White Young Green

Projected Methane Emissions from Abandoned Coal Mines in the UK

defra
Department for Environment
Food and Rural Affairs

thinking beyond construction

Projected Methane Emissions from Abandoned Coal Mines in the UK

Reference: REPORT/E005832/SK/DATE/Final/V1			
Issue		**Prepared by:**	**Verified by:**
V1		**Steven Kershaw** *BSc, PhD* ***Associate***	**Keith Whitworth** *BSc* ***Associate***
File Ref: O:Emissions\E005832			
IMC White Young Green Environmental PO Box 8182 Mill Lane Sutton-in-Ashfield Notts. NG17 2ZE ***Telephone: 01623 444611 Facsimile: 01623 440021 E-Mail: enviro.imc@wyg.com***			

Environmental Consultancy

This report has been prepared for and on behalf of DEFRA in response to their particular instructions, and any duty of care to another party is excluded. Any other party using or intending to use this information for any other purpose should seek the prior written consent of IMC White Young Green Environmental.

The conclusions reached are those which can reasonably be determined from sources of information, referred to in the report and from our knowledge of current professional practice and standards. Any limitations resulting from the data are identified where possible but both these and our conclusions may require amendment should additional information become available. The report is only intended for use in the stated context and should not be used otherwise.

Where information has been obtained from third parties, IMC White Young Green Environmental have made all reasonable efforts to ensure that the source is reputable and where appropriate, holds acceptable quality assurance accreditation. IMC White Young Green Environmental do not accept any liability for the accuracy of any information supplied by third parties.

CONTENTS

1. Introduction 1
2. Methane Reserve and Emissions from Mines Abandoned Before 2004 1
3. Methane Reserve Calculations for Mines Closed After 2004 2
4. Methods of Calculation of Projected Emission from Newly Closed Mines 4
  4.1 Hyperbolic Decay Model 5
  4.2 FPPROG 6
  4.3 Comparison of the Two Methods 6
  4.4 Emission as Percentage of Reserve 8
5. Calculation of Methane Emissions from Mines Closed After 2004 8
6. Projections of Total Methane Emissions from Abandoned Mines 9
7. References 12

Figures

Figure 2.1 Graph Showing Calculated Reserves and Projected Methane Emissions from Mines Abandoned pre-2005, for 2005 to 2050 2
Figure 3.1 Estimated Reserves for Collieries Closed from 2004 Onwards 4
Figure 4.1 Graph of Hyperbolic Decay Function and Colliery Data 5
Figure 5.1 Estimated Methane Emissions for Collieries Closed Post-2004 9
Figure 6.1 Summary of Estimated Methane Emissions 10

Tables

Table 2.1 Calculated Reserves and Corresponding Emissions from Mines Abandoned pre-2005, for 2005 to 2050 2
Table 3.1 Collieries and Closure Dates Assumed for Calculations 4
Table 4.1 Time in Years to Reach Percentage of Production Emission (FPPROG) 7

Projected Methane Emissions from Abandoned Collieries

1. Introduction

This work to project methane emissions from abandoned coal mines to 2050 has been carried out as an extension to DEFRA Project EPG 1/1/149 "Development of a Methodology for Estimating Methane Emissions from Abandoned Coal Mines in the UK" [1]. The projected emissions are calculated by adding the emissions from mines abandoned before 2004 (as in the full report) and emissions from collieries to be closed after that date.

The modelled closure of collieries has been matched to the losses to production to maintain consistency with *En*tec's work on the operating mines methane inventory [2]. On average, a reduction of about 1 million tonnes (Mt) production is equivalent to the closure of one colliery. It has been assumed that deep coal mined production will fall by 5Mt in the next 5 years (2005 to 2010), with a final 5Mt production being lost between 2021 and 2025.

The emission of methane from collieries after closure has been derived primarily using a hyperbolic function, which calculates emission over time as a proportion of emission during production. An alternative methane emission calculation method (FPPROG) has been examined and found to correspond in general form with the hyperbolic function. The emission during production has been calculated from colliery production specific emission values calculated for individual collieries, with an allowance for gas utilised during production. Where the emission calculated from the hyperbolic function falls below the emission based on 0.74% of reserve, the latter value is used to bring it into line with the emission calculations for the rest of the coalfields. In addition, emissions from collieries closed in the near future have had allowance made for mitigation of the gas being released beyond the first year following closure.

2. Methane Reserve and Emissions from Mines Abandoned Before 2004

The mine water and gas reserve models, used to calculate methane reserves from 1990 to 2004, have been revised to allow the models to run until the mine water levels recover. Gas reserves are calculated for every 5 years from 2005 to 2050. Gas emissions from the abandoned mines are calculated assuming that 0.74% of the gas reserve is emitted per annum, as set out in the full report.

During the period when an older mine floods, the major cause of reduced emissions is the rise in water level. Once the water level has stabilised, the gas reserve no longer reduces as a result of water rise. For the purpose of these calculations for 2005 to 2050, following water recovery, the gas reserve is reduced by an amount equal to the estimated quantity of methane emitted; that is 0.74% of the reserve.

Table 2.1 and Figure 2.1 show the total projected gas reserves for mines closed before 2004 for five year intervals from 2005 to 2050 and the calculated methane emissions in kilotonnes per year (kt/y) based on those reserves.

Table 2.1 Calculated Reserves and Corresponding Emissions from Mines Abandoned pre-2005, for 2005 to 2050

Year	Reserve (million m^3)	Methane Emission (kt/y)
2005	8,799	46
2010	7,154	37
2015	5,995	31
2020	4,701	24
2025	4,001	21
2030	3,489	18
2035	3,275	17
2040	3,140	16
2045	3,020	16
2050	2,907	15

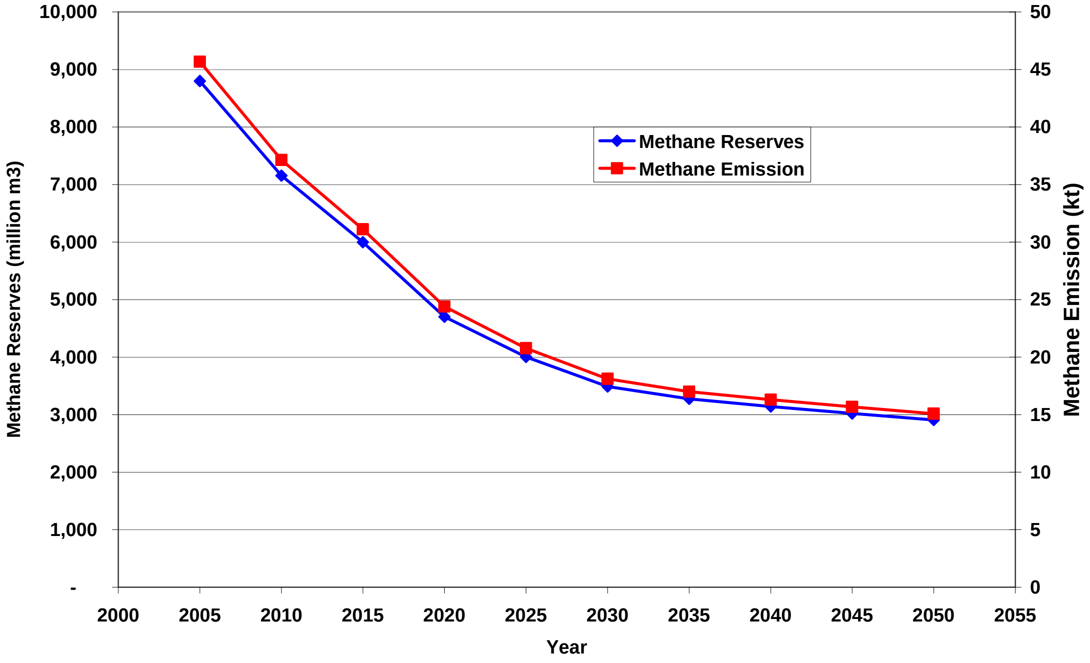

Figure 2.1 Graph Showing Calculated Reserves and Projected Methane Emissions from Mines Abandoned pre-2005, for 2005 to 2050

3. Methane Reserve Calculations for Mines Closed After 2004

Reserves have been calculated for all collieries closing after 2004 up to 2050. The method used is the same as that used in the full report [1] for other abandoned mine workings in the UK. The method comprises two main phases which are the water modelling and the gas reserve modelling. The water model calculates void space created by the mining activities as a function of depth. Combined with rates of water inflow (either measured or deduced) a rate of water level with time is obtained. The second phase is to combine the quantity of coal lying within the strata disturbed by mining (tonnes) with estimated methane contents of the coal (m^3/t) to provide an estimate of methane reserve in place within the coal (m^3). The reserve is also calculated as a function of depth. Rising water will cut off gas reserves and prevent methane emission. In consequence, by combining the water level as a function of time with the gas reserve as a function of depth, it is possible to obtain a function of reserve against time.

Colliery closures are consistent with reductions in production assumed by the DTI and *En*tec in calculating the emissions from operating mines [2]. The outline schedule for colliery closure is for five collieries to close between 2005 and 2010 (5Mt production) and three collieries to close between 2020 and 2025 (5Mt production).

Ellington colliery has low intrinsic methane constants and emissions are very low. Only the hyperbolic decay calculation produces an emission of 0.1kt/y in the year of closure, and thereafter the emission is effectively zero for the purposes of these calculations.

Harworth and Rossington are due to be mothballed next year so have been assumed for the purposes of the calculation to have shut in 2006.

