AN IMPROVED INVENTORY OF METHANE EMISSIONS FROM COAL MINING IN THE UNITED STATES

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IMPLICATIONS

Estimates vary somewhat, but methane from coal mines comprise about 15 percent of total domestic anthropogenic methane emissions. This study substantially increases the reliability of these estimates by adding emission measurements from 30 separate coal mine sites. Sampling efforts have focused on under-represented mining categories including surface mines, abandoned mines, and handling facilities. Two new quality assured and verified measurement methods have been developed for surface mines and coal handling facilities. The single path and plane-integrated open-path Fourier transform infrared spectroscopy techniques developed for surface mines have since been adopted for a number of other applications including landfills and animal containment facilities.

ABSTRACT

Past efforts to estimate methane emissions from underground mines, surface mines, and other coal mine operations have been hampered, to different degrees, by a lack of direct emissions data. Direct measurements have been completely unavailable for several important coal mining operations. A primary goal of this study was to collect new methane emissions measurements and other data for the most poorly characterized mining operations, and use these data to develop

an improved methane emission inventory for the U.S. coal mining industry. This required the development and verification of measurement methods for surface mines, coal handling operations, and abandoned underground mines, and the use of these methods at about 30 mining sites across the U.S. Although the study's focus was on surface mines, abandoned underground mines, and coal handling operations, evaluations were also conducted to improve our understanding of underground mine emission trends, and to develop improved national data sets of coal properties. Total U.S. methane emissions are estimated to be 4.669 million tons and, as expected, emissions from underground mine ventilation and methane drainage systems dominate (74 percent of the total emissions). On the other hand, emissions from coal handling, abandoned underground mines, and surface mines are significant, and collectively they represent about 26 percent of the total emissions.

INTRODUCTION AND BACKGROUND

Trends in Past Methane Emissions Estimates for Coal Mining

Over the last 30 years there have been numerous attempts to estimate the global emissions of methane from coal mining operations. Table 1 presents a summary of global methane emissions estimates developed by various researchers. Estimates range from 8.7 to 71 million tons per year.

Most estimates presented in Table 1 can be traced back to assumptions made by some of the earliest researchers. Estimates developed by Hitchcock and Wechsler[1], Ehhalt[2], Ehhalt and Schmidt[3], Seiler[4], Crutzen[5], and Cicerone and Oremland[6] were based in large part on simple methane emissions ratios developed by Bates and Witherspoon[7] and Koyama[8, 9]. More recent estimates by Boyer et al.[10] and Kirchgessner et al.[11] were developed by correlating mine emissions measurements data with various coal properties and mine production rates. The estimate of Fung et al.[12] was developed using a combination of global methane mass balances and atmospheric modeling techniques to infer a budget for all methane sources that best reproduces the spatial and seasonal variations of methane concentrations observed in the atmosphere. The estimate produced by the Coal Industry Advisory Board (CIAB)[13] yields a relatively low estimate of 26 million tons because of the low emissions factors used.

Methodological and other differences among the estimates in Table 1 make direct comparisons difficult. One problem is that the estimates represent different base years with different coal production rates and, presumably, different methane emissions. Some estimates did not include that all the coal produced globally account for hard coal only, excluding brown coals and lignite which contain low quantities of methane[4, 5, 6, 8, 9]. Only the estimates of Boyer et al.[10], CIAB[13], and Kirchgessner et al.[11] include estimates of post-mining operations, and none address the emissions characteristics of abandoned mines. Perhaps the most important difference to understand is that different emissions factors have been employed by the various researchers and, while it is not always explicit from the published papers, factors used range from 160 to 670 ft^3 of methane per ton of coal mined. The lowest emissions factors appear to have been based on the assumption that the amount of methane liberated during mining is limited to the methane originally contained in the mined coal. This is a negatively biased assumption for most underground coal mines, since it is now known that actual emissions are usually several times higher than the emissions associated with the mined coal alone[14].

While different approaches have been used to estimate emissions from coal mines in the past, they all share a common weakness; surprisingly few direct measurements have been used, and for some mining sources, direct measurements have been completely unavailable. Using new emissions measurements and other data, this paper presents improved estimates of methane emissions from U.S. coal mines.

Methane is formed in coal during the process of coalification, and the quality and quantity of the gas created and retained is a function of the original organic matter composition and the conditions of burial. Generally, more methane is formed during coalification than can be stored within the coalbed itself, so excess methane migrates into, and can be stored in, the surrounding strata. Methane is retained by the coalbed and surrounding strata as long as it remains under pressure and, assuming that no geologic processes breach the reservoir first, mining releases this pressure and the methane escapes.

Methane emitted from underground, surface, and abandoned coal mines is often released from both the coal seams and surrounding strata. In longwall mines the zone of disturbance can be large, depending on a variety of factors including size of the long wall, depth of mining, and thickness of coal extracted. Creedy [15] has estimated that zone may extend up to 160 meters into the roof rock and 40 meters below the seam being worked. Since additional coal and methane often exist within this zone, emissions from longwall mines are much greater than would be expected from the mined coal alone. Emissions escape from underground mines by various pathways including ventilation shafts, methane drainage systems, and post-mining coal crushing and handling operations[10, 16].

In areas where miners are working, methane levels must be kept below 0.5 percent. This is accomplished, in part, by sweeping the mine with large quantities of ventilation air. Although containing less than one percent methane, ventilation air contributes the largest amount to total emissions because the volume is so great.

Gas drainage systems are often employed at underground mines to relieve some of the burden on ventilation systems. Vertical wells can be drilled into the coal in advance of mining to drain methane from the coal and overlying strata. When a longwall miner passes under these wells and subsidence fractures the overlying strata, these wells can be converted into gob wells which drain the fractured area and prevent the release of gob gas into the mine workings. Horizontal boreholes and cross-measure boreholes can be drilled from within the mine into the coal and overlying strata, respectively. The methane is then conveyed to the surface through piping within the mine. In Europe, methane recovered by gas drainage systems is more commonly used as an energy source than in the U.S., where much of the gas is vented into the atmosphere. There is little published data on methane emissions from gas drainage systems, however, data obtained from industry representatives indicate that drainage may account for a large fraction of the total emissions associated with underground mines[10, 17].

Very few emissions measurements have been taken at surface mines. The limited data which do exist suggest that the primary sources of emissions include seam areas fractured by coal blasting, the lower most portions of surface mine pits (the pit floor), and inactive pits[18, 19]. In general, the strata overlying the coal at surface mines do not appear to be a significant source of emissions but, as in underground mines, emissions may be contributed from underlying seams, faults, or gas bearing reservoirs. Historically, methane emissions from surface mines have been thought to be much lower than from underground mines because of the lower gas contents associated with these relatively young and shallow coals. However, until this program was started there were no direct measurements available to demonstrate this.

After coal leaves a mine it typically undergoes a series of operations, collectively referred to as coal handling. This may include crushing, separation of impurities, size classification, drying, transportation, and storage. Different types of coals desorb methane at different rates, but since coal is usually removed from a mine within hours or days of being mined, some methane remains and is liberated from the coal during handling operations. To approximate these emissions, the assumption is generally made that a fraction of the original methane remains in the coal after mining, and that this is emitted completely to the atmosphere during post-mining operations. Creedy estimated that 40 percent of the methane contained in the mined coal is released after it leaves the mine[20]. The actual amount of gas that escapes into the atmosphere will be a function of the rate of methane desorption, the coal's original gas content, and the amount of time elapsed before coal combustion occurs.

