

METHANE EMISSIONS ESTIMATES & METHODOLOGY FOR ABANDONED COAL MINES IN THE UNITED STATES

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ABSTRACT

Anthropogenic sources of methane are the second largest contributor to global climate change, and coal mines are one of the major sources of methane emissions accounting for approximately 8-10% globally according to the Intergovernmental Panel on Climate Change (IPCC). The coal mine methane emission estimates, however, only include emissions from active, or working, mines. The IPCC has not approved, adopted, nor endorsed a methodology for abandoned underground mine emissions, and no country's inventory of greenhouse gas emissions includes abandoned mines. Because abandoned mines are known to vent methane and thereby contribute greenhouse gas emissions, the U.S. Environmental Protection Agency (EPA) has developed a methodology to estimate emissions from abandoned U.S. underground mines. The results show that abandoned mine emissions in the U.S., while not a large share of overall coal mine methane emissions, may increase total emissions by 5% in some cases. Although this methodology focuses on U.S. mines, with adjustments it may be useful in estimating emissions from abandoned mines in other countries.

1.0 INTRODUCTION

The US Environmental Protection Agency (EPA) quantifies methane emissions from coal mines as part of the Inventory of U.S. Greenhouse Gas Emissions and Sinks. The inventory does not include abandoned mine methane (AMM) emissions, because the Intergovernmental Panel on Climate Change (IPCC) has yet to accept, approve, or endorse a methodology for quantifying emissions from abandoned mines. Therefore, it is the intent of this paper to present a methodology to characterize and quantify methane emissions from known gassy abandoned mines in the US.

2.0 ABANDONED MINES AS A METHANE EMISSIONS SOURCE

Coalbed methane (CBM) becomes coal mine methane (CMM) when mining activity releases the gas. As work ceases and mines are abandoned the rate of gas liberation decreases, but does not stop completely. Following an initial rapid decline, abandoned mines can liberate methane at a near-steady rate over an extended period of time, or if flooded, may produce gas for only a few years.

3.0 FACTORS INFLUENCING METHANE EMISSIONS

In order to obtain an estimate of the total methane emissions from U.S. abandoned coal mines, it is necessary to understand the causes of variation in emission rates from individual mines. A number of factors can impact the rate of CMM emissions at abandoned mines, including: (1) Time since abandonment; (2) Gas content and adsorption characteristics of the coal; (3) Methane flow capacity; (4) Flooding; (5) Presence of vent boreholes; and (6) Seals.

3.1 TIME SINCE ABANDONMENT

For the purpose of calculating abandoned mine emissions, abandonment is defined to begin with the cessation of mine ventilation. The emission rate declines rapidly in early years and then flattens out, becoming almost constant at a low rate for many more years.

3.2 GAS CONTENT AND ADSORPTION CHARACTERISTICS OF COAL

The adsorbed volume of methane as a function of pressure can be characterized by mathematical functions that are based on theoretical adsorption properties. One function commonly used for methane adsorption on coal is called the Langmuir Isotherm. The Langmuir isotherm is generally expressed as:

$$V = V_L P / (P + P_L) \quad (1)$$

Where:

V = Volume of methane at standard temperature and pressure per ton of coal, m³/tonne or scf/t

V_L = Langmuir volume constant, m³/tonne or scf/t

P = Pressure in the coal cleat system, kPa or psia

P_L = Langmuir pressure constant, kPa or psia

The Langmuir constants V_L and P_L can be determined by fitting the function to experimental adsorption data.

3.3 METHANE FLOW CAPACITY OF THE MINE

Methane moves from within the micro-porous matrix of the coal to the cleat system by means of diffusion. Once the methane is within the cleat system, it is primarily in the free gas state and the laws of gas flow through porous media determine movement. For a gas, this function takes the form of **Equation 2**:

$$q = PI (P_w^2 - P_r^2)^n \quad (2)$$

The PI term combines the permeability of the rock, the viscosity of the gas, the geometry and configuration of the pressure sink and outside gas reservoir, and the thickness of the flow unit. By analogy, the mine and its connection to the atmosphere (vent shaft or overburden fracture conduit) can be substituted for the wellbore, with the unmined coal within and peripheral to the mine being the reservoir of stored methane. The rate of withdrawal (q) is a function of product of the PI term and the difference between a specified pressure at the well, (P_w), and the pressure at some outside boundary of the gas reservoir (P_r) the exponent, n, is empirically derived and accounts for turbulence and other non-ideal flow conditions (Slider, 1983).

