ABANDONED COAL MINE EMISSIONS ESTIMATION METHODOLOGY

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ABSTRACT

Methane contained in abandoned underground coal mines may represent an economically viable gas resource that, when utilized, can reduce emissions of methane to the atmosphere. Emissions from abandoned mines may come from unsealed shafts and vent pipes, or from strata surrounding the coal mine. Currently, U.S. EPA is in the process of developing a methodology for estimating and predicting long-term methane emissions from abandoned coal mines. The approach uses mathematical equations to describe the magnitude and rate of decline of the methane emissions. Field measurements of emissions from vent pipes aid in substantiating the estimate. U.S. EPA has also begun developing a database of information that can be used to characterize gassy coal mines at the time of closure. The database contains information such as active mine emissions, location of vents, rate of flooding, coal seam depth, overlying lithology, gas content and rank of coal, and date of closure, all of which affect the accuracy of the emission estimate. Collecting and verifying each of these parameters poses a significant challenge, since no one government agency compiles such a wide range of information. As a result, no complete data set currently exists on annual emissions from these abandoned mines.

1.0 BACKGROUND

The Intergovernmental Panel on Climate Change (IPCC) recognizes the need to characterize methane emissions from abandoned coal mines, but has not recommended a methodology for calculating abandoned mine emissions due to the lack of data [1]. However, the IPCC does make recommendations to investigate this source and estimated that approximately 8.9 billion cubic feet (Bcf) per year were being emitted in 1993 [2]. Previous studies based on U.S. Mine Safety and Health Administration (MSHA) data have estimated that at least 7,500 underground coal mines have been abandoned since 1970 in the U.S., which emit an estimated 7 to 35 Bcf of methane per year [3]. These estimates are based on pre-abandonment data and emissions measured at 20 abandoned underground coal mines in the Appalachian and Black Warrior Basins, but such estimates are wide ranging because of limited data.

U.S. EPA is currently conducting a comprehensive investigation to narrow the range of estimated emissions from abandoned underground coal mines. The large number of abandoned mines located in different geologic regions make it economically impractical to measure methane emissions from each individual mine. Various state and federal agencies track information on methane emissions from *active* coal mines, however, current emissions estimates for post-mining activities rely on coal basin-specific emissions factors, based on in-situ gas contents of the coal. By analyzing the historical emissions data, available databases, and information collected during field studies, U.S. EPA is now determining a reliable abandoned mines emissions estimate (with an acceptable level of uncertainty). This work employs field measurement data from selected abandoned coal mines located in various U.S. coal basins, together with a set of physically-based equations, to estimate and predict present and future methane emission rates.

The proposed methodology, described in the following sections of the paper, is a work-in-progress. It follows the "Tier 2" approach as recommended in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Under the Tier 2 guidelines, an emissions estimate can be based on a country or basin specific method, depending on the data available. To implement the Tier 2 approach, U.S. EPA examined emissions data from a limited number of mines and developed a family of decline curves based on established mathematical equations for emission-rate declines. U.S. EPA and its contractor, Raven Ridge Resources, Incorporated (Raven Ridge) are using statistical analysis and expert judgement to develop an emissions factor for abandoned mine emissions. One of the primary goals of the methodology is to establish a *simple* emissions model based on physical principles, available data, and measurements. As more data becomes available, Raven Ridge will develop a more accurate and narrower range of emissions factors for abandoned underground coal mines.

2.0 DETERMINING ABANDONED MINE EMISSIONS IN THE U.S.

2.1 Approach

In order the obtain an accurate estimate of the total methane emissions from U.S. abandoned coal mines, it is necessary to understand the variations in emissions rates from individual mines and the reasons for these variations. For example, the size of the mine void space and the resulting gas reservoir has an effect on the emission rate and concentration of methane in the coal mine gas. If a mine is largely flooded, then the resulting gas reservoir is reduced and small barometric pressure fluctuations can cause the mine to "breath", which means air is flowing into the mine during periods of high barometric pressure. Conversely, if a mine is dry and consists of a large gas reservoir, then substantial quantities of gas may be produced from the mine and barometric pressure changes cause only small variations to the emission rate. The model assumes that unless flooded, methane contained in a coal mine will eventually be emitted to the atmosphere.