Emissions from abandoned underground mines come from unsealed slopes and mine shafts, or from vents installed to prevent the buildup of methane in the mine after closure. Emission mechanisms at abandoned mines are highly uncertain. However, emissions are likely a function of diurnal and seasonal cycles related to changes in temperature and barometric pressure, longer-term changes brought on by processes such as mine flooding and the slow depletion of available methane, reservoir pressure, and the emissions produced by the mine when it was active.

Since methane in underground mines constitutes a safety hazard, methane emissions in U.S. mines are monitored quarterly by the Mine Safety and Health Administration (MSHA). As a consequence, active underground mine emissions are reasonably well known. In contrast, abandoned underground mines are not monitored, so their emission characteristics are poorly defined, and their exact numbers and locations can not be determined from available data. Methane emissions from surface mines and coal handling operations do not accumulate in significant quantities, and because there is little or no safety hazard, emission rates for neither have been measured in the past.

A primary goal of the study described in this paper was to collect new methane emissions measurements and other data for those poorly characterized mining operations described above, and to use these data to develop an improved emission inventory for the U.S. coal mining industry. This required the development and verification of measurement methods for surface mines, coal handling operations, and abandoned underground mines, and the use of these methods at about 30 representative mining sites across the U.S. In addition, research was conducted to improve underground mine emissions estimates, particularly for those mines that do not produce coal, but continue to liberate methane (temporarily inactive mines).

EMISSIONS MEASUREMENTS, EMISSION FACTORS, AND EMISSIONS ESTIMATES

Underground Mines

Emissions from underground mine ventilation shafts in the U.S. can be quantified using mine-specific emission measurements and other data collected by MSHA. Quarterly methane emission measurements collected by MSHA inspectors, quarterly coal production rates reported by mines to MSHA, and mine operational status codes reported by MSHA. Operational status codes and quarterly coal production rates were obtained from MSHA's Part 50 database[21], while quarterly emissions measurements were provided by MSHA district offices. These data were used to develop a mine-specific inventory of mineshaft emissions. Emissions from methane drainage systems at underground mines are dealt with separately.

As a starting point in developing mine-specific emissions estimates, a comprehensive list of mine sites was developed. Starting with all the underground mines listed in the Part 50 database, 622 sites permanently abandoned throughout 1995 and 70 sites with missing operational status codes were removed. This resulted in a final list of 1,659 underground mines with various operational status codes: producing, active but not producing, temporarily inactive, under construction, and closed. MSHA district offices provided emissions measurements from all four quarters of 1995 for 732 of these mines and no emissions estimation was required. These data accounted for 83 percent of the final emissions estimate for underground mine shafts. For the remaining 927 mines, MSHA measurements were unavailable for one or more quarters in

1995 and emission factors as a function of coal production had to be developed. Sufficient quarterly emissions measurements were available to develop mine-specific relationships of methane emissions to production for 276 of these mines. These measurements were not always associated with the 1995 time frame however, so data for 1994 and 1996 were used when necessary. For about 25 percent of the 276 mines, emissions ratios were developed relating quarterly methane liberated per unit of production. In most cases however, quarterly data were plentiful enough to develop mine-specific linear regressions of emissions versus production for which at least three data points were required. Regression equations were not used if the predicted emissions relationship was asymptotic, the equation did not follow the trend observed in the data by visual inspection, or the data were insufficient to develop a discernable trend. Emissions from these 276 mines account for 12 percent of the estimated emissions from underground mine shafts.

The remaining 651 mines either had little data available for estimating emissions, or did not produce coal for one or more quarters of 1995 but could still liberate significant quantities of methane while inactive. Inactive mines may continue to operate their ventilation systems to prevent methane buildup. Because measurements may not always be collected by MSHA during these periods, this inventory would underestimate emissions if inactive mine emissions were neglected.

Figure 1 shows how emissions and production are related at 33 inactive mines (termed E-status mines) that have the most complete and highest quality data available. The linear relationship between the average of the measured emissions when production occurs, and the average of the measured emissions when no production occurs, is shown in the figure. This equation is used to estimate emissions for E-status mines with missing MSHA measurements when insufficient data are available to develop a reliable mine specific-regression equation. The equation estimates inactive emissions based on a mine's active emissions rate. As Figure 1 shows, E-mines with average active emissions rates that range from about 3,000 cfd to 10,000 cfd can have inactive emissions that either approach zero, or have a value that is consistent with the linear relationship shown. For mines with active emissions rates that are less than 5,000 cfd, an emissions rate of zero is assigned for the inactive periods. If the active emissions are above 5,000 cfd, the relationship in Figure 1 is applied for inactive periods. Although direct measurements were available in several cases, there were 169 of the 651 mines for which inactive emissions were estimated for one or more quarters using the approach outlined above. The emissions associated with this estimation procedure account for about 4 percent of total shaft emissions.

The methods outlined so far account for about 99 percent of the estimated emissions from underground mine shafts. The remaining emissions were estimated using county-average emissions factors where available (ft^3/ton of coal), or a generic data set average emissions factor when no other options exist. A number of mines in the Part 50 data base were identified as under development, and these mines were assigned an emissions rate of zero. This was done because the status codes assigned indicate that, while shaft and slope development were underway, the coal seam had not been encountered.

Once production-based emissions factors or regression equations had been developed, mine-specific emissions were calculated. For those 927 mines lacking MSHA emissions data for one or more quarters of 1995 but which were active for portions of the year, emissions factors or regression equations were multiplied by the mine-specific quarterly coal production values reported in the Part 50 data base to obtain emissions for the active portions of the year. For those mines with periods of inactivity or which were wholly inactive, values from the relationship shown in Figure 1 and described in the accompanying text were multiplied by the number of inactive days to calculate emissions for the inactive portions of the year. Finally, these estimates were summed with the measured emissions from the 732 mines having complete data sets to obtain the total methane emissions from underground mine shafts.

Emissions from methane drainage systems like gob wells, in-mine horizontal boreholes, and vertical wells are significant on a national scale. There are limited data available for quantifying methane recovery by mine drainage installations, so it was necessary to rely on published estimates of gas liberation associated with individual mines[17, 22]. Of the mines reported to have used drainage systems in the past, 26 were found to be operational through 1995, and 3 were shutting down and assumed to operate for only a portion of 1995. Emissions from operating drainage systems were estimated using mine specific emissions factors published by the U.S. EPA[22]. These factors include both information provided by mine sites and estimated values, and each account for the methane recovered for use or sale at sites in the Warrior, Appalachian, and Western coal basins. As a percentage of total mine emissions, typical emissions factors used were 40 percent for gob wells and in-mine boreholes, and 40 to 53 percent for combinations of various technologies and gas sales scenarios. Three mines with drainage systems were closing down during 1995, and it was assumed that drainage system emissions at these sites continued to liberate emissions for six months after final coal production ceased. Gob wells can continue to liberate emissions from mined-out gob areas for six months to a year or more after mining has ceased.

Surface Mines

When this study was initiated, there were no emissions measurements available for surface coal mines. Since surface mine production represents a large fraction of the coal produced in the U.S. and abroad, new emissions measurements were collected at 6 surface mines to address this uncertainty. A practical and effective method for measuring methane emissions at these large and complex sites was unavailable, so two new methods were developed and validated using open-path Fourier transform infrared (FTIR) spectroscopy, meteorological measurements, and tracer gases released at known rates. Development of the two methodologies and their field validation are described in detail elsewhere[18, 23, 24]. Briefly, the single-path method uses one FTIR path to measure methane concentrations in the plumes downwind from exposed coal surfaces, while a tracer gas, sulfur hexafluoride, is released simultaneously to determine plume dispersion properties. Using on-site meteorological data and the measured methane and sulfur hexafluoride concentrations, emissions rates from the coal surfaces are then estimated using a plume dispersion model. The plane-integrated method analyzes a series of FTIR paths at several elevations above the ground. The advantage of the latter technique is that more of the plume is actually measured and less reliance is placed on the plume model. Both techniques were validated at a field site measuring known emissions rates of methane and sulfur hexafluoride from constructed area and volume sources. The techniques consistently measured emissions rates to within 30 percent of the known value and often to within 15 to 20 percent. In this study the plane-integrated method was used for inactive surface mine pits, while the single-path method was used at active mines.

