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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 ($MtCO_{2-e}$) 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 exists to reduce the rate of gas emission. In December 2007 Australia committed to join the Kyoto Protocol, which in part requires annual GHG emissions not to exceed 108% of 1990 levels by the end of the 2012 commitment period. The current Australian Federal Government is presently developing the Australian carbon pollution reduction scheme, which is due to be implemented by 2010. This scheme is expected to place a value on GHG emissions and thereby introduce a financial penalty/incentive on organisations to manage and reduce their GHG footprint. In the case of the Australian coal industry, with an estimated annual GHG contribution of 22.5 Mt CO_{2-e}, the introduction of the emissions reduction scheme will add in the order of half a billion dollars to the cost of operations (based on a carbon unit cost of \$20/t CO_{2-e}). In light of such a significant additional cost it can be expected that gas capture and emissions reduction will receive an unprecedented increase in attention and corporate support. This paper discusses the various sources of gas emission from underground coal mines and describes methods to improve both the capture and utilisation of this gas to reduce GHG emissions.

INTRODUCTION

Whether coal seam gas is considered a nuisance or threat, in the case of coal mine operators, or an opportunity, in the case of coalbed methane gas producers, it is essential that operators and planners understand the principles of gas generation, storage and its ability to be drained from the seam.

Gas is generated during the coalification process and the amount of gas present within a particular coal seam, known as gas content, is dependent upon a range of factors, which include; seam thickness, depth of burial, bounding strata type, coal geology, coal structure, coal strength, igneous activity and/or igneous sources, secondary biogenic activity and the ground stress regime.

The flow of gas in coal seams involves migration, through fractures and cleat, and diffusion through the coal matrix. Gas molecules diffuse through the coal matrix in response to concentration gradients and upon reaching the cleat system migrate in response to pressure gradients, obeying Darcy's Law. However as greater than 90% of the gas in coal is stored in micropores, diffusivity is the rate limiting factor for gas flow in most low permeability coals. 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.

Where the seam gas content is considered high, greater than 6-8 m^3/t, gas drainage is employed to reduce the naturally occurring gas content within a coal 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. Among the mines that employ gas drainage the complexity and effectiveness of the drainage systems varies significantly, ranging from boreholes that discharge into the mine return airways which in turn discharge to atmosphere via the mines ventilation fans, through to mines whose drainage boreholes are connected to surface drainage plant via complex reticulation network with subsequent downstream utilisation of the drainage gas.
In those mines considered to be less gassy and therefore not requiring gas drainage for operational issues 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 on Figure 1, which include:

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- Rib emission into both intake and return airways
- Emission from coal cutting – both development and longwall production
- Emission into longwall goaf from adjacent gas bearing coal seams and strata
- Emission from longwall goaf into connecting airways
- Emission from coal being removed from the mine via the coal clearance system

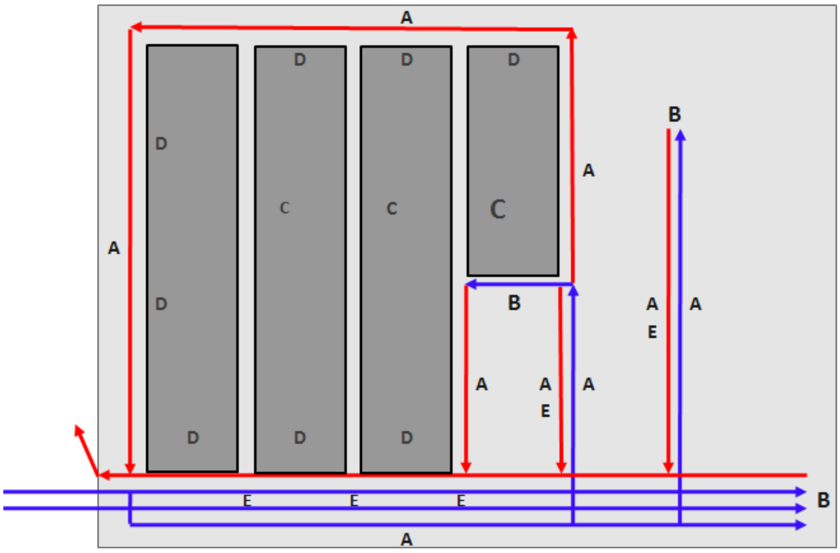

Figure 1: Conceptual mine layout illustrating the location of potential gas emission sources

