FUGITIVE EMISSIONS FROM COAL MINES

A REPORT UNDERPINNING THE NATIONAL INVENTORY

PREPARED FOR

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1 Introduction

The objective of the present study is to provide a basis for an inventory of greenhouse gas emissions from the coal mining industry. The IPCC Guidelines have been followed closely. In particular, we have followed Chapter 4, Fugitive emissions, of Volume 2, Energy, of the IPCC 2006 Guidelines [1].

Fugitive emissions are defined as:

"Intentional or unintentional release of greenhouse gases may occur during the extraction, processing and delivery of fossil fuels to the point of final use."

They are categorised as follows:

Table 1. Categories of emissions

DETAILED SECTOR SPLIT FOR EMISSIONS FROM MINING, PROCESSING, STORAGE AND TRANSPORT OF COAL		
1B	Fugitive emissions from fuels	Includes all intentional and unintentional emissions from the extraction, processing, storage and transport of fuel to the point of final use.
1B1	Solid fuels	Includes all intentional and unintentional emissions from the extraction, processing, storage and transport of solid fuel to the point of final use.
1Ba	Coal mining and handling	Includes all fugitive emissions from coal
1B1ai	Underground mines	Includes all emissions arising from mining, post-mining, abandoned mines and flaring of drained methane.
1B1ai1	Mining	Includes all seam gas emissions vented to atmosphere from coal mine ventilation air and degasification systems.
1B1ai2	Post-mining seam gas emissions	Includes methane and CO_2 emitted after coal has been mined, brought to the surface and subsequently processed, stored and transported.
1B1ai3	Abandoned underground mines	Includes methane emissions from abandoned underground mines.
1B1ai4	Flaring of drained methane	Methane drained and flared, or ventilation gas converted to CO_2 by an oxidation process should be included here.

		Methane used for energy production should be included in Volume 2, Energy, Chapter 2 'Stationary Combustion'.
1B1aii	Surface Mines	Includes all seam gas emissions arising from surface coal mining
1B1aii1	Mining	Includes methane and CO_2 emitted during mining from breakage of coal and associated strata and leakage from the pit floor and highwall
1B1aii2	Post-mining seam gas emissions	Includes methane and CO_2 emitted after coal has been mined, subsequently processed, stored and transported.
1B1aii3	Uncontrolled combustion & burning coal dumps	Includes emissions of CO_2 from uncontrolled combustion due to coal exploitation activities.

This Report therefore reviews the nature of the fugitive emissions, and describes the coal mining industry in general with some aspects specific to the South African industry. It then reviews the status of fugitive emissions in South Africa, from which it is concluded that they do not appear to fall into the key category as far as they have been quantified, but that there is one source that has not been quantified and which may yet become a key category. Finally the Tables for the categories given in Table 1 are completed.

2 Origin of fugitive emissions

Coal is an adsorber of gases. In particular, it adsorbs methane, CH_4, and carbon dioxide, CO_2. The adsorption follows the normal rules for the adsorption of gases on solid adsorbents. In particular:

- The gases are adsorbed essentially reversibly
- The solid can adsorb only a certain quantity under given conditions of temperature and pressure
- A high concentration of one gas can displace another adsorbed gas

Fugitive emissions of these two gases arise because the temperature of and/or pressure on the coal may change as it is mined, leading to the emission of these two gases.

Coal can also adsorb oxygen. Once the oxygen is adsorbed and in intimate contact with the coal, it can cause oxidation of the coal. The heat of oxidation can build up until such time as the coal reaches its ignition temperature, and spontaneous combustion results. In this case, CO_2 is produced as a fugitive emission from the unwanted combustion of the coal.

CH_4 and CO_2 are the only greenhouse gases of concern as fugitive emissions from coal mining and processing operations. Some nitrogen oxides, NOx, may arise from spontaneous combustion. As the temperature of combustion is generally low, the formation of nitrogen oxides from the air should be minimal, but coal has some inherent bound nitrogen which is often released as NOx during combustion. A literature search had failed to reveal any determination of this NOx, and it will be ignored in this study.

3 A description of coal mining, processing and transport

It is necessary to understand how coal is mined, transported and processed to understand how fugitive emissions can arise at various points. Coal normally exists as reasonably clearly defined seams, although the seams can be as narrow as a few mm. The seams are found at various depths in the earth's crust, generally less than 1000m below the surface.

The method of mining depends strongly on the seam depth. If the seam is less than about 80m deep, it can be mined from surface by removal of the material ("overburden") before the coal seam itself is mined. Below about 80m depth, underground mining is employed.

