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ESTIMATE OF GLOBAL METHANE EMISSIONS FROM COAL MINES

David A. Kirchgessner[1], Stephen D. Piccot[2*], J. David Winkler[3]

[1]U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711, USA
[2]Science Applications International Corporation
Air Pollution Research Programs Branch
3101 Petty Road, Durham, North Carolina 27707, USA
[3]Alliance Technologies Corporation
100 Europa Drive, Chapel Hill, North Carolina 27514, USA

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ABSTRACT

Country-specific emissions of methane (CH_4) from underground coal mines, surface coal mines, and coal crushing and transport operations are estimated for 1989. Emissions for individual countries are estimated by using two sets of regression equations (R^2 values range from 0.56 to 0.71). The first set is used to estimate the CH_4 content of coals in selected countries based on country-specific coal depth and other relevant parameters. The second equation relates this CH_4 content and the country's coal production rate to the emissions from coal mining operations. The regression equations developed in this study rely on documented relationships which exist between mine emissions, coalbed CH_4 content, coal production rate, and other coal properties. Only those independent variables which could be included at 95 percent confidence or greater were retained in the regression equations. Estimated global CH_4 emissions from coal mining are estimated to be 45.6 Tg for 1989.

1. INTRODUCTION

Methane (CH_4) is a radiatively important trace gas which accounts for about 18 percent of anthropogenic greenhouse warming. Atmospheric concentrations of CH_4 are now increasing at the rate of 1 percent per year (Smith and Tirpak, 1989). Although the global CH_4 cycle is not fully understood, significant sources of emissions (in order of decreasing emissions) include wetlands, ruminants, rice paddies, biomass burning, coal mines, natural gas transmission facilities, landfills, termites, and tundra (Wuebbles and Edmonds, 1991). Improved emissions estimates for these sources will allow their relative contributions to the global CH_4 cycle to be better understood, and will provide a means for focusing future emissions mitigation research.

Attempts made to estimate global emissions from coal mining operations have generally relied solely on global coal production data and emission factors derived from CH_4 contents of coalbeds (Koyama, 1963; Marland and Rotty, 1984; Cicerone and Oremland, 1988). These estimates are based on the assumption that emissions are equal to the amount of CH_4 trapped in the coal removed from the mine. Although this trapped CH_4 is liberated when coal is fractured and removed from the mine, there are other CH_4 release mechanisms in the mining process which this assumption fails to take into account. For example, CH_4 may be released from: (1) exposed coal surfaces throughout the mine workings (i.e., the roofs, floors, and walls); (2) gas which is trapped in the strata adjacent to the mined seams; and (3) underlying seams close to the seam being mined. Commonly cited global mine emissions estimates range from 25 to 45 teragrams (Tg) of CH_4/year, which corresponds to roughly 10 percent of total annual CH_4 emissions from anthropogenic sources (Cicerone and Oremland, 1988). A recent report contains emissions estimates as high as 33 to 64 Tg CH_4/year (Boyer *et al.*, 1990).

Underground, surface, and abandoned or inactive mines comprise the three general sources of mine related CH_4 emissions. Emissions from underground mines can be liberated from three sources: (1) ventilation shafts; (2) gob wells; and (3) crushing operations. Ventilation air, although generally containing 1 percent or less CH_4, contributes the majority of mine emissions because of the enormous volume of air used to ventilate mines. Gob wells are drilled into the area immediately above the seam being mined. They provide conduits for venting CH_4 which accumulates in the rubble-filled areas formed when the mine roof subsides following longwall mining. Their purpose is to remove CH_4 which would otherwise have to be removed by larger and more costly shaft ventilation systems. Currently, no published data for the release of CH_4 from gob wells exist. However, preliminary data obtained from the coal mining industry indicate that gob well CH_4 emissions could account for a significant fraction of the total emissions associated with some longwall mines (Sööt, 1991). Emissions data for crushing operations are also extremely limited.

In surface mines, the exposed coal face and surface, and in particular areas of coal rubble created by the blasting operation, are expected to provide the major sources of CH_4. As in underground mines, however, emissions may also be contributed by the overburden and by underlying strata. Emissions from abandoned mines may come from unsealed shafts and from vents installed to prevent the buildup of CH_4 in the mines.

The main purpose of this research is to develop an improved methodology for estimating global CH_4 emissions from underground coal mining operations and to produce a global emissions estimate using this methodology where country-specific estimates are not available. The underground mine methodology integrates data on coal production, coal properties, coalbed CH_4 contents (i.e., the volume of CH_4 per ton of coal), and coal mine ventilation air emissions from U.S. mines. The objective is to develop a procedure which can be used to estimate mine emissions from generally available coal analyses and production data where coalbed CH_4 data or emission estimates are not available for a country.

Since emissions data are presently not available for surface mines, this methodology is currently restricted to underground mines. The Air and Energy Engineering Research Laboratory (AEERL) of the U.S. Environmental Protection Agency (EPA) has embarked upon a measurements program to quantify CH_4 emissions from selected surface mines in the United States for later inclusion in this work. Until that time, surface mine emissions estimates are included here using simplified assumptions since the lack of data prevents more precise inclusion of surface mines at this time.

Similarly, virtually no data exist on emissions from handling operations (i.e., crushing, grinding, transport, and storage) although their magnitude will certainly depend, to a large extent, on the desorption characteristics of individual coals. These emissions will be estimated for now following precedents from the literature.

2. BACKGROUND

Numerous studies have examined the physical relationships which control the production and release of CH_4 by coal. These studies have been conducted either to evaluate the potential of coalbed CH_4 resources or to enhance the safety of underground mines. Generally, the studies address one of two topics: (1) factors controlling coalbed CH_4 content; or (2) factors controlling the concentration of CH_4 in the mine atmosphere and mine ventilation air.