Given the potential for high seam gas content and coal production capacity, coal mining is widely considered by community and government to be a major emitter of greenhouse gases. 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 specific gas emission (m^3/t) from all gas sources impacted by mining and the rate at which coal is produced (tonnes). Table 1 illustrates the scale of annual greenhouse gas emission, in tonnes of CO_2 equivalent, for a range of gas content and coal production capacities.

Should there be a value placed on carbon emissions and corresponding financial penalty imposed on mining companies based on net emissions it can be expected that strong corporate support will be provided to implement emission reduction measures. Should the cost of GHG emission be $20.00/t CO_{2-e}, the impact on a mine with an SGE of 15 m^3/t, producing 4.0 Mtpa, would be an additional $17.0 million per annum ($4.25/ROMtonne) 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 unit cost of carbon emission 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.

Table 1: 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 (tCO_{2-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.

GAS DRAINAGE – PRE-DRAINAGE

The use of inseam drilling ahead of mining for gas drainage was first introduced in Australia in 1980 to reduce the coal seam gas concentrations to levels sufficient to be managed by the mine ventilation system during both the roadway development and longwall coal extraction processes. 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 450-500m and have substantial surface access constraints which restrict access for surface based methods.

In gassy mines, such as those operating in the Bulli seam, it is common for substantial UIS drilling to be completed ahead of mine development, with in excess of 100,000 metres being drilled annually. The cost of such an intensive drilling program, along with the associated infrastructure, is in the order of $4-6 million per annum. A variety of drilling patterns and treatments are available, illustrated in Figure 2, with the most common pattern presently in use being the Fan pattern.

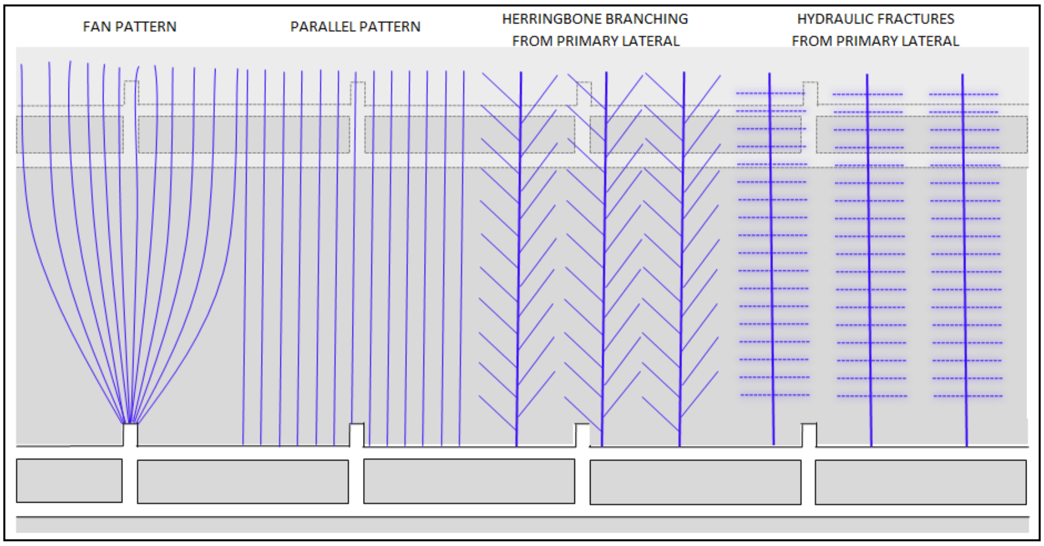

Figure 2: UIS drilling patterns and gas drainage enhancement options

Recent studies have been undertaken to evaluate the effectiveness of the intensive UIS gas drainage programs (Black and Aziz, 2008) and it was found that some 50% of the drilling effort delivered little to no benefit to gas content reduction. In such cases where the gas drainage system was not achieving optimum performance it is not uncommon for the mine to address the problem by drilling many more holes in the area, which essentially amounts to throwing good money after bad.

