Methane Emissions from Coal Mining

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1 Introduction

The importance of methane (CH_4) as a greenhouse gas is increasingly being recognized and has been the subject of numerous reviews.[1–4] There are many sources of methane, usually involving the degradation of organic matter to a more thermodynamically stable form, namely methane—and these include sources such as biomass, landfill, petroleum, and coal.

The coal industry is of considerable size and is spread over fifty countries. The total coal production worldwide in 1991, including brown coal and lignite, according to IEA Coal Research, was 4566 Mt. The major producers of hard coal in 1991 were China, 1087 Mt; USA, 825 Mt; former USSR, 485 Mt; India, 229 Mt; S. Africa, 181 Mt; Australia, 167 Mt; and the UK 96 Mt, whilst other countries are major producers of brown coal and lignites Colombia and Indonesia are becoming major producers. It is difficult to predict the role of coal over the next few decades because of the competing influences of natural gas and nuclear energy. At present 40% of the world coal is used for electricity production and, whilst there may be an initial decrease in coal use (at least in Europe, because of the increased use of natural gas), it seems likely that after a few years there will be a worldwide increase. IEA Coal Research suggest coal consumption will expand to 5500 Mt by the year 2000. Clearly methane emissions from coal production, handling, and combustion will be a significant component of global methane emissions for a considerable time.

The geological formation of coal, commonly called coalification, which involves an increase in carbon content and density as it changes from peat via lignite (65–72% mass C) to the hard coals such as bituminous coal (76–90% mass C) and anthracite (93% mass C), results in methane formation together with carbon dioxide and nitrogen as shown in Figure 1.

The quantities formed can be substantial as shown in Figure 2 although the

[1] T. M. L. Wigley and S. C. B. Raper, *Nature (London)*, 1992, **357**, 293.
[2] Estimation of Greenhouse Gas Emissions and Sinks. Final Report OECD Experts Meeting, 18–21 February 1991. Prepared for Intergovernmental Panel on Climate Change. Revised August 1991.
[3] Methane Emissions and Opportunities for Control, Workshop Results of Intergovernmental Panel on Climate Change, September 1990.
[4] International Workshop on Methane Emissions from Natural Gas Systems, Coal Mining and Waste Management Systems, 9–13 April 1990, Washington, DC, USA.

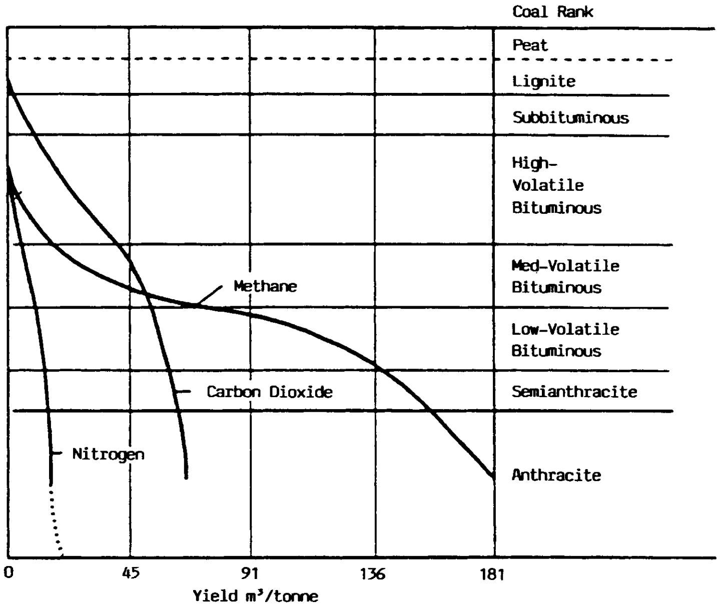

Figure 1 Gas quantities generated during coalification. Reprinted with permission from Reference 5.

actual quantities found today are a function of earth movement and erosion. They are, as might be expected, a function of depth, pressure, moisture content, and the extent of coalification, and have been discussed by a number of authors generally relating to specific countries or areas such as the US, Australia, Germany, and the UK.[4,10] Typical trends for US coals are shown[5] in Figure 2. Coal rank represents the differences in the stages of coal formation and is dependent on the pressure and temperature of the coal seam; high rank coal, such as bituminous coals, contain more CH_4 than low rank coal, such as lignite. Depth is important because it affects the pressure and temperature of the coal seam, which in turn determine how much CH_4 is generated during coal formation. If two coal seams have the same rank, the deeper seam will hold larger amounts of CH_4 because the pressure is greater at lower depths, all other things being equal. The translation of the methane content of coal into methane gas emission during mining is a complex matter involving the nature of the storage of the methane in the coal, its transmission through coal beds during mining operations, and the mining operations themselves where degassing and ventilation practices may vary.