The 5Mt production decrease between 2020 and 2025, is probably best represented as two 1Mt/y collieries and Daw Mill Colliery at 3Mt/y. Based on reserves and production rate Daw Mill Colliery is likely to continue to operate longer than any existing collieries and will close around 2025. For the projections it is assumed that two remaining collieries will close in the years between 2020 and 2024. For the two other collieries to close between 2020 and 2024, Welbeck and Kellingley have been chosen as representing the worst case scenario insofar as they may have the greatest emissions. Both collieries are assumed to close in 2004, again to provide an estimate of a worst case, with two large emissions taking place in the same year.

The three remaining collieries are, in order of increasing reserve, Tower, Maltby and Thoresby. For calculation purposes these are assumed to shut in the stated order between 2008 and 2010 for one set of calculations (“low to high”) and in the reverse order for a different set of calculations (“high to low”). This was done to get an idea of the sensitivity of the estimated emissions to order of closure, considering that the first few years after closure produce the highest emissions. A list of the collieries together with the assumed dates of closure for the purposes of the calculations are listed in Table 3.1.

The total projected gas reserves for mines closed after 2004 for five year intervals from 2005 to 2050 are shown in Table 3.2 and Figure 3.1. The projections show a general decrease in reserves due to flooding of the workings with steep increases due to recent and likely colliery closures between 2004 to 2010 and between 2020 and 2025.

Reserves for Silverdale colliery, which closed in 1986, have also been included as there has been limited emission to the atmosphere since that time due to utilisation. For the purposes of the calculations utilisation at Silverdale has been assumed to continue until 2010.

Table 3.1 Collieries and Closure Dates Assumed for Calculations

Colliery	Assumed Date of Closure	
	High to Low	Low to High
Silverdale	1998	1998
Ellington	2004	2004
Selby	2004	2004
Harworth	2006	2006
Rossington	2006	2006
Thoresby	2008	2010
Maltby	2009	2009
Tower	2010	2008
Kellingley	2024	2024
Welbeck	2024	2024
Daw Mill	2025	2025

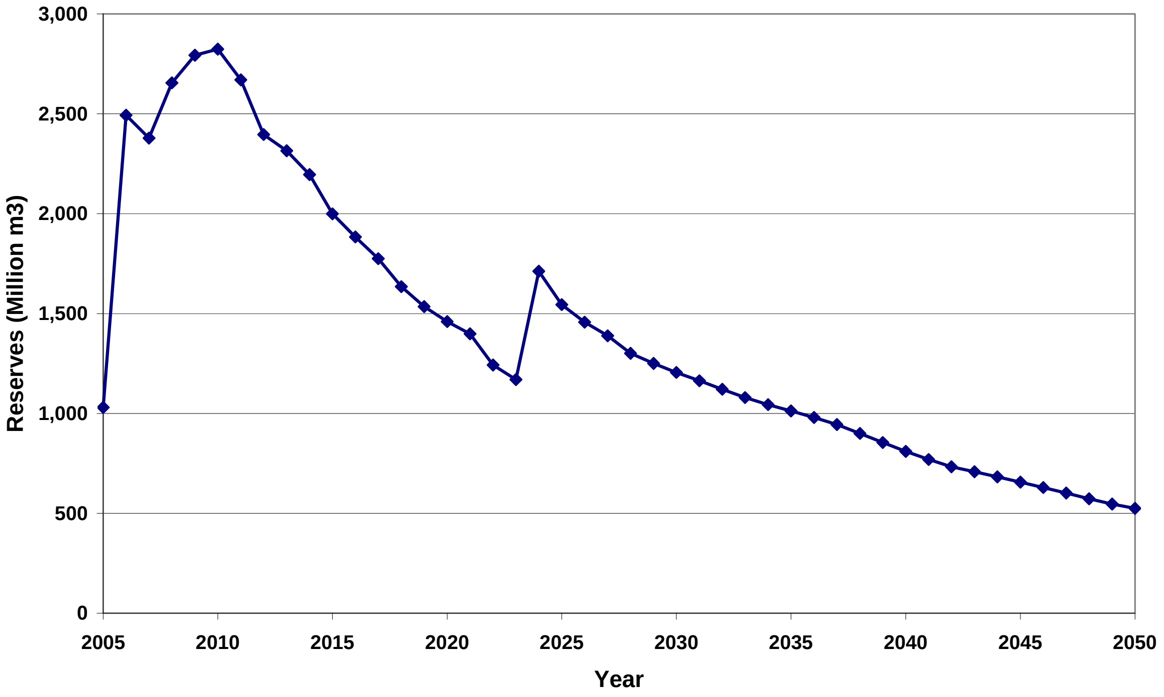

Figure 3.1 Estimated Reserves for Collieries Closed from 2004 Onwards

4. Methods of Calculation of Projected Emission from Newly Closed Mines

As indicated in Section 3 it is likely that all the deep operating mines will close during the period of the projections. The characteristic high levels of emission immediately following closure of operating mines cannot be easily incorporated into the general model which was designed to deal with major coalfields whose collieries have been closed for some years. Thus the effect of colliery closures is modelled separately. Two methods for estimating the decay of emission from recently closed collieries are discussed below. The first method uses an empirical hyperbolic decay curve derived from measured data which calculates emission as a proportion of the emission before closure. The second method uses a standard method for calculating emissions during mining operations extrapolated to calculate emissions following production. The relationship between these calculations and the emission based on a percentage of methane reserve will also be discussed.

