NOTE:
This document was prepared as an aide for the development of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2 (Energy), Chapter 4 (Fugitive Emissions). It is intended to provide greater insight into development of national-level abandoned mine methane emission inventories. Nothing in this document shall be construed to contradict the 2006 Guidelines. To the extent that there are any discrepancies between this white paper and the 2006 Guidelines, the Guidelines are the controlling document.

WHITE PAPER:

PROPOSED METHODOLOGY FOR ESTIMATING EMISSION INVENTORIES FROM ABANDONED COAL MINES

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Executive Summary

In countries where coal mining is a key source category for methane emissions, it is highly probable that abandoned coal mines also produce significant methane emissions. Even after closure and abandonment, coal mines that were significant methane emitters during active mining continue to emit methane, although at a reduced rate. Primary conduits for methane emissions from abandoned mines are old portals, vent pipes, and cracks and fissures in the overlying strata. Thousands of abandoned coal mines worldwide continue to emit methane, contributing to total global greenhouse gas emissions.

The United States Environmental Protection Agency (EPA) has recently completed an effort to quantify abandoned underground mine methane emissions in the U.S. both to improve the accuracy of the coal emissions inventory and to assess mitigation opportunities. Due to the unique features of abandoned mines, EPA developed a separate emissions estimation methodology for this subsource. This white paper proposes a methodology that can be used by individual countries with historical coal mining to incorporate methane emissions from abandoned coal mines in their national inventories.

Current guidelines of the Intergovernmental Panel on Climate Change (IPCC) establish three methodological levels (or tiers) for estimating greenhouse gas emissions depending on the level of detail available. For coal mining emissions, Tier 1, which produces estimates with the greatest degree of uncertainty, is based on a country's coal production data and globally-derived average emission factors. Tier 2, a more detailed estimate, is based on average country-specific emission factors, or (if available) on coal basin-specific emission factors. Tier 3, the most detailed estimate, is based on mine-specific emission factors and measurements. This paper presents a step-by-step methodology that may be used to account for abandoned coal mine methane emissions for Tiers 1, 2, and 3.

This paper describes the principal characteristics that influence abandoned coal mine emissions, such as time elapsed since abandonment, gas content, adsorption characteristics, coal permeability, and mine size. The two primary parameters used in estimating abandoned mine emissions are (1) the time (in years) elapsed since the mine was abandoned, relative to the year of the emissions inventory, and (2) the mine's "initial" methane emission rate at the time that it was abandoned. The time elapsed is particularly important; abandoned mine methane emissions sharply decrease as a function of time. Graphical representations illustrating the rapid drop in abandoned mine methane emissions as a function of time are known as "decline curves." Existing data on abandoned mine emissions appear to fit a hyperbolic model of declining emissions as a function of time. Based on estimated or known mine characteristics, theoretical decline curves are generated and used to predict abandoned mine methane emissions as a function of time. The Tier 1 and Tier 2 approaches are based on aggregations of these decline curve emissions.

Tiers 1 and 2 methodologies follow similar methodological structures that allow for inclusion of best-available data. Tiers 1 and 2 each provide two parallel approaches based on the type of data available: (1) the number of abandoned mines, or (2) the volume of coal production. Each country can select the most appropriate method

depending on the availability of either type of activity data from historical mining and coal production records. The Tier 3 methodology requires mine-specific information such as ventilation emissions from active mining, characteristics of the mined coal seam, mine size and depth, and the abandonment status or condition of the abandoned mine. For Tier 3, each country may generate its own decline curves based on known national- or basin-specific coal properties, or it may use more generic curves based on coal rank.

A country's abandoned mine emission inventory may consist of a combination of these different methodologies to reflect changing data availability for different historical periods. For example, emissions from mines abandoned during the first half of the twentieth century may be determined using a Tier 1 method, while emissions from mines abandoned after 1950 may be determined using a Tier 2 method if more accurate data are available for that time period. It is possible that even more detailed information may be available for mines abandoned since 1990 to enable use of a Tier 3 method. The methodology selected and the calculated emissions estimates should be based on the best available data.

Beginning with the 2005 emissions inventory, the United States plans to include abandoned coal mine methane emissions in its national greenhouse gas inventory. Other nations, including the United Kingdom and Germany, are investigating the inclusion of abandoned mine methane emissions in their greenhouse gas inventories. The proposed methodology presented in this white paper is based on several years of research and study of abandoned coal mines in the United States by the EPA's Coalbed Methane Outreach Program. It has been generalized so that it may be applicable to all ranks of coal mined globally.

1.0 Introduction

In countries where coal mining is a key source category, it is highly probable that abandoned coal mines also produce measurable methane emissions. Moreover, abandoned coal mine emissions may be noteworthy in countries where underground coal mining was, but is no longer, an important source category. Worldwide, approximately twenty countries[1] have or had major coal mining activities resulting in significant methane emissions.

Thousands of closed coal mines in the United States and other countries continue to emit methane, contributing to total global greenhouse gas (GHG) emissions. However, to date, coal mine methane (CMM) emission inventories are limited to operating (active) mines, in part, because of a lack of guidance on how to quantify emissions from abandoned mines. The unique conditions found in abandoned mines affect the character and rate of methane emissions, warranting a separate emissions estimation methodology from that employed for operating mines. This paper describes the methodology for determining methane emissions from abandoned underground coal mines developed by US EPA. Using this method, EPA plans to include methane emissions from abandoned mines in its national greenhouse gas inventory in 2005.

The U.S. Environmental Protection Agency (EPA) developed this methodology for estimating its national abandoned mine emissions based on country-specific and mine-specific data. These abandoned mine methane emissions represent about 5 to 10% of the U.S inventory of coal mine methane emissions (EPA, 2003). **Figure 1.1** shows abandoned coal mine emissions estimates for the U.S. from 1990-2002. In 2002, net U.S. abandoned mine methane emissions (accounting for emissions avoided due to recovery projects) have been estimated at 290 million cubic meters or nearly 200 teragrams (Tg) (4.1 million metric tons of carbon dioxide equivalent (CO_2e), using a global warming potential of 21 for methane).

[1] Countries identified as having significant methane emissions from coal mining in the present or past include Australia, Belgium, Bulgaria, China, Czech Republic, France, Germany, Greece, India, Japan, Kazakhstan, Mexico, Poland, Russia, South Africa, Spain, Ukraine, United Kingdom, and United States.

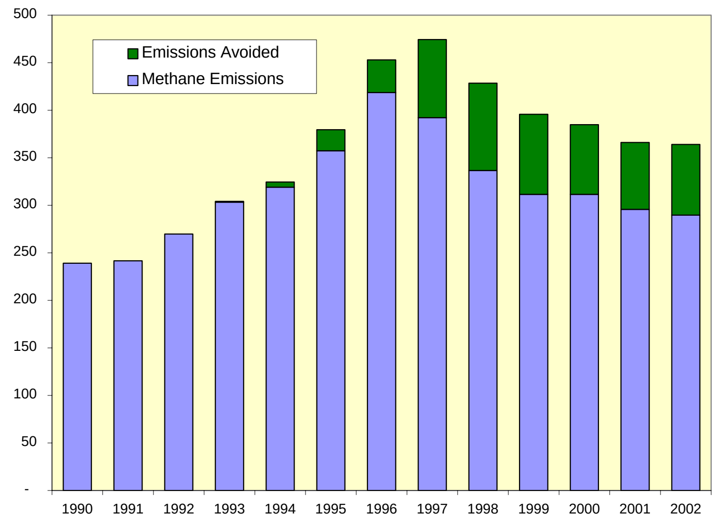

Figure 1.1 – Methane Emissions from US Abandoned Coal Mines, 1990-2002

The U.S. used this methodology to quantify methane emissions from abandoned U.S. mines for each year from 1990 through 2002. The process of developing a national inventory for abandoned mine methane (AMM) emissions consists of five basic steps:

1. Creating a database of gassy abandoned coal mines.
2. Identifying key factors affecting methane emissions (e.g., permeability, sealed or flooded status of mine, or time elapsed since abandonment) and develop coal basin-specific emission rate decline curves.
3. Validating mathematical models (decline curves) through a field measurement program.
4. Calculating a national emissions inventory for each year.
5. Adjusting for methane recovery and determining the net total emissions.

The UK and Germany are actively investigating the inclusion of abandoned mine methane emissions in their greenhouse gas inventories. The UK has made a preliminary emission estimate of approximately 1 million tons of CO_2e based on a partial survey of abandoned mine vents (DTI/Pub, 2004). The UK Department of Trade and Industry is continuing with a study to better characterize abandoned mine emissions. Germany has included AMM in its national inventory, but the emissions estimate and the details of its derivation are not publicly available.

The global level of methane emissions from abandoned mines is unknown at this time. The methodology presented in this paper, adapted from the U.S. approach, may be applied to most coal mining regions of the world and can help quantify global abandoned mine methane emissions.

This paper outlines steps to produce Tier 1, 2, or 3 emissions estimates from abandoned mines to generate emissions estimates even in countries where data are limited. For coal mining, Tier 1 (the least accurate estimate) is based on national coal production data and global average emission factors. Tier 2, a more detailed estimate, is based on national average emission factors, or (if available) on sub-national emission factors. Tier 3, the most detailed estimate, is based on mine-specific emission measurements. Following IPCC good practice guidelines, nations are encouraged to use hybrid approaches to develop emissions inventories by combining higher Tier methodologies for time periods for which they have more data with lower Tier methodology estimates for periods for which detailed information may not be available.

Because methane is a valued fuel source as well as a GHG, performing a national assessment to characterize the magnitude of these emissions may provide beneficial information about an economically attractive GHG mitigation strategy.

1.1 Coal Mine Methane as an Emissions Source

Coalbed methane is known as coal mine methane (CMM) when mining activity results in the release of methane into the mine works and eventually into the atmosphere. Gas released from overlying or underlying coal seams or strata during mining activities contribute to the CMM emissions from the mine. Not all coal mines are significant sources of methane emissions. In the United States, "gassy" mines are defined as mines that emit more than about 2,800 to 14,000 cubic meters per day (m^3/d) of methane[2] in coal mine ventilation emissions. Throughout this paper, the term "gassy" refers to mines that exceeded this emission threshold on an annual average basis when the mines were active.

Active mining practices may impact subsequent coal mine methane emissions from abandoned mines by increasing methane's ability to flow through coal seams. For instance, to ensure mine safety, best practices dictate that powerful ventilation systems remove methane from active underground coal mines. In addition, for particularly gassy mines, operators may 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] During active mining, the methane gas emitted through the ventilation and drainage systems is either released directly to the atmosphere or recovered and used. After abandonment, these boreholes and wells may increase methane transmission through coal seams, thus increasing the abandoned mine's emission rate.

1.2 Abandoned Coal Mine Emissions

As mines mature and coal seams are mined out, mines are closed and eventually abandoned. During the process of reclamation, abandoned mines are often sealed by filling shafts or portals with gravel and capping them with a concrete seal. Vent pipes and boreholes may be plugged with cement in a similar manner to oil and gas wells. Some abandoned mines are deliberately left with vent pipes and boreholes open to the atmosphere to provide a controlled release point for the methane.

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[2] Equivalent to about 0.1 to 0.5 million cubic feet per day (mmcfd).

[3] A "gob" or "goaf" is the rubble zone formed by collapsed roof strata caused by the removal of coal.

As active mining stops, the mine's total gas emissions decrease, but methane liberation from the remaining coal does not stop completely. Following an initial decline, abandoned mines can liberate methane at a near-steady rate over an extended period of time. Even if the mines have been sealed, methane may still be emitted to the atmosphere as a result of gas migrating through natural or manmade conduits. The emission rate is determined by the natural sealing character of the surrounding rock and the degree to which manmade structures have been sealed. Diffuse emissions 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 before the water effectively inhibits the coal mine methane from being released to the atmosphere. However, mines that remain only partially flooded can continue to produce methane emissions over a long period of time. Unfortunately, hydrological information about abandoned coal mines is difficult to obtain unless hydrologic monitoring wells are located in the mine.

In order to avoid miscounting of coal mine emissions (either active or abandoned), it is important to clearly define the term "abandoned mine." For instance, in some countries, such as the United States, a coal mine's ventilation fans may continue to operate for months or even years after coal production ceases due to local or state requirements. During this time, U.S. coal mines must report the methane emissions to the U.S. Mine Safety and Health Administration (MSHA), and these data are included in the *active* coal mine emissions inventory. In other countries, the definition of "abandoned mines" may differ. Regardless of the exact definition of abandoned mines, this methodology is applicable as long as each mine is classified in one and only one database (e.g., active *or* abandoned). For the purpose of this emissions inventory methodology, the term "abandoned" is defined as the time when all active mine ventilation ceases.

1.2.1 Factors Influencing Abandoned Mine Methane Emissions

Within a coalbed, methane is stored both as a free gas in the coal's pores and fractures, as well as in adsorbed form on the coal surface. As a result of mining activities, the partial pressure of methane in the fracture (cleat) system of the coal in and near the mine decreases, allowing the methane to desorb from the coal and move 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 the pressure differential between gas in the mine and atmospheric pressure, the methane will eventually flow through existing conduits and be released to the atmosphere.

Existing data on abandoned mine emissions, although sparse, appear to fit a hyperbolic model of declining emissions as a function of time. When emissions rate is plotted as a function of the time elapsed since the mine was abandoned, the resulting plot is called a "decline curve." Theoretical decline curves (e.g., functions predicting abandoned mine methane emissions as a function of time) can be derived based on estimated or known mine characteristics.

[4] The mine void refers to the mined out area of the coal seam.

In particular, four factors significantly impact the rate of CMM emissions from abandoned mines, as described below.

1. **Time Since Abandonment**

The time elapsed since the mine was abandoned is a critical factor affecting an abandoned mine's annual emissions because the mine's emissions decline steeply as a function of time elapsed.[5] To characterize the dependence of emissions as a function of time, US EPA has developed a set of decline curves, based on U.S. coal basins, that describe the rate at which methane from the coal seams of the abandoned mine is eventually released to the atmosphere.

2. **The Gas Content and Adsorption Characteristics of the Remaining Coal**

The gas content of the remaining coal located in and near the mine void is a function of pressure and the adsorption characteristics of the coal. Adsorption isotherms measure the adsorption capacity of coal seams at a given (constant) temperature. They are a metric for a particular coal seam's capacity to store methane and are therefore important for predicting methane emissions from abandoned mines. (Adsorption isotherms, which can be characterized by mathematical functions based on theoretical adsorption mechanisms, are used to calculate theoretical emissions from abandoned mine coal seams. One function commonly used to describe methane adsorption on coal is called the Langmuir Isotherm.

3. **The Gas Transmissibility of the Coal**

Methane moves from the microporous matrix of the coal to the macroporous structure and the coal cleat system via diffusion. Diffusion from the micropores into the cleat system is usually a relatively fast process. Rather, the rate-limiting step for gas production from coal is the ability of the gas to flow through the macropores and cleat system (Seidle and Arri, 1990). Here, the methane exists primarily in the free gas state, and its movement is determined by the laws of gas flow through porous media, such as Darcy's Law.

4. **The Ability of the Gas to Enter the Atmosphere**

The rate at which the methane within the mine void is emitted to the atmosphere from an abandoned mine is affected by the manner in which the mine was abandoned and whether or not it subsequently floods with water.

Vented mines. 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 and to the surface through fissures in the overlying strata.

Sealed mines. While many abandoned mines have open vents, some mines are sealed in an attempt to prevent unauthorized access or the escape of methane gas. Old shafts and drifts are commonly plugged with cement. Even for sealed mines, however, it is common for gas to leak out around these plugs or to make its way through fractures in the overlying strata. Although seals can impact the rate of flow, they are not considered to be effective at preventing atmospheric methane emissions over time.

[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.

Flooded mines. In many areas, abandoned mines may partially or completely flood, which decreases or completely shuts 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. Mine flooding often plays a determining 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 only a fraction of the total that would have been emitted if the mine had remained dry.

1.2.2 Key Issues

In addition to understanding the factors that influence AMM emissions, a country must consider the availability of critical information when estimating AMM emissions for a national inventory. Pertinent information and data must be compiled from different government agencies and mining-related organizations. The amount, type, and level of detail of available information will determine which approach to use for calculating an AMM inventory. Key information issues for consideration in developing an abandoned mine methane inventory are listed in **Table 1.1**.

Table 1.1 – Information Availability Issues for Developing Abandoned Mine Methane Emissions Inventories

Issue	Description	Recommendation
What types of data and mine information are available?	Some countries may collect coal production data while others may only know of coal mine locations. Methane emissions may or may not be reported.	Use data that are readily available and applicable to the most mines. Detailed information for a few mines may be extrapolated to a large number of mines.
Where are coal mine methane emissions reported?	Some countries collect and report methane emissions annually from the coal mining sector.	If a country does not collect emissions data, gassy mines should be identified and emissions estimates prepared based on local mine operator or on expert knowledge.
Can abandoned coal mine emissions be measured?	Methane emissions can be measured from any existing vent pipe or borehole using a vane anemometer and methane monitor. Diffuse emissions through overlying strata are difficult to accurately measure.	Methane flow rates must be measured for several days in order to normalize flows for swings in barometric pressure. Gas composition analysis to determine nitrogen content can be useful in determining air infiltration into the mine.
How can the venting, sealed, or flooding status of a mine be determined?	Governmental regulations and historical records may establish if an abandoned mine contains open vents or is sealed. Mine flooding rates are not usually reported.	Mine maps generally show the location of vent pipes or bore holes, which can then be field verified. Mine records may indicate water levels, pumping amounts, or areas or water intrusion.

This paper describes in detail the proposed methodological approaches and information requirements for developing emissions inventories under Tiers 1, 2, and 3 approaches.

Specifically, the selection of good practice methods, the benefits of using hybrid approaches, and determining emissions avoided for recovery projects are discussed in Section 2. Step-by-step explanations of the emissions calculation procedures for each Tier 1, 2 and 3 approach are included. Finally, the uncertainty associated with each approach is described in Section 2.5.

2.0 Methodological Issues

US EPA has developed a methodology for estimating annual emissions from abandoned mines. This section elaborates on the US approach as a basis for developing an emissions inventory. The different tiers and data requirements described below are presented as an option for other nations to adopt in developing abandoned mine emissions estimates.

Total national emissions from abandoned coal mines may be calculated using the following general equation:

Total Emissions = Emissions from Abandoned Underground Coal Mines
- Emissions Avoided Due to Recovery

Because the quality and quantity of data related to greenhouse gas emission sources vary by country and over time, the IPCC “three tier” approach may be used to generate abandoned mine methane emissions depending on data availability.