Under this program, over 30 site surveys were conducted at surface mines across the U.S., and most included the collection of spot methane concentration measurements using a hand held flame ionization detector. Based on these visits, and coal properties in the Refined Gas Content (RGC) database[25], it was concluded that auger/hilltop mining areas in various Appalachian mining locations and lignite production areas in Oklahoma, Texas, and the Dakotas liberate little or no methane. They were eliminated from further consideration. Figure 2 shows where surface coal mining occurred in 1995, and where surface mine testing was conducted. The Powder River region of Wyoming and Montana is the largest surface mining region in the U.S. (Campbell County, Wyoming is shown in black). This area accounts for about 55 percent of the non-lignite surface mined coal produced in the US, and all mines surveyed in this area were found to liberate methane. Four of the six sites tested were located within the Powder River region, and together, these sites accounted for 23 percent of the total coal produced in the region. Two of the sites tested contained large inactive pits that were also tested, and both were found to liberate significant quantities of emissions. The fifth and sixth sites tested were located in the Northern Appalachian region, an area which accounted for about 7 percent of the non-lignite surface mine coal produced in 1995.

Table 2a presents the results of measurements for active areas at the six mines tested, while Table 2b presents results for the two inactive sites tested. Total emissions for the active Powder River sites were found to be similar, while the Northern Appalachian region mines tested produced fewer emissions, primarily because of their small size and lower emissions rate. Active site emissions are a strong function of the area of exposed coal surfaces. Emissions per unit of exposed area were generally lower for Appalachian mines, presumably because of the lower porosity and seam thickness associated with these older coals. While Northern Appalachian mines may produce slightly lower emissions per unit area than Powder River mines, the data base was insufficient to statistically identify them as two separate populations and they were treated as one in this study. Area-based emission factors are used to estimate emissions in the inventory as described later.

Table 2b shows that emission factors for inactive pits were calculated on a length basis instead of an area basis as in the active pits. This was necessitated by the fact that the inactive areas had virtually no coal remaining. Further, emissions were found to be related to the linear extent of the exposed seams at the two inactive mines tested so the linear exposure of the coal seam around the sides of the pit was used as a basis. For inactive mines included in the inventory, these length-based emissions factors were used. While this makes it difficult to compare active and inactive site emission factors, it was consistently observed that emissions from inactive areas of sizes similar to the active areas were higher by at least a factor of two. This observation was not expected and the data developed for this study were not designed to explain it. However, the authors have observed that in active mines, a layer of coal 6 to 10 feet thick is left behind in the pit floor to avoid mixing dirt with the coal being sold. When this layer is penetrated, substantial gas evolution rates have been measured at several sites, and the source of this gas is the strata underlying the seam being mined. At inactive sites, this layer may have lost it's integrity over time (most inactive pits are several years old), providing channels for the continuous flow of gas from the underlying strata. This flow of underlying gas generally does not occur at active sites, because the coal layer maintains it's integrity, and the pit floor is quickly backfilled.

MSHA's Part 50 data shows that 628 million tons of coal were produced at surface mines in 1995, so after subtracting lignite and auger production reported by DOE, it was estimated that 536 million tons of "methane-producing" surface mined coal was produced in 1995. As a starting point in the inventory development process, a detailed mine-specific inventory was prepared for 33 individual Powder River mining operations using the area- and length-based emissions factors developed from the Powder River mines tested (Tables 2a and 2b). Not all Powder River mines were included in this analysis, but the combined production from the active mines examined accounts for about 40 percent of the "methane-producing" coal extracted by U.S. surface mines in 1995.

To support the use of the area- and length-based emissions factors at specific sites, surface mine dimensions were obtained for 16 active and 17 inactive sites using U.S. Geological Survey aerial photographs of Wyoming and Montana. Because the photos were taken in 1994, adjustments were made to more accurately represent 1995 active mine dimensions. The 1994 areas measured were divided by 1994 mine production, and this ratio was multiplied by the 1995 production to yield an estimate of the 1995 dimensions. These calculated areas were checked by comparing the calculated 1995 area to the areas measured at four Wyoming mines tested in 1995. All areas agreed within a few percent.

Once the dimensions of all active and inactive sites were determined, emissions were calculated by multiplying an emissions factor by the appropriate mine dimensions. For those mines tested, emissions factors from the actual tests were used. For the other sites, the average emissions factors presented in Tables 2a and 2b were used.

After examining the results of the Powder River analysis, it was concluded that emissions from surface mines are significantly lower than expected and as such, further efforts to develop mine-specific inventories were unjustified. Emissions associated with the remaining 60 percent of the “methane-producing” surface mined coal were estimated by extrapolating the Powder River results. Specifically, total emissions from the 16 active and 17 inactive mines were summed and then divided by the coal production from the 16 mines. This factor was multiplied by the remaining “methane-producing” coal production to yield an estimate of emissions from the remaining mining regions. One key assumption inherent in this extrapolation is that mines outside Powder River have emissions factors similar to Powder River mines. Limited funding prohibited testing in every surface mining region, but this assumption is supported by two tests conducted in the Northern Appalachian region, and over 30 mine surveys conducted in: Northern and Central Appalachia, Illinois/Indiana, Green River, Wind River, Arkoma, Warrior, Raton, and the Dakotas. A second assumption inherent in this extrapolation is that the emissions characteristics of inactive sites, and the relative number of inactive sites, are similar between the Powder River region and other mining areas.

Abandoned Underground Mines

Records compiled and maintained by MSHA indicate that thousands of underground mines have been abandoned since 1981, and that numerous abandoned mines exist in virtually every major mining region of the U.S. In the early 1990's a methane emissions measurement campaign was initiated under this program, and data for 21 abandoned mine sites have since been compiled.

Measurements were conducted at mines which had been closed and sealed, and which used vent pipes to exhaust methane that continued to build-up within the closed workings. Although not described in detail here, the measurement approach was simple; spot methane concentrations were measured with a portable non-dispersive infrared analyzer, and vent pipe flow rates were measured using a hand-held anemometer[26]. Continuous measurements were conducted at one site for a period of several months.

Although it was not possible to conduct measurements in all of the major underground mining regions of the U.S., the sites tested are in areas known to contain the majority of the abandoned sites. Twelve of the sites tested are located in the Central and Northern Appalachian basins, both areas that have experienced a disproportionate share of mine closures over the past 15 years. Four sites in the Illinois basin and five sites in the Warrior basin are also included.

The relatively small number of mines tested is an impediment to the development of robust emissions relationships. However, it was observed that if a mine floods after closure, emissions are negligible, while if no flooding occurs, emissions are likely to occur. Also, mines with relatively low active emissions rates (e.g., less than about 100,000 cfd) are likely to have less gas pressure buildup in the mine after closure. Thus, post closure emissions are likely to be negligible. It was also found that when abandoned mines liberate emissions, they are likely to be roughly proportional to the active mine emissions, and to be a function of time since abandonment. On a daily basis these emissions can vary with changes in atmospheric pressure.

Table 3 presents data collected for the 21 abandoned underground coal mines described above. About 50 percent of the sites tested were found to liberate some methane emissions (i.e., emissions greater than 0.5 percent of the mines active emissions), and when emissions did occur, they were generally between 2 and 30 percent of the active mine emissions. For the abandoned mines that liberated emissions, the average percent of active emissions was 17 percent. This factor is applied to estimate emissions from abandoned mines in the inventory judged to have a potential to liberate emissions (see later discussion). Although this emissions relationship uses all of the data currently available, the data is not abundant and the uncertainty that accompanies the estimate is recognized.

