permits will be available, which will generate a fresh market for emissions permit trading. It can be expected that as demand exceeds supply the cost of acquiring emissions permits will increase to such a point where it would otherwise be more cost effective for mining companies to implement measures to reduce the total volume of greenhouse gases emitted from their operations.

Should the cost of acquiring an emissions permit be A\$20/t$CO_{2\text{-}e}$, the impact on a mine with a SGE of 20 $m^3$/t, producing 4.0 Mtpa, would be an additional A\$22.75 million per annum (A\$5.70 per ROM tonne) in emissions penalties. For higher producing mines and/or those with greater specific gas emissions the cost of the penalties will be greater and will be further impacted should the cost of an emissions permit increase.

In order to reduce the net overall cost of minesite emissions it is expected that many operations will implement measures to capture and utilise coal seam gas, thereby reducing emissions.

**GAS DRAINAGE – PRE-DRAINAGE**

The use of inseam drilling for gas drainage ahead of mining was first introduced in Australia in 1980. The purpose of this early gas drainage was to reduce the coal seam gas content to a level where, during mining, the gas emission could be adequately diluted and managed by the mine ventilation system. Since 1980 underground-to-inseam (UIS) drilling has evolved from simple rotary drilling rigs, with limited directional control and depth capability, to the current technically advanced units incorporating down-hole motors capable of achieving depths in excess of 1,600 metres. The use of UIS drilling has expanded throughout the Australian coal mining industry to become the method of choice for underground gas drainage drilling, particularly in mining regions such as the Illawarra which operate at depths in the order of 450 to 500 metres and have many restrictions to surface access which limits the use of surface-based methods.

In gassy mines it is common for substantial UIS drilling and gas drainage to be completed ahead of mine development, with in excess of 100,000 metres being drilled annually. The cost of such intensive drilling programs, along with the associated infrastructure, is in the order of A$4-6 million per annum. A variety of drilling patterns and treatments are available, illustrated in Figure 3, the most common pattern being the Fan pattern due to the relatively large length of the adjacent gateroad covered from a single drilling site installation. There may be negative aspects associated with drill pattern designs such as the fan pattern. These include a) inability to preferentially orient boreholes to align with optimum drilling/drainage direction, b) inability to maintain boreholes on a positive grade to limit accumulation of water and fines within the borehole, and c) extremely close spacing between boreholes close to the collar allows flow of gas and fluid between holes which is a significant problem during drilling.

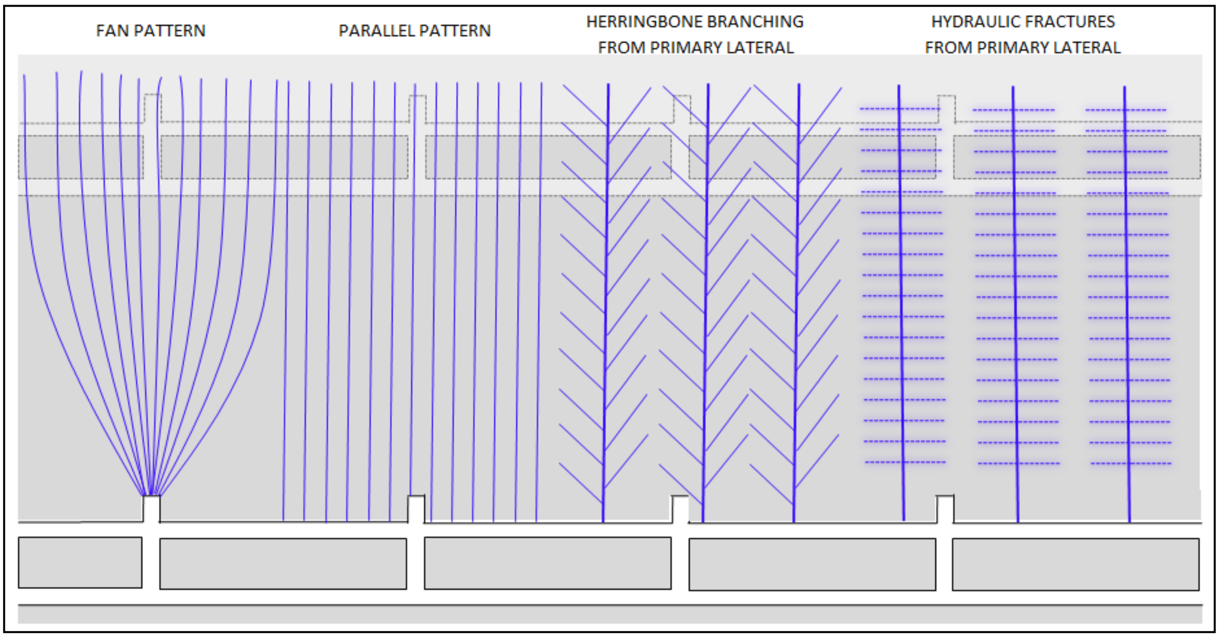


**Figure 3: Underground to inseam gas drainage drilling patterns and gas drainage enhancement options**

Previous studies undertaken by the author to evaluate the effectiveness of an intensive UIS gas drainage program (Black and Aziz, 2008) found significant variability in gas drainage performance both across and within distinct drilling fan patterns. The results from one particular study confirmed that some 50% of the total gas drainage drilling effort delivered little to no benefit to gas content reduction. Analysis of the factors that impacted gas drainage performance identified many factors, both geological and operational, that affected flow performance. It was however found that, at an operational level, the performance of the gas drainage program was not well understood and where the gas drainage system was not effective in reducing the gas content, rather than address the 'controllable factors' to improve drainage performance, it was common for the mine to simply drill many additional holes in the area.

Unfortunately these additional holes added very little value and were generally ineffective in increasing the gas drainage rate.

The range of site controllable factors that can have significant impact on the performance and effectiveness of a gas drainage program include:

1) Insufficient drainage time prior to the borehole being compromised when mined out by advancing development gateroads;
2) Insufficient monitoring of borehole performance to identify poor performing holes and subsequent management to address accumulations of water and/or coal fines within the borehole;
3) Insufficient monitoring and management of the gas reticulation pipe network allowing blockages, from water and/or coal fines, to significantly restrict flow capacity in sections of the range;
4) Poor standard of sealing holes following intersection by development allowing air ingress to the pipe range and reduced suction pressure;
5) Insufficient standpipe length and sealing (grouting) standard resulting in air dilution in the pipe range and reduced suction pressure;
6) Boreholes not drilled in the optimum orientation to achieve maximum drainage performance; and
7) Absence of in-hole dewatering in boreholes drilled down-dip resulting in in-hole water accumulation restricting gas desorption.

A further inherent problem with the UIS method of gas drainage is the dependence on mine development to form the roadways from which the drilling can be undertaken. Given the objective of most mining operations to achieve rapid development to form longwall blocks that can be extracted quickly to achieve high annual production, the amount of time available for drilling and draining the next gateroad in the development sequence is reduced. In areas with higher gas content and lower permeability there have been many examples where the seam gas content has not been reduced sufficiently, resulting in production delays. Also, during development production delays, the longwall typically continues to operate which further erodes development lead placing greater pressure on development and further reduces the available drainage lead time. In the extreme cases operations have opted to cut longwall panels short and therefore sacrifice valuable coal reserves rather than incur potentially significant production delays while waiting for sufficient gas to be drained.

It is therefore extremely important that mine operators clearly understand both the drainage characteristics of the future mining areas, particularly those areas expected to be slow draining, and the expected drainage time available, based on the mine production and drilling schedule. Where areas are identified that drainage time is expected to be insufficient it will be necessary to employ additional drainage methods and possibly stimulation treatments to avoid production delays or loss of reserves.

A method that offers a significant increase in drainage time is Surface-to-Inseam (SIS) drilling. Originally vertical wells were drilled from the surface to intersect the various gas bearing seams however these wells achieve very low surface contact with the respective seams and, in the absence of high permeability and favourable drainage characteristics, the resulting gas drainage flow rates were quite low. Methods were developed to stimulate the gas production performance of these wells, which included under-reaming, cavity completion, and hydraulic fracturing.

Advances in the development of drilling technology led to the introduction of deviated well drilling, also known as radius drilling. This method involves initially commencing the drilling with a vertical, or near vertical, section and then bending the drill string through an acceptable radius, which is governed by the capability of the drill string, to intersect the coal seam, or target drilling horizon, horizontally and then continuing to drill and extend the borehole at the desired horizon to the planned borehole length. A range of radius drilling designs are presented by Logan et al. (1987) and illustrated in Figure 4. The total length of the inseam section of such boreholes is capable of exceeding 2,000 metres; however the length is principally dictated by the capacity of the drill rig and the drilling fluids used.

Following the introduction and development of the SIS drilling technology in Australia the use of Medium-Radius Drilling (MRD), employing a typical bend radius of 250 to 350 metres, has seen widespread application, particularly in the Queensland Coalbed Methane (CBM) industry. MRD is now becoming a favoured method in many Queensland coal mine pre-drainage programs with increasing application in the Hunter Valley and Illawarra regions.

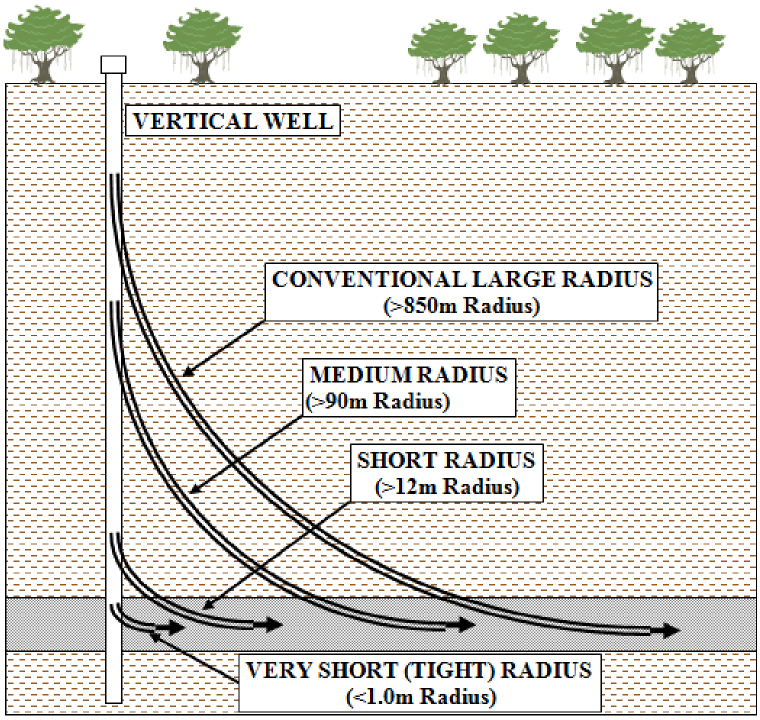


**Figure 4: Surface to inseam horizontal drainage drilling technologies (Logan et al., 1987)**

## GAS DRAINAGE – POST-MINING (GOB) DRAINAGE

The gas released during and subsequent to the longwall mining process represents the major source of coal mine gas emission, particularly in situations where additional gas bearing coal seams and strata are located in close proximity to the seam being extracted. In the case of mines operating in the Bulli seam the total specific gas emission during longwall extraction is in the order of 35-45 $m^3$/tonne. Mines with high gas emission rely on effective gas drainage techniques to avoid significant gas related production delays and to maintain the safety of the mine and its workforce. There have been many methods used by mines to drain gas from both the active and sealed goaf, these underground based methods include:

a) Cross-measure boreholes – boreholes drilled above and/or below the working seam located along the length of the longwall panel;
b) Back-of-block drainage – boreholes drilled above the working section to connect into the goaf to remove accumulated high purity gas;
c) Goaf seal drainage – removal of gas from sealed goaf via pipes passing through seals; and
d) Horizontal directional drilling – long boreholes drilled above and/or below the working seam and oriented parallel to the longwall panel which connect to the forming goaf to drain the accumulating gas.

Although the underground gas drainage methods are capable of removing very high volumes of gas (well in excess of 2,500 lps), there are many examples where the rate of gas emission has exceeded the capacity of the drainage system resulting in gas-related production delays. For mines in such situations the use of additional surface-based gas drainage techniques are likely to be required. One such technique is the use of vertical boreholes, located toward the tailgate side of the longwall panel and drilled ahead of the retreating longwall face. The bottom of the hole is typically located a distance of 10-35 metres above the roof of the working section. Following the passing of the longwall face and goaf formation, suction is applied to the goaf drainage borehole and the gas accumulating in the goaf is drawn to the surface, typically through the use of vacuum plants to overcome the ventilation pressure within the mine. Figure 5 illustrates the method of vertical well goaf drainage typically employed at Australian underground coal mines.