3.4 MINE FLOODING

Over time, abandoned mines may partially or completely flood with water. This will partially or completely shut off gas flowing into the mine.

3.5 ACTIVE VENTS

At some abandoned mines, vent pipes are in place to relieve the buildup of pressure resulting from desorption and flow of methane into the mine void.

3.6 MINE SEALS

Seals can be found at many mines, but it is common for gas to leak out around these plugs or to make its way through fractures in the overlying strata to the surface.

4.0 STEPS TO DEVELOPING THE METHODOLOGY

- **Step 1:** Create a Database A database was compiled containing information on abandoned coal mines having active mine emissions greater than 100 mcf (thousand cubic feet per day).
- **Step 2:** Develop Coal Basin-Specific Decline Curves Coal basin-specific adsorption characteristics and coal mine-specific emission data were used to develop inputs for a numerical model.
- **Step 3:** Validation Through Field Measurements A series of field measurements were conducted at abandoned mines across the country.
- **Step 4:** Calculate a National Emissions Inventory by Year The emission estimates were calculated by mine according to their status: venting, flooded, sealed, or unknown status.

4.1 DEVELOPING A DATABASE

In order to develop a comprehensive list of gassy abandoned mines in the U.S., EPA combined emissions information from several data sources. USBM, and MSHA data are available for mines closed since 1972, but for mines closed prior to 1972, EPA used state information in seven states with gassy mines. It was found that 374 gassy coal mines had closed since 1972 and estimated that 145 gassy mines had closed from 1920-1972.

Since 1990, MSHA has provided EPA with information on all coal mines with emissions greater than 100 mcf (except for the years 1991 and 1992, when ventilation fan data was not collected). Of particular note, the 1997 emissions dataset was a complete MSHA dataset consisting of all active coal mines with detectable emissions (586 mines), not just mines with emissions greater than 100 mcf. The data show that mines emitting greater than 100 mcf comprised 98% of emissions for all mines with reportable emissions (EPA, 2002). The USBM studies showed similar results for the 1970s. Therefore, for this study, it is reasonably assumed that the 145 pre-1972 mines and 374 post-1971 mines are a representative sample of the population of mines that produce 78% and 98% of methane emissions from abandoned mines, respectively.

4.1.1 MINE STATUS INFORMATION

The study identified the status of 64% of the gassy abandoned mines in the database, as either:

- Vented to the atmosphere,
- Sealed to some degree (either earthen or concrete seals), or
- Flooded (enough to inhibit methane flow to the atmosphere).

4.2 DEVELOP COAL BASIN-SPECIFIC DECLINE CURVES

Data on the key constraints affecting methane emissions (adsorption characteristics, pressure, flow capacity and abandonment status) are not available for all of the gassy U.S. underground coal mines. However, the methane ventilation rate before abandonment and the date of abandonment are available for all post-1971 mines. In addition, the abandonment status and several adsorption isotherms for the most commonly mined coals in each coal basin are published (Masemore, et al., 1996). Methane reductions were forecast through time using decline curve analysis.

4.2.1 FORECASTING EMISSIONS THROUGH TIME

Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline. The USBM measured daily emissions at the Cambria Mine in Pennsylvania for over 3 years, of which approximately 1.5 years were measured after the gob area was sealed (Garcia

et al., 1994). **Figure 1** shows the methane emissions rate for the period after the gob area was sealed, thus representing an abandoned mine area.

4.2.2 DIMENSIONLESS DECLINE CURVES WITH FLOW SIMULATION

In order to forecast methane emissions through time for a given mine, it is necessary to apply a decline function to the mine that is initiated at the time of abandonment. To do this, EPA has used a reservoir simulator that combines Darcy's law and material balance equations to build a series of dimensionless decline curves applicable to each coal basin.

4.2.3 DATA AVAILABILITY AND UNCERTAINTY

The emission rate and the date of abandonment are generally available for mines abandoned after 1972. This rate was used as the initial rate for each mine's decline curve. Estimated closure dates and emission rates were used for mines prior to 1972. The parameters for which values must be estimated for each mine in order to predict its decline curve are:

- The coal's adsorption isotherm;
- Methane flow capacity as expressed by permeability; and,
- Pressure in the remaining coal at abandonment

It was found that calculated emissions are much more sensitive to permeability and initial emission rate than to either initial pressure or adsorption isotherm. The dimensionless decline curves used in the inventory calculations, therefore, were generated by using mid-case values for initial pressure and the average basin isotherm, but include low, mid and high values for permeability and initial emission rate in the probabilistic analysis.

4.2.4 ADSORPTION ISOTHERMS

Masemore et al. (1996) compiled numerous adsorption isotherm parameters for each coal basin. Average values of these isotherms are shown in **Figure 2**.

4.2.5 PERMEABILITY

In order to ensure that a sufficiently broad range of uncertainty was assigned to this parameter, values of 0.1, 1.0 and 10.0 md were chosen as the low, mid and high values

4.2.6 PRESSURE AT ABANDONMENT

Shut-in pressures were measured at boreholes in several abandoned mines. They ranged from essentially atmospheric up to 27 psia. An initial pressure of 20 psia was used to generate the decline curves.

4.2.7 MSHA VENTILATION AIR EMISSION VALUES

The initial emission rate data is from the USBM and MSHA, which are instantaneous readings taken quarterly. The combination of the error introduced by the instantaneous, as opposed to continuous measurements, and the imprecision of the measurement equipment result in the quarterly instantaneous readings being 10% underestimated to 30% overestimated (Mutmansky and Wang, 2000).

4.2.8 EMISSION CALCULATIONS USING MINE STATUS

4.2.8.1 Vented mines

The emissions from a vented mine are calculated by simply using Darcy's Law with the known elapsed time since closure, the distribution of active mine emission rates based on the error ranges previously discussed, and three sets of decline constants for each basin, (a low, mid and high set).

4.2.8.2 Flooded mines

An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five

basins. The exponential equation was matched to the emissions data using a least squares, curve-fitting algorithm.

4.2.8.3 Sealed mines

Seals have an inhibiting effect on the rate of flow of methane into the atmosphere compared to the rate that would be emitted if the mine had an open vent. The total volume emitted will be the same, but will occur over a longer period. The methodology, therefore, treats the emissions predictions from a sealed mine in a manner similar to emissions from a vented mine, but uses a lower initial rate depending on the degree of sealing. (**Figure 3**).

5.0 FIELD MEASUREMENTS

5.1 VALIDATION THROUGH FIELD MEASUREMENTS

EPA conducted a series of field measurements at abandoned mine vent locations across the U.S. Vent pipes are the only place at an abandoned mine where methane emissions can be accurately measured. Of the 374 post-1972 mines listed in the database, 54, or 14%, are known to have vent pipes still in place. EPA attained access to only seven mines, but two were nearly flooded at the time of the study and produced little methane. EPA analyzed an additional five flooded mines, and measurements from a 1991-1994 EPA study of abandoned mine vents at 21 mines were also used.

5.1.1 UNFLOODED MINES

Between November 1998 and February 2000, EPA recorded measurements at the five mines that were not flooded. EPA found that correlating gas flow rates to barometric pressure is key to obtaining representative field measurements for decline curve validation. Figure 4 is a plot of measurements for the field data recorded and plotted against predicted emissions as part of the two studies from 1991-2000.

5.1.2 FLOODED AND FLOODING MINES

Of the flooded mines investigated, five of the seven mines producing no emissions had been abandoned less than 10 years, while the remaining two had been abandoned for over 15 years. **Figure 4** shows the exponential decline curve fitted to the flooding mines that produced methane emissions. Based on the data, it could be assumed that most U.S. mines prone to flooding will become completely flooded within 8 years and therefore no longer have any measurable methane emissions.

6.0 CALCULATING METHANE EMISSIONS INVENTORY BY YEAR

The annual emissions by mine (in the form of a probability distribution) were summed by Monte Carlo simulation to provide yearly emissions by mine status, which are then summed to produce a probability distribution of emissions by year for the total U.S. In order to assign an emission rate to the unknown status mines it was assumed that the population of unknown mines is similar to the population of the known status mines in terms of the percentage of sealed, vented or flooded mines. Emissions from mines of unknown status are calculated three ways; as vented, flooded, and sealed. Probability density functions of the results are generated for each status type. These are then multiplied by the percentage of each known status type in each coal basin.

6.1 1990 BASELINE INVENTORY

For the 1990 baseline year, the abandoned mines emission inventory was based on 230 mines known to have closed since 1972 and an estimated 145 mines closed from 1920-1971. As described in the previous sections, EPA

used initial emission rates based on MSHA reports, time of abandonment, basin-specific decline curves influenced by a number of factors to calculate annual emissions for each mine in the database. In addition, since the pool of post-1972 gassy mines is assumed to account for 98% of emissions, the modeled results were multiplied by 1.02; similarly the results of the 1920-1971 mines were multiplied by 1.22 since they account for 78% of the emissions. As a result, EPA estimates that methane emissions from U.S. abandoned coal mines in 1990 range from 195 to 286 million cubic meters, with a median value of 239.

6.2 EMISSIONS FOR 1991-2000

In order to determine the abandoned mine emissions for 1991 through 2000, EPA used several sources of information. Using MSHA data and EPA annual coal mine emissions inventory data, EPA was able to identify and calculate the ventilation emissions and degasification amounts from 144 additional mines that were closed from 1991-2000. Methane degasification amounts were added to ventilation data for 14 mines that closed between 1992 and 2000. For these mines, the total methane liberation rate (ventilation plus degasification) rather than just the ventilation rate was used as the initial rate for the abandoned mine emissions decline curve.

6.3 ADJUSTMENTS FOR METHANE RECOVERY PROJECTS

Once the 1991-2000 estimates were calculated, it was downwardly adjusted to reflect abandoned mine methane that is recovered and used. No adjustment was made in 1990-1992, because no data was found for abandoned CMM recovery projects were in operation at that time. Since most all recovery projects produce much more gas than would be emitted naturally, it is assumed that the negative pressure applied to the mine void (for purposes of recovery) would negate any additional diffuse emissions from the mine.

7.0 RESULTS OF 1990 THROUGH 2000 METHANE EMISSIONS INVENTORY

Figure 5 shows how gross abandoned mine emissions ranged from 239 to 474 million M3 during the decade, varying as much as 80 million M3 from year-to-year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. **Figure 5** also shows the net abandoned mine emissions for each year. Due to the large number of mine closures from 1994 to 1996, emissions peaked in 1996 with 76 gassy mines closing during the three-year period. In spite of this rapid rise, mine closures and abandoned mine emissions have been on the decline or nearly level since 1996. The abandoned mine emissions estimate for 2000 was down to 385 million M3 (excluding recovery).

8.0 CONCLUSIONS

Even though emissions rates for abandoned mines decline through time, active mine emissions (or initial emissions rate) for U.S. mines continue to increase on an individual mine basis. The downward trend in total abandoned mine emissions since 1996, however, is expected continue as well, because there exists a relatively small number of gassy mines to close in the future. Since no recognized methodology currently exists for abandoned mines, the emissions estimation methodology and results described in this report may be considered for quantifying this sub-source category. The methodology is flexible enough to allow the inclusion of additional mines into the inventory as information

becomes available, so as to update annual emissions inventories. The methodology can also be employed to predict future emissions from existing underground coal mines for any given year.

9.0 REPORT FIGURES

Figure 1 – Emission rate from gob well

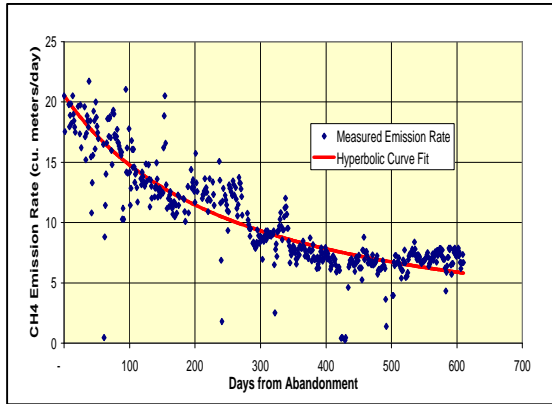


Figure 2: Average methane adsorption isotherm by U.S.

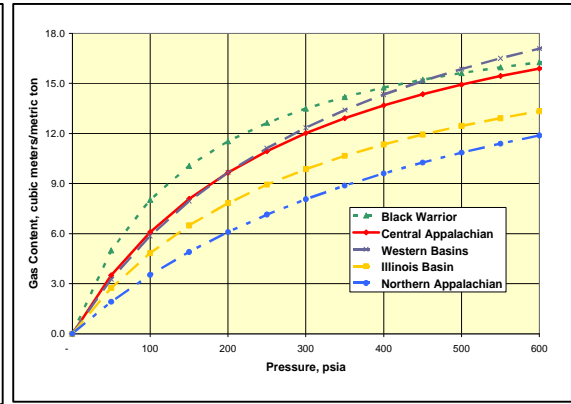


Figure 3: The effect of sealing on abandoned mine emissions relative to emission rate at closure

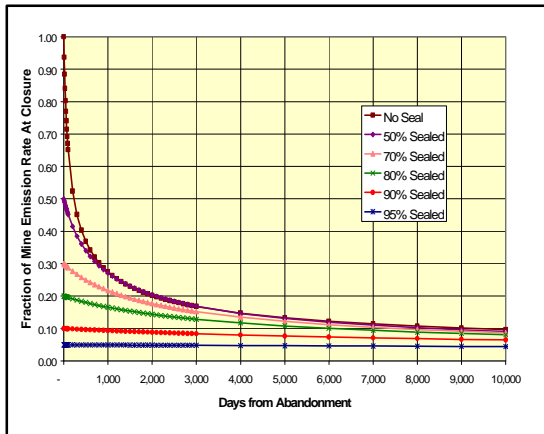


Figure 4: Decline curves for flooded mines (fit to field data) and unflooded mines (field data validates modeled curve)

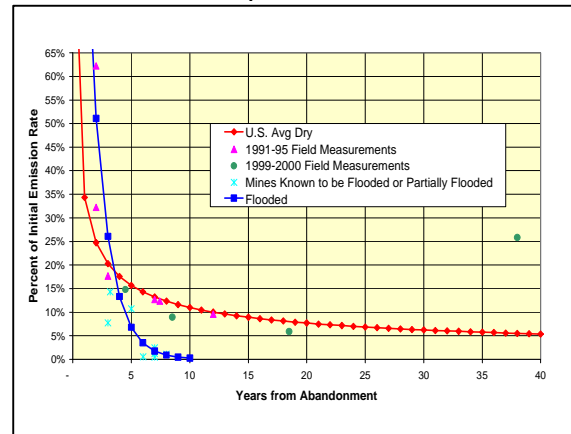
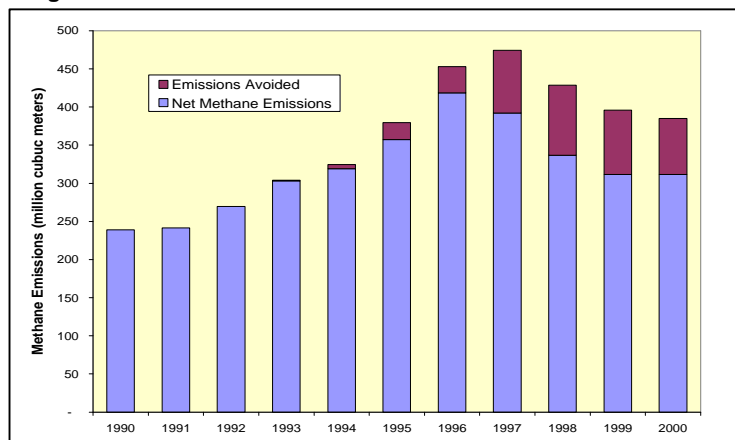


Figure 5: Abandoned Mine Methane Emissions Estimate for 1990-2000



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