4.1 Hyperbolic Decay Model

A hyperbolic function can be used to estimate the rate of gas emission from abandoned mines. This type of model has been considered in a number of cases; most recently in the case of the US Environmental Protection Agency's methodology for estimating methane emissions (2004) [3]. A study by the National Coal Board in 1969 [4] looked at the reduction in emission of methane after cessation of working. The emissions were normalised with respect to operating emission levels expressed as a percentage. The study collected thirty three data points for 21 collieries and a hyperbolic curve suggested a best fit of :

$$F=65/(t+1.5)$$

Where F is the proportion of the operating emission (%) and t the time in years.

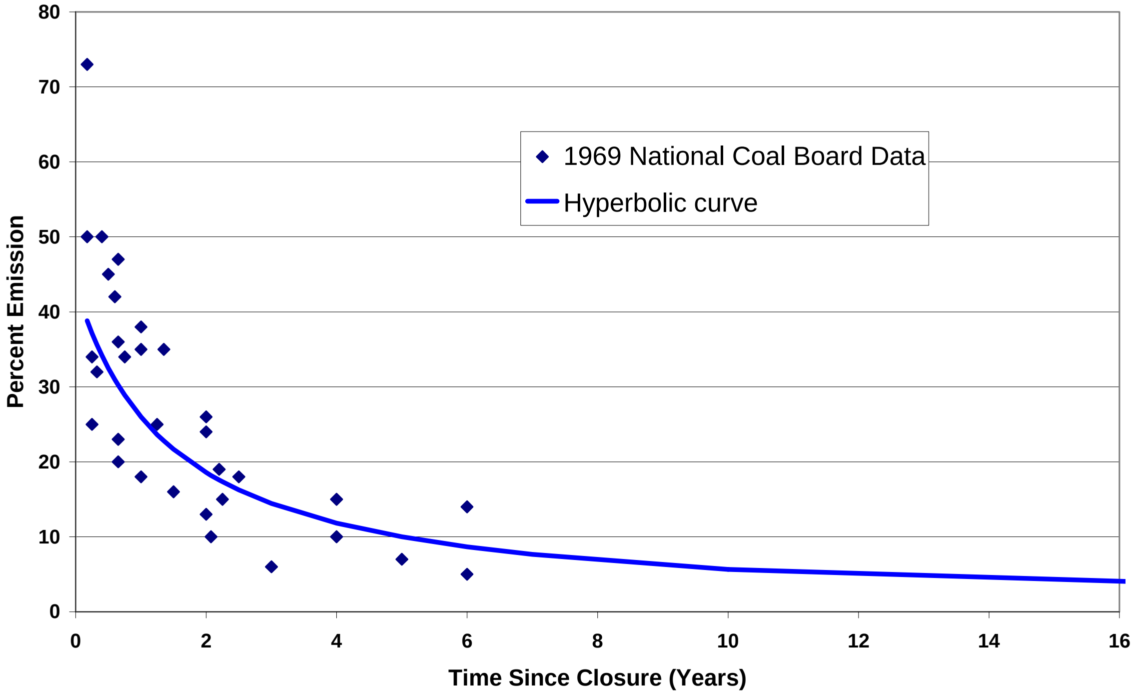

Figure 4.1 Graph of Hyperbolic Decay Function and Colliery Data

It is therefore possible, knowing the emission rate at closure, to estimate the emissions for following years given the above equation.

4.2 FPPROG

A program called FPPROG (**F**iredamp **P**rediction **Prog**ram) was developed under British Coal to calculate the emissions of methane from longwall faces in the UK [5]. FPPROG was used to calculate the quantities of methane released during planned mining operations and ascertain the requirements for methane drainage and ventilation air quantities.

FPPROG calculates the emission from both the worked seam and from the seams in the strata above and below as they generally produce the bulk of the methane flow. The emission from the unworked seams decreases with distance away from the worked seam, due to the reduced degree of disturbance from mining. The total methane emission from the coal, Q (cubic meters of gas per tonne coal m^3/tonne), after time t is calculated by the following equation:

$$Q = Q_0 \left\{ 1 - \exp\left(\frac{t}{t_0}\right)^n \right\}$$

Where Q_0 is the original gas content of the coal in m^3/tonne, t_0 is a time constant and n a constant (found to be 1/3 by experiment). FPPROG calculates t_0 assuming that it increased exponentially with vertical distance from the worked seam, the rate of increase being greater for the seams below than the seams above. The rate of emission (m^3/s) from the coal is the rate of change of Q with time.