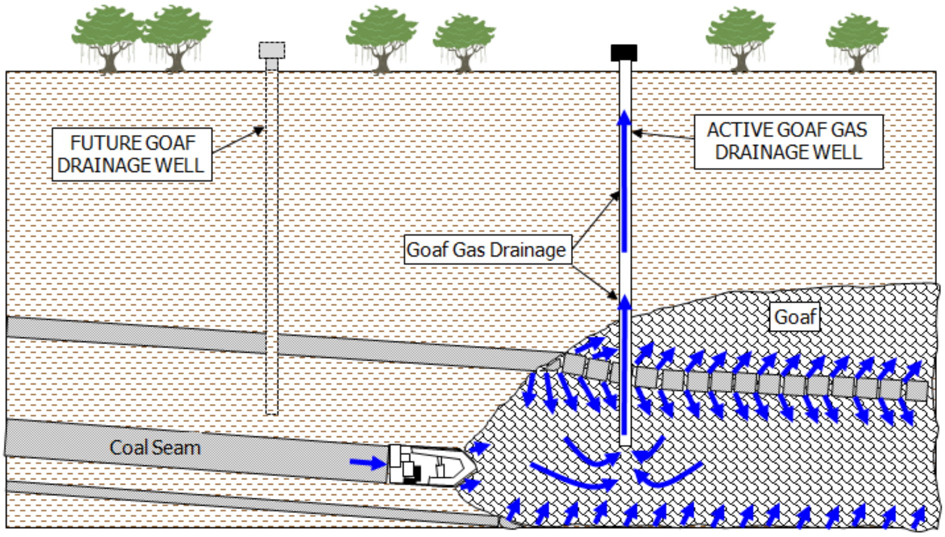


**Figure 5: Vertical well surface-based goaf gas drainage**

With the ever increasing pressure being applied to mine operations through urban development and environmental sensitivity the use of vertical goaf drainage wells, which are typically spaced no greater than 300-400 metres apart, represents a high impact, particularly given the need for ancillary plant such as drainage plant, emissions reduction plant (e.g. flare units) and/or gas reticulation pipelines to service the wells. In situations where significant surface access restrictions exist, mines may be prevented from employing vertical well surface goaf drainage which may result in restricted production through inability to manage total gas emissions. In such cases alternative gas drainage methods must be developed and utilised. One such alternative method, proposed by the first author, is the use of radius drilling to form boreholes parallel to the longwall block, positioned typically toward the tailgate side of the longwall face, approximately 30-50 metres above the roof of the working section, drilled ahead of the retreating longwall face. As the longwall face passes the end of the borehole and connection to the goaf occurs, suction is applied to the goaf drainage borehole to remove the accumulating gas. Due to the nature of goaf formation relative to the longwall face the position of the open end of the horizontal drainage borehole can be expected to remain relatively constant throughout the operating life of the well, resulting in a more stable and overall higher gas production rate than is achievable through the use of vertical goaf drainage wells. An advantage of the use of radius drilling for the formation of horizontal goaf drainage wells is the ability to drill multiple laterals to achieve multiple connections to the goaf which improves both the system reliability and total gas production capability for a given borehole diameter. Figure 6 provides an illustration of one particular horizontal goaf drainage well design. This design shows the primary lateral(s) section of the well located above the working seam, within the zone that will become fractured following coal extraction. Multiple branches are drilled from the primary lateral(s) down into the primary caving zone, the zone that will become highly fractured during goaf (gob) formation. In this design, where the primary lateral is positioned within the fractured zone, it can be expected that this main section of the well will remain partially viable and able to draw gas for a longer period post-caving, thereby enabling gas to be extracted from deeper within the goaf. The branch sections into the primary caving zone serve to remove the gas accumulating immediately behind the operating longwall face to reduce face gas concentrations. This design is favourable for gas utilisation as it offers the dual benefits of gas removal from the face area through the branch sections into the primary caving zone, to improve mine safety and productivity, as well as draining additional gas from the deeper goaf area through the main lateral(s) section, located above the branch sections, in the less physically disturbed fractured zone.

The characteristics of the deformed strata within the subsidence zone due to longwall mining are described by Forster and Enever (1992) in Figure 7 and per discussion with Guo (2008).