This complexity fundamentally arises because the methane exists within the

[5] M. C. Irani, P. W. Jeran, and M. Deul, 1974, ICF Resources, 1990.
[6] D. P. Creedy, *Q. J. Eng. Geol.*, 1991, **24**, 109.
[7] D. Buchanan and D. P. Creedy, Report produced for the Working Group on Methane Emissions, The Watt Committee on Energy, 1993.
[8] C. Mitchell, Energy Policy, 1991, 849.
[9] I. M. Smith and L. L. Sloss, Methane emissions from coal, IEAPER/04, IEA Coal Research, 1992.
[10] Coal Industry Advisory Board, Global methane emissions from the coal industry, October, 1992.

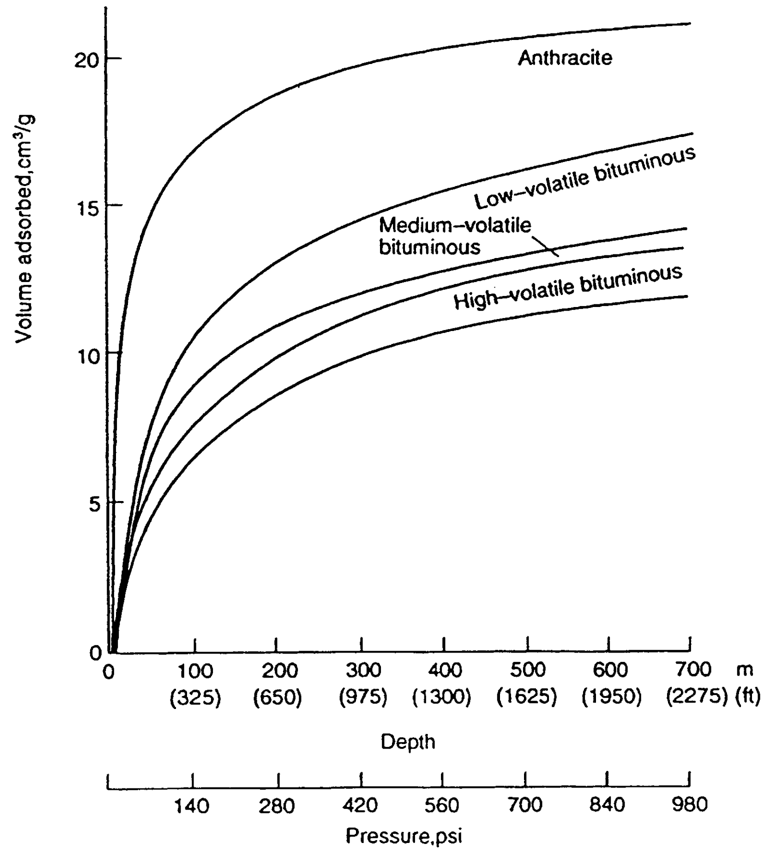

Figure 2 Relationship between adsorbed methane volumes and depth and pressure for different coal ranks. Reprinted with permission from Reference 5.

micro-pore structure of the coal, mainly as adsorbed layers. The amount present is effectively a function of the available internal pore surface area—a function of coalification—and the level of competing adsorbing or pore blocking species, such as water, and is, of course, a function of pressure.

2 Knowledge About the Emission Sources

Emissions may occur from operational and abandoned deep mines and from surface mines which may operate at a variety of depths and which have a relatively large exposed area. In addition, there are emissions from mined coal during transportation and combustion, but the latter are not dealt with here.