There are two variants of both surface and underground mining. In one method of surface mining, known as "opencast" mining, the overburden is removed over a large area and dumped as waste. The exposed coal is then removed, leaving a large open pit. In the second method, "strip mining", a trench is dug to expose the coal. The coal is removed, and then the trench is filled with material from a new trench dug parallel to the original. When mining is complete, the surface can be restored at close to the original topography.

In underground mining, the first method leaves pillars in place to support the roof. There are various ways of doing this, referred to as "bord-and-pillar" or "shortwall" mining. In the second method, there are no pillars and the roof is allowed to collapse behind the face being mined. This is referred to as "longwall" mining.

In most surface mining operations, the coal is removed by truck. Underground, the coal is generally moved by conveyors over most of its travel, although hoisting in skips up shafts may be used in deeper mines.

The raw coal usually contains unwanted material, either because it has been necessary to cut some waste either side of the coal seam, or because waste entered the coal during its formation. The coal, being organic in its origin, has a lower density than the waste. It can thus be separated from the waste by methods based on the density difference. The methods employed vary depending on the size of the coal.

Coal greater than about 50mm in size is placed in a bath of "heavy medium", which is a mixture of water and a fine, heavy mineral such as magnetite. The coal floats and is drawn off from the surface. The waste sinks and is removed from below the surface. Both the float and sink material are washed with clean water to remove the heavy medium. The quality of the float product can be adjusted by changing the density of the medium in the bath – better quality is associated with lower density.

Coal between about 50 and 0.5mm in size is typically cleaned in either a dense medium cyclone or a jig. In a dense medium cyclone, the coal is mixed with the dense medium and pumped tangentially into a conical vessel. The denser waste concentrates near the wall of the vessel and travels down and out of an orifice at the bottom. The lighter coal collects near the centre of the vessel and is drawn off by a pipe. In a jig, the raw coal is fed over a pulsating bath, and the lighter particles tend to move upwards as the bath is pulsed, again allowing the coal to be separated from the waste.

Coal smaller than 0.5mm in size becomes quite difficult to clean, and even more difficult to dewater after cleaning. Various processes are employed, with varying efficiencies of recovery. There remains, typically, a fraction of the order of 0.1mm in size which cannot be further cleaned and is very difficult to dewater. It is normally discarded as slurry and stored in a pond.

The coal is often double washed. The first washing recovers a low-ash, high-grade fraction that commands a premium price. The discard from this washing is rewashed to recover a lower grade material that is suitable as a power station feed, and the final discard is then dumped.

In South Africa, the high-grade fraction typically travels by belt overland to a railhead, where it is loaded for transport to Richards Bay (primarily), or Durban or Maputo, for export. Comparatively small tonnages of high-grade material are used in South Africa itself, primarily as a reductant in the processing of metallic ores such as chromium and manganese, and are moved by road or rail. Most of the low-grade fraction is moved by overland belts to the power stations for electricity generation. The other major use for essentially raw coal is for liquid fuels synthesis. The coarse coal is gasified with steam and oxygen; the finer fraction is burned for steam generation and to produce the power needed for oxygen separation.

4 A review of South African studies

In support of the first National Inventory, an assessment was made of the coal-bed methane content of South African coal mines[2]. This concluded that, because the concentration of methane in the South African coals was significantly less than the default values employed in the Reference Method, the emissions were probably about one-fifth of the default values. These preliminary conclusions were the subject of extended confirmation [3, 4, 5, 6, 7].

The Intergovernmental Panel on Climate Change default factors were based upon a model involving:

1. The even distribution of the methane throughout the seam
2. Retention of the methane within the coal measures due to hydrostatic pressure
3. Release of the pressure and thus of the retained methane because of mining
    - 3.1 Firstly from the broken surface of the newly mined coal
    - 3.2 Secondly, and more slowly, from deeper in the newly mined coal, and
    - 3.3 Finally, more slowly still, from pillars, roof and floor created by mining.

Thus as long as mining continued, there would be a general and reasonably constant release of methane, which would reduce shortly after the rate of mining was reduced, and more slowly once mining ceased, when the only methane sources were the floor, roof and pillars.

Measurements failed to confirm this model in South African coal mines. The release of methane from the majority of underground South African coal mines was anything but steady. It was characterised by short bursts of relatively high concentration, followed by extended periods when methane was essentially undetectable. The results of these studies led to a model for the release of methane involving:

- Prior desorption of methane from the coal mass, probably due to heating by the sort of plutonic events that gave rise to dykes and sills in many mines. This is a unique aspect of the Gondwana coal of Southern Africa; worldwide for other coals have been impacted by similar plutonic activity.
- Storage of that released methane in cleats and fissures.
- Eventual release of the stored methane when the individual microstores establish a route to atmosphere either through mining or ground movement, the latter possibly mining-induced.