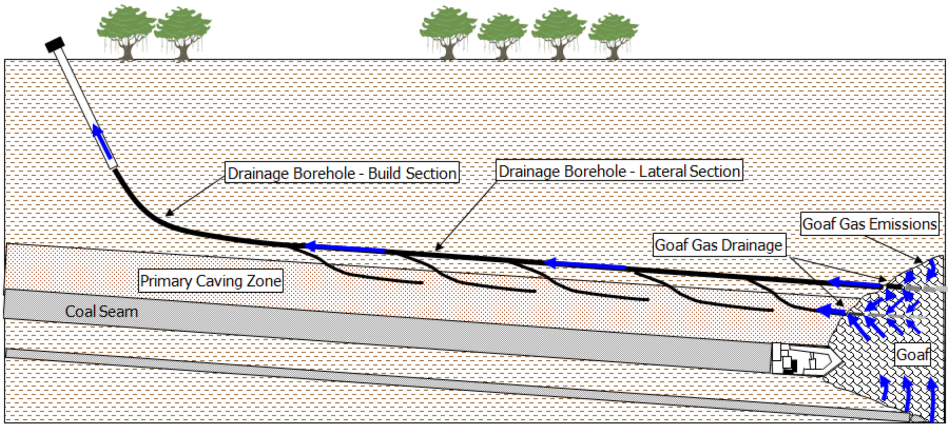


**Figure 6: Horizontal well surface-based goaf gas drainage – dual horizon gas extraction**

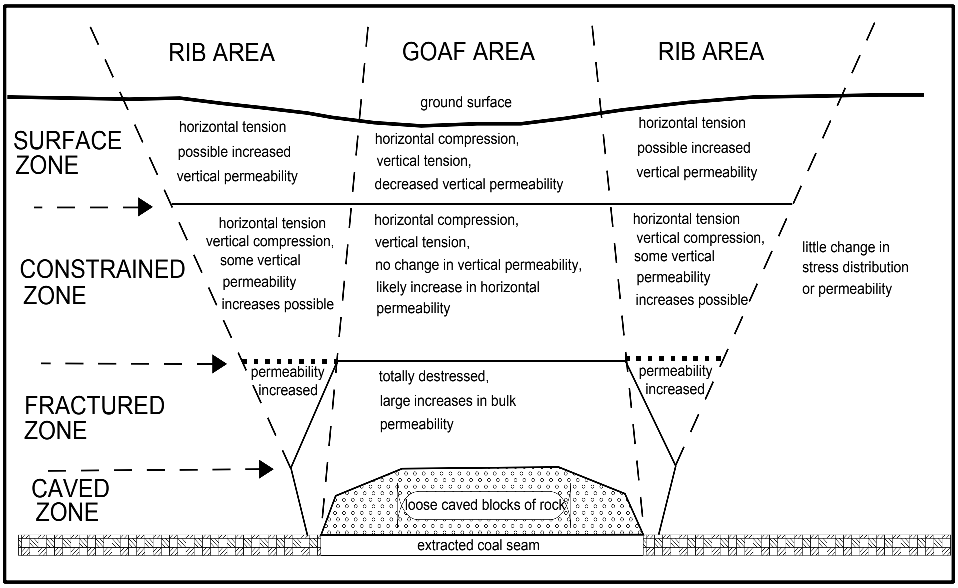


**Figure 7: Zones of mining induced strata deformation (Forster and Enever, 1992)**

An alternative horizontal goaf drainage production well design is shown in Figure 8. This design features the main lateral(s) sections of the well located above the working seam, within the primary caving zone. During longwall production the inbye sections of the lateral(s) are lost in the formation of the goaf. However the connection of the drainage well to the goaf is maintained and gas extraction continues along the reducing length of the lateral sections of the well.

The position of the lateral(s) relative to the working seam is a critical factor in the well design. Where the separation distance is too small there is a high risk of drawing ventilation air into the well through the highly permeable material in the caved zone. In this situation the production rate of the well must be reduced to minimise dilution, which adversely impacts gas extraction capability, leading to gas management issues within the mine. However, if the separation distance is too great and the lateral sections of the well are located too high into the fractured zone, or in the constrained zone, there is a reduction in permeability and the well is incapable of drawing sufficient gas from the caving zone and therefore has limited effect on reducing gas emission immediately behind the longwall face. Therefore the caving characteristics of the longwall goaf must be understood and considered in the drainage well design in order to achieve optimum gas production.