Emissions from Deep Mining

The calculation of methane emissions from coal mining is complex. Methane emissions and the rates of release will differ at each mine due to the way the coal is mined, the different qualities of coal mined, the different working depths, the types of ventilation, the different drainage or predrainage and capture systems

Table 1 Estimated underground emission factors for selected countries

Country	*Emissions Factor*/m^3 $tonne^{-1}$
Former Soviet Union	17.8–22.2
United States	11.0–15.3
Germany (East and West)	22.4
United Kingdom	15.1
Poland	6.8–12.0
Czechoslovakia	23.9
Australia	15.6

that are used, and other factors such as the geology of the mining area; for example, the density of coal seams. In most underground mines methane is removed by ventilation in which large quantities of air pass through the mine and this air, typically containing a concentration of one per cent methane or less, is exhausted into the atmosphere. In some mines, however, more advanced methane recovery systems may be used to supplement the ventilation systems and ensure mine safety. These recovery systems involve drilling into the unmined coal seams and typically produce a higher concentration of methane ranging from 35% to 95%. In some countries, some of this recovered methane is used as an energy source, while other countries vent it to the atmosphere. Recent technological innovations are increasing the amount of methane that can be recovered during coal mining and the options available to use it. Thus, methane emissions could be reduced from this source in the future.

In an earlier OECD methodology,[4] a single emission factor of 27.1 m^3 of methane $tonne^{-1}$ of coal mined was recommended for all underground mining. This factor included both emissions from mining and from post-mining emissions associated with underground coal production.

Based on more recent studies and additional country-specific emission data, the 1993 meeting of the OECD Experts Group in Amersfoort, The Netherlands recommended revising this emission factor to reflect some additional issues.[11] First, use of a range of emission factors is suggested to reflect the large variation possible in methane emissions from underground mines in different coal basins and countries. Second, this emission factor should represent only those emissions associated with underground mining and post-mining emissions should be handled separately.

The OECD Experts Group[11] recommends revised global average emission factors of 10 to 25 m^3 $tonne^{-1}$ of coal mined (not including post-mining activities). This range reflects the findings of various country studies, as shown in Table 1. As more detailed emissions data are published by various countries, the factors can be further revised, if necessary.

In order to calculate methane emissions from coal mining, very detailed mine-by-mine, seam-by-seam validated information is required; however, in some smaller coal producing countries a simpler approach may be used. Therefore a three tier approach was devised.

The first approach—called the Global Average Method—uses a pre-determined

[11] D. Kruger, Proceedings of the International IPCC Workshop on Methane and Nitrous Oxide, Amersfort, Ed. Ar. van Amstel, RIVM, 1993.

range of emission factors (based on experience in a number of countries) to estimate emissions. The most complex third approach—called the Mine Specific Method—develops emissions estimates using detailed emission data for most, if not all, of a country's underground coal mines. In between these two methods is an intermediate second approach, called the Basin or Country Average Method, in which more limited information, including either measurements from a subset of mines, can be used to refine the range of possible emission factors presented in the Global Average Method. Each of these approaches is described in more detail below.

Tier 1: Global Average Method. The simplest method for estimating methane emissions is to multiply the underground coal production by a factor or range of factors representing global average emissions from underground mining, including both ventilation and degasification system emissions. This method may be selected in cases where total coal production from underground mines is available but more detailed data on mining emissions, geological conditions, and coal characteristics, are not; thus there is a high degree of uncertainty associated with it. The Tier 1 Equation is shown below.

$$\text{Low } CH_4 \text{ Emissions (tonnes)} = \text{Low } CH_4 \text{ Emission Factor } [m^3\ CH_4 \text{ (tonne of coal mined)}^{-1}] \times \text{(Underground Coal Production (tonnes)} \times \text{Conversion Factor} \quad (1a)$$

$$\text{High } CH_4 \text{ Emissions (tonnes)} = \text{High } CH_4 \text{ Emission Factor } [m^3\ CH_4 \text{ (tonne of coal mined)}^{-1}] \times \text{Underground Coal Production (tonnes)} \times \text{Conversion Factor} \quad (1b)$$

Where the Low CH_4 Emission Factor equals $10\ m^3\ tonne^{-1}$ and the High CH_4 Emission Factor is $25\ m^3\ tonne^{-1}$. Note the Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane, $1.49 \times 10^9\ m^3\ Mt^{-1}$.

Tier 2: Country or Basin Average Method. The Tier 2 approach, which is a Basin or Country Average Method, can be used to refine the range of emission factors used for underground mining by incorporating some additional country- or basin-specific information. Basically, this method enables a country with limited available data to determine where within the range of global average emissions their underground coal mines are likely to lie. Some countries, for example, may have enough available data to determine that their mines are quite gassy and that the low end of the global average range significantly underestimates their emissions, while other countries may find the opposite.