- Tier 1 uses global emission factors and requires only minimal information on past mining activity
- Tier 2 uses country or coal basin emission factors that are specific to the type of coal mined and country or basin specific activity factors
- Tier 3 is based on mine-specific information to arrive at emission factors and uses mine-specific measurements

Tiers 1 and 2 follow the same methodological structure that allows for different levels of data quality and certainty. These approaches may be tailored to the type of data that are available (either number of mines abandoned or coal production as a function of time). Tiers 1 and 2 each provide two parallel approaches, A and B, to estimate abandoned coal mine emissions using emission factors and activity data. These approaches are labeled Tier 1A and 1B and Tier 2A and 2B, as described below.

Approach A: Number of Abandoned Mines
This approach is based on an estimate of the number of abandoned coal mines in a given country. Other key information includes an estimation of the time when those mines were abandoned (e.g., the length of time abandoned prior to the emissions inventory year of interest).

Approach B: Coal Production Volume
Because some nations may lack information pertaining to the actual number, location, or date of abandonment for many abandoned mines, an alternate approach allows for use of historical coal production estimates as a function of time.

The primary parameters used to estimate abandoned mine emissions for both of these approaches are twofold:

(1) The time (in years) elapsed since the mine was abandoned (relative to the year of the emissions inventory) and
(2) The mine's initial methane emission rate at the time that it was abandoned.

The precipitous decrease in abandoned mine methane emissions as a function of time elapsed since the mine was abandoned have been modeled. These models may be used to predict annual methane emissions from an abandoned mine as a function of time. The Tier 1 and Tier 2 approaches are based on summations of declining emissions from individual mines.

2.1 Selection of Good Practice Methods

Figure 2.1 illustrates a decision tree that corresponds to the US national inventory approach. This decision tree could be used to help decide which methodological approach (Tier 1, 2, or 3) to use in developing an emissions estimate for abandoned mines. Below is a description of the decision tree process.

First, has coal mining ever been conducted in the country?

If not, abandoned mine emissions are not applicable and the country may simply report "Not occurring."

If yes, are mine-specific emissions or characteristics (e.g., coal permeability) available for individual abandoned mines? If so, Tier 3 methodology, which incorporates mine-specific details, is the most appropriate methodology (as outlined in Figures 2.4 and 2.5 and described in detail in Section 2.3.3 below). If there are any methane recovery projects occurring at abandoned mines, data should be available and Tier 3 methodology is most appropriate.

If mine-specific information is not available, are the total number of abandoned mines and their approximate abandonment date known? Alternatively, are historic coal production volumes at now-abandoned mines known? If yes to either of the above questions, proceed to Box 2, which is a Tier 2 approach. Tier 2A incorporates coal-basin-specific information as well as estimated coal mine abandonment dates. In the alternative, a Tier 2B approach incorporates information about the volumes of coal produced from gassy abandoned coal mines as a function of time can also be used to estimate abandoned mine methane emissions. The specific steps in the Tier 2 approaches are illustrated in Figure 2.3.

Is coal mining a key source category for this nation and are abandoned mines a significant subcategory? If so, more data should be collected that would allow for Tier 2 or Tier 3 estimation of abandoned mine emissions.

If not, a Tier 1 methodology would be appropriate to develop default estimates for abandoned mine emissions, using available data about coal production volumes or number of abandoned mines and multiplying by default emission factors. Two possible Tier 1 methods are described in this white paper: Tier 1A uses available data on the number of abandoned coal mines, and Tier 1B uses available information about the volume of coal produced. The detailed steps in the Tier 1 approaches are shown in Figure 2.2.

If no such aggregate data are available, one should try to estimate these figures to make a rough estimate of emissions from abandoned mines.

Below are outlines of each of the three tier methodologies. For both Tier 1 and Tier 2, this paper describes two parallel methodologies depending on the type and quality of data available. The Tier 3 methodology is based on data from individual abandoned mines. These approaches are described below.

2.1.1 Tier 1

The Tier 1, or "Global Average Method," of estimating abandoned coal mine methane emissions requires a minimum amount of activity data. This method uses the following information:

(1) Time interval in which most of the coal mines closed in a given country. A default time interval of 25 years is recommended (e.g., 1900 – 1925; 1925 – 1950; 1950 – 1975; or 1975 – present); *and*

(2) One of the following:
  - (a) An estimated percent of the total number of coal mines that are gassy, *or*
  - (b) The estimated percent of the amount of gassy coal produced.

Using the first parameter and an emissions factor table, annual emissions are calculated using the following basic forms of the equation:

Number of Mines Method (Tier 1A):

Emissions = Number of Abandoned Coal Mines x % Mines that are Gassy x Emissions Factor

Coal Production Volume Method (Tier 1B):

Emissions = Coal Produced x % Coal produced that is gassy x Emissions Factor

A process flow diagram that illustrates the steps in this calculation is shown in **Figure 2.2** and is described in detail in Section 2.3.

2.1.2 Tier 2

For the Tier 2, or "Country or Basin Specific Method," national experts develop emissions factors unique to a country or basin based on a limited amount of activity data. Tier 2 allows for the selection of several time intervals throughout the twentieth century when coal mines were abandoned. Recommended Tier 2 time intervals are shown in **Table 2.1.**

Table 2.1.: Recommended Tier 2 time intervals

Time Period	Recommended Interval
1900-1980	10 years
1980-1985	5 years
1985-present	1 year

Tier 2 uses the following activity data:

- Number of mines abandoned (method A), or volume of coal produced (method B)
- Percent of all active mines that are gassy (A), or percent of all coal produced that is gassy (B),

- Number of coal mines (A) or amount of coal “abandoned” (B) during any given time period,
- Estimated coal mine emissions (A) or specific emissions (B) for each time interval

For the Tier 2 method, expert judgment and statistical analysis can be used to estimate emissions based on emissions measurements from a limited number of mines. Once the estimates have been made for each time interval, the values are multiplied by an emissions factor, which take into account mined coal rank. The selection and application of these emission factors is described in Section 2.2. The development of decline curves from which these emission factors are derived is discussed in **Appendix A**.

The basic form of the equation for both Tier 2 approaches is as follows:

Number of Mines Method (Tier 2A):

Emissions = Number of Coal Mines Abandoned x % Percent Gassy Mines x Average Emissions Rate x Emission Factor

Coal Production Volume Method (Tier 2B):

Emissions = Coal Production x % Gassy Coal x Abandonment Rate x Specific Emissions x Emission Factor

A process flow diagram for using these methods is shown in **Figure 2.3** and is described in detail in Section 2.3.

2.1.3 Tier 3

The Tier 3, or Mine Specific Method, is based on activity data including mine-specific emissions measurements from ventilation and degasification systems for periods when each mine was active. This methodology also incorporates the time elapsed since abandonment and emissions factors based on dimensionless decline curves using mine-specific characteristics. These mine-specific characteristics include:

- Coal adsorption characteristics (adsorption isotherm),
- Gas content which may measured or be expressed as a function of depth or mine void pressure
- Permeability of the remaining coal to gas,
- Mine size (mined out volume)
- Amount of coal in contact with the void
- Status of the mine, i.e., vented, flooded or sealed

Because of the mine-to-mine variability in these parameters, the Tier 3 methodology produces the most accurate national estimate of abandoned mine emissions. The Tier 3 methodology also provides flexibility. Each country may generate their own decline curves based on known national- or basin-specific coal properties, or it may use more generic curves based on coal rank.

Tier 1 and 2 emission factors are based on decline curves of a freely-venting abandoned mine: a dry mine with unrestricted flow to the atmosphere from the mine void. However, the Tier 3 approach, incorporates the different abandonment status of each mine according to its condition as vented, flooded, or sealed. Each condition requires different sets of emission factor decline curves. The nature and derivation of these decline curves are discussed in Appendix A.

If emissions have been measured from the vent pipes of an abandoned mine during the inventory year in question, these measurements can be used directly as part of the Tier 3 methodology. If emissions have been measured for a time period different from the inventory year in question, the measured value can be used in conjunction with a family of decline curves to select the best curve to extrapolate emissions backward or forward in time.

A process flow diagram for using these methods is shown in **Figure 2.4 and 2.5** and is described in detail in Section 2.3.

2.1.4 Hybrid Approaches

In order to create the most accurate emissions inventories, it is possible to use hybrid approaches that combine methodologies from Tiers 1 and 2 or Tiers 2 and 3. For instance, individual coal mine emissions data necessary for a Tier 3 approach are generally more readily available for the most recent years or decades, while for more historical periods, coal production records may be available for use in a Tier 2 approach.[6]

For example, nations that have access to only sparse historical emissions data may have enough information to estimate their national inventory using a Tier 1-2 hybrid approach. For the most recent years, for which better data are available, a country may opt to use the Tier 2 method, while using the Tier 1 approach for historical periods for which little data are available. Similarly, a country that possesses sufficient historical data with data gaps for certain time intervals may opt to use Tier 2 methods overall, and may choose to use Tier I defaults for the years for which data are missing.

2.2 Activity Data

Tier 1

For Tier 1, qualitative information for a country's underground coal mining activity is sufficient for estimating national emissions. The critical information is either (a) the total number of abandoned mines, or (b) historical coal production. Once this key information is estimated, global default values and emissions factors are used to calculate national emissions. Country experts also need to estimate the time period(s) when either most of the mines were abandoned or when most of the coal was produced. This information may be obtained from appropriate national or international agencies, regional industry experts, or local historians.

Tier 2

For Tier 2, data from national or regional underground coal mining activities are sufficient for estimating national emissions. These data may be obtained from appropriate national, state, or provincial agencies, or companies active in the coal industry. If a

[6] For example, the oldest mine-specific coal mine emissions data in the US date back only to 1971, while coal production records date back to the beginning of the twentieth century. Mine-specific degasification data are available only since the late 1980s. As a result, the US abandoned mine emissions inventory uses a Tier 2-3 hybrid method.

country consists of more than one coal region or basin, production and emissions data may be disaggregated by region. Expert judgment and statistical analysis may be used to estimate ventilation emissions or specific emissions based on measurements from a limited number of mines. Also, values used for determining emissions factors such as gas content, permeability, coal rank, and mine depth may be collected for each individual basin or region.

Tier 3
For Tier 3, abandoned coal mine emissions estimates may be based on mine-specific ventilation and degasification measurements. In this methodology, Tier 3 emissions factors are based on historical emissions data from when the mine(s) were active, abandoned mine emissions measurements (if available), and mine-specific coal characteristics such as gas content, depth, and permeability. In addition, information regarding the status of the abandoned mine, such as degree of flooding and the quality or integrity of the sealing of the mine (communication with atmosphere), is used to determine the appropriate emissions rate decline curve.

2.3 Emissions Factors and Calculations

In this methodology, emission factors used to estimate methane emissions from an abandoned mine are derived from dimensionless "decline" curves, which represent the diminishing methane emissions from abandoned mines as function of time. These curves are derived from theoretical numerical simulation models based on parameters such as coal permeability, adsorption characteristics and gas content. Decline curves may be developed for specific mines, coal basins, or coal ranks. An example of a decline curve is shown in **Figure 2.6**. This figure shows both the simulation derived decline curve and the hyperbolic decline curve fit to the simulation output. It has been found that the hyperbolic equation most closely describes the variety of decline curves generated from the numerous simulation models prepared during this study.

Methane emissions from an abandoned mine decrease rapidly as a function of time elapsed since the mine was abandoned. Thus, one of the most important parameters in estimating abandoned mine emissions is the number of years elapsed from the time the mine was abandoned to the emissions inventory year in question.

Decline curve derived emission factors are used to calculate emissions in each of the Tiers 1, 2, and 3 methodologies as described in the following section.

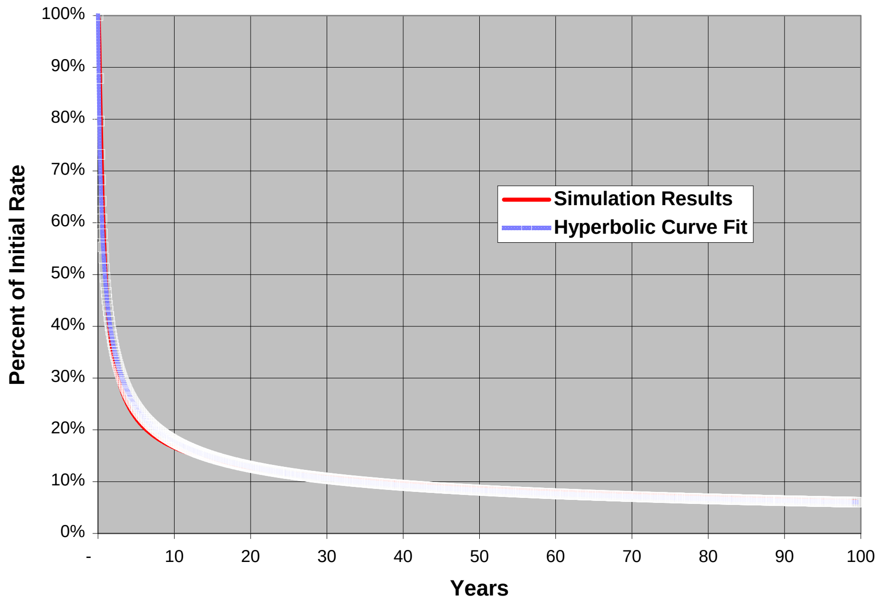

Figure 2.6. Dimensionless decline curve for non-flooded, vented abandoned mine showing both simulation results and hyperbolic decline curve fit to the simulation results

2.3.1 Tier 1: Global Default Approach

Figure 2.2 illustrates steps for estimating emissions from an abandoned mine using a Tier 1 approach. The numbered boxes are discussed in detail below.

Step 1.1: Can the total number of abandoned mines be estimated? If a good estimate of the number of coal mines that have been abandoned is available, continue to Tier 1A methodology (**Step 1A.1**). If the total number of mines cannot be adequately estimated, perhaps the total amount of coal produced can be more accurately estimated, go to **Step 1.2** and proceed with Tier 1B methodology.

Step 1.2: If the total volume or mass of coal produced is known continue to **Step 1B.1.** If the total volume of coal produced historically is unknown and cannot be estimated, go to **Step 1.3.**

Step 1.3. The emissions estimate is indeterminable.

Tier 1A - Number of Mines Approach

This approach incorporates the following information:
(1) An estimate of the total number of abandoned mines,
(2) The percent of mines that were gassy, and
(3) The approximate time (date interval) that most of the coal mines were abandoned.

Step 1A.1: Estimate the number of underground coal mines that have been abandoned in the country since 1900. For the purposes of estimating abandoned mines, prospect excavations, and hand cart mines of only a few acres in size should be disregarded.

Step 1A.2: Estimate the time interval when most of the gassy coal mines were abandoned during the twentieth century.

Choose one (or more) time interval(s) among the following:[7]

1. 1900 – 1925
2. 1925 – 1950
3. 1950 – 1975
4. 1975 - present

Step 1A.3: Estimate the number (percentage) of coal mines that would be considered gassy. Based on the time interval selected in **Step 1A.2**, choose an estimated percentage of gassy coal mines from the high and low values listed in **Table 1A.1**.[8] Actual estimates can range anywhere from 0 - 100%. When choosing within the high and low default values listed in **Table 1A.1**, a country should consider all available historical information that may contribute to the percentage of their mines that are gassy, such as coal rank, gas content, and depth of mining.

Table 1A.1 – IPCC Percent Gassy Coal Mine Defaults

Time Interval	Low	High
1900-1925	0%	10%
1925-1950	3%	50%
1950-1975	5%	75%
1975-Present	8%	100%

Step 1A.4 - Select the inventory year of interest (between 1990 and the present) for the emissions estimation.

[7] NOTE: If information is available about more than one specific time period, multiple time periods may be combined in the Tier 1 approach. For example, this could be the case if it were known or estimated that 25% of mines were abandoned between 1900 and 1925 and the remainder were abandoned between 1925 and 1950.

[8] The default values listed in **Table 1A.1** are synthesized from the US coal mining study (EPA 2004B) and may not reflect conditions in any particular country. Since 1990, the percentage of gassy coal mines operating in various coal fields in the United States has ranged from 8 – 87%. The national average percentage of mines that are gassy is 15% (EPA 2004B).

Step 1A.5 - Select the emissions factor from **Table 1A.2**[9] based on the dates used in **Steps 1A.2 and 1A.4**:

Table 1A.2 – Default Emission Factors, Million m^3/mine				
	Time interval of interest			
Inventory Year	1900 – 1925	1925 - 1950	1950 - 1975	1975 – Present
1990	0.281	0.343	0.478	1.561
1991	0.279	0.340	0.469	1.334
1992	0.277	0.336	0.461	1.183
1993	0.275	0.333	0.453	1.072
1994	0.273	0.330	0.446	0.988
1995	0.272	0.327	0.439	0.921
1996	0.270	0.324	0.432	0.865
1997	0.268	0.322	0.425	0.818
1998	0.267	0.319	0.419	0.778
1999	0.265	0.316	0.413	0.743
2000	0.264	0.314	0.408	0.713
2001	0.262	0.311	0.402	0.686
2002	0.261	0.308	0.397	0.661
2004	0.259	0.306	0.392	0.639
2005	0.258	0.304	0.387	0.620
2006	0.256	0.301	0.382	0.601
2007	0.255	0.299	0.378	0.585
2008	0.253	0.297	0.373	0.569
2009	0.252	0.295	0.369	0.555
2010	0.251	0.293	0.365	0.542
2011	0.249	0.290	0.361	0.529
2012	0.248	0.288	0.357	0.518

Step 1A.6 - Calculate inventory year emissions using Equation 1A.1:

Equation 1A.1

$\text{Emissions}_{\text{Year}}$ = Step 1A.1 x Step 1A.3 x Step 1A.5; or

$\text{Emissions}_{\text{year}}$ = Number of Abandoned Coal Mines x % Gassy Coal Mines x $\text{Emission Factor}_{\text{year}}$

Tier 1B - Coal Volume Approach

This approach incorporates the following information:
(1) The amount of coal produced from the abandoned mines,
(2) The percent of that coal that was "gassy", and
(3) The estimated time interval when most of the gassy coal was abandoned.

[9] The emission factors provided in **Table 1A.2** are derived using a default dimensionless decline curve for high volatile B bituminous coal (see **Appendix A**) and the default gassy mine emission rate which is 8.7 million m^3/yr.

Step 1B.1 – Estimate the volume of coal produced since 1900 through underground coal mining. The historical coal production may not necessarily reflect the current mining activity or conditions in the country. Production estimates may be obtained from governmental agencies or ministries in the energy or minerals sectors.

Default estimation of coal volume produced. In the absence of any database of historical coal production, the volume of coal produced may be estimated as follows. Estimate the mined-out area (in square kilometers) and multiply by 1.40×10^6 (as shown in Equation 1B.1).[10]

Equation 1B.1

Coal Production ton = Mined-Out Area (sq. km) x (1.40×10^6)

Step 1B.2 - Estimate the time interval when most of the gassy coal mines were abandoned during the twentieth century. Intervals of 25 years (default) are recommended for Tier 1.