A six-step process was used to estimate emissions from abandoned mines. The data used to support the method are presented in Table 4.

1. The number of underground mines abandoned since 1981 was identified for each MSHA region based on MSHA's Part 50 data base (Table 4, column 1). Reliable data for pre-1981 closures are unavailable, so emissions from this group were neglected. Because of the significant risk posed by closed and vented

underground mines, mines abandoned prior to 1981 are probably backfilled and permanently sealed by now, and their emissions are likely insignificant.

2. For 6 of the 10 MSHA district offices, inspectors in those offices were asked to identify the number of abandoned mines containing emissions vent pipes. These values, shown in column 5 of Table 4 ("from MSHA"), are based on the best recollections of inspectors because records on closures are incomplete. For the remaining 4 districts that were unable to provide these data, an alternative approach was used to estimate the number of capped and vented mines (Step 3).

3. Abandoned mines that were closed with shaft vents in place were approximated for 4 MSHA districts by extrapolating from a subset of all abandoned mines (i.e., mines closed in the early to middle 1990's). MSHA inspectors determined the closure status of this subset to provide an estimate of the number of mines vented in the early to mid 1990's. The ratio of vented mines to total abandoned mines in the subset was multiplied by the number of mines abandoned since 1981 to estimate the number of mines closed with vents in the district since 1981. The subset results are shown in columns 3 and 4 in Table 4.

4. Not all vented mines identified in column 5 of Table 4 will liberate emissions. For those vented mines from Steps 2 and 3 which have a potential to produce emissions, emissions are approximated based on the 21 abandoned mine sites tested. It was assumed that 50 percent of the capped and vented mines in column 5 liberate emissions as outlined in an earlier section.

5. Abandoned mine emissions are estimated as a function of active mine emissions. An average active mine emissions rate was approximated for each MSHA region

using the underground mine inventory (Table 4, column 6). If an abandoned mine has a vent pipe that produces significant emissions, the mine is likely to have had a high emissions rate when active. Thus, when determining the average active mine emissions rate shown in column 6, only those underground mines with emissions rates equal to or greater than 100,000 cfd were included. The average active mine emissions rate was multiplied by 0.17 to approximate the post closing emissions rate as described earlier in Section 2.1.

6. The number of vented mines producing emissions in each MSHA region from Step 3 was multiplied by the emissions per closed mine for that region from Step 4, to estimate the total emissions from all abandoned mines in that region.

Coal Handling Operations

Direct emissions measurements from coal handling systems are unavailable and impractical to collect. When this program was initiated, most coal handling inventories were based on estimates of the amount of methane remaining in coal after mining. Expressed as a percent of the original in-situ gas content, post-mining gas contents of 40 percent for British coals, and 25 to 60 percent for other areas were reported[27-30]. Assuming all of this methane is liberated before combustion occurs, handling emissions in those studies were estimated by multiplying assumed post-mining coal gas contents based on these estimates, by annual coal production values.

Mining regions where large volumes of high gas content coals are produced contribute most to coal handling emissions estimates, and in an effort to improve the emissions inventory, coal handling operations at underground mines in the Black Warrior and Central Appalachian basins were targeted for the collection of new measurements. Standard methods were used to develop methane desorption rate curves for broken coal samples collected at the mine mouth, and to identify the fraction of methane remaining relative to the coal's original in-situ gas content. Measurements were conducted at two underground mines in the Central Appalachian basin (Virginia and eastern Kentucky) and one mine in the Warrior basin (Alabama).

The tests consisted of obtaining a representative set of mined coal samples from conveyor belts at the mine mouth (prior to on-site preparation facilities). The ASTM method D-2234 for manual sample collection was used to ensure that representative samples of broken coal and coal particles were collected from the conveyor belts. Between 13 and 30 samples were collected at each site, and the collection occurred at regular intervals over periods of from 1 to 3 days. Samples were inserted into coal desorption canisters that were assembled and operated based on guidelines provided by the U.S. Bureau of Mines for the Direct and Modified Direct methods[31]. Once the samples were sealed, routine monitoring of pressure increases was conducted, enabling the development of relationships between the desorbed gas volume and elapsed time. A gas chromatograph was used to identify and quantify hydrocarbons (including methane) desorbing from the coal, and to quantify the effects of oxygen sorption. Samples were routinely monitored and bled for several months until no measurable pressure increases occurred, after which the sample was crushed, the volume of gas that evolved during crushing determined, and the total gas volume calculated.

Table 5 summarizes the measurement results for the three sites tested. The mines provided the in-situ gas content values reported for coal located at each mine site, but these values are not necessarily for coal collocated with the coal being mined during the coal handling tests; the nearest samples available were used. The post-mining gas contents measured were between 55 and 72 percent of the in-situ gas content of the coal before mining. These values are used to estimate emissions in the inventory as described later. Previously reported values are lower than these results, suggesting that post-mining emissions are higher than previously thought.

The gas remaining in coal after mining for all Warrior basin mines is represented in the inventory by the value determined from the Alabama test. For the Central Appalachian basin, the average of the two tests conducted in this region was used. To estimate the gas remaining for other coal mining regions, the measurement test results were used with Airey's model and a national data set of coal properties to approximate regional values of the gas remaining after mining. Airey's model closely matches desorption curves, and was developed based on a theoretical treatment of gas emissions from broken coal[32]. In order to apply Airey's model to calculate the fraction of gas remaining, two parameters were needed: sorption time and "synthetic" exposure time. The RGC database was used to estimate an average sorption time for each basin[25]. This database contains over 1,000 gas content measurements collected by the U.S. Bureau of Mines (BOM) in the 1970's and 1980's. The original raw measurements provided to the authors by BOM were digitized to facilitate: (1) the automation of data quality assurance checks, (2) the execution of temperature and pressure corrections, and (3) the analysis of coal properties by region and seam.

The synthetic exposure time is that time between the initial exposure of the coal in the mine and its eventual mining and removal from the mine. Using data from the three test sites, a synthetic exposure time was calculated by substituting the known measurement data (fraction of gas remaining and sorption times) into Airey's model. For the three test sites, synthetic exposure time values of 8.1, 9.5, and 11.6 days were determined for the Alabama, Virginia, and Kentucky mines respectively. To estimate the gas fraction remaining for the other basins, an average synthetic exposure time of 9.3 days was used. This average value was substituted, along with basin specific average sorption times from the RGC database, into Airey's model to calculate the fraction remaining values for the Arkoma, Northern Appalachian, Illinois, and Western underground mine coal fields.

For surface mines, the synthetic exposure times assigned above cannot be used because the rate of mining, size of the coal seams, and nature of surface mine operations vary greatly from underground mines. Although actual measurement data would be useful, the gas desorption equation used by the Bureau of Mines (BOM) to describe gas desorbing from coal cores, was applied to approximate the gas remaining in surface minable coals after mining[31]. The desorption rate equation is very similar to Airey's model except that it describes desorption from solid cores. Observations of surface mining operations in the western U.S. indicate that: (1) at any given time, the removal of overburden exposes about a 1 month supply of coal, and (2) once the coal is blasted, it is hauled away within a five day time period.

Application of the desorption rate equation to western mining configurations suggests that virgin coal that is 25 feet or more from the ambient atmosphere has a gas content that is close to its virgin value. Thus, it is estimated that a significant fraction of the original gas remains after the coal leaves the mine, a finding that is consistent with the unexpectedly low emissions rates measured at active surface mines in Wyoming. For western mines, a synthetic exposure time of 5 days was assigned, and substitution of this value, along with average sorption times obtained from the RGC database, produces gas remaining values of 72 percent. For eastern surface mines, a synthetic exposure time of 3 days was assigned due to the relatively rapid coal removal occurring in those mines. Sorption parameters and gas remaining values are summarized in Table 6.