The best means of making this assessment is to examine measurement data from a limited number of underground coal mines to estimate where within the Global Average Emission Factor range a country's mines fall and what a reasonable narrower range of emission factors might be. Making this estimate will require judgement on the part of the estimator regarding the adequacy of the available data and its uncertainty. If sufficient expertise is not available to make such judgements, it is recommended that the Tier 1 approach (the Global Average Method) be used to prepare emissions estimates.

In some cases, measurement data on emissions from mines may be unavailable but a country will still seek to develop a more refined estimate based on other types of available data. In such cases, a country may seek to develop a simple emissions model based on physical principles or make judgements based on an evaluation of available data.

It should be noted that while the Tier 2 approach can provide some additional information about methane emissions in a particular country or coal basin, the estimates will still be quite uncertain because of the absence of comprehensive and reliable emissions data. This approach should thus be used only in cases where there is a strong need to make an estimate that is more refined than the Tier 1: Global Average Method, and not enough data are available to prepare an estimate using the Tier 3: Mine Specific Method.

Tier 3: Mine Specific Method. Because methane is a serious safety hazard in underground mines, many countries have collected data on methane emissions from mine ventilation systems, and some also collect data on methane emissions from mine degasification systems. Where such data are available, the more detailed Tier 3 approach, called the Mine Specific Method, should provide the most accurate estimate of methane emissions from underground mines. Since these data have been collected for safety, not environmental reasons, however, it is necessary to ensure that they account for total emissions from coal mines. The key issues that should be considered when using mine safety data, as well as the recommendations of the OECD Experts Group for resolving them, are shown in Table 2.

The only data required for the equation is the *in situ* methane content of a seam, or an average *in situ* methane content for a mine or country. However, because of the factors outlined, the total quantity of methane emitted from the mine significantly exceeds the *in situ* methane content of the mined coal, this factor being typically from 2–5 in Europe and 4–10 in the USA. The relationship between adsorbed methane volumes and depth and pressure vary for different coal ranks as shown in Figure 2.

These two basic approaches that can be adopted for the estimation of the contribution of methane as a result of the mining of coal are discussed further in the following sections.

The Technique Based on In situ *Methane Content*

Here the methane emissions are related to the *in situ* methane content as described above and this method had earlier been suggested for adoption for the IPCC/OECD inventory.[2] The emission equation selected is:

$$\text{Methane emissions in m}^3\text{ of methane per tonne of coal mined} = (2.04 \times \textit{in situ}\text{ methane content}) + 8.16$$

This emission equation was derived from a detailed, empirical analysis[5] of the measured total methane emission rates from 50 US mines. It was found, when using the standard deviation around the mean as a measure of uncertainty, that the actual methane emission value could be up to 23% higher or lower than the

Table 2 Key issues for consideration when using Tier 3: Mine Specific Method

Issue	*Description*	*Recommendation*
Where and how are ventilation system emissions monitored?	When used to develop overall methane emission estimates, the optimal location for ventilation air monitors is at the point where ventilation air exhausts to the atmosphere.	If ventilation emissions are not monitored at the point of exhaust, emission data should be corrected based on estimated additional methane emissions between the point of measurement and the point of exhaust to the atmosphere.
Are ventilation system emissions monitored and/or reported for all mines?	In some countries, emissions are only reported for 'gassy mines'.	Estimates should be developed for non-gassy mines as well. Estimates can be prepared using information about the definitions of gassy and non-gassy mines and data on the total number of mines.
Are methane emissions from degasification systems reported?	Some countries collect and report methane emissions from ventilation and degasification systems, while others only report ventilation system emissions. Both emission sources must be included in emissions estimates.	If degasification system emissions are not included, those mines with degasification systems should be identified and estimates prepared on emissions from their degasification systems. Emissions estimates can be based on knowledge about the efficiency of the degasification system in use at the mine or the average efficiency of degasification in the country.

predicted level. This is increased to 33% higher or lower than the predicted level when used in countries other than the USA to take account of the range of mining operations and the differences in *in situ* methane contents worldwide.

