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Research and Development

METHANE EMISSIONS FROM THE
NATURAL GAS INDUSTRY
Volume 11: Compressor Driver Exhaust

Prepared for

Energy Information Administration (U. S. DOE)

Prepared by

National Risk Management
Research Laboratory
Research Triangle Park, NC 27711

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16. ABSTRACT The 15-volume report summarizes the results of a comprehensive program to quantify methane (CH4) emissions from the U.S. natural gas industry for the base year. The objective was to determine CH4 emissions from the wellhead and ending downstream at the customer's meter. The accuracy goal was to determine these emissions within +/-0.5% of natural gas production for a 90% confidence interval. For the 1992 base year, total CH4 emissions for the U.S. natural gas industry was 314 +/- 105 Bscf (6.04 +/- 2.01 Tg). This is equivalent to 1.4 +/- 0.5% of gross natural gas production, and reflects neither emissions reductions (per the voluntary American Gas Association/EPA Star Program) nor incremental increases (due to increased gas usage) since 1992. Results from this program were used to compare greenhouse gas emissions from the fuel cycle for natural gas, oil, and coal using the global warming potentials (GWPs) recently published by the Intergovernmental Panel on Climate Change (IPCC). The analysis showed that natural gas contributes less to potential global warming than coal or oil, which supports the fuel switching strategy suggested by the IPCC and others. In addition, study results are being used by the natural gas industry to reduce operating costs while reducing emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Emission	Stationary Sources	14G
Greenhouse Effect	Global Warming	04A
Natural Gas		21D
Gas Pipelines		15E
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FOREWORD

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

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METHANE EMISSIONS FROM THE NATURAL GAS INDUSTRY, VOLUME 11: COMPRESSOR DRIVER EXHAUST

FINAL REPORT

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RESEARCH SUMMARY

Title	Methane Emissions from the Natural Gas Industry, Volume 11: Compressor Driver Exhaust Final Report
Contractor	Radian International LLC
	GRI Contract Number 5091-251-2171 EPA Contract Number 68-D1-0031
Principal Investigator	Carole J. Stapper
Report Period	March 1991 - June 1996 Final Report
Objective	This report describes a study to quantify the annual methane emissions from compressor driver exhaust, which is a significant source of methane emissions within the gas industry.
Technical Perspective	The increased use of natural gas has been suggested as a strategy for reducing the potential for global warming. During combustion, natural gas generates less carbon dioxide (CO_2) per unit of energy produced than either coal or oil. On the basis of the amount of CO_2 emitted, the potential for global warming could be reduced by substituting natural gas for coal or oil. However, since natural gas is primarily methane, a potent greenhouse gas, losses of natural gas during production, processing, transmission, and distribution could reduce the inherent advantage of its lower CO_2 emissions.
	To investigate this, Gas Research Institute (GRI) and the U.S. Environmental Protection Agency's Office of Research and Development (EPA/ORD) cofunded a major study to quantify methane emissions from U.S. natural gas operations for the 1992 base year. The results of this study can be used to construct global methane budgets and to determine the relative impact on global warming of natural gas versus coal and oil.
Results	The national annual emissions for compressor drivers in each industry segment are as follows: production, 6.58 ± 200% Bscf; gas processing, 6.84 ± 130% Bscf; transmission, 10.2 ± 17.1% Bscf; and storage, 1.19 ± 27.2% Bscf.

Based on data from the entire program, methane emissions from natural gas operations are estimated to be 314 ± 105 Bscf for the 1992 base year. This is about 1.4 ± 0.5% of gross natural gas production. The overall program also showed that the percentage of methane emitted for an incremental increase in natural gas sales would be significantly lower than the baseline case.

The program reached its accuracy goal and provides an accurate estimate of methane emissions that can be used to construct U.S. methane inventories and analyze fuel switching strategies.

Technical Approach

The industry has two primary types of compressor drivers that fire natural gas: 1) reciprocating engines and 2) turbines. Methane emissions result from the incomplete combustion of natural gas in the driver, which allows methane to exit the driver in the exhaust stream.

The techniques used to determine methane emissions were developed to be representative of annual emissions from the natural gas industry. However, it is impractical to measure every source continuously for a year. Therefore, annual emissions for compressor drivers were determined by extrapolating measured emissions using activity factors where the national emissions estimate is the product of the emission factor and the activity factor.

Emissions test data for each driver type were collected by Southwest Research Institute (SwRI) for compressors in natural gas industry service. SwRI data for emissions, fuel use rates, and compressor model numbers were used with data in GRI's TRANSDAT compressor database to develop the emission factors. Equations relating the SwRI data and the distribution of compressor models and operating hours found in TRANSDAT were developed to calculate emission factors for each type of compressor driver.

Activity factors for each industry segment were developed using site visit data, company surveys and databases, and data published in the American Gas Association's *Gas Facts* and the *Oil & Gas Journal*. The national annual emissions for each industry segment were then calculated as the product of the emission factor and activity factor for each compressor driver.

Project Implications

For the 1992 base year the annual methane emissions estimate for the U.S. natural gas industry is 314 Bscf ± 105 Bscf (± 33%). This is equivalent to 1.4% ± 0.5% of gross natural gas production. Results from this program were used to compare greenhouse gas emissions from the fuel cycle for natural gas, oil, and coal using the global warming potentials (GWPs) recently published by the Intergovernmental Panel on Climate Change (IPCC). The analysis showed that natural gas contributes less to potential global warming than coal or oil, which supports the fuel switching strategy suggested by IPCC and others.

In addition, results from this study are being used by the natural gas industry to reduce operating costs while reducing emissions. Some companies are also participating in the Natural Gas-Star program, a voluntary program sponsored by EPA's Office of Air and Radiation in cooperation with the American Gas Association to implement cost-effective emission reductions and to report reductions to the EPA. Since this program was begun after the 1992 baseline year, any reductions in methane emissions from this program are not reflected in this study's total emissions.

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1.0 SUMMARY

This report is one of several volumes that provide background information supporting the Gas Research Institute and U.S. Environmental Protection Agency Office of Research and Development (GRI-EPA/ORD) methane emissions project. The objective of this comprehensive program is to quantify the methane emissions from the gas industry for the 1992 base year to within ± 0.5% of natural gas production starting at the wellhead and ending immediately downstream of the customer's meter.

This report quantifies the amount of unburned methane released in compressor driver exhaust in natural gas production, gas processing, and transmission. Emissions from generator driver exhaust, while minor, are also included in this report. Emission estimates for each industry segment were based on data from one or more of the following sources: 1) site visits, 2) company databases; and 3) published data. The factors that affect the quantity of methane emissions from compressor drivers are: type of driver, horsepower, and operating hours.

Compressor driver exhaust is a significant source of methane emissions. It accounts for 24.8 Bscf of methane emissions, which is about 7.9% of methane emissions from the natural gas industry.

2.0 INTRODUCTION

In the natural gas industry there are two primary types of compressor drivers that fire natural gas: 1) reciprocating engines, and 2) gas-fired turbines. Methane emissions result from the incomplete combustion of the natural gas, which allows some of the methane in the fuel to exit in the exhaust stream. Compressor driver exhaust emissions represent a significant source of methane emissions in all of the industry segments where these sources are present. Emissions from generator driver exhaust, while minor, are also included in this report.

Annual emissions were calculated as the product of the emission factor and the activity factor. To develop the compressor driver emission factors, test data from Southwest Research Institute (SwRI) and GRI's TRANSDAT compressor database[1] were used. The activity factors were developed to characterize the compressor drivers in each industry segment. Data were gathered from site visits, company databases, and published data from the American Gas Association (A.G.A.) and the *Oil and Gas Journal*.

This report describes how the emissions from compressor driver exhaust were determined. Section 3 discusses the data used to make the emission estimates. Section 4 presents the development of the emission factors for engines and turbines. Section 5 describes the development of the activity factors for each industry segment (production, processing, and transmission, including storage and generators). The annual emissions for each segment and the overall national emissions estimate are provided in Section 6. Conclusions are given in Section 7. This report is one of several documents prepared for the GRI/EPA methane emissions project.

3.0 DATA SOURCES

Compressor driver exhaust emissions had been identified in earlier studies as a significant source of methane emissions. However, these studies were based on limited data and did not calculate error bounds for the estimated emissions. This study collected and evaluated a large number of data for compressor drivers and performed an error analysis of the emissions estimate. This section provides background information on previous studies and an introduction to the data and the approach used for the current study

3.1 Previous Studies

Previous estimates of methane emissions from compressor driver exhaust have ranged from about 114 Bscf (2.2 Tg/yr) to 11.5 Bscf (0.22 Tg/yr).[2,3] The 114 Bscf estimate, from Pipeline Systems, Inc. in 1990, was based on an estimated emission factor established by the South Coast Air Quality Management District (1120 lb/MMscf fuel).[2] This estimate used a "model" installation to describe typical compressor facilities for field production, transmission, storage, and gas processing; then used these "model" installations to extrapolate to a national estimate. The "model" installations were based on site visits to three production facilities, three pipeline systems, five injection/withdrawal plants, and two gas plants. Eight of the site visits were in California, two were in Texas, and the remaining site visits were in the Central Plains Region. The estimate from Pipeline Systems, Inc. was based on a limited number of data and are probably biased due to the disproportionate use of California sites.

The 11.5 Bscf estimate was a preliminary estimate developed in 1992 as part of the GRI/EPA methane emissions project.[3] (The preliminary emissions estimate is described in detail in the paper titled "National Estimate of Methane Emissions from Compressors in the U.S. Natural Gas Industry," which can be found in Appendix A.) This estimate was based on data published by A.G.A. and data contained in the GRI TRANSDAT compressor database. The GRI TRANSDAT database includes data from

A.G.A. and SwRI. A.G.A. data are gathered from government agencies, such as U.S. Department of Energy (DOE) and Federal Energy Regulatory Commission (FERC), and from surveys of its member companies in transmission and distribution. SwRI data were generated during a field testing program on natural gas compressor driver emissions and operating characteristics.

This preliminary study assumed that the GRI TRANSDAT database included information on all compressors used in the natural gas industry when it only contained data collected from transmission companies. Therefore, this study underestimated methane emissions from compressor driver exhaust for the natural gas industry.

3.2 TRANSDAT Database

The GRI TRANSDAT database is actually composed of three data subsets: Industry Database, Operating Database, and Test Database. The Industry Database lists 8282 compressor drivers (engines and turbines) used in the gas industry in 1989. Horsepower in this database is given by compressor model number for each gas company and accounts for a total of 16.2 million horsepower (MMhp), installed. TRANSDAT data were collected from transmission companies, and it may include a limited amount of data on compressors used for production and processing. The Operating Database contains annual operating hours and operating horsepower for 1515 compressors (3.2 MMhp, total). The Test Database contains emissions data from field tests collected by SwRI and includes data on methane emissions, fuel use, fuel use rate, and horsepower for 241 compressors.