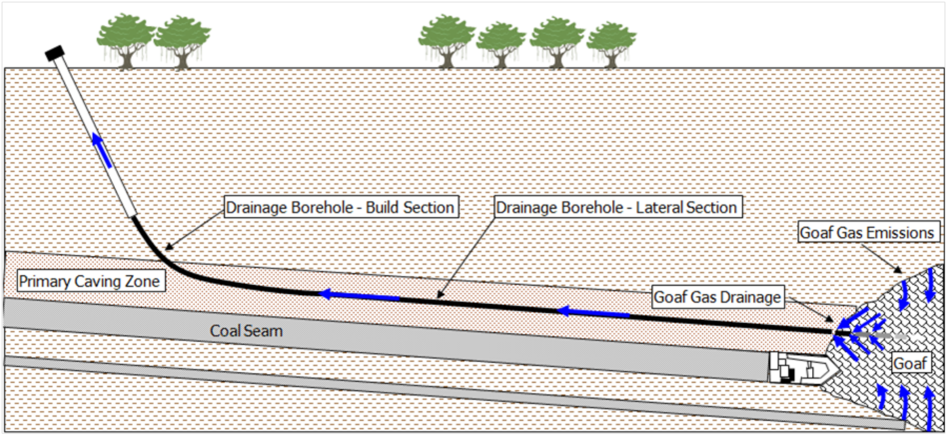


**Figure 8: Horizontal well surface-based goaf gas drainage – single horizon gas extraction**

## GAS UTILISATION

Prior to the introduction of government schemes and incentives to encourage the utilisation of coal mine methane only three Australia mines actively utilised gas for power generation, being Appin, West Cliff and Tower collieries. The majority of gas emission from other mines was vented to atmosphere with only a few exceptions that employed flaring. Following the introduction of government incentive schemes such as the NSW Greenhouse Gas Abatement Scheme (GGAS) and the federal government's Greenhouse Friendly Program, a number of new gas utilisation projects have commenced.

Flaring is the simplest form of emissions reduction and simply involves the burning of methane gas to produce carbon dioxide and water. Where flares are to be located close to developed areas it may be necessary to minimise the visual impact of the project. In such cases enclosed flare units have been developed to limit the height of the flame so as to minimise the impact on the local community, however such units do have a reduced flaring capacity.

The utilisation of coal mine methane in the generation of power has the potential to increase the financial benefits from abating a given volume of gas. In the case of power generation the financial benefits are derived from the sale of both the accumulated carbon credits and electricity.

Turbines were first devices used in Australia to generate electricity from coal mine methane. The first two Australian coal seam gas turbine installations, rated at 14.7 MW and 12.0 MW (Bishop and Battino, 1989), were located at Appin and West Cliff Collieries and operated between the years 1986 to 1995 and 1984 to 1999 respectively. However increasing maintenance costs and inefficiencies associated with variable drainage gas concentration led to the decommissioning of these units. Both units were replaced by internal combustion engine technology that utilised methane gas as the primary fuel. The most common internal combustion engine utilising methane gas for minesite power generation are the 1.0 MW units (e.g. Caterpillar 3516 and GE Jenbacher 320) although both larger and smaller units are available. There are now eight coal mine methane gas power generation projects operating at Australian coal mines, and these include:

- Appin (54 MW)
- Tower (40 MW)
- Moranbah North (40 MW)
- Grasstree (32 MW)
- Oaky Creek (12-20 MW)
- Glennies Creek (10 MW)
- Tahmoor (7 MW)
- Teralba (6-8 MW)

The largest source of coal mine methane (CMM) is the dilute methane emitted from mine ventilation shafts. Known as Ventilation Air Methane (VAM), this gas is difficult to capture and use because it has a low methane concentration. VAM emissions are typically characterised by large airflows and low concentrations, ranging from 0.1 to 1.5%, but more typically 0.3 to 0.5%. Further adding to the complexity of mitigating VAM is the large airflow volumes associated with mine ventilation systems, typically ranging from 150 to 350 $m^3/s$. It has been estimated that greater than 55% of all CMM emissions originate from mine ventilation shafts, thus VAM offers both the greatest opportunity and challenge for coal mine emission reduction and energy production.