Though designed for working collieries, the nature of the governing equation means that it may also be used for periods following production. The gas source represents a number of seams with different time constants which have been degassing for variable periods depending on how long ago they were affected by the mining process. The degassing equation used in FPPROG has been employed to consider the changes in emission both during and after production. By assuming a steady rate of production from one seam, a spreadsheet using the above equation has been developed to calculate the growth of emission during the period of production. Emissions grow due to the continual increase in size of the gas source. However, following cessation of production, no new sources are being produced so gas emissions will fall due to the effect of degassing. The spreadsheet calculates this reduction in emission by summing the emissions from coal disturbed at different times during the production phase.

4.3 Comparison of the Two Methods

An example of a comparison between the two methods is presented in Figure 4.2. The emission at a colliery is greatest from the working faces and initially the gas evolved at a colliery rises rapidly on onset of production. However, the abandoned faces still continue to contribute to the emission of methane, albeit at gradually decreasing effect. As a result the emission from the colliery tends to level off with increasing age, assuming no increases in rate of production. On cessation of production, the high gas flows from freshly disturbed seams terminates abruptly, with a consequential rapid drop in emission from the mine. The rate of decrease of emission reduces with time, as the coal seams with the greatest time constants continue to release gas at low rates.

The strata section used for the calculations in Figure 4.2 is from Stillingfleet in the Selby coalfield. The hyperbolic and FPPROG curve are not identical, but are very similar in form. Similar patterns are found for other strata sections around the country, but with variable curvatures. The curvature of the build up and the decay of methane emission is a function of the distribution of seams within the strata. Where the bulk of the coal in the strata lies at some distance from the worked seam, the time constants will be large, with a consequential slow build up of emission and a slow decay on termination of production. However, where the bulk of the coal in the strata lies close to the worked seam the time constants will be low and hence the build up and decay of the emission will take place rapidly.

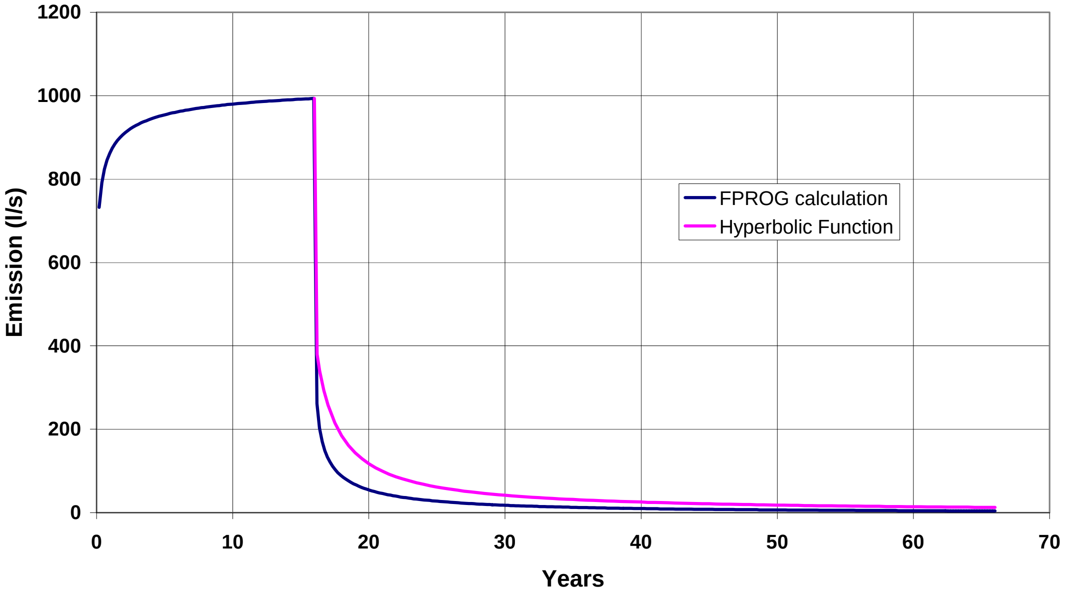

Figure 4.2 A Comparison Between the Hyperbolic Function and FPPROG for Stillingfleet Colliery (Selby)

As an illustration of the variation in rates of decay for different strata sections Table 4.1 lists the times taken in years for calculated emissions to fall to 2%, 1% and 0.74% of the calculated operating emissions prior to closure. Collieries have been chosen which were effectively only mining one seam, which, in its present form, is what FPPROG can make calculations for. It can be seen that there can be a wide range of time scales over which emissions can fall. Stillingfleet, shown in Figure 4.1, can be seen to lie in the mid range of values.