Studies in the first group have identified pressure, coal rank, and moisture content as important determinants of coalbed CH_4 content. Kim related gas content to coal temperature and pressure, and in turn to coal depth (Kim, 1977). After including coal analyses data to represent rank, Kim produced a diagram relating gas content to coal depth and rank. Although the validity of the rank relationship has been questioned, it generally appears to have been accepted by recent authors (Lambert *et al.*, 1980; Murray, 1980; Ameri *et al.*, 1981; Schwarzer and Byrer, 1983). Independently of Kim's work, Basic and Vukic established the relationship of CH_4 content with depth in brown coals and lignite (Basic and Vukic, 1989).

Several studies have recognized the decrease in CH_4 adsorption on coal as moisture content increases in the lowest moisture regimes (Anderson and Hofer, 1965; Jolly *et al.*, 1968; Joubert *et al.*, 1974). Moisture content appears to reach a critical value above which further increases produce no significant change in CH_4 content. Coals studied by Joubert *et al.* showed critical values in the range from 1 to 3 percent (Joubert *et al.*, 1974).

Investigations which attempt to identify correlates of CH_4 content in coal mine ventilation air include those by Irani *et al.* (1972) and by Kissel *et al.* (1973). Irani *et al.* developed a linear relationship between CH_4 emissions and coal production depth for mines in five seams. Kissel *et al.* demonstrated a linear relationship between CH_4 emissions and coalbed CH_4 content for six mines. Although both studies suffer from a paucity of mines and/or seams in their analyses, Kissel *et al.* made the important observation that mine emissions greatly exceed the amount expected from an analysis of coalbed CH_4 content alone. Emissions are produced not only by the mined coal, but also by the coal left behind and by surrounding strata. For the six mines studied, emissions per ton mined exceeded coalbed CH_4 per ton by factors of from six to nine.

3. METHODS

As shown in Figure 1, the development of the emissions estimation procedure for underground mines focuses on two areas: (1) evaluations of characteristics which affect coalbed CH_4 content; and (2) evaluations of mine shaft emissions characteristics. The first area examines the independent variables controlling coalbed in-situ CH_4

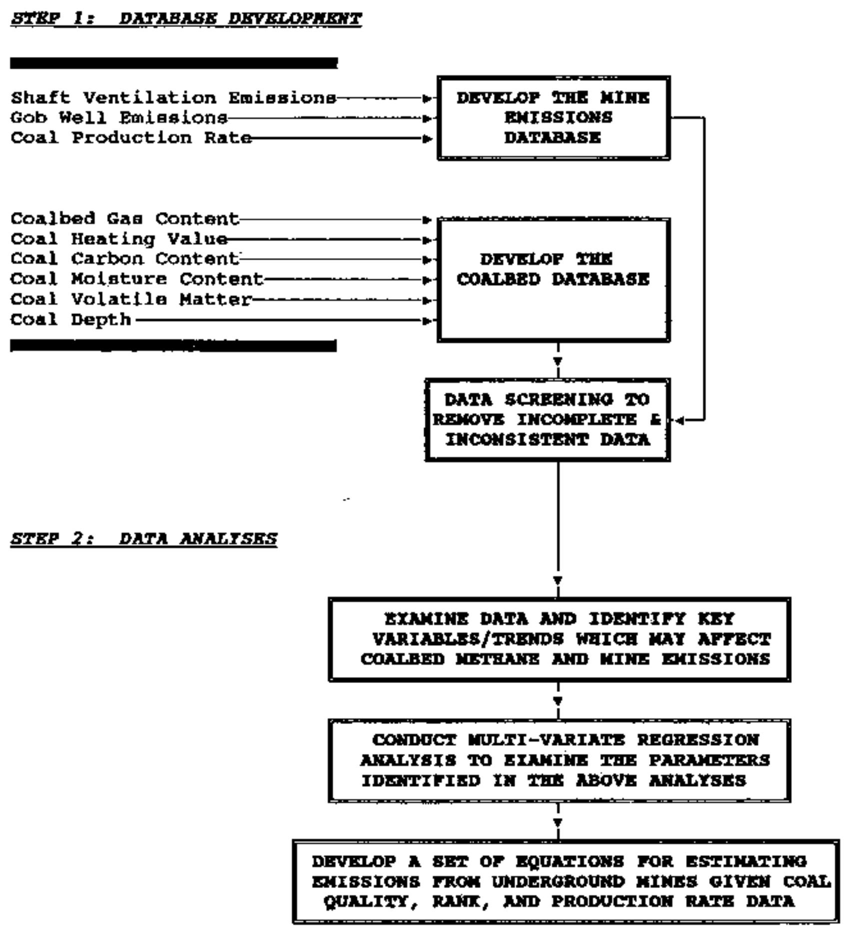

FIGURE 1. Overview of the technical approach.

content, and applies regression analyses to estimate key relationships. The dependent variable, coalbed CH_4, and numerous combinations of independent variables were subjected to regression analyses. The equations having the highest R^2 and the lowest Mallows C_p statistic were selected. In addition, only equations with terms having students t-statistics of two and above were used (i.e., there is at least 95 percent confidence that the term is statistically significant). The second path follows the same course in attempting to quantify factors controlling CH_4 emissions in mine ventilation air. In both cases, analyses include data collection, data screening, identification and evaluation of independent variables, and the estimation of regression equations with supporting statistics. The remainder of this section describes these procedures in detail.

3.1 Coalbed Data Analysis

The purpose of this portion of the analysis is to produce a method for estimating coalbed CH_4 values when actual CH_4 values are not available for a country. The method relies on the use of generally available coal properties such as depth, heating value, and proximate analysis data. Four sources of data were used to estimate regression equations for coal bed CH_4 content. Data on U.S. coalbed CH_4 contents have been compiled by Diamond *et al.* for the U.S. Bureau of Mines and by Tremain for the Colorado Geological Survey (Tremain, 1980; Diamond *et al.*, 1986). The Tremain data include coal depth and coal analyses. The Diamond database, in addition to CH_4 values, includes only coal depth, rank, and ash content. The coal analyses needed to supplement the Diamond data were found in Schwarzer and Byrer and in Bureau of Mines' files (Schwarzer and Byrer, 1983). A total of 148 data sets were identified which were both complete and for which the CH_4 analyses were internally consistent. Since the deepest active U.S. coal mines are approximately 670 meters (m) deep, the 11 data sets which exceed this depth were eliminated. A total of 137 data sets were finally included in the coalbed database.