The reasons identified for the failure and poor performance of such a significant percentage of the boreholes in the drainage program include:

1) Insufficient drainage time prior to intersection by development gateroads;
2) Insufficient monitoring and management of borehole performance resulting in low to no flow due to accumulation of water and/or coal fines within the borehole;
3) Insufficient monitoring and management of the gas reticulation pipe network due to blockages or significantly restricted flow capacity due to the accumulation of water and/or fines in sections of the range;
4) Poor standard of sealing holes following intersection by development resulting in air in 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 drilled down-dip and not in the optimum orientation for maximum drainage performance; and
7) Absence of in-hole dewatering where boreholes have been 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 reliance on mine development to be completed in order to provide access to areas where 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 reducing. 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. During development production delays the longwall typically continues to operate which erodes development lead placing even greater pressure on development and further reduces the available drainage lead time. In the extreme cases operations have chosen to cut longwall panels short and therefore sacrifice valuable 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.

Further drilling technology development 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 3. 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 250-350m, 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 consideration is being given to trials in the Illawarra.

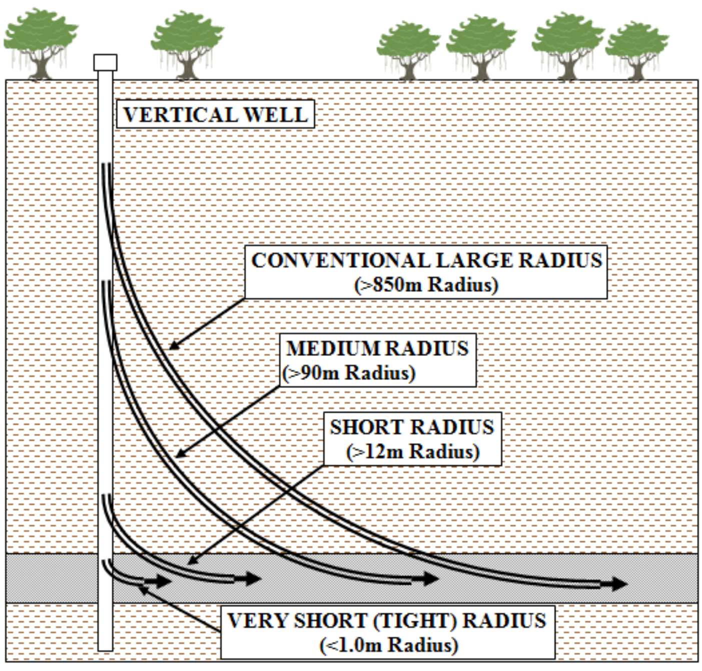

Figure 3: Surface to inseam horizontal drainage drilling technologies, after Logan *et. al*. (1987)

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GAS DRAINAGE – POST-MINING (GOAF) 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, located in close proximity to the seam being extracted releases its stored gases. In the case of mines operating in the Bulli seam the combined impact of gas liberated from all effected sources during longwall extraction is in the order of 35-45 m^3/tonne. In cases where high gas emission occur the use of effective gas drainage techniques is essential to minimise gas related production delays and 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 (≫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 goaf drainage techniques may be appropriate. 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. Figure 4 illustrates the method of vertical well goaf drainage typically employed.