Because of the complex nature of quantifying abandoned mine emissions, a multi-step approach was adopted. First, a database was developed which identifies mines that are potential emitters, which are abandoned mines, and when active, had emissions greater than 2,833 cubic meters per day (m^3/d) or 100,000 cubic feet per day (ft^3/d). The mines were then categorized according to major coal basin, or state and county where appropriate. Equation sets were developed from a history of gas decline curves and verified through field measurements at vent pipes located at existing abandoned coal mines. Because of the impacts that barometric pressure changes have on flow rates, a field-sampling program that quantified the "average emissions" from a measured mine had to be developed. The family of decline curves produced a range of emissions factors that were correlated to the specific emissions of the coal mine. A final, or average emissions factor, is then used to determine the abandoned mine emissions inventory for the U. S.

2.2 Data Base

U.S. EPA collected data from various state and federal agencies about mines during *active* mining operations. These were used as the initial basis for estimating methane emissions after mines are abandoned. Abandoned mines that emitted more than 2,833 m^3/d (100,000 ft^3/d) of methane during active mining were selected from the MSHA Mine Information System (MIS) database as well as older Bureau of Mines (BOM) databases. U.S. EPA believes that the resulting 310 mines produce the majority of methane emissions from abandoned mines. Where possible, Raven Ridge collected information on each of these mines from state and federal regulatory agencies, and/or from the mine operators. Individual mine datasets may include mine-specific maps, mine acreage, depth of workings, degree of flooding, and whether the mine is sealed or venting to the atmosphere.

This characterization process was further refined based on the assumption that coal basins can be classified according to similarities in lithology, coal rank, depth of the coal, gas content, and hydrologic characteristics.

2.3 Mine Flooding

An important factor in quantifying long-term methane emissions from abandoned mines is the impact of groundwater flooding. Once a mine is filled with water, the hydrostatic pressure significantly reduces methane emission from the surrounding coal and rock. Raven Ridge believes that when the hydrostatic head in the mine reaches the top of the caved and relaxed zones, the mine is completely saturated and the methane emission rate becomes zero. Using preliminary information on the hydrology in the various coal basins, only a selected percentage of mines will flood at a rate that appreciably affects the rate of emissions. Consequently, the probability of a mine flooding in a selected coal region was determined for each coal basin. Using this probability, the percentage of mines that flood within a given coal basin can be estimated. It is assumed that once flooded, these mines and their subsequent methane emissions will be excluded from the emissions inventory.

2.4 Underground Mine Seals

The degree to which the mine seals leak, and the subsequent impact on post-mining emissions, is a difficult parameter to quantify. Experience suggests that all seals leak to some degree. This leakage may be due to faulty seals, relaxation of the surrounding strata resulting in fractures, or the general deterioration of seals with time. For the purposes of this investigation, it was assumed that all seals in abandoned coal mines leak. It is further assumed that over a sufficient time period, pressure builds up behind a leaking seal such that the sealed void space eventually contributes as much methane gas to a venting mine as would be contributed by the same void space if a seal was not present.

2.5 Field Measurement Program

If methane emissions from the mined coal seam and surrounding rock are substantial and the mine void space is sufficient to create a large gas reservoir, then methane will be consistently emitted from the mine with some degree of variability in flow rate. On the other hand, if the mine is not gassy or a large portion of the mine is flooded, thereby reducing the gas reservoir volume, then methane emissions are not sufficient to overcome periods of high barometric pressure. This results in air flowing *into* the mine, diluting methane concentrations. Over the long term, however, there will be a net discharge of methane from the mine to the atmosphere.

One of the keys to predicting methane emissions from an abandoned mine is determining the *average* methane emissions rate from the mine. The goal of the field study was to determine the measurement interval and duration necessary to yield an average methane emission rate from a mine vent. Determining the average emission rate is crucial to estimating total mine emissions and predicting future emissions rates.

2.5.1 Measurement methodology

Raven Ridge conducted a series of field measurements at abandoned mine vent locations across the U.S. Personnel used vane anemometers and methane detectors to determine gas flow rates and concentrations, respectively, at mine vents. An anemometer measures the velocity of gas flow through a shaft or vent pipe of known cross sectional area. The velocity is multiplied by the cross sectional area of the shaft (or vent pipe) to determine the flow rate. The methane detector measures the real-time concentration of methane gas emitting from the mine. By multiplying the percentage of methane gas by the flow rate measurements, field personnel can determine the volume or mass flux of methane gas escaping from an abandoned mine.