For example, each nation may choose one (or more) time interval(s) among the following:

1. 1900 – 1925
2. 1925 – 1950
3. 1950 – 1975
4. 1975 – present

Step 1B.3 - Estimate the percentage of coal that was produced by mines that would be considered gassy. For the appropriate time interval selected in **Step 1B.2**, choose an estimated percent gassy coal produced from the ranges shown in **Table 1B.1**. **Table 1B.1** contains low and high defaults for percent of coal produced that was gassy for each time period.[11] Actual values for an individual nation may range from zero to 100%. When choosing from the ranges shown in **Table 1B1**, a country should consider any available information that may impact the coal gassiness in their coal basins, such as coal rank, gas content, depth of mining, and permeability.) [12]

Comment [RCC1]: See below

Table 1B.1 - IPCC Percent Gassy Coal Defaults

Time Interval	Low	High
1900-1925	0%	30%
1925-1950	10%	50%
1950-1975	15%	70%
1975-Present	20%	100%

[10] This approach is based on assumptions of a 2 meter-thick coal seam, a 50% coal extraction factor, and a 1.35 tonne/m^3 coal seam density.

[11] While estimates range from 0 - 100%, gassy coal produced from various coal fields in the United States have ranged from 25 – 95% since 1990, averaging nearly 60%. The default values listed in Table 1 are synthesized from the US coal mining study (EPA 2004B) and may not reflect conditions in any particular country.

[12] United States data show that historically, gassy mines produced more coal than non-gassy mines. This may be because larger mines, which produce more coal per time period, tend to be gassier than smaller mines.

Note that **Tables 1A.1 and 1B.1** have different values. The high and low values provided on these tables were based on a study of gassy mines and coal production in several coal basins of the United States. Both tables show a trend toward a greater percentage of gassy mines and gassy coal production primarily because of the increasing mining depth. The percent of gassy mines and the percent of gassy coal produced, however, are only loosely correlated.

Step 1B.4 - Select the inventory year of interest (between 1990 and the present) for the emissions estimation.

Step 1B.5 - Select an emissions factor from Table 1B.2 based on the dates selected in **Steps 1B.2 and 1B.4.**[13]

Table 1B.2 - Default Emission Factor, Million m^3/ Million Ton

	Time interval of interest			
Inventory Year	1900 - 1925	1925 – 1950	1950 - 1975	1975 – Present
1990	0.063	0.076	0.106	0.303
1991	0.062	0.076	0.104	0.268
1992	0.062	0.075	0.102	0.243
1993	0.062	0.074	0.100	0.224
1994	0.061	0.074	0.099	0.208
1995	0.061	0.073	0.097	0.195
1996	0.060	0.072	0.096	0.185
1997	0.060	0.072	0.094	0.176
1998	0.060	0.071	0.093	0.168
1999	0.059	0.071	0.092	0.161
2000	0.059	0.070	0.091	0.155
2001	0.059	0.069	0.089	0.149
2002	0.058	0.069	0.088	0.144
2003	0.058	0.068	0.087	0.140
2004	0.058	0.068	0.086	0.136
2005	0.057	0.067	0.085	0.132
2006	0.057	0.067	0.084	0.128
2007	0.057	0.066	0.083	0.125
2008	0.056	0.066	0.082	0.122
2009	0.056	0.065	0.081	0.119
2010	0.056	0.065	0.080	0.117
2011	0.056	0.064	0.080	0.114
2012	0.055	0.064	0.079	0.112

Step 1B.6 - Calculate inventory year emissions using Equation 2:

Equation 1B.1

Emissions $_{Year}$ = Step 1B.1 x Step 1B.3 x Step 1B.5; or

[13] The emission factors provided in **Table 1B.2** are derived from the product of a default dimensionless decline curve (derived for high volatile B bituminous coal, as shown in **Appendix A**). The default gassy mine specific emission value is 18.7 m^3/tonne, and the default gassy coal abandonment rate is 8.7%. The derivation of two default emission values is discussed in the Tier 2B calculation approach section.

$$\text{Emissions}_{year} = \text{Coal Production} \times \%\ \text{Gassy Coal} \times \text{Emission Factor}_{year}$$

2.3.2 Tier 2 - Country or Coal Basin Specific Approach

Figure 2.3 is a process flow diagram that describes a process for developing an abandoned mine methane emission inventory using more detailed data than a Tier 1 approach. The numbered boxes in **Figure 2.3** are discussed in detail below .The information incorporated into Tier 2 estimations may include all or some of the following country- or basin-specific data:

- Gassy mine emission rates and how they have changed through time
- Specific emission rates (m^3/tonne of coal mined) and how they may have changed through time
- Number of gassy mines abandoned as a function of time
- Volume of coal abandoned as a function of time
- Type (rank) of coal mined which may vary through time and within a basin or country

Choose Tier 2A or 2B methodology based on available data quality. This approach for Tier 2 emissions estimations includes a choice of two alternative methods, depending on the type and quality of available data:

– The number of abandoned mines method (Tier 2A) or

– The produced coal volume method (Tier 2B).

If available data sets are of equal quality, Tier 2A (number of mines approach) is preferred because it is more accurate. The coal production volume approach (Tier 2B) requires estimation of an additional variable (coal abandonment rate), which adds uncertainty to the calculations.

Tier 2A - Number of Mines Approach

Step 2A.1: Determine time intervals to use in calculations. First, a nation should select the time period during which gassy coal mines were abandoned and apportion that period into time intervals based on available data. Ideally, as the time period of interest approaches the inventory year, the time interval decreases. For example, if available, coal production could be compiled annually since 1985. **Table 2A.1** shows recommended time interval divisions.

Table 2A.1 Suggested time intervals

Time Period when mine was abandoned	Interval
1900-1980	10 years
1980-1985	5 years
1985-present	1 year

Step 2A.2: Number of abandoned mines by time interval. Once the time period of interest has been identified, the estimated number of coal mines abandoned may be apportioned into the appropriate time intervals.

Step 2A.3: Percent of gassy mines by time interval. For each time interval, the percentage of coal mines that are believed to have been gassy mines should be estimated.

One may estimate the number of gassy mines based *quantitatively* on current active coal mine information or *qualitatively* on coal rank, depth, gas content, size, and mining methods. For example, generally speaking, deeper coal mines that recover higher rank coals are gassier than shallow, low rank coal mines, and longwall mines are generally gassier than room and pillar mines. If a given coal basin produces primarily low volatile bituminous coal from mines greater than 500 meters in depth and is known to have had problems with methane, a very high percentage of the abandoned mines will probably be gassy. Conversely, if a basin produces primarily sub-bituminous C coal from mines less than 500 meters deep and has had little history of methane problems, a smaller percentage of mines will be gassy.

The percentage of gassy coal mines has increased in recent years due to changing production methods over time. For instance, early in the twentieth century coal mines were operated by hand in shallow coal seams, producing relatively few methane emissions compared to present-day coal mines in deep seams using longwall mining methods.

Individual national estimates of the percentage of gassy mines may range anywhere from 0 to 100%. In the United States, the number of gassy coal mines operating in various coal fields have ranged from 8 – 87% since 1990; the national average of gassy mines is only 15%. If other data is not available, **Table 1A.1** can be used to bracket probable % gassy mine estimates.

Step 2A.4: Average emission rate by time interval. Estimate the average emission rate of the abandoned gassy coal mines when the mines were active.

For a country or basin for which historical mine emission data are not available, estimate the emissions of gassy coal mines based *quantitatively* on current active coal mine emissions information or *qualitatively* on coal rank, depth, gas content, size, and mining methods. As with the discussion above on percent gassy mines (**Step 2A.3**), the average mine emission rate can vary by country, by basin and within a basin depending on combinations of the above parameters. The average emission rate can also vary with time, generally increasing as average mine size and depth increases through time.

As an example of how initial emission rates (e.g., emissions of abandoned mines at the time of abandonment) have increased over the last century, **Figure 2.7** shows U.S. data for average gassy mine emissions prior to abandonment by year.[14]

[14] For example, in the U.S., in 1971 (earliest year for which data are available), gassy mines averaged 11.3 million m^3/yr. By the year 2000, average gassy mine emissions had increased to 36.8 million m^3/yr per mine.

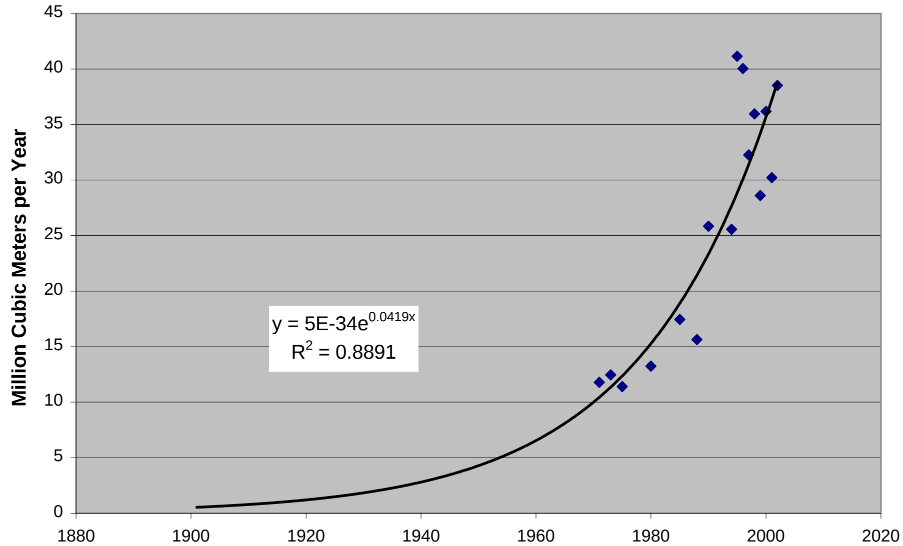

Figure 2.7: Average yearly mine methane emissions for gassy U.S. coal mines

Equation 2A.1 may be used to estimate the average gassy coal mine emissions based on the regression shown in **Figure 2.7.**

Equation 2A.1 Default value
Average Gassy Coal Mine Emissions (Mm^3 per year) = $5E\text{-}34e^{0.0419t}$

Where t is the year of abandonment

Use the midpoint date from the **Step 2A.2** intervals to estimate the average active mine emission rate for coal mines using **Equation 2A.1**.

Figure 2.8 shows a histogram of the available U.S. data on active mine emissions prior to abandonment (all mines are grouped together, regardless of abandonment date). Statistics for U.S. abandoned mine characteristics when the mines were active are shown in **Table 2A.2**.

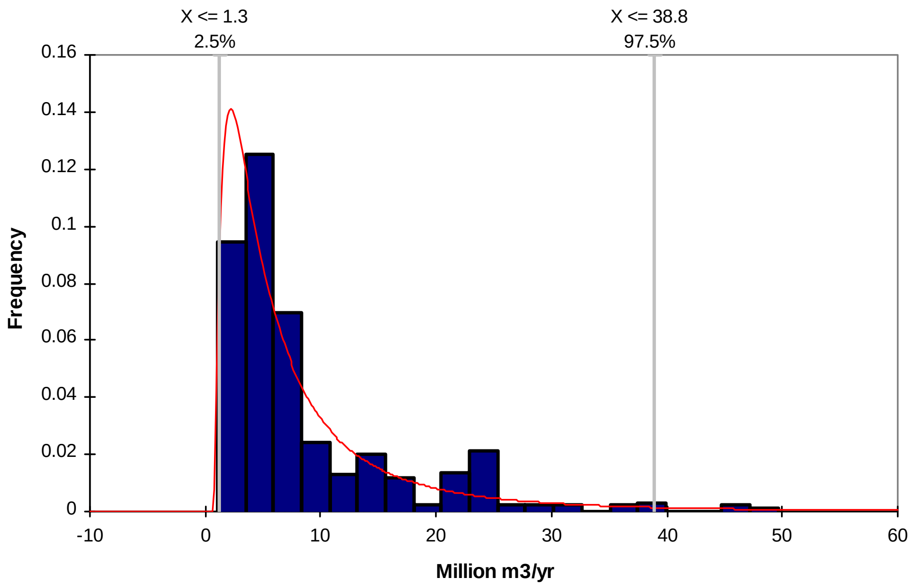

Figure 2.8. Histogram of all available U.S. data for active mine emissions prior abandonment with lognormal distribution curve-fit

Table 2A.2: Statistics of active mine emissions prior to abandonment

Parameter	**Emissions, million m^3/yr**
Mean	8.7
Mode (estimated)	3.6
Median	4.1
Std. Deviation	8.9
2.50% (Default low value)	1.3
97.50% (Default high value)	38.8

The values for the 2.5% and 97.5% probabilities provide the 95% confidence interval and may be used for low and high estimates if country or basin specific data does not exist.

Step 2A.5: Choose inventory year - Select the inventory year between 1990 and the present for the emissions estimation.

Step 2A.6: Select an appropriate decline curve - Select decline curve coefficients from **Table 2A.3**.

Table 2A.3:
Equation Coefficients for Tier 2

Coal Rank	a	b
Anthracite	1.72	-0.58
Bituminous	3.72	-0.42
Sub-bituminous	0.27	-0.99

The coefficients provided in **Table 2A.3** are based on generic decline curves generated by a conceptual numerical emissions model of an abandoned mine using the values for gas content and permeability applicable to each type of coal. **Appendix A** discusses the values of the parameters used in the numerical model and their basis.

Step 2A.7: Calculate the emission factor using **Equation 2A.2** based on the difference in years between the dates determined in **Steps 2A.2 and 2A.5**.

Equation 2A.2
$\text{Emission Factor} = (1 + aT)^b$

Where "a" and "b" are constants that are unique to each decline curve and T is the years to inventory year based on the mid point of the time interval for which the calculation is being done. A separate emission factor calculation needs to be done for each time interval selected in **Step 2A.1**.

Step 2A.8 - Calculate inventory year emissions using the following equation for each time interval:

Equation 2A.3

Emissions_{Year} = Step 2A.2 x Step 2A.3 x Step 2A.4 x Step 2A.6; or

Emissions_{year} = Number of Abandoned Coal Mines x Percent Gassy Mines x Average Emissions Rate x $\text{Emission Factor}_{year}$

Sum the emissions calculated for each time interval to arrive at the total abandoned mine emissions for that inventory year.

Tier 2B - Coal Production Volume Approach

Step 2B.1: Determine time intervals to use in calculations - Select the time period during which gassy coal mines operated and were abandoned. Divide that period into time intervals for grouping the data. As the time period of interest approaches the inventory year, the interval should decrease. For example, coal production should be compiled annually for 1985 and subsequent years. **Table 2A.1** above shows recommended time interval divisions that incorporate the impact of rapid changes in emissions occurring soon after abandonment and the slow change in emissions with the passage of time.

Step 2B.2: Coal production by time interval - Once the time period of interest has been identified, apportion the estimated amount of coal produced into the appropriate time intervals.

Step 2B.3: Percent of gassy coal by time interval - Estimate the percent of coal that was produced from gassy mines for each time interval. For mines for which these data are not available, estimate the percent of coal that was gassy.

The percent of gassy coal mined is likely to have been lower during earlier time periods due to improving production methods and changing technology over time. For instance, early in the twentieth century coal mining was done by hand in shallow coal seams, producing relatively few methane emissions compared to present-day coal mining production in deep seams using longwall mining methods. In absence of specific information, **Table 1B.1** can be used to develop low and high estimates.

Step 2B.4: Gassy coal abandoned by time interval. To develop an initial emission rate for use with the time dependent emission factor, two pieces of data are required: the mass of coal abandoned and the active mine specific emission value (m^3 of methane emitted per ton of coal mined in **Step 2B.5** below).

The **coal abandonment rate** is simply the fraction of coal that would have been produced but is not produced because of mine closures. This value can be determined from the number of active mines, and the number of mines abandoned over a specific time interval. For example, if there were ten mines producing at the beginning of the time period and one of those mines closed, 10% of the coal is assumed to have been abandoned, If the total production rate from these ten mines was 10 Mton/year then the coal abandoned will be 10 Mton/year x 0.1 = 1 Mton/year. If more detailed information regarding gassy coal production and abandonment through time, this assumption may not be needed.

Figure 2.9 shows the abandonment rate for U.S. underground coal mines. This rate is based on the assumption that the mines being abandoned produced the same amount of coal per mine as the average per mine production of the total population of mines.

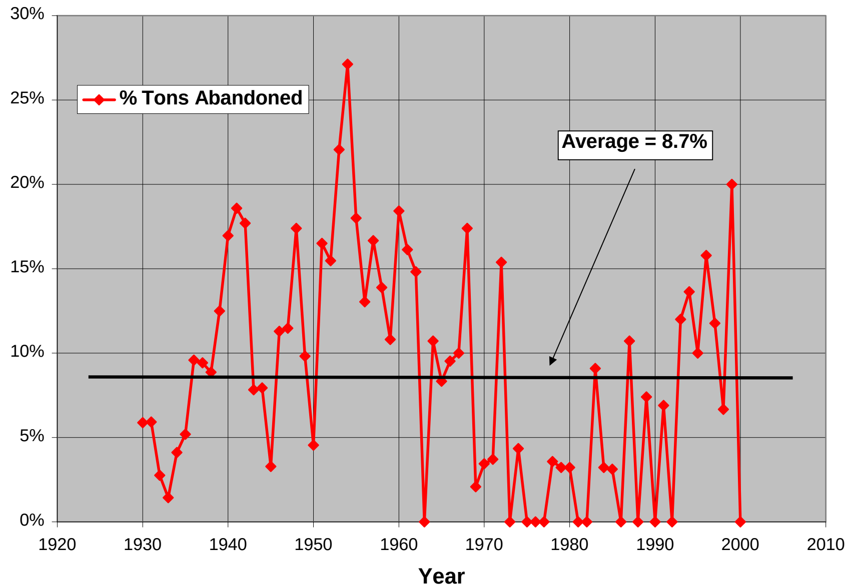

Figure 2.9: Percent of total coal production that has been abandoned by year in the U.S.

The average value for abandonment rate in the United States over the time period 1930 to 2000 is 8.7% with a standard deviation of 6.6%. **Table 2B.2** presents U.S. coal abandonment rate information by decade (EPA 2004B).

Table 2B.2: Percent of coal produced that was abandoned during a decade (U.S. data)

Decade	Total Coal Abandoned
1930	6%
1940	12%
1950	15%
1960	11%
1970	4%
1980	4%
1990	9%

Step 2B.5: Gassy mine Specific Emission (SE) by time interval - Estimate the average specific emissions (m^3/ton of coal mined) of coal produced from gassy mines for each time interval.

As an illustration of gassy mine specific emissions, **Figure 2.10** shows the specific emissions data for gassy U.S. coal. The average of this data is 18.7m3/ton with a standard deviation of 1.7m3/tonne.