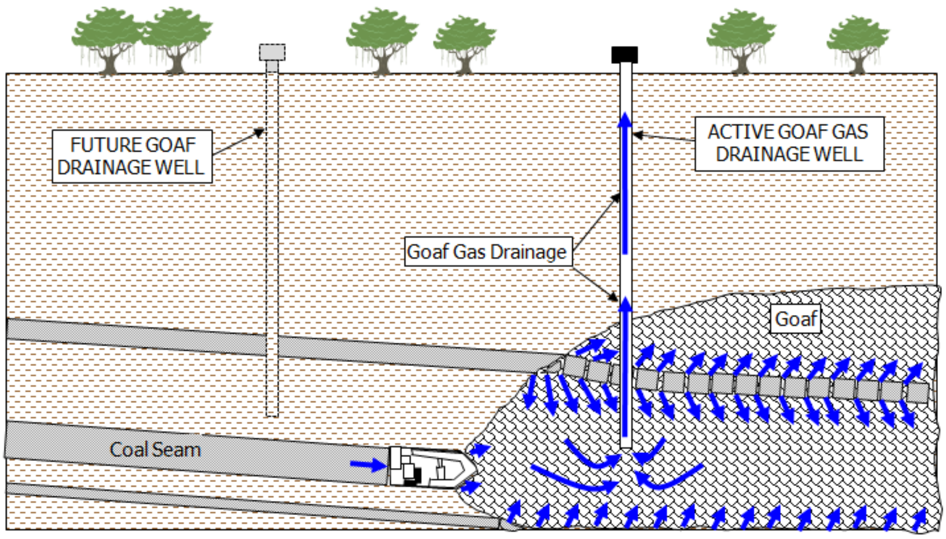

Figure 4: Vertical well surface-based goaf gas drainage

With the ever increasing pressure being applied to mine operations through urban development and environmental sensitivity the use of vertical goaf drainage wells, typically spaced no greater than 300-400 metres apart, represents a high impact, particularly give the needs 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 on 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 stable and overall greater gas production capacity than that which is achievable through the use of vertical goaf drainage wells. Figure 5 provides an illustration of one particular horizontal goaf drainage well design.

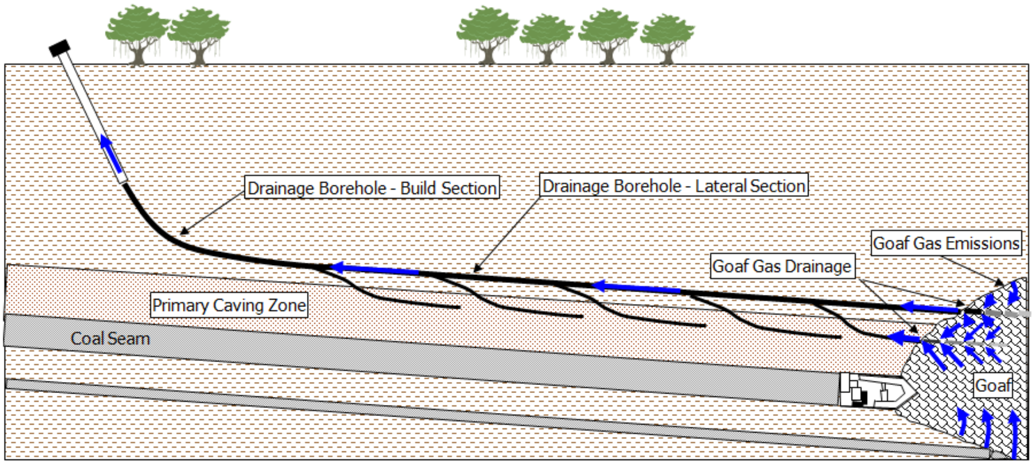

Figure 5: Horizontal well surface-based goaf gas drainage

A further advantage of the use of radius drilling for the formation of horizontal goaf drainage wells is the ability to drill multiple laterals to form multiple connections to the goaf which improves both redundancy and overall gas production capability. A production and financial comparison between the use of single and twin lateral horizontal well has been provided in Figure 6.