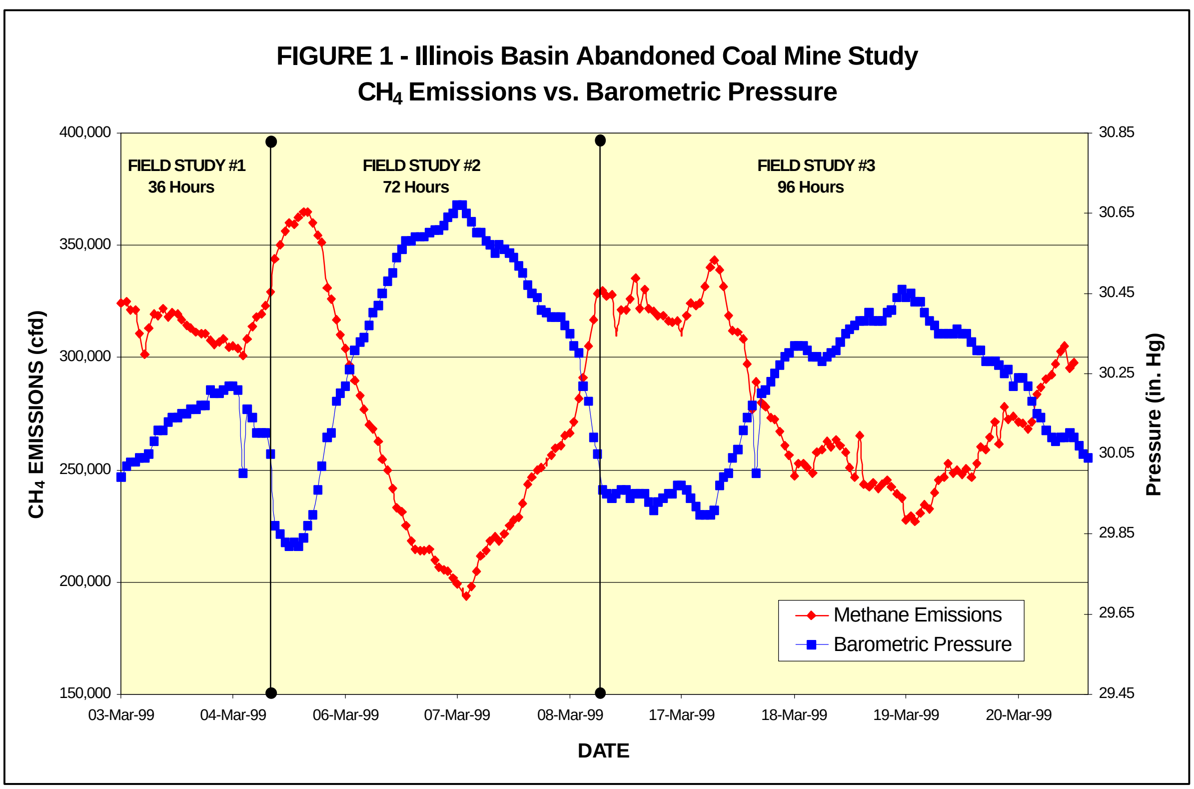
There are several correction factors necessary to convert anemometer flow and methane concentration measurements to standard methane emission values. Method factors are defined as the ratio of the true velocity to the anemometer measurement for each vent or pipe size. U.S Bureau of Mines conducted a series of measurements for pipes smaller than 12 inches [4]. Based on their work, method factors for 4-, 6-, and 8-inch pipes are 0.68, 0.71. and 0.78, respectively. The National Coal Board of the United Kingdom had previously developed method factors for correcting vane anemometer measurements for 12 to 30 inch pipes. Results indicated that for pipes larger than 12 inches, a method factor of 0.85 is sufficient for conversion purposes.

According to the same study, the effects of density changes due to methane concentrations using anemometers *calibrated in air* are miniscule. Corrections are also necessary for reporting gas emissions under standard temperature and pressure (STP) conditions. Since elevation and temperature conditions at most mines do not vary greatly, corrections are generally not significant.

2.5.2 Results of Illinois Basin Study

During the spring of 1999, Raven Ridge used an abandoned mine vent in the Illinois Basin to collect gas flow and quality data in order to correlate flow rates with barometric pressure. In a previous U.S. EPA study, abandoned mine emissions data was based on a single measurement or daily measurements at a bore hole or vent pipe [5]. Unfortunately, the data sets consisting of paired daily readings collected over long periods of time produced a poor correlation and an average emission rate could not be accurately determined. As part of the 1999 study, Raven Ridge set out to determine what field measurement methodology could produce a *statistically valid* average emission rate for a given mine, accounting for variations that occur due to barometric fluctuations.

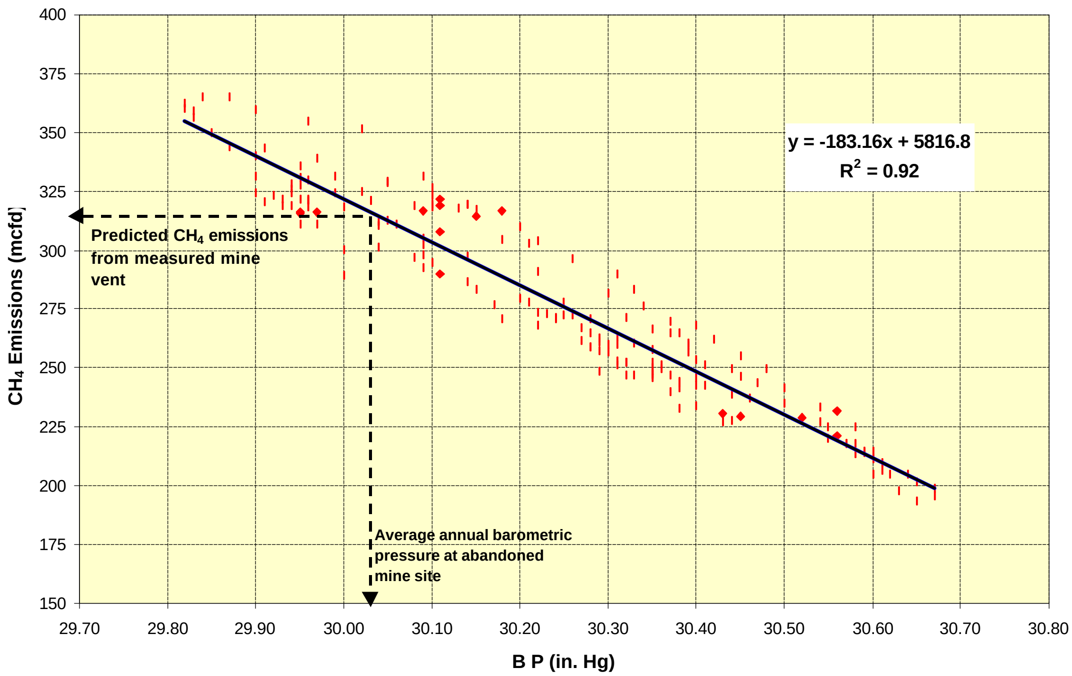
The mine selected for the study had been closed for 37 years, but a three-inch vent pipe remained intact and continued to vent methane into the atmosphere. Flow measurements were recorded every hour at the vent pipe over three 2-4 day periods. Matching hourly barometric pressure data was obtained from the Midwestern Climate Center. Figure 1, which is a plot of the three data sets, shows the strong relationship between the methane emissions from the vent and barometric pressure. It is also important to note the magnitude of variation in the flow rate, which further underscores the fact that daily measurements may not be reflective of the average flow rate. Therefore, hourly flow measurements recorded for 72 hours are recommended in order to determine an average flow rate for a given mine vent.



Further analysis shown in Figure 2 verifies the excellent correlation of flow and barometric pressure, where the equation describing the relationship has a correlation coefficient (R) equal to 0.96. The average annual barometric pressure in the county where the mine was located was 30.03 inches of mercury. Even though daily readings ranged from 5,524 m^3/d (195,000 ft^3/d) to 10,340 m^3/d (365,000 ft^3/d), the average methane emissions rate for the vent pipe, based on the equation in Figure 2, would be 8,966 m^3/d (316,500 ft^3/d).

FIGURE 2

Linear Regression of Methane Emissions vs. Barometric Pressure



2.6 Gas Production and Decline Curves

Abandoned coal mines consist of a complex network of underground mined areas surrounded by strata of varying lithologies. In addition, mined areas collapse to form "gob" that further complicates the void space geometry. The major gas producing areas of the coal mine are the gob areas, which provide exposure to the largest surface area of rock containing methane. Raven Ridge also assumed that methane liberation into a mine is a diffusion-limited process. Gas from the coal matrix and surrounding rock diffuses to nearby cleats and fractures where Darcian flow dominates the transport of methane to the mine. The pressure gradient driving the flow from the fractures to the mine was assumed to be under equilibrium conditions with the mined regions once the mine has been abandoned.

Originally, Raven Ridge proposed a draft methodology using an exponential decline curve, yielding relatively minor emissions after several hundred days. For mines that become flooded after abandonment and whose methane emissions essentially cease, this exponential decline in emissions rates may be appropriate. However, there are data for mine emissions that contradicts an exponential decline, especially in mines that remain dry for extended periods of time. For example, the Nelms Mine in eastern Ohio, and the Cambria and Gateway mines in southwestern Pennsylvania have been producing gas at nearly constant levels for up to 15 years. It has been shown repeatedly that once the coal extraction ends, methane emissions dramatically drop, then decline at a slow rate. The form of this type of curve, shown in Figure 3, is *hyperbolic*.

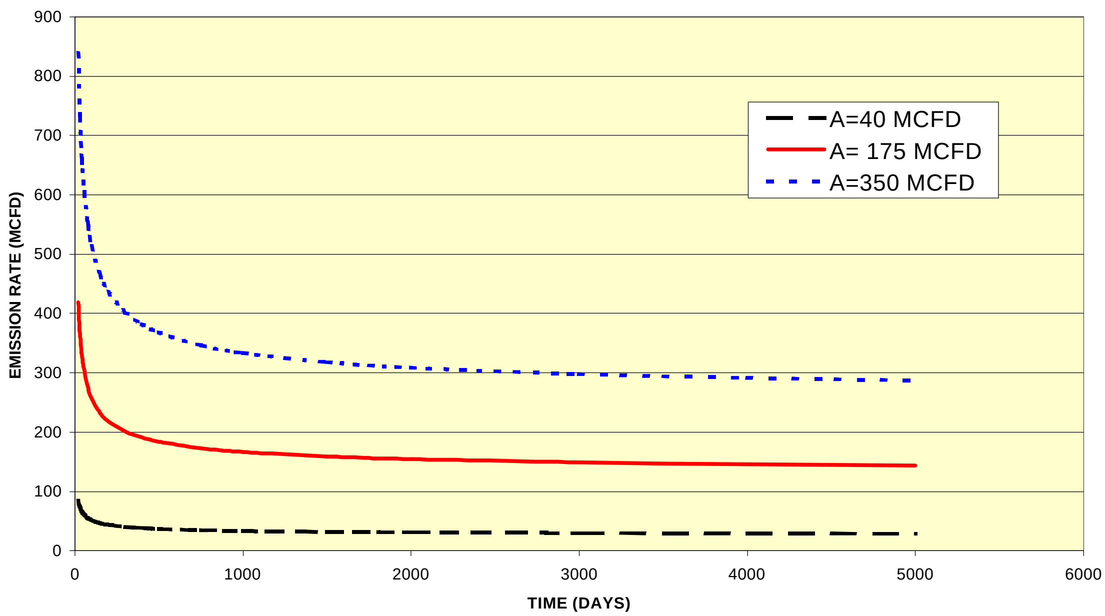


Figure 3: Family of Decline Curves for Predicted Methane Emissions Based on Field Measurements

By using a hyperbolic curve, it is not critical that initial methane emissions be measured immediately after the mine is abandoned. The relative error for future methane emission estimates based on different initial emission values is minor. This is one advantage of using a hyperbolic equation, as opposed to an exponential equation that predicts rapid emission rate changes within a few months or within the first year after abandonment.

2.7 Comparison of Mine Emissions and Specific Emission Data

Currently, the MSHA database provides annual coal production and mine emissions information for individual underground coal mines operating in the U.S. Specific emissions are defined as the methane emissions produced by the coal mine in a given period of time divided by the amount of coal produced during that same time interval. By comparing emissions data that Raven Ridge recently gathered at several abandoned coal mines in the U.S. with the specific emissions of those mines, a range of emissions factors was established. The data was also used to establish hyperbolic-curve equations that best fit the data. Raven Ridge then used these curves to estimate emissions from abandoned mines for which there were known specific emissions, but no available field measurements.

3.0 CONCLUSIONS

This methodology can be used to calculate the U.S. national abandoned coal mine emissions inventory. To accomplish such an inventory, U.S. EPA is examining many regional-specific physical parameters such as the type of coal, gas content, depth of burial, and developing basin-wide averages. This data analysis is necessary to provide a narrower, basin-specific estimate of methane emissions even though very little data exists for some abandoned mines. In addition, U.S. EPA hopes to apply hyperbolic decline curves established by this methodology to active coal mines preparing to close, thus predicting their long-term methane emission rate. By doing so, mines that are considered the best candidates for gas recovery and use can be easily identified prior to closing. With interest in abandoned mine gas development on the rise, there is a growing need to quantify the long-term potential of abandoned coal mines as a gas resource. Finally, this methodology provides a more accurate way for countries to establish their baseline emissions inventory for abandoned mines and account for the possibility of future greenhouse gas reductions.

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