Table 4.1 Time in Years to Reach Percentage of Production Emission (FPPROG)

Colliery	Percent of Production Emission		
	2%	1%	0.74%
Thorne	4.4	10.6	14.6
Riccall	4.6	12.9	18.5
Stillingfleet	1.7	5.5	8.2
Wistow	1	3.5	5.4
Wistow (shallow)	0	0.2	0.3
Daw Mill	0.2	0.8	1.2

The comparison of FPPROG and the hyperbolic function provides additional confidence that the hyperbolic function models the general form of decay of emission with time. However, FPPROG is not designed to make emission calculations of multiple seam working. Consequently it is proposed that the hyperbolic function should be used to model the emission from most newly closed mines. An exception is Daw Mill which FPPROG identifies as likely to have very rapid decay. Therefore, emission calculations for Daw Mill should be based on an FPPROG decay curve rather than using the hyperbolic function.

4.4 Emission as Percentage of Reserve

In addition to these two methods for calculating methane emissions from recently closed collieries, emissions may be calculated by assuming that 0.74% of the methane reserve is emitted per year, as detailed in the full report. However, as mentioned previously, this is likely to significantly underestimate emissions for collieries soon after closure. Table 4.1 shows that emissions from mines could reach the 0.74% of reserve level in the order of 10 years.

In order to bring the calculations for closed and closing collieries in line there is a good case for using the 0.74% of reserve values once emissions calculated using the hyperbolic function fall below those values. Consequently, for each year following closure an emission is calculated based on the hyperbolic curve and also assuming an emission of 0.74% of reserve. Where the emission based on the reserve is greater than that based on the hyperbolic function the prior value is used.

5. Calculation of Methane Emissions from Mines Closed After 2004

Future emissions from newly closed collieries are calculated by applying the hyperbolic decay function to the emission before closure. The emission before closure is calculated using specific atmospheric emission figures (m^3/t) for individual collieries, based on emission and production figures from UK Coal. In the case of Daw Mill, which is likely to have a rapid decay of emissions due to the methane coming from within close proximity to the mined seam, a decay function based on FPPROG has been used rather than the hyperbolic function. In addition an estimate of methane utilised or burned at the collieries has been added to provide the total methane generated. The calculated future emissions have been modified, to take into account mitigating factors as described below.

Because of flooding the gas source is likely to be reduced as a function of time and hence emissions are likely to fall as a result. Consequently, the value of emission calculated with the hyperbolic curve has been reduced in proportion with the reduction methane gas reserve over the same period. It has been assumed that the hyperbolic function does not take the action of flooding into account, because the decay is similar to the decay using FPPROG where no flooding is considered. Additionally we have no information on any flooding associated with the data from which the hyperbolic curve is derived; the mines in question may have had their water levels controlled to prevent flooding of adjacent collieries.

In the future, following the DTI study of methane mitigation [6], it is likely that methane from newly closed mines will be treated to reduce the emission to atmosphere beyond 2006. However, operational constraints may make implementation of these measures difficult in the first year after closure. Emissions have, therefore, been calculated on the basis that the emission from the first year after closure is included in the inventory in full, but thereafter only 30% of the emission will be included in the inventory, based on practical constraints. Because of the time required to bring a control scheme into operation it is further assumed that implementation does not come into effect until 2008. Because such a control scheme would concentrate on the sites with greatest emission, the mitigation is assumed to apply only where emissions at a site are in excess of 0.5kt per year.

Emissions from Collieries closed 2005 onwards have also been calculated by using an emission based on 0.74% of reserve per annum. These calculated emissions have also been reduced to allow for methane mitigation measures on the same basis. Where the percent emission is greater than the hyperbolic decay calculation, the percent emission has been used to bring the emission figures for collieries closing after 2005 in line with those already closed.

Figure 5.1 shows the emissions from all the collieries closed post 2004, with the collieries closed from "low to high" reserve and from "high to low" reserve as described in Section 5.1.