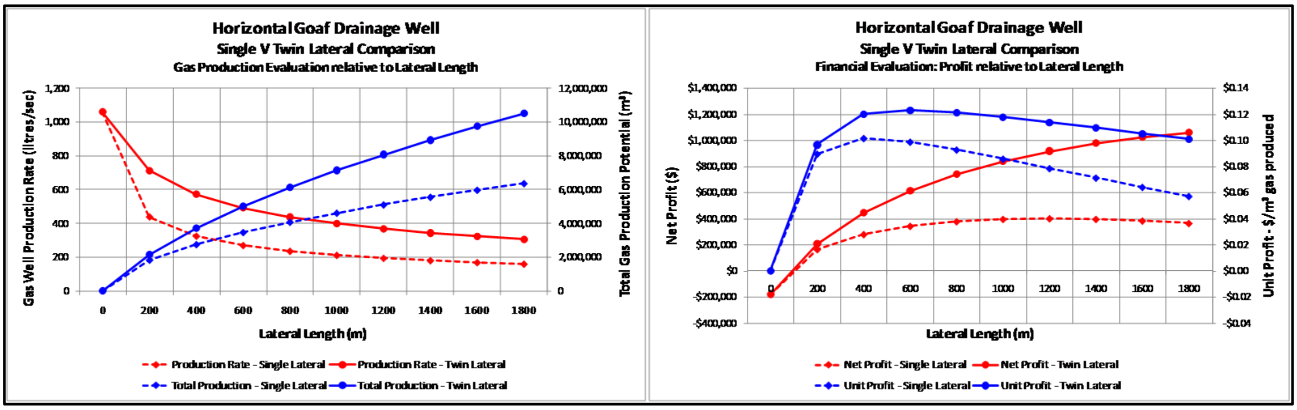

Figure 6: Comparison between single and twin lateral horizontal goaf drainage well production and economic performance

GAS UTILISATION

Prior to the introduction of government schemes and incentives for 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 few exceptions that employed flaring. Following the introduction of schemes such as the NSW Greenhouse Gas Abatement Scheme (GGAS) and the federal government's Greenhouse Friendly program, a number of 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 not to be seen by the local community.

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 carbon credits, and electricity.

Turbines were first used to generate electricity from coal mine methane. The two Australian gas turbine installations, both rated at 15MW, were located at Appin and West Cliff collieries and operated between the years 1986 to 1995 and 1984 to 1999 respectively. The increasing maintenance costs and inefficiencies associated with variable drainage gas concentration led to the decommissioning of these units. These 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 (54MW)
- Tower (40MW)
- Moranbah North (40MW)
- Grasstree (32MW)
- Oaky Creek (12-20MW)
- Glennies Creek (10MW)
- Tahmoor (7MW)
- Teralba (6-8MW)

The largest source of coal mine methane (CMM) is the dilute methane emitted from mine ventilation shafts. Known as Ventilation Air Methane (VAM), 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 0.1-1.5%, 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 emission reduction and energy production potential.

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 from this oxidation to generate electricity. Table 2 provides a summary of a variety of known VAM utilisation technologies that exist or are being developed.

Table 2: Summary of VAM utilisation technology development

Vendor / System	Description	Country	Development Status
MEGTEC / Vocsidizer	Thermal flow-reversal reactor (oxidiser). Heat energy used to superheat steam to power a steam turbine.	United Kingdom Australia USA	8,000m^3/hr unit installed at British Coal (1994). 6,000m^3/hr unit installed at Appin Colliery (2002). 250,000m^3/hr unit installed at West Cliff Colliery (2007) powering a conventional 6MW steam turbine. 50,000m^3/hr unit installed at CONSOL's Windsor Mine (2007) .
BIOTHERMICA / Vamox	Thermal flow-reversal reactor (oxidiser)	USA Canada	50,000m^3/hr unit being installed at Jim Walter Resources No.4 Mine (Blue Creek Coal) (2009). 8,500m^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. Seeking to commercialise the technology and undertake minesite demonstration project.
EESTECH / HCGT	Waste coal and VAM co-fired in rotary kiln. Compressed air heated in heat exchanger powers a gas turbine.	Australia	CSIRO designed 1.0MW prototype demonstration unit successfully trialled. 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). 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.

CONCLUDING REMARKS

With the imminent introduction of the Australian government's Carbon Reduction Scheme there will be potentially significant financial incentive for coal mines to implement effective gas drainage and utilisation strategies to reduce the volume of methane gas emitted to the atmosphere.

A number of methods available to drain and capture coal mine methane have been presented along with a range of commonly encountered problem 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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