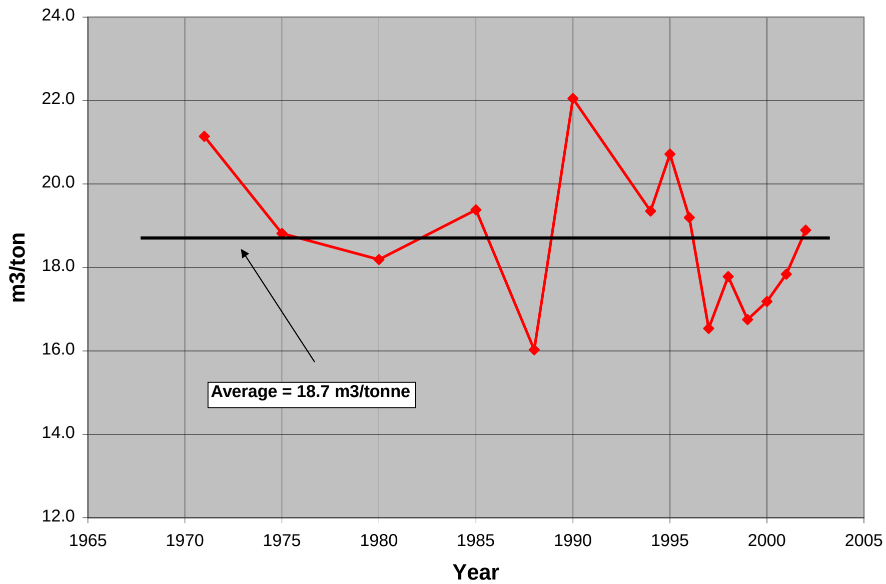

Figure 2.10: Specific emission values for gassy U.S. coal

Specific emission values have been reported for other countries (see **Table 2B.3).**[15]

Table 2B.3: Estimated Specific Emission values for selected Countries

Country	Emission Factors(m3/tonne)	Source
Former Soviet Union	17.8 - 22.2	US EPA, 1993c
United States	11.0 - 15.3	US EPA, 1993a
Germany (East & West)	22.4	Zimmermeyer, 1989
United Kingdom	15.3	BCTSRE, 1992
Poland	6.8 - 12.0	Pilcher et al., 1991
Czechoslovakia	23.9	Bibler et al., 1992
Australia	15.6	Lama, 1992

Overlying or underlying strata may contribute to in situ coal mine methane emissions making the actual specific emissions several times that of the measured gas content of the coal itself. Generally, specific emissions can be four to seven times greater than in-situ gas content.

Step 2B.6: Choose inventory year - Select the inventory year of interest (between 1990 and the present) for the emissions estimation.

[15] Data in Table 2B.3 are taken from the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Table 1-54 p. 1.105)

Step 2B.7: Select an appropriate decline curve - Select a decline curve equation from **Table 2A.3** above.

The equations provided in **Table 2A.3** are based on generic decline curves generated by a conceptual numerical emissions model of an abandoned mine using the values for gas content and permeability applicable to each type of coal. **Appendix A** discusses the values of the parameters used in the numerical model and their basis.

Step 2B.8: Obtain emission factors for each time interval - Calculate the emission factor using **Equation 2B.1** based on the difference in years between the dates determined in **Steps 2B.1 and 2B.6**.

Equation 2B.1

Emission Factor (fraction of initial emissions rate at t_o) = $(1 + aT)^b$

Where "a" and "b" are constants that are unique to each decline curve and T is the years to inventory year based on the mid point of the time interval for which the calculation is being done. A separate emission factor calculation needs to be done for each time interval selected in **Step 2B.1**.

Step 2B.9 - Calculate inventory year emissions using the following equation for each time interval:

Equation 2B.2

$\text{Emissions}_{\text{Year}}$ = Step 2B.2 x Step 2B.3 x Step 2B.4 x Step 2B.5 x Step 2B.8; or

$\text{Emissions}_{\text{year}}$ = Coal Production x % Gassy Coal x Abandonment Rate x Specific Emissions x $\text{Emission Factor}_{\text{year}}$

Sum the time interval emissions to calculate total inventory year emissions.

2.3.3 Tier 3 - Mine-Specific Approach

Figure 2.3 is a process flow diagram for generating an abandoned mine methane emission inventory using mine-specific information. The Tier 3 Method is based on activity data, including mine-specific emissions measurements from ventilation and degasification systems for periods when each mine was active. This methodology also incorporates the time elapsed since abandonment and emission factors based on dimensionless decline curves and mine-specific characteristics, including some or all of the following:

- Coal adsorption characteristics (adsorption isotherm)
- Gas content which may measured or be expressed as a function of depth or mine void pressure
- Permeability of the remaining coal to gas
- Mine size
- Amount of coal in contact with the void
- Condition of the mine: e.g. vented, flooded, or sealed

The Tier 3 methodology provides flexibility. Each country may generate their own decline curves based on measured data or known national- or basin-specific coal properties or it may use more generic curves based on coal rank that are provided in this document.

The emission factors for Tiers 1 and 2 are based on decline curves of a freely-venting abandoned mine (i.e., a dry mine with unrestricted flow to the atmosphere). In contrast, the Tier 3 approach is based on the known or assumed the abandonment condition of the mine (i.e., whether it is venting, flooding or sealed). Each abandoned mine type is associated with its own set of emission factor decline curves, as described below.

Step 3.1: Select an abandoned mine – Select a mine to use as the basis for an emissions estimate.

Step 3.2: Determine abandonment date of mine – Estimate the abandonment date for the selected mine. The abandonment date should be consistent for all mines in the country's inventory. For purposes of this methodology, the abandonment date is assumed to be the date when all active mine ventilation ceases.

Step 3.3: Average emission rate at time of closure – Estimate the average emission rate at closure. This can be determined by the last measured emission rate or (preferably) an average of several measurements taken the year prior to abandonment. This will be subject to the judgment of the experts performing the inventory.

Step 3.4: Choose inventory year - Select the inventory year of interest (between 1990 and the present) for the emissions estimation.

Step 3.5 - Have emissions been measured? – Have the emissions from an open vent or diffuse emissions from this abandoned mine been measured? If they have not, proceed to **Step 3.7** (Select an appropriate decline curve). Otherwise, go to **Step 3.6**.

Step 3.6: Are emissions data available for the inventory year? – If methane emissions have been measured at the abandoned mine for the inventory year of interest then they can be directly entered into the inventory (go to **Step 3.10**). If they have been measured but not for the inventory year of interest they must be adjusted forwards or backwards in time using an applicable decline curve. This is addressed in the sub-routine for selecting an appropriate decline curve (**Step 3.7**).

Step 3.7: Select an appropriate decline curve – This subroutine, illustrated in **Figure 2.4,** is described below.

Step 3.7.1: Measured emission rate available? – It is possible that direct accounting of the abandoned mine's emissions could be made if the emission rate from a vent has been measured. If no measurements have been made, go to **Step 3.7.6**.

Step 3.7.2: Is mine vent always open? – If the mine vent is always open its status may be defined as vented for the purpose of this inventory; go to **Step 3.7.3**. If the mine is sealed and the vent is normally closed the mine should be considered to be sealed; go to **Step 3.7.13**.

Step 3.7.3: Calculate measured vent emissions as a fraction of active mine emissions – Divide the measured vent emission rate by the mission rate when the mine was active to obtain the emission factor for use in **Step 3.7.4**.

Step 3.7.4: Select active vent decline curve that matches measured data –Figure 2.11 provides an example of how a decline curve equation is selected. This series of curves are for sub-bituminous coal mines where the first letter relates to permeability (L – Low, M – Mid, H – High) and the second letter refers to relative mine size (L – Small, M – Mid H – Large) Based on the time since abandonment, this graph may be used to select the decline curve that is closest to the reference point value determined in **Step 3.7.3**. In the example shown, the point lies between Curves HH and MM. Use available information to decide which curve to use for extrapolation backward or forward in time to the inventory year of interest. Graphs and decline equations are provided in Appendix B for the various coal ranks by relative mine size and permeability.

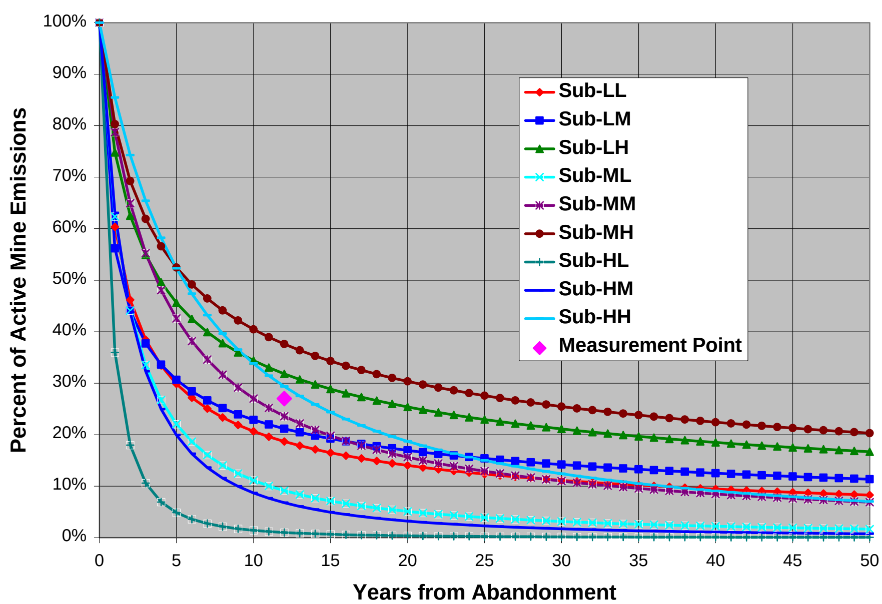

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Figure 2.11: Example of a family of decline curves used to extrapolate an emission factor from a measured point to the inventory year of interest.

Step 3.7.5: Return to Tier 3 flow chart Step 3.8 – Continue with inventory process.

Step 3.7.6: Classify the abandoned mine status as venting, sealed, or flooding – Use governmental agencies, mining ministries or experts and/or regulations regarding mine sealing or venting to determine the mine's status.

Step 3.7.7: Is the mine flooded or flooding? – If the mine is known or strongly suspected of being flooded or flooding with ground or surface water, use the flooded status decline curve (**Step 3.7.8).** Otherwise go to **Step 3.7.10**.

Step 3.7.8: Use flooding mine decline curves - This decline curve can be developed by local experts or by using **Equation 3.1**. It was found in the United States that flooding mines had a very rapid decline to essentially zero after about eight years of abandonment. The flooded mine equation was empirically derived from data collected in the United States

Equation 3.1

$$\textbf{Flooding mines, fraction of initial emissions rate} = e^{(-Dt)}$$

Where

q = current emission rate, m^3/yr
q_i = emission rate at abandonment, m^3/yr
D = decline rate, fraction per year
t = time since abandonment, yr

The coefficient "D" was determined to be -0.672 through curve fitting measured emissions data at flooding mines.

Step 3.7.9: Return to Tier 3 flow chart Step 3.8.

Step 3.7.10: Is there a mine vent that is always open? – If the mine vent or vents are always open to the atmosphere and the mine is not flooded or flooding go to **Step 3.7.11**; otherwise go to **Step 3.7.13**.

Step 3.7.11: Select vented mine decline curves – Select either decline curves prepared by in-country experts or the generic curves provided based on coal rank.

Step 3.7.12: Return to Tier 3 flow chart Step 3.8.

Step 3.7.13: Select sealed mine decline curves – The sealed mine decline curves represent a fraction of the vented curves because the seals provide significant resistance to the methane's migration through the coal seam and eventual escape to the atmosphere. These estimations are based on the assumption that sealed mines still emit the same total amount of methane as a vented mine, but their emissions occur over a longer period of time. This assumption is based on the premise that there is (practically) never a perfectly sealed abandoned gassy coal mine. The methane will leak to the atmosphere around the plugged shafts and/or through fractures in the overburden. Sealed mine equations are based on a sealing factor and a decline parameter (the "a" coefficient) that has been modified from the actively venting model to reflect the less rapid depletion of the gas given its restricted flow.

Equation 3.2

$$\textbf{Sealed mines, fraction of initial emissions rate} = c(1 + aT)^b$$

Where "a" and "b" are constants that are unique to each decline curve and T is the years to inventory year based on the mid point of the time interval for which the calculation is being done. The coefficient "c" represents the degree of sealing of the mine. There are three possibilities used based on a study conducted for reference US EPA 2004a. These are:

- the mine is 50% sealed,
- the mine is 80% sealed,
- the mine is 95% sealed,

These qualitative assessments translate to "c" coefficients of 0.5, 0.2, and 0.05. The 80% sealed is defined as the mid case.

An example matrix of decline equations for the different status mines is shown in **Table 3.1**. These equations represent "mid case" parameters. A number of decline equations can be generated if local experts believe that there are significant differences between mining districts. A more complete description of the derivation of these curves can be found in **Appendix A**. Equations for the decline curves based on combinations of mine size and permeability of venting mines for the three coal types are provided in Tables B4, B5, and B6.

Comment [RCC2]: I could generate similar tables for the sealed mines, but this would take about one day.

Table 3.1: Example equation matrix for coal type and mine status

Status	Anthracite	Bituminous	Sub-bituminous
Venting	$(1+1.72t)^{-0.58}$	$(1+3.72t)^{-0.42}$	$(1+0.27t)^{-0.99}$
Flooding	Exp(-0.672t)	Exp(-0.672t)	Exp(-0.672t)
Sealed	$0.2(1+0.098t)^{-0.58}$	$0.2(1+0.077t)^{-0.42}$	$0.2(1+0.035t)^{-0.99}$

Step 3.7.14: Return to Tier 3 flow chart Step 3.8.

Step 3.8: Determine emission factor from decline curve and abandonment time – Use the selected decline equation for the mine and the number of years between abandonment and the inventory year to calculate the emission factor.

Step 3.9: Calculate individual mine emissions for inventory year – Use the emission factor together with emission rate at abandonment in **Equation 3.2** to determine the mine's emission for the inventory year of interest.

Equation 3.2

$$\text{Emissions}_{\text{Year}} = \text{Step 3.3 x Step 3.8; or}$$

$$\text{Emissions}_{\text{year}} = \text{Emission rate at closure x Emission Factor}$$

Step 3.10: Add to list of abandoned mine emission for inventory year – Add the calculated or measured (see **Step 3.6**) emission value for this mine to the other mines in the inventory.

Step 3.11: Sum abandoned mine emissions for annual inventory – Sum all mines whose emissions have been determined for the Tier 3 inventory.

Methodological note regarding double counting: For a given country, emissions estimates for some mines may be developed using the Tier 1 or Tier 2 methodology. These Tier 1 or Tier 2 estimates for groups of mines may be added to the Tier 3 – derived emissions estimates to arrive at a national total inventory, as long as each mine (or group of mines) has only been accounted for once.

2.4 Emissions Avoided

Recovery and use of AMM is becoming more common especially in North America and Europe. The emissions avoided because of these projects should be subtracted from the emissions inventory. Typically, AMM projects employ the use of vacuum pumps to extract the methane from the mine void. Thus, the methane is produced at a rate greater than it would have been emitted to the atmosphere naturally (e.g., it is “accelerated” methane production). In these cases, AMM production will exceed the calculated emissions avoided for a given year, which would result in a calculated “negative” emissions rate for the mine.

If an abandoned mine site has an active recovery project, it is probable that sufficient information exists to calculate a Tier 3 emission forecast. One recommendation for calculating net emissions is to consider this emissions forecast, or some fraction thereof, as the baseline for inventory purposes. Since the emissions avoided must not exceed the baseline for any given inventory year, it is possible that such ”accelerated” methane recovery projects can produce *several* years’ worth of baseline emissions in one year. The cumulative production from such AMM projects could be accounted as “emissions avoided” for the number of years required it takes to equal the calculated cumulative baseline emissions.

AMM project recovery or production data may be publicly available through appropriate government agencies depending on the end use. Production data are usually in the form of metered “gas sales” and often are publicly available in oil and gas industry databases. Furthermore, an additional amount of undocumented AMM may be recovered and used during the extraction and compression of the gas. These amounts, which could account for 3 to 8% of additional AMM recovery added to the gas sales, are not typically measured and may therefore need to be estimated. For projects that use recovered AMM for electricity generation, metered flow rates and compression factors (if available) can be used to account for the gas recovered. However, public records will most likely reflect electricity produced. If so, the heat rate or efficiency of the electricity generator can be used to determine its fuel consumption rate.

Protocols for emissions trading schemes differ in their procedures to take into account methane recovery from AMM projects, especially whether they are considered as emission reductions in the year produced. General agreement has not been reached on this issue.

2.5 Uncertainties Related to Inventory Assessment

By definition, the uncertainty of inventory values generated using the Tier 1 methodology are greater than values derived from Tier 2 methodology, which will in turn be greater than those derived using Tier 3. The range of uncertainty associated with these different emission factors has been estimated here for the Tier 1 emission factors and for the emission factor decline equations used in Tiers 2 and 3. It is up to the compiler of each national emissions inventory to characterize the range of uncertainty for activity data (e.g., number of mines abandoned for Tier 1A, or specific emissions for Tier 2B).

Tier 1

The primary causes of the uncertainty related to the Tier 1 methodology include the following:

- The global nature of the emission factors. The range of uncertainty of these factors is intentionally large to account for the range of uncertainty in the parameters that affect emission factors such as mine size and depth and coal rank.
- A time interval specifying the "initial time" during which the mine was abandoned and emissions officially began. Because emissions from abandoned mines are strongly time dependent, selecting a single interval that best represents the dates of closure for all mines is critical in establishing an emissions rate.
- The activity data. Both the number of gassy abandoned mines (method A) and the amount of coal that has been produced from gassy mines (method B) are strongly country-dependent. The uncertainty will be defined by the availability of historic mining and production records.

Tier 2

The primary causes of uncertainty related to the Tier 2 methodologies include the following:

- The country- or basin-specific emission factors. Uncertainty is associated with the emission factor decline equations for each coal rank. This uncertainty is a function of the inherent variability of gas content, adsorption characteristics, and permeability within a given coal rank.
- The number of mines producing, or volume of coal produced, of a given coal rank.
- The number of mines abandoned through time.
- The coal abandonment rate through time.
- The percent of gassy mines or coal produced through time.

Tier 3

The Tier 3 methodology has lower associated uncertainty than Tiers 1 and 2 because the emissions inventory is based on mine-specific information on active emission rates and abandonment times.[16]

The primary uncertainties associated with emissions inventories generated using the Tier 3 methodology include the following;

- Active mine emission rate.
- Decline curve equation that describes the function relating adsorption characteristics and gas content of the coal, mine size, and coal permeability.
- Status of the abandoned mine (vented, flooded or sealed).

[16] Although the range of uncertainty associated with estimated emissions from an individual mine may be large, summing those uncertainties actually reduces the range of uncertainty of the final inventory, per the central limits theorem (Murtha 2002).