Technical applications for VAM use include direct use as a principal energy source in oxidation units, lean-burn turbines, and kilns, where it is mixed with coal fines or other combustible materials. In addition to direct greenhouse gas abatement it is also possible to recover and transfer the heat produced during methane destruction to generate electricity. Table 3 provides a summary of a variety of known VAM utilisation technologies that exist or are being developed (Anon, cited online 2009). The first commercial power generation plant that utilises VAM for the generation of electricity is located at West Cliff Colliery, in Australia. The plant, known as WestVAMP, shown in Figure 9, has been designed to utilise 20% of the mines total 350 $m^3/s$ ventilation exhaust air capacity, with an optimum VAM concentration of 0.9-1.0% $CH_4$ to produce 6.0 MW of electricity.

**Table 3: Summary of VAM utilisation technology development**

| Vendor / System | Description | Country | Development Status |
|---|---|---|---|
| MEGTEC / Vocsidizer | Thermal flow-reversal reactor (oxidiser).<br>Heat energy used to superheat steam to power a steam turbine. | United Kingdom<br>Australia<br>USA | 8,000$m^3$/hr unit installed at British Coal (1994).<br>6,000$m^3$/hr unit installed at Appin Colliery (2002).<br>250,000$m^3$/hr unit installed at West Cliff Colliery (2007) powering a conventional 6MW steam turbine.<br>50,000$m^3$/hr unit installed at CONSOL's Windsor Mine (2007) . |
| BIOTHERMICA / Vamox | Thermal flow-reversal reactor (oxidiser) | USA<br>Canada | 50,000$m^3$/hr unit being installed at Jim Walter Resources No.4 Mine (Blue Creek Coal) (2009).<br>8,500$m^3$/hr unit being installed at Quinsam Mine, British Columbia (2009). |
| CANMET / CH4MIN | Catalytic flow-reversal reactor (oxidiser) | Canada | 500mm pilot plant constructed to demonstrate technology.<br>Seeking to commercialise the technology and undertake minesite demonstration project. |
| EESTECH / HCGT | Waste coal and VAM co-fired in rotary kiln.<br>Compressed air heated in heat exchanger powers a gas turbine. | Australia | CSIRO designed 1.0MW prototype demonstration unit successfully trialled.<br>Seeking minesite demonstration opportunities. |
| CSIRO / VAMCAT | Lean-fuelled gas turbine with catalytic combustor (1.0% VAM) | Australia | Demonstration unit (25kW) installed at Panyi Mine, Huainan, China. |
| FlexEnergy / Lean-fuelled catalytic microturbine | Lean-fuelled Capstone microturbine (1.3% VAM) | USA | Multiple 30kW units operating at abandoned Akabira Mine, Japan |
| Ingersoll-Rand / Lean-fuelled recuperated microturbine | Lean-fuelled IR Power Works microturbine (1.0% VAM) | USA | 1x70kW unit installed at CONSOL's Bailey Mine utilising mine drainage gas (2007).<br>2x250kW units installed on wellhead at PetroChina's Changging oil field (2008). |
| EDL / Carburated gas turbine (CGT) | Lean-fuelled Solar gas turbine with patented combustor (1.6% VAM) | Australia | 2.7MW SOLAR Centaur gas turbine tested at EDL's Appin power station. |
| EDL / Ancillary VAM use | VAM used to supplement combustion air in Caterpillar 1.0MW engines | Australia | VAM successfully used to supplement combustion air intake to CAT 1MW gas engines at Appin power station. |

**Figure 9: West Cliff Colliery mine ventilation air methane abatement and utilisation plant – WestVAMP**

## CONCLUDING REMARKS

With the imminent introduction of the Australian government's Carbon Pollution Reduction Scheme coal mines, particularly those gassy mines with high greenhouse gas emissions, can expect to incur significant financial penalties when having to purchase sufficient emissions permits to account for their total emission. When faced with this potentially significant additional operating cost many operators will consider options to reduce total emissions and therefore the number of emissions permits that must be acquired. Therefore it can be expected that an increased number of mining operations, both open cut and underground, will seek to introduce, or improve existing, gas drainage and utilisation projects.

A variety of gas drainage techniques, both from the surface and from within operating underground mines, have been presented in this paper along with a range of commonly encountered problems that exist within coal mine gas drainage systems that prevent optimum drainage system performance and effectiveness from being achieved. A variety of methods for utilising the drained gas are also presented.

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