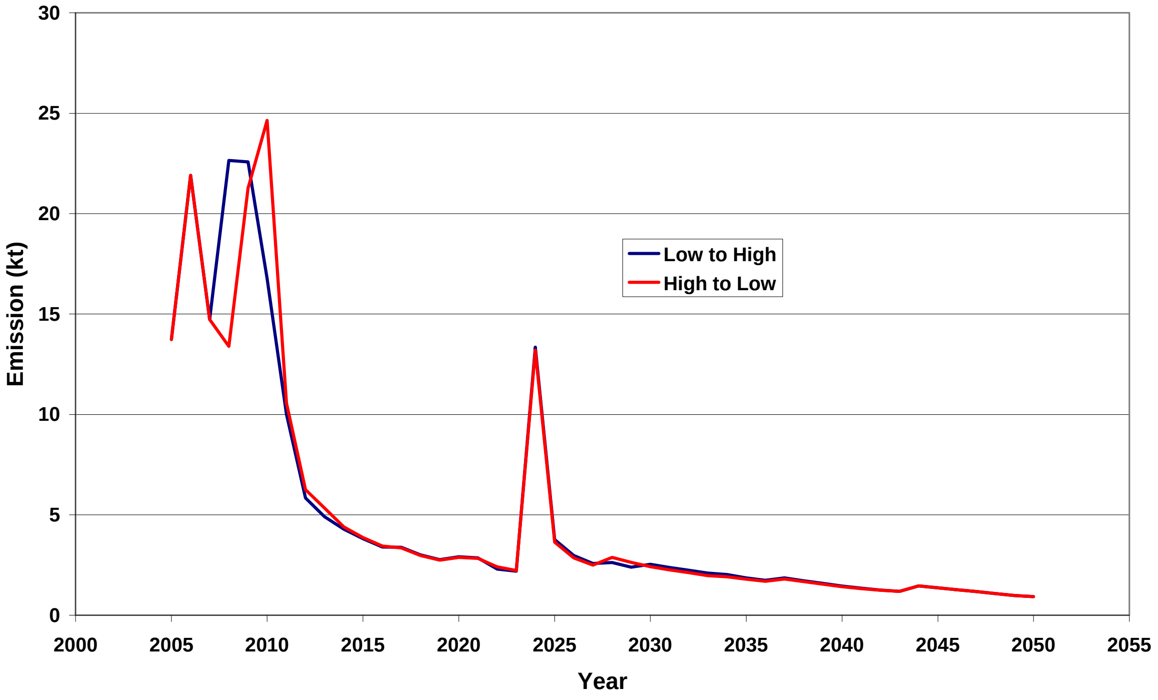

Figure 5.1 Estimated Methane Emissions for Collieries Closed Post-2004

Figure 5.1 shows that both "low to high" and "high to low" estimates are similar except during the years of and just after closure. The "high to low" figures are slightly the worst case and will be used as estimates for future emissions.

6. Projections of Total Methane Emissions from Abandoned Mines

Table 6.1 contains the estimated methane emissions from abandoned mines to 2050. Annual emission data for collieries closed pre-2005 are obtained by interpolating between the 5 year calculated values. Emissions for the collieries closed in 2005 onwards have been listed for the "low to high" and high to low" conditions, together with total emissions for the two conditions.

This information is shown in Figure 6.1. As indicated in the previous section the "high to low" figures are taken to be the future estimate, and are used in the total emission estimate. It is clear that recent closures and closures in the near future are likely to make significant step increases in the total emissions for the next 5 to 10 years. It is expected that corresponding step reductions in methane emissions would be observed in the working mine emission inventory. The longer term emissions trend from newly closed collieries will fall off to lower levels with time, re-establishing the general downward trend of emissions.