A national abandoned mine emission inventory may consist of a combination of a several different methodologies. For example, the emissions from mines abandoned during the first half of the twentieth century may be determined using a Tier 1 method, while emissions from mines abandoned after 1950 may be determined using a Tier 2 method. The Tier 1 and Tier 2 methods will each have their own uncertainty distribution. It is important to properly sum these distributions in order to arrive at the appropriate range of uncertainty for the final emissions inventory (IPCC 2000).

3.0 Conclusions

Methane emissions from abandoned coal mines may be a significant source of GHG emissions for at least twenty countries worldwide. However, the global level of methane emissions from abandoned mines is unknown at this time. This proposed methodology may provide an opportunity for countries to estimate their abandoned coal mine methane emissions and even to identify economically viable methane mitigation opportunities.

Estimating emissions from abandoned mines is complex due to the time dependence of emission factors, which are based on time elapsed since mines were abandoned. In addition, the activity data required for an inventory calculation are actually *historical* mining information, e.g., the emission rates of an abandoned mine during the period when it was actively producing coal.

The volume of methane remaining in the “available” coal seam decreases as methane is released from the abandoned coal mine, resulting in declining production and emissions of methane in subsequent years. A mathematical equation that describes this emissions decline may be used to predict the volume of gas that is being liberated for any subsequent period as a function of the initial methane liberation rate when the mine was active. In other words, the emission factor is time dependent and changes annually. If adequate data are available, mine-specific information may be used to generate decline curves based on mine size, coal seam gas content, adsorption characteristics, and coal permeability.

The methodology proposed in this white paper incorporates time-dependent emission factors with historical activity data. This approach for estimating abandoned mine emissions employs the IPCC three tier system so that each country may develop the most accurate emission estimates possible, depending on the quality and quantity of data available.

- Tier 1 uses global emission factors and activity data and requires only minimal information on past mining activity
- Tier 2 uses country or coal basin emission factors that are specific to the type of coal mined and country- or basin-specific historical activity factors
- Tier 3 is based on mine-specific emission factors as well as measured, mine-specific activity data

This paper proposes two alternative methods for Tiers 1 and 2 to enable countries to use the type of historical data that is more readily available or dependable. Using a top-down approach, the simple assessment techniques of Tier 1 and 2 provide an estimate of the range of methane emissions that may be attributed to abandoned mines in a specific country. This information may help to determine whether these mines are a significant source of GHG emissions for that nation. If so, a more rigorous emissions assessment approach (e.g., Tier 3) may be warranted.

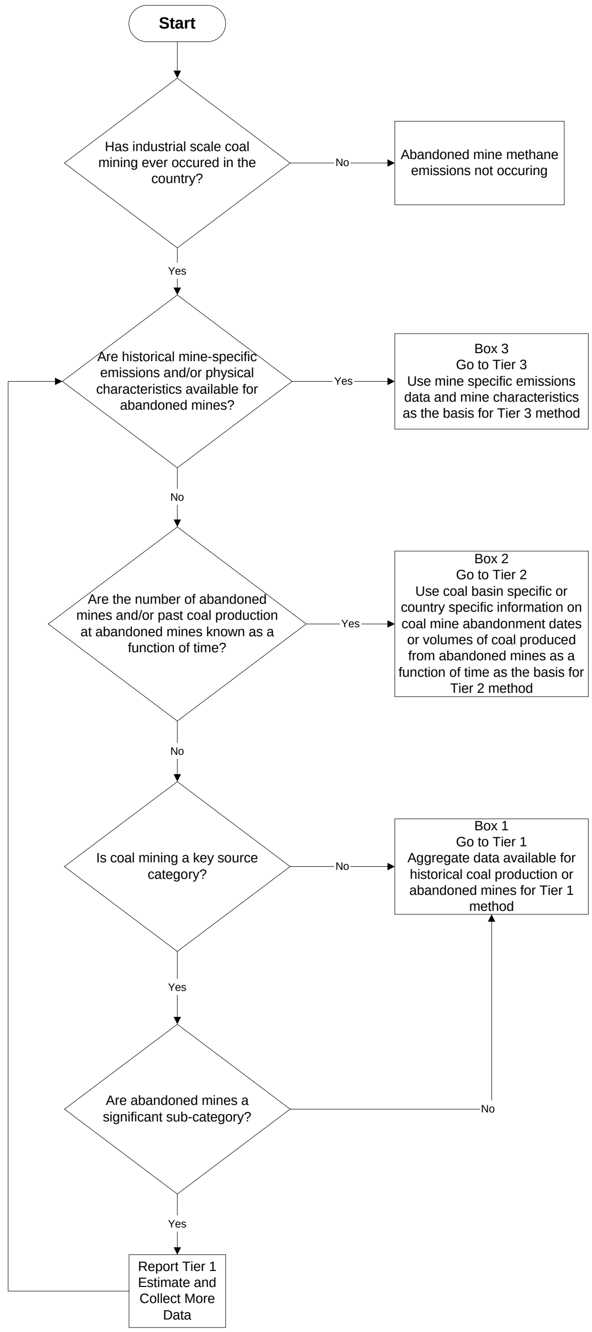

Figure 2.1: Decision Tree Diagram for Abandoned Coal Mines

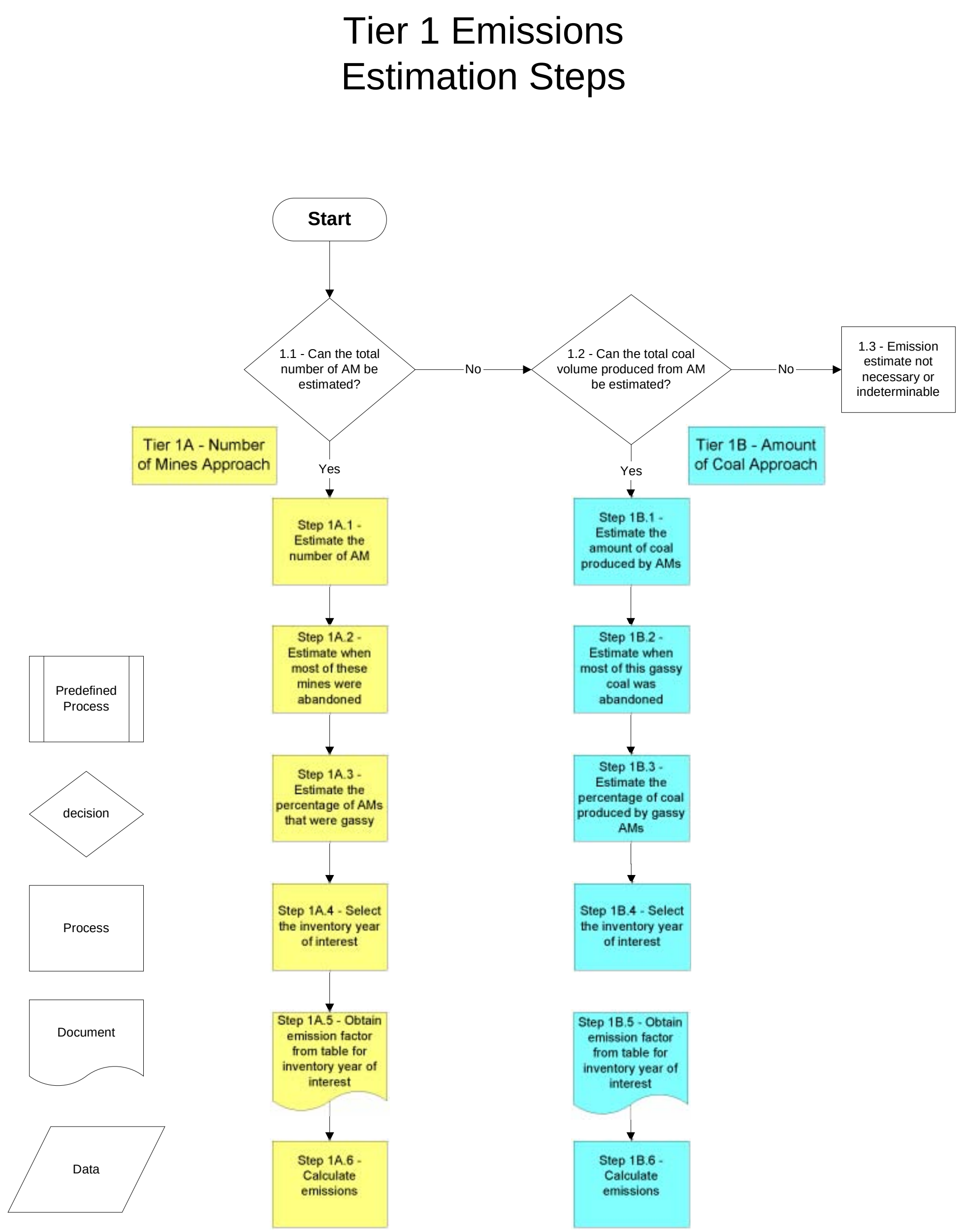

Figure 2.2: Description of steps in Tier 1 Methodology for abandoned mine methane emissions

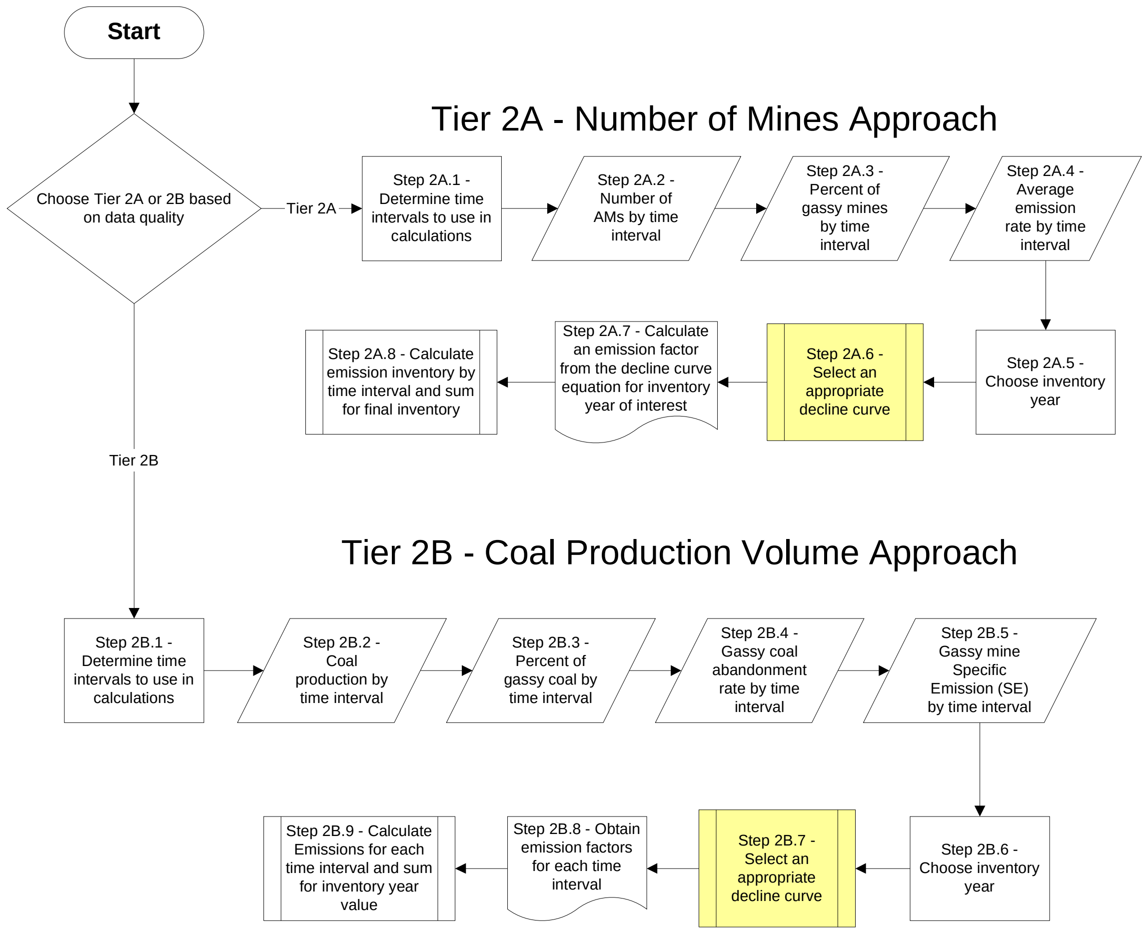

Figure 2.3: Description of steps for Tier 2 Methodology abandoned mine methane emissions

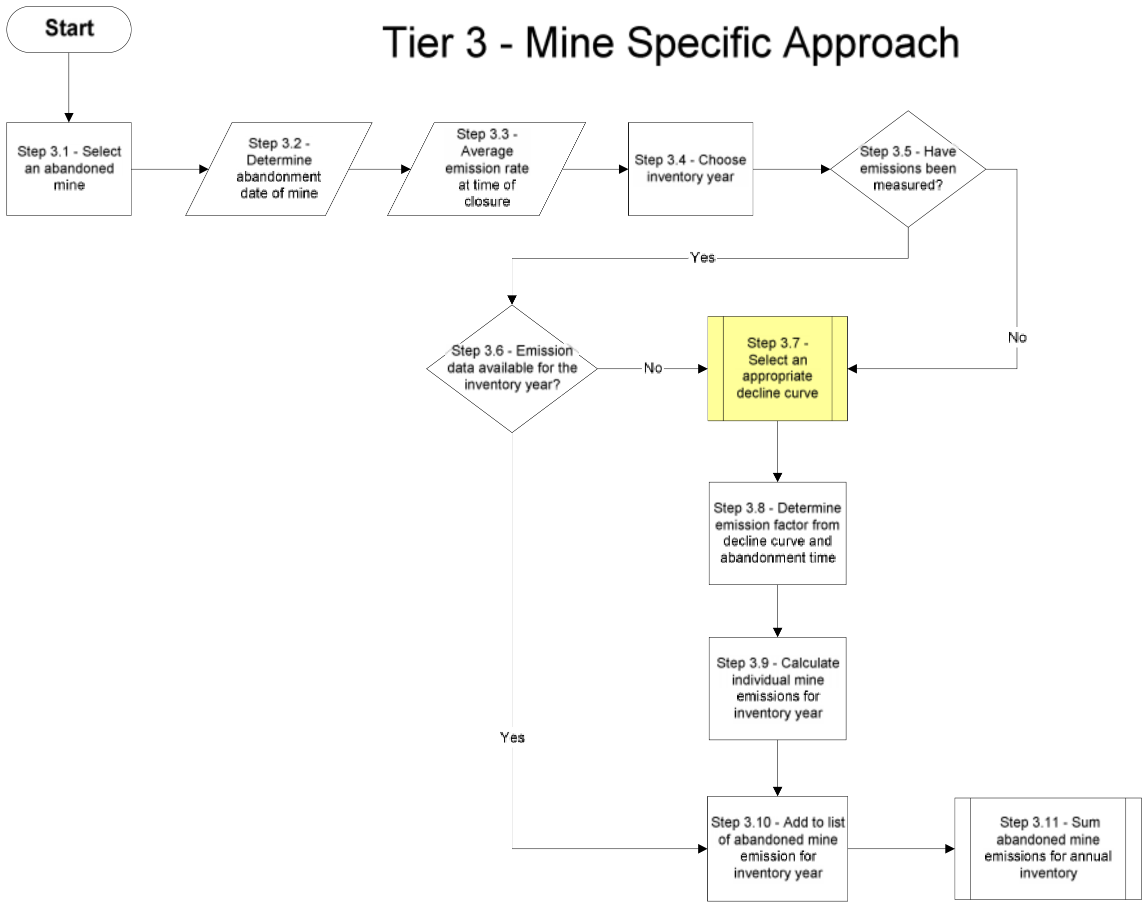

Figure 2.4: Description of steps for Tier 3 Methodology abandoned mine methane emissions

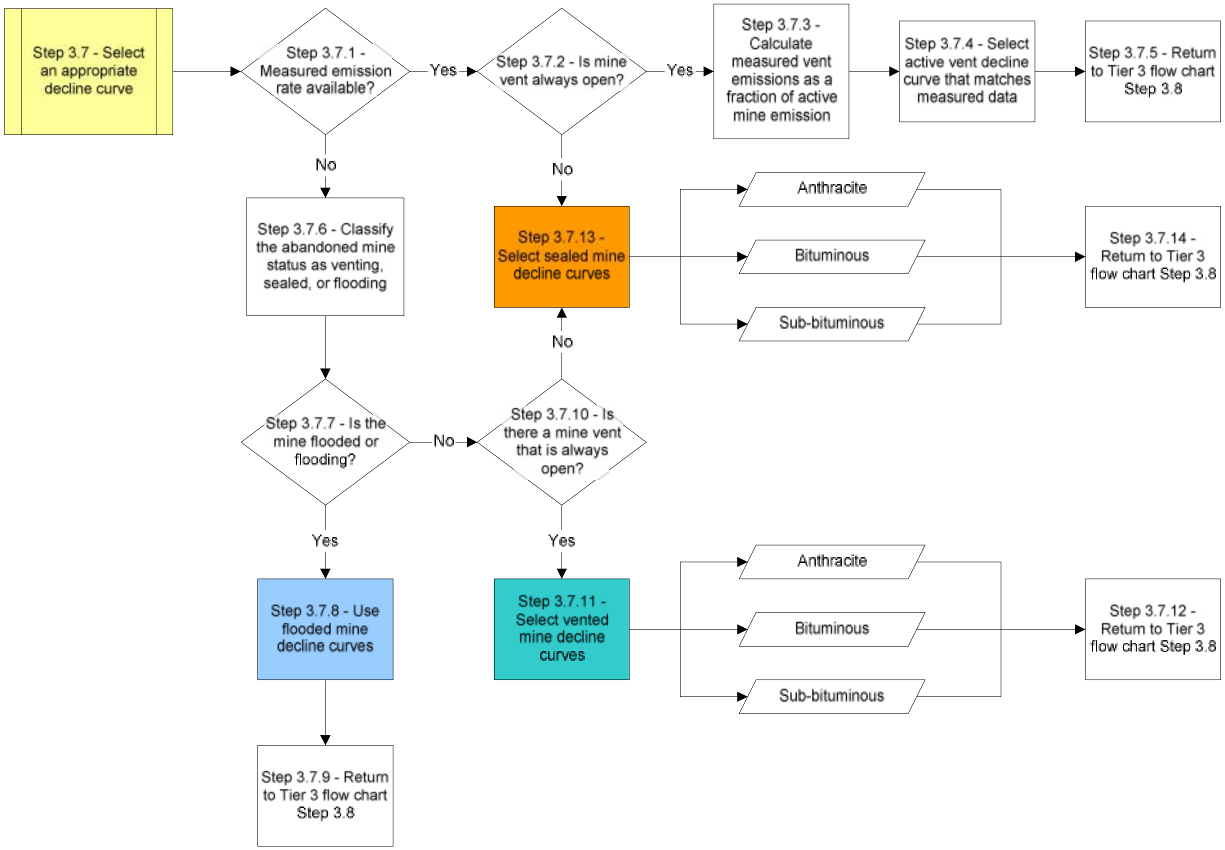

Figure 2.5: Description of steps for Tier 3 abandoned mine methane emissions Methodology for selecting an emission factor decline curve

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Appendix A

Construction of Emission Factor Decline Curves

Time-dependent emission factors play an integral role in the abandoned mine methane emissions inventory methodology proposed in this white paper. The rate at which coal mine methane emissions from abandoned mines decrease as a function of time is reflected in the shape of the emission factor decline curves. These curves depend on several physical parameters of the mines and associated coal properties. For an individual mine, these parameters include:

- Methane content
- Adsorption characteristics of the coal in communication with the mine void
- Methane flow capacity of the mine

Methane Adsorption Characteristics of Coal

Compared to many sedimentary rocks, coal beds have a large capacity to store methane gas.[17] 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).[18] **Figure A1** illustrates the methane storage capacity of a middle-rank coal compared with the storage capacity of a similar mass of (non-adsorbing) sandstone with a porosity of 15%. This figure illustrates that coal seams can hold 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/ton).[19]

[17] 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.
[18] The density of the adsorbed methane is approximately its liquid density at atmospheric pressure boiling point (Yee et al., 1993).
[19] 32 scf/ton is approximately equal to 1 m^3/ton.