Table 1 describes the final coalbed database used to estimate coalbed CH_4 regression equations. As the table shows, the database represents most major coal producing regions in the United States; there are coal samples from eight states and 14 coal seams. A wide range of coal ranks is included, as evidenced by the range of heating values covered: 22,078 to 38,555 J/g (moisture- and ash-free basis). Although no overriding bias is apparent in the database, it is noted that the Illinois Basin coals are not well represented.

Coalbed CH_4 contents in both databases were measured using the Direct Method adopted by the U.S. Bureau of Mines and were reported in three components of the total (Diamond and Levine, 1981):

1) desorbed gas - the amount of gas released from a coal sample placed in a sealed canister at atmospheric pressure. This gas may take from a few hours to several months to desorb.

2) lost gas - the amount determined by extrapolation of the desorption curve back to time zero, which accounts for gas lost to the atmosphere after the coal is sampled and before it is placed in the canister.

3) residual gas - the amount of gas released when the coal is ground after the desorption process is completed.

TABLE 1. CHARACTERISTICS OF THE COALBED DATABASE

- Number of Coal Samples = 137
- Number of Seams = 14
- Range of Coal Characteristics

Moisture:	0.3 - 3.5 %
Heating Value:	22,078 - 38,555 J/g
Seam Depth:	23 - 546 m
Fuel Ratio:[a]	0.67 - 5.46

- Geographic Coverage

State	Number of Data Sets
Alabama	26
Colorado	29
Illinois	1
Ohio	3
Pennsylvania	33
Utah	1
Washington	2
West Virginia	42
Total	137

[a]Fixed carbon/volatile matter.

At this point, decisions were made regarding the form of the dependent variable and the terms to include as independent variables in the regression equations. Lost gas, because of the varying amounts of time which may elapse before the sample is placed in a container, and because different methods of extrapolation are used, may introduce uncertainty into the total gas analysis (Kim, 1977; Rightmire *et al.*, 1984). Since it would be undesirable to introduce this additional uncertainty into the regression analyses, it was concluded that values for lost gas would be removed prior to regression analyses and would be factored back in after the analyses were complete. Based on the literature cited earlier, the principal coal characteristics affecting CH_4 content appeared to be measures of pressure, rank, and moisture content. Therefore, depth, as a surrogate for pressure, and moisture content were included as independent variables. Heating value was chosen as an independent variable since it is known to increase with coal rank. Fuel ratio, the ratio of fixed carbon to volatile matter, was chosen as the fourth independent variable. It is recognized that fixed carbon increases and volatile matter decreases as rank increases (Stach *et al.*, 1975). Therefore, the fuel ratio was considered to be a reasonable surrogate for coal rank.

The next step was to produce the plots shown in Figures 2, 3, 4, and 5 of desorbed plus residual CH_4 versus each independent variable. The purpose was to verify visually the relationships reported in the literature and to confirm the validity of the surrogate variables chosen for pressure and rank. The plots were also used to identify both the nature of the relationships and breaks in the data which might suggest dividing one or more of the independent variables into separate regimes. The plot in Figure 3 suggests that the moisture relationship is not

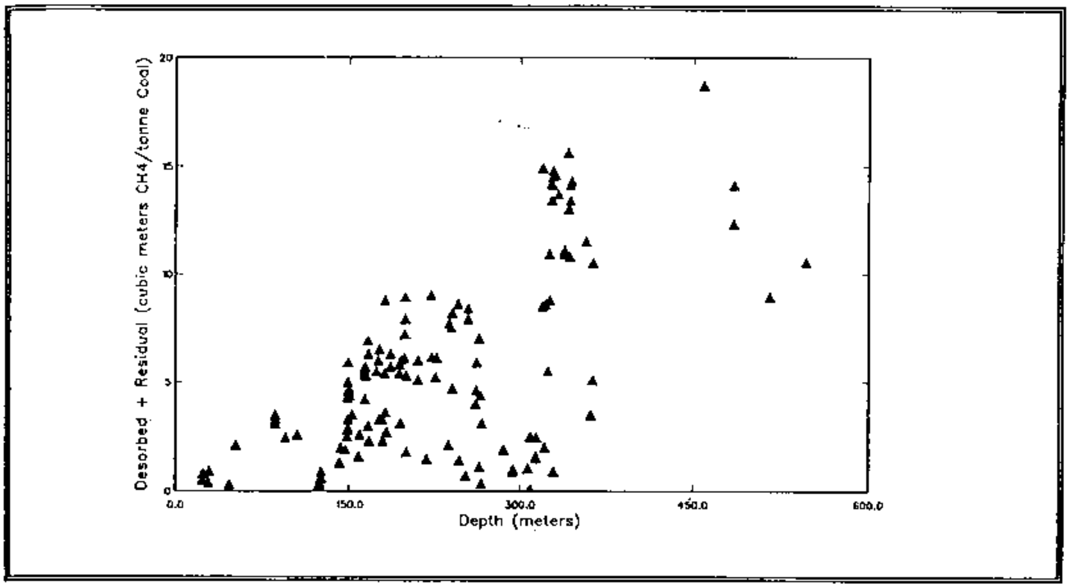

Figure 2. Depth versus CH_4 content.