Ideally it would be useful to be able to deduce methane emission levels from data based on coal rank and depth by deducing the *in situ* methane content (via Figure 2, say) and hence to the related methane emissions.[5] However, a recent UK study[6,7] has shown that large errors can be involved in even deducing *in situ* methane content. Clearly many other factors, particularly geological, come into play.

Emissions from Abandoned Deep Coal Mines

Some methane is also released from coal waste piles and abandoned mines. Coal waste piles are comprised of rock and small amounts of coal that are produced during mining along with marketable coal. There are currently no emission measurements for this source. Emissions are believed to be low, however, because much of the methane probably would be emitted in the mine and the waste rock would have a low gas content compared to that of the coal being mined. Emissions from abandoned mines may come from unsealed shafts and from vents installed to prevent the build-up of methane in mines. There is very little information on the number of abandoned mines, and data are currently unavailable on emissions from these mines. Most available evidence indicates that methane flow rates decay rapidly once deep mine coal production ceases.[7] In some abandoned mines, however, methane can continue to be released from surrounding strata for many years. In Belgium, France, and Germany, for example, several abandoned mines are currently being used as a source of methane which can be added to the gas supply system.[9] Due to the absence of measurement data for both coal waste piles and abandoned mines, no emissions estimates have been developed for these sources.

Methane flow rates decay rapidly once deep mine coal production ceases.[6] Underground measurements taken a few weeks after coal production has ceased are available together with the observation that old, sealed-off districts do not generally produce significant methane flows, other than during rapid barometer falls. When water pumping is halted on abandonment of a mine, water levels start to rise underground. Once the workings are flooded no further gas release or migration will occur. Abandoned mines therefore do not emit significant quantities of methane to the atmosphere and, at the most, these are estimated to be 1% of the normal ventilation emissions. This is almost insignificant compared with other emissions.

Emissions from Surface Mining

In surface mines, exposed coal-faces and surfaces, as well as areas of coal rubble created by mining operations, are believed to be the sources of methane. As in underground mines, however, emissions may come from the overburden, which is rubblized during the mining process, and underlying strata, which may be fractured and destressed due to removal of the overburden. Because surface mined coals are generally of lower rank and less deeply buried, they do not tend to contain as much methane as underground mined coals. Thus, emissions per tonne of coal mined are believed to be much lower for surface mines.

Indeed, little data exists on which to base emission from surface mines. The EPA have undertaken a study on a large Powder River Basin surface mine in Wyoming using long path FTIR spectroscopy. Other US studies have indicated emission contents in the range of 0.03 to $4\,m^3\,t^{-1}$ and an average value of $2.5\,m^3\,t^{-1}$ has been accepted. However, some recent figures obtained in the UK[6,7] suggest a lower value of $0.5 \pm 0.3\,m^3\,t^{-1}$.

As far as making accurate estimates is concerned, two possible approaches for estimating methane emissions from surface mining are suggested by the OECD Experts Group[11] similar to those developed for underground mining, but the results are more uncertain due to the absence of accurate emissions data.

(*i*) *Global Average Method.* As for underground mining, the simplest approach for surface mines—called the Global Average Method— is to multiply surface coal production by a range of emission factors representing global average emissions, as shown in the equation below:

$$\text{Low } CH_4 \text{ Emissions (tonnes)} = \text{Low } CH_4 \text{ Emission Factor } [m^3\ CH_4\ (\text{tonne of coal mined})^{-1}] \times \text{Surface Coal Production (tonnes)} \times \text{Conversion Factor} \quad (2a)$$

$$\text{High } CH_4 \text{ Emissions (tonnes)} = \text{High } CH_4 \text{ Emission Factor } [m^3\ CH_4\ (\text{tonne of coal mined})^{-1}] \times \text{Surface Coal Production (tonnes)} \times \text{Conversion Factor} \quad (2b)$$

Where the Low CH_4 Emission Factor equals 0.3 m^3 $tonne^{-1}$ and the High CH_4 Emission Factor is 2.0 m^3 $tonne^{-1}$. This does not include post-mining emissions.

Given the lack of information and measurements on methane emissions from surface mines, this range must be considered extremely uncertain, and it should be refined in the future as more data become available.