The result of these processes is that the methane content of the mine air can vary on a random basis and even fall to very low values, as had been observed. In addition the slow release of methane from mined coal meant that the contribution of such methane to the overall methane in the air must be low, as had been independently derived in early studies. Moreover the release of methane from pillars, roof and floor must be far less than required by desorption phenomena assumed in the IPCC model.

It must be stressed that the South African coal mine ventilation air contains very little methane, relative to mines elsewhere. It was necessary to take large samples, and have them analysed by high precision gas chromatography in chemical laboratories. Typical values were <0.1% CH_4 in air, and many samples were below 0.001%.

Attempts to measure methane emissions from surface coal mining operations showed no detectable methane. Coal from surface operations, which was milled and exposed to atmosphere, adsorbed methane from the air rather than releasing it. It is concluded that methane release from surface operations is negligible.

On underground mines, there were 243 high-precision determinations of the methane content of the return air from 27 different production shafts on producing underground mines, representing about 19.6% of the tonnage of raw coal mined underground in 2002-3. The specific emission factor for the return air was $0.77 m^3$ CH_4/t raw coal.

There were 191 determinations of the seam gas content [8, 9], and the average *in situ* seam gas content was 0.71 m^3/t coal. The release of methane was not significantly dependant on the average depth of mining, or on the ambient pressure. Methane was released from the fresh raw coal at a rate that varied log-log with time. The average rate of log-log decrease was -0.15, which indicates that after 1 day the average content of freshly-mined coal would have fallen from 0.71 to 0.35 m^3/t, after 10 days to 0.25 m^3/t and after 100 days to 0.17 m^3/t. Fine grinding of the coal caused the almost instantaneous release of all methane from the coal.

These results permit an estimation of the emission from unmined coal. Most freshly mined coal would have left the mine within 1 day, so it would have contributed at most (0.71-0.35) = 0.36 m^3/t to the return air, so the methane release from exposed, unmined coal would amount to (0.77-0.36) = 0.41 m^3/t raw coal.

It is further possible to estimate the emissions from mined coal once it has left the mine. If it contains on average 0.35 m^3/t after 1 day, and 0.17 m^3/t after 100 days, and it is reasonable to assume that it will either have been used or exported within 100 days, then the emissions from raw coal post mining will amount to (0.35-0.17) = 0.18 m^3/t raw coal.

It must be stressed that there are large errors associated with these estimates, which have relative standard deviations close to 1. The source of these errors lies in the very sporadic nature of the emissions. To the reduce the relative standard deviations to significantly lower levels would require continuous measurement of the methane content of the return air over extended periods. The measurement would need to be of high precision (±1 ppm) at low methane concentrations (of the order of 200ppm), involving expensive instrumentation. The effort does not seem justified in view of the relatively low quantities of methane involved.

In a few cases methane desorbed from coal was analysed for CO_2. The average content was about 9% (+10 - 6%) of the total gas emitted. The emissions of CO_2 resulting from mining are therefore estimated at 10% of the emissions of methane.

Data on coal production were obtained. Statistics used to be produced by the Minerals Bureau of the Department of Minerals and Energy, but these have now been essentially outsourced to private industry, which kindly made historical data available[10]. The data for 1999, 2000 and 2001 are given in Table 2.

We lack data on methane emissions from anthracite, but it appears to be low. The tonnage of anthracite mined, some two million tons, or less than 1% of the bituminous coal production, suggests it may be ignored as not contributing significantly to the emissions.

Table 2 South African Coal Production, 1999-2001, Tonnes by Mining Method

MINING METHOD	COAL TYPE	1999	2000	2001
LONGWALL	BITUMINOUS	1,868,442	2,260,746	4,981,478
OPENCAST	ANTHRACITE	127,101	120,863	522,522
	BITUMINOUS	141,371,521	150,282,060	131,839,324
BORD AND PILLAR	ANTHRACITE	2,338,351	2,009,550	1,580,404
	BITUMINOUS	108,330,154	109,797,877	121,100,109
STOOPING	BITUMINOUS	28,660,893	27,890,575	29,813,909
TOTAL		282,696,462	292,361,671	289,837,746

A further source of emissions is that from coal waste dumps. Data relevant to this question were derived during the studies leading to the preparation of the national inventory of discard and duff coal in 2001 [11]. The tonnage of waste generated each year may be judged from the difference between the raw coal supply and the saleable production, as given in Table 3 [8].