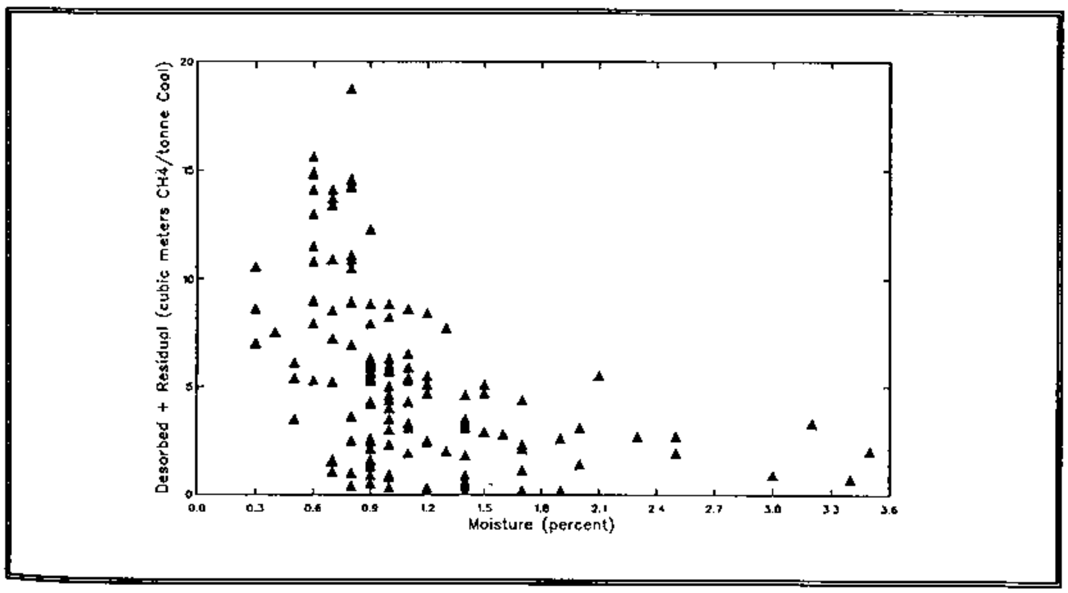

Figure 3. Moisture versus CH_4 content.

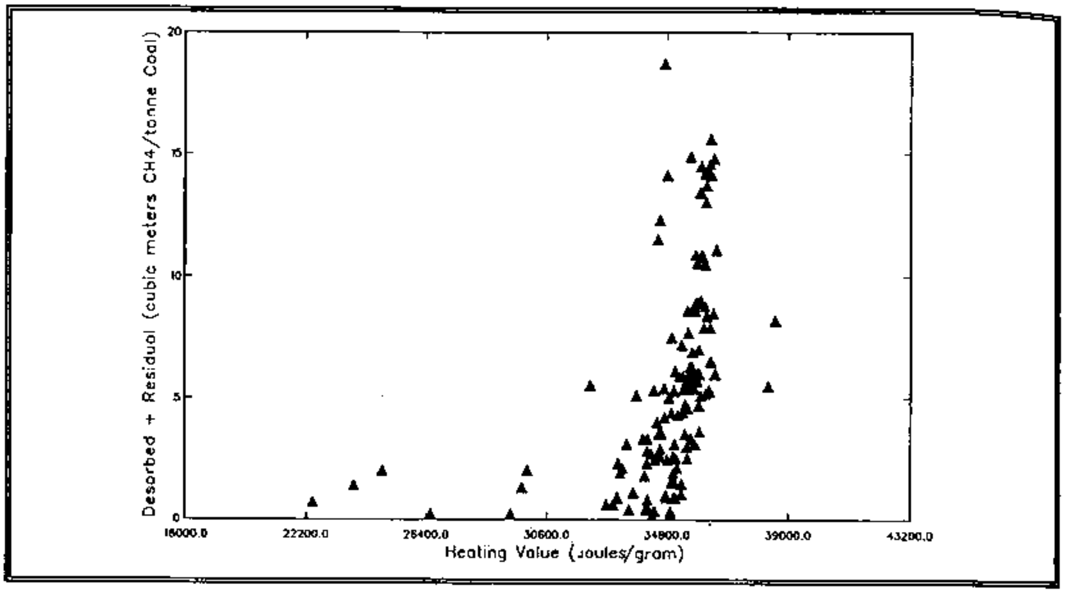

Figure 4. Heating value versus CH_4 content.

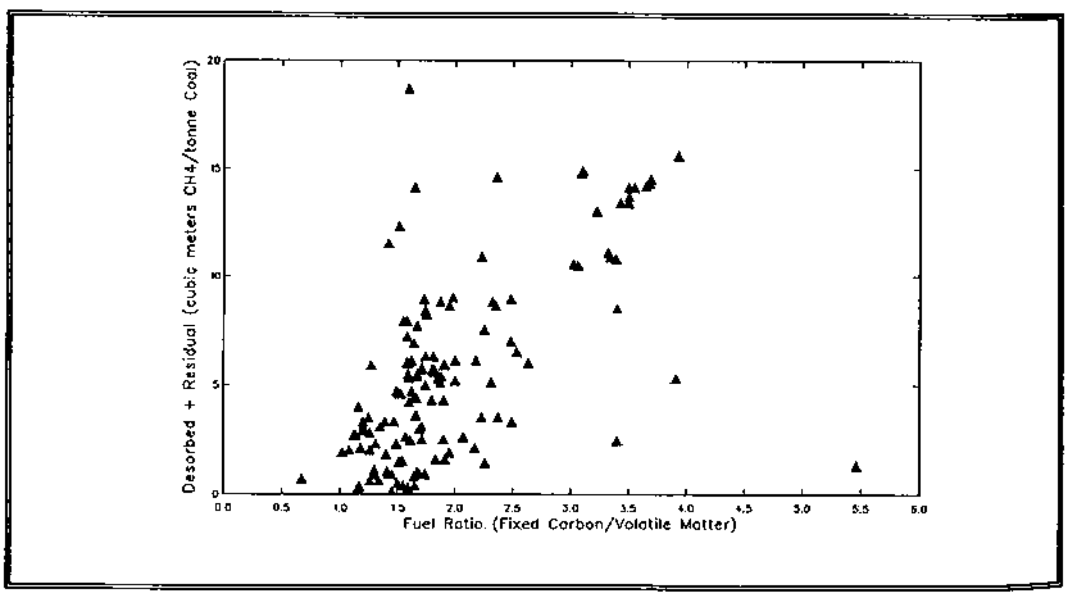

Figure 5. Fuel ratio versus CH_4 content.

linear. The heating values in Figure 4 suggest that the data might appropriately be divided into two regimes at about 34,860 J/g. Regression analyses were performed using breakpoints from 32,536 to 36,022 J/g to determine the best fit, and a heating value of 34,860 J/g was chosen as the most appropriate breakpoint. Dividing the data into two regimes produced better results than treating all of the data together. Multivariate regressions were performed on all combinations of independent variables for both regimes. The two equations finally selected are shown in Table 2, along with the supporting R^2 and Mallows C_p statistics. The regression t-statistic for each equation term is noted in parentheses immediately below the term.