(*ii*) *Country or Basin Specific Method.* A second tier estimation of methane emissions—called the 'Country or Basin Specific Method'—can be used if additional information is available on *in situ* methane content and other characteristics of a country's surface mined coals. This approach enables a country to develop emission factors that better reflect specific conditions in their countries. Depending on the degree of detail desired, emissions can be estimated for specific coal basins or countries, using the equation below:

$$CH_4 \text{ Emissions (tonnes)} = \textit{In situ} \text{ Gas Content } [m^3\ CH_4\ (\text{tonne})^{-1}] \times \text{Fraction of Gas Released During Mining (\%)} \times \text{Multiplier Reflecting the Contribution of Surrounding Strata} \times \text{Surface Coal Production (tonnes)} \times \text{Conversion Factor} \quad (3)$$

The *in situ* Gas Content represents the methane actually contained in the coal being mined, as determined by measuring the gas content of coal samples. Average values for a coal mine, coal basin, or country could be developed, depending on the level of detail in the estimate.

The Fraction of Gas Released During Mining represents the percentage of the *in situ* gas content that is assumed to be emitted during the mining process, as opposed to during post-mining activities. Estimates of this fraction will vary depending on a particular coal's characteristic methane desorption rate, local mining practices, and other factors. A likely range for this fraction appears to be between 60 and 100 per cent, based on recent studies.

The Multiplier Reflecting the Contribution of Surrounding Strata represents the possibility that more methane will be emitted during surface mining than is contained in the coal itself because of emissions from the strata above or below the coal seam. There is significant uncertainty about the potential contribution of methane from the surrounding strata in surface mines because of the likelihood that these strata have low gas contents and that much of the methane would have been released naturally prior to mining. However, one measurement study has found that the surrounding strata could increase emissions by as much as five times as compared with the gas contained in the coal. Selection of the multiplier should incorporate information about the coal characteristics, local mining practices (such as mine depth), and the geology of the basin. Based on current analyses, it appears that a reasonable range for this multiplier is between 1 and 5.

Post-mining Activities

Like surface mining emissions, there are currently few measurements of methane emissions from post-mining activities. In fact, many past studies have overlooked this emission source, while others have developed only rudimentary estimation methodologies. Two possible approaches for estimating emissions from post-mining activities are recommended by the OECD Experts Group.[11]

Tier 1: Global Average Method. For the simplest estimates, a global average emission factor can be multiplied by coal production for underground and surface mining. It is important to distinguish between underground and surface mined coals because the gas contents are likely to be very different and hence emissions could vary significantly.

The recent OECD Experts Workshop[11] recommends emission factors of 0.9 to 4 m^3 $tonne^{-1}$ for underground mined coal, based on recent studies and for surface mined coals emission factors of 0 to 0.2 m^3 $tonne^{-1}$ are recommended.

Tier 2: Country or Basin Specific Method. Emissions estimates can be refined if additional data are available on coal characteristics. This method may be preferable if higher tier methods have been used to estimate emissions from underground and surface mines.

The *In situ* Gas Content represents the methane actually contained in the coal being mined, as determined by measuring gas contents in coal samples. Average values for a coal mine, coal basin, or coal country could be developed, depending on the level of detail in the estimate.

Total Emissions from Coal Mining Activities

The total methane releases as a result of coal mining activities will be the summation of emissions from underground mining (ventilation and degasification systems), surface mining, and post-mining activities. To the extent that methane is recovered and used that would otherwise have been released to the atmosphere during coal mining, the recovered quantity should be subtracted from the emission total.

Data are readily available to develop general emissions estimates using the Tier 1 approach—the Global Average Methods for underground, surface, and post-mining activities. For these estimates, the only required data are country statistics on underground and surface coal production, which are available from domestic sources, such as energy ministries, or from the OECD/IEA, which publishes Coal Information and Coal Statistics.

On the basis of this type of analysis the global methane emissions has been estimated[12] to be 35 ± 10, with other estimates similar to this, IPCC 1992 used higher emission factors, now known to be erroneous and the value of 100 Tg yr^{-1} should be discarded. The current data suggests a value of about 45 ± 10 Tg yr^{-1}. Of this about 35% results from the coal industry in China, about 25% from that in the USA, and about 3% from the UK.

3 Technical Option for Emissions Control

All of the methods described above, with the possible exception of the Mine Specific Method, assume that all of the methane liberated by mining will be emitted to the atmosphere. In many countries, however, some of the methane recovered by mine degasification systems is used as fuel instead of being emitted. Wherever possible, the emission estimates should be corrected for the amount of methane that is used as fuel, by subtracting this amount from total estimated emissions.