Estimates of post-mining emissions should account for that portion of gas that may remain in coal and be combusted. The approach taken here attempts to account for this by estimating coal transport route and on-site storage times, and then relating these times to basin average coal desorption rates. The Energy Information Administration's (EIA) coal transportation rate data were used to identify the quantity and destination of shipped coal[33]. Since rail transportation is the primary mode for distributing coal to other states, the times required for transporting and loading/unloading trains were examined. Route times were estimated to range from between 21 days to 30 days for out-of-state distribution. Coal consumed within each state is predominantly transported via trains and trucks, and a route time of 14 days was assigned to all non-western locations. Exported coal is transported by water. Due to the long distance traveled and slow traveling speeds, it was assumed that the route time for this coal is 100 days. Once coal arrives at its destination, it is often stored on stockpiles before being utilized. Based on EIA's estimates, 30 days was assigned to represent the storage process. The coal distribution statistics are assumed to be identical for both surface and underground coals because transportation data specific to the method of mining are not readily available. Table 5 summarizes the key data used.

Coal handling emissions were estimated using basin-level production data for 1995 provided by DOE[34]. Multiplication of basin-level production, in-situ gas contents and gas remaining values define the maximum emissions possible. Using the sorption rates, route times, and storage time allows this maximum value to be refined by accounting for the time available for desorption before combustion, and the specific desorption properties of each basin.

RESULTS AND DISCUSSION

Table 7 presents a comprehensive methane emissions estimate for the U.S. coal mining industry in 1995. Total emissions are estimated to be 4.669 million tons and, as expected, emissions from underground mine ventilation and methane drainage systems dominate (74 percent of the total emissions). On the other hand, emissions from coal handling, abandoned mines, and surface mines are significant, and collectively represent about 26 percent of the total emissions.

The Energy Information Administration (EIA) routinely publishes methane emissions estimates for US coal mining, and the estimate published for 1995 is 4.386 million tons[35]. This is about 6 percent lower than the estimate presented here because EIA’s estimates for some mining categories are somewhat lower, and their estimate does not include abandoned underground mines. Differences in the estimates between this study and EIA's can be examined in Figure 3.

The figure shows that estimates from this study are higher than EIA's for all mining categories except surface mines. It also shows that the most significant differences are associated with coal handling of surface mined coal (0.236 million tons higher), underground mine ventilation shafts (0.182 million tons higher), abandoned underground mines (0.154 million tons), and surface mines (0.398 million tons lower). For coal handling of underground mined coal, the emissions are similar, even though the gas available for release is assumed to be higher in this study. This is because EIA's estimate assumes all the gas trapped in coal escapes to the atmosphere, whereas coal route and storage assumptions used here indicate some methane trapped in coal is combusted before it has a chance to escape.

About 94 percent of the emissions from underground mines are produced by a relatively small number of gassy mines; i.e., mines liberating 100,000 cfd and greater. Table 8 shows a breakdown of emissions from various classes of mines based on operational status recorded in MSHA's Part 50 database. Most emissions are liberated from actively producing mines, but emissions are also produced from inactive mines, particularly gassy mines that must maintain ventilation during sustained periods of zero production. Emissions from temporarily closed mines are estimated to be low because most are small mines operating in non-gassy areas. However, measurements are rarely taken at these sites and uncertainty exists, particularly if the closed mine operates in a gassy area.

Figure 4a is a geographical representation of the emissions from underground mines in the U.S. Emissions are shown on a county-basis, with the top 13 counties specifically identified. It is clear from the map that a large proportion of the emissions occur within three mining areas;

the northern Appalachian region (northern West Virginia and Pennsylvania), the Warrior basin (central Alabama), and the Colorado coal-fields. Figure 4b shows the average mine emissions rate for each county, and as expected, counties with high emissions in Figure 4a generally correspond to counties with high mine-average emissions rates. The exception is the Illinois/Indiana mining region. Although this region liberates comparatively low emissions, the potential to produce high emissions exists as evidenced by the gassy mines located there. If production in this region increases, emissions increases could be significant.

According to MSHA records, there have been 7,325 underground mines permanently abandoned in the US since 1981. Although this is a substantial number, many of these sites are small mines that operated in or near non-gassy areas, and relatively few maintain vents to the atmosphere. Emissions and other data from MSHA suggest that the number of mines abandoned in gassy areas of the Appalachian region is high, but it should be noted that many abandoned mines in this region are small hill top or auger mines where little or no emissions potential exists despite the original gas content of the coal beds.

National emissions estimates for abandoned underground mines are presented in Table 9. As the table shows, total emissions are estimated to be 0.154 million tons. There are no known estimates developed for this category of mines, so there is no basis for comparison. However, with the limited measurements and weak demographic information available for this mining category, this estimate should be used with caution, and further examination of the gassy areas should be conducted to improve estimates for this category, and to allow an assessment of the energy resources involved.

Table 10 summarizes the estimated coal handling emissions. Coal production data published by the EIA were used to develop these estimates because their format was more conducive to developing handling estimates than the MSHA data. Differences in production between the two data sets are small (less than a few percent), and do not add significant uncertainty to the estimates. Emissions for surface mined coal are higher than previous estimates reported in the literature, so the total emissions from both surface mine sites and surface coal handling operations (0.378 million tons) are similar to others' estimates of total emissions from surface mines (0.540 million tons from EIA). Although this study does not alter the total emissions picture for surface mined coals appreciably, it does suggest the primary point of release is not the mine site. However, unlike underground coal, handling estimates for surface coal are not based on direct measurements, so these estimates should be used with caution.

Emissions estimates for active surface mines are significantly lower than previously thought (0.098 million tons). Emissions from Powder River mines make up about 60 percent of the total, while emissions from other non-lignite/non-auger producing areas account for the remaining emissions. Although the surface mine estimate presented here is lower than previous estimates, it is the first to be developed from direct emissions measurements at active and inactive surface mine sites. The relatively low gas contents of surface minable coals, and the lack of gassy strata surrounding many surface mined seams, and the relatively high percentage of gas remaining after mining may have contributed to the relatively low emissions measured at surface mine sites.

CONCLUSION

A primary goal of this program was to improve the emissions estimates for the most uncertain mining categories. This goal was accomplished with the collection of emissions measurements at over 30 coal mining sites including 6 active surface mine sites, 2 inactive surface mine sites, 3 coal handling sites, and 21 abandoned underground mine sites. These data have improved our understanding of the emissions characteristics of individual sources, but additional improvements could be achieved by collecting measurements for: (1) surface mine coal handling, (2) abandoned underground mines in gassy areas, (3) methane drainage systems used at underground mines, and (4) inactive and temporarily closed underground mines in gassy areas.

This study has estimated the 1995 methane emissions from all major mining sources in the U.S. The emissions are estimated to be 4.669 million tons, which is 6 percent higher than estimates published by DOE for 1995. The estimated emissions contributions from individual mining sources are as follows: underground mine shafts and portals (49 percent), methane drainage systems at underground mines (24 percent), coal handling of underground mined coal (15 percent), abandoned underground mines (4 percent), coal handling of surface mined coal (3 percent), and surface mines (2 percent). The following source-specific emissions trends and findings are noted:

- Abandoned Mines: About half of the mines tested liberate emissions, and mines that are flooded do not liberate emissions. When emissions occur, they are generally between 2 to 30 percent of the active mine emissions.