Table 3 Waste coal generation, 1999-2001, tonnes

	1999	2000	2001
Raw coal mined	280,231,010	290,231,258	287,734,820
Saleable tonnes	221,927,696	222,739,215	222,105,086
Waste	58,303,314	67,492,043	65,629,734

In each year, approximately 7 million tonnes of slurry was generated [9], so waste coal amounted to between 51 and 60 million tonnes. The survey [9] identified 488 million tonnes of waste coal, of which 239 million tonnes was on active dumps and 249 million tonnes on defunct dumps. About 1 200 million tonnes was recorded as having been dumped over about 35 years prior to 2000, so the survey identified about 41% of the total. There was confidence that most of the active dumps had been identified, so this would mean that about 700 million tonnes had been lost. Some dumps were known to have been reprocessed to recover a middlings steam-coal fraction, and some were known to have been recovered to serve as backfill in mines. This suggests that about 500 million tonnes of waste had burned over 35 years, or about 14 million tonnes per year. In 2000, some 69 million tonnes were still burning, although it is known that improved methods of construction and of extinguishing fires since that time have meant that little dumped coal continues to burn. This similarly suggests a rate of burning of around 10 million tonnes per annum.

The specific emission of CO_2 from burning dumps will be about half that of coal, because the calorific value of the waste averages about 12 MJ/kg. We assume an average value of 540kg/t waste burned, or 275 m^3/t.

The final source of emissions is that from old underground coal mines in which the residual coal in pillars has spontaneously combusted due to continued availability of air. In several places in Mpumalanga large areas have been rendered unusable due to continuing combustion of the residual coal. Moreover there is evidence that the zone of combustion has spread from the seam that was mined to unmined seams nearby. Nevertheless the problem has not been quantified, and indeed, a 2001 environmental survey of the province of Mpumalanga [12] identified only burning coal wastes and acid mine drainage as problematic, not the burning mines themselves. However, a later review [13] clearly identified one abandoned mine, Transvaal and Delagoa Bay, near Witbank, as a significant source of air pollution. “The 750 ha colliery site lies between the township of KwaGuqa and the industrial area of Ferrobank. Since closure in 1953, the fires have been out of control and in 1995, flames could be seen above ground.” To have burned for about 50 years after abandonment, the rate of combustion must have averaged over 1 million tonnes coal per year on this one mine. However, in the absence of better quantification, we must merely note this source of greenhouse gases and look for further research to fill out the picture.

A further possible source which has not been examined is the loss of methane from abandoned mines. Most underground mines today are closed off to prevent entry, and methane will build up to equilibrium in the mine. Any leaks to atmosphere will permit the escape of the methane build up. As, however, methane levels are generally low by international standards, the contribution of this potential source to greenhouse gas emissions has not been quantified.

5 Summary data

The results of the survey of data in the previous section have been entered on Excel spreadsheets provided by the IPCC, and submitted separately. Below is a copy of the final output, for a 2000 base year.

Sector		**Energy**				
Category		**Solid Fuels**				
Category Code		**1B 1**				
Sheet		**1 of 1 (CH_4 and CO_2 emissions from underground and surface coal mining and handling (Tier)**				
CH_4 Emissions						
		A Amount of Coal Produced (tonne)	**B** Emission Factor (m^3 $tonne^{-1}$)	**C** Methane Emissions (m^3) C = A*B	**D** Conversion Factor (Gg CH_4 m^{-3})	**E** Methane emissions (Gg CH_4) E=C*D
Underground	Mining	139949198	0.77	107760882.5	$0.67x10^{-6}$	72.2
	Post-Mining	139949198	0.18	25190855.64	$0.67x10^{-6}$	16.9
Surface	Mining	150282060	0	0	$0.67x10^{-6}$	0
	Post-Mining	150282060	0	0	$0.67x10^{-6}$	0
Emissions of drained gas		**NA**	**NA**		$0.67x10^{-6}$	
					Total	**89.1**
CO_2 Emissions						
		A Amount of Coal Produced (tonne)	**B** Emission Factor (m^3 $tonne^{-1}$)	**C** Carbon dioxide Emissions (m^3) C=A*B	**D** Conversion Factor (Gg CO_2 m^{-3})	**E** CO_2 Emissions (Gg CO_2) E=C*D
Underground mines	Mining	139949198	0.077	10776088	$1.83x10^{-6}$	19.7
	Post-Mining	139949198	0.018	2519086	$1.83x10^{-6}$	4.6
Surface	Mining	150282060	0	0	$1.83x10^{-6}$	0
	Post-Mining	150282060	0	0	$1.83x10^{-6}$	0

Uncontrolled combustion		14000000	275	3850000000	$1.83x10^{-6}$	7045.5
					Total	**7069.8**
CO_2 emissions from CH_4 flaring						
		A Volume of methane combusted (m^3)	**B** Conversion Factors ($Gg\ CH_4\ m^{-3}$)	**C** Stoichio-metric Mass Factor	**D** CO_2 emissions ($Gg\ CO_2$) D=A*B*C	
Underground mines	Mining	0	$0.67x10^{-6}$	2.75	0	
				Total	**0**	

6 Acknowledgement

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