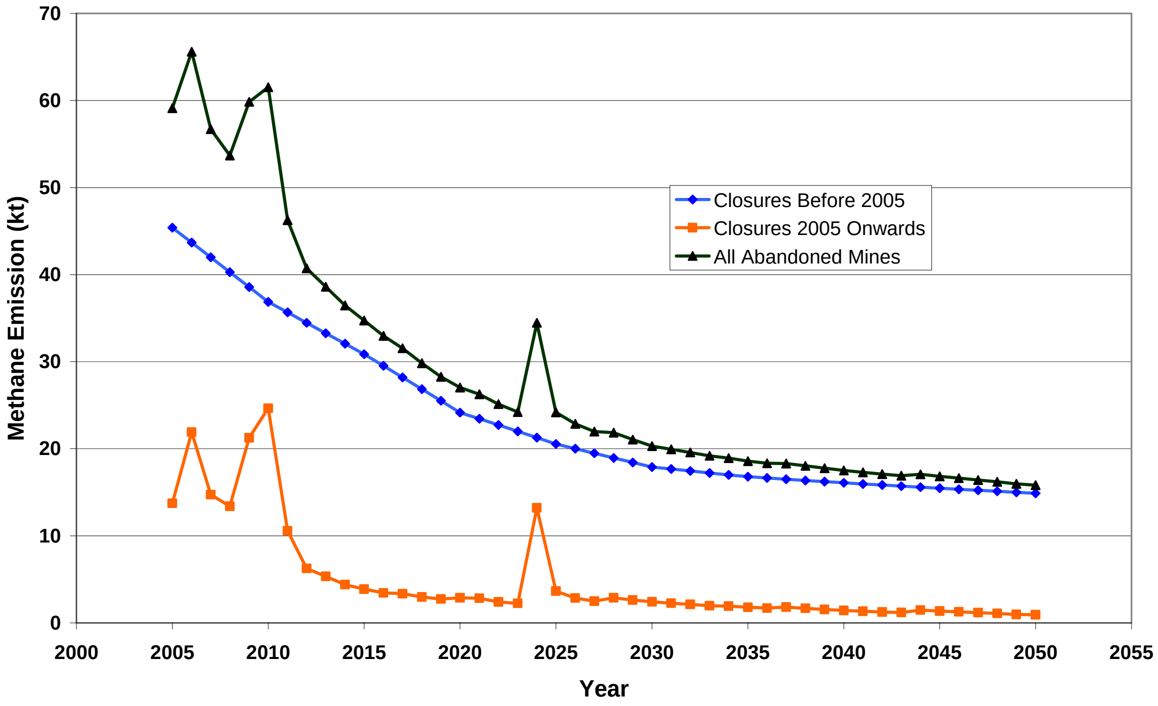

Figure 6.1 Summary of Estimated Methane Emissions

In summary, these projections are based on the premises listed above. Any changes, particularly with regard to the closure dates, may have a substantial effect on the pattern of gas emission, though are not expected to alter the downward trend significantly. The figures presented here represent spikes in emission, due to colliery closure, which are unlikely to be exceeded.

Table 6.1 Estimated Emissions from Abandoned mines 2005 – 2050

Projected Methane Emissions from Abandoned Coal Mines					
(kt)					
Year	Collieries closed			Total Emission	
	Pre 2005	2005 onwards			
		Low to High	High to Low	Low to High	High to Low
2005	45.4	13.7	13.7	59.1	59.1
2006	43.7	21.9	21.9	65.6	65.6
2007	42.0	14.7	14.7	56.7	56.7
2008	40.3	22.7	13.4	62.9	53.7
2009	38.6	22.6	21.3	61.2	59.8
2010	36.9	16.8	24.6	53.6	61.5
2011	35.7	10.0	10.6	45.7	46.2
2012	34.5	5.8	6.2	40.3	40.7
2013	33.3	4.9	5.3	38.2	38.6
2014	32.1	4.3	4.4	36.4	36.5
2015	30.9	3.8	3.9	34.7	34.7
2016	29.5	3.4	3.4	32.9	33.0
2017	28.2	3.4	3.4	31.6	31.5
2018	26.8	3.0	3.0	29.9	29.8
2019	25.5	2.8	2.7	28.3	28.3
2020	24.2	2.9	2.9	27.1	27.0
2021	23.4	2.9	2.8	26.3	26.3
2022	22.7	2.3	2.4	25.0	25.1
2023	22.0	2.2	2.2	24.2	24.2
2024	21.3	13.4	13.2	34.6	34.5
2025	20.5	3.8	3.6	24.3	24.2
2026	20.0	3.0	2.9	23.0	22.9
2027	19.5	2.6	2.5	22.1	22.0
2028	19.0	2.6	2.9	21.6	21.8
2029	18.4	2.4	2.6	20.8	21.1
2030	17.9	2.5	2.4	20.4	20.3
2031	17.7	2.4	2.3	20.0	19.9
2032	17.4	2.2	2.1	19.7	19.6
2033	17.2	2.1	2.0	19.3	19.2
2034	17.0	2.0	1.9	19.0	18.9
2035	16.8	1.9	1.8	18.6	18.6
2036	16.6	1.7	1.7	18.4	18.3
2037	16.5	1.9	1.8	18.4	18.3
2038	16.4	1.7	1.7	18.1	18.0
2039	16.2	1.6	1.6	17.8	17.8
2040	16.1	1.5	1.4	17.5	17.5
2041	16.0	1.3	1.3	17.3	17.3
2042	15.8	1.3	1.3	17.1	17.1
2043	15.7	1.2	1.2	16.9	16.9
2044	15.6	1.5	1.5	17.1	17.1
2045	15.5	1.4	1.4	16.8	16.8
2046	15.4	1.3	1.3	16.6	16.6
2047	15.2	1.2	1.2	16.4	16.4
2048	15.1	1.1	1.1	16.2	16.2
2049	15.0	1.0	1.0	16.0	16.0
2050	14.9	0.9	0.9	15.8	15.8

7. References

1. Kershaw. S, Development of a methodology for estimating emissions of methane from abandoned coal mines in the UK, White Young Green for the Department for the Environment, Food and Rural Affairs. (GA01039) 2005

2. Corden. C, Entec, Private Communication (2005)

3. Franklin, P., Scheehle, E., Collings R.C., Cote M.M. and Pilcher R.C. White Paper: Proposed Methodology for Estimating Emission Inventories from Abandoned Coal Mines. USEPA, Prepared for 2006 IPCC Greenhouse Gas Inventories Guidelines Fourth Authors Experts Meeting. Energy : Methane Emissions for Coal Mining and Handling, Arusha, Tanzania (2004)

4. National Coal Board. Technical Committee on the Utilisation of Methane, *Memorandum No 8*. National Coal Board. Aug 1969

5. Dunmore, R and Kershaw S, The Application of Firedamp Prediction Techniques. The Mining Engineer, June 1983.

6. IMC, Coal Mine Methane – Review of the Mechanisms for Control of Emissions, DTI, 1994