The Operating and Test Databases were combined to generate a fourth database, the Emissions Database, that was then used to develop weighted emission factors. This database combines compressor model number, methane emissions, fuel use rate, and annual operating hours for 775 reciprocating engines and 86 gas-fired turbines. Therefore, the emissions can be calculated for each of the 775 engines and 86 turbines as they were operated during the year using SwRI emissions data.

3.3 Current Study

Data were gathered during this study to supplement the GRI TRANSDAT database to account for emissions from all industry segments. Data were collected during site visits and company surveys to determine the number of compressors and their horsepower and operating hours. Because it is not practical to visit every site or test every compressor driver, a method was developed using emission factors and activity factors to calculate total emissions from compressor drivers based on a limited data set. The emission and activity factors were defined such that their product would equal the total emissions from compressor driver exhaust for each segment of the industry. Emissions from reciprocating engines and turbines were evaluated separately.

For most source categories in the gas industry, the emission factor is defined as the average emission rate determined from a large number of randomly selected sources. The activity factor is then the total number of sources within the source category, such as the total count of compressor drivers. However, for compressor driver exhaust, the emission factor was evaluated in terms of emissions per horsepower·hour (scf/hp·hr) since this has less variability than an emission factor per compressor unit. By calculating emissions on a per horsepower basis the variability in emissions due to compressor size can be eliminated. As a result, the activity factor is horsepower·hours per year. This means that:

$$\text{Total Emissions (scf)} = \text{EF (scf/hp·hr)} \times \text{AF (hp·hr)} \quad \textbf{(1)}$$

The site visit and company survey data provided information on activity factors for the various segments of the industry, and SwRI test data were used to develop the emission factors. However, the emission factor was not based on a simple average of the SwRI test data because the emission factor needed to be weighted to reflect the compressor population of the industry and because some compressor models are used as baseloaded compressors and operate a higher percentage of the time. For these reasons, A.G.A.'s Operating Database, which contains horsepower, operating hours, and model numbers for over 1500 compressors, was used to develop weighted industry emission factors for reciprocating engines and turbines. The emission factors for engines and turbines are 0.240 scf/hp·hr ± 5% and 0.0057 scf/hp·hr ± 30%, respectively. The method for calculating these weighted emission factors is described in the following section.

4.0 COMPRESSOR DRIVER EXHAUST EMISSION FACTORS

The emission factors for reciprocating engines and gas-fired turbines were determined from compressor test data collected by SwRI and weighted to reflect both the population of compressor models and their operating hours in the natural gas industry. The information needed to develop the weighting procedure was available in GRI's TRANSDAT database.

SwRI followed several procedures to ensure the quality of their compressor data. First, the emissions analyzers were calibrated using gases certified by the National Institute of Standards and Testing. Second, an oxygen molar balance was performed between the reactants and the products of combustion to verify the results. Third, each of the data trends was inspected graphically in an effort to identify potential outliers. There were generally five data points for each test, and any of the points that did not follow the trend were marked as outliers. Data that were collected by outside sources and provided to SwRI for inclusion in their study were also scrutinized graphically to validate the results. Where technically justified, statistical outliers were discarded in the development of the emission factors for the GRI/EPA methane emissions project.

An average emission rate was calculated for each model of compressor engine and turbine driver in the Emissions Database using the test data collected by SwRI for that model. Using the fuel use rate and average emission parameter for each compressor model, the emission rate was calculated as follows:

$$\overline{ER}_{(m)} = \overline{EP}_{(m)} \times \overline{FUR}_{(m)} \qquad (2)$$

where:

$\overline{ER}_{(m)}$ = average emission rate for model, m (scf/hr)
$\overline{EP}_{(m)}$ = average emission parameter for model, m (scf CH_4/scf fuel)
$\overline{FUR}_{(m)}$ = average fuel use rate for model, m (scf fuel/hr)

The methane emissions for each compressor driver in the Emissions Database were calculated by multiplying the emission rate (Equation 2) by the annual operating hours for each engine or turbine. The total emissions for each model of compressor driver in the database were calculated as follows:

$$E_{(m)} = \sum_{i=1}^{M} (\overline{ER}_{(m)} \times HR_{i}) \tag{3}$$

where: $E_{(m)}$ = total emissions for model, m(scf)
HR_{i} = annual operating hours for compressor i, (hr/yr)
M = number of compressors of model, m

The total emissions for all compressor drivers in the database were the sum of the total emissions calculated for each model.

$$TE = \sum_{m=1}^{K} \bar{E}_{(m)} \tag{4}$$

where: TE = total emissions for database, (scf)
K = number of unique compressor models

These emissions were calculated based on data from 775 engines and 86 turbines and weighted to reflect the distribution of compressor models found in the gas industry as well as the percentage of time these models are operated. Emissions can also be affected by the compressor load. However, the emissions are generally linear over a fairly large range of operating horsepower. To ensure that significant differences did not exist between the horsepower at which the compressor drivers are typically operated and the horsepower at which they were tested, the following comparison was made:

$$\sum_{i=1}^{N} hp_{(test)\ i} \overset{?}{\approx} \sum_{i=1}^{N} hp_{(operating)\ i}$$

The two values agreed to within 2%.[3]

The emission factors, for engines and turbines, were then calculated using the following equation.

$$\text{Emission Factor} = TE \;/\; \left[\sum_{i=1}^{N} \overline{HP}_i \times \left(\sum_{i=1}^{N} HR_i \;/\; N\right)\right] \tag{5}$$

where: $\overline{HP}$ = average operating horsepower during HR, (hp)

HR = annual operating hours, (hr/yr)

N = number of compressors

The values obtained are:

$$\text{Engines: } \frac{1.165 \times 10^9 \text{ scf}}{(1.3 \times 10^6 \text{ hp}) \times (3742 \text{ hr/yr})} = 0.240 \text{ scf/hp·hr}$$

$$\text{Turbines: } \frac{0.005 \times 10^9 \text{ scf}}{(0.4 \times 10^6 \text{ hp}) \times (2326 \text{ hr/yr})} = 0.0057 \text{ scf/hr·hr}$$

Confidence limits were calculated for the emission factors based on the variation in SwRI's field test data. Table 4-1 shows the statistics used to determine the 90% confidence limits for each of the emission factors. The resulting uncertainty is ± 5% for reciprocating engines and ± 30% for gas-fired turbines (using a 90% confidence limit).

TABLE 4-1. SwRI FIELD TEST EMISSION FACTOR STATISTICS

Driver Type	No. Tests	No. Models	Average Emission Factor (lb Methane/lb fuel)	Standard Deviation (lb Methane/lb fuel)
Engines	902	229	0.0307	0.0279
Turbines	105	12	0.000107	0.000187

Appendix B contains the source sheet for compressor driver exhaust emissions, which summarizes the approach taken to calculate the emission factors. The source sheet also summarizes the activity factors used to determine the overall national emissions estimate from compressor drivers. The next section describes the development of these activity factors.

5.0 COMPRESSOR DRIVER ACTIVITY FACTORS

Information from site visits, company surveys, A.G.A.'s *Gas Facts*, and the *Oil & Gas Journal* was used to develop the activity factors. Data on horsepower and operating hours were obtained from site visits and company databases for compressor drivers located at 297 field gathering stations, 18 gas processing plants, 51 transmission compressor stations, and 11 underground storage stations. Data for electric generator drivers at 41 transmission compressor stations and 3 underground storage fields were also obtained from the site visits and company databases.

Compressors used for gas lift (oil production) were excluded from the following analysis, since this gas is not marketed and is not considered part of the natural gas industry. Some sites used electrically driven compressors. These electrically driven compressors were also excluded in the development of the activity factors, since they have no exhaust and therefore have no methane emissions.

For the production industry segment, horsepower·hour data were provided by one company for 516 engines located at 244 gathering stations. Production data for 53 gathering stations (from site visits and company surveys) were analyzed separately and are presented in Appendix C for comparison. For each of the remaining industry segments, separate horsepower and operating hour estimates were made, which were multiplied together to get the horsepower·hour activity factors.

Data were gathered for engines and turbines, allowing separate activity factors to be developed for the two driver types. Data were also gathered for installed versus active horsepower in each industry segment (based on operating hours). Finally, data were gathered that could be used to estimate national emissions from each of the natural gas industry segments (e.g., site data for gas throughput).

The national estimates were extrapolated using 1992 data as the base year, except for the transmission segment estimate of compressor station horsepower that uses 1989 data as the base year. A more detailed explanation of this variation appears in Section 5.3.1. The following sections describe the development of the horsepower·hour estimate for production and the horsepower and annual operating hour estimates for processing and transmission (including storage and generators). Section 5.4 summarizes the resulting activity factors for all of the industry segments.

5.1 Production Industry Segment

Table 5-1 shows the production segment horsepower·hour data provided by one company for 516 reciprocating engine compressor drivers. These data included compressor units with operating hours listed as 8760 hr/yr. It was assumed that these were maximum operating hours, not actual operating hours. Since no other data were available for these units, extensive quality checks were not possible, so the data were used as provided. Turbine drivers were excluded from this analysis due to the small number of these drivers in production (only one reported in the company database used for this analysis) and the low methane emission factor for turbines.

TABLE 5-1. COMPRESSOR DRIVER DATA FOR PRODUCTION SEGMENT

Business Unit	No. Engines	MMhp·hr	MMcfd
Gulf Coast			
BU1	15	121.0	478.6
BU2	12	28.8	89.8
BU3	177	755.9	396.6
Central Plains			
BU4	68	233.1	731.6
BU5	244	104.4	624.0
TOTAL	516	1243.2	2320.6

The company data were provided by business unit and then grouped into two geographic areas corresponding to the Gulf Coast (onshore and offshore) and Central Plains regions described in Volume 5 on activity factors.[4] There were no production data available for the Pacific Mountain and Atlantic & Great Lakes regions. However, the two regions without data account for only 9.5% of the total U.S. marketed natural gas production. While this company database was not a perfect microcosm of the production segment, it was the most comprehensive database available and should be a reasonable representation of the production segment.

The total company horsepower·hours per production (hp·hr/MMcfd) and the total U.S. marketed natural gas production for 1992 were used to extrapolate to a national estimate of compressor engine driver horsepower·hours. Table 5-2 shows the company production data and the U.S. production data used for this calculation.[5] The resulting activity factor is 27,460 MMhp·hr.

$$\text{Engine hp}\cdot\text{hr} = \frac{\text{Company MMhp}\cdot\text{hr}}{\text{Company MMcfd}} \times \text{U.S. Marketed Gas MMcfd} \qquad (6)$$

$$= \frac{1243.2\ \text{MMhp}\cdot\text{hr}}{2320.6\ \text{MMcfd}} \times 51265\ \text{MMcfd}$$

$$= 27{,}460\ \text{MMhp}\cdot\text{hr}$$

TABLE 5-2. REGIONAL DATA FOR PRODUCTION SEGMENT EXTRAPOLATION

Region	Company Production MMcfd	National Marketed Production MMcfd
Pacific Mountain	NA	2696
Gulf Coast	965.0	31544
Central Plains	1355.6	14860
Atlantic & Great Lakes	NA	2166
TOTAL	2320.6	51265

Confidence limits were assigned to be ± 200% based upon an engineering analysis. Rigorous propagation of the error using the ratio method produced an estimate for the upper bound of ± 576% (185,630 MMhp·hr). The ratio method assumes that sites are randomly sampled, so that a large site is proportionately representative of a large section of the population (see Volume 4 on statistical methodology).[6] However, an analysis of this bound showed it to be unreasonably high. A.G.A.'s *Gas Facts* reports that lease and plant fuel usage for 1992 was 1.2 trillion scf.[7] Assuming all of this fuel was fired in compressor drivers, this would produce 150,080 MMhp·hr. In reality, much of this fuel is actually used in heater burners; therefore, the actual upper bound must be well below 150,080 MMhp·hr (± 447%). A separate analysis of the company database produced an upper bound of only 66,490 MMhp·hr (± 119%). This estimate was based on average horsepower·hours by business unit and applied a confidence limit analysis to the average of these data. Each alternative approach resulted in lower confidence limits than the calculated ± 576%; therefore, the confidence limits were set at ± 200%.

5.2 Processing Industry Segment

Horsepower

Horsepower in gas processing could be extrapolated to estimate a national total by using either plant throughput or plant count. Horsepower is technically related to plant pressure (ΔP) and throughput. However, there are no national figures for average plant ΔP. Without the ΔP factor, plant horsepower is not related to throughput alone. Therefore, national gas plant horsepower was determined by averaging the values obtained when extrapolating by throughput and by plant count.

Table 5-3 shows the installed horsepower and gas throughput for each of the 10 sites visited in the processing segment (gas plants). The engine/turbine horsepower split for this segment is 44.7% engines and 55.3% turbines. The first extrapolation method uses the average site horsepower per plant throughput and the national gas plant throughput for

1992 to calculate the processing segment horsepower.[8] This gives a total compressor driver horsepower of about 2.2 MMhp for engines and 2.8 MMhp for turbines in the processing segment.

TABLE 5-3. COMPRESSOR DRIVER DATA FROM PROCESSING SEGMENT SITE VISITS

Site	Installed Engine hp[a]	Installed Turbine hp[a]	MMcfd
GP1	8300	35000	350
GP2[b]	0	27000	750
GP3	0	20000	140
GP4	3700	0	60
GP5	11000	0	49
GP6	6740 (20000)	0	56
GP7	5925 (17490)	0	40
GP8	6267 (18500)	0	130
GP9	6267 (18500)	0	130
GP10	36600	23000	70
TOTAL[c]	84799	105000	1775
AVERAGE	8480	10500	177.5

[a] Total site horsepower (including gas lift for oil recovery) is shown in parentheses.
[b] Estimated.
[c] Excludes gas lift.

<u>THROUGHPUT METHOD:</u>

$$\text{Engine hp·hp} = \frac{\text{Total Site hp}}{\text{Total Site MMcfd}} \times \text{U.S. Throughput} \qquad (7)$$

$$= \frac{84799 \text{ hp}}{1775 \text{ MMcfd}} \times 46510.7 \text{ MMcfd}$$

$$= 2.22 \text{ MMhp}$$

$$\text{Turbine hp} = \frac{105000 \text{ hp}}{1775 \text{ MMcfd}} \times 46510.7 \text{ MMcfd}$$

$$= 2.75 \text{ MMhp}$$

The second extrapolation method uses the average installed horsepower per site and the total number of gas plants in the United States in 1992 to calculate the processing segment horsepower.[7] This gives a total compressor driver horsepower of about 6.2 MMhp for engines and 7.6 MMhp for turbines in the processing segment.

SITE METHOD:

$$\text{Engine hp·hp} = \frac{\text{Total Site hp}}{\text{Total Number of Sites}} \times \text{U.S. Gas Plants} \tag{8}$$

$$= \frac{84799 \text{ hp}}{10 \text{ Plants}} \times 726 \text{ Plants}$$

$$= 6.16 \text{ MMhp}$$

$$\text{Turbine hp} = \frac{105000 \text{ hp}}{10 \text{ Plants}} \times 726 \text{ Plants}$$

$$= 7.62 \text{ MMhp}$$

An average of the results of the two extrapolation methods is used to determine the national estimate for compressor driver horsepower in the processing segment. The average engine horsepower is 4.19 MMhp, and the average turbine horsepower is 5.19 MMhp. Both estimates are based on the total installed horsepower from the sites visited, excluding horsepower used for gas lift.

Confidence limits were calculated for the average site visit hp/MMcfd and average site visit hp/plant using the ratio method. Confidence limits for the U.S. gas plant throughput and the total U.S. number of gas plants were estimated to be ± 5% and ± 2%, respectively.[4] The uncertainty for the first extrapolation method (based on throughput) is ± 114% for engines and ± 120% for turbines. The uncertainty for the second extrapolation method (based on number of plants) is ± 71.4% for engines and ± 7.6% for turbines. For the average of the two methods, the uncertainty is ± 132% for engines and ± 99.4% for turbines (90% confidence limits).

Operating Hours

Table 5-4 shows the "operating hours" for the compressor drivers at the 10 sites visited plus operating hour data from two company databases for an additional 18 gas plants. For the site visit data, actual operating hours were only available for two of the sites. For the remaining eight sites, compressors that were running during the site visit were assigned annual operating hours of 8760. Compressors that were idle were assigned annual operating hours of 0. One company database (17 plants) included operating hours of 8760 for some units. These data may be maximum hours, not actual hours. However, no other data were available for these units, so the data were used as provided. The operating hours listed for each site in Table 5-4 are the average hours for all of the drivers at the site. Confidence limits were calculated for the operating hours estimate from the variation of the site data. The resulting uncertainty is ± 11.5% for engines and ± 48.4% for turbines (90% confidence limits).

5.3 Transmission Industry Segment

The activity factor estimates for the transmission segment include horsepower and operating hours for compressor stations and storage fields. These estimates have been calculated for compressor drivers and generator drivers at both types of facilities. Section 5.3.1 discusses the compressor driver activity factor estimates for compressor stations. (Site visit data for transmission compressor stations are included in Appendix D for comparison.)

TABLE 5-4. ANNUAL OPERATING HOURS FOR PROCESSING SEGMENT

Site	No. of Engines[a]	Average Operating Hours	No. of Turbines[a]	Average Operating Hours
GP1[b]	7	6257	2	4380
GP2	0	--	1	8423
GP3[b]	0	--	1	8760
GP4[b]	4	4380	0	--
GP5[b]	7	5006	0	--
GP6[b]	6 (16)	2920	0	--
GP7[b]	4 (12)	6570	0	--
GP8[b]	1 (4)	8760	0	--
GP9[b]	1 (4)	8760	0	--
GP10	15	5724	5	3816
GP11	2	0	0	--
GP12	5	7376	0	--
GP13	4	4617	0	--
GP14	5	8570	0	--
GP15	9	7949	0	--
GP16	1	8760	0	--
GP17	14	8760	0	--
GP18	10	4043	0	--
GP19	3	5840	0	--
GP20	11	8760	0	--
GP21	7	5325	0	--
GP22	46	8760	0	--
GP23	8	8760	0	--
GP24	10	5011	0	--
GP25	8	6487	0	--
GP26	5	8176	0	--
GP27	1	8760	0	--
GP28	9	7949	0	--
TOTAL	203		9	
AVERAGE[c]		6626		6345
90% LIMIT[c]		± 11.5%		± 48.4%

[a] Total number of drivers (including gas lift for oil recovery) are shown in parentheses.
[b] Based on active (8760 hrs) versus idle (0 hrs).
[c] Based on site averages.

Section 5.3.2 discusses the compressor driver activity factor estimates for underground storage fields. Activity factor estimates for generator drivers are discussed in Section 5.3.3.

5.3.1 Compressor Station Horsepower and Hours

Horsepower

The transmission compressor station horsepower estimate is based on the GRI TRANSDAT database, which includes transmission, storage, and associated field compression for 1989. TRANSDAT has not been revised since the 1989 data were collected; therefore, for these activity factors, 1989 was used as the base year. It is not possible to separate the compressor data in GRI TRANSDAT by the specific application; however, an adjustment for storage compressor horsepower can be made based on data from A.G.A. for 1989. While the GRI TRANSDAT data could be adjusted to a 1992 basis using A.G.A.'s transmission horsepower data, this approach was rejected because the annual data showed no trend and differences were attributed to changes in reporting protocols by A.G.A.'s member companies.

GRI TRANSDAT's Industry Database contains information on 7489 reciprocating engines and 793 gas turbines. The total installed horsepower for these compressors is 11.2 MMhp for engines and 5.0 MMhp for turbines, which accounts for about 97% of the gas utility industry installed horsepower reported by A.G.A. for 1989 (16.7 MMhp).[7] A.G.A.'s data were gathered through a survey of their member companies and includes approximately 96% of total gas industry sales. The GRI TRANSDAT horsepower can be adjusted for the 1989 storage horsepower reported by A.G.A. (1,462,971 hp) to give 10.2 MMhp for engines and 4.5 MMhp for turbines. GRI TRANSDAT'S engine/turbine horsepower split of 69.1% engines and 30.9% turbines was applied to the storage horsepower before adjusting the totals.

A.G.A. also separately reports that 13.9 MMhp is for transmission in 1992.[7] This is based upon the annual A.G.A. survey issued to member companies. GRI TRANSDAT horsepower, less the storage segment, is about 6% higher than the A.G.A. number. This discrepancy probably results from differences in the field gathering horsepower reported by GRI TRANSDAT and A.G.A.. Currently, there is no way to separate this type of horsepower from that used for mainline transmission. No other adjustments to the GRI TRANSDAT horsepower data were made during this study.

Horsepower in the GRI TRANSDAT Industry Database is reported as site totals. The national estimate for transmission compressor stations is simply a sum of all of these site totals. As a result, the uncertainty could not be calculated from the data as was done for the other industry segments. Therefore, confidence limits for compressor station horsepower were conservatively estimated by engineering judgement to be ± 10% for each type of compressor driver.

Operating Hours

The average annual compressor operating hours for the transmission segment was determined from information reported on FERC Form No. 2 for the year 1992. In the FERC database, transmission companies report the total number of operating hours per stage of compression for each compressor station. The total number of stages of compression operating on the date of peak demand is also reported by station. The value for operating hours was divided by the total number of stages to give the average annual operating hours for the station. The average annual operating hours at every station for all the companies in the FERC database were then summed and divided by the total number of stations to produce the nationwide activity factor. Transmission compressor station annual operating hours were 3787 hours per year. For a few stations the information in the FERC database was not considered to be accurate (less than 1% of the total), so the average operating hours for the rest of the company's stations was applied to the station with questionable data. Confidence limits for the FERC operating hours were calculated to be ± 4.0%.

Because the FERC database does not identify the type of driver, reciprocating engine or turbine, a procedure was developed to split the total average operating hours (3787 hr/yr) between the two types. The FERC data were weighted by the total number of each type of driver using data from GRI TRANSDAT as shown in the following equation.

$$\frac{793_{turbines}\,(T_{hr}) + 7489_{recips}\,(R_{hr})}{(793_{turbines} + 7489_{recips})} = 3787 \text{ hr/yr (FERC)} \qquad \textbf{(9)}$$

where: T_{hr} = Turbine operating hours, hr/yr
R_{hr} = Reciprocating engine operating hours, hr/yr

The following relationship between T_{hr} and R_{hr} was based on data provided by a company for 107 transmission compressor stations, which included 89 turbines and 524 reciprocating engines.

$$\frac{T_{hr}}{R_{hr}} = \frac{2718 \text{ hr/yr}}{5086 \text{ hr/yr}} = 0.53 \qquad \textbf{(10)}$$

Using these two equations to solve for T_{hr} and R_{hr} resulted in annual operating hours of 2118 hr/yr for turbines and 3964 hr/yr for reciprocating engines.

Confidence limits for the transmission compressor station operating hours were calculated to be $\pm$ 31.3% for turbines and $\pm$ 13.9% for reciprocating engines. The confidence limits were based on assumed uncertainties of $\pm$ 10% for the GRI TRANSDAT data and calculated confidence limits for both the FERC and company data.

5.3.2 Underground Storage Horsepower and Hours

Horsepower

Horsepower data from A.G.A.'s *Gas Facts* were used for this industry segment. A.G.A. reports that for 1992 the total installed compressor horsepower associated with underground storage was 1,920,441 horsepower (entire United States).[7] The horsepower data were gathered by A.G.A. through a survey of their member companies, which includes approximately 96% of total gas industry sales. Since GRI TRANSDAT includes storage compressor horsepower, the horsepower split between engines and turbines was assumed to be the same as the split found in this database (69.1%, engines and 30.9%, turbines). As a result, the horsepower attributed to engines is 1.33 MMhp and to turbines is 0.59 MMhp. Confidence limits for storage horsepower (engines and turbines) were calculated based on an assumed ± 5% uncertainty for the A.G.A. horsepower and an assumed ± 10% uncertainty for the GRI TRANSDAT horsepower splits.

Operating Hours

Table 5-5 shows the operating hours of compressors at four sites surveyed and the operating hours provided by one company for their seven storage fields. The operating hours listed are the average hours for all of the drivers at the site. Confidence limits were calculated for the operating hour estimate from the variation of the site data. The resulting uncertainty is ± 23.1% for engines and ± 620% for turbines (90% confidence limits).

5.3.3 Generator Driver Horsepower and Hours

The generator driver estimates are based on site visit data and data provided by one company for 34 transmission compressor stations and three storage fields. Site visit data were collected for generator drivers (for electricity generators) at seven of the transmission compressor stations surveyed. For compressor stations, an average generator

TABLE 5-5. ANNUAL OPERATING HOURS FOR STORAGE SEGMENT

Site	No. of Engines	Average Operating Hours	No. of Turbines	Average Operating Hours
US1	9	2400	0	--
US2	14	5122	4	52.5
US3	2	5607	0	--
US4	3	1155	0	--
US5-1	5	2700	0	--
US5-2	3	3813	0	--
US5-3	3	5832	0	--
US5-4	4	3727	0	--
US5-5	3	3390	0	--
US5-6	4	3327	0	--
US5-7	0	--	2	5781
TOTAL	50		6	
AVERAGE[a]		3707		2917
90% LIMIT[a]		± 23.1%		± 620%

[a] Based on site averages.

horsepower per station was established to determine total generator horsepower. Similarly, for storage fields, an average generator horsepower per field was established to determine total generator horsepower.

Data for generators used in transmission compressor stations are shown in Table 5-6. Only one turbine driver was installed at the 41 facilities surveyed; therefore, the data shown in Table 5-6 represent an engine/turbine horsepower split of 97%/3%. Using the average installed horsepower per station, the total number of transmission compressor stations in the United States for 1992 was used to extrapolate to a national estimate of 1.45 MMhp for reciprocating engine generator drivers and 0.045 MMhp for turbine generator drivers.[9] The number of compressor stations is an estimate based on data from FERC Form No. 2 for 46 transmission companies and is described in Volume 5 on activity factors.[4]

p

p

TABLE 5-6. GENERATOR DRIVER DATA FROM TRANSMISSION COMPRESSOR STATIONS

Site	No. Engines	Installed Engine hp	Average Operating Hours	No. Turbines	Installed Turbine hp	Average Operating Hours
GS1	3	1542	3232	0	0	--
GS2	1	514	0	0	0	--
GS3	2	1028	1095	0	0	--
GS4	0	0	--	0	0	--
GS5	2	3500	88	0	0	--
GS6	1	500	88	0	0	--
GS7	1	500	88	0	0	--
GS8-1	3	1110	9	0	0	--
GS8-2	5	1501	1688	0	0	--
GS8-3	1	30	0	0	0	--
GS8-4	1	435	2	0	0	--
GS8-5	4	2190	4455	1	1080	474
GS8-6	2	590	4379	0	0	--
GS8-7	1	435	0	0	0	--
GS8-8	4	1780	2279	0	0	--
GS8-9	1	195	895	0	0	--
GS8-10	1	225	0	0	0	--
GS8-11	1	60	0	0	0	--
GS8-12	1	227	12	0	0	--
GS8-13	1	640	5217	0	0	--
GS8-14	3	1148	4756	0	0	--
GS8-15	5	1974	5290	0	0	--
GS8-16	1	435	0	0	0	--
GS8-17	2	940	4392	0	0	--
GS8-18	3	1177	2060	0	0	--
GS8-19	7	2135	3660	0	0	--
GS8-20	2	816	33	0	0	--
GS8-21	2	816	0	0	0	--
GS8-22	2	290	0	0	0	--
GS8-23	4	1556	27	0	0	--
GS8-24	1	435	0	0	0	--
GS8-25	2	370	129	0	0	--
GS8-26	1	435	1	0	0	--
GS8-27	1	100	0	0	0	--
GS8-28	1	195	398	0	0	--
GS8-29	2	784	4902	0	0	--
GS8-30	1	436	6	0	0	--
GS8-31	7	2365	4370	0	0	--
GS8-32	1	625	254	0	0	--
GS8-33	2	816	269	0	0	--
GS8-34	1	150	0	0	0	--
TOTAL	87	35006		1	1080	
AVERAGE[a]		854	1352		26	474
90% LIMIT[a]			± 38.0%			± 620%[b]

[a] Based on site averages.
[b] Assumed equal to compressor turbine drivers at storage fields.

p

$$\text{Engine hp·hr} = \frac{\text{Total hp}}{\text{No. Stations}} \times \text{No. U.S. Stations} \tag{11}$$

$$= \frac{35006 \text{ hp}}{41 \text{ Stations}} \times 1700 \text{ Stations}$$

$$= 1.45 \text{ MMhp}$$

$$\text{Turbine hp} = \frac{1080 \text{ hp}}{41\text{Stations}} \times 1700 \text{ Stations}$$

$$= 0.045 \text{ MMhp}$$

Confidence limits were calculated for the horsepower estimates from the variation of the data. The uncertainty calculated for the compressor station estimate is ± 10%. The resulting uncertainties of the national estimates of generator driver horsepower are ± 23.3% for reciprocating engines and ± 166% for turbines (90% confidence limits).

Table 5-6 also shows the annual operating hours for the generators at compressor stations. The operating hours listed are the average hours for all of the drivers at the station. The wide variation reflects the sites that use generators for continuous electricity generation versus the sites that use generators only for emergency backup. Since there was only one data point for turbine drivers, the uncertainty was assumed to be the same as that for turbine compressor drivers in underground storage at ± 620%. Confidence limits were calculated for the reciprocating engine operating hours estimate from the variation of the data. The resulting uncertainty is ± 38.0% (90% confidence limits).

Data for generators used in storage fields are shown in Table 4-7. The data were provided by one company for 9 storage fields, but only 3 fields had generators. The data shown represent an engine/turbine horsepower split of 60%/40%. Using the average installed horsepower per field, the total number of storage fields in the United States for 1992 was used to extrapolate to a national estimate of 0.085 MMhp for reciprocating engine generator drivers and 0.057 MMhp for turbine generator drivers. The number of storage fields is from A.G.A.'s *Gas Facts* (475 storage fields).[7] Confidence limits were calculated for the horsepower estimates from the variation of the data. The resulting uncertainties of the national estimates of generator horsepower are $\pm$ 126% for reciprocating engines and $\pm$ 184% for turbines (90% confidence limits).

$$\text{Engine hp}\cdot\text{hr} = \frac{\text{Total hp}}{\text{No. Fields}} \times \text{No. U.S. Fields} \tag{12}$$

$$= \frac{1611 \text{ hp}}{9\text{Fields}} \times 475 \text{ Fields}$$

$$= 0.085 \text{ MMhp}$$

$$\text{Turbine hp} = \frac{1080 \text{ hp}}{9 \text{ Fields}} \times 475\text{Fields}$$

$$= 0.057 \text{ MMhp}$$

Table 5-7 also shows the annual operating hours for the generators at storage fields. The operating hours listed are the average hours for all of the drivers at the field. Since there was only one data point for turbine drivers, the uncertainty was assumed to be the same as that for turbine compressor drivers in underground storage at $\pm$ 620%. Confidence limits were calculated from the variation in the operating hours data. The resulting uncertainty is $\pm$ 377% (90% confidence limits).

TABLE 5-7. GENERATOR DRIVER DATA FROM STORAGE FIELDS

Site	No. Engines	Installed Engine hp	Average Operating Hours	No. Turbines	Installed Turbine hp	Average Operating Hours
GF1	1	1000	77	0	0	--
GF2	0	0	--	0	0	--
GF3	0	0	--	0	0	--
GF4	0	0	--	0	0	--
GF5	0	0	--	0	0	--
GF6	0	0	--	1	1080	36
GF7	0	0	--	0	0	--
GF8	2	611	306	0	0	--
GF9	0	0	--	0	0	--
TOTAL	3	1611		1	1080	
AVERAGE[a]		179	191		120	36
90% LIMIT[a]			$\pm$ 377%			$\pm$ 620%[b]

[a] Based on site averages.
[b] Assumed equal to compressor turbine drivers at storage fields.

Generator drivers in production and processing were not included in this analysis since these sources are negligible. Production generators are rare. Processing generators are more common but rarely operate. The generator data reported by one production and processing company accounted for less than 3% of their total drivers and corresponded to less than 0.01 Bscf methane emissions.

5.4 Industry Activity Factors

The two main types of compressor and generator drivers in the natural gas industry are reciprocating gas engines and gas-fired turbines. Horsepower·hour data were available for the production industry segment activity factor calculation. Two pieces of information were needed to calculate the activity factors (hp·hr) for each type of driver in each of the remaining industry segments. These were the installed horsepower and the average annual operating hours. The final hp·hr activity factors were calculated using the national estimates for compressor horsepower and average operating hours for these industry segments, as described in the preceding sections. Table 5-8 summarizes each of these estimates and shows the resulting activity factors for both engines and turbines by industry segment. The table also includes the 90% confidence limits calculated for each factor. Activity factor confidence limits were propagated from the confidence limits for the individual terms using a standard statistical approach.

TABLE 5-8. COMPRESSOR DRIVER ACTIVITY FACTORS FOR EACH INDUSTRY SEGMENT

Industry Segment	Installed Engine MMhp[a]	Installed Turbine MMhp[a]	Annual Hours Engine	Annual Hours Turbine	Engine MMHp · hr	Turbine MMHp · hr
Production	NA	NA	NA	NA	27,460 ± 200%	0
Processing	4.19 ± 132%[b]	5.19 ± 99.4%[b]	6626 ± 11.5%	6345 ± 48.4%	27,760 ± 133%	32,910 ± 121%
Transmission						
Compressor Drivers	10.2 ± 10.0%	4.55 ± 10.0%	3964 ± 13.8%	2118 ± 31.3%	40,380 ± 17.1%	9635 ± 33.0%
Generator Drivers	1.45 ± 23.3%	0.045 ± 166%	1352 ± 38.0%	474 ± 620%	1962 ± 45.4%	21.2 ± 1215%
Storage						
Compressor Drivers	1.33 ± 13.5%	0.59 ± 13.5%	3707 ± 23.1%	2917 ± 620%	4922 ± 26.9%	1729 ± 626%
Generator Drivers	0.085 ± 126%	0.057 ± 184%	191 ± 377%	36 ± 620%	16.3 ± 621%	2.05 ± 1312%

[a] Does not include horsepower associated with gas lift for oil recovery or with electric drivers.
[b] Average of two estimation methods.

6.0 NATIONAL COMPRESSOR DRIVER EMISSION ESTIMATES

The annual emissions for compressor drivers were determined by multiplying the emission factors (Section 4) by the horsepower-hour activity factors (Section 5) for reciprocating engines and gas-fired turbines and adding these values for each industry segment. Table 6-1 shows the resulting emissions for each industry segment and the overall national emissions estimate for each type of compressor driver. Using the same approach for error propagation, the total annual emissions from compressor drivers and generator drivers for the entire industry are estimated to be 24.8 Bscf ± 64%.

TABLE 6-1. COMPRESSOR DRIVER EMISSIONS FOR THE NATURAL GAS INDUSTRY BY SEGMENT

	Driver	
	Engines, Bscf	**Turbines, Bscf**
Production	6.58 ± 200%	0.00
Processing	6.65 ± 133%	0.186 ± 129%
Transmission	9.68 ± 17.9%	0.0546 ± 45.7%
Storage	1.18 ± 26.9%	0.00979 ± 654%
Generators	0.474 ± 45.6%	0.000132 ± 1163%
TOTAL	24.57 ± 65.1%	0.256 ± 97.8%

Approximately 92% of the emissions from compressor driver exhaust are estimated to be from reciprocating engines used in the production, processing, and transmission segments; another 5% of the emissions are from engines in the storage segment. If generator drivers are included, the percentages for all drivers are 94% and 5%, respectively. All other categories are negligible in comparison; therefore, it is more important to accurately determine the activity factors for reciprocating engines in production, processing, and transmission.

7.0 CONCLUSIONS

As a result of the data generated in this study, the natural gas industry emissions from compressor driver exhaust were estimated to be 24.8 Bscf ± 64%. Nearly 99% of the methane emissions are from reciprocating engines, and approximately 40% of the methane emissions are from engines in the transmission industry segment. The methane emissions from compressor driver exhaust represent about 7.9% of the methane emissions from the entire natural gas industry.[10] Table 7-1 shows how these emissions rank with respect to the other sources identified in each industry segment.

TABLE 7-1. RANKING OF COMPRESSOR DRIVER EXHAUST EMISSIONS BY INDUSTRY SEGMENT

Industry Segment	Compressor Driver Emissions[b] Bscf	Segment Emissions[9] Bscf	Segment Emissions from Compressor Drivers %
Production	6.58	84.4	7.8
Processing	6.84	36.4	18.9
Storage	1.19	18.2	6.5
Transmission	10.2	98.3	10.4
Distribution	0	77.0	0
TOTAL[a]	24.8	314.3	7.9

[a] Compressor driver totals are for reciprocating engines and gas-fired turbines combined.
[b] Includes generator drivers.

Compressor driver exhaust emissions represent a significant source of methane emissions in all of the industry segments where these sources are present. Since almost all of the emissions are due to reciprocating engines, any further work should focus on these types of drivers. The confidence limits on the engine emission factor were ± 5% while the error bound on the activity factor ranged from ± 17.1% to ± 621%. Therefore, improving the engine activity factors would have the greatest impact on the precision of the emissions estimate.

As part of the requirements for Title V operating permits, many facilities will implement recordkeeping practices that may benefit this type of data collection. If companies were to collect horsepower-hour data for each compressor driver, the emission factors developed as part of this project would allow a direct way to determine their methane emissions. Access to these databases would also provide the resource to improve the natural gas industry activity factors for compressor drivers. Using this kind of data would further improve the precision of the overall compressor driver exhaust emissions estimate.

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APPENDIX A

National Estimate of Methane Emissions from Compressors in the U.S. Natural Gas Industry

National Estimate of Methane Emissions from Compressors in the U.S. Natural Gas Industry

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INTRODUCTION

The combustion of natural gas emits much less carbon dioxide per unit of energy generated than other fossil fuels. For this reason, one strategy that has been suggested for reducing global warming is to encourage switching from other fossil fuels to natural gas. However, methane is currently thought to be a more potent greenhouse gas than carbon dioxide; if so, leakage of natural gas (which is approximately 90 percent methane) could reduce or eliminate the advantage of using natural gas because of its lower carbon dioxide emissions.

Two major issues must be addressed before the consequences of the fuel switching strategy can be evaluated. First, there is a need to better define the impact of methane relative to carbon dioxide on global warming. Second, it is important to better define methane emissions from the gas industry. Because of the latter issue, the Gas Research Institute (GRI) and the U.S. Environmental Protection Agency (EPA) have developed a cooperative program to quantify methane emissions from U.S. gas operations. Currently, estimates of methane emissions from the gas industry range from 0.5 to 4.0 percent of production. The GRI/EPA program is a comprehensive program to determine methane emissions from the wellhead to the customer's meter. The goal is to determine emissions to within approximately 3 billion cubic meters (m^3), or 100 billion standard cubic feet (scf), which is approximately 0.5 percent of U.S. production. To achieve this overall accuracy, an accuracy target has been established for each source category in the natural gas industry.

One source category is the exhaust from compressor engines that are used to move the gas through the system. Compressors are located in production fields, processing plants, gas storage facilities, and along transmission lines. A preliminary study indicated that the exhaust from compressor engines might account for more than 50 percent of the industry's methane emissions.[1] Because the uncertainty in this early estimate was quite large, Radian Corporation conducted a study to determine methane emissions from both reciprocating and turbine compressor engines. The accuracy target established by the GRI/EPA program was to determine the emissions for this source category within 30 billion scf.

In this study, methane emissions were estimated by multiplying the methane emission rate of the unit by the activity of the unit. The emission rate expresses the amount of emissions per operating characteristic, independent of the other features of the unit. The activity expresses the operating characteristic of the unit which was, in this case, either a reciprocating engine or gas turbine. For example, when the operating characteristic is fuel usage, the activity is annual fuel used by compressors. When the operating characteristic is operating time, the activity is hours of operation (per year).

The emission rates used in this study were in the form of methane emissions per hour. The activity of each unit was the annual operating hours for that unit. A national estimate of annual methane emissions was determined from emissions estimates using available data for compressors in the natural gas industry.

APPROACHES

The Ideal Emission Estimate

Ideally, the annual methane emissions from compressors in the natural gas industry would be determined from the sum of the annual emissions from each unit in the industry, where the emission rate may vary over time and from unit to unit. This relationship is expressed by the following equation:

$$\text{Emissions} = \sum_{i=1}^{N} \int [ER_i\ (t) \times A_i\ (t)]\ dt \tag{1}$$

where $ER_i(t)$ is the instantaneous emission rate at time (t) for compressor$_i$, $A_i(t)$ is the instantaneous activity at time (t) for compressor$_i$, and N is the total number of compressor units in the industry. To reflect annual emissions, the integral in Equation (1) is evaluated over the time interval t_1 to t_2, where $t_2 - t_1$ is equal to one year. This approach produces no uncertainty in annual emissions.

Emission Estimate Using Test Data

The ideal approach was considered impractical because it would require a massive data-gathering effort by the industry. Fortunately, a substantial amount of data was available for both the emission rates and activity factors of compressor engines. For the emission rates, data for reciprocating engines and gas turbines were available for a number of models that were tested during relatively short time periods. Values for the annual activity of compressors, in terms of operating hours, were also available for some models. If data for all compressors in the industry were available, the following equation could be used to estimate methane emissions:

$$\text{Emissions} = \sum_{i=1}^{N} [ER_i\,|_{\Delta t=test} \times A_i(t)\,|_{\Delta t=1year}] \tag{2}$$

where ER_i is the emission rate of $compressor_i$ (in grams of methane per hour) evaluated over the time period of the test; where the activity, A_i, of $compressor_i$ corresponds to the annual operating hours of $compressor_i$; and where N is the total number of compressor units in the industry. This equation assumes that the emission rate of the compressors during the test period represents the emission rate of the compressors during the year, on the average.

Methane emissions from compressors will vary from manufacturer to manufacturer and model to model. Assuming that the compressors are properly maintained, differences in methane emissions, even for the same model, also will be caused by operating the compressors at different horsepower levels or speeds, or for longer or shorter periods of time in order to satisfy the operational needs of the system.

Figure 1 illustrates the relationship between operating load and emissions for a Cooper Bessemer two-cycle engine.[2] The figure shows the total hydrocarbon emission rate at varying loads, where speed is used to lower horsepower. Total hydrocarbon emissions can be considered a surrogate for methane emissions, since methane is expected to comprise a large portion (over 90 percent) of total hydrocarbon emissions from compressors. The data show that the emission rate for a Cooper Bessemer engine increased at lower loads, with a 40 percent increase in emissions at 50 percent of rated horsepower (full load), and a possible 100 percent increase if loads close to 30 percent of full load are used. A similar increase in methane emissions can be expected for other engine and turbine models, although the magnitude of the increase for other models is not known at this time.

The emission rate of any compressor, then, is a function of the rated horsepower and operating horsepower. The equation below summarizes this relationship:

$$ER_i = f\,(ER_i^{\circ},\ Hp_i^{\circ},\ Hp_i) \tag{3}$$

where ER_i is the operating emission rate of $compressor_i$; ER_i° is the emission rate of $compressor_i$ at the rated horsepower, Hp_i°; and Hp_i is the operating horsepower. The data from the Cooper Bessemer illustrate that a linear relationship can be used to represent emissions for this engine as a function of horsepower, within 3 percent accuracy, over the range of horsepower from 50 to 100 percent of rated horsepower. In this situation, the average horsepower at which the engine operates over the year (as in Equation (2)) could be used to evaluate the integral in Equation (1) without any loss of accuracy.

If the information needed to develop Equation (3) was known for all engines and the relationship between horsepower and emissions for each engine was linear, the following equation could be used to more accurately estimate annual methane emissions from compressor engines from test data:

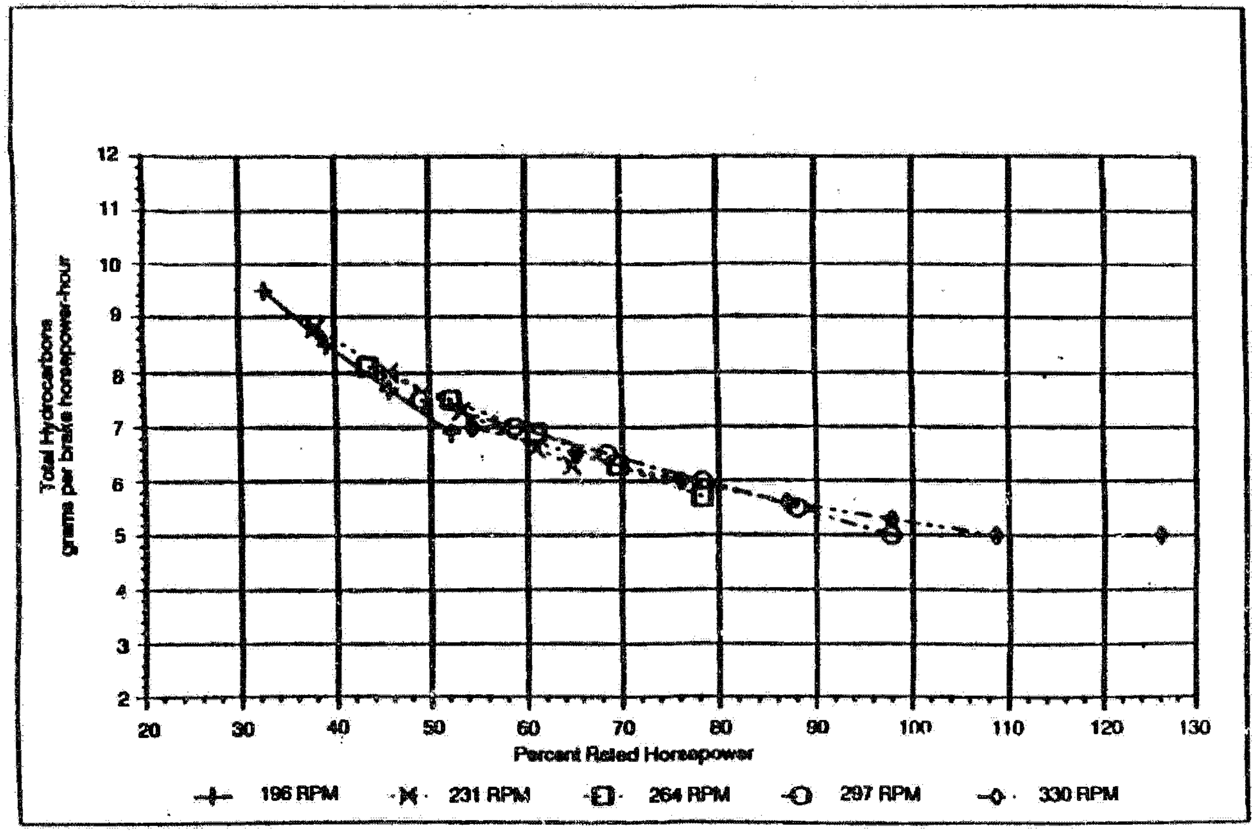

Figure 1. Effect of horsepower and speed on total hydrocarbon emissions for a Cooper Bessemer 2 cycle engine[2]

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$$\underset{\text{(grams)}}{\text{Annual Emissions}} = \sum_{i=1}^{N} \left[\text{ER (Hp)}_i \times \text{Annual Hours (Hp)}_i \right] \tag{4}$$

where ER $(Hp)_i$ is the emission rate of $compressor_i$ as a function of horsepower (in grams of methane per hour); Annual Hours $(Hp)_i$ are the annual operating hours of $compressor_i$ at a specified horsepower; and N is the total number of compressor units in the industry.

Scaled-up Emission Estimate Using Test Data

Although emission and activity data for all compressors in the industry were not known, an estimate of methane emissions for the industry was made by proportioning the emissions for a subset of the industry (with known emission and activity data) according to the proportion of horsepower contributed by this subset. This approach assumes that the emission rates for the test engines during the test period and the operating hours estimated for the subset represent the average operation of compressors in the industry. A more detailed description of this approach is found in the Method section of this paper.

It was found that for the emission test data, on the average, the compressor emission rates were measured at virtually the same horsepower as the operating horsepower that was recorded for the compressors with the activity data (where the average horsepower of the compressors for the test data was equal to 0.985 times the average of the horsepower for the activity data). Therefore, knowledge of the relationship between horsepower and emissions was not needed for the analysis presented here.

An estimate of methane emissions using test data for a subset of the industry may underestimate actual industry emissions if many compressors are operated at lower loads for a significant period of time, since methane emissions are likely to increase when compressors are operated at less than full load. Future work in this area should include an analysis of the relationship between horsepower and methane emissions, so that individual compressor emission rates can be estimated with more accuracy.

DATABASES

Description of the Databases

A number of databases were obtained for this study, that provided information on compressor emissions and operations. The databases were part of GRI's TRANSDAT compressor module.[3] Two databases in the compressor module contain information about the distribution of compressors in the natural gas industry. One of the databases is an almost complete listing of engines and turbines in the gas industry, accounting for 16.2 million out of the 16.7 million total horsepower that was reported by the American Gas Association (AGA) for this industry in 1989.[4] This "Industry Database" contains information concerning 8,282 compressors in the natural gas industry. However, individual compressor horsepower is not reported in the database; only the total horsepower for all compressors of a specific type is reported for each gas company.

A second smaller database in the compressor module (the "Operating Database") is a subset of the Industry Database (with 1,515 units) corresponding to 3.2 million total horsepower. The Operating Database is the only database in TRANSDAT that contains information on annual operating hours for each unit. The operating horsepower of each compressor is also recorded in the database. The data in the Operating Database were obtained from an AGA survey of 112 companies in ozone nonattainment areas, where NO_x emissions were minimized. Because emissions of NO_x and hydrocarbons are inversely related, the operation of compressors to minimize NO_x will likely increase emissions of hydrocarbons and, hence, of methane. Consequently, the data in the Operating Database, such as the operating horsepower, may represent maximum methane emission conditions. The use of these data, then, presents a conservative estimate of industry emissions, if the data is representative of the industry as a whole.

Data from emissions tests performed by Southwest Research Institute are contained in a third database in TRANSDAT (the "Test Database"). During the emission tests, the compressors were operated at close to full load (rated horsepower). Methane emissions, fuel use, fuel use rate, and horsepower were recorded for each emissions test for 241 models of engines and turbines. Since there was some variation in horsepower in the multiple emissions tests for the same compressor, it may be possible to define the relationship between horsepower and methane emission rate for the 241 models of compressors in this database. With this information, it would be possible to extrapolate from the test conditions to actual operating conditions at lower horsepower levels. Because of the limitations of this study, an analysis of this type was not performed.

Because the Test Database contains only emission data and the other databases contain only operating data, a fourth database was developed that contains data for compressors for which information was found in both the Operating Database and Test Database. This fourth database was called the "Emissions Database." A total of 775 reciprocating engines and 86 gas turbines (out of 1,515 units in the Operating Database) fit the criteria and were included.

Table 1 describes the contents of each of the four databases.

Model-Matching Hierarchy

A model-matching schema was designed to maximize the amount of correlation between the Test Database data and the Industry and Operations Databases. Originally, when the compressors were matched according to exact model names, the Test Database accounted for only 38 percent of the units

TABLE 1. DESCRIPTION OF THE DATABASES

Data	Industry Database			Operating Database			Test Database			Emissions Database		
	Engines	Turbines	Total	Engines	Turbines	Total	Engines	Turbines	Total	Engines	Turbines	Total
Total Units	7,489	793	8,282	1,385	130	1,515	229	12	241	775	86	861
Manuf/Model[a]	922	144	1,066	318	31	34[illegible]	229	12	241	120	7	127
Total Hp (10^6)	11.2	5.0	16.2	2.4	0.8	3.2	NA	NA	NA	1.3	0.4	1.7
Total Hours (10^6)	NA[b]	NA	NA	4.6	0.3	4.9	NA	NA	NA	2.9	0.2	3.1

[a]Number of unique compressor models in the database.

[b]Not applicable.

in the Operating Database and only 7 percent of the Industry Database. Through consultations with experts in the field of compressor emissions, a three-step hierarchy was designed to match more data in the Industry and Operating Databases to the Test Database.

The first step, therefore, in the hierarchy was based on an exact match. For instance, an Ajax DPC-360 engine in the Industry or Operating Database was identified with Test Database data for an Ajax DPC-360 in Step (1) of the hierarchy.

The second step in the matching procedure matched compressors by substring name, where the horsepower of both compressors was within ± 20 percent. An example of Step (2) in the hierarchy was a match of a Clark BA8T engine with a Clark HBA8T engine (common substring of BA8T), where the horsepower for the Clark HBA8T engine in the Emissions Database was 1,911, and was 2,050 for the Clark BA8T engine in the Industry Database. The third step in the hierarchy consisted of matching the rated horsepower per cylinder (± 20 percent) in compressors with similar initial names (manufacturer) but with varying substrings. An example of Step (3) is a match of a Clark BA5 engine, with 248 horsepower per cylinder (total horsepower = 1,242) and a Clark BA8 engine, with 211 horsepower per cylinder (total horsepower = 1,000).

Following the execution of the three steps in the model-matching hierarchy, 37 percent of the models and 57 percent of the units in the Operating Database (and 23 and 55 percent, respectively, in the Industry Database) were matched to emissions data. The execution of the three-step hierarchy also increased the amount of data in the Emissions Database to a total of 1.7 million horsepower, from the previous total of 1.3 million horsepower after Step (1) only, and accounting for over one-half of the horsepower in the Operating Database and Industry Database.

METHOD TO ESTIMATE METHANE EMISSIONS

The Emissions Database was used to estimate methane emissions from compressors in the natural gas industry. The method used to calculate emissions is described below.

Equations

An average emission rate was obtained for each model of compressor engine and turbine in the Emissions Database from the average of all methane emission tests in the Test Database for that model. Since the time period in which each test was conducted was not given, the emission rates, in units of grams of methane per hour, were calculated from the reported methane emissions per unit of fuel (in grams per m^3) and the reported fuel use rate (in m^3 per hour) for each compressor, as in the equation below:

$$\underset{(g/hr)}{\text{Emission Rate}_i} = \underset{(g/m^3)}{\text{Average Emission Rate}_i} \times \underset{(m^3/hr)}{\text{FUR}_i} \tag{5}$$

where FUR_i was the average fuel use rate for compressor_i.

The methane emissions for each compressor were then calculated as in Equation (6) below:

$$\underset{(grams)}{\text{Emissions}_i} = ER_i \times \text{Annual Operating Hours}_i \tag{6}$$

where ER_i was the methane emission rate of compressor_i calculated with Equation (5), and Annual Operating Hours_i were obtained from the data for compressor_i in the Emissions Database.

To determine the total methane emissions for the compressors in the Emissions Database, the following equation was used:

$$\underset{(grams)}{\text{Annual Emissions}} = \sum_{i=1}^{N} [ER_i \times \text{Annual Operating Hours}_i] \tag{7}$$

where the emissions from each unit are calculated as in Equation (6), and N was the total number of compressors in the database.

Estimate of National Emissions

If data for all compressors in the industry were available, a national estimate could be calculated using Equation (7). Since the compressors in the Emissions Database were only a subset of the compressors in the natural gas industry, a procedure was necessary to relate the methane emissions calculated with Equation (7) to a national estimate.

The ratio of the total horsepower from compressors in the industry (16.7 million horsepower) to the total horsepower of the compressors in the Emissions Database (1.7 million horsepower) was used to scale up the methane emissions calculated in Equation (7) by a factor of (16.7/1.7), or 9.8, to estimate national emissions. This relationship is shown in the equation below:

$$\begin{array}{c}\text{National Methane}\\ \text{Emissions}\end{array} = \begin{array}{c}\text{Methane Emissions for}\\ \text{Emissions Database}\end{array} \times \overset{\text{Scaling Factor}}{\frac{Hp_I}{Hp_{ED}}} \tag{8}$$

where Hp_I is the total horsepower in the industry[4] and Hp_{ED} is the total horsepower in the Emissions Database, which produce a scaling factor of 9.8.

RESULTS

National Emission Estimate

An estimate of national methane emissions from compressors using the approach discussed above was 0.22 teragrams (Tg) of methane. Over 99 percent of the emissions were estimated to be from reciprocating engines and less than 1 percent from gas turbines. This estimate was based on the assumption that the compressors in the Emission Database represent compressors used in the natural gas industry, on the average. If the industry compressors are operated at horsepower levels much less than the rated horsepower, the methane emissions estimated here could underestimate the industry emissions, since methane emissions are thought to vary inversely with horsepower.

Field, Plant, and Pipeline Compressor Emissions

Compressors are used in field and plant operations as well as in transmission activities. The emission estimate above does not apportion methane emissions among the segments of the natural gas industry that use compressors. The U.S. Department of Energy (DOE) provides estimates of the amount of fuel used in field (lease), plant, and pipeline applications, and these estimates were used to apportion methane emission estimates among the sources.[5] The methane emission estimates were based on the assumption that all the fuel reported for field and plant purposes was used by compressors. This assumption is likely to be an overestimate, because fuel is known to be used for field and plant purposes by equipment other than compressors. Although the portion of lease and plant fuel used for other purposes was not known, estimates of the fuel used by these sources served as rough estimates of fuel used by compressors in field, plant, and pipeline operations.

The result of using DOE estimates of fuel use was that 39 percent of total compressor fuel was attributed to field compressors, 26 percent to plant compressors, and 35 percent to pipeline. It is likely, however, that a higher percentage of total compressor fuel is used for pipeline, and that lower portions are used for field and plant. The AGA estimated that 84 percent of total compressor horsepower was used for the pipeline[4]; if fuel use can be assumed to be proportional to horsepower, the percent of fuel used by pipeline compressors could be over twice as high as the estimate based on the DOE information.

Since methane emissions were assumed to be proportional to fuel use, the DOE breakdown in fuel among the three sources of compressor emissions in the natural gas industry was used to apportion the national estimate of 0.22 Tg of methane emissions between the three sources. The results were that, of the total 220 megagrams (Mg) of annual methane emissions estimated for compressors in the industry, 86 Mg of methane was estimated to be emitted from field compressors, 57 Mg from plant compressors, and 77 Mg from pipeline compressors. As discussed above for apportioning fuel use between these three sources, the emissions from pipeline compressors were probably underestimated, and the portions for the other two sources were overestimated. Another

5 The generator driver horsepower (compressor stations) is based on the total installed

possible error in the breakdown of emissions was the assumption that the emission rate and operating characteristics of compressors in field, plant, and pipeline applications were similar.

UNCERTAINTY IN EMISSION ESTIMATES

Since the true value of methane emissions from compressors in the natural gas industry is not known, the accuracy of the estimate of 0.22 Tg of methane emissions cannot be assessed. However, the data can be used to produce an approximation of the uncertainty in the emission estimate. Like confidence intervals, the uncertainty estimated for a value can describe, with a high degree of confidence, the range in which the true value lies.

The target uncertainty for the total estimate of methane emissions from all sources in the natural gas industry was close to 3 billion m^3 (100 billion scf). Because there are many segments in the natural gas industry that emit methane that are part of the overall methane emission estimate in the GRI/EPA project, the goal for each segment was to produce a methane estimate with as little uncertainty as possible. The target uncertainty for compressors was approximately 800 million m^3 (30 billion scf).

The following explains the procedure used to estimate the uncertainty in the annual methane emission estimate from compressors and the results of this estimate.

Basis of Uncertainty in the Compressor Emission Estimate

The only sources of uncertainty in the approach described above that could be estimated were the analytical error associated with the test data used to calculate the methane emission rates and the scale-up to national emissions based on the ratio of the horsepower in the Emissions Database to the estimate of compressor horsepower in the industry.

The uncertainty in the hydrocarbon analysis was estimated to be ± 10 percent, based on the expected gas chromatograph (with a flame ionization detector) capabilities. Likewise, the uncer.ainty associated with fuel flow measurements was estimated to be ± 2.5 percent. The uncertainty associated with the scale-up between the Emissions Database and total industry horsepower was more difficult to quantify. Two indirect assessments of this uncertainty are discussed below, using comparisons between the Emissions Database and the Industry Database, which was taken to be a fairly good representation of the industry as a whole. The uncertainty for the scale-up to nationwide emissions was estimated to be approximately 1 percent, based on estimated significant figures in total horsepower. For an estimated industry horsepower of 16.7 million, the uncertainty was estimated to be 0.17 million horsepower; for the Emissions Database, with 1.7 million horsepower, the uncertainty was estimated to be 0.017 million horsepower.

3. U.S. Department of Energy/Energy Information Administration. *Natural Gas Annual*, 1992.

Procedure to Calculate Uncertainty

The software "@Risk"[6] was used to estimate the uncertainty in the estimate of methane emissions from compressors. The variables of uncertainty were entered into the program along with the values discussed above. The "@Risk" uncertainty estimating procedure recalculated the total methane emission estimate using Latin Hypercube sampling from normally distributed intervals along the range of each variable, defined by the expected value and the (estimated) standard deviation of that value. In the case where the standard deviation was estimated from significant figures, a uniform interval (as opposed to a normally distributed interval) was used for the Latin Hypercube sampling.

In the "@Risk" program, the recalculation was performed 500 times, each time using a different value in the interval of each variable in the emission equations. The results of the 500 calculations, excluding values below zero, were analyzed for variation about the mean. The uncertainty was reported as the coefficient of variation, or the standard deviation divided by the mean, as a percent.

Estimates of Uncertainty

The uncertainty for the estimate of methane emissions from compressor engines and turbines, at 0.22 Tg (11.5 billion scf), was estimated to be approximately 1 percent, or 4.3 million m^3 (0.15 billion scf). This value is well below the 800 million m^3 target for compressor engines and turbines.

Comparison of the Database

One component of uncertainty in the methane emission estimate that could not be quantified for the uncertainty analysis was the degree to which the compressors in the Emissions Database represented the compressors in the industry. The Emissions Database was compared with the Industry Database in two procedures that were designed to assess the representativeness of the Emissions Database for compressors in the industry and, indirectly, the uncertainty associated with the scaling factor.

Figures 2 and 3 are plots for engines and turbines, respectively, showing the total horsepower for each model in the Industry Database versus the total horsepower of that model in the Emissions Database. The line formed from the relationship between the total horsepower for each database was plotted on each graph. For engines, a line through 11.2 million and 1.3 million, the total horsepower for engines in the Industry and Emissions Databases, respectively, constituted the ideal relationship between the total horsepower for each type of engine in the two databases. Similarly, for turbines, a line through 5 million and 0.4 million produced the ideal relationship for the total horsepower for each type of turbine in the two databases. The figures show that the horsepower contribution of the compressors in the Emissions Database was higher than the horsepower

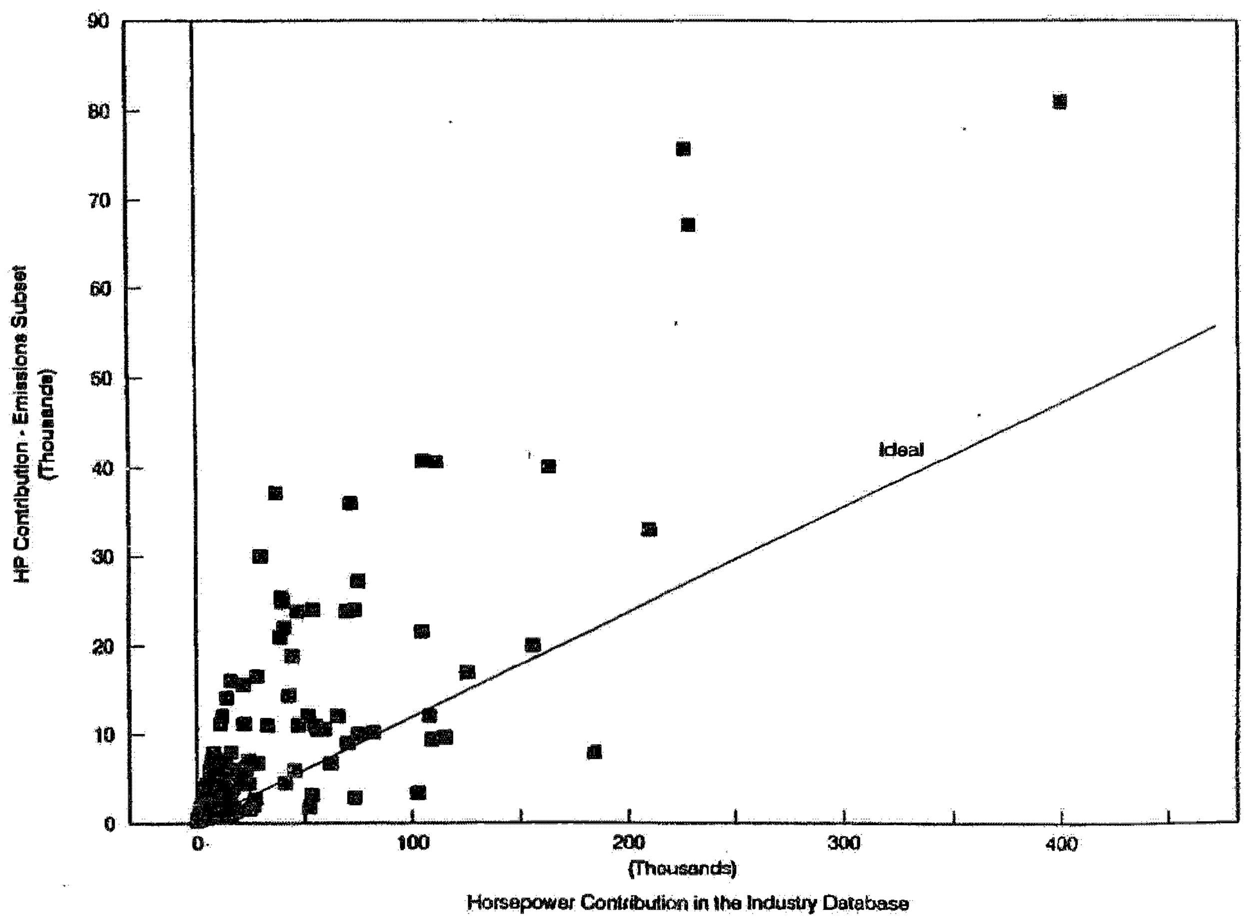

Figure 2. Relative horsepower contribution of each engine model in the Emissions and Industry Databases

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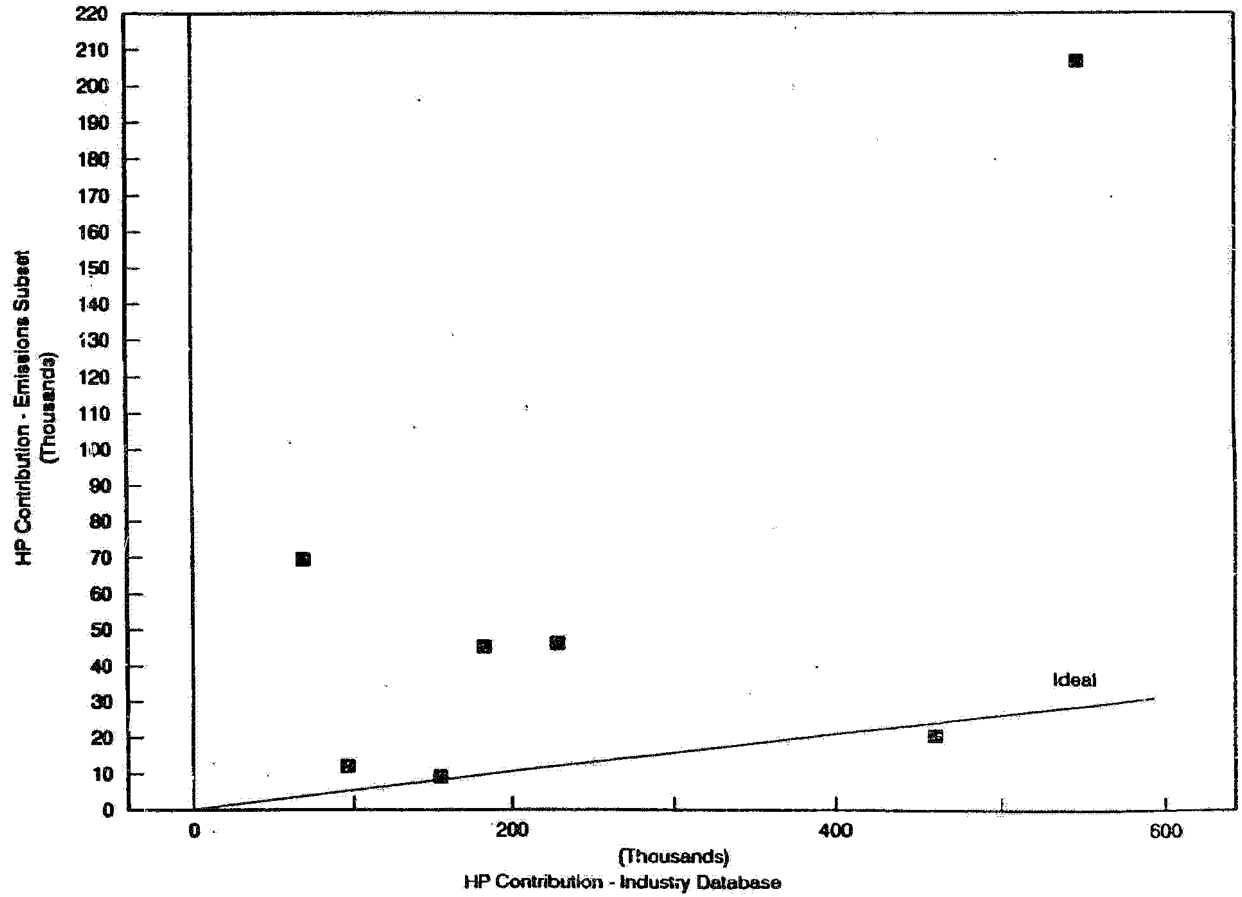

Figure 3. Relative horsepower contribution of each turbine model in the Emissions and Industry Databases

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contribution in the Industry Database. However, the trend in general is in a positive direction for both databases, showing that compressors that contribute a large amount of horsepower to the total in one database also contribute significantly to the other. Conversely, compressors that are small contributors in one database are of similar ranking in the other. This comparison presents a qualitative assessment of the representativeness of the Emissions Database for the industry's compressors.

A more quantitative assessment of how well the Emissions Database represents industry compressors was performed using a comparison between the emission factors derived from the Emissions Database and the Industry Database, with the Industry Database used as a close approximation of compressors in the natural gas industry. To determine the emission factors for the Emissions Database, an overall average emission factor was calculated for engines and turbines, separately, after Step 1 in the hierarchy, where only the data that were exact matches with the compressors in the Test Database were included. Overall average emission factors were calculated for engines and turbines, weighting the model-specific emission factors for each engine and turbine, respectively, by the horsepower contribution of that model in the Emissions Database.

To determine the emission factors for the Industry Database, model-specific emission factors were developed after Step III in the hierarchy, and overall average emission factors were calculated for engines and turbines, weighted by the horsepower contribution of the engine and turbine models, respectively, in the Industry Database. The results were that the overall average emission factors calculated for the Emissions Database were 18 grams of methane emitted per m^3 of fuel for engines, and 0.16 grams of methane emitted per m^3 of fuel for turbines. The overall average emission factors calculated for the Industry Database were 20 grams of methane emitted per m^3 of fuel for engines, and 0.17 grams of methane emitted per m^3 of fuel for turbines. This analysis showed quantitatively that the Emissions Database was a fairly good representation of the Industry Database and, therefore, the industry.

CONCLUSIONS AND RECOMMENDATIONS

The annual methane emissions estimate of 0.22 Tg for compressors in the natural gas industry was less than the previous estimate of 2.2 Tg by a power of 10. Although compressors are still a significant source of methane emissions, this estimate reduces the importance of compressors in the assessment of the natural gas industry's contribution to global warming.

The uncertainty for the estimate, at 4.3 million m^3 of methane (0.15 billion scf), was much less than the portion of total industry methane emissions contributed by compressors, and was 0.15 percent of the target uncertainty (100 billion scf) for the industry.

Future work in this area should include an assessment of the effect of compressor operation, in terms of horsepower, on the methane emission rate.

On the basis of the data on this subject, the annual methane emissions could be higher than the current estimate by a factor of 2, if compressor operation is at horsepower levels significantly lower than compressors' rated horsepower.

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APPENDIX B

Source Sheet P-1

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P-1
ALL-SEGMENT SOURCE SHEET

SOURCES:	Compressors, Generators
OPERATING MODE:	Normal Operation
EMISSION TYPE:	Unsteady, Combusted (Compressor Driver Exhaust)
ANNUAL EMISSIONS:	24.4 Bscf ± 64%

BACKGROUND:
Compressors are used to move gas through the system. They are located in production fields, processing plants, gas storage fields, and along transmission lines. Methane emissions are found in compressor driver exhaust (reciprocating engines and gas turbines) because of the incomplete combustion of the natural gas burned as fuel.

EMISSION FACTOR: (0.240 ± 5% scf/hp·hr, engines and 0.0057 ± 30% scf/hp·hr, turbines)
An average emission rate was calculated for each model of compressor engine and turbine in the GRI TRANSDAT Emissions Database (1), which is based on compressor tests conducted by Southwest Research Institute (SwRI). The emission rates were calculated from the reported methane emissions per unit of fuel and the reported fuel use rate (FUR) for each compressor model, as follows:

$$\overline{ER}_{(m)} = \overline{EP}_{(m)} \times \overline{FUR}_{(m)} \qquad (1)$$

where: $\overline{ER}_{(m)}$ = average emission rate for model, m (scf/hr)

$\overline{EP}_{(m)}$ = average emission parameter for model, m (scf CH_4/scf fuel)

$\overline{FUR}_{(m)}$ = average fuel use rate for model, m (scf fuel/hr)

The following equation was used to determine the total emissions for the 86 turbines and 775 reciprocating engines in the Emissions Database.

$$TE = \sum_{m=1}^{K} \left[\sum_{i=1}^{M} \left(\overline{ER}_{(m)} \times HR_i \right) \right]_m \qquad (2)$$

where: TE = total emissions for database, (scf)

HR_i = annual operating hours for compressor i, (hr/yr)

K = number of unique compressor models

M = number of compressors of model, m

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The emission factors, for engines and turbines, were then calculated using the following equation.

$$\text{Emission Factor} = TE \Big/ \left[\sum_{i=1}^{N} \overline{HP}_i \times \left(\sum_{i=1}^{N} \overline{HR}_i / N \right) \right] \qquad (3)$$

where: $\overline{HP}$ = average operating horsepower during HR, (hp)

HR = annual operating hours, (hr/yr)

N = number of compressors

This equation considers that some models could be operated at a higher percentage of the time because they are base loaded compressors. The average emission factors for the compressor drivers in the Emissions Database are 0.240 scf/hp·hr for reciprocating engines and 0.0057 scf/hp·hr for turbines.

EF DATA SOURCES:

1. "National Estimate of Methane Emissions from Compressors in the U.S. Natural Gas Industry" (2).

EF ACCURACY: ± 5%, engines and ± 30%, turbines

Basis:
The accuracy for the EF is estimated based on propagation of error from the spread of samples in the database. However, engineering judgement was used to assign accuracy for two of the individual terms in the equation, as follows:

1. Hydrocarbon analysis was estimated to be ± 10%, based on the generally accepted accuracy of gas chromatographs (flame ionization detector).

2. Likewise, fuel flow measurements were estimated to be ± 2.5%.

ACTIVITY FACTORS: (horsepower·hour)

Horsepower·hour data were available for the production industry segment activity factor calculation. Two pieces of information are needed to calculate the activity factor, which is expressed as horsepower·hours (hp·hr) for each type of driver in each of the remaining industry segments. These are the installed horsepower and the average operating hours. The following table presents these parameters and the resulting activity factors for both engines and turbines in each segment of the industry. The sources and methods for calculating all the values presented in the table below are given in the next section: AF Data Sources.

It is estimated that about 94% of the emissions in compressor and generator driver exhaust are from reciprocating engines used in production, processing, and transmission, with about 5% attributable to reciprocating engines used in storage. All other categories are negligible in comparison. