U.S. EPA Coalbed Methane Outreach Program

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

METHANE EMISSIONS FROM ABANDONED COAL MINES IN THE UNITED STATES: EMISSION INVENTORY METHODOLOGY AND 1990-2002 EMISSIONS ESTIMATES

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COALBED METHANE OUTREACH PROGRAM

The Coalbed Methane Outreach Program (CMOP) is a U.S. Environmental Protection Agency (EPA) voluntary program. CMOP works with coal companies and related industries to identify technologies, markets, and means of financing for the profitable recovery and use of coal mine methane (a greenhouse gas) that would otherwise be vented to the atmosphere. CMOP assists the coal industry by profiling coal mine methane project opportunities at the nation's gassiest mines, by conducting mine-specific technical and economic assessments, and by identifying private, federal, state, and local institutions and programs that could facilitate project development.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

Weights and Measures

cf	cubic feet
Bcf	billion cubic feet
Gg	gigagrams = 10^9 grams
kg	kilogram = 10^3 grams
km	kilometer = 10^3 meter
km^2	square kilometer
kPa	kilopascals = 10^3 Pascals
mcf	thousand cubic feet
mcfd	thousand cubic feet per day
m^3	cubic meter
md	millidarcies = 10^{-3} Darcies
mmcf	million cubic feet
P_L	Langmuir pressure
psia	pounds per square inch absolute
psig	pounds per square inch gauge
scf	standard cubic feet
t	short ton
tonne	metric ton
V_L	Langmuir volume

Acronyms

AMDB	Abandoned Mine Database
BHP	Bottom hole pressure
CO_2e	Carbon Dioxide global warming equivalent
CBM	Coalbed Methane
CFD	Computational fluid dynamics
CMM	Coal Mine Methane
EIA	Energy Information Administration
GHG	Greenhouse gas
GRI	Gas Research Institute
IPCC	Intergovernmental Panel on Climate Change
MSHA	U.S. Mine Safety and Health Administration
P	Pressure
STP	Standard temperature and pressure
USBM	United States Bureau of Mines
U.S. EPA	United States Environmental Protection Agency
V	Volume

Conversion Factors

1 million m^3 = 35.315 mmcf
1 tonne CO_2e = 2.483 Mcf CH_4
1 kPa = 0.145 psi
1 m^3/tonne = 32.04 scf/t gas storage
1 mcf CH_4 = 0.0001926 Gg CH_4

EXECUTIVE SUMMARY

Coal mine methane (CMM) emissions are one of the major sources of anthropogenic methane emissions in the U.S., accounting for approximately 10 percent of total emissions. Current CMM emission estimates, however, only include emissions from active, or working, mines and do not account for methane vented from abandoned mines. The United States Environmental Protection Agency (EPA) has recently completed an effort to quantify abandoned underground mine methane (AMM) emissions both to improve the accuracy of the CMM emissions inventory and to assess mitigation opportunities. According to these estimates, detailed in this report, AMM emissions increased total U.S. coalmine methane emissions by about 13 billion cubic feet (Bcf) in 2002, or about 5% of total U.S. CMM emissions.

U.S. EPA prepares an annual inventory to identify and quantify the country's anthropogenic sources and sinks of greenhouse gas emissions. In addition to fulfilling its commitment to the United Nations Framework Convention on Climate Change (UNFCCC) to publish and make available a national inventory of greenhouse gas emissions, the U.S. develops the inventory because systematically and consistently estimating national and international emissions is a prerequisite for accounting for reductions and evaluating mitigation strategies.

Thousands of closed coal mines in the United States and other countries continue to emit methane, contributing to the total greenhouse gas emissions from coal mining. The unique features of abandoned mines, however, require a separate emissions estimation methodology from that employed for operating mines. To date, the coal mine methane (CMM) emission inventory is limited to operating (active) mines, in part because the Intergovernmental Panel on Climate Change (IPCC) has not provided guidance on how to quantify emissions from abandoned mines. This report proposes a credible methodology for determining methane emissions from abandoned underground coal mines and uses this methodology to quantify methane emissions from abandoned U.S. mines for each year from 1990 through 2002.

The method outlined in this report is consistent with the "Tier 2" approach for estimating emissions from active mines as described in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1997). Under this approach, data availability dictates whether emissions estimates are based on a country- or basin-specific method. This method consists of five steps, as described below:

- Step 1: **Create a database on abandoned gassy mines.** Based on an analysis of methane emissions at operating mines, 98% of all CMM emissions come from mines that emit more than 100 mcfd (thousand cubic feet per day). Assuming that emissions profiles for abandoned mines are correlated to their emissions during active mining operations, EPA compiled a database containing information on 374 abandoned coal mines that produced emissions greater than 100 mcfd when they were active. The database includes the name, location, coal basin, date of abandonment, emission rate at closure, and status (venting, flooded, sealed, or unknown status) of each mine. For mines closing since 1990, the emission rate includes both ventilation emissions and emissions from degasification systems.

- Step 2: **Identify the factors affecting methane emissions and develop coal basin-specific decline curves.** Several important factors impact mine methane emissions, including the gas content of the coal, flow capacity in the coal seam and the mine void, and the time since abandonment. The latter is especially important because gas emissions decline significantly following closure and level off over time. Coal basin-specific geological data and coal mine-specific emission data were used to develop input parameters for a numerical model. Decline curves were then used to forecast abandoned mine methane emissions as a function of time since the mine was abandoned, given the characteristics of a specific coal basin.

- Step 3: **Calibrate through field measurements.** Field measurements are an important tool used to verify whether theoretical calculations accurately reflect actual emissions from abandoned mines. A series of field measurements were conducted at seven abandoned mines across the country. The goal of the field study was to determine the measurement interval and duration necessary to accurately predict average methane emission rates from a mine vent. The field measurements were also used to test the accuracy of the basin-specific decline curves. Measurements from a previous EPA study (Kirchgessner, 2001) of abandoned mine vents at 21 mines were used to validate these results.

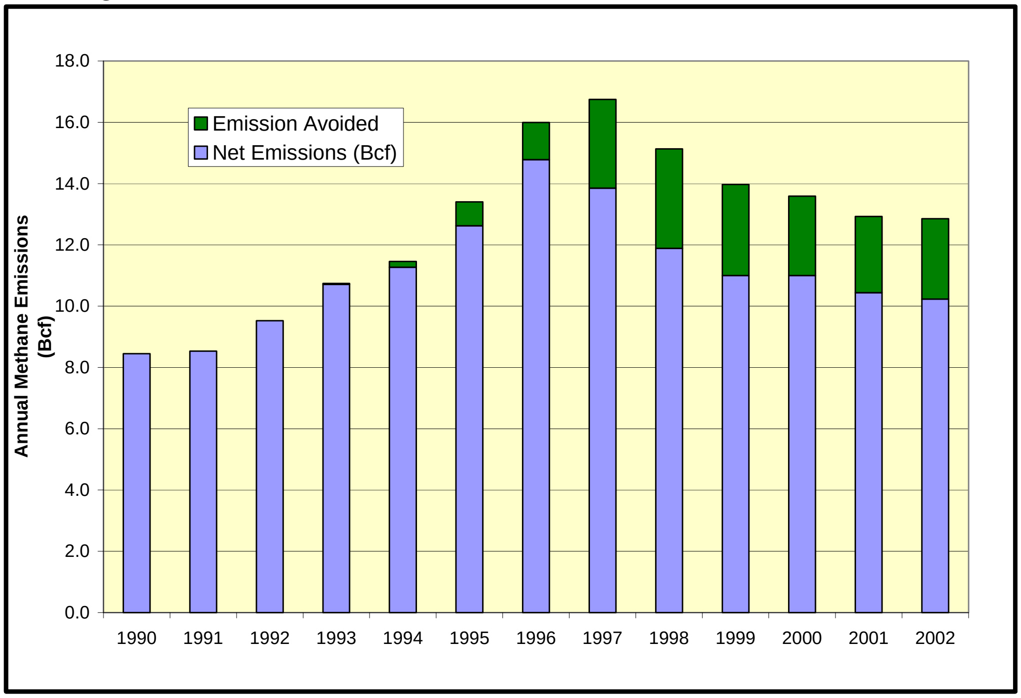
- Step 4: **Calculate a national emissions inventory for each year.** Once decline curves were developed, emission estimates of each mine were calculated according to their status: venting, flooded, sealed, or unknown. To arrive at a total abandoned mine emission inventory in a given year, Monte Carlo simulations were used to sum the probability distributions for the mines within each basin, and then to sum the emission distributions for the basins.

- Step 5: **Adjust for methane recovery and determine the net total emissions.** Methane recovery projects are known to exist at about 20 abandoned mines in the US. The quantity of gas recovered and used at the abandoned mine projects is subtracted from the total emissions to determine the net total emissions.

Employing this methodology, abandoned mine emissions for 1990 were estimated to range from 6.9 to 10.1 billion cubic feet (Bcf), or 2.8 to 4.1 million tonnes CO_2 equivalent (CO_2e), with a best estimate of 8.4 Bcf or 3.4 million tonnes CO_2e. For the year 2002, additional contributions of emissions from 163 gassy mines that closed between 1991-2002, increases the range of emissions estimates to 10.9 to 14.7 Bcf (4.4 to 5.9 million tonnes CO_2e), with a best estimate of 12.8 Bcf (5.2 million tonnes CO_2e). However, mine methane recovery projects reduce abandoned mine methane emissions by approximately 2.6 Bcf (1.0 million tonnes CO_2e), bringing the net emissions for 2002 to approximately 10.2 Bcf (4.1 million tonnes CO_2e). **Figure 1** shows the estimated annual abandoned coal mine methane emissions for 1990 - 2002, including emissions avoided due to methane recovery projects.

This methodology and the calculated emissions estimates are based on the best available data. At a 95% confidence interval, the current level of uncertainty is approximately $\pm$ 20%. This uncertainty range accounts for four important areas of uncertainty that could significantly impact the emissions inventory calculations: limited data on mines closed before 1972, biases in the U.S. mine ventilation data, no data on mine drainage before 1990, and exclusion of surface mine emissions. There are also important uncertainties associated with poor data availability for coal permeability, the condition of abandoned mines (whether sealed or flooded), and, where applicable, the effectiveness of mine seals.

Figure 1. Abandoned Mine Methane Emissions Estimates, 1990-2002



The methodology and emission estimates presented in this report are a first attempt to quantify emissions from abandoned coal mines in the U.S. EPA will continue to refine the methodology to quantify abandoned mine emissions with greater certainty. Some important next steps include:

- Identifying all abandoned mine methane recovery projects in the U.S. that operated from 1990 to the present and obtaining data on emission reductions;
- Obtaining more field data to verify methodological results and to serve as the basis for refinements to the methodology;
- Developing methodologies to set baselines and calculate emissions avoided on a project-specific basis; and
- Incorporating the abandoned mine emissions into the U.S. *Inventory of Greenhouse Gas Emissions and Sinks*.

1.0 Introduction

EPA prepares an annual inventory of its greenhouse gas (GHG) emissions to track U.S. progress in meeting its commitments under the United Nations Framework Convention on Climate Change (UNFCCC). Active coal mines, which account for nearly 10% of U.S. anthropogenic methane emissions, are included in the U.S. inventory. Coal mines release methane, a greenhouse gas over 20 times more potent than carbon dioxide, as a direct result of the coal mining process. In 2002, operating coal mines liberated 174 billion cubic feet (Bcf) of CMM. Of this amount, 44 Bcf was recovered, resulting in net emissions of 130 Bcf (53 million metric tons of carbon dioxide equivalents, or million tonnes CO_2e) from active mines (EPA, 2002).[1]

In the U.S., extensive data availability has facilitated the development of emissions estimates for active mines with a high degree of confidence. The location and operating status of the mines are known; vent air emissions are measured by the Mine Safety & Health Administration (MSHA) at least quarterly; and gas volumes sold are recorded by state tax authorities or oil and gas boards. In addition, many coal mining companies in the U.S. voluntarily cooperate with EPA to refine the methane emission estimates.

In contrast, quantifying emissions from thousands of abandoned mines across the country has proven much more challenging. For many of these mines, there are few if any data, especially for mines closed before 1972. Some of these abandoned mines continue to emit methane, contributing to total greenhouse gas emissions from the coal sector. EPA conducted this study to determine the magnitude of abandoned coal mine methane emissions and to assess the technical feasibility of including this source in the U.S. greenhouse gas emissions inventory. Consistent with the stated goals of the U.S. Greenhouse Gas Inventory, the purposes of this study are twofold: 1) to develop a credible methodology for determining methane emissions from abandoned underground coal mines, and 2) to quantify those emissions for each year from 1990 through 2002. The methodology developed in this report incorporates quantitative models with coal basin-specific parameters, calibrated with field measurements at several mines. These emission calculations were used in conjunction with a comprehensive database of U.S. mines abandoned since 1972 to generate an aggregate estimate of U.S. abandoned mine methane emissions for each year from 1990 to 2002.

1.1 Greenhouse Gas Inventory Guidelines and Practices

Current guidelines of the Intergovernmental Panel on Climate Change (IPCC, 1997) establish three different methodological levels (called "tiers") for estimating greenhouse gas emissions depending on the level of detail available. For coal mining, the three tiers are described as follows:

- Tier 1: the least accurate estimate; based on national coal production data and global average emission factors.

[1] 130 Bcf CH_4 = 130 x 10^9 ft^3 CH_4 x (0.04246 lb CH_4 / ft^3 CH_4) x (21 lb CO_2 / lb CH_4)(GWP) x (1 kg $C0_2$ / 2.2 lb CO_2) x (metric tonne/1000 kg) = 52.7 million metric tonnes CO_2 equivalent (CO_2e). Here, the factor of 21 lb CO_2 to 1 lb CH_4 reflects the global warming potential (GWP) of CH_4, which is 21 times greater than CO_2 on a mass basis over a 100 year time frame.

- Tier 2: a more detailed estimate; based on national average emission factors, or if more specific emission factors are available, on sub-national emission factors.
- Tier 3: the most detailed estimate; based on mine-specific emission measurements.

The methodology developed in this report is consistent with Tier 2 guidelines. Under this approach, emissions estimates can be based on country- or basin-specific methods, depending on data availability. In the U.S., data on the gas content of coal are readily available, both for entire coal basins and within each basin. To implement the Tier 2 approach, EPA examined emissions data from hundreds of gassy active mines, as well as a limited number of abandoned mines. Computer simulation of post-mining emissions, together with the available emissions data, produced basin-specific decline curves based on established mathematical equations for gas rate declines. Following general IPCC guidance, EPA relied on both statistical analysis and expert judgment to develop emissions factors for abandoned mine emissions in each U.S. coal basin.

1.2 Definition of an Abandoned Coal Mine

In order to avoid double counting or undercounting of emissions, it is important to clearly define the term "abandoned mine."[2] The Mine Safety & Health Administration (MSHA) classifications for inactive or non-producing mines are as follows:

1) *Non-Producing, Men Working:*	No coal being produced, but persons are maintaining equipment.
2) *No One Working, Temporarily Abandoned:*	Coal production has ceased, mine may reopen in near future.
3) *No One Working, Permanently Abandoned:*	Mine has been abandoned for more than 90 days.

Although the MSHA definitions are practical from an operational perspective, they are not as clear when defining mine emissions as active or abandoned. Often, a coal mine will stop producing coal (e.g., Category 2 above), but it will continue to operate ventilation fans for months or even years afterwards. During this time, the coal mine must report the methane emissions to MSHA as part of the *active* coal mine emissions inventory. Thus, it would be double-counting to include them as part of the *abandoned* coal mine emissions inventory. Taking this into account for this methodology, the term **"abandoned"** is defined for purposes of developing an emissions estimate as the time when active mine ventilation ceases.

1.3 Previous Attempts to Estimate Abandoned Mine Emissions

While the IPCC has recommended that emissions from abandoned mines be included in the GHG emissions inventory, it has not yet provided any methodological guidance on how to

[2] The Mine Safety & Health Administration (MSHA) catalogs information on individual mines using Federal Information Processing Standards (FIPS) codes. For coal mines, MSHA assigns both an operational and auxiliary status regarding mining activities; these codes are defined in the Code of Federal Regulations (30 CFR Part 50, User's Handbook).

calculate abandoned mine emissions, due in large part to the lack of reliable data (IPCC, 1997). EPA's earlier efforts to develop a methodology for abandoned mine emissions resulted in wide-ranging estimates, from 1 to 34 Bcf per year. In a separate EPA study on developing improved methane emission estimates at coal mining operations, 1995 abandoned mine emissions were estimated to be 7.4 Bcf, based on pre-abandonment data and vent pipe emissions measured at 21 abandoned underground coal mines in the Appalachian and Black Warrior basins (Kirchgessner et al., 2001).

1.4 Report Structure

The report outlines a logical approach for estimating CMM emissions. An overview of each major section is presented below.

Section 2.0 **Abandoned Mines as a Source of Methane Emissions**
This section describes the location of gassy underground mines in the U.S. and introduces readers to the factors affecting methane emissions from abandoned coal mines.

Section 3.0 **Coal Mine Methane Emissions Data**
This section describes the data sources for abandoned mines in the U.S., including data limitations, and summarizes these data.

Section 4.0 **Emissions Estimation**
This section outlines the quantitative procedures to estimate abandoned mine methane emissions. Because methane emissions at abandoned mines will decline over time, basin-specific decline curves were developed to calculate emission estimates for individual mines. These mine-specific emissions were then totaled to develop a national estimate. Because taking measurements at every abandoned mine is not practical, the proposed methodology incorporates a probabilistic analysis (Monte Carlo simulation) to develop a range of emissions estimates with a high degree of confidence.

Section 5.0 **Calibration Through Field Measurements**
This section describes the field measurements EPA undertook to validate the calculated estimates.

Section 6.0 **Estimating Emissions from Mines Closed Before 1972**
This section presents the results of EPA's efforts to gather data and quantify abandoned mine emissions from mines closed before 1972. Unfortunately, critical data are missing for mines closed prior to 1972, including the active mine emissions data, time of abandonment, number of gassy mines, and mine status. Therefore, this information was estimated based on extrapolations from physical, geologic and hydrologic constraints that apply to mines closed after 1972.

Section 7.0 **Results of the 1990-2002 Abandoned Mine Methane Emissions Inventory**
This section presents the estimates of total methane liberated from abandoned U.S. mines annually from 1990 through 2002. Net emission estimates include adjustments for mine methane recovery projects. This section also discusses the range of variability and uncertainty in the calculations.

Section 8.0 Conclusions

This section presents conclusions and proposed next steps to set a roadmap for possible future activities to improve these emissions estimates for abandoned mines, and to develop methodologies for project-specific baselines.

2.0 Abandoned Mines as a Source of Methane Emissions

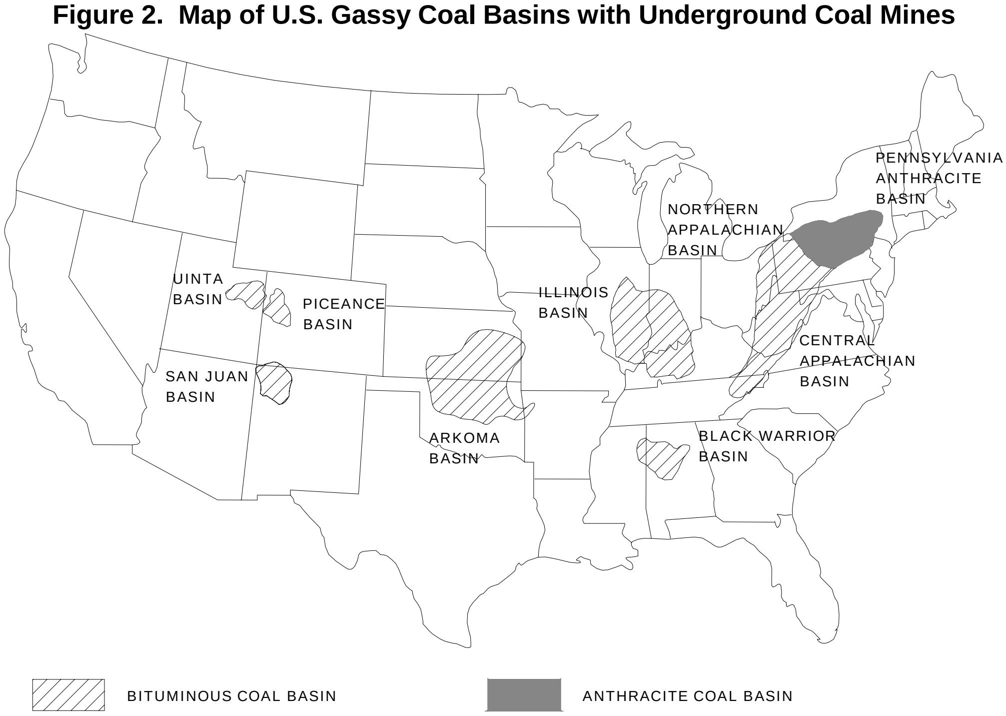
2.1 Overview of Coal Mine Methane

Coalbed methane is formed during coalification, the process that transforms plant material into coal. Organic matter accumulates in swamps as lush vegetation dies and decays. As this organic matter becomes more deeply buried, the temperature and pressure increase, subjecting the organic matter to extreme conditions that transform it into coal and methane, as well as byproducts including carbon dioxide, nitrogen, and water. As heat and pressure continue to increase, the carbon content ("rank") of the coal increases.

The methane trapped in coal seams is commonly referred to as coalbed methane (CBM) or coal seam gas. Generally, the deeper the coal seam and/or higher the coal rank, the higher the methane content. Coalbed methane is known as coal mine methane (CMM) when mining activity releases the methane, a potent greenhouse gas.

Not all coal seams are gassy (generally defined as mineable seams capable of producing more than 100 mcfd in coal mine ventilation emissions). In the U.S., gassy coals are located in the Appalachian Basins in the East, Black Warrior Basin in the South, the Illinois Basin in the Central U.S., and several western basins such as the San Juan and Powder River Basins. **Figure 2** shows the locations of gassy coal basins in the U.S.

Figure 2. Map of U.S. Gassy Coal Basins with Underground Coal Mines



2.1.1 Active Coal Mine Emissions

To ensure mine safety, active underground coal mines must remove methane from the mine using powerful ventilation systems. For particularly gassy mines, operators employ methane drainage systems to supplement their ventilation systems. In the U.S., these drainage systems consist of pre-mine vertical boreholes (drilled from the surface), in-mine horizontal boreholes drilled prior to mining, or vertical or in-mine gob wells.[3] The methane gas emitted through the ventilation and drainage systems is either released directly to the atmosphere or recovered and used.

2.1.2 Abandoned Coal Mine Emissions

As mines mature and coal seams are mined out, mines are closed and eventually abandoned. Often, mines may be sealed by filling shafts or portals with gravel and capping them with a concrete seal. Vent pipes and boreholes may be plugged in a similar manner to oil and gas wells.

As active mining stops, the mine's gas production decreases, but the methane liberation does not stop completely. Following an initial decline, abandoned mines can liberate methane at a near-steady rate over an extended period of time. The gas migrates up through conduits, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when methane migrates to the surface through cracks and fissures in the strata overlying the coal mine.

After they are abandoned, some mines may flood as a result of intrusion of groundwater or surface water into the void. Flooded mines typically produce gas for only a few years.

2.2 Factors Influencing Mine Methane Emissions

Within a coalbed, methane is stored both as a free gas in coal's pores and fractures, as well as on the coal surface through physical adsorption. As the partial pressure of methane in the fracture (cleat) system of the coal decreases, the methane desorbs from the coal and moves into the cleat system as free gas. The pressure differential between the cleat system and the open mine void[4] provides the energy to move the methane into the mine. Driven by this pressure differential between the gas in the mine and atmospheric pressure, the methane will eventually flow through existing conduits and will be emitted to the atmosphere.

Many factors can impact the rate of CMM emissions at both active and abandoned mines. The most important factor is the total gas (methane) content of the coal, which has been directly linked to methane emissions from mining activities (Grau, et al. 1981, EPA, 1990)

The time since abandonment is a critical factor affecting an abandoned mine's annual emissions, as the mine's emissions decline steeply as a function of time elapsed.[5] EPA has developed a decline curve, which describes the rate at which methane continues to desorb from

[3] A "gob" or "goaf" is the rubble zone formed by collapsed roof strata caused by the removal of coal.
[4] The mine void refers to the mined out area of the coal seam.
[5] The decline of CMM emissions begins with the cessation of coal production, although abandoned mine emissions officially begin only when active (forced) ventilation of the mine ceases.

the coal after abandonment, moves into the mine void, and is eventually released to the atmosphere. The decline curves are strong functions of time: the methane emissions rate decreases rapidly in the years immediately after a mine closure, and flattens out after several decades. The development of these decline curves is described in Section 4 of this report.

Other factors impacting the rate of methane emission include mine size, flooding, sealing, and the coal's permeability, porosity, and water saturation.

The remainder of this section discusses in greater detail several additional factors influencing abandoned mine emissions:

- Gas content and adsorption characteristics of coal
- Methane flow capacity of the mine
- Mine flooding
- Open (active) mine vents
- Mine seals

Each of these factors can impact methane emissions independent of the other factors, but in almost all cases several factors are important.

2.2.1 Gas Content and Adsorption Characteristics of Coal

Compared to many sedimentary rocks, coal beds have the capacity to store a large amount of methane gas.[6] Coal can hold a significant amount of methane in the adsorbed state because of the extensive internal surface area of the coal matrix (up to 250 square meters/gram, or 2.4 billion square feet per ton).[7] **Figure 3** illustrates the methane storage capacity of a middle rank coal compared with the storage capacity of a similar mass of (non-adsorbing) sandstone having a porosity of 15%. This figure illustrates that coal can contain significant quantities of methane even at very low pressures. The gas content of coal is generally expressed as standard cubic feet per short ton (scf/ton), or cubic meters per metric ton (m^3/tonne).[8]

This difference in storage capacity is due primarily to coal's internal pore structure. For example, porosity in sedimentary rock (e.g. sandstone and limestone) is mostly in the mesopore (20 to 500 angstroms) and macropore (>500 angstroms) range. In contrast, a significant fraction of the coal matrix is in the micropore range (<20 angstroms).[9] The methane content at a given temperature and pressure generally increases with coal rank because of the increase in the percentage of micropores and surface area available for methane adsorption (**Figure 4**).

[6] The quantity of gas that can be stored in the pore space of most sedimentary rock is a function of temperature and pressure as described by the real gas law.
[7] The density of the adsorbed methane is approximately its liquid density at atmospheric pressure boiling point (Yee et al., 1993).
[8] 32 scf/ton is approximately equal to 1 m^3/tonne.
[9] As coal increases in rank, the pore structure of the matrix changes. The percentage of the total matrix porosity in the micropore range increases with increasing rank from about 30% for a lignite to about 80% for an anthracite (Gan, et. al., 1972).

Figure 3. Comparison of methane storage capacity of sandstone and coal

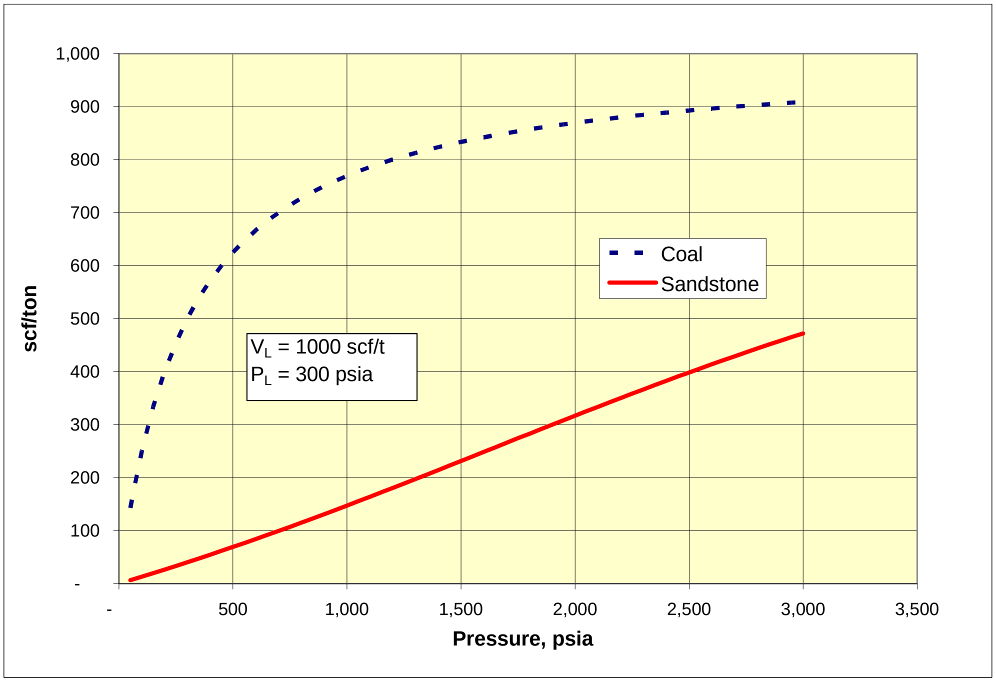
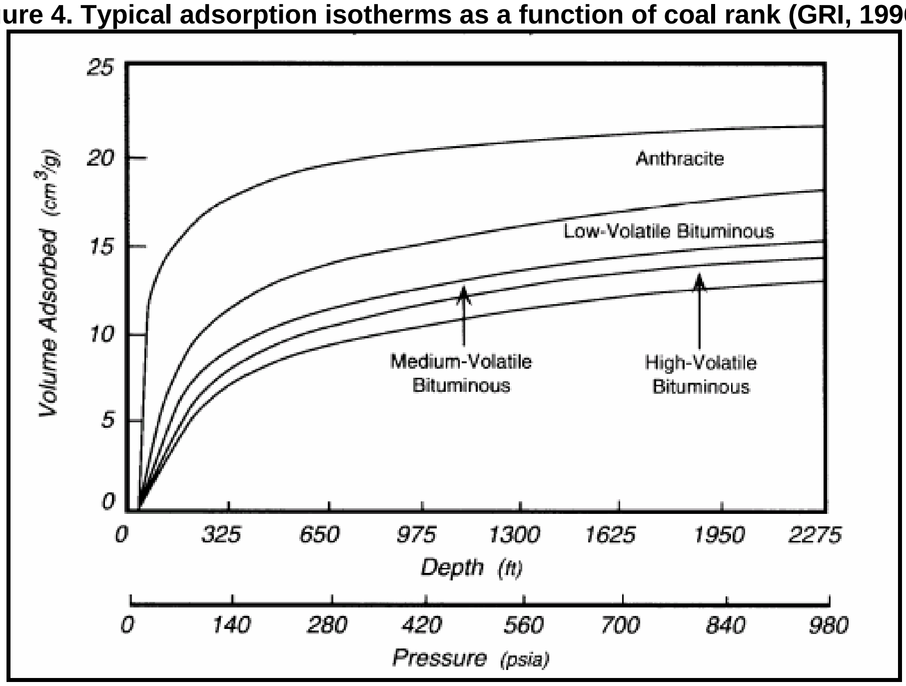


Figure 4. Typical adsorption isotherms as a function of coal rank (GRI, 1996)[10]



The curves shown in **Figure 4** are called adsorption isotherms because they are measured at a constant temperature.[11] Adsorption isotherms can be characterized by mathematical functions based on theoretical adsorption properties. One function commonly used for methane

[10] Depth indicated in Figure 4 is derived from the fresh water pressure gradient of 0.43 psi/ft (GRI, 1996).
[11] At constant pressure, increasing temperature decreases the amount of adsorbed methane.

adsorption on coal is called the Langmuir Isotherm, which is based on the ideal case of a single layer of molecules adsorbed on the coal surface.[12] The Langmuir isotherm is generally expressed as:

$$V = V_L P \;/\; (P + P_L) \qquad \textbf{(Equation 1)}$$

where:

V = Volume of methane at standard temperature and pressure per ton of coal, m^3/tonne (or scf/t)
V_L = Langmuir volume constant, m^3/tonne (or scf/t)
P = Pressure in the coal cleat system, kPa (or psia)
P_L = Langmuir pressure constant, kPa (or psia)

Both of the Langmuir constants V_L and P_L can be determined by fitting the function to experimental adsorption data. The Langmuir volume V_L represents the maximum storage capacity of the coal. The Langmuir pressure P_L is the pressure at which half of the Langmuir volume is achieved. The lower the Langmuir pressure for a given Langmuir volume, the more methane may be stored at lower pressures. The amount of gas stored at low pressures is important for predicting abandoned mine emissions, where there is lower pressure in the coal cleat (fracture) system due to depletion during active mining. The steeper the adsorption isotherm at low pressures, the more gas will adsorb or desorb per unit pressure change.

2.2.2 Methane flow capacity of the mine

Methane moves from within the microporous matrix of the coal to the macroporous structure and the cleat system via diffusion. This diffusion from the micropores into the cleat system is almost always fast enough that it is not the rate-limiting step for gas production from coal. Rather, the limiting factor is the ability of the gas to flow through the macropores and cleat system (Seidle and Arri, 1990).

Once the methane reaches the macropores and cleat system, it exists primarily in the free gas state. Here, its movement is determined by the laws of gas flow through porous media, such as Darcy's Law. For linear flow of an incompressible liquid, Darcy's law is of the form

$$q = (kA/\mu)(dp/dl) \qquad \textbf{(Equation 2)}$$

where:

q = volumetric rate in cm^3/sec
k = permeability in Darcys
A = the cross-sectional area perpendicular to flow in cm^2
μ = the viscosity of the fluid in centipoises
dp/dl = the change in pressure per unit length or pressure gradient in atm/cm

The form of Darcy's law must be modified for gases, for which both viscosity and volume are functions of pressure. Several key parameters for determining gas flow through a porous medium such as a coal mine include the following:

[12] The adsorbent refers to the solid surface; the adsorbate refers to the adsorbed gas.

- Permeability, k, a property of the porous media (coal) plays a major role in the rate at which gas can flow from the unmined coal into the void space of the abandoned mine. Unfortunately, measurements of the absolute permeability of coal are scarce.

- The area, A, across which gas moves from the unmined coal into the void space can be very large because of the large areas of exposed coal in an underground mine. Determining the coal's surface area in an abandoned mine is very difficult.

- The pressure gradient from the coal to the void space of the mine decreases over time as the gas is released and the pressure in the coal seam is reduced. As a result, the emissions rate from an abandoned mine decreases over time.

In an application related to coal mine methane production, gas production from oil and gas wells is predicted using Darcy's Law together with material balance equations. In this context, the well acts as a material sink whose rate of withdrawal (q) is a function of the difference between a specified pressure at the well, (P_w), and the pressure at some outside boundary of the gas reservoir (P_r). For a gas, this function takes the following form:

$$q = PI\,(P_w^2 - P_r^2)^n \qquad \textbf{(Equation 3)}$$

where:

q = volumetric rate of gas production
P_w = pressure at the well
P_r = pressure of the gas reservoir
PI = Productivity Index
n = empirically derived exponent[13]

By convention, flow from the reservoir to the well (q) is a negative value. **Equation 3** is essentially the same as **Equation 2**, modified for a gas and combining 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 into the PI term.

By analogy, the coal mine and its connection to the atmosphere (via the vent shaft or overburden fracture conduit) acts as the wellbore, and the unmined coal within and peripheral to the mine is the reservoir of the stored methane. The PI can be considered a constant at the low pressures involved in coal mining. The application of **Equation 3** to abandoned mine methane emission forecasting will be discussed later in this report.

2.2.3 Mine flooding

Over time, abandoned mines may partially or completely flood, which will decrease or completely shut off gas flowing into the mine. The inhibition of gas flow depends on the pressure balance between the gas within the coal and the water in the coal cleat system. Even if the gas phase is at a higher pressure than the water phase, the presence of water will substantially inhibit gas flow into the mine. As the water level rises in a mine, the gas flow will be reduced more rapidly than it would have otherwise, because as the coal cleat becomes re-saturated with water, its relative permeability to gas decreases. Thus, the presence of water in the coal cleat system decreases the apparent permeability of the coal seam.

[13] The exponent n accounts for turbulence and other non-ideal flow conditions (Slider, 1983).

Mine flooding plays a critical role in methane emissions from abandoned coal mines. For example, even if a coal mine contains a large quantity of methane and the coal is highly permeable, if the mine rapidly floods the total methane emitted will be far less than if the mine had remained dry.

2.2.4 Active vents

At some abandoned mines, vent pipes relieve the buildup of pressure resulting from desorption and flow of methane into the mine void. These vents are installed to prevent methane from migrating into surrounding strata. An abandoned mine with an open (or “active”) vent will behave very much like a natural gas well (at a much lower pressure regime).

Methane emissions from venting mines are a function of the pressure differential between the vent and the gas in the coal bed. The surface opening of the vent is at atmospheric pressure, while the gas within the unmined coal seam near the mine void will range from atmospheric pressure (14.7 psi, or 1.01 bars) to tens of psi (more than 1 bar) above atmospheric pressure.

Mines with open vents are known to "breathe" with atmospheric changes. In other words, the mines emit methane during times of low atmospheric pressure and pull air in during times of high atmospheric pressure. The effect of barometric pressure on measured vent emission rates is described in Section 5.2.

2.2.5 Mine seals

While many abandoned mines have active (open) vents, some mines are sealed in an attempt to prevent unauthorized access or the escape of methane gas. Even during active mining, seals are placed in worked-out areas of the mine to reduce fresh air ventilation requirements as a cost-saving measure. Old shafts and drifts are commonly plugged with cement.

It is common, however, for gas to leak out around these plugs or to make its way through fractures in the overlying strata. The seals are generally assumed to leak even at very low pressure differentials (e.g., a few tenths of a psi), and they typically degrade over time. Although mine seals can impact the rate of flow, they are not considered to be effective at preventing atmospheric methane emissions over time.

3.0 Coal Mine Methane Emissions Data

The first step in developing an emissions inventory is collecting information on abandoned mines. There are numerous abandoned mines in the United States, and it is impractical to visit, measure, and collect mine-specific data from individual mines. Thousands of U.S. coal mines that operated during the 20th century have since closed.[14] MSHA estimates that over 7,500 underground coal mines have been abandoned just since 1980 as a result of significant restructuring in the coal industry (U.S. Department of Labor, 2000). Throughout the 1990s, on average, 14 gassy mines were abandoned each year. Therefore, to estimate U.S. abandoned mine emissions with a reasonable degree of confidence for this study, EPA relied on historical emissions data, available MSHA databases, and information collected during field studies. EPA emissions estimates are also based on known characteristics of coal basins, including lithology, coal rank, coal depth, coal seam gas content, and hydrologic characteristics.

Emissions data for coal mines has been compiled only since 1971, originally by U.S. Bureau of Mines (USBM), and currently by MSHA. Thus, gathering historical information for abandoned mines in the U.S. is difficult for mines abandoned prior to 1972, for which very few data exist. EPA has developed a methodology to estimate emissions contributions from these older abandoned mines based on extrapolation from mines closed in and after 1972 (this methodology is described in detail in Section 6). The remainder of this section and Section 4.0 describe data sources and methodology for estimating emissions from mines abandoned in or after 1972.

3.1 Coal Mine Emissions Data

For mines abandoned in or after 1972, EPA compiled data from several key sources to characterize abandoned mines and their emissions. **Table 1** shows the data sources that EPA used to compile a database of gassy abandoned mines.

- **Mine Safety and Health Administration (MSHA).** The largest source of data assembled on abandoned mines is the MSHA Coal Mine Information System (MIS) Database, which contains information for over 7,500 coal mines abandoned since 1980, categorized on the basis of average daily emissions. The MSHA MIS database lists 98 mine closures during the 1980s for mines that had active emissions greater than 200 mcfd. Since 1990, MSHA has provided EPA with information on all coal mines with emissions greater than 100 mcfd.[15] One limitation of this data set is that it includes only ranges of emissions data, rather than more precise estimates.[16]

- **United States Bureau of Mines (USBM).** The USBM produced a series of five information circulars on coal mine emissions from 1971-1985. EPA used these reports to identify gassy

[14] Only a small portion of all US mines are gassy. In 2001, for example, approximately 125 of nearly 600 operating underground coal mines (20%) contained detectable methane levels in ventilation air and were considered gassy (methane emissions above 100,000 cubic feet per day). The percentage of gassy mines was much lower during the early- and mid-twentieth century, when most coal mining occurred in small shallower mines.

[15] Except for the years 1991 and 1992, when ventilation fan data were not collected.

[16] All mines reporting emissions greater than 200 mcfd were designated as one of three categories: 200 - 500 mcfd, 500-1,000 mcfd, or >1,000 mcfd.

active mines with emissions greater than 100 mcfd that closed during this period. Subsequently, EPA also used these data to establish average basin-specific emission rates for gassy mines. To estimate emissions from individual mines that closed during the 1980s, EPA extrapolated from the USBM information to determine basin-average emission rates for the mines with emissions greater than 1 mmcfd.

- **State agencies.** Some additional comprehensive mine opening and closure information was obtained through state mine and mineral agencies. Mine maps were available for some mines through coal mine operators and state geologic surveys.

Table 1. Data sources used to compile gassy abandoned coal mines database

Year	Data Source	Range of Vent Emissions	Degasification Data	Number of Mines
1971	USBM	> 100 mcfd	No	199
1973	USBM	> 100 mcfd	No	178
1975	USBM	> 100 mcfd	No	196
1980	USBM	> 100 mcfd	No	200
1985	USBM (partial list)	> 100 mcfd	No	85
1980 –1990	MSHA MIS Database	> 200 mcfd	No	98
1990 – 2002 (excluding ’91 & ’92)	MSHA Quarterly Reports	> 100 mcfd	Yes	95 - 182

EPA used these data sets to compile a list of abandoned gassy mines that constitute the vast majority of abandoned mine emissions. This was a multiple step process:

1. First, EPA was able to establish a national profile of abandoned active mines. The 1997 MSHA mine methane emissions dataset consisted of all (586) active coal mines with detectable emissions, not just mines with emissions greater than 100 mcfd. Based on these 1997 active mine data, EPA determined that mines emitting greater than 100 mcfd comprised 98% of emissions for all mines with reportable emissions (EPA, 2002). The USBM data showed similar results for the 1970s.

2. EPA used an analogous assumption that the profile of abandoned mines is substantially similar to the profile of active mine emissions: that is, that 98% of abandoned mine emissions come from mines that produced 98% of their emissions when they were active. In other words, mines that emitted more than 100 mcfd when they were active will contribute more than 98% of the total abandoned mine emissions when they are closed.

3. EPA determined which abandoned mines constitute a representative sample population of abandoned mines. 393 mines that were abandoned between 1972 and 2002 produced emissions greater than 100 mcfd when they were active (**Table 2**). Analogous to the known distribution of active mine methane emissions, these 393 abandoned mines are assumed to account for 98% of all abandoned mine emissions. Thus, these mines constitute the sample population used as the basis for estimating methane emissions from all abandoned mines in the U.S..

Table 2. Abandoned Coal Mines by Basin

Coal Basin	Total No. of Abandoned Coal Mines	Coal Mines That Had Active Emissions >100 mcfd (Years 1972 – 2002)	Gassy Mines as a % of Total Mines
Central Appalachian	6075	178	2.9
Northern Appalachian	834	101	12.1
Penn. Anthracite	312	0	0.0
Illinois	100	64	64.0
Black Warrior	68	14	17.9
Piceance	28	14	50.0
Uinta	28	15	54.0
San Juan	2	0	0.0
Other	135	8	6.0
Total	**7582**	**393**	**5.0**
From 2002 MSHA Data base			

3. 2 Mine status information

Additional mine-specific information was collected on each of the targeted mines from state and federal regulatory agencies and from the mine operators where possible. Information collected included:

- Mine-specific maps
- Mined-out acreage
- Locations of vents and shafts
- Degree of flooding
- Status of mine (e.g., sealed or venting to the atmosphere)

Table 3 shows the status of the 393 gassy abandoned mines in the database.[17] The entire list of 393 coal mines in the database can be found in **Appendix A,** including the status of the mine (if known), the date of abandonment, emissions at abandonment, and coal basin. Of the 393 mines, 244 (62%) of these abandoned mines were classified 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).

The status of the remaining 149 mines (38%) is unknown. These "unknown" mines were classified into one of these three categories by generalizing on the basis of other mines in a given coal basin, using a probability distribution analysis. For example, in the Black Warrior basin, 92% of the mines are known to flood once they are abandoned, but only 21% of the mines in the Northern Appalachian basin do so (**Table 3**). As a result, one would expect a larger

[17] Information regarding the status of abandoned mines was obtained from state government agencies in ten states (**Appendix B).**

percentage of the abandoned mines in the Black Warrior basin to be flooded compared with abandoned mines in the Northern Appalachian basin.

Table 3. Status of Abandoned Mines in U.S. Database

Basin	Sealed (% of Known)	Vented (% of Known)	Flooded (% of Known)	Total Known	Unknown Status	Total Mines
Central Appalachia	24 (25%)	25 (26%)	48 (49%)	97 (54%)	83 (46%)	180
Illinois Basin	18 (55%)	3 (9%)	12 (36%)	33 (52%)	31 (48%)	64
Northern Appalachia	36 (49%)	23 (31%)	15 (20%)	74 (74%)	26 (26%)	100
Warrior Basin	1 (8%)	0 (0%)	12 (92%)	13 (93%)	1 (7%)	14
Western Basins	20 (74%)	5 (19%)	2 (7%)	27 (77%)	8 (23%)	35
Total	**99 (43%)**	**56 (16%)**	**89 (42%)**	**244 (62%)**	**149 (38%)**	**393**

Data on adsorption isotherms, gas content, flow capacity and abandonment status are not available for all of the 374 gassy U.S. underground coal mines known to be abandoned since 1972. However, the methane ventilation rate before abandonment and the date of abandonment are available for the post-1971 abandoned mines. Mine degasification data are available from 1990 to present. Several adsorption isotherms for the most commonly mined coals in each coal basin are documented (Masemore, et al., 1996), as described below in Section 4.4.1.

4.0 Emissions Estimation

4.1 Overview

Once the database of abandoned mines is compiled, it is possible to calculate emissions based on the factors described in Section 2.2. **Figure 5** illustrates the steps involved in the calculation procedure.

As Figure 5 indicates, the template for calculating abandoned mine methane emissions is based primarily on the status of the mine, whether flooded, vented, sealed, or unknown. Emissions calculations for each type follow a similar sequence of steps.

- **Vented mines.** Closed mines are often intentionally left vented to the atmosphere to allow methane to escape and prevent the dangerous or explosive buildup of methane underground. Even after active ventilation measures (such as fans) cease and the mine is officially abandoned, the open access to the atmosphere impacts the mine's methane emissions. To estimate emissions from abandoned vented mines, this methodology uses basin-specific decline curves to develop low, mid-range, and high emission factors that are incorporated into probability distributions for annual emissions. The methodology for calculating emissions from vented mines is described in Section 4.6.1.

- **Flooded mines.** Abandoned mines frequently partially or completely fill with water from surrounding strata. The water impedes the escape of the methane in the coal seam, effectively trapping it. Emissions estimates for abandoned flooded mines are based on emission factors (low, medium, and high) that are incorporated into probability distributions for annual emissions. The methodology for calculating emissions from flooded mines is described in Section 4.6.2.

- **Sealed mines.** The efficiency of the seal impacts emissions from abandoned sealed mines. Emission factors are based on low, mid-range, and high emission factors for each seal type, which are incorporated into annual probability distributions. The methodology for calculating emissions from sealed mines is described in Section 4.6.3.

- **Unknown mines.** To estimate their emissions, abandoned mines of unknown status must be assigned a classification as vented, flooded, or sealed. This apportionment, based on the proportion of these types for abandoned mines that are known, is described in Section 4.7.1.

4.2 Forecasting Abandoned Mine Methane Emissions Using Decline Curves

The methane emission rate of a mine before abandonment is a function of the gas content of the coal, the rate of coal mining, and the flow capacity of the mine. In this respect, methane emissions from active mines are very similar to conventional gas wells, where the initial rate of a water-free conventional gas well reflects both the gas content of the producing formation and the productivity index of the well. Production from conventional gas wells as a function of time is commonly forecast using decline curve analysis. The physical basis for decline curve analysis and its application to abandoned mine emission forecasting are described below.

Existing data on abandoned mine emissions through time, although sparse, appear to fit a hyperbolic model of decline. For example, USBM measured daily emissions at the Cambria Mine in Pennsylvania[18] for over 3 years, including approximately 1.5 years after the gob area was sealed (Garcia et al., 1994). As shown in **Figure** 6**,** a hyperbolic decline equation matches this set of data with a correlation coefficient (R^2) equal to 0.88, indicating a statistically significant correlation.

An examination of **Equation 3** (page 13) reveals why methane emission rates from abandoned mines decline over time. As methane leaves the system, the reservoir pressure, P_r, declines as described by the isotherm. At the same time, both the mine pressure ($P_w \approx 1$ atm for vented mines) and the PI term are essentially constant at the pressures of interest (atmospheric to 30 psia). Thus, the flowrate q becomes smaller (q is defined as a negative number by convention).

Methane production from abandoned coal mines can be estimated based on the decline curve (Equation 3) used in conjunction with material balances. Fetkovitch et al. (1994) have generated a rate-time equation that can be used to predict future gas production. These authors combined the pseudosteady state flow equation (**Equation 3**) with a material balance equation that calculates the pressure loss as material is removed. The resulting expression for gas production as a function of time clearly shows that gas production declines in a hyperbolic fashion:

$$q = q_i(1+bD_it)^{(-1/b)} \qquad \textbf{(Equation 4)}$$

Where:

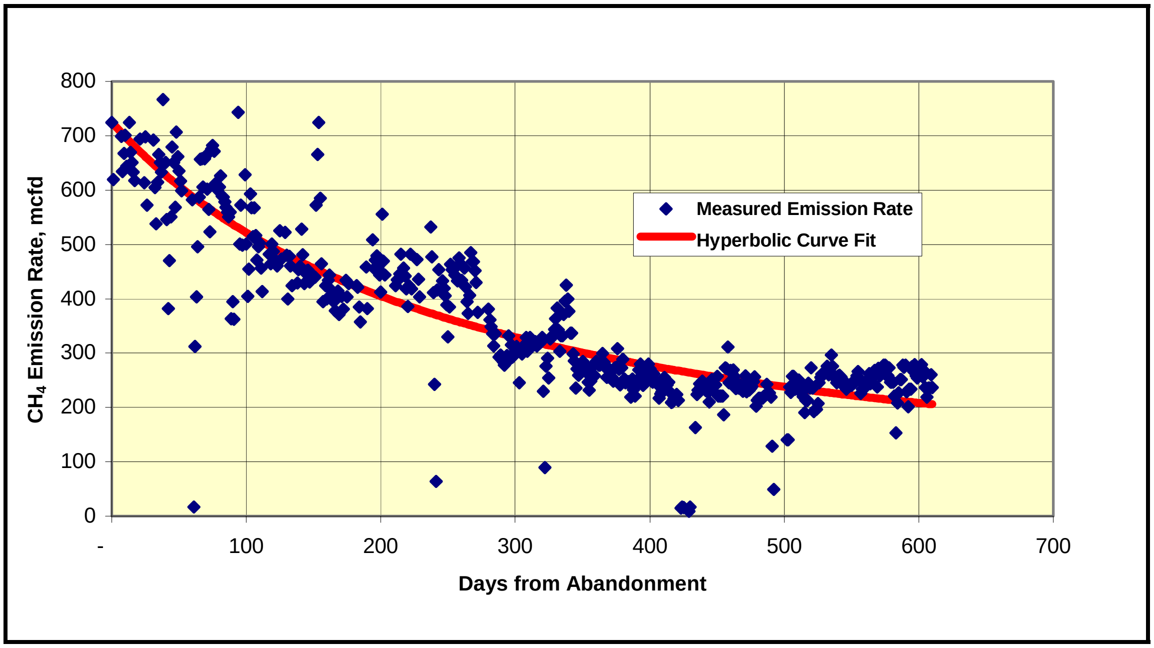
q = the gas rate at time t in mcf/d
q_i = the initial gas rate at time zero (t_o) in mcf/d
b = the hyperbolic exponent, dimensionless
D_i = the initial decline rate, 1/yr
t = elapsed time from t_o in years

The coefficients b and D_i can be determined by fitting **Equation 4** to measured rate data. Unfortunately, historical information on methane emission rates from abandoned mines is very rare. The only parameters in **Equation 4** that are readily available from the abandoned mine database are the emission rate at the time of abandonment (q_i) and the date of abandonment (t_o). The values for the coefficients D_i and b must be obtained in other ways. Once determined, **Equation 4** can be used to forecast future gas production. Several key parameters that affect the flow of methane from a mine, including flow capacity, pressure in the coal at abandonment, and the gas storage as a function of pressure (represented by the adsorption isotherm) are implicitly incorporated into this equation's coefficients.

[18] This particular well used a blower to maintain a constant low pressure on the wellhead, which accelerated gas production but did not affect the hyperbolic nature of the decline curve.

Figure 5. Methodology for Calculating Abandoned Mine Emissions

Figure 6. Cambria Mine gob well decline curve



4.3 Generating Dimensionless Decline Curves with Flow Simulation

To forecast methane emissions over time for a given mine, one must characterize the gas production of that mine as a function of time (e.g, a decline function), and initiated at the time of abandonment. To accomplish this, EPA has used a computational fluid dynamics (CFD) flow simulation model.[19]

To illustrate how a decline curve can be built with the CFD simulator, a conceptual model of a non-flooding, actively venting mine was built. The numerical model was configured such that the volume of the mined-out areas, or void volume, was 10% of the model bulk volume.[20] The remaining volume was coal in communication with the void volume. This coal represents both the coal remaining in the mined seam and unmined coal seams in communication with the void volume because of roof and floor fracturing and relaxation.

The model was configured to simulate a single component (methane), single-phase (gas) system for a period of 100 years. The model was initialized at 20 psia in the void with the outer boundaries acting as barriers to flow. The coal permeability was set at 1 millidarcy and the average adsorption isotherm for the Central Appalachian coal basin was used as the adsorbed methane storage function. The minimum pressure was limited to one atmosphere.

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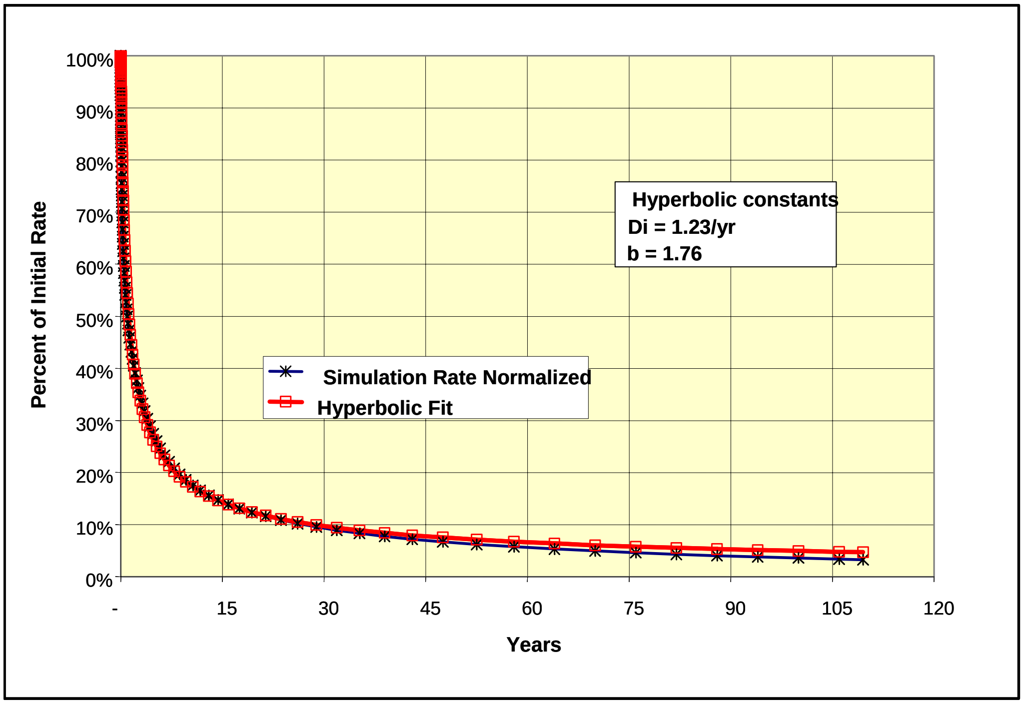
[19] CFD software uses the rate equations of gas flowing through a porous media (conservation of momentum) with material balance equations (conservation of mass) in combination with an initial pressure and boundary conditions that define the flow geometry.

[20] The 10% void volume value was based on a proprietary study of several abandoned mine complexes, which accounted for the volume of coal peripheral to the mine workings.

According to the idealized case in the model, the gas from the mine void depletes rapidly, reducing the methane pressure in the mine, which in turn allows desorption of methane from the coal. This methane then migrates to the void area where it is removed from the system. In generating the family of dimensionless emission decline curves, the conceptual model size was held constant and the methane flow capacity (PI in Equation 3) was modified by adjusting the permeability. Modifications of this procedure for flooded and sealed mines will be discussed in following sections.

Figure 7 shows the resulting methane production decline curve for a non-flooded, actively vented mine. This figure is normalized to the initial emission rate (q/q_i), which allows this curve to be applied to mines with differing initial emission rates, as long as they have similar initial pressures, permeability and adsorption isotherms. This figure is based on an isotherm for the Central Appalachian basin, a permeability of 1 md, and an initial pressure of 20 psia.

Figure 7. Dimensionless decline curve for non-flooded, actively venting abandoned mine



4.4 Data Availability and Uncertainty

Generating mine-specific methane production decline curves requires the estimation of several key parameters:

- Initial gas emission rate at time t_o
- The coal's adsorption isotherm
- Permeability (a measure of methane flow capacity)
- Mine pressure at abandonment

For mines abandoned during or after 1972, two key data are generally available: average methane emissions rate while mine was active, and the date of abandonment. The initial gas flow rate at time t_o (closure) can be estimated, by assuming it is approximately equal to the average methane liberation rate for each mine (ventilation plus drainage) while the mine was active.[21] Methane drainage information is available on a mine-specific basis since 1990.

To estimate mine-specific values for parameters such as coal adsorption isotherm coefficients, permeability, and pressure at time of abandonment, a probability distribution was generated based on the most likely value and the probable range of values for each parameter. This range of values is not meant to capture extreme values; rather, the probability distribution helps to select values that represent the highest and lowest quartile. Specifically, values are chosen at the ten-percentile and the ninety-percentile of the cumulative probability density function of the parameter. For example, 0.1, 1.0 and 10.0 md were selected as the low, mid and high values for permeability. This means that 10% of all coal permeability values are less than 0.1 md, and 90% are less than 10.0 md. Similarly, 50% of coal permeability values are expected to be above 1.0 md and 50% are below 1.0 md. Where measured data are lacking, values such as permeability are selected based on expert opinion.

Once the low, mid-range, and high values are selected, they are applied to a probability density function, using a Monte Carlo simulation to combine these distributions as either summations or products. This technique combines the statistical distribution of the data by randomly sampling values from each distribution, performing the mathematical operation, then repeating the task numerous times. The Monte Carlo simulation provides a rigorous approach to combining uncertainties expressed as probability distributions, but the calculated results ultimately depend on the adequacy of the underlying statistical model. The uncertainties associated with combining different probability distributions using Monte Carlo simulations are described in **Appendix C.**

4.4.1 Adsorption Isotherms

Masemore et al. (1996) compiled numerous adsorption isotherm parameters for each coal basin. **Table 4** lists the number of isotherms available by coal basin. Based on these datasets, ranges could be determined for the P_L and V_L parameters of the adsorption isotherms, using the low, mid and high values from the probability distribution. Average values of these isotherms are shown in **Figure 8**. **Figure 9** shows the adsorption isotherms for the Central Appalachian coal basin at the low-pressure range of interest.

Table 4. Adsorption isotherms available for each coal basin

Basin	Central Appalachia	Illinois	Northern Appalachia	Black Warrior	Western
# of Isotherms	11	4	22	16	41

[21] While the actual emission rate at the time of closure may be somewhat more accurate than average active mine emissions, these data are generally not available. Moreover, ventilation rates during a mine's final closure would represent the ventilation of only a small part of the mine where the final work is conducted, since presumably seals have already been installed throughout the mine workings.

Figure 8. Average methane adsorption isotherm for U.S. coal basins

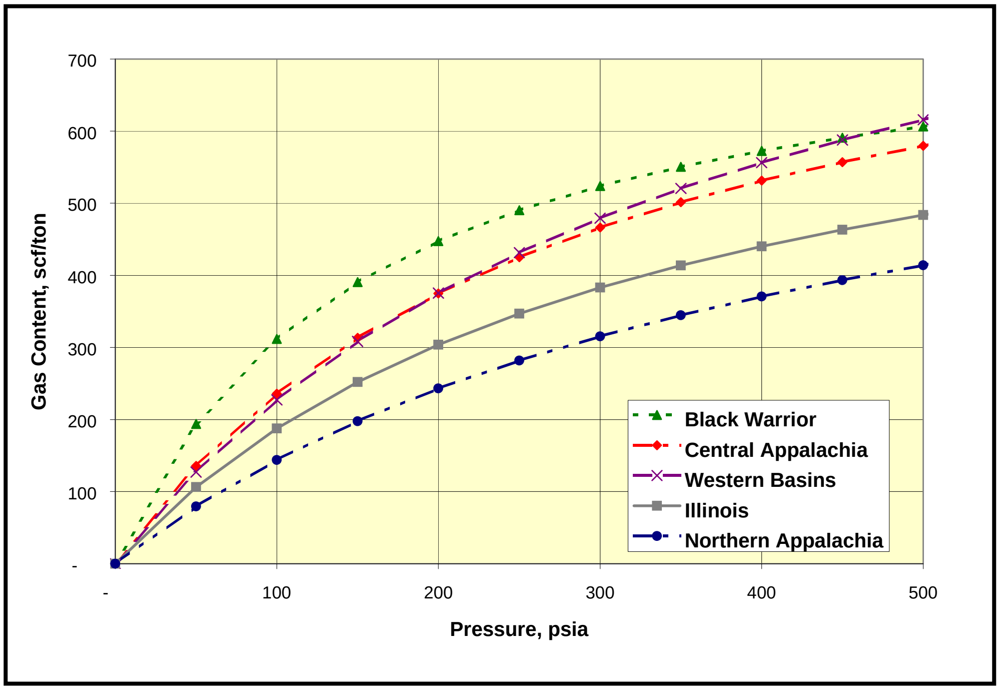
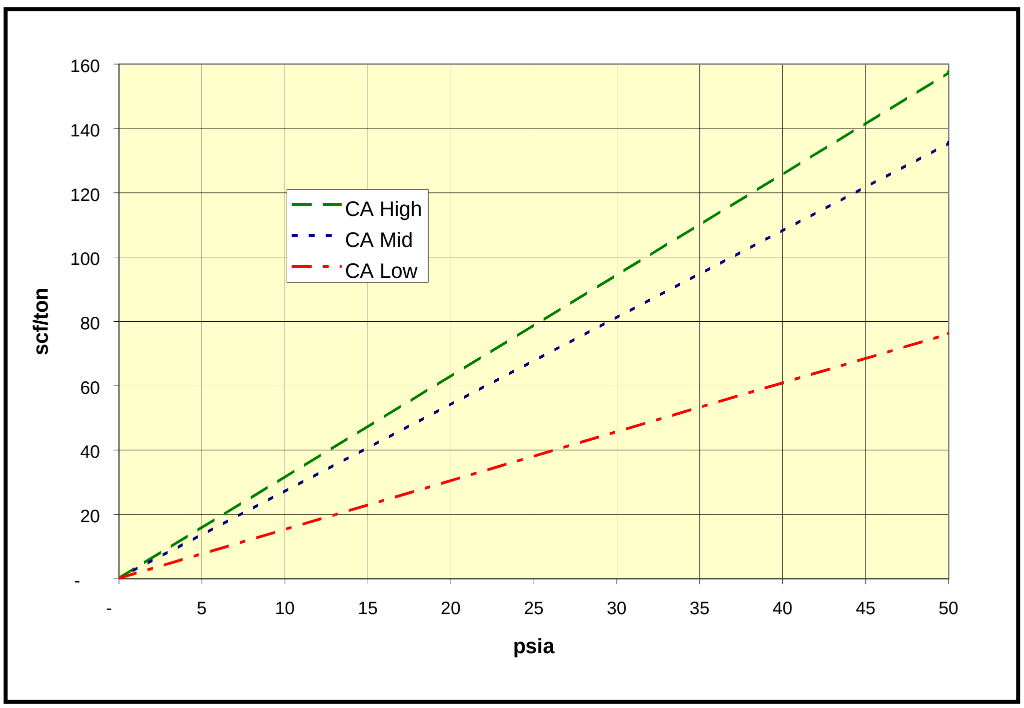


Figure 9. Methane adsorption as a function of mine pressure for the Central Appalachian Basin



4.4.2 Permeability

Coal permeability data are limited. The few data that are available generally come from borehole injection tests into unmined coal or from analysis of the production profile of coalbed methane wells. These data are generally proprietary; therefore, a range of permeability values was selected based on expert judgment. To ensure a sufficiently broad range for this parameter, the low and high values for permeability were selected to be 0.1 and 10.0 millidarcy (md), respectively with a mid case value of 1.0 md.

4.4.3 Pressure at abandonment

Mine pressure could be measured by closing a vent and allowing the void area to approach equilibrium with the pressure in the surrounding unmined coal. Unfortunately, no data have been published on the pressure within abandoned mines. Proprietary information on shut-in pressures measured at some abandoned mines, range from essentially atmospheric up to 27 psia. The impact of barometric pressure on abandoned mine methane emissions is described in **Appendix D.**

For this model, initial pressures of 17, 20, and 30 psia were used to represent the low, mid-range, and high values.

4.4.4 Initial Emissions Rates: Ventilation Air Emissions

Ventilation air methane emissions rates from active mines are used as in indicator of a mine's initial emission rate at time of abandonment. To calculate these initial rates, EPA used emissions data from underground ventilation systems from active mines, obtained from USBM and MSHA, based upon averages of quarterly instantaneous readings. The MSHA quarterly readings for ventilation emissions were assigned a probability distribution, which became the basis for the initial mine emissions rates used in this inventory.

Some errors are inherent in the measured ventilation emissions data. For example, a degree of imprecision is introduced into the readings because the measurements are not continuous. Mutmansky (2000) showed that individual mine emission measurements vary from ±10% to ±20%. Additionally, the measurement equipment used by MSHA introduced a bias of +2% to +16%, resulting in an average of 10% overestimation of annual methane emissions (Mutmansky and Wang, 2000). The combination of these two measurements and calculation methods result in the quarterly instantaneous readings ranging from 10% underestimated to 30% overestimated.

4.5 Sensitivity Analysis for Adsorption Isotherm, Permeability, and Pressure

A sensitivity analysis was performed to determine if the range of uncertainty for three parameters (adsorption isotherm, represented by V_L and P_L; permeability; and pressure at abandonment) is large enough to significantly affect the emissions inventory. If an individual parameter does not have a significant effect on the outcome, the mid-case value of the parameter can be used in the calculations. Conversely, if the sensitivity analysis indicates that the outcome is significantly affected by the parameter value, then three values of the parameter (high, medium, and low values) are input into a probability distribution.

Sensitivity analysis calculations are presented in **Appendix E**. For example, the 1990 emissions for the Central Appalachian basin are much more sensitive to permeability than to either initial pressure or the adsorption isotherm. Therefore, inventory calculations, use only mid-case values for initial pressure and the mid-case basin-specific isotherm, but include the range of values for permeability for the probabilistic analysis.

4.6 Annual Emission Estimations As a Function of Mine Status

Estimating emissions from an abandoned mine for any given year after its closure depends upon the status of the mine: whether it is open to the atmosphere through one or several vents, flooded, or partially sealed. Approaches for estimating emissions for each of these types of mines are described below.

4.6.1 Venting Mines

Emissions from a vented mine are calculated using **Equation 4** (page 19). Mine-specific values are input for the known elapsed time since closure, the average active mine emission rate, and three sets of decline constants for each basin (a low, mid and high case). These decline curves are based on the simulated decline curves (see **Figure 7**) that were generated using the average adsorption isotherm for the coal basin, an initial pressure of 20 psia, and permeability values of 0.1, 1.0 and 10.0 md. The calculated emission rates represent the low, mid and high values, with the low and high values representing an 80% range of certainty.

The time since abandonment is perhaps the most important determinant of mine emissions in the early years after closure because of the rapid rate of emissions decline.

4.6.2 Flooded Mines

Empirical observations suggest that methane emissions from flooded mines decline rapidly, and that the flooding process dominates the other factors affecting methane emissions. In fact, the very rapid methane emissions decline rate for flooded mines suggests that their contribution to long-term methane emissions will be insignificant.

Based on these considerations, no attempt was made to arrive at a theoretical model of this process; rather, this approach uses measured data to fit a decline curve equation. An exponential equation was developed from emissions data measured at eight abandoned mines, located in two of the five major U.S. coal basins, known to be filling with water. Using a least squares, curve-fitting algorithm, emissions data were matched to this exponential equation. There were not enough data to establish basin-specific equations, as was done with the vented and non-flooding mines. The following equation represents methane emissions from flooded mines as a function of time:

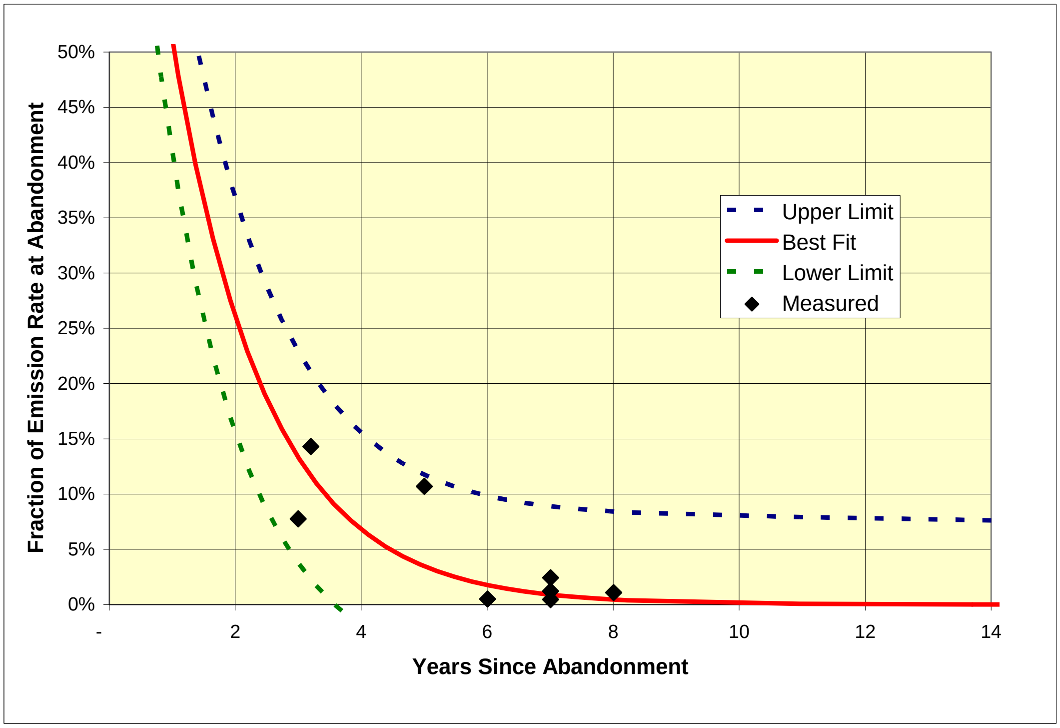
$$q = q_i e^{(-Dt)} \qquad \textbf{(Equation 5)}$$

where:

q = the gas flow rate at time t in mcf/d
q_i = the initial gas flow rate at time zero (t_o) in mcf/d
D = the decline rate, 1/yr
t = elapsed time from t_o in years

Figure 10 shows the normalized emission rate compared to the initial emission rate as a function of time since abandonment. The graph shows measured data from eight flooded mines, the best-fit curve for those data points (solid line), and the 95% confidence interval (dashed lines).

Figure 10. Emission model for abandoned flooding mines



4.6.3 Sealed Mines

Seals have an inhibiting effect on the rate of flow of methane into the atmosphere compared to open-vented mines. The total volume of methane emitted will be the same, but it will occur over a longer period. Accordingly, this methodology treats the emissions prediction from a sealed mine in a similar manner to emissions from a vented mine, but using a lower initial emissions rate that depends on the degree of sealing. The CFD simulator was again used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The degree of sealing, or the percent sealed (X_s), is defined by Equation 6:

$$\mathbf{X_s = 100 * (1 - q_{is} / q_i)} \qquad \textbf{(Equation 6)}$$

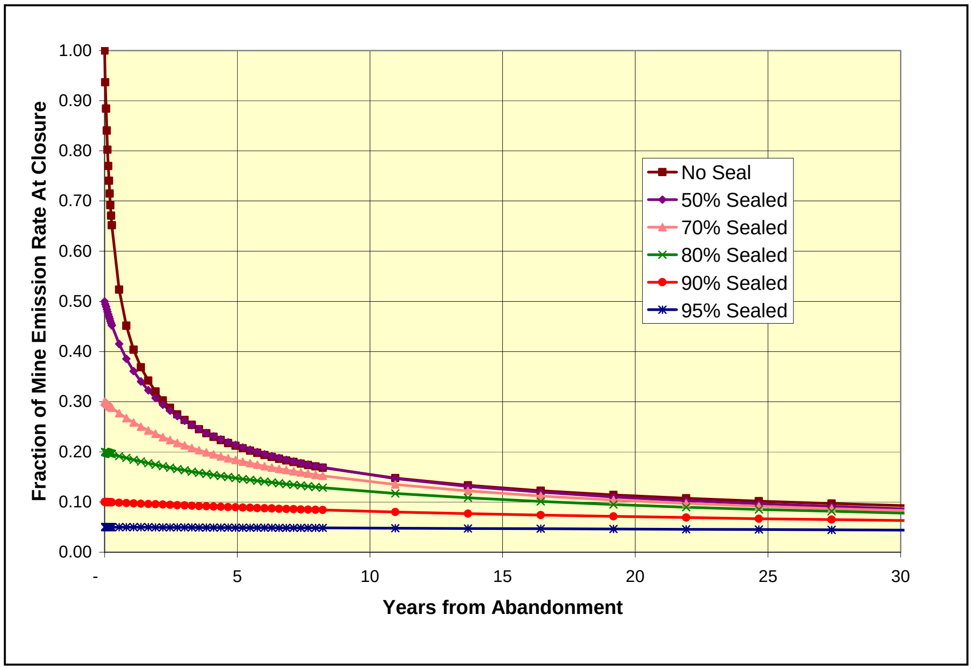
where:

q_{is} = initial emissions from abandoned mine at time t_o (after sealing)
q_i = emission rate at abandonment prior to sealing

Figure 11 shows a set of decline curves for several cases with different degrees of sealing for a mine in the Black Warrior Basin. The emission rates are normalized to the emission rate of the mine at the time of closure. This graph illustrates how the rate of decline decreases as the degree of sealing (percent sealed) increases.

Unfortunately, no measurements of diffuse emissions are available to calibrate the sealed mine emission rate calculations. Therefore, the decline curves shown in Figure 11 were used to select the high, mid-range, and low values for sealed mine emissions. As 11 illustrates, the difference in emission rates between an unsealed mine and a 50% sealed mine is insignificant after a year of closure. However, significant differences are seen in the fractional emission rates between cases for 50%, 80% and 95% closure achieved for sealed mines. Thus, these values were selected as the low, mid-range, and high range values for the extent of mine sealing, respectively.

Figure 11. Emission model for abandoned mines with different degrees of sealing



4.7 Calculating Annual Methane Emissions

To calculate annual methane emissions from abandoned mines, a spreadsheet workbook was developed for each inventory year, containing data for 364 gassy mines abandoned since 1972. These mines are estimated to account for 98% of abandoned mine emissions in those years. For mines of known condition, the emissions are calculated according to the methods described previously for each type (venting, flooded, or sealed). Probability distributions of total annual emissions for each mine are summed to provide yearly emissions classified by mine status, which are then aggregated to determine total annual emissions. Emissions for mines of unknown status are calculated and incorporated into the total annual emissions inventory as described below. Example calculations for each type of mine for the year 2000 are shown in **Appendix F.**

4.7.1 Mines of Unknown Status

To calculate emissions for mines whose status is unknown, it was assumed that the population of these unknown status mines is similar to the population of mines that are known to be sealed, venting, or flooded. That is, the percentage of sealed, venting, or flooded mines is assumed to be consistent for all the mines in a given basin. This assumption is reasonable because abandonment practices such as backfilling shafts and portals are uniform within a given state. In addition, the hydrogeology and flooding characteristics of mines are similar within most of the U.S. basins, although they can vary greatly in Central Appalachia.

Three probability density functions of the total emissions from these mines are calculated assuming that they are either venting, flooding, or sealed. The probability density function for each status type is then multiplied by the percentage of mines known to be vented, flooded or sealed within each basin. **Table 5** shows the percentage of each known status type for the year 2000 inventory.

Table 5. Distribution of (known) types of abandoned mines for year 2000

Basin	Sealed %	Venting %	Flooded %
Central Appalachia	25%	26%	49%
Illinois Basin	56%	6%	38%
Northern Appalachia	48%	32%	21%
Warrior Basin	8%	0%	92%
Western Basins	76%	16%	8%

4.7.2 Combining the known status and unknown status inventories

To arrive at a total abandoned mine emission inventory, the distributions from the known and unknown status mines are summed using Monte Carlo simulation. The distribution for the total basin value for the year 2000 inventory is shown in **Figure 12.** From the distributions for each basin, a probability table can be constructed, as shown in **Table 6.** The emission distributions of the individual basins were added together using Monte Carlo simulation to produce the probability distribution for the combined basins.[22] **Table 7** converts the emissions inventory for all abandoned mines in the U.S. from units of cubic feet of methane to metric tons of carbon dioxide equivalent (CO_2e).

[22] The mean of the total basin distribution will equal the sum of the mean of the basin distributions. The probability of the 2.5% values of all basins occurring is 0.025^5 = 1.0E-08, which is why the 2.5% value of the total distribution is greater than the sum of the 2.5% values of each basin. Accordingly, the 97.5% value of the total distribution is less than the sum of the 97.5% values of each zone.

Figure 12. Year 2000 emissions inventory: Total methane emissions from abandoned mines

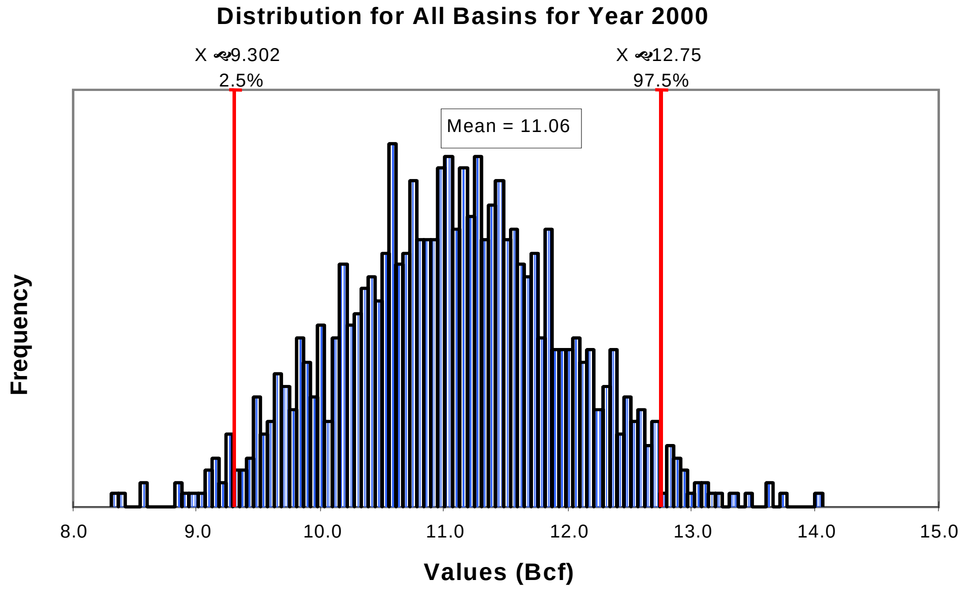


Table 6. Year 2000 abandoned mine emissions by coal basin, Bcf

Basin	2.5% Probability	50% Probability	97.5% Probability	Mean
Central Appalachia	3.2	4.5	5.8	**4.5**
Illinois Basin	0.70	1.0	1.4	**1.0**
Northern Appalachia	2.2	2.7	3.2	**2.7**
Warrior Basin	0.27	0.94	1.8	**0.97**
Western Basins	1.3	1.8	2.5	**1.9**
Total	**9.3**	**11.1**	**12.8**	**11.0**

Table 7. Year 2000 Abandoned Mine Methane Emissions, Tonnes of CO_2e

Basin	2.5% Probability	50% Probability	97.5% Probability	Mean
Central Appalachia	1,297,075	1,810,396	2,339,099	1,813,577
Illinois Basin	283,434	407,555	575,287	414,150
Northern Appalachia	872,747	1,087,689	1,297,761	1,087,483
Warrior Basin	110,154	376,608	723,240	390,591
Western Basins	530,668	745,404	1,008,743	751,990
Total	**3,748,640**	**4,456,451**	**5,139,777**	**4,457,789**

5.0 Calibration through Field Measurements

In developing abandoned mine emission estimates, field measurements serve two important roles. First, they provide empirical data for model inputs. One of the keys to estimating methane emissions from an abandoned mine is determining the *average* methane emissions rate from the mine in order to project future emissions rates. The field measurement program was designed to determine the measurement interval and duration necessary to accurately calculate an average methane emission rate from a mine vent. Second, field measurements verify whether theoretical calculations serve as a reliable proxy for real outcomes or events. In this case, field measurements tested the accuracy of the mathematical decline curves used for basin-specific emissions estimates.

Previously, EPA's Office of Research and Development (ORD) initiated a field research program in the early 1990s (Kirchgessner, et al., 2001), collecting data for 21 abandoned mines located throughout the Northern and Central Appalachian, Black Warrior, and Illinois basins. Seven of the mines that produced no methane were documented to be at least partially flooded. Of the 14 mines that were producing methane, seven were also documented to be at least partially flooded. This study was limited by the fact that only single or one-day measurements at each borehole or vent pipe were recorded, and the results were not normalized for average barometric pressure.

For the present study, EPA conducted a series of field measurements at abandoned mine vent locations across the U.S., with the goal of measuring actual methane emissions at a representative sample of mines with vent pipes. Vent pipes are the only feasible sites at an abandoned mine to accurately measure methane emissions. Of the 393 abandoned mines in the database, 55 (14%) are known to have vent pipes still in place. Unfortunately, limited access to the mines precluded measurement of all but seven mines.[23] Two of these seven mines were nearly flooded at the time of the study and produced little methane.

5.1 Field Measurement Methodology

Between November 1998 and February 2000, EPA recorded measurements at five unflooded abandoned mines to which the agency had access. Measurements were recorded at two abandoned mines located in Ohio and Virginia continuously for 6-12 hours. EPA also measured three additional mines located in Illinois and Colorado, recording measurements hourly for 3-4 days, normalizing them to average barometric pressures.

At the five abandoned mines where measurements were conducted, vane anemometers[24] and methane detectors were used to determine gas flow rates and concentrations, respectively. Several correction factors are necessary to convert anemometer flow and methane concentration measurements to standard methane emission values, to account for the blocking factor of the vanes and provide an empirical correction for the velocity profile.[25]

[23] EPA contacted mine operators and landowners that controlled over 50 of the candidate abandoned mines, but attained access to only seven mines.

[24] An anemometer measures the velocity of gas flow through a shaft or vent pipe of a known cross-sectional area.

[25] USBM conducted a series of measurements for pipes smaller than 12 inches in diameter (Garcia, et al., 1987). Based on their work, method factors for 4-, 6-, and 8-inch diameter pipes are 0.68, 0.71 and 0.78,

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

As part of this study, EPA monitored the effects of barometric pressure on mine venting, since atmospheric pressure can impact the rate of methane release from abandoned mines. Results of these measurements are shown in Appendix F.

5.2 Compilation of Data

Figure 13 shows EPA's measurements of abandoned mine methane emissions field data collected during the two studies (1991-2000). The emission rate decline curves are shown separately for each coal basin, with the dashed lines indicating the 10 and 90 percentile emission predictions. The solid lines indicate the 50% emission predictions. As these graphs illustrate, emission rates from nine of the ten abandoned mines that were measured fall very close to the predicted mid-case decline rate for their respective basins.

Of the seven flooded mines with no methane emissions investigated, five mines had been abandoned for less than 10 years, while the remaining two had been abandoned for over 15 years. Of the nine flooded mines that produced methane emissions, six (67%) fell within a 95% predictive confidence interval of the exponential equation defined in Equation 5 (also shown in **Figure 10**). These data suggest that most U.S. mines prone to flooding will become mostly flooded within 8 years and after 14 years no longer have any measurable methane emissions. Based on this assumption and until additional data can be collected, this methodology uses an average U.S. decline rate for all flooding mines.

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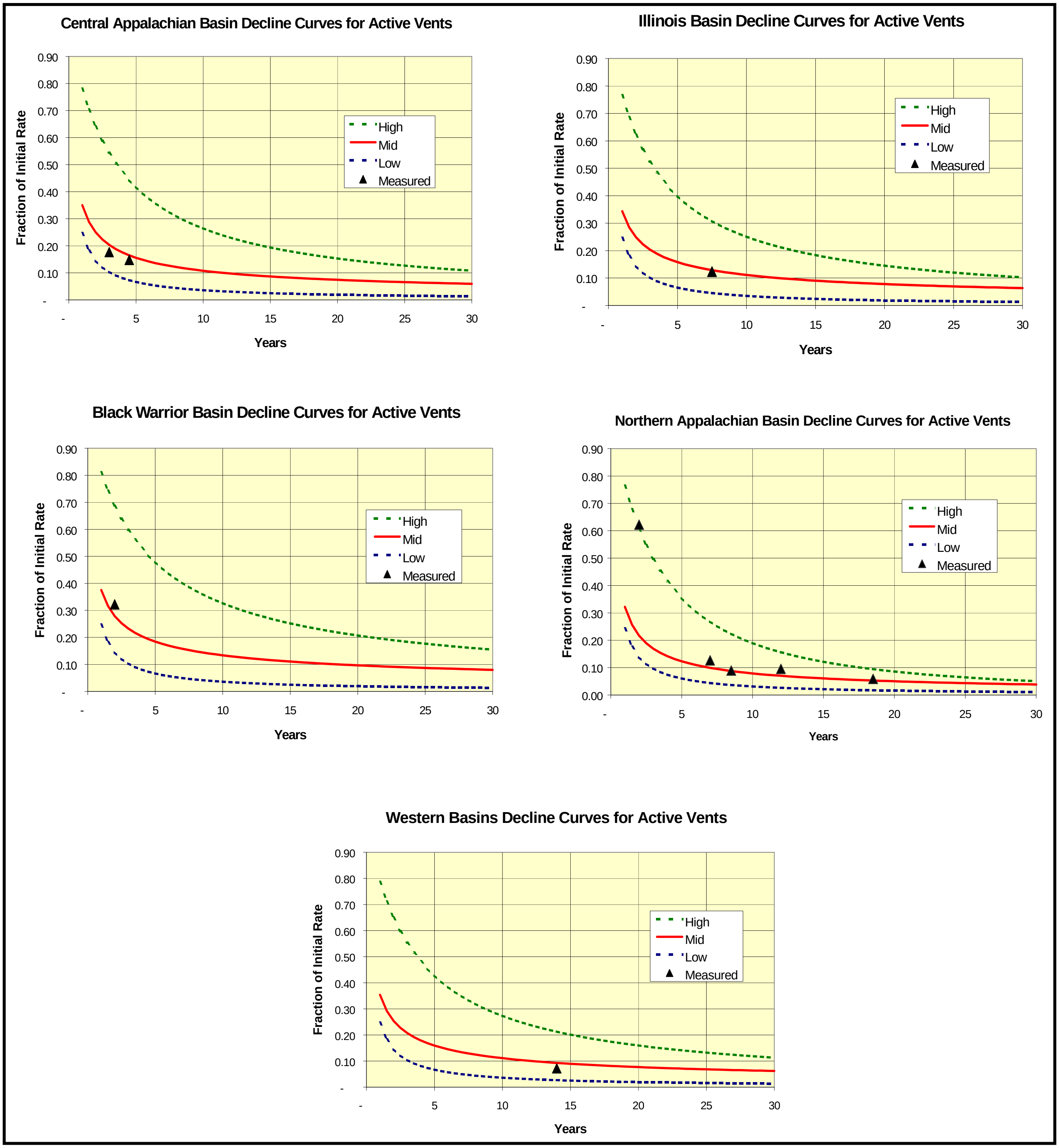
respectively. The National Coal Board of the United Kingdom had previously developed method factors for correcting vane anemometer measurements for 12 to 30 inch diameter pipes (Northover, 1957). Furthermore, results indicated that for pipes larger than 12 inches in diameter, a method factor of 0.85 is sufficient for conversion purposes.

Figure 13. Vented emissions from unflooded, abandoned mines in U.S. coal basins



6.0 Estimating Emissions from Mines Closed Before 1972

For mines abandoned in or after 1972, data are readily available, including comprehensive active mine emissions data, date of abandonment, number of gassy mines, mine status, and even coal production on a state and county basis. In contrast, most of the information needed to calculate emissions from abandoned mines is largely unknown for mines closed before 1972.

Emissions from the pre-1972 mines may be characterized using the dimensionless decline curves described in this report. Key data needed to use a modified version of the post-1971 methodology for the pre-1972 mines include the number of suspected gassy mine closures, the dates of closure, and the emissions rate at closure. For this report, EPA makes the reasonable assumption that pre-1972 mines are governed by the same physical, geologic and hydrologic constraints that apply to 1971, 1973, and 1975 coal mine datasets. The major reason for this is that most mining methods at that time were still room and pillar mining.

To extrapolate emissions estimates for mines abandoned before 1972, EPA compiled information from several USBM studies (1971, 1973, and 1975). In addition, EPA obtained statewide mine closure dates for Colorado and Illinois throughout the 20th century, and used this information for establishing national trends. EPA determined that most coal mine emissions in the U.S. originate in relatively small geographic areas. For example, during the 1970s, nearly 80% of CMM emissions came from seventeen counties in seven states.

Based on these data, EPA applied basin-specific decline curve equations to 145 gassy coal mines estimated to have closed between 1920 and 1971 in the U.S, representing 78% of the active mine emissions during that time. Mines abandoned before 1972 are estimated to have contributed 1.7 Bcf methane emissions to the 1990 abandoned mine emissions inventory.

6.1 Historical Trends in Gassy Mine Emissions

The gassy mine population in the U.S. is geographically limited to specific coal seams within a few coal basins. The population of gassy mines (those with emissions >100 mcfd) in the U.S. has remained stable since 1971, numbering between 100-200 mines. Based on several historical observations, it is reasonable to assume that there were fewer gassy mines during the early days of mining:

1) Historic trends in mine size indicate exponential growth in recent years. A USBM study has shown that the average mine size in 1985 was one half of those in 1995. Thus, extrapolating backward from this trend suggests that pre-1972 mine sizes would be much smaller than those in 1985 would.

2) Many of the gassy mines closed after 1972 had operated since early in the 20th century, particularly in the Pittsburgh coal seam, where the largest concentration of gassy mines in the U.S. is located.

3) Coal mines operating in coal seams at depths up to 2000 feet in Virginia (e.g., Pocahontas #3) and Alabama (Mary Lee), which produced a significant portion of the U.S. emissions in the 1970s, and even today, only began operating in the 1940s.

4) Prior to the 1970's, all underground mining in the U.S. was through room and pillar operations. Longwall production, associated with high gas production, was not introduced widely until the 1970s. These historic production trends created smaller mine voids that exposed less coal and other gassy strata, therefore probably emitting less gas.

5) Historical records indicate that prior to 1920, there were far fewer gassy coal mines (by current standards) operating at only a fraction of the production rates practiced after 1920.

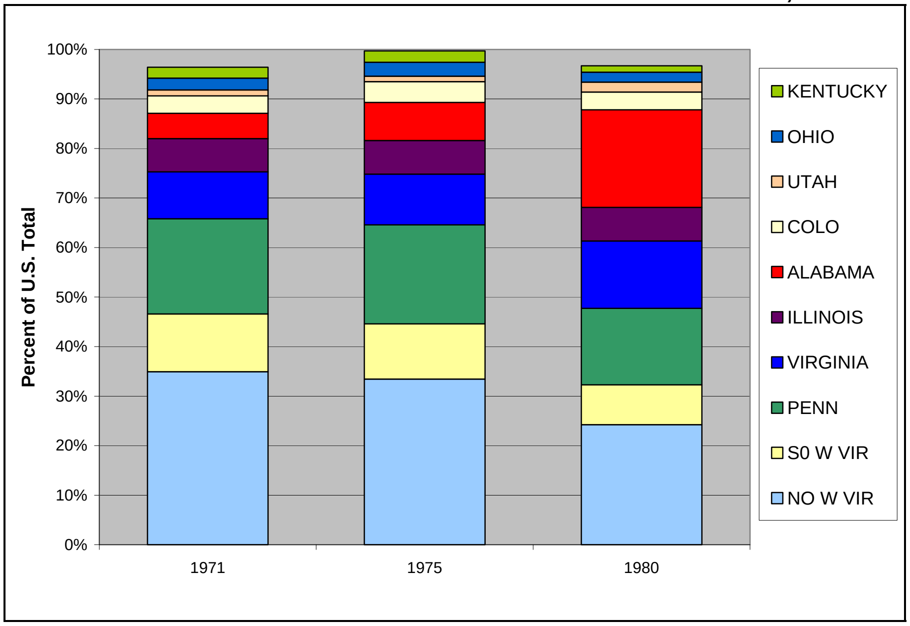
EPA estimates that emissions from mines closed before 1920 would emit less than 0.1 Bcf of methane during 1990, making it an insignificant contribution to the 1990 emissions inventory baseline. Thus, EPA's estimate of abandoned mine emissions in this inventory is based only on mines that were closed since 1920.

6.2 Estimating the Locations of Gassy Mines Abandoned Before 1972

The geographic distribution of active mine methane emissions during the 1970s is assumed to represent emissions from mines abandoned prior to 1972. The primary justification for this assumption is that the room and pillar mining methods used in 1971 were similar to those used in previous decades.

The oldest, most comprehensive dataset of underground coal mine emissions that EPA has found is a 1972 USBM Circular listing emissions for all mines in the U.S. (>100 mcfd) during 1971 (Irani, 1972). Emissions from these coal mines originated in 64 counties located in eleven states. Of these, the nine states shown in **Figure 14** made up 95 - 99% of the total methane emissions from active coal mines in 1971.

Figure 14. Active Coal Mine Methane Emissions from Nine States, 1971 – 1980



Seven states (Pennsylvania, West Virginia, Virginia, Alabama, Illinois, Colorado, and Utah) produced over 90% of the total U.S. active mine emissions from 1971-1980.

- The Northern Appalachian basin states were by far the largest contributors during the 1970s, emitting approximately 50% of all U.S. emissions. Pennsylvania and northern West Virginia are the principal representatives of the Northern Appalachian basin. .[26]

- Central Appalachian Basin states contributed approximately 25% of U.S. mining emissions during the 1970s. Southern West Virginia and Virginia are the principal contributors.[27]

- The next highest group of producing states, Illinois, Alabama, and Colorado, each contributed significantly to the U.S. total mining emissions.

- Utah and Colorado represent the Western Basins.

U.S. coal mine emissions are even more concentrated than these numbers suggest. 78% of all U.S. coal mine emissions originated from only 17 counties within seven states. Other counties each accounted for less than 1% of the national emissions. Because of the relatively high uncertainty associated with the pre-1972 data, identifying more mines would only reduce the uncertainty incrementally. Therefore, EPA used these 17 counties as a representative sample of coal mines in all five major U.S. coal basins that constituted the majority of coal production from gassy underground mines. Emissions from these 17 counties have been scaled to account for emissions from all U.S. mines.[28]

EPA compiled a list of 145 (suspected) gassy mines located in these 17 counties that had closed prior to 1972. **Table 8** lists the counties and the number of mines estimated to be in each county.[29]

[26] Emissions from abandoned mines in Ohio constitute 2% of the total emissions from this basin and are considered negligible in comparison.
[27] Kentucky mine emissions were only 2% of total emissions; Kentucky's emissions are divided between the Central Appalachian and Illinois Basins. Kentucky was therefore considered negligible in comparison.
[28] Since these mines represent 78% of the total emissions, they are multiplied by a scaling factor of 1.22 to account for all U.S. emissions.
[29] In Colorado, Utah, Illinois, Virginia, and Alabama, EPA obtained the information directly from state agencies or from old state publications. In fact, Colorado and Illinois had databases that included mine closure dates since the late 1800s. For Pennsylvania and West Virginia, the number of mines was estimated using maps showing all the mines that had once operated.

Table 8. Gassy Abandoned Mines Located in 17 Counties

County	State	Number of Mines
Franklin	IL	23
Pitkin	CO	18
Buchanan	VA	17
Raleigh	WV	15
McDowell	WV	12
Cambria	PA	12
Jefferson	AL	9
Washington	PA	9
Indiana	PA	7
Las Animas	CO	7
Marion	WV	4
Marshall	WV	3
Carbon	UT	3
Monongalia	WV	2
Greene	PA	2
Tuscaloosa	AL	1
Jefferson	IL	1
TOTAL		**145**

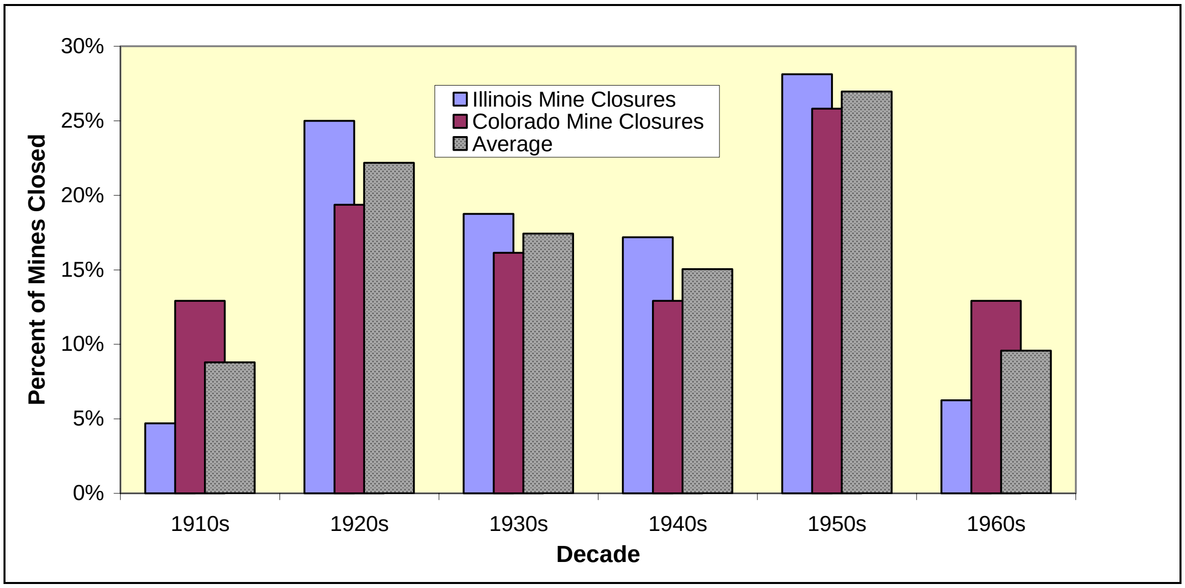
6.3 Estimating Date of Abandonment for Pre-1972 Mines

EPA was able to estimate the date of abandonment for mines closed prior to 1972 based on extrapolation from historical records of gassy mine closures. While researching historical coal mine information at the state level, EPA found that the states of Illinois and Colorado had compiled historical coal mine opening and closure dates for each county dating back to the late 1800s. From these data, a histogram was developed of Illinois and Colorado mine closures in counties known to have gassy mines. This subset of mines represents 34% of the total number of pre-1972, gassy mines and 30% of the total abandoned mine emissions.

As **Figure 15** illustrates, mine closures in the two states show consistent patterns since 1910, including an increased number of mine closures following World Wars I and II. Based on a reasonable assumption that mine closures in these two states followed national trends, EPA used the average to estimate the approximate closure dates (decade) for mines in all 17 counties. The mid-decade date (e.g. 6/30/1925) was selected as the nominal "closure date" for mines closed in a given decade.[30]

[30] This selection of mid-decadal closure has a minimal impact on the estimated emissions rate. For example, the incremental change in emission rates caused by adjusting the nominal closure date by up to 4 years will be less than 1% because of the extended time since abandonment (e.g., 20 to 70 years for the 1990 emissions inventory).

Figure 15. Mine Closures in Colorado and Illinois, 1910 – 1960



6.4 Estimating Initial Emission Rates for Pre-1972 Mines

Once the number of abandoned mines and their approximate closure dates have been established, the next step is to determine the mine's initial emission rate at the time of abandonment.

EPA conducted a statistical analysis of all the active mine emissions originating in the 17 counties for the years 1971, 1973, and 1975, based on data from the USBM circulars. The data were aggregated to the state level in order to use larger samples of mine data. [31] **Table 9** summarizes the distributions for the seven states.

There were three key steps in determining the distribution of initial methane emission rates:

1) 100 mcfd was defined as the minimum emissions rate.

2) The maximum emission rate for each state was based on the USBM data sets.

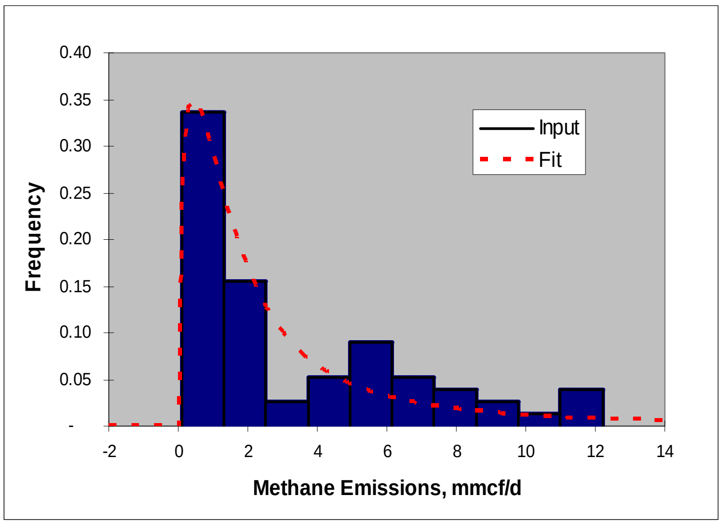
3) Distribution functions were fitted to the datasets to calculate the probability distribution of the statewide emission inventory. In most cases, the best fit was either a log-normal or an inverse Gaussian distribution; however, in some cases other distributions were found to be better fits. **Figure 16** illustrates a function that was fitted to the northern West Virginia dataset using a "log-logistic" distribution.

[31] West Virginia was divided into two "states" because its mines occur in two coal basins.

Table 9. Distributions of Methane Emissions from USBM Datasets from 1971-1975

STATE	AL	VA	S WV	UT	CO	IL	PA	N WV
Minimum Emission Rate (mmcfd)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Mean of Data Distribution (mmcfd)	1.0	1.1	0.6	0.4	1.0	0.7	1.0	2.6
Maximum Emission Rate (mmcfd)	6.1	8.5	5.0	1.9	3.5	2.4	6.0	12.2

Figure 16. Active mine emissions for northern West Virginia



6.5 Calculating Total Abandoned Mine Methane Emissions for Mines Closed Prior to 1972

The initial emission rate distributions for mines in these gassy counties were used as inputs for the post-1972 basin-specific decline equations. Emissions for each inventory year were calculated for mines closed during each of the five decades (1920s through 1960s) and then summed. Because it is unknown whether the mines are sealed or venting, a conservative approach assumes that the mines could still be venting.

Based upon the presumed similarity of hydrologic conditions for mines abandoned before and after 1972, a basin-specific factor was used to account for flooding. All mines abandoned prior to 1972 that had flooded would have been closed for at least 19 years by 1990 and, presumably, would have completely flooded out by then. To derive a net, or relative, emissions number, emissions were reduced by the percentage of flooding mines in each of the basins (summarized in **Table 3**).

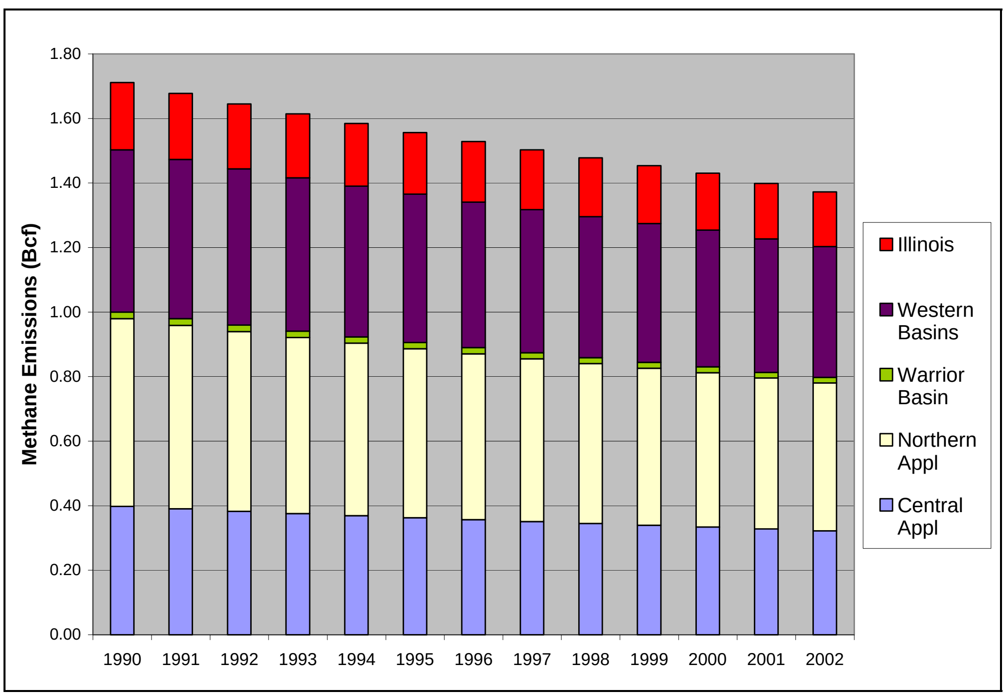
Table 10 shows the emissions contribution for all mines closed in each decade to the 1990 inventory of total abandoned mine emissions.

Table 10. Contribution of mines closed from 1920-1969 (by decade) to the 1990 inventory

Decade of mine closure	1920s	1930s	1940s	1950s	1960s	Total emissions from mines closed, 1920-1969
Mine methane emissions in 1990 (Bcf)	0.258	0.277	0.279	0.611	0.286	1.712
Relative contribution of pre-1970 closures to 1990 emissions inventory	15.1%	16.2%	16.3%	35.7%	16.7%	100.0%

The annual emissions inventory totals for 1990 – 2002 calculated in this report (Section 7) include emissions from the 145 mines abandoned prior to 1972. The pre-1972 mines contributed 1.7 Bcf (0.7 million tonnes CO_2e) to the 1990 emissions inventory (20% of the total), and declined to 1.4 Bcf (0.6 million tonnes CO_2e) by the year 2000 (10% of the total). **Figure 17** shows the emissions contribution for each coal basin from mines abandoned prior to 1972 for the 1990-2002 inventories The range of uncertainty associated with the pre-1972 emissions analysis is discussed in Section 7.4.

Figure 17. Emissions contribution from mines abandoned prior to 1972 to the 1990-2002 inventories



7.0 Results of the 1990 - 2002 Abandoned Mine Methane Emissions Inventory

7.1 1990 Baseline Inventory

For the 1990 baseline year, the abandoned mines emissions inventory was based on emissions from 145 suspected gassy mines that closed from 1920 – 1971 (estimated as described in the previous section) as well as 249 mines closed after 1972 that are known to have active mine methane ventilation emission rates greater than 100 mcfd at the time of abandonment.

As described previously, EPA used estimated initial emission rates (based on MSHA reports for post-1972 mines), time of abandonment, and basin-specific decline curves to calculate annual emissions for each mine in the database. Because coal mine degasification data is not available for years prior to 1990, the estimated initial emission rates reflect ventilation emissions only.

The gassy mines for which emissions were calculated are assumed to account for 98% of total national emissions. Therefore, to account for total post-1971 abandoned mine emissions, this estimate was multiplied by 1.02. EPA estimates that 1990 methane emissions from post-1971 U.S. abandoned coal mines range from 5.6 to 7.9 Bcf (2.3 to 3.2 million tonnes CO_2e), with a median value of 6.6 Bcf (2.7 million tonnes CO_2e) at the 95% confidence level.

7.2 Emissions for 1991-2002

To determine the post-1971 abandoned mine emissions for 1991 through 2002, EPA used several sources of information. Using MSHA data and EPA annual coal mine emissions inventory data, EPA identified and calculated the ventilation emissions and degasification volumes from 144 mines that were closed from 1991-2002 (**Figure 18**).[32] **Table 11** shows the number of gassy mines closed each year by coal basin.

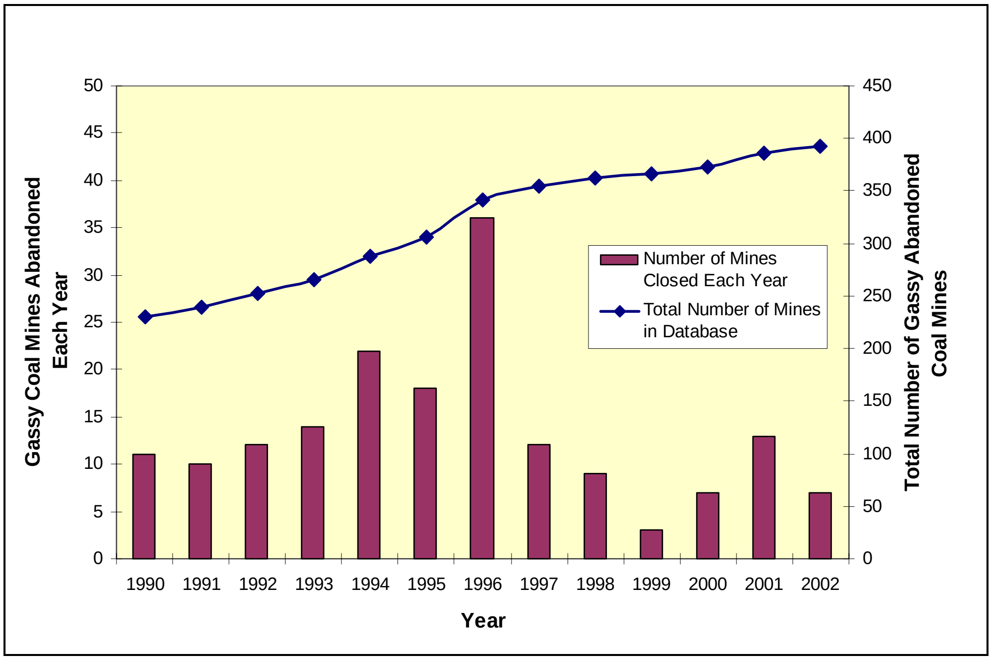
For nearly all mines closed between 1990 and 2002, the initial methane emission rate at time of abandonment reflects ventilation emissions only. However, for 14 mines that closed between 1992 and 2002, degasification data were available, so the initial emissions rate for these 14 mines includes the total methane liberation rate (ventilation plus degasification).

Table 11. Cumulative Number of Gassy Coal Mines Abandoned Annually, 1990 - 2002

Coal Basin	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Central Appalachian	105	108	114	119	131	143	157	162	164	166	168	176	180
Illinois Basin	35	37	38	40	44	47	53	56	59	59	61	62	64
Northern Appalachian	60	64	68	74	80	82	94	97	97	97	98	99	100
Black Warrior	9	9	9	10	10	10	11	12	13	14	14	14	14
Western U.S.	21	22	23	23	23	25	27	28	30	31	33	35	35
U. S. Total	**230**	**240**	**252**	**266**	**288**	**306**	**342**	**355**	**363**	**367**	**374**	**386**	**393**

[32] An additional 17 mines closed from 1991-2002, but they were reopened for coal mining activity. Emissions from these mines were never added to the abandoned mine database.

Figure 18. Gassy Coal Mines Abandoned Annually (1990-2002)



7.3 Inventory Adjustments for 1990 – 2002 Methane Recovery Projects

Once the total methane emissions for 1990 - 2002 were calculated, they were adjusted to reflect abandoned mine methane emissions that are recovered and used. No known or reported abandoned mine methane recovery projects were in operation from 1990 – 1992, and therefore emissions inventories for these years have not been adjusted.

Conceptually, estimating annual emissions for abandoned mines with recovery projects consists of two key steps: (1) calculating the estimated emission rate without the recovery project, and (2) subtracting the project-specific emissions estimate for individual mines as appropriate.[33] The total annual "avoided" emissions are determined by subtracting the total project-specific emissions from the annual total that was calculated assuming no recovery projects.

Table 12 shows the number of abandoned mine methane recovery projects that were operating from 1990-2002, and the emissions avoided as a consequence of those projects. It is important to note that the emissions avoided values do not represent the amount of gas produced from each project, but rather the amount of emissions that would have occurred had the project not been in place. Recovery projects often rely on blowers and other equipment that may pull more methane out of the mine than likely would be vented naturally.[34] Therefore, some of the CMM captured at an abandoned mine recovery project is not always considered an avoided emission.

[33] In actuality, the emissions avoided were integrated as part of the Monte Carlo simulation, rather than subtracted at the end of the calculation.

[34] For this analysis, it is assumed that the negative pressure applied to the mine void to facilitate methane recovery would negate any additional diffuse emissions from the mine.

Furthermore, EPA assumes that the projects produce gas equal to or greater than the emissions avoided value; therefore, the presence of the project reduces the mine emissions to zero.[35]

Table 12. Abandoned Mine Methane Recovery Projects

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
# of Recovery Projects	0	0	0	1	2	3	4	11	13	14	15	17	21
Emissions Avoided (mmcf)	0	0	0	34	190	779	1,214	2,899	3,244	2,975	2,587	2,487	2,625

7.3.1 Summary of U.S. Emissions

Figure 19 shows that *gross* abandoned mine emissions ranged from 8.4 to 16.8 Bcf during the decade, varying by as much as 2 Bcf from year to year. Fluctuations were due to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Abandoned mine emissions peaked in 1996 due to the large number of mine closures from 1994 to 1996 (76 gassy mines closed during this three-year period). Abandoned mine emissions have declined since 1996, due primarily to the decreased number of closures; fewer than twelve gassy mine closures occurred during each of the years from 1998-2002. The abandoned mine emissions estimate for the year 2002 had declined to 12.9 Bcf (5.2 million tonnes CO_2e, excluding recovery projects), compared to a peak of nearly 16.7 Bcf (6.7 million tonnes CO_2e) in 1996. **Figure 20** shows the *net* emissions in units of CO_2e and Gg of methane.

Table 13 summarizes the abandoned coal mine emissions for each basin from 1990 to 2002. The majority of abandoned mine emissions originate from mines located in the Central and Northern Appalachian basins. On average, mines abandoned in these two basins make up 72% of the mines in the database and between 65-75% of the U.S. abandoned mine emissions.

Figure 21 shows that the Central Appalachian basin is by far the largest contributor to the post-1971 abandoned mines emission inventory. Interestingly, the overall ranking of the basins differed only slightly up until 1997, but since that time emissions contributions from the Central and Northern Appalachian basins have declined, while emissions from the Western and Warrior basins have risen. This change reflects the geographical shift in U.S. coal production away from the Appalachian basin.

[35] The only exception known is the Blue Creek Mine project, which was an active mine project until 1999. It produced only 0.2bcf in 2002, but the emissions avoided potential was 0.6 Bcf. The reason is that, for now, the recovery project is simply a continuation of the small number of active mine gas wells that were operating prior to closure.

Figure 19. Abandoned Mine Methane Emissions Estimate for 1990-2002

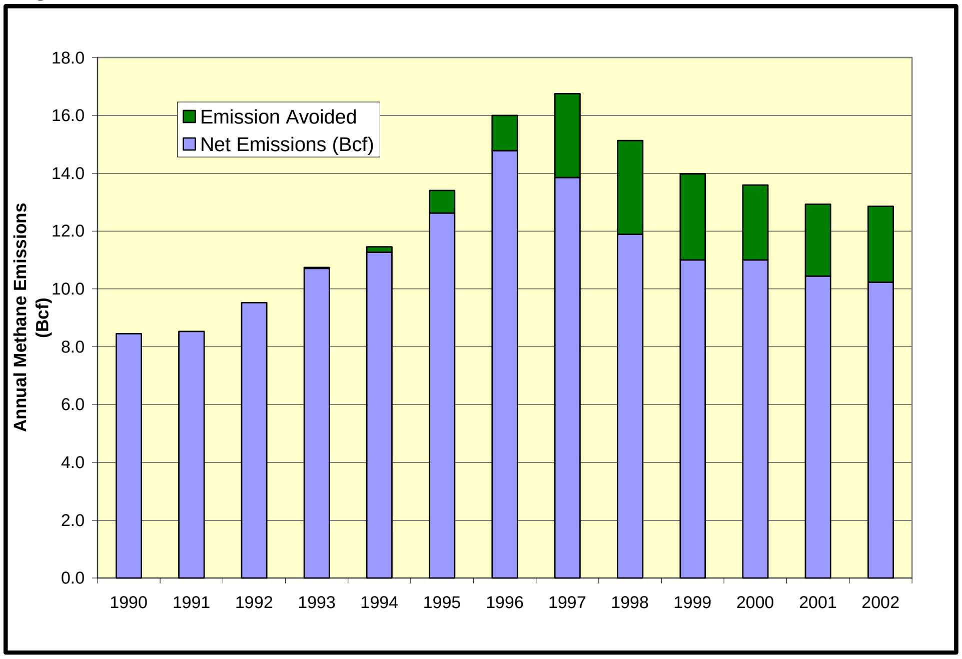


Figure 20. Net Abandoned Mine Emissions (CO_2e and Gg Methane)

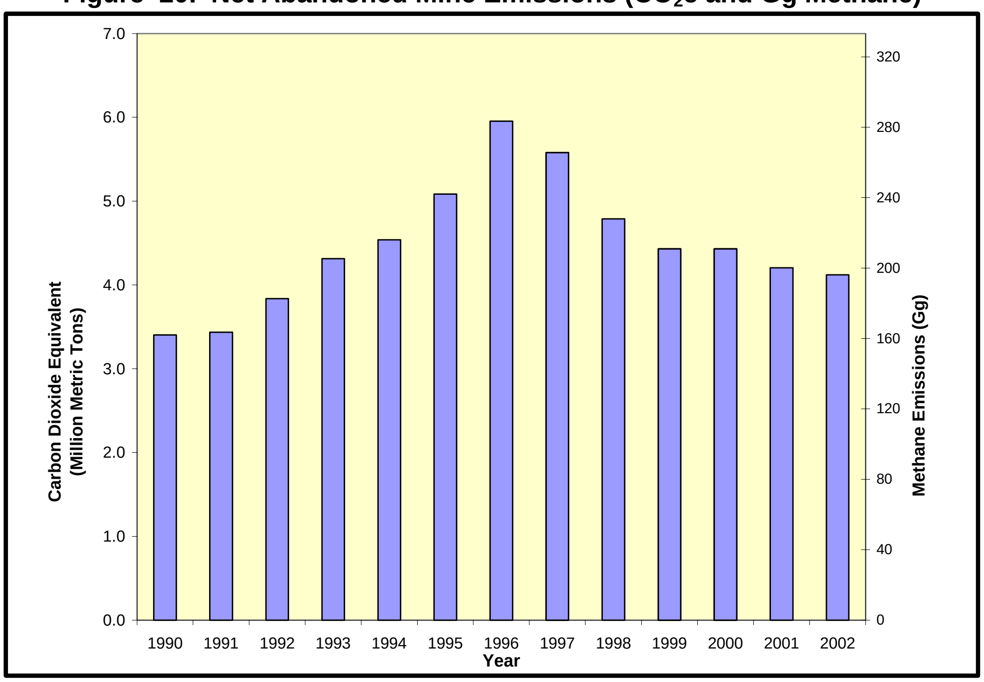
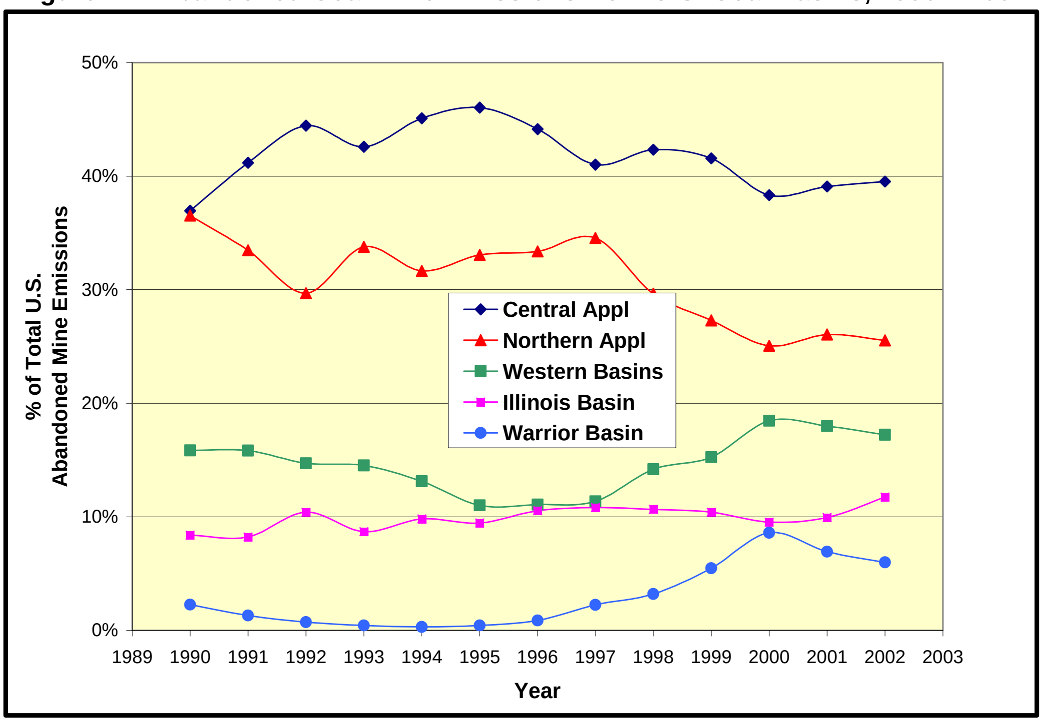


Table 13. Summary of Abandoned Coal Mine Emissions by Basin (Bcf/yr)

		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Central Appalachian Basin	Methane Liberated	3.12	3.51	4.23	4.57	5.17	6.17	7.06	6.87	6.47	5.81	5.21	5.05	5.08
	Emissions Avoided	0.00	0.00	0.00	0.00	0.16	0.75	0.63	0.96	1.49	1.27	1.02	0.95	0.89
	Net Emissions (Bcf)	**3.12**	**3.51**	**4.23**	**4.57**	**5.01**	**5.42**	**6.43**	**5.91**	**4.98**	**4.54**	**4.19**	**4.11**	**4.19**
Illinois Basin	Methane Liberated	0.71	0.70	0.99	0.93	1.12	1.27	1.69	1.81	1.63	1.46	1.30	1.29	1.51
	Emissions Avoided	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.04	0.04	0.26
	Net Emissions (Bcf)	**0.71**	**0.70**	**0.99**	**0.93**	**1.12**	**1.27**	**1.69**	**1.81**	**1.57**	**1.41**	**1.25**	**1.24**	**1.25**
Northern Appalachian Basin	Methane Liberated	3.09	2.85	2.83	3.63	3.63	4.43	5.34	5.79	4.53	3.82	3.41	3.37	3.28
	Emissions Avoided	0.00	0.00	0.00	0.03	0.03	0.03	0.59	1.47	1.30	1.31	1.18	1.08	1.00
	Net Emissions (Bcf)	**3.09**	**2.85**	**2.83**	**3.59**	**3.59**	**4.40**	**4.75**	**4.32**	**3.23**	**2.51**	**2.22**	**2.28**	**2.28**
Warrior Basin	Methane Liberated	0.19	0.11	0.07	0.05	0.03	0.06	0.14	0.38	0.49	0.77	1.17	0.89	0.77
	Emissions Avoided	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.12	0.20
	Net Emissions (Bcf)	**0.19**	**0.11**	**0.07**	**0.05**	**0.03**	**0.06**	**0.14**	**0.38**	**0.49**	**0.77**	**1.15**	**0.77**	**0.57**
Western Basins	Methane Liberated	1.34	1.35	1.40	1.56	1.50	1.48	1.77	1.90	2.17	2.13	2.51	2.32	2.21
	Emissions Avoided	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.40	0.35	0.32	0.29	0.27
	Net Emissions (Bcf)	**1.34**	**1.35**	**1.40**	**1.56**	**1.50**	**1.48**	**1.77**	**1.44**	**1.77**	**1.78**	**2.19**	**2.03**	**1.94**
U. S. Total	Methane Liberated	8.44	8.53	9.53	10.74	11.46	13.40	15.99	16.75	15.28	13.98	13.59	12.93	12.86
	Emissions Avoided	0.00	0.00	0.00	0.03	0.19	0.78	1.21	2.90	3.24	2.97	2.59	2.49	2.62
	Net Emissions (Bcf)	**8.44**	**8.53**	**9.53**	**10.71**	**11.27**	**12.62**	**14.78**	**13.85**	**12.04**	**11.00**	**11.00**	**10.44**	**10.23**

Figure 21. Abandoned Coal Mine Emissions from U.S. Coal Basins, 1990 – 2002



7.4 Key Assumptions and Areas of Uncertainty

Uncertainties in the emission inventory results from data gaps, methodology, and key assumptions made in developing an estimate of abandoned mine emissions. This section identifies and attempts to quantify these uncertainties.

Four important areas of uncertainty described in this report could significantly impact the emissions inventory calculations:

1) Limited data on mines closed before 1972
2) Biases in U.S. mine ventilation data
3) Lack of data on mine drainage before 1990
4) Exclusion of surface mine emissions.

Each of these key areas of uncertainty is discussed briefly below.

7.4.1 Limited data on mines abandoned before 1972

The limitations on data available for mines abandoned prior to 1972 have been dealt with in this emissions inventory using the methodology described in Section 6.

7.4.2 Biases in U.S. mine ventilation data

U.S. mine ventilation data, as received from MSHA, has inherent limitations because it is reported in broad classification ranges. In addition, research has suggested that the MSHA data is inherently biased to overestimate ventilation emissions, with estimated error of +30% to – 10% (Mutmansky and Wang 2000).

7.4.3 Lack of data on degasification prior to 1990

Comprehensive data on degasification systems prior to 1990 are not available. Therefore, EPA's estimates of pre-1990 mine methane emissions includes only mine ventilation emissions. For mines closed since 1990, EPA compiled estimates of methane liberated using degasification systems in addition to ventilation. For mines using degasification systems for which no data are available, EPA assigned default recovery efficiencies.

Because methane liberated from degasification systems prior to 1990 was not incorporated in this inventory, the total active mine emissions estimate used from 1972–1989 for this inventory may be underestimated by approximately 6.5%. This figure is based on USBM's estimate for 1973, that total coal mine ventilation emissions accounted for 93.5% of the total methane liberated from U.S. coal mines (Irani, et al, 1974).

However, the overall impact on the emissions inventory of not accounting for degasification systems may be less than 6.5%, since many of the mines are suspected to be flooded or sealed, which would dramatically decrease their emissions. Abandoned mine emissions rapidly decline during the early years after abandonment, further mitigating the impact of potential marginal increases in the initial emissions rate.

7.4.4 Exclusion of surface mine emissions

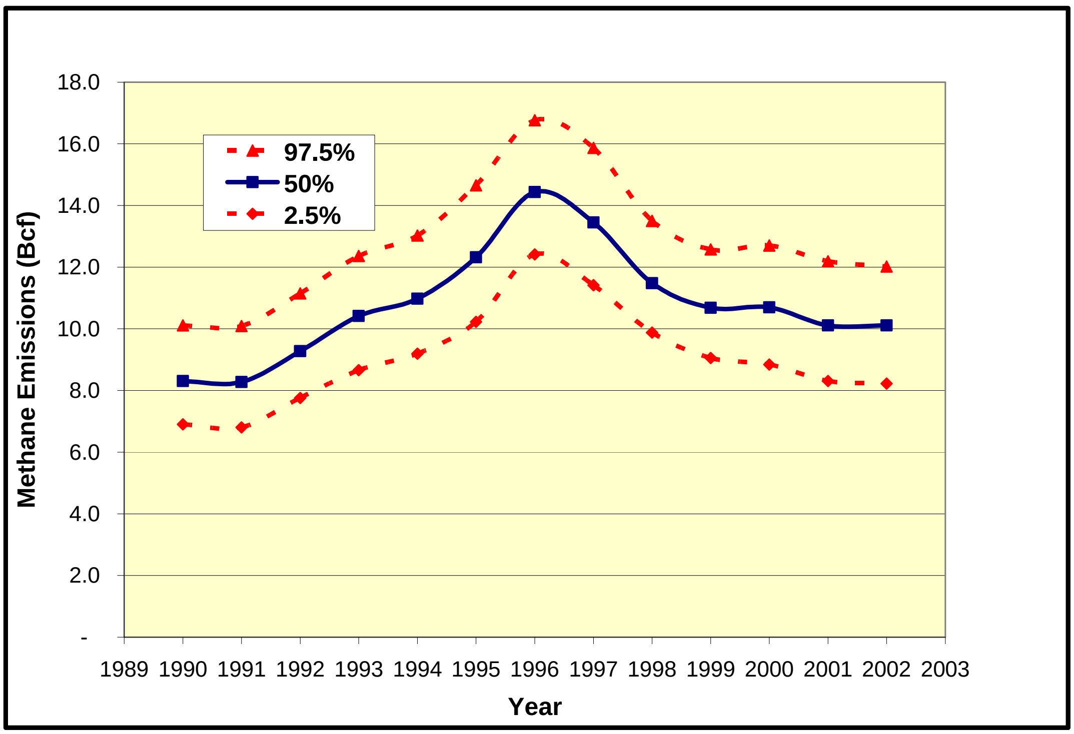
Surface mines are included in the U.S. inventory of *active* coal mine methane emissions, but have not been included in this abandoned mine emissions inventory. In 2002, active surface mines emitted 25.4 Bcf (10.2 million tonnes of CO_2), or 19% of total U.S. coal mine methane emissions. Although some abandoned surface mines may contribute methane emissions, it is assumed that they constitute a negligible share of abandoned mine emissions. The coal seams mined at the surface are shallow, and therefore less likely to have a high gas content. In addition, regulations often require reclamation of the mined void, which for surface mining may involve leveling and covering the mined-out area.

7.4.5 Total estimated uncertainty range

These key uncertainties, as well as those associated with coal permeability, mine seal effectiveness, abandonment status, and the Monte Carlo simulation[36] result in an estimated range of certainty of ± 20%. **Figure 22** shows the high and low estimate range within a 95% confidence interval for net emissions. For each of the years in this inventory, the estimated mean-value emissions varied from the 50% case (the most likely case) by only ±3%. The 50% case was developed from an uncertainty analysis with a 95% confidence interval. Statistically, the closeness of the calculated mean to the probability distribution analysis results indicates that the sample population of gassy mines used for the analysis has a normal distribution.

The IPCC considers an uncertainty level of ± 20% to 55% acceptable for Tier 2 coal mine methane emissions inventories (IPCC, 1997). When compared to other IPCC Tier 2 emission inventories, the methodology used in this report produced a fairly narrow range of values. The range is relatively narrow in part because mine-specific data (required for a Tier 3 inventory) is used. The largest degree of uncertainty is associated with abandoned mines of unknown status, (which account for 36% of the mines), which have an overall uncertainty of ± 60%.

Figure 22. Range of Abandoned Mine Methane Emissions (net) Estimates for 1990-2002



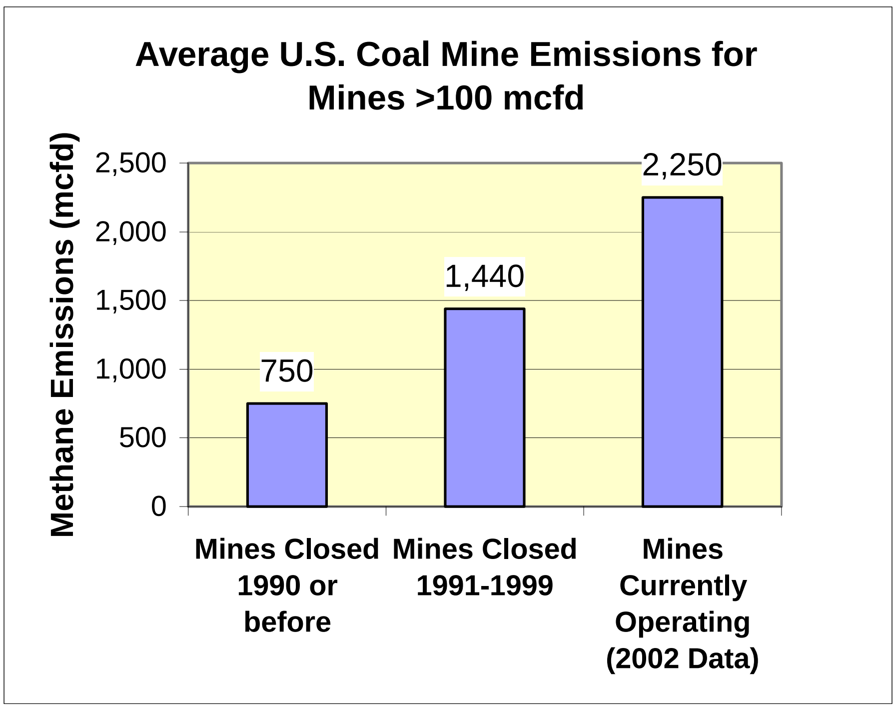
[36] Uncertainties associated with the Monte Carlo simulation are described in **Appendix B.**

7.5 Projecting future emissions from abandoned coal mines

The total methane liberated from active underground mines continues to decrease for U.S. mines.[37] Yet active mine emissions (and therefore initial emission rates for mines at time of abandonment) continue to increase from individual mines. As more mines incorporate longwall mining techniques, ventilation equipment becomes more sophisticated, and mining depths increase, the emissions from active coal mines are likely to continue to increase. **Figure 23** shows that the per-mine average ventilation emissions for gassy coal mines that were closed from 1991-1999 nearly doubled from the 1990 inventory. Furthermore, average ventilation emissions for currently operating mines (with emissions greater than 100 mcfd) are more than double that of the active-mine emissions for mines closed from 1991-1999.

Although the specific emissions of active gassy mines in the U.S. are increasing, the actual number of active mines has decreased. For example, fewer than 125 gassy mines have been operating in the U.S. since 1995 (EPA, 2002), and only 95 gassy mines were active in 2002. Underground coal production in the U.S. has been declining since 1997, with a corresponding decrease in the associated mine methane emissions. As a result of these trends, the downward trend in total abandoned mine emissions since 1996, shown in **Figure 22**, is expected continue as fewer gassy mines remain to close.

Figure 23. Trends in Coal Mine Emissions from Active Gassy U.S. Mines



The methodology for creating this inventory allows estimation of future abandoned mine emissions, by coupling predicted decline curves with presumed closure dates for currently active mines. Abandoned mine emissions could then be forecasted for any given year. In

[37] According to *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2000*, the methane liberated from underground mines decreased by 13.5 million tonnes of CO_2 equivalent, from 67.6 million tonnes to 51.1 million tonnes. This equates to a reduction of 32.4 Bcf or slightly less than 1 Bm^3.

addition, this estimation methodology allows coal mining regions with high emissions or emission anomalies to be identified. Most importantly, this methodology may be used to determine the effect that abandoned mine emissions may have on the U.S. Greenhouse Gas Inventory in future years.

8.0 Conclusions

EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks* includes methane emission estimates for underground mining, surface mining, and post-mining activities at active mines.[38] The emissions estimation methodology and results described in this report enables the quantification of emissions from abandoned mines, for which there is currently no recognized methodology.

This methodology has been designed to produce robust estimates and to incorporate new data as available. It allows annual emissions inventories to be readily updated, because it is flexible enough to allow additional mines to be included in the inventory as information becomes available. In addition, the method can be used to predict future emissions from existing underground coal mines for any given year. Furthermore, the mine database is thorough and representative of the majority of methane emissions from abandoned mines in the U.S. Finally, the method requires minimal inputs: active mine emissions, mine closure dates, and coal adsorption isotherm data. Thus, it could potentially be used to estimate coal mine methane emissions in other nations.

The methodology and emission estimates presented in this report are the first attempt to systematically quantify emissions from abandoned coal mines in the U.S.. EPA will continue to refine the methodology to quantify abandoned mine emissions with greater certainty. Important next steps include:

- Researching additional sources for data on mines closing before 1972 to further refine estimates for emissions from the pre-1972 mines
- Developing more accurate estimates of the percentage of gas liberated by drainage systems before 1990
- Identifying all abandoned mine methane recovery projects in the U.S. that operated from 1990 to the present and obtaining data on emission reductions
- Considering the results of any additional work being conducted with regard to the uncertainty in MSHA ventilation emission data
- Obtaining more field data to verify methodological results or serve as the basis for refinements to the methodology
- Developing methodologies to set baselines and calculate emissions avoided on a project-specific basis
- Incorporating the abandoned mine emissions into the U.S. Inventory of Greenhouse Gas Emissions and Sinks
- Evaluating the method for its application to other countries, and if not, developing a more universal methodology

[38] Post-mining emissions are emissions from coal during storage (e.g. in piles) and transportation (e.g. while in train cars) prior to the coal's usage as fuel.

Several other countries have also begun to quantify their abandoned mine emissions. As EPA continues refining its methodology and estimates, we welcome comments and suggestions on this report and the methodology, as there are many potential gains from critical input and coordination.

9.0 References

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APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
OK	Haskell	Arkoma	Choctaw Coal		10/29/90	0.35
OK	Le Flore	Arkoma	Howe No 1		*06/10/72*	1.6
OK	Okmulgee	Arkoma	Pollyanna No 4		10/11/96	0.35
KY	Harlan	Central Appl.	No. 10 Wisconsin Steel Mine		*6/10/1972*	0.1
KY	Harlan	Central Appl.	Creech No 1		6/15/1995	0.2
KY	Harlan	Central Appl.	Harlan No.1		7/10/1995	0.2
KY	Harlan	Central Appl.	Arch No. 37		1/21/1999	1
KY	Henderson	Central Appl.	Retiki	Sealed	02/03/95	0.35
KY	Johnson	Central Appl.	White Ash No 1		*06/10/77*	0.35
KY	Leslie	Central Appl.	No 2		08/29/96	0.35
KY	Leslie	Central Appl.	Unicorn No.2		8/29/1996	0.2
KY	Leslie	Central Appl.	No. 60		05/07/01	0.3
KY	Letcher	Central Appl.	Scotia Mine		*06/10/82*	0.4
KY	Martin	Central Appl.	Peter Cave No 1		*06/10/77*	0.15
KY	Martin	Central Appl.	Wolf Creek No.3	Sealed	*06/10/77*	0.75
KY	Martin	Central Appl.	Wolf Creek No 4	Flooded	10/2/1995	1
KY	MeCreary	Central Appl.	Justus		06/15/94	0.35
KY	Pike	Central Appl.	Big Creek No 2		*06/10/81*	0.15
KY	Pike	Central Appl.	Leslie	Sealed	*06/10/81*	0.75
KY	Pike	Central Appl.	Scotts Branch		*06/10/81*	0.35
KY	Pike	Central Appl.	No. 1 Mine (D)		10/20/82	0.35
KY	Pike	Central Appl.	No. 2 Mine (D)		12/16/82	0.35
KY	Pike	Central Appl.	No. 6 Mine (D)		03/04/83	0.35
KY	Pike	Central Appl.	No. 1 Mine (D)		06/14/83	0.35
KY	Pike	Central Appl.	No. 1 Mine		11/14/88	0.35
KY	Pike	Central Appl.	Ovenfork Mine		1/15/1992	*2.4*
KY	Pike	Central Appl.	Mate Creek No 2		*06/10/94*	0.75
KY	Pike	Central Appl.	No 3		*06/10/94*	0.35
KY	Pike	Central Appl.	No.9		8/25/1995	0.1
KY	Whitley	Central Appl.	No. 1		08/15/86	0.35
KY	Whitley	Central Appl.	Blue Gem No 1		02/27/97	0.35
TN	Clearborne	Central Appl.	Matthews Mine		12/29/1990	0.2
TN	Rosedale	Central Appl.	Volunteer No 1		*06/10/74*	2.5
TN	Sequatchie	Central Appl.	Kelly's Creek No. 63		2/18/1994	0.1
VA	Buchanan	Central Appl.	Jewell No 18		*06/10/82*	0.15
VA	Buchanan	Central Appl.	LAMBERT FORK	Flooded	06/18/85	0.75
VA	Buchanan	Central Appl.	WINSTON MINE NO 10	Sealed	02/25/92	0.35
VA	Buchanan	Central Appl.	No 1	Flooded	04/23/93	0.35
VA	Buchanan	Central Appl.	1-A Mine	Venting/ partially Flooded	*06/10/93*	0.35
VA	Buchanan	Central Appl.	VIRGINIA POCAHONTAS 4	Sealed/ Recovering Methane	8/9/1993	*2.4*
VA	Buchanan	Central Appl.	Raven No. 1	Flooded	*6/10/1994*	0.1
VA	Buchanan	Central Appl.	VP 1	Recovering Methane	*06/10/94*	7.5
VA	Buchanan	Central Appl.	Big Creek Seaboard No. 1	Venting	8/18/1995	*2.4*
VA	Buchanan	Central Appl.	Beatrice Mine	Sealed	12/5/1995	6.8
VA	Buchanan	Central Appl.	No 4	Flooded	03/21/96	0.35
VA	Buchanan	Central Appl.	Virginia Pocahontas No 2	Sealed/ Recovering Methane	12/11/1996	2.8
VA	Buchanan	Central Appl.	VP No 3	Recovering Methane	*12/10/1997*	7.3

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
VA	Buchanan	Central Appl.	1-A		3/12/2001	0.25
VA	Dickenson	Central Appl.	Splashdam	Partially Flooded	09/27/95	0.35
VA	Dickenson	Central Appl.	McClure No 1	Flooded	8/20/1996	1.4
VA	Dickerson	Central Appl.	Moss No 3	Flooded	*06/10/76*	1.4
VA	Lee	Central Appl.	No. 1 Mine		04/28/92	0.35
VA	Lee	Central Appl.	#1		03/24/94	0.75
VA	Lee	Central Appl.	Holton	Flooded	01/23/97	0.35
VA	Russell	Central Appl.	Chaney Creek No 2	Flooded	*06/10/74*	0.35
VA	Russell	Central Appl.	MOSS NO. 2	Flooded	07/15/83	1.3
VA	Russell	Central Appl.	HURRICANE CREEK	Flooded	06/29/87	0.35
VA	Russell	Central Appl.	Moss No 3A2	Flooded	03/18/88	0.75
VA	Russell	Central Appl.	Moss No 4	Adjacent to strip mine	01/11/89	0.75
VA	Tazewell	Central Appl.	Amonate No 31		09/26/94	2.2
VA	Tazewell	Central Appl.	No 1	Flooded	*06/10/95*	0.35
VA	Wise	Central Appl.	PRESCOTT NO 1	Flooded	02/20/81	0.35
VA	Wise	Central Appl.	No 7		*06/10/82*	0.15
VA	Wise	Central Appl.	Virginia No 1		*06/10/82*	0.15
VA	Wise	Central Appl.	Wentz B Portal	Flooded	*06/10/82*	0.35
VA	Wise	Central Appl.	Osaka No 2		06/16/89	0.35
VA	Wise	Central Appl.	Prescott No 2 Mine	Sealed	01/11/94	0.35
VA	Wise	Central Appl.	No 1	Flooded	04/08/94	0.35
VA	Wise	Central Appl.	No. 2	Flooded	5/24/1995	0.1
VA	Wise	Central Appl.	Bullitt Mine	Venting	08/01/95	0.75
VA	Wise	Central Appl.	Wentz No 1	Flooded	01/25/96	0.35
VA	Wise	Central Appl.	Pierre	Venting	01/31/96	0.35
VA	Wise	Central Appl.	Har-Lee No 3	Sealed	04/29/96	0.35
VA	Wise	Central Appl.	No 1	Flooded	05/08/96	0.35
VA	Wise	Central Appl.	Deep No 20	Venting	01/08/97	0.35
VA	Wise	Central Appl.	#12		5/21/1999	0.1
VA	Wise	Central Appl.	Sargent Hollow		7/12/2001	0.2
WV	Boone	Central Appl.	Ferrell No 17	Flooded	*06/10/82*	0.35
WV	Boone	Central Appl.	HAMPTON NO 3 MINE	Flooded	02/02/87	0.35
WV	Boone	Central Appl.	Wharton No. 4		3/23/1987	0.2
WV	Boone	Central Appl.	HAMPTON NO 4	Flooded	01/23/91	0.35
WV	Boone	Central Appl.	Birchfield No 1	Venting	*06/10/92*	1.5
WV	Boone	Central Appl.	Oasis No. 1		*06/10/96*	1.1
WV	Boone	Central Appl.	Lightfoot No. 1		2/9/2000	0.2
WV	Brooke	Central Appl.	Beech Bottom		*06/10/74*	0.35
WV	Brooke	Central Appl.	Valley Camp No 1		*06/10/82*	0.35
WV	Fayette	Central Appl.	Royal No 5	Sealed	*06/10/77*	0.35
WV	Fayette	Central Appl.	Siltix	Flooded	10/23/87	0.35
WV	Kanawha	Central Appl.	No 34		*06/10/72*	0.35
WV	Kanawha	Central Appl.	Cannelton No 8	Venting	04/05/83	0.35
WV	Kanawha	Central Appl.	MADISON NO 1 MINE		06/14/84	0.35
WV	Kanawha	Central Appl.	Lady Dunn No 105	Flooded	11/12/87	0.75
WV	Lincoln	Central Appl.	Five Block No 4 Mine		09/26/80	0.75
WV	Logan	Central Appl.	Guyan No 5	Flooded	*06/10/74*	0.35
WV	Logan	Central Appl.	No 4-H	Sealed	*06/10/74*	0.35

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
WV	Logan	Central Appl.	Paragon	Flooded	*06/10/74*	0.15
WV	Logan	Central Appl.	NO 1 CEDAR GROVE	Flooded	09/26/80	*2.4*
WV	Logan	Central Appl.	Dehue	Sealed	11/14/85	0.35
WV	Logan	Central Appl.	Guyan No 1	Flooded	07/03/90	0.35
WV	McDowell	Central Appl.	Cannelton No 3 & 4	Venting / Partially Flooded	*06/10/74*	0.35
WV	McDowell	Central Appl.	Pocahontas No 7		*06/10/74*	0.15
WV	McDowell	Central Appl.	Maitland	Venting / Partially Flooded	*06/10/77*	1
WV	McDowell	Central Appl.	U.S. Steel No 14-4	Venting / Partially Flooded	*06/10/77*	1.4
WV	McDowell	Central Appl.	NEWHALL NO 6 MINE	Venting/ Partially Flooded	10/01/79	0.75
WV	McDowell	Central Appl.	SHANNON BRANCH MINE	Flooded	11/05/82	1.3
WV	McDowell	Central Appl.	GARY NO 10	Sealed	02/28/84	0.75
WV	McDowell	Central Appl.	Little B Mine No 2	Sealed	12/19/85	*2.4*
WV	McDowell	Central Appl.	Keystone No 1 Mine		04/01/87	0.35
WV	McDowell	Central Appl.	Ogla	Flooded	06/17/88	1.6
WV	McDowell	Central Appl.	No 4 Mine	Sealed	06/27/88	*2.4*
WV	McDowell	Central Appl.	U.S. Steel No 2	Venting/ Partially Flooded	*06/10/91*	0.9
WV	McDowell	Central Appl.	ANGUS	Venting	10/24/95	0.35
WV	Mingo	Central Appl.	National No 25		*06/10/74*	0.35
WV	Mingo	Central Appl.	Gary No 20-B		*06/10/82*	0.15
WV	Mingo	Central Appl.	No 19		07/02/90	0.35
WV	Mingo	Central Appl.	Rocky Hollow		11/19/94	0.35
WV	Nicholas	Central Appl.	Sewell No 4		*06/10/72*	0.75
WV	Nicholas	Central Appl.	Coalbank Fork No 9		02/27/82	*2.4*
WV	Nicholas	Central Appl.	Mine #3		04/26/82	*2.4*
WV	Nicholas	Central Appl.	Mine No 4		07/27/82	*2.4*
WV	Nicholas	Central Appl.	No 24 Mine		09/15/82	*2.4*
WV	Nicholas	Central Appl.	Mine No 4		09/20/82	*2.4*
WV	Nicholas	Central Appl.	Hewett Fork No 1A		01/05/83	*2.4*
WV	Nicholas	Central Appl.	Big Foot Coal 4-B Mine		03/21/83	*2.4*
WV	Nicholas	Central Appl.	Stone Run 6A		06/14/83	*2.4*
WV	Nicholas	Central Appl.	SEWELL #1A		04/22/86	0.35
WV	Nicholas	Central Appl.	SEWELL NO 1		09/06/88	0.35
WV	Nicholas	Central Appl.	Donegan No 10		06/14/90	0.35
WV	Nicholas	Central Appl.	Mine No 1		06/24/93	*2.4*
WV	Nicholas	Central Appl.	Long Run Deep Mine No 1		04/17/96	*2.4*
WV	Nicholas	Central Appl.	Hutchinsons Branch Mine No. 1		06/26/00	0.25
WV	Raleigh	Central Appl.	East Gulf	Flooded	*06/10/74*	1
WV	Raleigh	Central Appl.	Bethlehem No 46	Flooded	*06/10/77*	0.15
WV	Raleigh	Central Appl.	Macalpin #3	Flooded	10/19/79	0.3
WV	Raleigh	Central Appl.	ECCLES NO 5	Flooded	10/01/81	0.75
WV	Raleigh	Central Appl.	KEYSTONE NO 4-A MINE	Flooded	07/21/82	0.35
WV	Raleigh	Central Appl.	SLAB FORK NO 8	Flooded	02/06/84	0.75
WV	Raleigh	Central Appl.	SLAB FORK NO. 10 MINE	Flooded	02/06/84	0.75
WV	Raleigh	Central Appl.	WINDING GULF # 4	Flooded	02/06/84	0.35
WV	Raleigh	Central Appl.	ECCLES NO 6	Flooded	06/28/85	0.35
WV	Raleigh	Central Appl.	KEYSTONE NO 4 MINE	Flooded	10/01/85	0.35

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
WV	Raleigh	Central Appl.	KEYSTONE NO 5 MINE	Flooded	12/31/85	0.35
WV	Raleigh	Central Appl.	SKELTON MINE	Flooded	12/08/86	0.35
WV	Raleigh	Central Appl.	Macalpin	Flooded	07/06/89	0.35
WV	Raleigh	Central Appl.	Bonny	Sealed/ Recovery Pending	*06/10/90*	3.4
WV	Raleigh	Central Appl.	No 4 Mine	Venting/ Partially Flooded	1/29/1991	2.9
WV	Raleigh	Central Appl.	Beckley	Flooded	7/1/1992	3.7
WV	Raleigh	Central Appl.	KEYSTONE NO 2 MINE	Flooded	5/7/1993	0.6
WV	Raleigh	Central Appl.	Tommy Creek #1	Flooded	03/20/96	0.35
WV	Raleigh	Central Appl.	Maple Meadow Mine	Sealed/ Recovery Pending	7/10/1998	2.6
WV	Upshur	Central Appl.	Adrian Mine		*6/10/1977*	0.2
WV	Upshur	Central Appl.	Queen # 14 Mine		11/05/82	*2.4*
WV	Upshur	Central Appl.	Grand Badger No 1A Mine		08/08/83	*2.4*
WV	Webster	Central Appl.	Smoot		01/22/97	0.35
WV	West	Central Appl.	Dixianna		*06/10/72*	0.35
WV	Wyoming	Central Appl.	Buckeye Coll.	Sealed	*06/10/74*	0.15
WV	Wyoming	Central Appl.	Kepler	Venting/ Partially Flooded	*06/10/74*	0.75
WV	Wyoming	Central Appl.	Otsego		*06/10/74*	0.15
WV	Wyoming	Central Appl.	Itmann No 4	Flooded	*06/10/76*	1
WV	Wyoming	Central Appl.	GASTON NO 2 MINE		01/15/82	0.35
WV	Wyoming	Central Appl.	Beckley No 1	Venting/Partially Flooded	2/9/1982	0.7
WV	Wyoming	Central Appl.	National Pocahontas	Venting/Partially Flooded	01/31/84	0.75
WV	Wyoming	Central Appl.	ITMANN #3	Sealed	05/20/87	1.4
WV	Wyoming	Central Appl.	Beckley No 2	Venting/Partially Flooded	6/21/1988	1
WV	Wyoming	Central Appl.	ITMANN # 1 AND SHOP	Sealed	06/12/92	0.35
WV	Wyoming	Central Appl.	Shawnee Mine	Venting/Partially Flooded	11/7/1994	*2.4*
WV	Wyoming	Central Appl.	KOPPERSTON NO. 1	Sealed	01/10/96	0.35
WV		Central Appl.	Mine No 1		12/13/82	*2.4*
WV		Central Appl.	Bells Creek Mine No. 1		6/10/1998	0.50
IL	Christian	Illinois	Peabody No. 10		7/10/1994	0.75
IL	Clinton	Illinois	Monterey No 2		07/25/96	0.75
IL	Douglas	Illinois	Zeigler #5	Sealed	05/27/87	0.35
IL	Douglas	Illinois	Murdock		11/1/1996	*0.75*
IL	Franklin	Illinois	Old Ben No 27		02/05/87	0.75
IL	Franklin	Illinois	Old Ben No 25	Venting Methane	*9/10/1994*	1
IL	Franklin	Illinois	Old Ben No 21		11/13/95	1.4
IL	Franklin	Illinois	Old Ben No 24	Sealed	7/10/1998	1.2
IL	Franklin	Illinois	Old Ben No 26	Sealed	7/10/1998	1.6
IL	Gallatin	Illinois	Eagle No. 2		*06/10/94*	0.75
IL	Gallatin	Illinois	Eagle No 1		05/15/96	0.35
IL	Hamilton	Illinois	Inland No 2		*06/10/82*	0.35
IL	Jefferson	Illinois	Inland No 1		*06/10/82*	1.1
IL	Jefferson	Illinois	Orient #3	Sealed	02/01/84	1.5
IL	Jefferson	Illinois	Orient #5	Sealed	02/01/84	1.5
IL	Jefferson	Illinois	Wheeler Creek		04/04/88	0.75
IL	Jefferson	Illinois	Orient No 6	Sealed /	3/13/1997	1

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
				Recovering Methane		
IL	Montgomery	Illinois	Crown	Sealed	*06/10/72*	1
IL	Montgomery	Illinois	Crown #2	Sealed	*06/10/82*	1.1
IL	Montgomery	Illinois	HILLSBORO MINE		12/02/83	0.35
IL	Perry	Illinois	Kathleen		08/23/95	0.35
IL	Randolph	Illinois	Baldwin No 1		*06/10/82*	0.35
IL	Randolph	Illinois	No 11		*06/10/82*	0.15
IL	Randolph	Illinois	Spartan	Sealed	12/10/97	0.35
IL	Saline	Illinois	No 16	Flooded	*06/10/72*	0.15
IL	Saline	Illinois	No 5	Flooded	*06/10/72*	0.15
IL	Saline	Illinois	Sahara No 20	Flooded	*06/10/82*	0.35
IL	St. Clair	Illinois	River King Underground		05/11/90	0.35
IL	Williamson	Illinois	ZEIGLER #4 UG	Sealed	11/14/80	0.75
IL	Williamson	Illinois	ORIENT NO. 4	Sealed	09/01/87	0.75
IL		Illinois	Big Ridge Mine		3/15/1997	0.60
IN	Gibson	Illinois	Kings	Sealed	*06/10/74*	0.35
IN	Sullivan	Illinois	Thunderbird	Sealed	*06/10/72*	0.75
IN	Sullivan	Illinois	Buck Creek		2/2/1998	0.35
KY	Hopkins	Illinois	East Diamond	Venting/Flooded	*06/10/72*	0.35
KY	Hopkins	Illinois	Island Creek No 9	Venting/Flooded	*06/10/74*	0.35
KY	Hopkins	Illinois	FIES MINE	Venting/Flooded	01/11/80	1.1
KY	Hopkins	Illinois	ZEIGLER NO 9 MINE		01/11/80	0.75
KY	Hopkins	Illinois	Drake No 4	Flooded	04/27/82	0.35
KY	Hopkins	Illinois	Providence No 1	Venting/Flooded	*06/10/83*	0.35
KY	Hopkins	Illinois	Busick Mine		06/29/83	0.35
KY	Hopkins	Illinois	Green River No.9		5/1/1992	1.2
KY	Hopkins	Illinois	West Hopkins	Sealed/Filled	*06/10/94*	0.35
KY	Hopkins	Illinois	Richland Mine		9/21/2000	0.2
KY	Muhlenberg	Illinois	Drake No 1	Sealed/Filled	*06/10/72*	0.35
KY	Muhlenberg	Illinois	Crescent	Flooded	*06/10/77*	0.75
KY	Muhlenberg	Illinois	River Queen Underground No 1	Flooded	02/02/81	0.35
KY	Muhlenberg	Illinois	Star Underground	Flooded	05/15/96	0.35
KY	Ohio	Illinois	ALSTON NO 3 MINE		02/06/81	0.35
KY	Ohio	Illinois	Peacock Coal Mine No.		02/01/83	0.75
KY	Ohio	Illinois	KEN NO 4 MINE		09/01/84	0.35
KY	Union	Illinois	Pyro No 2	Sealed	*06/10/74*	0.35
KY	Union	Illinois	Peabody Camp No 2	Sealed	*06/10/83*	0.35
KY	Union	Illinois	Pyro No. 11 Highway		11/15/1991	0.2
KY	Union	Illinois	Pyro No. 9 Slope William Station		11/15/1991	1.2
KY	Union	Illinois	Camp No.2		8/20/1993	0.4
KY	Union	Illinois	Hamilton No 2	Venting/Flooded	03/18/94	0.35
KY	Union	Illinois	Hamilton No 1	Venting/Flooded	05/14/96	0.35
KY	Webster	Illinois	Dorea	Sealed/Filled	01/29/93	0.35
KY	Webster	Illinois	Wheatcroft #9		*06/10/96*	1.9
KY	Webster	Illinois	Smith U/G mine		9/21/2000	0.35
OH	Belmont	Northern Appl.	Powhatan No 4	Venting	*06/10/78*	0.75
OH	Belmont	Northern Appl.	POWHATAN NO 5 MINE	Venting	03/31/81	0.35

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
OH	Belmont	Northern Appl.	POWHATAN NO 1	Sealed	02/16/82	0.75
OH	Belmont	Northern Appl.	Powhatan No 3	Venting	03/18/83	0.35
OH	Belmont	Northern Appl.	ALLISON MINE	Venting	01/11/84	0.35
OH	Belmont	Northern Appl.	Saginaw no 1	Venting	06/17/93	0.35
OH	Harrison	Northern Appl.	Nelms #1	Sealed/ Recovering Methane	*06/10/77*	1.9
OH	Harrison	Northern Appl.	Rose Valley No. 6		8/28/1980	0.5
OH	Harrison	Northern Appl.	VAIL	Venting	01/04/84	0.35
OH	Harrison	Northern Appl.	Oak Park No 7	Sealed/ Recovering Methane	05/13/88	0.75
OH	Harrison	Northern Appl.	NELMS NO 2	Venting	2/29/1996	1.5
OH	Jefferson	Northern Appl.	Jensie	Venting	*06/10/74*	0.35
OH	Monroe	Northern Appl.	POWHATAN 7 MINE	Temporary Seal	08/03/92	0.35
OH	Perry	Northern Appl.	Sunnyhill No. 9 South		7/10/1991	0.1
OH	Vinton	Northern Appl.	Raccoon #3		09/25/89	0.35
PA	Allegheny	Northern Appl.	Oakmont		05/01/80	0.35
PA	Allegheny	Northern Appl.	HARMAR MINE	Sealed	01/13/89	0.35
PA	Allegheny	Northern Appl.	Renton Mine		10/23/1992	0.7
PA	Allegheny	Northern Appl.	Allegheny No. 2 & Portal No. 3		10/25/1993	0.1
PA	Allegheny	Northern Appl.	Newfield	Sealed	06/26/95	0.75
PA	Allegheny	Northern Appl.	OCEAN #5 MINE	Sealed	03/18/97	0.35
PA	Armstrong	Northern Appl.	Harold No 1		*06/10/74*	0.15
PA	Armstrong	Northern Appl.	Jane Nos 1 & 2		*06/10/84*	0.75
PA	Armstrong	Northern Appl.	DAVID MINE	Sealed/Adjacent to Dianne Mine	02/27/96	0.35
PA	Armstrong	Northern Appl.	Jane	Sealed	08/22/96	0.75
PA	Cambria	Northern Appl.	Bethlehem No 31	Sealed	*06/10/78*	0.35
PA	Cambria	Northern Appl.	Bethlehem No 77	Flooded/ Pumping Water	*06/10/78*	0.35
PA	Cambria	Northern Appl.	Nanty Glo No 31	Sealed	*06/10/84*	0.35
PA	Cambria	Northern Appl.	Bethlehem No 32	Sealed/ Recovering Methane	09/17/85	4.5
PA	Cambria	Northern Appl.	Lancashire No 25	Sealed	03/05/86	0.35
PA	Cambria	Northern Appl.	Lancashire No 20	Sealed	09/09/88	0.9
PA	Cambria	Northern Appl.	Cambria Slope No 33	Recovering Methane	7/15/1994	8.5
PA	Centre	Northern Appl.	Rushton		12/31/1992	0.4
PA	Fayette	Northern Appl.	Isabella	Sealed	*06/10/74*	0.35