TABLE 2. RESULTS OF REGRESSION ANALYSIS

Regime	Equation	Number of Data Sets	R^2	Mallows C_p
HV < 34,680 J/g	IS = 0.0159 D + 2.781 ($1/M^2$) - 2.228 (4.682) (4.332) (-2.659)	47	0.56	3.0
HV > 34,680 J/g	IS = 0.0136 D + 0.0015 HV + 2.6809 FR - 56.4901 (4.318) (3.587) (6.526) (-3.808)	90	0.71	4.0

where: HV = Heating value (J/g coal [moisture- and ash-free basis])
IS = In-situ residual + desorbed gas (m^3 CH_4/tonne of coal)
D = Depth (m)
M = Moisture content (%)
FR = Fuel ratio (fixed carbon/volatile matter)

The final step in this portion of the methodology development was to develop a means of adding lost gas values to the desorbed plus residual in-situ CH_4 values determined by the regression equations in Table 2. To make this conversion, data from a study by Eddy *et al.* and data compiled by Diamond *et al.* were used to calculate a lost gas to desorbed plus residual gas ratio for each of seven coal ranks (Eddy *et al.*, 1982; Diamond *et al.*, 1986). The coal ranks and calculated ratios are shown in Table 3. After calculating the desorbed plus residual gas using one of the regression equations from Table 2, the result is multiplied by the appropriate ratio from Table 3 to obtain a value for lost gas. The sum of lost, desorbed, and residual gas yields an estimate of the total in-situ CH_4 content of the coal.

3.2 Mine Emissions Data Analysis

The purpose of this portion of the methodology development was to construct a method for determining mine emissions from measured or estimated coalbed CH_4 contents and coal production data. A mine emissions database was first constructed of the following data (Irani *et al.*, 1972; Irani *et al.*, 1974; Irani *et al.*, 1977; Nielson, 1977; Grau, 1987):

- Actual CH_4 emissions from U.S. mine shafts

TABLE 3. RATIOS OF LOST TO DESORBED PLUS RESIDUAL CH_4 BY COAL RANK

ASTM Coal Rank	Lost CH_4/(Desorbed + Residual CH_4)
Anthracite	0.11
Low-volatile Bituminous	0.10
Medium-volatile Bituminous	0.20
High-volatile Bituminous	0.05
High-volatile B Bituminous	0.13
High-volatile C Bituminous	0.10
All Other Types	0.11

- In-situ CH_4 content from the coalbed database
- Coal production
- Gob well emission factors

Table 4 summarizes the characteristics of the database. The database includes 269 mine-specific observations of actual CH_4 emissions from mine shafts. The year for each of these observations is also noted (data from 1970 to 1985 were used). Annual coal production rates for each mine where emissions information exists are included in the database. In-situ CH_4 contents were assigned to each mine using the data contained in the coal bed CH_4 database described earlier. In most cases, an in-situ value for the same county and seam was assigned to a mine. For longwall mining methods using gob wells, the use of shaft emissions data alone would understate actual mine emissions by the amount of gas withdrawn from the gob wells. To correct for this understatement, gob well emissions data were obtained from Sööt (1991). Using these data, it was assumed that, if longwall mining began in the year for which shaft emissions data were available, the emissions for that mine were increased by 30 percent. If longwall mining began in a year prior to the year for which shaft emissions data were available, the emissions were increased by 60 percent. No factor was applied if longwall mining was not used.

A multivariate regression analysis was performed on the database to examine the effects of coalbed CH_4 content and coal production rate on mine emissions. The relationship that best predicts mine CH_4 emissions is shown in Table 5 ($R^2 = 0.59$). T-statistics are parenthetically noted below each term. Figure 6 is a plot showing the actual emissions data and the resulting "best fit" equation for this analysis (see "predicted" line in figure).

The form of the equation used represents the standard slope-intercept form for a linear relationship. This form was chosen for several reasons. First, examination of the emissions database and results from earlier research efforts suggest that a linear relationship may exist. In addition, the emissions database and observations made earlier by Irani *et al.* (1972) indicate that emissions can occur at underground mines even at very low or zero production rates. Thus, the equation form used should have a non-zero intercept, allowing a value for emissions to be determined when the production term is zero.

TABLE 4. CHARACTERISTICS OF THE MINE EMISSIONS DATABASE

- Number of Observations = 269
- Years Included in the Database: 1970-1985
- Number of Seams = 7
- Range of Mine Characteristics

Methane Emissions:	0.0028 - 0.4871 million m^3 per day
Coal Production:	323 - 13,641 tonnes per day

- Geographic Coverage

State	Number of Data Sets
Alabama	27
Illinois	33
Kentucky	5
Ohio	9
Pennsylvania	47
Virginia	29
West Virginia	119
Total	269

TABLE 5. RESULTS OF MINE EMISSIONS REGRESSION ANALYSIS

$$\text{Mine Emissions} = \underset{(8.23)}{1.08 \times 10^{-7}} \text{ (Coal Production x In-situ } CH_4 \text{ Content)} + \underset{(4.67)}{31.44} - \underset{(-4.85)}{26.76} \text{ (Dummy Variable)}$$

where:

Mine Emissions	= total emissions of CH_4 from the mine shaft and gob wells (if present) (10^6 cubic meters per year)
Coal Production	= annual production of coal (tonnes of coal per year)
In-situ CH_4	= total CH_4 content of the unmined coal (cubic meters CH_4 per tonne coal)
Dummy Variable	= 1 if (Coal Production x In-situ CH_4 content) $< 7.6 \times 10^6$ = 0 if (Coal Production x In-situ CH_4 content) $\geq 7.6 \times 10^6$

4. GLOBAL EMISSIONS ESTIMATE

4.1 Underground Mines

A summary of the country-specific data assembled on coal characteristics and coal depth is shown in Table 6. These are representative of the data which were used to calculate coalbed CH_4 contents using the regression equations from Table 2. Maximum, minimum, and average values are presented only to offer the reader an idea of the range of values found and to show where in the range the majority of values reside. These average values

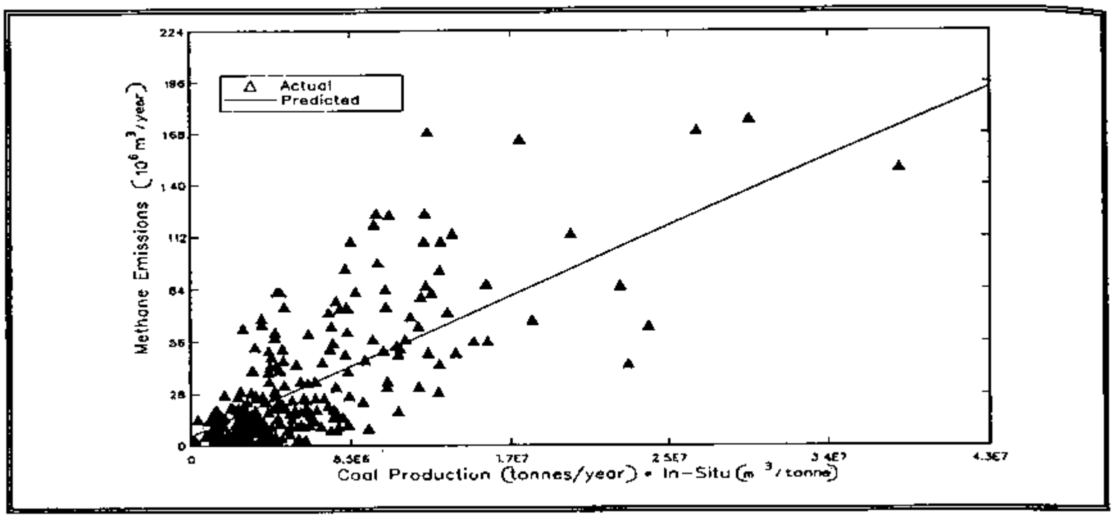

Figure 6. CH_4 emissions from underground mines.

cannot be used to adequately predict coalbed CH_4 contents on a country-by-country basis. Gas content measurements data were used instead of the regression equation to represent in-situ CH_4 content for the United Kingdom (Creedy, 1991).

Table 7 shows the country-level 1989 coal production, the range of calculated coalbed CH_4 values, and calculated CH_4 emissions. The coalbed CH_4 values are calculated using the types of data presented in Table 6 and the appropriate regression equation from Table 2. CH_4 emissions estimates are derived using the coal production and coalbed CH_4 contents in the regression equation from Table 5. For West Germany, emissions data developed by German coal industry analysts were used (Treskow and Fitzner, 1987). The U.K. emissions may be considered an upper-end estimate since it does not account for the small fraction of CH_4 that is collected and used rather than released. When information on coal mine CH_4 recovery and use was available (i.e., United States, Poland, and West Germany), the amount of CH_4 recovered and used was subtracted from a country's total emissions. For example, in Poland it is assumed that 19 percent of the potential CH_4 emissions is utilized (Pilcher *et al.*, 1991).

The countries listed in Table 7 produce 81 percent of the world's coal from underground mines. Thus, emissions for the remaining 19 percent of underground production were assumed to be equal to 19 percent of total underground mine emissions. Total global emissions from underground mines are estimated to be 36.0 Tg/year.

4.2 Surface Mines

Very little data exist on which to base estimates of emissions from surface mines. A single emission analysis has been conducted to date by the EPA at a large Powder River Basin surface mine in Wyoming (Kirchgessner *et al.*, 1992). Using open-path Fourier transform infrared (FTIR) spectroscopy, an emission rate of about 4,814 m^3/day was determined. Using a single coalbed CH_4 content for the same county and coal seam, it was estimated

TABLE 6. SUMMARY OF COUNTRY-SPECIFIC COAL CHARACTERISTICS

	Moisture (%)			Depth (meter)			Heating Value (joules/gram)			Fuel Ratio		
Country	max	min	avg	max	min	avg	max	min	avg	max	min	avg
China	27.5	1.2	9	---	---	302	36,594	18,592	30,012	12.4	0.4	4.3
Former Soviet Union	32.3	6.5	12.2	654	135	402	34,095	32,768	33,249	---	---	---
Poland	10	5.1	8.4	---	---	627	30,444	29,106	29,650	---	---	---
United States	12.4	0.9	5.3	406	105	226	35,841	30,312	34,016	4	1.1	1.6
Australia	---[a]	---	2	500	215	358	29,185	26,733	28,155	1.7	1.5	1.6
India	---	---	5.2	400	50	212	---	---	34,628	---	---	---
South Africa	7.9	1.1	3.3	160	69	85	36,589	25,748	32,115	13.03	1.65	3.3

[a]Not available.

TABLE 7. SUMMARY OF ESTIMATED GLOBAL METHANE EMISSIONS FROM COAL MINES FOR 1989

Country	1989 Underground Mine Coal Production (10^6 tonnes)	Disaggregation Level	Coalbed Methane Values (m^3/tonne)			Emissions	
			Average	Maximum	Minimum	(10^6 m^3/yr)	(Tg/yr)
China	1,053	21 Provinces	4.0	13.9	2.7	12,942	9.3
Former Soviet Union	418	6 Basins	5.6	9.2	2.2	11,045	7.9
Poland	181	3 Basins	7.8	7.8	7.7	5,013	3.6
United States	356	19 Basins	3.9	11.4	0.2	4,871	3.5
United Kingdom	71[a]	12 Basins	6.0	18.4	0.3	1,756	1.3
West Germany	73	4 Basins	-	-	-	1,529	1.1
Australia	59	3 Basins	4.6	7.1	2.1	1,529	1.1
India	95	8 States	2.0	4.7	0.3	935	0.7
South Africa	115	4 Basins	0.9	1.4	0.6	963	0.7
Country Total	2,421					40,583	29.2
Rest of World	567					9,487	6.8
Total (Underground)	2,988					50,070	36.0
Total (Surface)						9,629	6.9
Total (Handling)						3,770	2.7
Total (Surface + Underground)						63,469	45.6

[a]1990-1991 Production

that, at the mine's actual coal production rate of 11.8 million tonnes per year, potential emissions from the mined coal alone should be 1,008 m^3/day. This would suggest, as noted by Kissell *et al.* (1973) for underground mines, that actual mine emissions exceed, by a factor of about five in this case, the emissions which would be expected based on coal production and coalbed CH_4 content alone.

Rightmire *et al.* (1984), in their study of coalbed CH_4 resources in the United States, report 38 analyses of shallow coals (104 m deep or less) with CH_4 contents ranging from 0.03 to 3.6 m^3/tonne coal. One analysis of 9.6 m^3/tonne for the Arkoma Basin was not included because it is known to be anomalously high for shallow coals. Coalbed CH_4 analyses for shallow coals from other countries are lacking, so this study is temporarily making the gross assumption that the range of 0.03 to 3.6 m^3/tonne coal reflects the CH_4 content range for shallow coals worldwide. Multiplying the average value for this range (1 m^3/tonne) by 1987 world surface coal production of about 1.8 X 10^9 tonnes/year (Boyer *et al.*, 1990), and expanding the results by a factor of five as discussed above, produces an estimate of about 6.3 Tg/year. Adjusting this value upward by 10 percent to represent 1989 coal production yields an estimate of 6.9 Tg/year. As additional surface mine emissions are sampled under the EPA test program, the factor by which actual surface mine emissions exceed expected emissions may change, in which case this portion of the emissions estimate will require modification.

4.3 Handling Operations

No data were found on CH_4 emissions from handling operations. Boyer *et al.* (1990) estimate that 25 percent of the CH_4 contained in the mined coal is released during post-mining operations. There is no compelling reason not to follow this precedent for now, therefore coal handling emissions presented in Table 7 were estimated by assuming that 25 percent of the in-situ CH_4 content for all coal produced is released in post-mining operations.

5. RESULTS AND DISCUSSION

5.1 Estimates of Coalbed Methane and Mine Emissions

The regression equations developed in this study are generally believed to be satisfactory for predicting CH_4 emissions from underground coal mining. Two equations were produced for estimating coalbed CH_4 contents, one for coals greater than 34,680 J/g heating value and one for coals equal to or less than 34,680 J/g. The equations are felt to be of high quality in that the coal characteristics which could be retained in the equations at a 95 percent confidence level or better also have a sound geological base for inclusion and produce satisfactory R^2 values. The coal characteristics included follow patterns predicted in the literature cited. Depth or pressure is a dominant factor in coalbed CH_4 content because it affects not only the generation of CH_4 but also its retention in the reservoir. Depth appears in both equations. Moisture also plays an important role in CH_4 retention, which may explain its strong effect on the equation for lower heating value and, presumably, shallower coals. At shallow depths, where geologic factors may have compromised a reservoir's integrity and the coals are generally of lower rank, moisture levels are known to strongly affect sorption capacity. The link between heating value and fuel ratio (fixed carbon/volatile matter) in the equation for higher heating value coals is predictable because the parameters are process-related. With increasing depth-related pressures, the process of coalification eliminates volatile matter, which in turn increases the heating value and fuel ratio. These two characteristics define coal rank, and CH_4 content is strongly tied to coal rank.

It should be noted that the equations for predicting coalbed CH_4 are extremely sensitive to coal depth and do not produce credible results for shallow coals at depths of less than about 90 m. This is not surprising because very few coalbed CH_4 analyses for shallow coals were available during the initial development of the regression equations.

The single regression equation which predicts mine emissions suggests that CH_4 from an underground coal mine will be emitted even when coal production is not occurring, as originally noted by Irani *et al.* (1972). The equation predicts that, at zero production, CH_4 emissions will be approximately 12,801 m^3/day. The actual emissions at zero production would depend on factors such as the size of the mine and the in-situ CH_4 content of the coal. This equation also predicts that CH_4 emissions will increase from this zero production level in proportion to both the in-situ CH_4 content and the production rate. The equation has an R^2 value of 0.59 which means that almost 60 percent of the variation in CH_4 emissions from the mines can be explained by the independent variables. This R^2 value is satisfactory, given the small number of independent variables and, more importantly, the difficulty of predicting a complex physical phenomenon with so few variables.

A dummy variable is included in the equation to help explain CH_4 emissions from coal mines. An understanding of mining processes suggests that there are technological and geological factors which are not adequately characterized in the database and which may affect CH_4 emissions from mines. These factors may include the extensiveness of the mine workings (i.e., a surrogate for the area of exposed coal surfaces) and the presence of underlying or adjacent coal seams. In this case, a dummy variable is helpful in determining if there are differences in CH_4 emissions from mines that cannot be adequately explained by the existing data. The statistical significance of this variable strongly suggests that there are factors which differ between mines with low and high values of the product of coal production and in-situ CH_4 content.

The mine emissions regression results were tested to determine if serial correlation of the error terms is present. This analysis shows that serial correlation of the error term is present and that there is a relationship between the year in which the emissions data were gathered and the level of emissions from mines in the data set used. This trend may be due to effects associated with technological change, such as the increased use of longwall mining, which has taken place since 1970. It could also be due to a recently observed trend in the United States toward mining increasingly deeper and gassier coal seams (Grau, 1987). The final regression equation used was selected from a series of equations which were estimated with the expressed intent of excluding this U.S.-specific trend. This was done to avoid biasing the global estimate.

The data were also organized by level of coal production in a mine. The regression results show that there is no serial correlation when data are organized by production level. This suggests that the equation used to predict CH_4 emissions does not systematically over- or under-predict emissions from mines with high or low production levels.

5.2 Global Emissions Estimates

When country-specific data are entered, the mine emissions equation produces a global estimate of CH_4 emissions from underground mines of 36.0 Tg/year for 1989. Gross estimates for surface mine emissions and coal handling emissions based on minimal data produce average values for 1989 of about 6.9 and 2.7 Tg/year, respectively. Together, these values produce an estimate of global CH_4 emissions from coal mining of 45.6 Tg/year. This represents the upper end of the range cited by Cicerone and Oremland (1988), and about the middle of the range estimated by Boyer *et al.* (1990). Comparing the results of these studies could be misleading since this study is unique in basing its estimates on those country-specific properties of coal which are known to affect coal CH_4 contents. To examine the accuracy of this study, it is probably more appropriate to compare the U.S. estimate from this study to an estimate of U.S. mine emissions for 1985 prepared by Grau (1987), based on actual mine emission measurements. Grau estimates total emissions from underground bituminous coal mines to be about 2.3 Tg/year. Expanding this number by 10 percent to simulate a 1989 production level and adding 8 percent to allow for unaccounted for gob well emissions, the estimate becomes 2.7 Tg/yr. Total U.S. underground mine emissions from this study are 3.5 Tg/yr, making the Grau estimate about 75 percent of the estimate in this study. Even with these simple comparisons, the estimates are strikingly similar and suggest the validity of the procedure used in this study. It should also be noted that the estimated emissions of 3.6 Tg/year from Polish mines agree well with an independent estimate of 3.3 Tg/year developed from Polish mine measurements (Pilcher, 1991).

Finally, the sensitivity of the estimates to changes in various coal parameters must be addressed. While equations of the type used in this study are believed to be capable of producing representative results, their ability to do so depends on the quality of the country-specific data. To determine the sensitivity of the global emissions estimates to the parameters of concern, analyses were performed on the three largest foreign coal producers. As expected, the country-specific estimates are quite sensitive to the depth values. Changing depths by 10 percent changes the emission estimate by 10 to 15 percent. Changing the depth values by 30 percent changes the estimate by about 40 percent. This emphasizes the need for having representative data on depth. This is especially critical for China, since only minimal depth data were available for that country and it is estimated to be the largest source of mine related CH_4 emissions globally (see Tables 6 and 7).

The sensitivity of the estimates to heating value was a matter of concern because many coals have heating values near the 34,860 J/g breakpoint, which determines the regression equation to be used for coalbed CH_4 determinations (see Table 2). Where all coals within 7 percent of this breakpoint were moved to the other side of the breakpoint and reanalyzed, emissions estimates changed by only 10 percent, suggesting that errors in the heating value estimates for countries would not cause large errors in the global estimate. Moisture does not appear to be of concern, since those countries having a significant number of values near the knee of the curve in Figure 3 are relatively small producers.

Little can be said at this time about the estimation procedure for surface mines. Shallow coals are infrequently analyzed for CH_4 because they are not regarded as an economic CH_4 resource and because CH_4 is not a safety problem in surface mines. With this general lack of coalbed CH_4 data, and only a single measurement of surface mine CH_4 emissions, an admittedly unsophisticated estimation procedure has been temporarily adopted. The estimate of 6.9 Tg/yr is not strongly supportable but a better estimation procedure cannot be developed until better data are available.

Data are also lacking for CH_4 emissions from coal handling operations. However, the CH_4 desorption rates for many coals are sufficiently slow that post-mine emissions must certainly be significant and cannot be ignored here. It has been assumed that 25 percent of the CH_4 content of mined coals is released after the coal leaves the mine. This produces an estimate of global emissions from handling operations of 2.7 Tg/year.

Data for abandoned mines appear to be totally lacking at this time. It is known that some mines may continue to emit CH_4 for a period of time after abandonment, and in 1966 the U.S. Bureau of Mines estimated that there were over 60,000 inactive and abandoned coal mines in the United States (Scott and Hays, 1975). While it is clear that this category of mines must make a contribution to coal mine CH_4 emissions on a global basis, an estimate of the emissions must be deferred until data become available. The Air and Energy Engineering Research Laboratory is currently engaged in collecting measurements data for a group of abandoned coal mines.

6. CONCLUSIONS

The methodology employed in this study relies on documented relationships which exist between mine emissions, coalbed CH_4 content, coal production rate, and other coal properties. A new set of mathematical equations was developed which quantifies these relationships. In the process of developing these equations, analyses suggested that the relationships between emissions and coal properties are even more complex than expected and that all causative factors in the relationships have not been fully defined. Several geological and technological factors, not currently included in the databases, could potentially influence mine emission rates. The relationships are of sufficient quality, however, that the emissions estimation procedure for underground mines is regarded as representative and reliable. Additional surface and abandoned mine data, and handling operation data could lead to a revised global estimate at a later date, since the full impact of these categories is not known. Improved country-specific data could also have a significant impact on the estimate.

The global estimate of 45.6 Tg/yr for CH_4 emissions from coal mines is thought to be reasonable. It is the first attempt to produce this estimate using country-specific coal properties which actually influence production and retention of CH_4 by the coal reservoir. It also appears that the methodology developed here is applicable at the province, basin, and possibly seam levels if a sufficiently detailed database on coal properties and production is available.

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