The numbers and locations of all vented abandoned mines are highly uncertain.

- Coal Handling: Higher than expected gas contents occur in coal leaving underground mines. Some of this gas is likely burned before it has a chance to escape the coal.

- Surface Mines: Lower than expected surface mine emissions occur, and a significant fraction of these emissions come from inactive surface mine sites.

- Active Underground Mines: Emissions from active producing mines are well understood, but emissions from inactive and temporarily closed mines located in gassy areas require additional data and study. Emissions from methane drainage systems are high, but few measurements are publicly available.

ACKNOWLEDGEMENTS

This study was conducted under a Cooperative Agreement with the U.S. Environmental Protection Agency, Air Pollution Prevention and Control Division. The authors wish to thank the Mine Safety and Health Administration for their support in compiling and assessing national emissions and other data sets, and for their assistance in the planning and execution of field testing at abandoned mine sites. We also wish to express our appreciation for the professional support of several coal mining companies in the Powder River basin, Warrior basin, and

Appalachian Basins. Without their active support, the new measurements data reported here would not have been possible. The authors thank the many Southern Research Institute staff who have supported this effort over the years including: Eric Ringler, Jill Webster, Jeff Lanning, John Sokash, Wyn Lewis-Bevan, and Jim Bradey. We also thank researchers from other firms that supported this program including David Winkler, Ajay Chadha, Phil Marsosudiro, Bill Hurget, Peet Soot, and Joel Rucker. Finally, thanks to Karl Schultz of EPA's Coalbed Methane Outreach Program for his input and data on deep mine gas drainage systems, and to Pat Diamond and Gerald Finfinger of the U.S. Bureau of Mines for providing advice and support on the numerous occasions that we requested it.

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Table 1. Estimates of global methane emissions from coal mining operations.

Table 2a. Measured emissions for active U.S. surface mines.

Table 2b. Measured emissions for inactive U.S. surface coal mines.

Table 3. Measured emissions from abandoned and vented underground mines.

Table 4. Inventory data for abandoned underground mines.

Table 5. Post-mining measurements results.

Table 6. Post-mining emissions inventory estimation method.

Table 7. 1995 Methane emissions from coal mining in the U.S.

Table 8. Breakout of emissions from underground mines by activity status.

Table 9. Estimated methane emissions from abandoned underground mines for 1995.

Table 10. 1995 Coal handling emissions for specific basins.

Table 1. Estimates of global methane emissions from coal mining operations.

Researcher	Base Year	Emissions (million tons/yr)
Koyama (1963, 1964)	1960	22
Hitchcock and Wechsler (1972)	1967	8.7 to 30.5
Ehhalt and Schmidt (1978)	1967	8.7 to 30.5
Seiler (1984)	1975	33
Crutzen (1987)	(assume mid-1980s)	37
Cicerone and Oremland (1988)	(assume mid-1980s)	28 to 50 (average 39)
Boyer et al. (1990)	1987	36 to 71 (average 53)
Fung et al. (1991)	(assume mid-1980s)	39
Kirchgessner et al.(1993a)	1989	50.3
CIAB (1994)	1990	26

Table 2a. Measured emissions for active U.S. surface mines.

Mine Site	Coal Production (10^6 tons/yr)	Methane Emissions (tons/yr)	Exposed Area (ft^2)	Methane Emissions Factor ($tons/ft^2$-yr)	Mining Region
A	14.00	1,354	3,089,429	0.000438	Powder River
B	16.80	1,253	3,389,056	0.000370	Powder River
C	9.90	786	1,911,686	0.000411	Powder River
D	15.30	1,369	3,203,366	0.000427	Powder River
E	1.20	43	129,168	0.000333	Northern App.
F	0.24	5	21,500	0.000241	Northern App.
Average	**---**	**---**	**---**	**0.000370**	**---**

Table 2b. Measured emissions for inactive U.S. surface coal mines.

Mine Site	Coal Production (10^6 tons/yr)	Methane Emissions (tons/yr)	Pit Length (ft)	Methane Emissions Factor (tons/ft-yr)	Mining Region
A	0	3,399	5,168	0.064	Powder River
B	0	3,185	5,120	0.062	Powder River
Average	---	---	---	**0.063**	---

Table 3. Measured emissions from abandoned and vented underground mines.

Mine No.	Coal Basin	Year Closed	Flooding Status	Measured CH_4 (ft^3/day)	Emissions When Active (ft^3/day)	Percent of Active
1	C. Appal.	1985	Flooded	5,033	1,100,000	0.5
2	C. Appal.	1992	Partial flood	294,500	3,800,000	7.8
3	C. Appal.	1990	Dry	433,107	2,450,000	17.7
4	C. Appal.	1988	Partial flood	80,250	750,000	10.7
5	C. Appal.	1987	Partial flood	0	350,000	0.0
6	C. Appal.	1987	Partial flood	4,854	950,000	0.5
7	C. Appal.	1985	Partial flood	149	150,000	0.1
8	C. Appal.	1985	Partial flood	4,863	200,000	2.4
9	C. Appal.	1984	Partial flood	3,288 (est.)	300,000	1.1
10	Illinois	1983	Unknown	37,000	300,000	12.3
11	Illinois	Unknown	Unknown	0	1,100,000	0.0
12	N. Appal.	1980	Dry	200,000	2,100,000	9.5
13	N. Appal.	1993	Dry	404,374	650,000	62.2
14	Warrior	Circa 1975	?	4,000	300,000	1.3
15	Warrior	1993	Partial flood	579,800	1,800,000	32.2
16	Warrior	1985	Flooded	0	700,000	0.0
17	Warrior	1985	Flooded	0	400,000	0.0
18	Warrior	Circa 1985	Flooded	40,361	3,300,000	1.0
19	Illinois	1977	Flooded	0	n/a	0.0
20	Illinois	1984	Flooded	0	n/a	0.0
21	N. Appal.	Circa 1985	dry	500,000	3,950,000	12.7

Table 4. Inventory data for abandoned underground mines.

MSHA Region	Underground Mines Abandoned Since 1981	Mines in Sample Set Abandoned in the Early 1990's		Abandoned Mines With Vents[1]	Regional Average Active Mine Emissions (ft^3/day /mine)
		No. Abandoned	No. With Vents		
1	300	12	0	0	0
2	170	21	1	8	2,515,185
3	305			2 (from MSHA)	2,421,654
4	1,667			56 (from MSHA)	1,353,987
5	1,169			4 (from MSHA)	3,690,027
6	1,857	212	1	9	444,754
7	1,671	109	1	15	5,121,006
8	34			6 (from MSHA)	1,306,066
9	96			14 (from MSHA)	1,447,352
10	56			14 (from MSHA)	448,742

1. Estimated via extrapolation from the sample set unless specified. The note "from MSHA" indicates estimates were obtained directly from the MSHA district office for all known capped and vented mines.

Table 5. Post-mining measurements results.

Location	Basin	Gas Content of In-Situ Core Samples (ft^3/ton)	Gas Content of ROM Coal Samples (ft^3/ton)	Number of Samples/ Days Sampled	Gas Remaining After Mining (% of In-Situ)
Walker County, AL	Warrior	144	104	30/3	72
Wise County, VA	C. Appal.	107	65	13/1	61
Martin County, KY	C. Appal.	96	53	17/2	55

Note: All gas contents are on a moisture and ash free basis. ROM means run of mine (raw, uncleaned coal).

Table 6. Post-mining emissions inventory estimation method.