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
PA	Greene	Northern Appl.	WARWICK MINE NO. 2	Sealed	05/01/80	0.35
PA	Greene	Northern Appl.	ROBENA MINE	Flooded	02/12/84	2.1
PA	Greene	Northern Appl.	GATEWAY MINE	Venting	12/9/1992	2.6
PA	Greene	Northern Appl.	Nemacolin Mine		3/25/1996	0.6
PA	Greene	Northern Appl.	Shannopin Mine	Sealed	3/25/1996	1
PA	Greene	Northern Appl.	Lazarus		6/13/1996	0.6
PA	Greene	Northern Appl.	Monongahela Resource	Venting	06/13/96	0.35
PA	Greene	Northern Appl.	Warwick Mine No 2	Flooded/Pumping Water	3/10/1997	1.1
PA	Indiana	Northern Appl.	CONEMAUGH NO. 1		09/23/82	0.35
PA	Indiana	Northern Appl.	Greenwich Collieries No 1		8/1/1988	0.3
PA	Indiana	Northern Appl.	Urling No. 1	Venting	12/18/1989	0.7
PA	Indiana	Northern Appl.	Florence No. 1		3/7/1990	0.2
PA	Indiana	Northern Appl.	Urling No. 3	Venting	1/3/1991	0.7
PA	Indiana	Northern Appl.	Greenwich Collieries No 2		03/13/93	1.2
PA	Indiana	Northern Appl.	Homer City		6/30/1993	1.7
PA	Indiana	Northern Appl.	Florence No. 2		10/4/1994	0.3
PA	Indiana	Northern Appl.	Lucerne No 8		03/31/95	0.35
PA	Indiana	Northern Appl.	Lucerne No. 9	Sealed/ Partially Flooded	8/23/1995	0.35
PA	Indiana	Northern Appl.	Marion	Sealed*	01/23/97	0.75
PA	Indiana	Northern Appl.	Lucerne No. 6 Extension		5/24/2000	0.3
PA	Luzerne	Northern Appl.	Forge Slope		*06/10/72*	1.5
PA	Luzerne	Northern Appl.	No. 19 Wanamie Colliery		*6/10/1972*	0.2
PA	Somerset	Northern Appl.	BIRD #2	Flooded	10/30/91	0.75
PA	Somerset	Northern Appl.	BIRD #3	Flooded	10/30/91	0.4
PA	Somerset	Northern Appl.	Grove No. 1		12/21/1994	0.35
PA	Washington	Northern Appl.	VESTA #4 MINE	Sealed	04/14/80	0.35
PA	Washington	Northern Appl.	Beth Ellsworth No 51	Flooded	*06/10/83*	0.75
PA	Washington	Northern Appl.	WESTLAND #2	Sealed	09/27/83	0.35
PA	Washington	Northern Appl.	Marianna No 58	Sealed/ Partially Flooded	8/31/1988	2.2
PA	Washington	Northern Appl.	Clyde		12/9/1994	0.1
PA	Washington	Northern Appl.	VESTA #5 MINE		04/17/96	1.6
PA	Washington	Northern Appl.	MONTOUR #4	Flooded	05/22/96	3

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
PA	Washington	Northern Appl.	Westland		05/22/96	0.75
PA	Westmoreland	Northern Appl.	Banning No 4	Flooded	*06/10/83*	0.75
PA	Westmoreland	Northern Appl.	DELMONT	Flooded	03/04/88	0.35
PA		Northern Appl.	Hutchinson	Flooded	*06/10/74*	0.35
WV	Barbour	Northern Appl.	Boulder Mine	Sealed	03/17/83	*2.2*
WV	Barbour	Northern Appl.	BADGER NO. 15 MINE	Sealed	02/26/84	0.35
WV	Barbour	Northern Appl.	BADGER NO 14 MINE	Sealed	08/28/85	0.35
WV	Gilmer	Northern Appl.	Kanawha #1	Sealed	09/15/82	*2.2*
WV	Gilmer	Northern Appl.	Kanawha #2	Sealed	11/02/82	*2.2*
WV	Grant	Northern Appl.	Potomac	Sealed	04/07/80	0.35
WV	Harrison	Northern Appl.	Compass No 2	Sealed	*06/10/74*	0.75
WV	Harrison	Northern Appl.	Mars No 2	Flooded	*06/10/74*	0.75
WV	Harrison	Northern Appl.	Williams	Venting/ Partially Flooded	*06/10/78*	*2.2*
WV	Harrison	Northern Appl.	Pioneer Mine	Venting/ Partially Flooded	11/12/82	*2.2*
WV	Marion	Northern Appl.	Consol No 9	Venting/ Recovering Gas	*06/10/77*	1.4
WV	Marion	Northern Appl.	No 93	Venting	*06/10/78*	1
WV	Marion	Northern Appl.	Phillip Sporn No 1		*06/10/79*	0.35
WV	Marion	Northern Appl.	Bethlehem No 44	Venting	10/1/1979	0.3
WV	Marion	Northern Appl.	Consol No. 20	Venting/ Recovering Gas	10/1/1982	1.1
WV	Marion	Northern Appl.	Bethlehem No 41	Venting/ Partially Flooded	02/15/83	0.75
WV	Marion	Northern Appl.	JOANNE MINE	Venting	03/10/83	1.3
WV	Marion	Northern Appl.	Federal No 1	Venting	03/24/87	1.8
WV	Marion	Northern Appl.	Tygart River	Flooded/ Pumping Water	08/26/93	0.35
WV	Marshall	Northern Appl.	Alexander	Venting/ Partially Flooded	7/10/1981	*2.2*
WV	Marshall	Northern Appl.	Ireland	Venting	*06/10/94*	1.5
WV	Mason	Northern Appl.	Putnam		*06/10/72*	0.35
WV	Monongalia	Northern Appl.	Pursglove No. 15		9/14/1989	2.1
WV	Monongalia	Northern Appl.	Blacksville No 1		*06/10/93*	2.9
WV	Monongalia	Northern Appl.	Arkwright No 1	Sealed/Recovering Methane	5/24/1996	4.2
WV	Monongalia	Northern Appl.	Osage No. 3		5/25/1996	5.3
WV	Preston	Northern Appl.	#1	Sealed	09/14/82	*2.2*
WV	Preston	Northern Appl.	H & H Mine No 2	Sealed	03/22/83	*2.2*

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
WV	Preston	Northern Appl.	#3 Mine	Sealed	07/19/83	*2.2*
WV	Taylor	Northern Appl.	Keg No 1		11/15/82	*2.2*
CO	Delta	Piceance	Hawks Nest East	Venting	1/3/1986	0.9
CO	Delta	Piceance	Somerset Mine	Sealed	2/16/1989	0.7
CO	Delta	Piceance	Bowie No 1	Venting Methane	12/10/1998	1.2
CO	Gunnison	Piceance	Bear Creek Mine		10/12/79	0.7
CO	Gunnison	Piceance	BEAR MINE	Sealed	05/27/82	0.75
CO	Gunnison	Piceance	Bear No 3	Flooded	04/01/97	0.35
CO	Mesa	Piceance	Roadside North Portal	Sealed	2/25/2000	0.7
CO	Mesa	Piceance	Roadside South Portal	Venting/ Partially Flooded	4/25/2000	0.4
CO	Moffat	Piceance	Eagle No 5		03/04/96	0.35
CO	Pitkin	Piceance	COAL BASIN	Sealed	02/27/81	1.6
CO	Pitkin	Piceance	L.S.Wood	Sealed	12/02/85	2.4
CO	Pitkin	Piceance	Thompson Creek No. 1	Sealed	09/01/86	0.35
CO	Pitkin	Piceance	Dutch Creek No. 2	Sealed	7/1/1988	*1.7*
CO	Pitkin	Piceance	Dutch Creek No 1	Sealed	10/4/1992	2.9
CO	Fremont	Raton	Southfield Mine		5/10/2001	0.35
CO	Las Animas	Raton	Allen		*06/10/84*	0.75
CO	Las Animas	Raton	Golden Eagle	Sealed/ Recovering Methane	5/30/1996	4.5
NM	Colfax	Raton	York Canyon Mine		3/3/1986	0.3
NM	Colfax	Raton	Cimarron	Sealed	10/10/98	0.75
UT	Carbon	Uinta	Carbon No 2		*06/10/74*	0.35
UT	Carbon	Uinta	Kennilworth	Sealed	*06/10/74*	0.75
UT	Carbon	Uinta	Braztah No 3		*06/10/79*	0.35
UT	Carbon	Uinta	Price River No. 3		*06/10/82*	0.9
UT	Carbon	Uinta	Price River No. 5		*06/10/82*	0.3
UT	Carbon	Uinta	Beehive	Sealed	03/27/87	*1.7*
UT	Carbon	Uinta	Castle Gaste Portal #5	Sealed	03/31/88	*1.7*
UT	Carbon	Uinta	Sunnyside Mine No. 3	Sealed	09/20/90	*1.7*
UT	Carbon	Uinta	Castle Gate Mine	Sealed	10/23/91	0.75
UT	Carbon	Uinta	Sunnyside Mine No. 1	Sealed	6/27/1994	*1.7*
UT	Carbon	Uinta	Soldier Canyon	Venting	10/10/1999	2.6
UT	Emery	Uinta	Trail Mountain Mine		6/29/2001	0.85
UT	Grand	Uinta	Wilberg	Sealed	02/05/90	*1.7*
UT	Sevier	Uinta	Emery	Sealed	08/01/95	0.35
AL	Jefferson	Warrior	Flat Top	Flooded	*06/10/79*	1
AL	Jefferson	Warrior	Bessie Mine		*06/10/82*	1
AL	Jefferson	Warrior	Concord No 1	Flooded	*06/10/84*	4.5
AL	Jefferson	Warrior	Mulga	Flooded	*06/10/84*	1.2
AL	Jefferson	Warrior	MAXINE MINE	Flooded	10/02/89	0.35
AL	Jefferson	Warrior	NEBO MINE	Flooded	10/02/89	0.35
AL	Jefferson	Warrior	Chetopa	Flooded	*06/10/96*	0.75
AL	Jefferson	Warrior	Blue Creek No. 3	Sealed/ Recovering Methane	10/1/1999	12.3
AL	Shelby	Warrior	Segco No 2	Flooded	*06/10/72*	0.35
AL	Shelby	Warrior	BOONE NO. 1		12/10/1998	1.3
AL	Walker	Warrior	Gorges No 7	Flooded	*06/10/79*	0.35

APPENDIX A. U. S. Abandoned Coal Mine Database

State	County	Coal Basin	Mine Name	Current Emissions Status	Date Abandoned	Active Mine Emissions (mmcfd)
AL	Walker	Warrior	Segco No 1	Flooded	*06/10/84*	0.75
AL	Walker	Warrior	Mary Lee No 2	Flooded	*06/10/93*	0.35
AL	Walker	Warrior	Mary Lee No 1	Flooded	*5/10/1997*	1.5

APPENDIX B. State Agencies and Organizations with Information on Abandoned Coal Mines and Regulations

Geological Survey of Alabama
420 Hackberry Lane (W.B. Jones Hall)
The University of Alabama
Tuscaloosa, Alabama 35486-6999
(205) 349-2852

Colorado Department of Natural Resources
Division of Minerals and Geology
1313 Sherman St., Rm. 215
Denver, CO 80203
(303) 866-3567

Illinois Department of Natural Resources
Illinois Office of Mines and Minerals
300 W. Jefferson, Suite 300
Springfield, IL 62701-1787
(217) 782-6791

Illinois State Geological Survey
615 E. Peabody
Champaign, IL 61820
(217) 333-4747

Indiana Department of Natural Resources
Bureau of Mine Reclamation
402 W. Washington St., Rm. W295
Indianapolis, IN 46204
(317) 232-1547

Geological Survey
Indiana University
Energy Resources Division
611 North Walnut Grove
Bloomington, IN 47405-2208
(812) 855-7636

Kentucky Department of Mines and Minerals
P.O. Box 2244
Frankfort, KY 40602
(502) 573-0140

Ohio Department of Natural Resources
Division of Mines and Reclamation
1855 Fountain Square, Bldg. H-3
Columbus, Ohio 43224
(614) 265-6633

Pennsylvania Dept. of Environmental Protection
Bureau of Abandoned Mine Reclamation
Rachel Carson State Office Building
PO Box 8476
Harrisburg, PA 17105-8476
(717) 783-2267

Pennsylvania Dept. of Environmental Protection
Bureau of Abandoned Mine Reclamation
Rachel Carson State Office Building
P.O. Box 8461
Harrisburg, PA 17105-8461
(717) 787-5103

Utah Department of Natural Resources
Division of Oil, Gas, and Mining
Abandoned Mine Reclamation
1594 West North Temple, Suite 1210
P.O. Box 145801
Salt Lake City, Utah 84114-5801
(801) 538-5349

Virginia Dept. of Mines, Minerals, and Energy
PO Box 900
U.S. Route 23 South
Big Stone Gap, VA 24219
(540) 523-8100

West Virginia Dept. of Environmental Protection
Office of Abandoned Mine Lands & Reclamation
PO Box 6064, NRCCE Bldg.
Morgantown, WV 26505
(304) 293-2867 ext. 5460

West Virginia Dept. of Environmental Protection
Office of Mining & Reclamation
10 McJunkin Road
Nitro, WV 25143
(304) 759-0510

Appendix C. Combining Uncertain Parameters Using Monte Carlo Simulation

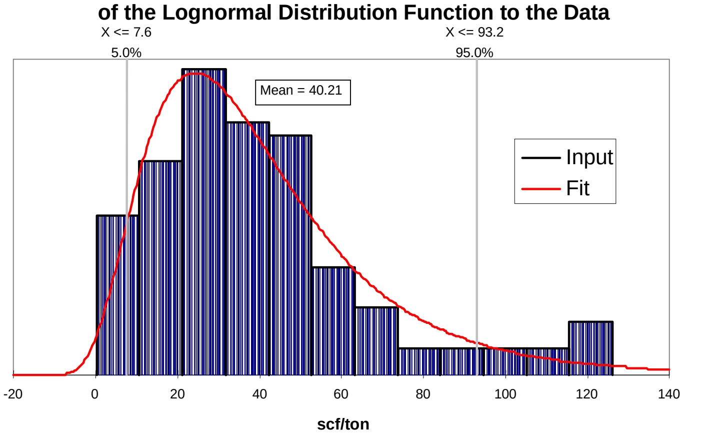
The IPCC guidelines for GHG inventory reporting require that the values be reported to within a 95% confidence interval. In other words, that there is a 95% probability that the true value will lie within a specified interval (or, conversely, a 5% chance that the true value will lie outside of this interval). Because the methodology presented in this report relies on combining variables with uncertain values, a technique was needed that allowed the statistical uncertainty of those values to be captured in the calculated abandoned mine methane emission value for a given inventory year. One way to do this type of analysis is through Monte Carlo simulation.

The purpose of this appendix is to explain the process of combining probability distributions within mathematical functions, such as products and sums, using Monte Carlo simulation and to help provide an understanding of the nature of the results. The stepwise calculation of the volume of methane emitted from a vented abandoned mine for the inventory year 1992, and its associated confidence interval, will be used as an example to illustrate the process. The methane emissions for several mines will then be summed using Monte Carlo simulation to provide a frequency distribution, and hence the confidence interval, for the emission inventory of those abandoned mines.

Quantifying uncertainty

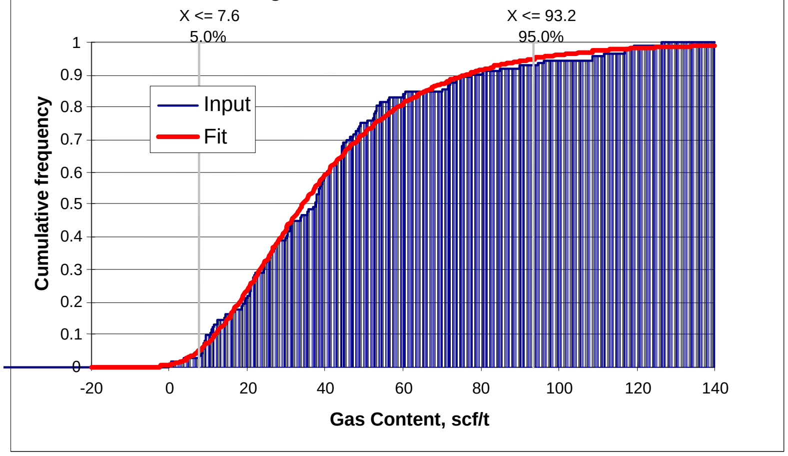
The term "variables with uncertain values" means that if the variable of interest is measured repeatedly, the value of that variable will be different with each measurement. This difference can be related to measurement error or variations through time or by sample location. If the value is measured numerous times, the frequency of occurrence of a value or range of values can be determined and an experimental frequency histogram is created. **Figure C-1** is an example of a frequency histogram of gas content data from a coal basin in the United States. A continuous probability distribution function can be fitted to the frequency histogram of the measured data. It is generally the probability distribution function that is used within mathematical expressions to generate a frequency histogram of the result. A lognormal distribution function is the best fit to the histogram in **Figure C-1**, but there are several functions available to choose from, each with a different general shape. The @Risk® add-in to Microsoft Excel used in this inventory contains a subroutine that fits a set of probability distribution functions to the experimental frequency histogram and then ranks each function by the goodness of fit using three different statistical tests.

Figure C-1. Histogram of Gas Content Data and the Best Fit of the Lognormal Distribution Function to the Data



Another way that data distributions are often presented is by the cumulative frequency diagram. **Figure C-2** is a cumulative frequency diagram of the data shown in **Figure C-1** including the lognormal cumulative probability function. Both of these figures show delimiters at the 5% and 95% frequency. The meaning of these values is best understood from **Figure C-2**. The 5% value of 7.6 scf/t means that 5% of the time a sampled value will be 7.6 scf/t or less or, conversely, that 95% of the time a sampled value will be 7.6 scf/t or more. There is a 95% chance that a sampled value will be 93.0 scf/t or less, or a 5% chance that it will be 93.0 scf/t or greater. These values represent the 90% confidence interval. In other words, there is a 90% chance that a sampled value will lie between 7.6 and 93.0 scf/t.

Figure C-2. Cumulative Probability of Gas Content Data and Best Fit of the Lognormal Distribution Function to the Data



Methodology review

The methodology for determining the methane emissions from an abandoned underground coal mine for a particular inventory year uses mathematical prediction techniques based on material balance and the behavior of gas flowing through a porous adsorptive media, coal, to the atmosphere. Section 4.2 in the main body of the report describes how a set of dimensionless emission rate decline curves were generated for each U.S. coal basin based on these principles. These decline curves were then fitted to a hyperbolic equation of the form:

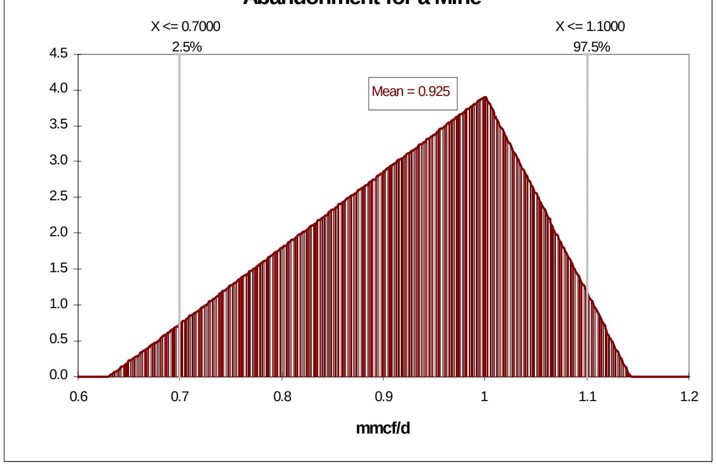
$$q/q_i = (1+bD_i t)^{(-1/b)}$$

Where:

q is the gas rate at time t in mmcf/d
q_i is the initial gas rate at time zero (t_o) in mmcf/d
b is the hyperbolic exponent, dimensionless
D_i is the initial decline rate, 1/day
t is elapsed time from t_o, days

Based on these decline curves and the time since abandonment, the emissions for a given inventory year are determined.

Figure C-3. Uncertainty of the Initial Emission Rate at Abandonment for a Mine



Using probability distributions as variables

A single value of the yearly emissions can be calculated from the single values of the initial emission rate and the decline coefficients, b and D_i. The initial emission rate (q_i), however, is uncertain. The measured emissions have an estimated uncertainty of plus 10% and minus 30% within a 95% confidence interval (as discussed in Section 4.4.4). In the example above, the measured emissions at closure was 1.0 mmcf/d, plus 0.1 mmcf/d or minus 0.3 mmcf/d. This information can be characterized as a triangular probability function with a mean value of 0.925 as shown in **Figure C-3**. Using this function in place of the single value for initial emission rate will result in a frequency histogram of the yearly methane emission for this mine in 1992.

Unfortunately, the initial emission rate is not the only uncertainty in the hyperbolic equation. The hyperbolic decline coefficients are also uncertain. The decline coefficients for the Central Appalachian Basin are listed in **Table C-1**. The low, mid and high cases relate to low, mid and high permeability uncertainty (see section 4.4.2). The range of values is not meant to capture the extreme values, but values that represent the highest and lowest quartile of the data distribution. These are specified as the values at the ten-percentile and the ninety-percentile of the cumulative probability function of the parameter.

Table C-1. Central Appalachian Hyperbolic Decline Coefficients

Case	b	D_i, 1/day
Low (P10)	1.079	0.00892
Mid (P50)	1.834	0.00874
High (P90)	1.014	0.00077

Figure C-4 shows the three emissions decline profiles based on these coefficients for the example mine data in **Table C-2**. Given an abandonment date and an emission rate at the time of closure, as in **Table C-2**, the mid-range case emission estimate for the inventory year 1992 can be calculated using the following function.

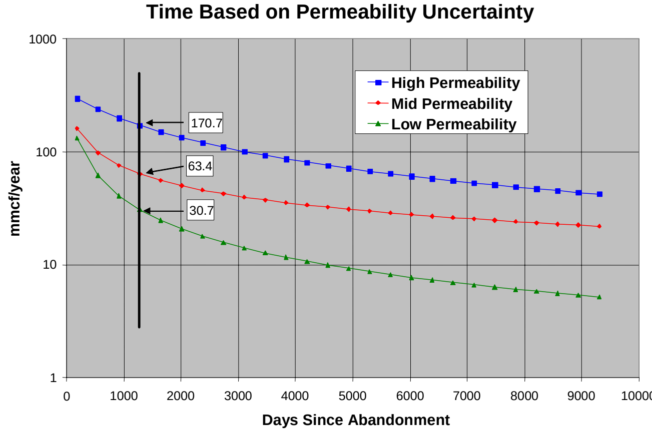
$$q = 63.4 = 365 * 0.925\ (1+1.83 * 0.0087 * 1278)^{(-1/1.83)}$$

Table C-2. Sample inventory calculation for a vented mine

Coal Basin	Mine Name	Status	Date of Abn.	Active Mine Emissions (mmcf/d)	Time Since Closure, days	Mid Emission (mmcf/yr)	High Emission (mmcf/yr)	Low Emission (mmcf/yr)
CA	Example	Venting	06/21/88	0.925	1278	63.4	170.7	30.7

Calculating the emission rate probability function for the low, mid or high permeability case for an inventory year can be done on a personal computer using a spreadsheet program with "add-in" Monte Carlo simulation software such as @Risk®. The software randomly selects a value for the initial emission rate variable based on the probability of this value occurring as described by the triangular probability function (**Figure C-3**). This value is used to calculate a value of the

Figure C-4. Single Abandoned Mine Emissions Through Time Based on Permeability Uncertainty



yearly emissions for the inventory year of interest. This sampling process is repeated numerous times (the number of times is set by the user) producing the probability function for the emission rate for that inventory year. This is shown by **Figure C-5,** which represents sampling the triangular probability function and calculating the result 5,000 times for the low, mid and high emissions estimates shown in **Table C-2**. Each of the forecasted distributions has an uncertainty range of plus 10% and minus 30% relative to the mode as shown in **Table C-3**.

Table C-3. 95% confidence intervals and percent difference for example mine emissions for 1992 by permeability case, mmcf

Case	P2.5%	Mode	P97.5%	% Difference Low	% Difference High
Low Permeability	48.0	68.1	75.4	-30%	10%
Mid Permeability	23.2	33.1	36.5	-30%	10%
High Permeability	129.2	184.3	203.0	-30%	10%

Distributions within distributions

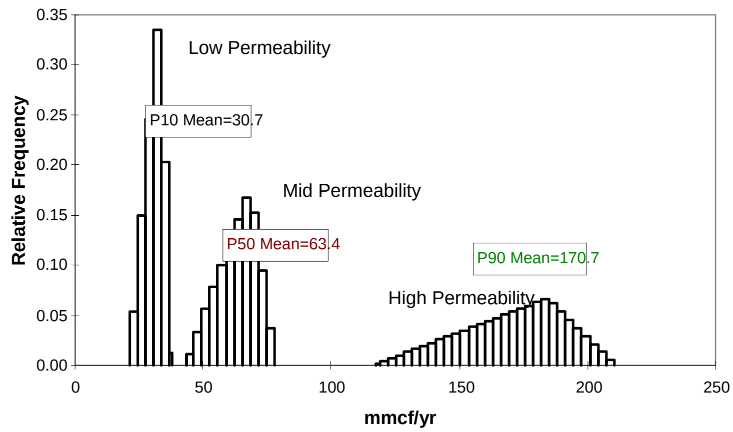


Figure C-5. Yearly Emission Volumes Based on Permeability and Emission Rate At Closure Uncertainties

In order to generate a single probability density function of the emissions for this mine for 1992, the low, mid and high distributions need to be combined. Here the probability density function depicts the frequency of occurrence of the range of values that potentially may occur, plotted versus the probability of any given outcome occurring. Generating this probability density function is accomplished by selecting the low, mid and high emission distributions as the low, mid and high points in another triangular distribution shown in **Figure C-6**. The endpoints (which are specified as the means of each distribution) are defined as the P10, mode and P90 because this is how the permeability ranges were characterized when generating the decline curves. A condition must be applied to this distribution so that no negative emission values are returned in the final distribution. The final distribution is shown in **Figure C-7**. This distribution shows that the emission for inventory year 1992 is between 12.3 and 210.7 mmcf at a 95% confidence interval with a mean of 96.5 mmcf. This is a range of plus 118% and minus 87% relative to the mean of the distribution. **Figure C-8** shows the mean predicted for yearly emissions for this mine with the 95% confidence interval.

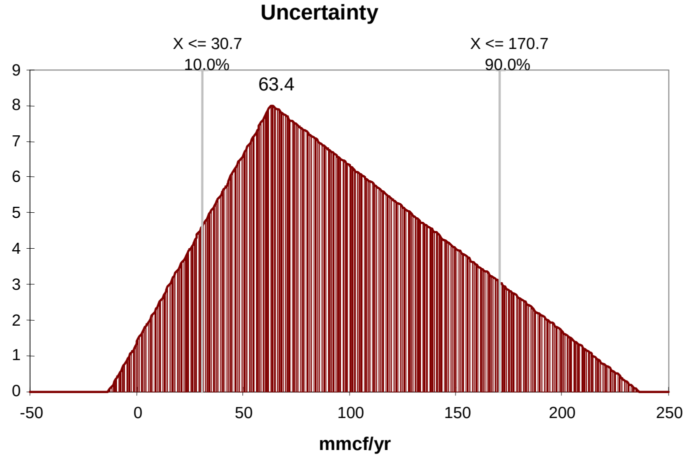


Figure C-6. Static Triangular Distribution for Uncertainty

Figure C-7. Initial Rate Distribution and Permeability Distribution Combined

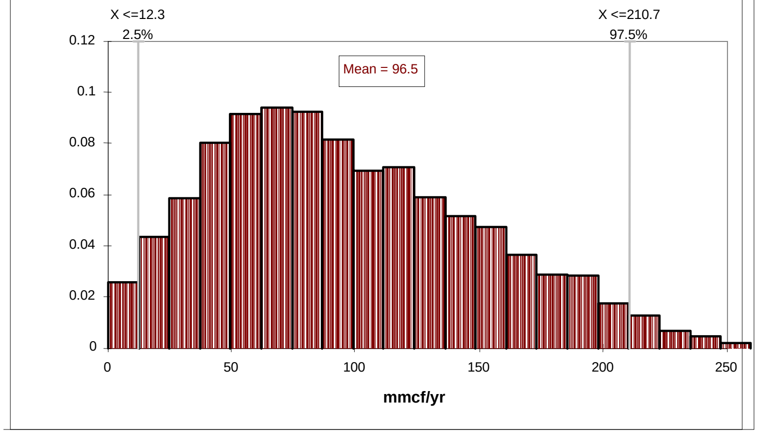
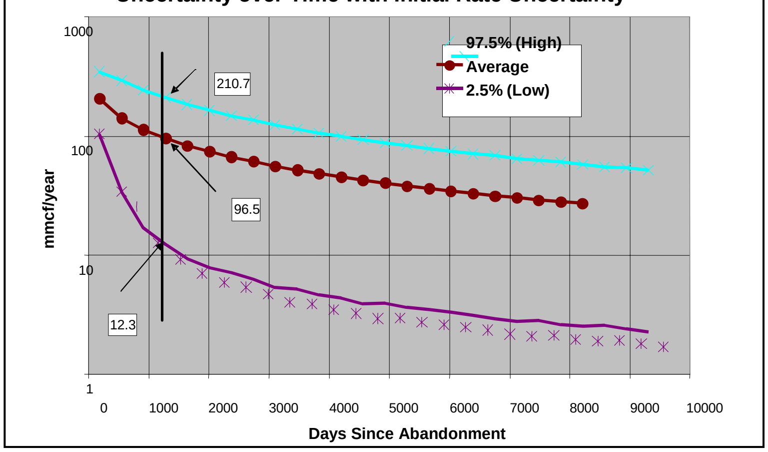


Figure C-8. Single Abandoned Mine Emissions Uncertainty over Time with Initial Rate Uncertainty



Summing distributions

The probability distribution of the emissions and their associated confidence intervals will be different for each mine for any given inventory year. Summing these distributions is an appropriate way to determine the basin total emissions and the associated uncertainty. Intuitively, one might expect that the range of uncertainty of a combination of highly uncertain predictions would yield an even more uncertain result, while, in fact, the opposite is true. **Table C-4** lists a subset of vented Central Appalachian basin mines for inventory year 1992 with the mean value of their calculated yearly emissions, the 2.5% and 97.5% probability values, and their percent difference relative to the mean. The result of the summed distributions is also shown on the bottom line of **Table C-4**. The sum of the mean values for each mine's emission distribution is the same as the mean of the summed distributions. However, the summation of the values of the 2.5% probabilities is much smaller than the 2.5% probability value of the summed distributions. Similarly, the sum of the 97.5% probability values is much larger than the 97.5% probability value of the summed distributions. The range of uncertainty of the summed distributions is significantly smaller than the range of uncertainty of the individual distributions for a given confidence interval.

Table C-4. Partial list or Central Appalachian abandoned coal mines and their mean emission estimate with the 95% confidence interval bounding values							
Mine Name	**Mean**	**2.5% Prob.**	**97.% Prob.**	**%Diff Low**	**%Diff High**	**Std Dev**	**Coefficient of Variation**
Cannelton No 8	18.6	1.8	40.8	-90%	119%	10.4	56%
U.S. Steel No 14-4	52.1	4.9	113.1	-91%	117%	28.8	55%
Maitland	37.3	3.5	81.2	-91%	118%	20.8	56%
Beckley No 2	89.4	10.6	195.3	-88%	118%	49.6	55%
Beckley No 1	34.3	3.3	76.0	-90%	121%	19.3	56%
Kepler	19.4	1.9	41.7	-90%	115%	10.6	55%
Newhall No. 6 Mine	21.1	2.0	45.6	-91%	116%	11.8	56%
Sewell No 4	14.9	1.5	31.5	-90%	112%	8.1	54%
Sums (or Averages*) of Values	**287.2**	**29.0**	**625.2**	**90%***	**117%***	**19.9***	**55%***
Sum of Distributions	**287.2**	**165.4**	**429.6**	**-42%**	**50%**	**68.0**	**24%**

Conclusions

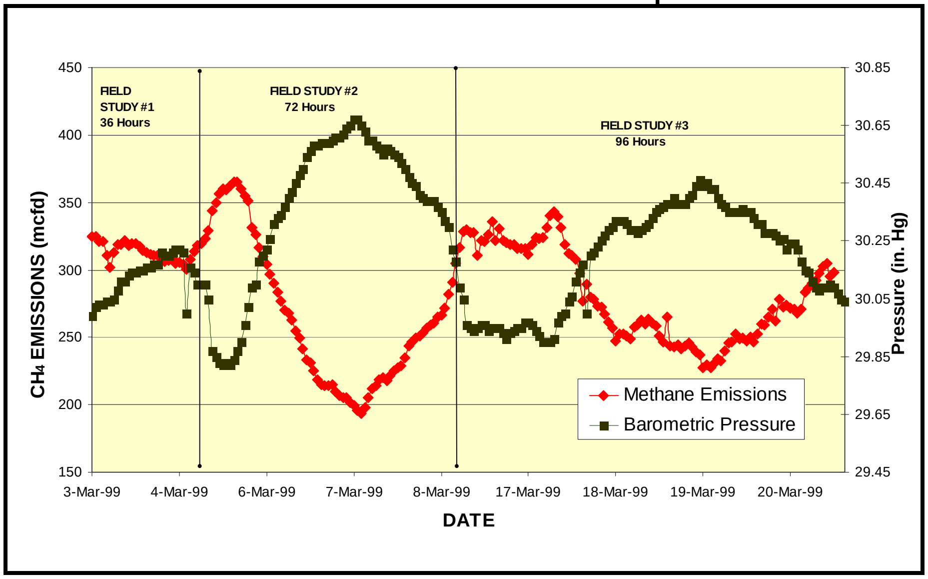
This process may seem counterintuitive. For example, an individual mine in **Table C-4** (Beckley #1) located in the Central Appalachian Basin had an uncertainty range of plus 121% and minus 90% for the 1992 inventory. After that mine is combined into a larger group of mines (classified by coal basin), the resulting range of uncertainty for the Central Appalachian Basin mine group is plus 41% and minus 32%. Furthermore, the range of uncertainty associated with the entire population of abandoned mines compiled for the 1992 inventory results in an even lower range of plus or minus 20%. The above example illustrates the phenomenon, supported by the central limits theorem, that the coefficient of variation (standard deviation divided by the mean) of the sum of distributions is smaller than the coefficient of variation of the component distributions.

APPENDIX D. Effect of Barometric Pressure

During the spring of 1999, EPA collected gas flow and quality data from an abandoned mine vent in the Illinois basin to correlate flow rates with barometric pressure.[39] The mine selected for the study had been closed since 1962, but a three-inch vent pipe remained intact and continued to vent methane into the atmosphere. This mine is considered representative of gassy abandoned mines in the Illinois basin region.[40]

Figure D-1, which shows all three data sets taken, clearly illustrates the strong inverse relationship between barometric pressure and methane emissions from the mine vent. As barometric pressure increases, mine emissions decrease. As the graph illustrates, the 72-hour and 96-hour studies resulted in roughly the same average emission rate. Based on these measurements, EPA determined that 72-hour flow measurements are sufficient for determining a mine's average flow rate.[41]

Figure D-1. Illinois Basin field measurements of barometric pressure and mine emissions



Correlating gas flow rates to barometric pressure is critical for obtaining representative field measurements for decline curve validation. The correlation between gas flow and barometric pressure is shown in **Figure D-2**. The linear regression equation describing the relationship resulted in a correlation coefficient (R^2) equal to 0.92.

---

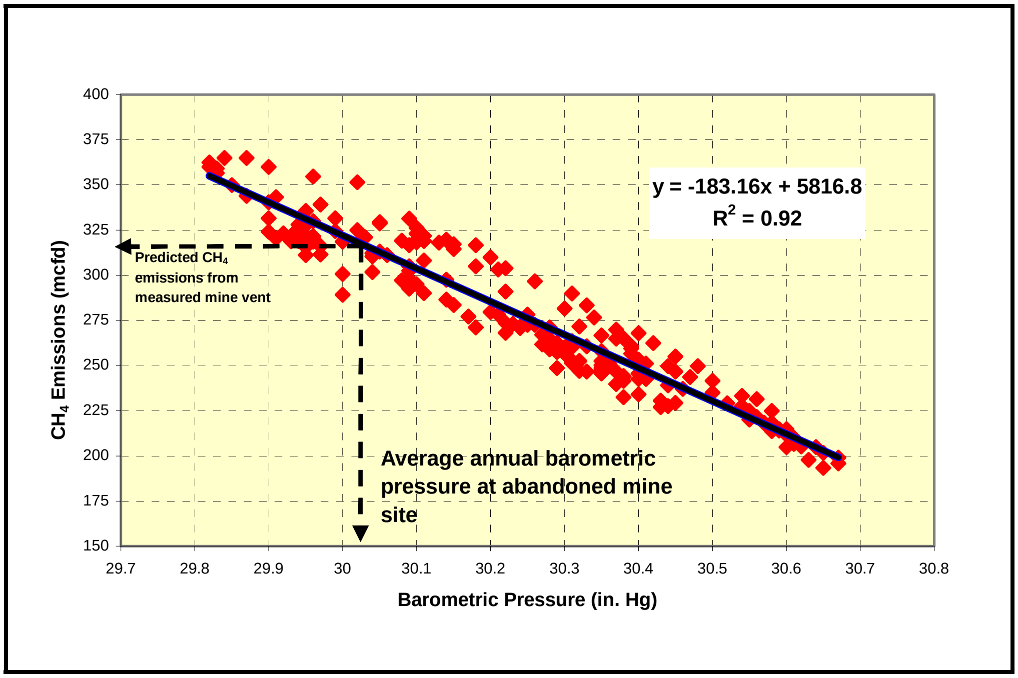
[39] Flow measurements were recorded at the vent pipe every hour over three 2-4 day periods to determine the minimum time necessary to obtain representative emissions data. Corresponding hourly barometric pressure data obtained from the Midwestern Climate Center indicates that the average annual barometric pressure for this county was 30.03 inches of mercury. Variations in barometric pressure during the study were typical of the annual variation. The calculated average methane emissions rate for the vent pipe equaled 316.5 mcfd; daily readings ranged from 195 to 365 mcfd.
[40] This mine is of room and pillar type, 500 to 600 feet deep, and includes the Herrin #6 coal seam.
[41] Daily variations in the flow rate mean that daily measurements may not be reflective of the average flow rate.

For this study, only field-measured gas flow rates were normalized to account for average annual barometric pressure. Emission rates derived from numerical modeling were based on a constant barometric pressure of one atmosphere.

Ideally, one would measure diffuse emissions from sealed mines, through surface cracks and fissures, to more accurately determine the degree to which mines are sealed (referred to in terms of percentage sealed). Some techniques exist to measure these diffuse emissions (e.g., using infrared detectors), but resource limitations prohibited their use for this study.

Of the 374 mines in the U.S. abandoned mines database, only about 14% maintain vents to the atmosphere. Therefore, basing emissions estimates on field data alone would result in an unrepresentative and biased estimate. Therefore, additional field measurements could be used to further calibrate emission estimates. It would be particularly useful to extend such measurements to sealed mines since they comprise such a significant component of the inventory.

Figure D-2. Correlation between mine methane emissions and barometric pressure



Appendix E. Sensitivity Analysis Calculations

To test the sensitivity of emissions calculations to three parameters (adsorption isotherm, as represented by V_L and P_L, permeability, and pressure at abandonment) involves 27 calculations for each mine for each inventory year, since three values of each parameter must be tested (high, low, and mid-range). A sensitivity analysis was performed to determine if the range of uncertainty of these three parameters is large enough to make a significant difference in the outcome of the calculation. If a parameter does not have a significant effect on the outcome, the probability analysis is not necessary and the mid-case value of the parameter can be used in the calculations.

To test the sensitivity of the calculations to the range of uncertainty, seven cases were generated using the values shown in **Table E-1**. Gas content of coal mines at low pressures is most sensitive to the value of the Langmuir Pressure, to which it is inversely proportional. The Langmuir Volume has little effect.

Table E-1. Parameter values used in sensitivity analysis

Parameter	High	Mid	Low
Permeability, md	10	1	0.1
Pressure, psia	30	20	17
P_L, psia	176	286	667
V_L, scf/ton	712	911	1093

These values were combined and used in the CFD model to calculate an emission inventory number using a set of mine data from the Central Appalachian basin. **Table E-2** lists the results, which are shown graphically in **Figure E-1**. The mine is assumed to be emitting methane to the atmosphere through one or several vents as opposed to being sealed or flooded.

Table E-2. Results of parameter sensitivity test

Permeability	Pressure	Isotherm	Emissions, Bcf/yr
High	Mid	Mid	8.877
Mid	Mid	Mid	4.259
Low	Mid	Mid	1.627
Mid	High	Mid	4.970
Mid	Low	Mid	4.049
Mid	Mid	High	4.504
Mid	Mid	Low	3.546

Figure E-1. Range of uncertainty for 1990 methane emissions for the Central Appalachian basin associated with key parameters.

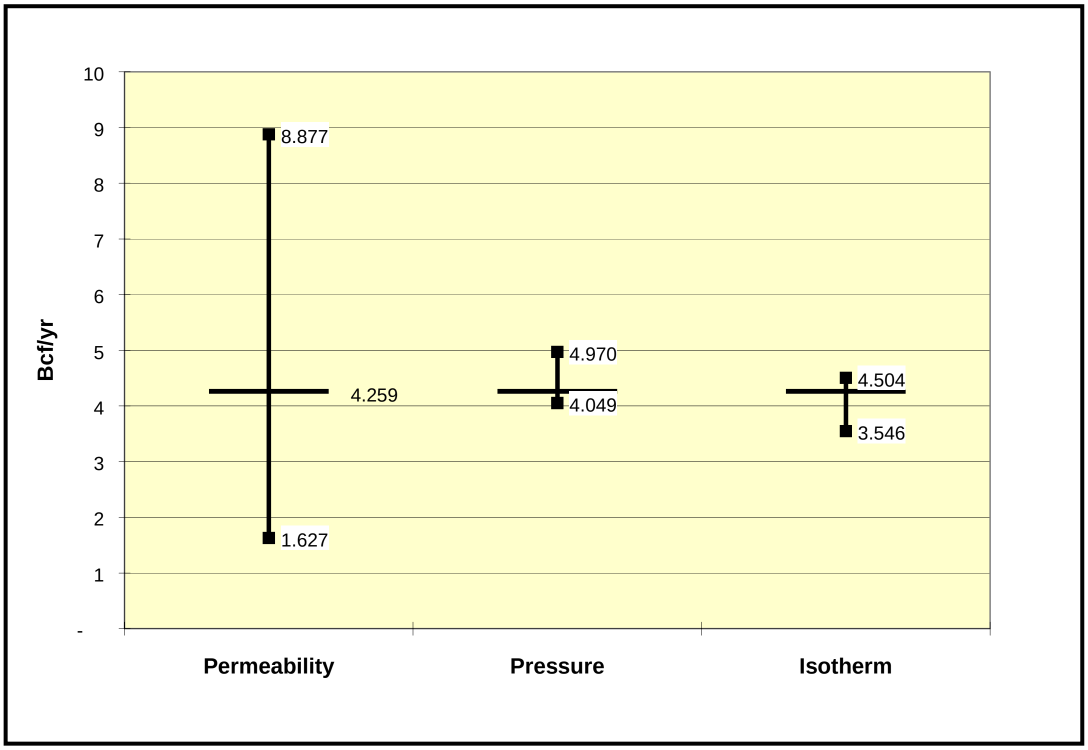


Figure E-1 shows that the calculated emissions for 1990 for the Central Appalachian basin are much more sensitive to permeability than to either initial pressure or the adsorption isotherm. Inventory calculations, therefore, use mid-case values for initial pressure and the mid-case basin isotherm, but include the range of values for permeability for the probabilistic analysis.

APPENDIX F. Emissions Inventory: Sample Calculations According To Mine Types

Venting Mines

The low, mid and high emission calculations are based on decline equations derived from the simulation model using the mid case adsorption isotherm for the basin, using permeability values of 1.0, 10.0 and 0.1 md, respectively. **Table F-1** shows the results from the spreadsheet for the year 2000 inventory.

Table F-1. Sample inventory calculation for a venting mine

Coal Basin	Mine Name	Status	Date of Abn.	Active Mine Emissions (mmcf/yr)	Time Since Closure, days	Mid Emission (mmcf/yr)	High Emission (mmcf/yr)	Low Emission (mmcf/yr)
Central Appl.	Cannelton No 8	Venting	04/05/83	323.644	6480	9.349	20.146	3.533

The mid case equation for Central Appalachian Basin (shown below) is based on **Equation 4:**

$$q = q_i(1+bD_it)^{(-1/b)}$$

$$q = 9.349 = 323.64(1+1.83 * 0.0087 * 6480)^{(-1/1.83)}$$

Different decline curve equation sets are used for each coal basin, because each basin has a unique adsorption isotherm, which affects the decline curves calculated for each permeability value.

The resulting three emissions estimates for each basin are then used to define a triangular distribution for each mine (**Figure F-1**). The 10% and 90% probabilities shown in **Table F-1** and **Figure F-1** are used to represent the lower and upper quartiles of the distribution.

This methodology uses the entire triangular distribution of emissions for each mine as input for a Monte Carlo simulation. This produces a probability distribution of emissions for the population of all venting abandoned mines (**Figure F-2).**

The frequency histogram shown in **Figure F-2** is the result of randomly sampling the triangular distribution of emissions for each mine (e.g., in **Figure F-1**) one thousand times and adding them together. Additional trials did not significantly change the mean or the variance of the distribution. The brackets on the x-axis show the 95% certainty bounds.

Figure F-1. Distribution of Year 2000 Emissions for a vented abandoned mine

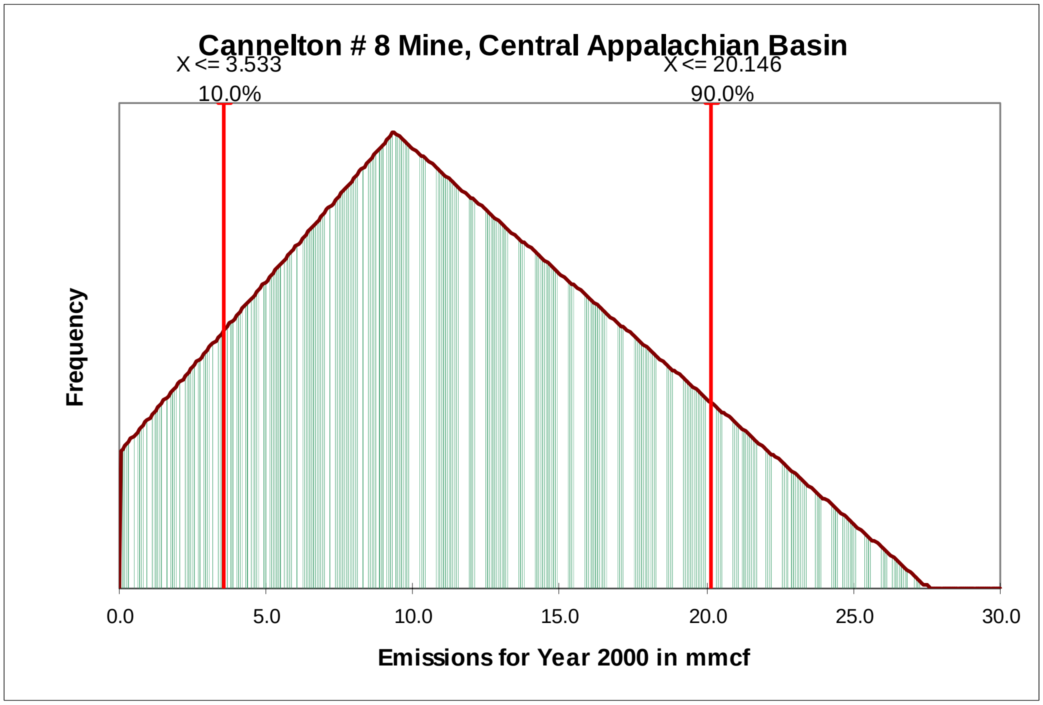
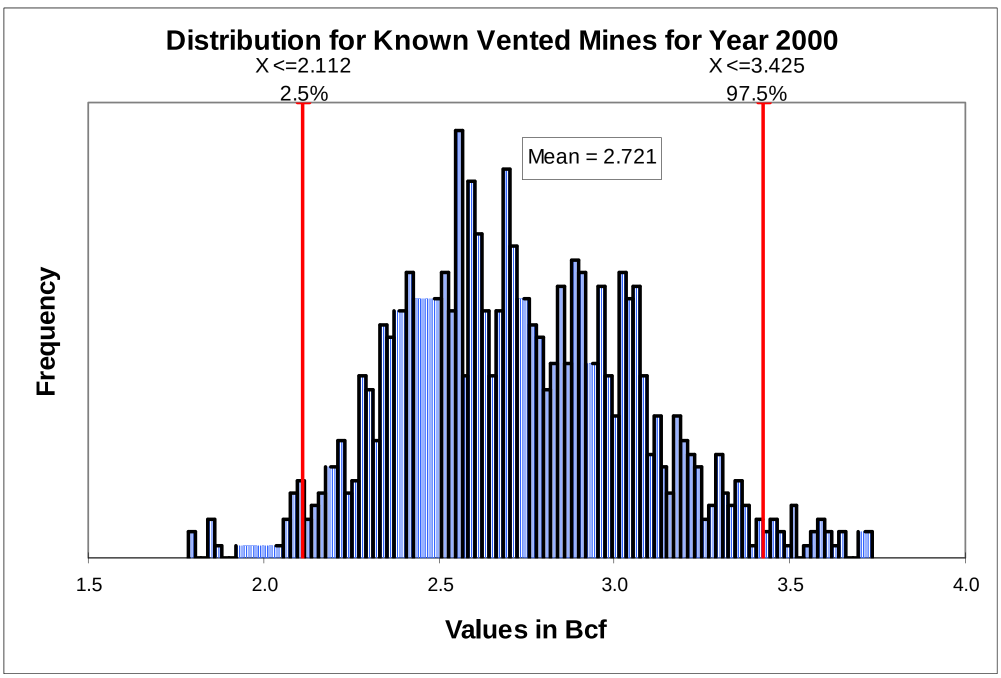


Figure F-2. Probability density function for vented abandoned mines emissions for the year 2000



Flooded Mines

The calculation procedure for flooded, but still venting, mines is very similar to that for dry venting mines except that an exponential function is used rather than a hyperbolic function. For the mid-range case shown in **Table F-2** below, emissions are calculated using **Equation 5**:

$$q = q_i e^{(-Dt)}$$

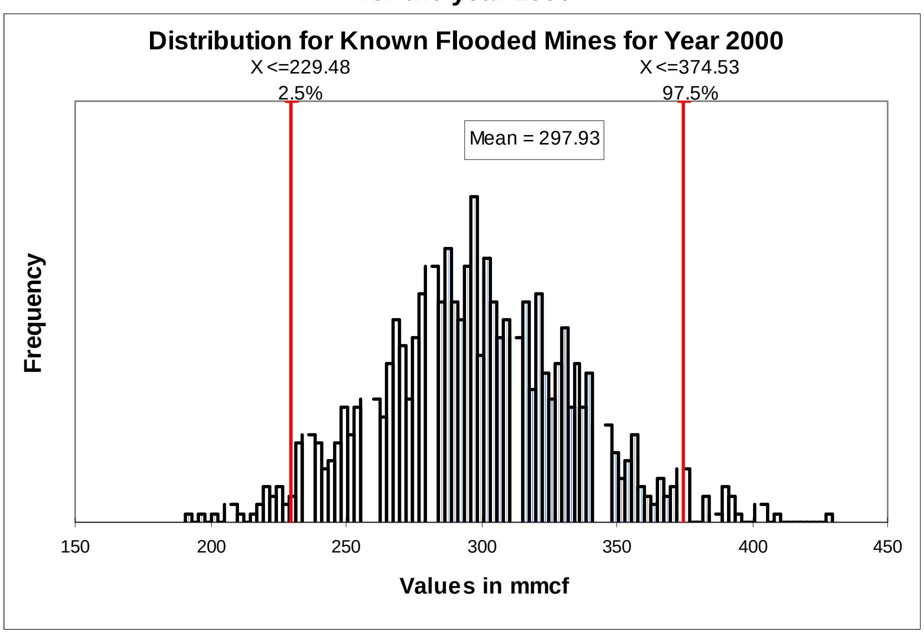
$$0.223 = 1022\exp(-\ 0.672(4580/365))$$

For flooded mines, the exponential constant D in Equation 5 is the same for all basins because it is a simple empirical curve fit to measured data. The low, mid and high emission values, as shown in **Table F-2,** are used to define a triangular distribution. The triangular distributions for all flooded mines are summed to generate a probability distribution for the emissions inventory for the year 2000 (**Figure F-3**).

Table F-2. Sample inventory calculation for a flooded mine

Coal Basin	Mine Name	Status	Date of Abn.	Active Mine Emissions (mmcf/yr)	Time Since Closure, days	Mid Emission (mmcf/yr)	Low Emission (mmcf/yr)	High Emission (mmcf/yr)
Central Appl.	Ogla	Flooded	06/17/88	1022	4580	0.206	0.039	1.106

Figure F-2. Probability density function for flooded abandoned mines emissions for the year 2000



Sealed Mines

The sealed mine calculations average the low, mid-range, and high emission factors based on the permeability uncertainty for each of the "percent sealed" cases of 50%, 80%, and 95%. Here, the 80% sealed case is treated as the most likely or mid-range case. The average emission factor for each of the three values of percentage sealed is used to define a triangular distribution, which is then used in the Monte Carlo simulation to create a probability density function for emissions from sealed abandoned mines. The probability density plot for the year 2000 emissions inventory for sealed mines is shown in **Figure F-4**.

Figure F-4. Probability density function for year 2000 emissions from sealed abandoned mines