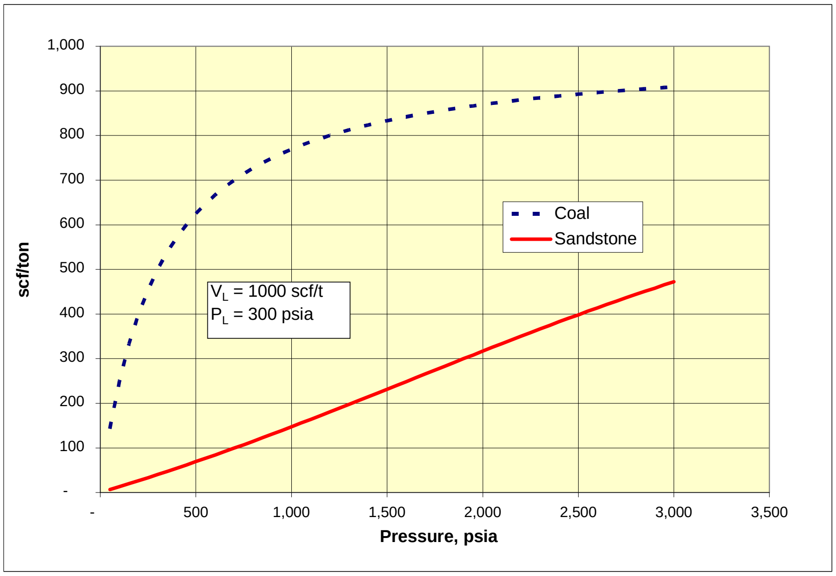

Figure A1. Comparison of methane storage capacity of sandstone and coal

The curve shown in **Figure** A1 that measures the adsorption of methane in a given mass of coal is called an adsorption isotherm because it is measured at a constant temperature.[20] Adsorption isotherms can be characterized by mathematical functions based on theoretical adsorption properties. One function commonly used for 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.[21] The Langmuir isotherm is generally expressed as:

$$\mathbf{V = V_L\, P / (P + P_L)}$$

where:

- V = Total volume of adsorbed 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, kilopascal (kPa), or pounds per square inch absolute (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 can be stored at lower pressures.

[20] At constant pressure, increasing temperature decreases the amount of adsorbed methane.

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

In abandoned mines, the pressure of the methane (and therefore the methane content) in the coal in contact with the mine void area is lower than its initial value before mining began. This drop in methane pressure is due to the coal's exposure to atmospheric pressure and purging of methane through the mine's ventilation system. However, the slow movement of gas from the coal to the void keeps the methane gas pressure in the coal not directly in contact with the void area above atmospheric pressure. Based on this pressure differential, methane will therefore continue to flow into the mine void for long periods of time.[22]

The total amount of coal in contact with the mine void is directly related to the mine size. The larger the mine, the greater amount of coal that remains within the mined boundaries. Larger mines also have greater surface areas of unmined coal exposed at their perimeters and borders.

Methane flow capacity of the mine

Methane reaches the atmosphere thorough a tortuous path and by several mechanisms:

- Diffusion in the adsorbed state from the coal matrix to the fracture system of the coal.
- Laminar flow through the fracture system (also referred to as the Darcy flow).[23]
- Free flow of the gas through the mine void with restrictions caused by roof collapse and man-made seals
- Flow from the mine void through vent pipes or fractures in the overburden or shaft seals to the atmosphere.

The total flow capacity of the mine is a combination of these pathways. The diffusion rate is related to the nature of the coal-gas adsorption. The Darcy flow is related to the permeability of the fracture system to the flow of methane. The flow of gas through the void is related to the mine's degree of compartmentalization and whether it is wholly or partially flooded. Finally, the flow of methane from the mine void to the surface depends on the status of the abandoned mine (i.e., whether it has an open vent or has been sealed).

Emission factor decline curves based on numerical modeling

Predicting the future emissions from abandoned mines is complex. U.S. EPA has relied on a commercially available Computational Fluid Dynamics (CFD), using a numerical simulation model originally developed for oil and gas reservoir simulations to predict emissions from abandoned mines. This model was adapted for abandoned mines and based on reasonable combinations of physical attributes for the mine flow capacity, gas content, and adsorption characteristics of the coal.

The numerical simulator includes a coalbed methane module that incorporates the physics of the adsorption and diffusion phenomenon within the flow and material balance equations.

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[22] Measured pressures at shut-in vent pipes in abandoned mines ranging from 0 to 34 psig (US EPA)

[23] This laminar flow can be described by Darcy's law.

There are several key steps in developing a decline curve with the CFD simulator. First, a conceptual model of a non-flooding, mine with an open vent was built. The numerical model was configured such that the volume of the mined-out areas, or void volume, is 10% of the model bulk volume.[24] The remaining mine volume (90%) consists of coal in communication with the void volume. This coal represents both the coal remaining in the mined seam as well as unmined coal seams in communication with the void volume through roof and floor fracturing and relaxation.

The model was configured to simulate the flow of a single component (methane), single-phase (gas) system for a period of 100 years. The parameters of importance needed to characterize this model include the following:

- Initial pressure of the gas in the coal matrix (adsorption pressure)
- The Langmuir isotherm that best describes the adsorption characteristics of the methane on the coal
- The relative volume of the void compared to the remaining coal
- The permeability of the remaining coal
- The permeability of the mine void
- The size of the mine void

It has been demonstrated that by fine-tuning the model parameters, given some coal property and mine size data together with extended flow rate measurements, a model can be built that will satisfactorily predict future methane production from abandoned mines (Collings, 2003). Unfortunately, for emissions inventory purposes little of this detailed data will be available, especially for Tier 1 or 2 methodologies. For this reason EPA suggests that a family of decline curves be generated using various reasonable combinations of values of the above parameters. For Tiers 1 and 2, decline curves are based on coal rank, primarily because this information is generally known within a coal region, but also because certain broad statements about gas content and permeability can be applied based on coal rank:

- In General, the higher the coal rank, the greater its capacity to hold adsorbed gas, as shown in **Figure A2**.
- The higher rank coals tend to have a more poorly developed fracture (cleat) system which is the primary conduit for the flow of the desorbed gas to the mine void. This results in a lower permeability for the coal remaining in and near the mine void.

[24] 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.

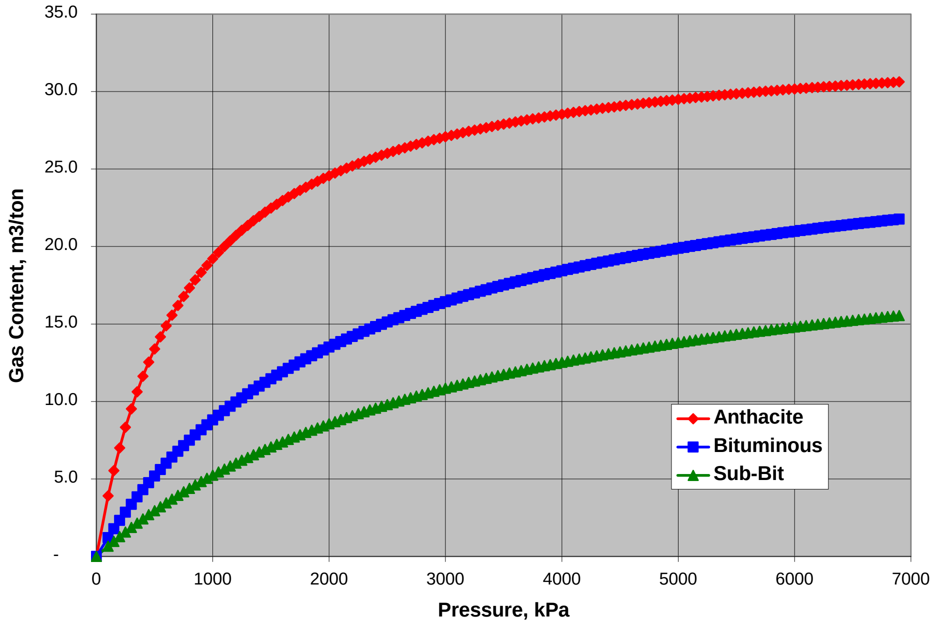

Figure A2. Typical adsorption isotherms as a function of coal rank (EPA 2004B)

Very little data have been compiled and published regarding coal permeability. A literature review provided the data in **Table A1** (EPA 2004). No published data were found for anthracite; these values were estimated based on proprietary data and personal communications. Not surprisingly, the most readily available pertained to bituminous coal, the primary coal rank produced in the United States by underground mines.

Table A1: Ranges of permeability for various coal ranks, millidarcy (md)

Coal Rank	Low	Mid	High
Anthracite	0.01	1.0	10.0
Bituminous	0.8	9.0	37.0
Sub-bituminous	10.0	100.0	1000.0

The emission factor decline curves generated for each of the coal ranks are based on the combination of parameters shown in **Table A2**.

Table A2: Parameter values used in creating emission factor decline curves

Coal Rank	Permeability, md	Langmuir Volume, m^3/ton	Langmuir Pressure, kPa
Anthracite	1.0	34	772
Bituminous	9.0	29	2294
Sub-bituminous	100.0	23	3447

The other relative parameters were independent of the coal rank. Their values were set as follows:

- All of the models were initialized at 138 kPa. The vent pressure was set at one atmosphere (101.0 kPa).
- The mine void was set at 10% of the bulk volume of the model.
- The permeability of the mine void was set at 75,000 md.
- The mine area was set at 16 km^2.
- The mine was assumed to drain a volume of coal 1500 meters from the periphery.

The outer boundary of the model was closed (i.e., no influx or outflow of gas across the outer boundary). In theory, the permeability of an open void should be infinite. However, because of restrictions within the mine related to roof falls and man-made barriers, the value used in this model is 75,000 md, which has proven to be a good approximation. An illustration of such a conceptual model is shown in **Figure A3**.

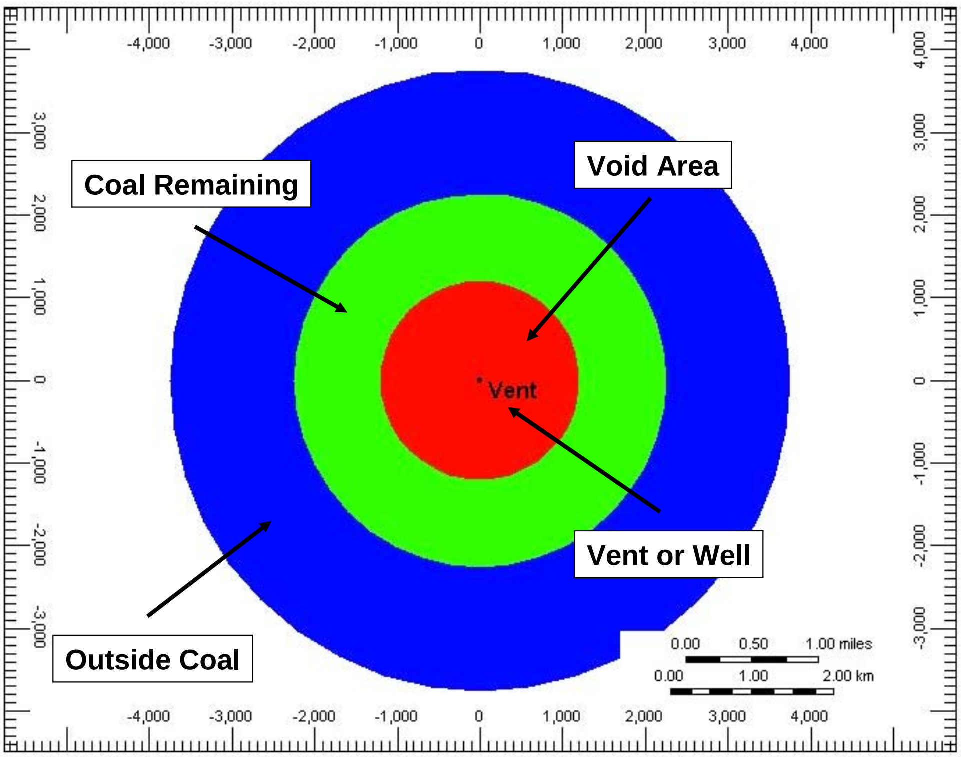

Figure A3: Aerial view of a conceptual mine model used in the CFD simulator to predict methane emissions through time for a dry mine with an open vent.

In the model simulation of an ideal-case vented, non-flooded mine, the gas from the mine void depletes rapidly. Thus, methane pressure in the mine is reduced, which in turn allows desorption of methane from the coal. The methane then migrates to the void area where it is emitted and removed from the mine system. Modifications of this simulation for flooded and sealed mines are described in EPA's abandoned mine methodology (US EPA, 2004).

Figure A4 shows the resulting methane production decline curve for a non-flooded, mine with an open vent. 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.

The form of the hyperbolic decline equation is:

$$\textbf{Emission factor} = (1+at)^b$$

Where "a" and "b" are coefficients derived from the curve fit to the simulation model results, and t is number of years since abandonment. The resulting emission factor is multiplied by the yearly emissions during active mining prior to abandonment to calculate the inventory year emissions.

Decline equations for open-vented, non-flooded mines for different coal ranks are listed in **Table A3**.

Table A3: Emission factor decline equations by coal rank

Coal Rank	Equation
Anthracite	$(1+1.72t)^{-0.58}$
Bituminous	$(1+3.72t)^{-0.42}$
Sub-Bituminous	$(1+0.27t)^{-1.00}$

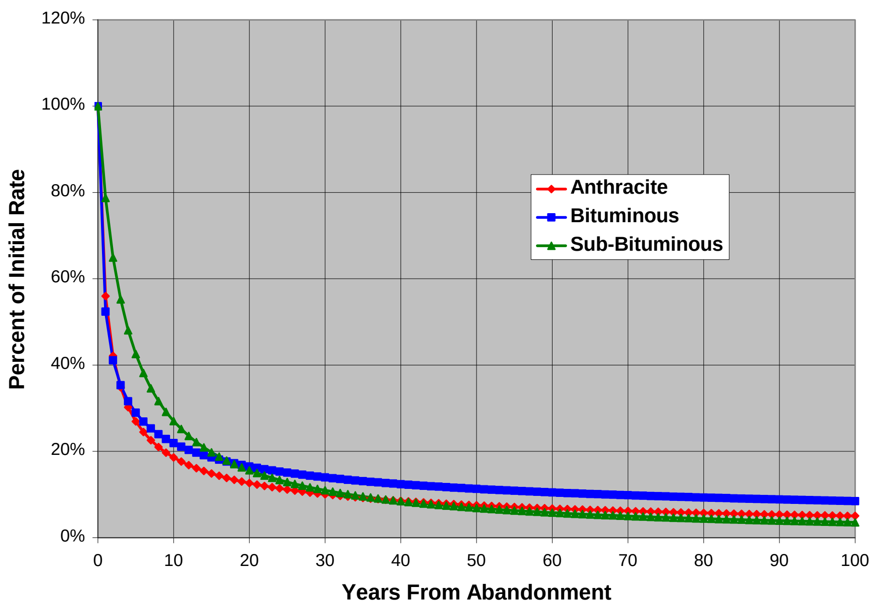

Figure A4: Emission factor decline curves based on coal rank

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Appendix B

Suggested Emission Factor Decline Equations for Use in Estimating Abandoned Mine Methane Emissions through Time

This appendix is presented as an annex to the White Paper: “Proposed Methodology For Estimating Emission Inventories From Abandoned Coal Mines.” Decline curves, their equations, and their associated parameters are presented for use where country-specific decline curves are not available. They are intended to be generic curves based on combinations of coal rank, permeability and mine size. They have been generated based on information available for coal basins of the United States. Individual countries may choose to build their own decline curves based on locally available data. **Appendix A** describes the process used and assumptions made to generate these decline curves.

Physical parameters used in modeling emission factors

The decline curves are grouped by coal rank, primarily because the rank of the mined coal is generally known within a coal region, but also because certain broad statements about gas content and permeability can be applied based on coal rank:

- In general, the higher the coal rank, the greater its capacity to hold adsorbed gas.
- The higher rank coals tend to have a more poorly developed fracture (cleat) system which is the primary conduit for the flow of the desorbed gas to the mine void. This results in a lower permeability for the coal remaining in and near the mine void.

Adsorption isotherm data publicly available in the United States was used to generate average isotherm parameters for Anthracite, Bituminous and Sub-bituminous coals. These are shown in **Table B1** (Masemore 1996).

Table B1: Langmuir adsorption isotherm parameters

Coal Rank	Langmuir Volume, m^3/ton	Langmuir Pressure, kPa
Anthracite	34	772
Bituminous	29	2294
Sub-bituminous	23	3447

Another study associated with the US EPA abandoned mine emissions inventory (EPA 2004B) compiled public information on permeability by rank as shown in **Table B2**.

Table B2: Ranges of permeability for various coal ranks, millidarcy (md)

Coal Rank	Low	Mid	High
Anthracite	0.1	1.0	10.0
Bituminous	0.8	9.0	37.0
Sub-bituminous	10.0	100.0	1000.0

Another study was an analysis of the size distribution of abandoned mines in the Illinois basin of the United States. From this distribution, three representative mine sizes were selected (small, medium, and large) to generate the decline curves, shown in **Table B3**.

Table B3: Selected size categories for abandoned mines			
	Square km	**Hectare**	**Acre**
Small	3	300	741
Medium	15	1500	3707
Large	75	7500	18533

The referenced areas are based on a single seam coal mine. The model assumed a 2.5 meter thick coal seam (see **Appendix A**).