Basin	Average Gas Content of In-Situ Coal (ft^3/ton)	Average Sorption Time[1] (days)	Average Gas Remaining (%)	Percent of Coal Transported/Route Time (days)		
				In-State	Foreign	Out-Of State
Underground Mining						
Arkoma	338	18	56	83%/14	0%	17%/14
Central Appal.	147	21	58	17%/14	29%/100	54%/21
Illinois	57	41	73	33%/14	6%/100	61%/21
North Appal.	109	94	90	34%/14	7%/100	59%/30
Black Warrior	233	27	72	72%/14	24%/100	4%/21
Western	102	31	72	46%/20	4%/100	50%/30
Surface Mining[2]						
Arkoma	192	30	76	83%/14	0%	17%/14
Black Warrior	31	30	76	17%/14	29%/100	54%/21
Central Appal.	64	30	76	33%/14	6%/100	61%/21
Illinois	35	22	74	34%/14	7%/100	59%/30
North	41	61	78	72%/14	24%/100	4%/21
Other Western	16	11	72	46%/20	4%/100	50%/30
Powder River	12	16	72	10%/20	1%/100	89%/30

1. Sorption time is the time required for coal to desorb 67 percent of its total gas content.
2. Gas content of surface mining is the average of all seams at depths of 200 feet or less.

Table 7. 1995 Methane emissions from coal mining in the U.S.

Mining Activity	Methane Emissions (million tons CH_4)
Underground Mines	
Ventilation Shafts & Portals	2.298
Methane Drainage Systems	1.139
Abandoned Underground Mines	0.154
Surface Mines	0.098
Coal Handling	
Underground Coal	0.701
Surface Coal	0.279
Total Emissions	**4.669**

Table 8. Breakout of emissions from underground mines by activity status.

Status Code	Status Description	No. of Mines	Emissions (million tons)	Percent of Total Shaft Emissions
A-1	Production occurred in all 4 quarters of 1995	631	3.163	92
A-2	Production occurred in 3 quarters of 1995	101	0.034	1
E	Not producing for at least 3 quarters, but mine is still operational (men working)	142	0.104	3
C	Temporarily closed for at least 3 quarters	326	<0.001	< 1
F	Not producing, not operating	93	0	0
Misc.	A mixture of the above and mines with status codes for two or fewer quarters	366	0.137	4

Table 9. Estimated methane emissions from abandoned underground mines for 1995.

MSHA Region	Estimated Emissions (million tons)
1	0.000
2	0.013
3	0.003
4	0.051
5	0.010
6	0.002
7	0.051
8	0.007
9	0.013
10	0.004
Total	**0.154**

Table 10. 1995 Coal handling emissions for specific basins.

Basin and Mining Method	Coal Production (1,000 tons/yr)	Methane Emissions (million tons)
Underground Mining		
Arkoma	25	0.000
Central App.	166,553	0.314
Illinois	69,661	0.067
North App.	97,396	0.182
Black Warrior	17,606	0.065
Western Coal Fields	45,013	0.073
Subtotal	396,254	0.701
Surface Mining		
Arkoma	14,112	0.045
Black Warrior	7,036	0.003
Central App.	106,250	0.115
Illinois	37,038	0.022
North App.	39,371	0.025
Misc. Western	41,574	0.011
Powder River	300,958	0.058
Subtotal	546,339	0.279
Grand Total	**942,593**	**0.980**

Note: Surface production does not include lignite and hill top/auger mining.

Figure 1. Log-log plot of average quarterly emission rates at 33 non-producing underground coal mines.

Figure 2. Surface mine production and location of test sites (values bracketed within the legend are numbers of counties).

Figure 3. Comparison of coal mine emissions estimates developed under this study with estimates published by the EIA.

Figure 4a. Underground mine emissions by county.

Figure 4b. Average emission rate for mines located in indicated counties.

Figure 1. Log-log plot of average quarterly emission rates at 33 non-producing underground coal mines.

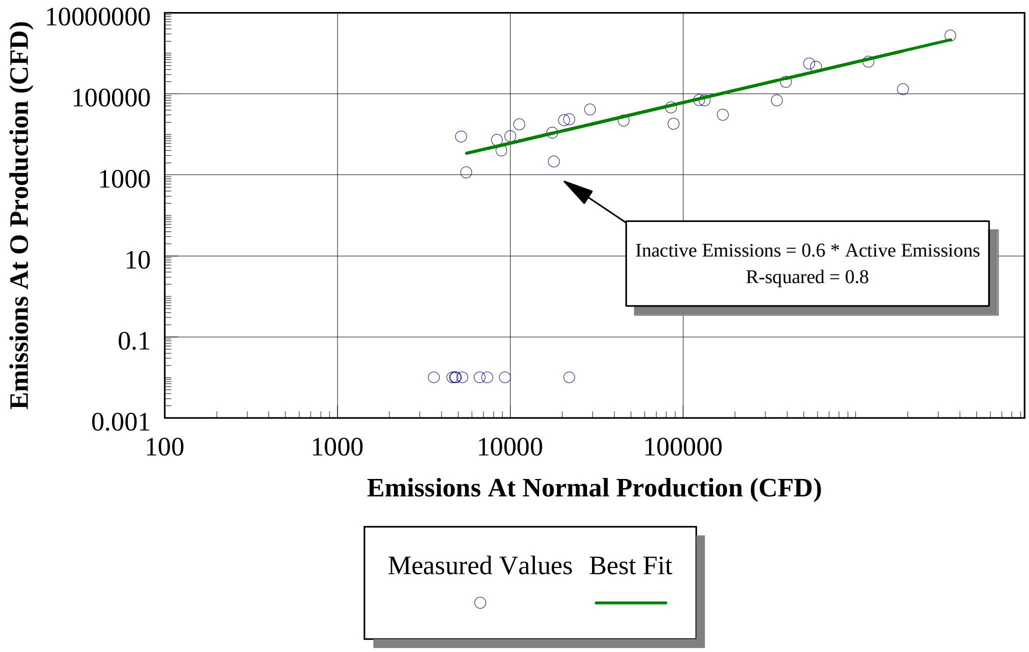
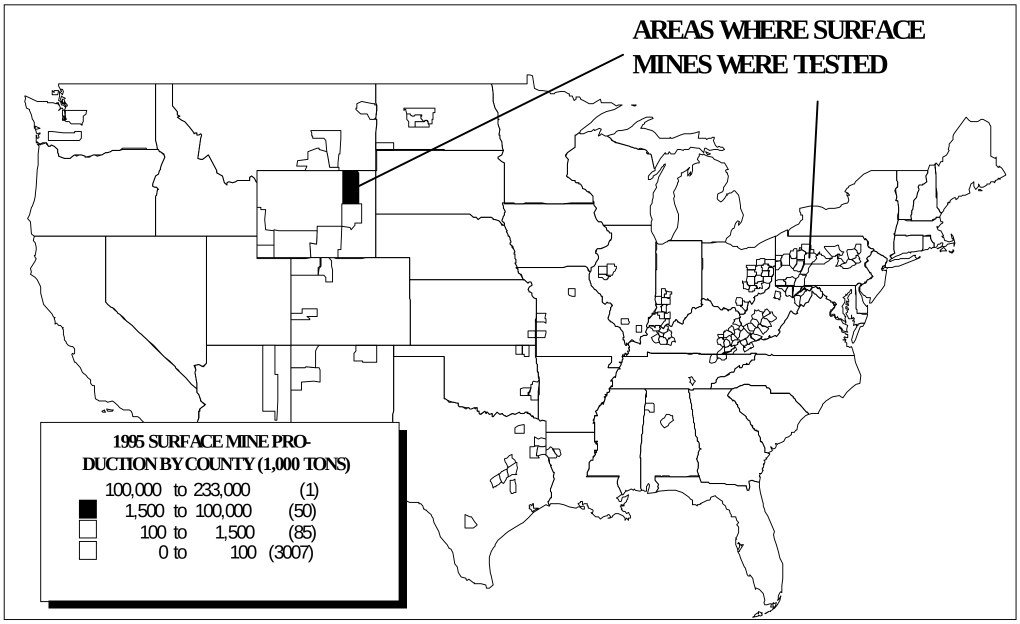


Figure 2. Surface mine production and location of test sites (values bracketed within the legend are numbers of counties).