In several countries, data on the disposition of methane recovered by degasification systems (*i.e.* whether it is used or emitted to the atmosphere) can be obtained from the coal industry or energy ministries. In Poland, for example, its mine degasification systems recovered 286 million m^3 of methane in 1989, of which 201 million m^3 was used and the remaining 85 million m^3 was emitted to the atmosphere.

Since the quantity of methane released is mainly a result of deep coal mining activities it seems likely that this activity is the best one to which to devote attention initially, as is indeed the case. Surface mining produces less methane over a greater distributed area and is much more difficult to handle technically. However, in view of the rapid expansion in opencast mining in many countries, much more attention must be devoted to this area. The approach taken would vary from country to country, but general principles have been noted and are given in a number of reports.

Techniques for removing methane from deep mine workings have been developed primarily for safety reasons, because it is highly explosive in air in concentrations between 5 and 15 mol %. These same techniques have been adapted in some places to recover methane so that the energy content of this fuel is not wasted. Methane emissions into the atmosphere can be reduced by up to 50–70% at gassy mines using available techniques. Emissions can potentially be reduced by up to 90%, depending upon the demonstration of additional technologies. However, generally this is not the case on a worldwide basis and overall recovery may be in the 0–20% region. Furthermore, about 10–15% of the methane present is removed in the mined coal, although a substantial part of this is burned while still in the coal.

[12] J. Lelieveld, P. J. Crutzen, and C. Brühl, *Chemosphere*, 1993, **26**, 739.

Important factors when considering options for reducing methane emissions from deep coal mining are: mine conditions (*e.g.* gassings); current mine gas systems; potential gas quality and use options; and technical and economic resources. In particular, the quality of gas that is recovered will determine the possible utilization options. Therefore, each of the four identified options is a coherent project based on recovering and utilizing a certain quality of gas.

Pre-mining Degasification. This strategy, often termed pre-draining, recovers methane from virgin seams before coal is mined. The advantage of this strategy is that methane is removed before the air from the mine workings can mix with it, and consequently a higher calorific value gas mixture is recovered (32–37 MJ m^{-3}). High quality gas will have a higher heating value and can also be used as chemical feedstock. Pre-mining degasification can be an in-mine or surface operation. When done inside the mine, boreholes can be drilled anywhere from six months to several years in advance of mining. The surface approach to pre-mining degasification requires more advanced technology and equipment, and therefore has higher capital costs than enhanced gob well recovery. These higher costs can be justified by the increased recovery of methane using surface drilling techniques.

Enhanced Gob Well Recovery or Post-drainage. The methods available are as follows: this strategy recovers methane from the gob area of a coal mine—the highly fractured area of coal and rock that is created by the caving of the mine roof after the coal is removed. Gob areas can release significant quantities of methane into the mine, and if this gas is recovered before entering the mine, ventilation requirements can be reduced. Typically, gob gas is diluted by mine air during production so a medium quality gas is obtained (11–29 MJ m^{-3}), which can be used in a variety of applications, including on-site power generation and residential and industrial heating. Enhanced gob well recovery can involve in-mine and/or surface wells, using existing, proven technology that is currently employed in many countries. The capital requirements are low compared with the potential for methane recovery.

Deep-mining Ventilation Air Utilization. Most mine gas is released to the atmosphere by the venting of in-mine air with large fans. For safety reasons, ventilation is necessary in deep coal mines. The recovery technology is basic, but operating costs can be high if the mine is gassy. The vented air is extremely dilute, at less than 1% methane but can be concentrated by a variety of methods and the use of membranes and pressure swing absorption techniques are promising. In addition, the use of such recovered methane as combustion air in turbines or boilers is feasible.

Application of Techniques. Methane emissions from coal mining constitute a wasted energy resource and often integrated recovery is used. Maximum utilization of this resource can involve a combination of two or three strategies, to provide an integrated methane recovery system. Technological and capital requirements are moderately high. However, effective use of these strategies can lead to the recovery of sufficient methane to justify these costs. Benefits of these strategies include improved mine safety and productivity and the recovery of a clean and convenient energy source.

The major challenge for the future, however, is to develop economically viable technologies for open-cast mining. Pre-drainage can be useful but additional techniques applicable to the mining operations are required.

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