Nine models were built for each coal rank that combined the three size uncertainties with the three permeability uncertainties. Plots for each rank and grouped by mine size follow the text. **Tables B4** through **B6** list the decline equations derived from the model results for each combination of parameters. Note that "t" is the number of years from abandonment.

Table B4: Emission Factor Equations for Anthracite

Equation Name	Permeability	Mine Size	Equation
ALS	Low	Small	$(1+4.07t)^{-0.52}$
ALM	Low	Medium	$(1+4.42t)^{-0.56}$
ALL	Low	Large	$(1+1.70t)^{-0.59}$
AMS	Mid	Small	$(1+4.22t)^{-0.47}$
AMM	Mid	Medium	$(1+1.72t)^{-0.58}$
AML	Mid	Large	$(1+0.28t)^{-0.74}$
AHS	High	Small	$(1+3.33t)^{-0.44}$
AHM	High	Medium	$(1+1.99t)^{-0.48}$
AHL	High	Large	$(1+0.45t)^{-0.59}$

Table B5: Emission Factor Equations for Bituminous

Equation Name	Permeability	Mine Size	Equation
BLS	Low	Small	$(1+5.37t)^{-0.45}$
BLM	Low	Medium	$(1+3.51t)^{-0.51}$
BLL	Low	Large	$(1+0.68t)^{-0.59}$
BMS	Mid	Small	$(1+3.04t)^{-0.45}$
BMM	Mid	Medium	$(1+3.72t)^{-0.42}$
BML	Mid	Large	$(1+0.51t)^{-0.57}$
BHS	High	Small	$(1+0.80t)^{-0.74}$
BHM	High	Medium	$(1+1.75t)^{-0.46}$
BHL	High	Large	$(1+0.72t)^{-0.47}$

Table B6: Emission Factor Equations for Sub-bituminous

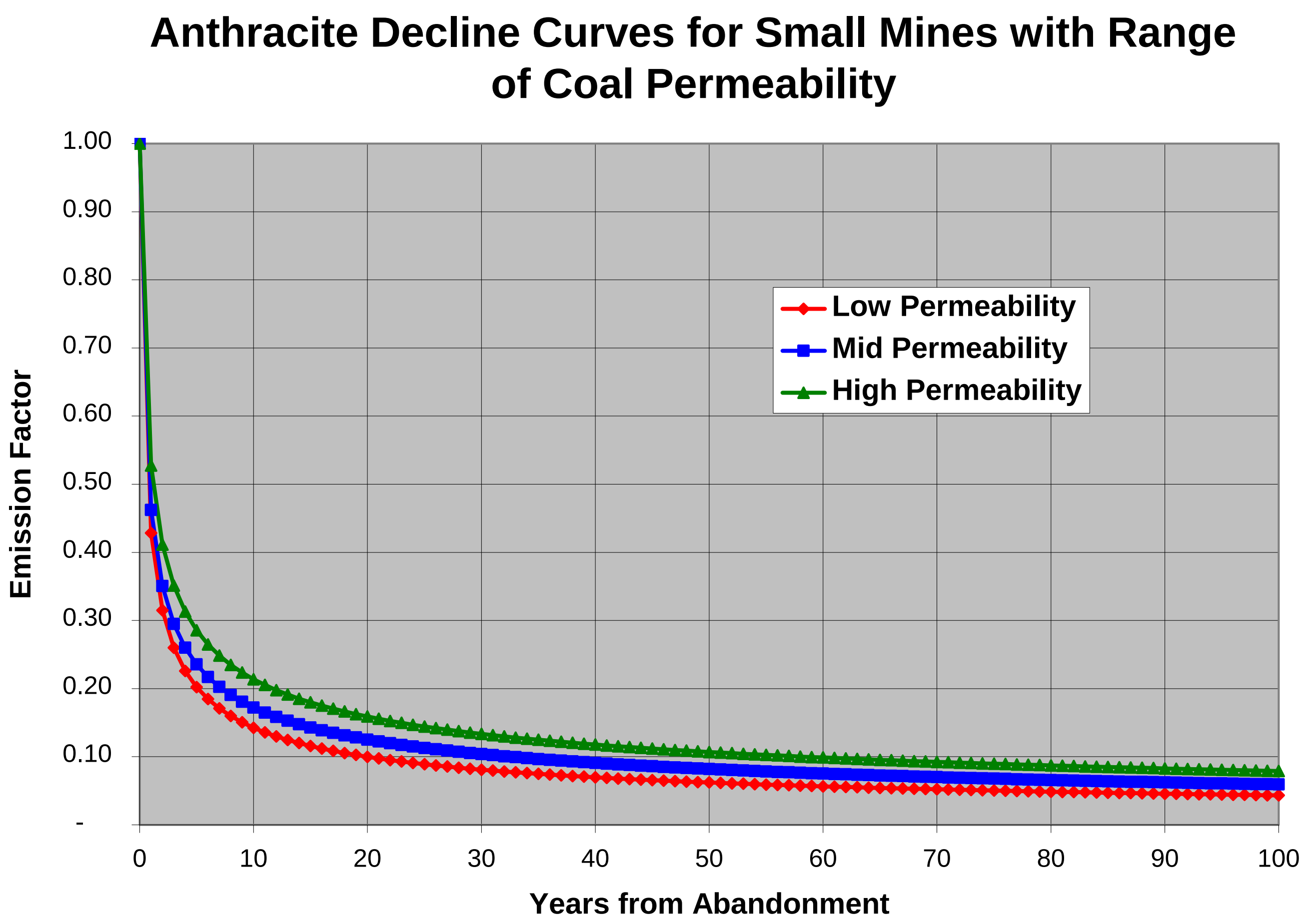
Equation Name	Permeability	Mine Size	Equation
SLS	Low	Small	$(1+1.36t)^{-0.59}$
SLM	Low	Medium	$(1+2.67t)^{-0.44}$
SLL	Low	Large	$(1+0.84t)^{-0.48}$
SMS	Mid	Small	$(1+0.43t)^{-1.31}$
SMM	Mid	Medium	$(1+0.27t)^{-1.00}$
SML	Mid	Large	$(1+0.61t)^{-0.46}$
SHS	High	Small	$(1+0.59t)^{-2.20}$
SHM	High	Medium	$(1+0.30t)^{-1.77}$
SHL	High	Large	$(1+0.12t)^{-1.35}$

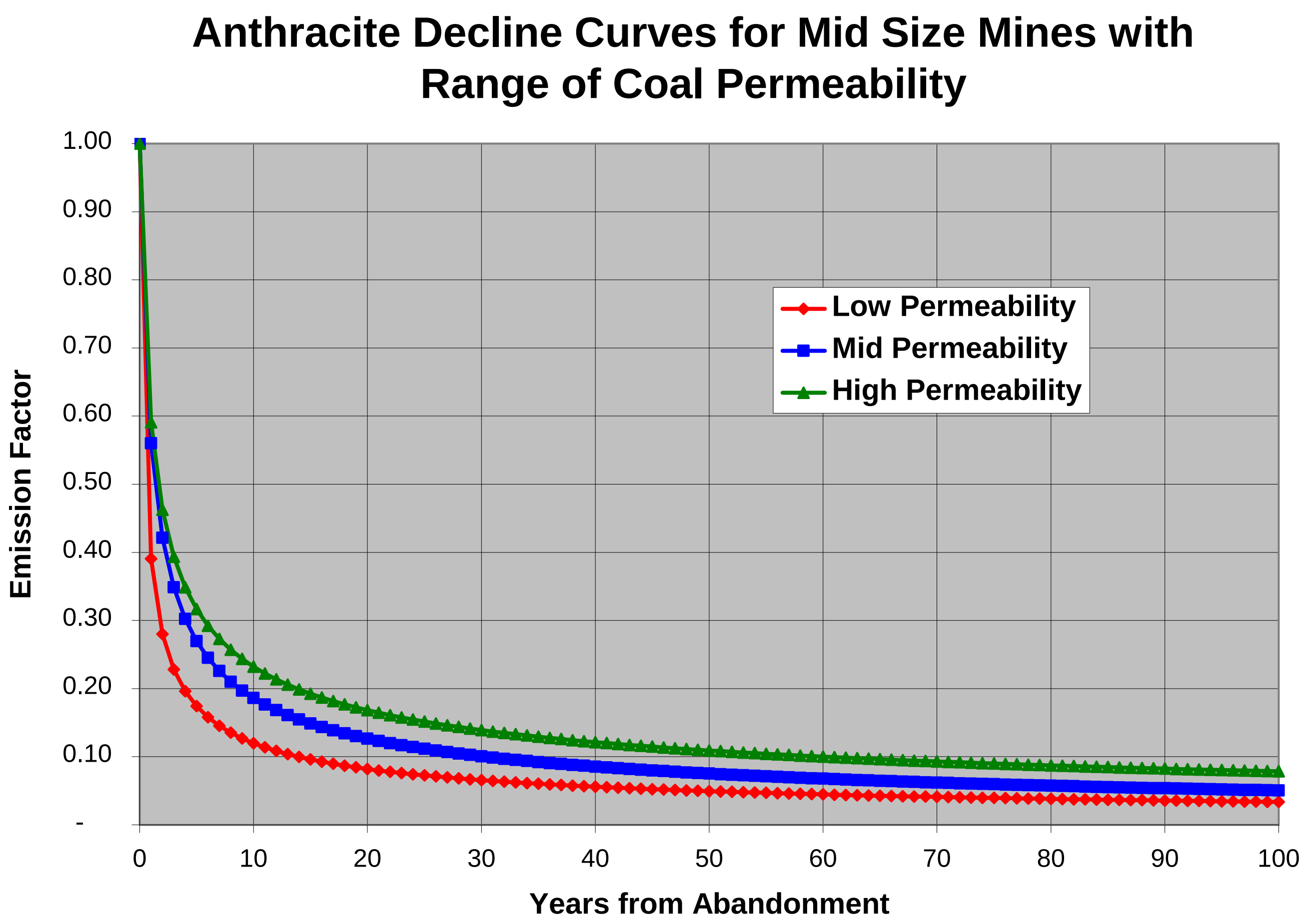
The calculated emission factor at a given time since abandonment is to be multiplied by the yearly emissions at the time of abandonment. The shape of the emission factor decline curve will be influenced by both the mine size and the permeability as will the rate of emissions at abandonment.

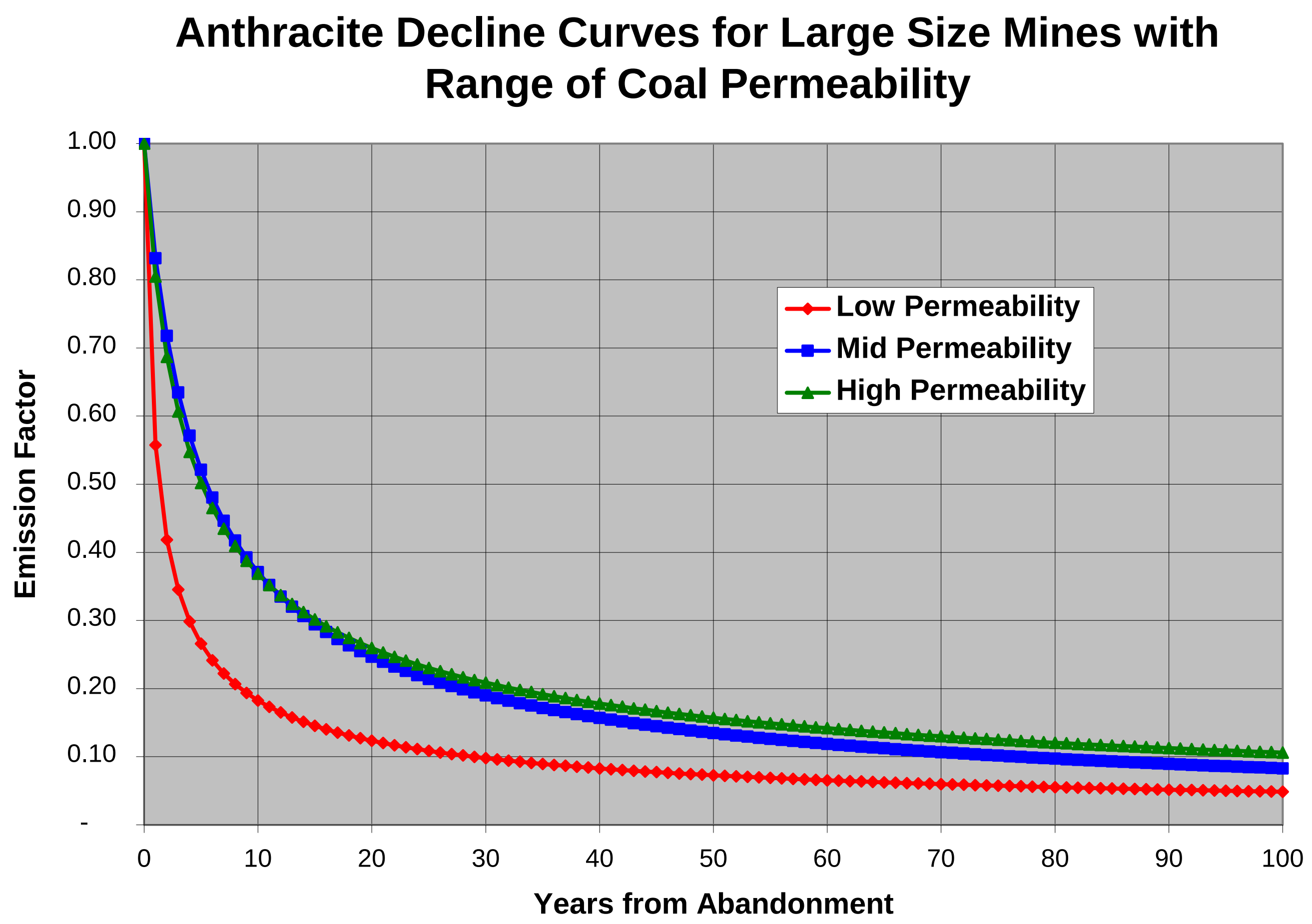
References

Masemore, S., S. Piccot, E. Ringler, and W. P. Diamond, 1996, Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States, EPA-600/R-96-065, Washington, D.C.

U.S. Environmental Protection Agency, 2004b. Background documents developed under EPA's Coalbed Methane Outreach Program for abandoned coal mine research study.


Anthracite Decline Curves for Small Mines with Range of Coal Permeability
Emission Factor
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
0
10
20
30
40
50
60
70
80
90
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability


Anthracite Decline Curves for Mid Size Mines with
Range of Coal Permeability
Emission Factor
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
0
10
20
30
40
50
60
70
80
90
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability


Anthracite Decline Curves for Large Size Mines with Range of Coal Permeability
Emission Factor
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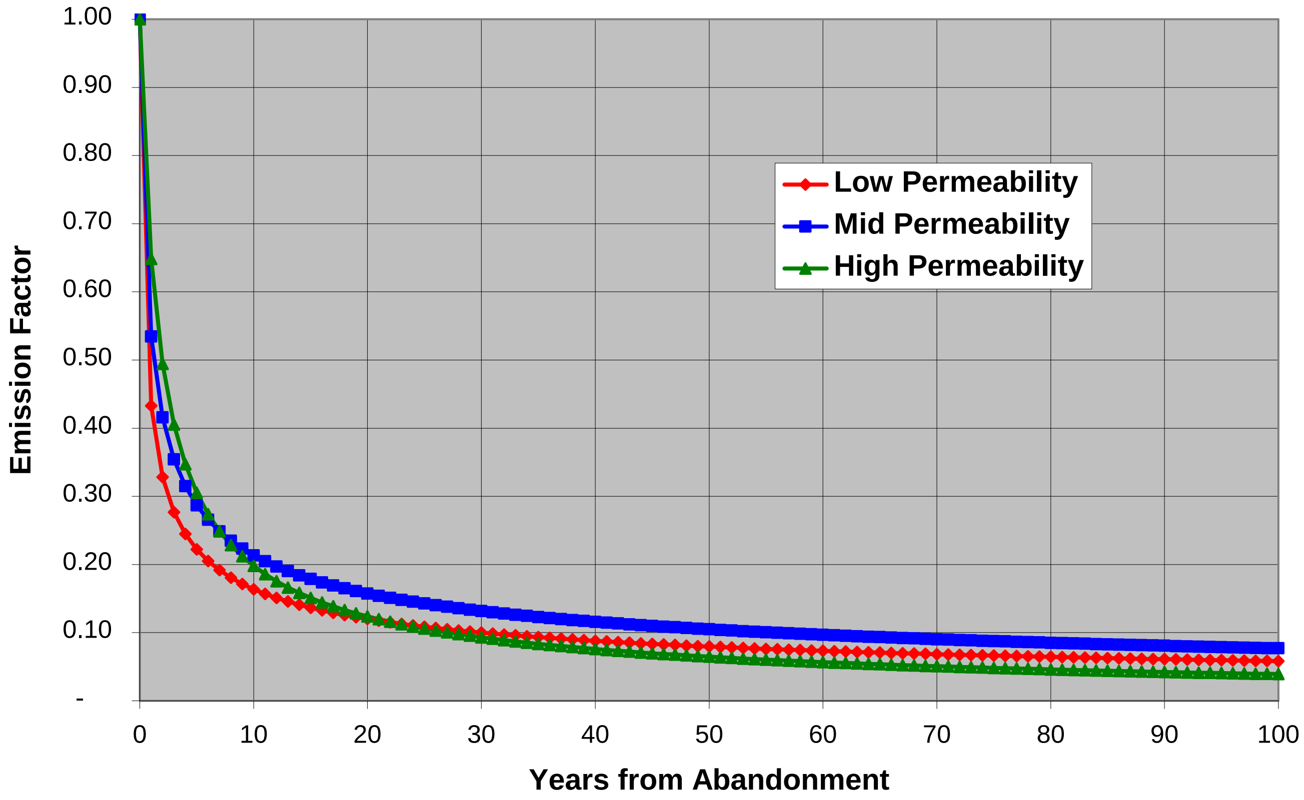
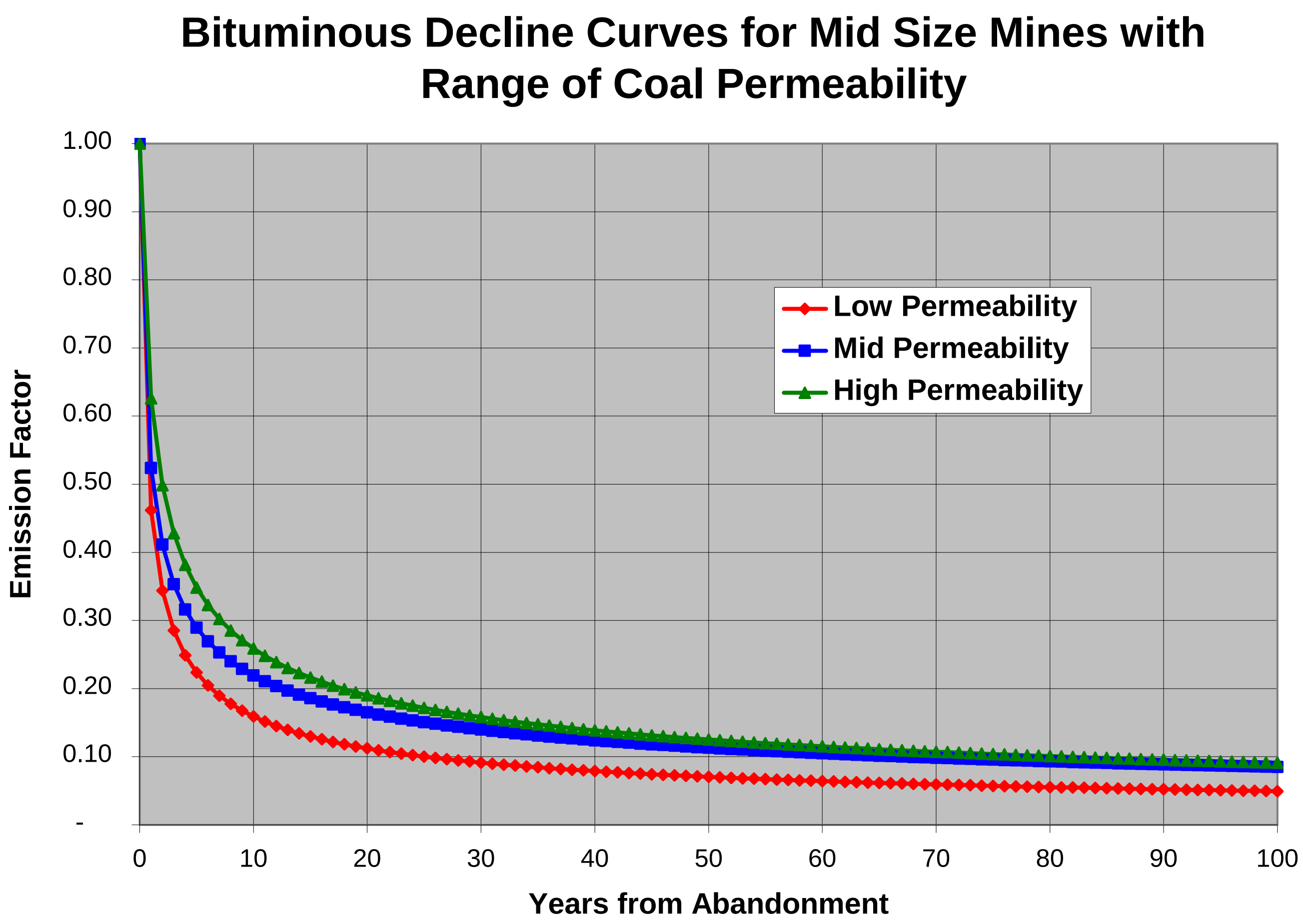
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
0
10
20
30
40
50
60
70
80
90
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability

Bituminous Decline Curves for Small Mines with Range of Coal Permeability




Bituminous Decline Curves for Mid Size Mines with Range of Coal Permeability
Emission Factor
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
0
10
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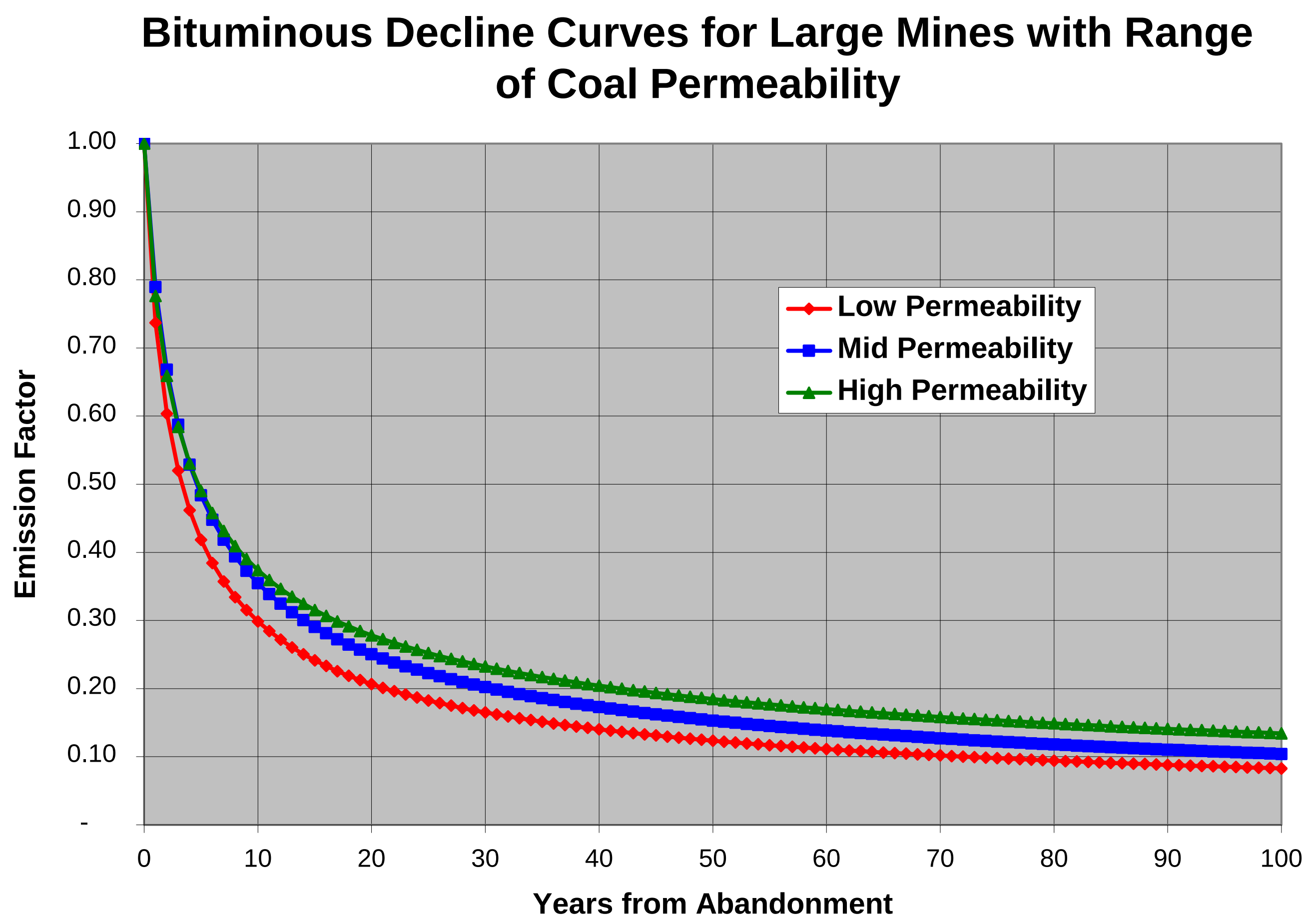
70
80
90
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability


Bituminous Decline Curves for Large Mines with Range of Coal Permeability
Emission Factor
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
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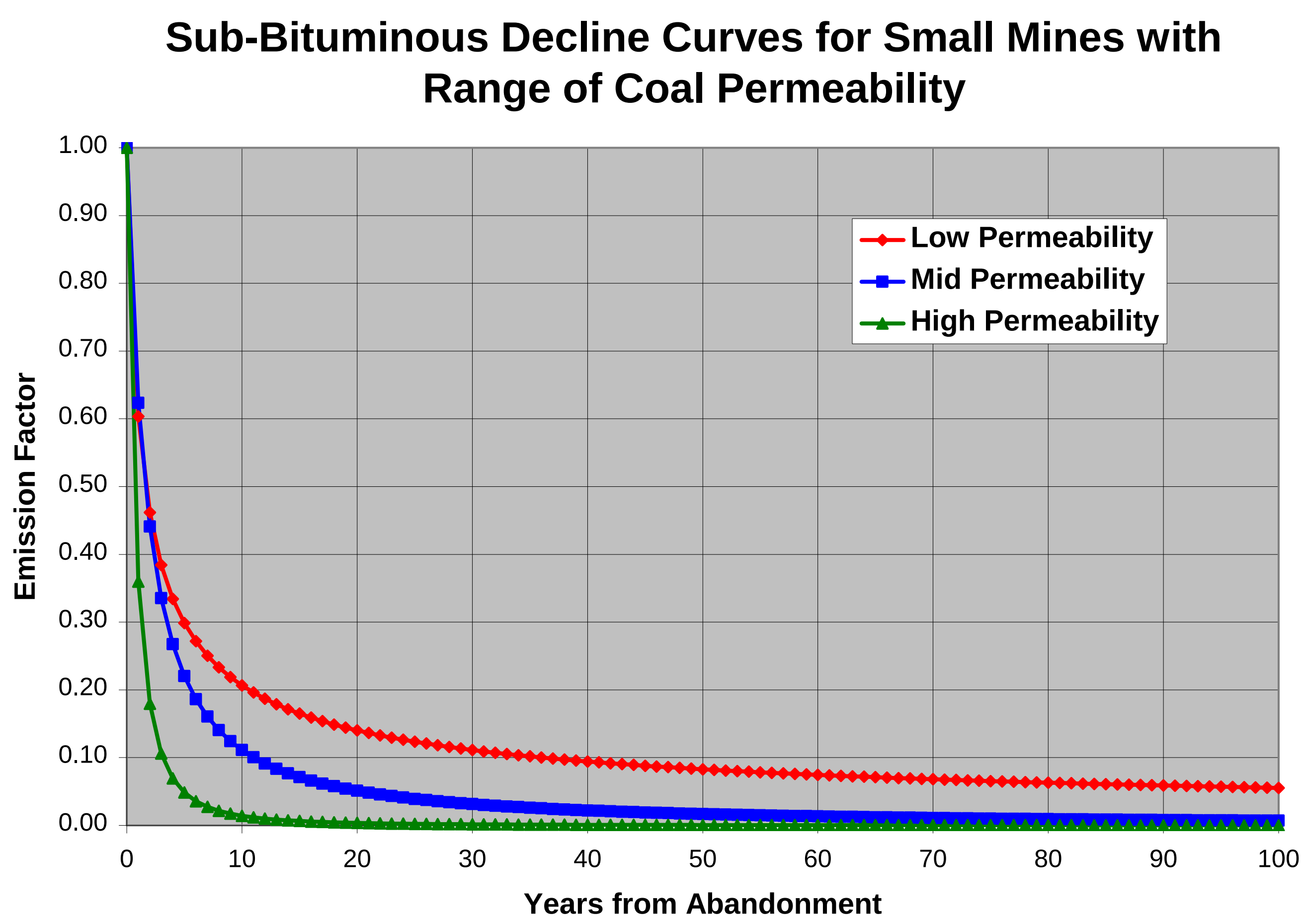
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability


Sub-Bituminous Decline Curves for Small Mines with Range of Coal Permeability
Emission Factor
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0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
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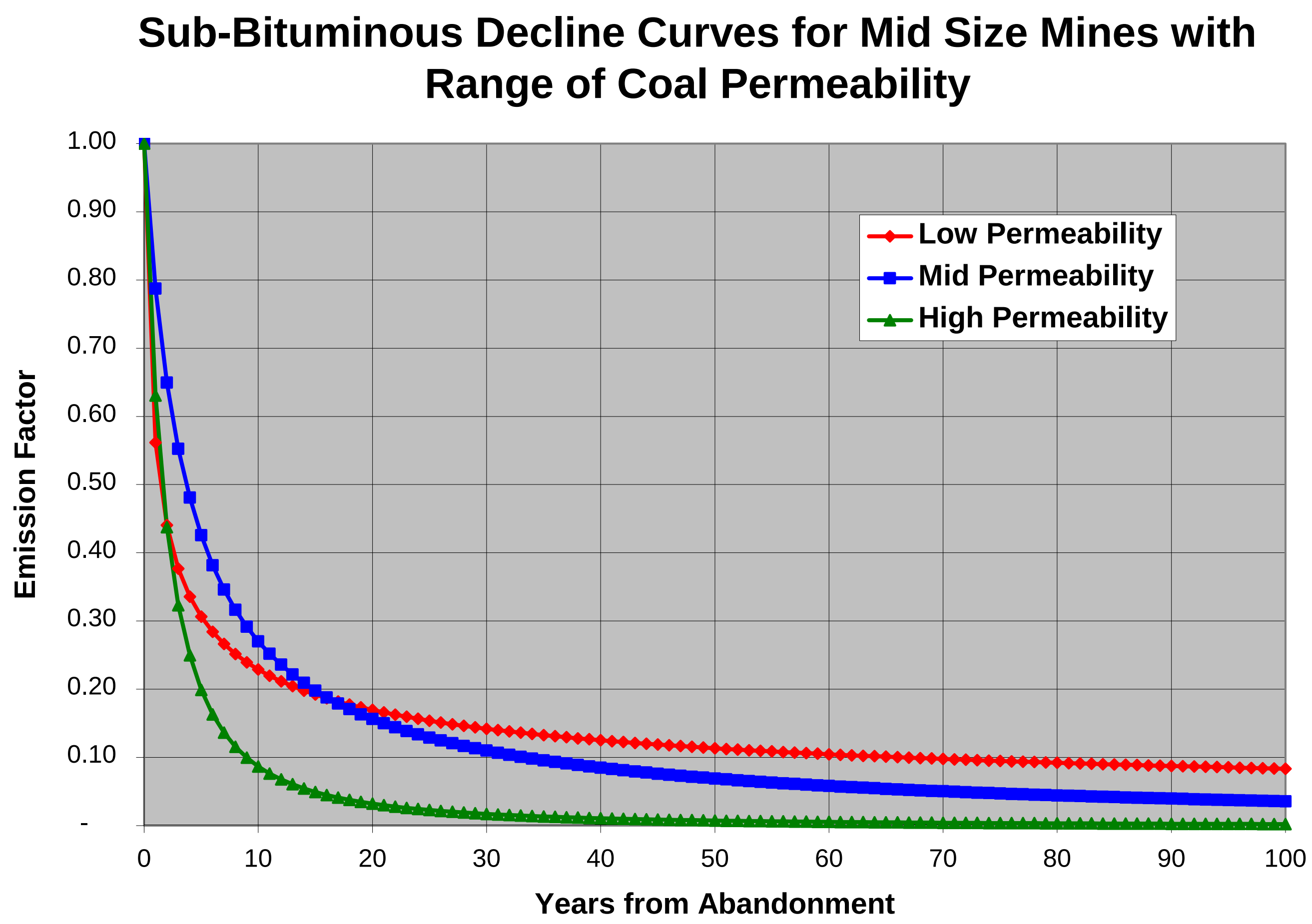
50
60
70
80
90
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability


Sub-Bituminous Decline Curves for Mid Size Mines with Range of Coal Permeability
Emission Factor
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
0
10
20
30
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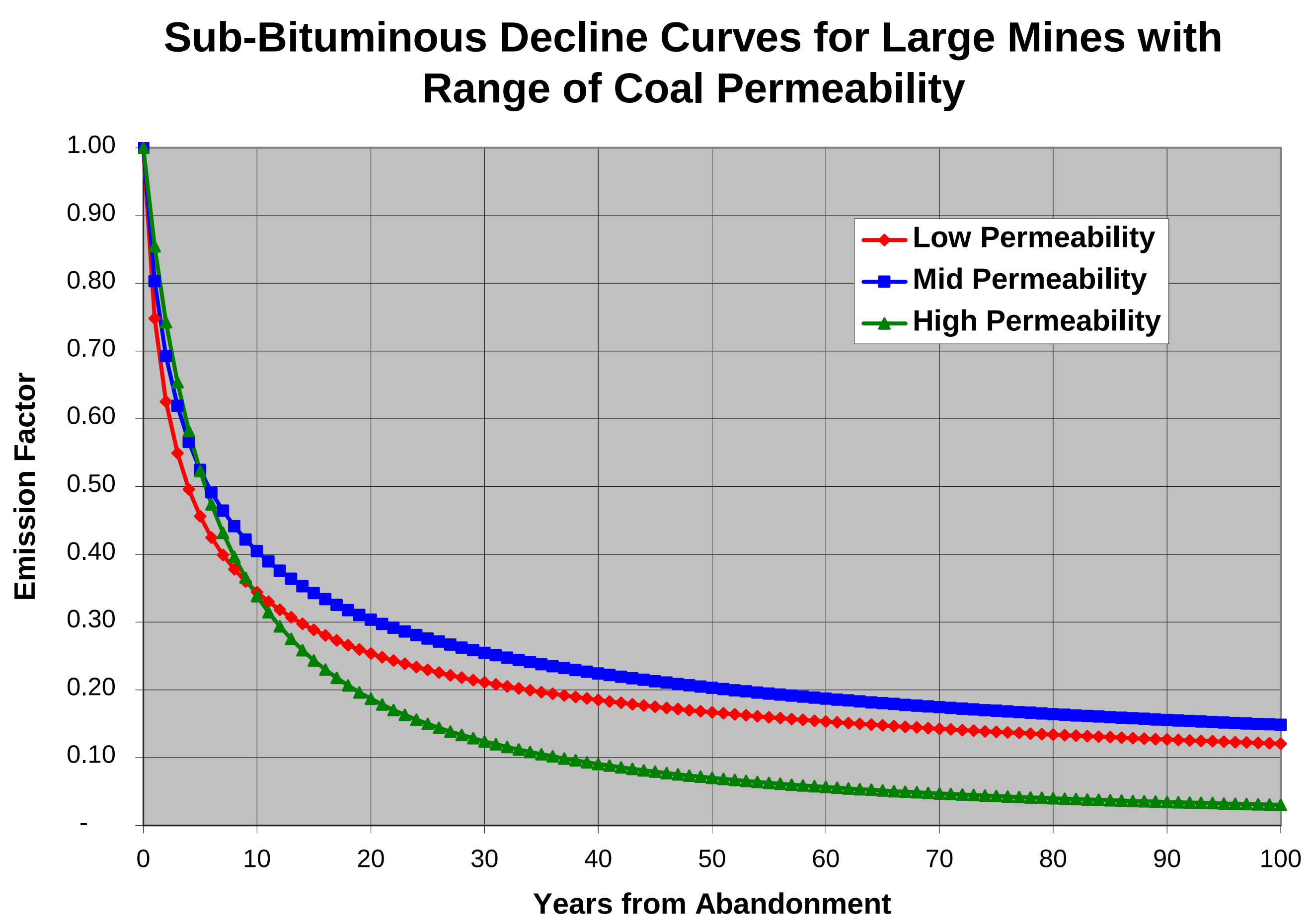
70
80
90
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability


Sub-Bituminous Decline Curves for Large Mines with Range of Coal Permeability
Emission Factor
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
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90
100
Years from Abandonment
Low Permeability
Mid Permeability
High Permeability