Legend Note: Bracketed values represent the number of counties.

Figure 3. Comparison of coal mine emissions estimates developed under this study with estimates published by the EIA.

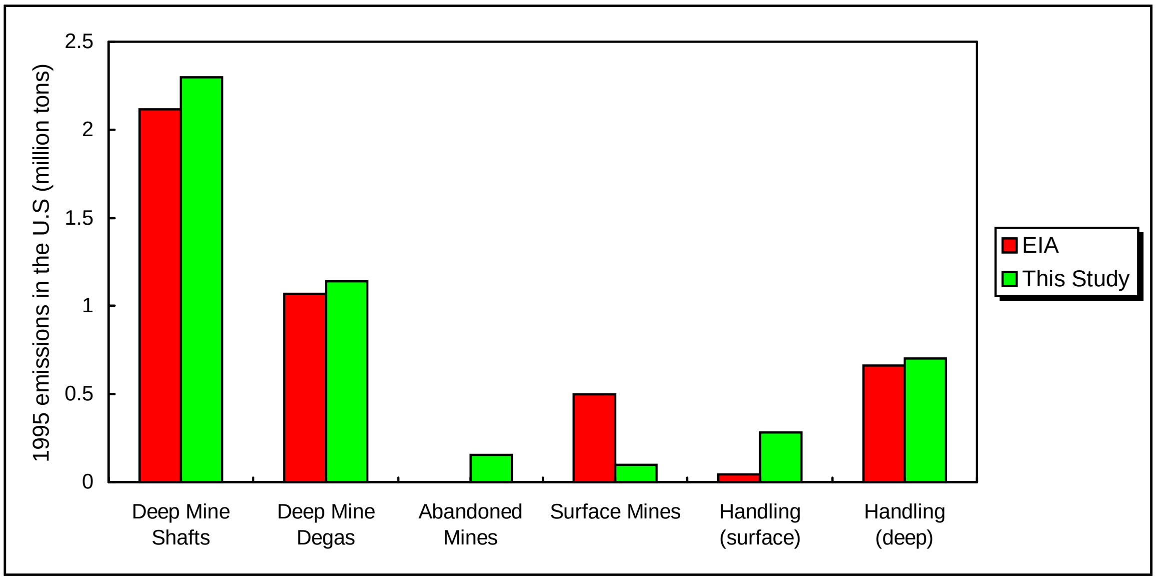
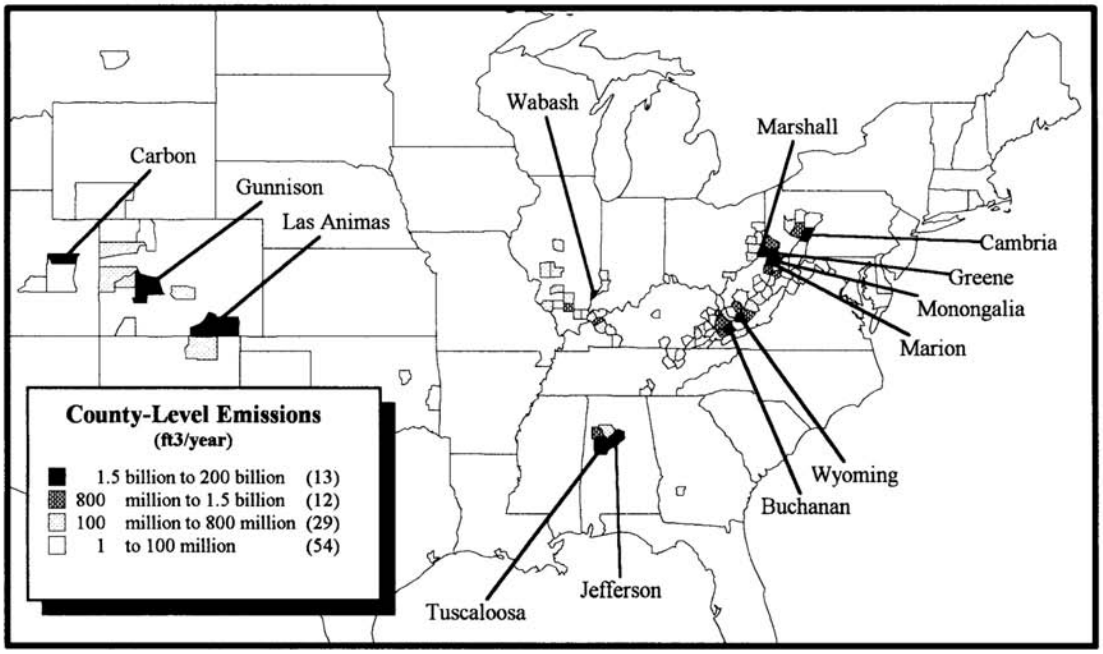
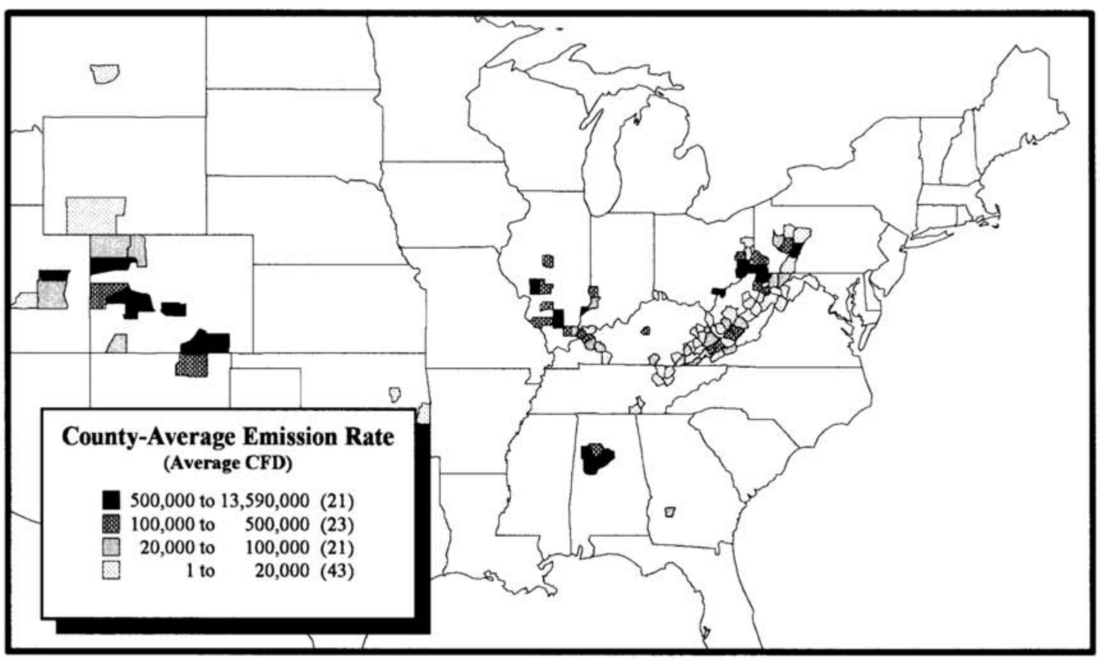


Figure 4a. Underground mine emissions by county.



Legend Note: Bracketed values represent the number of counties.

Figure 4b. Average emission rate for mines located in indicated counties.



Legend Note: Bracketed values represent the number of counties.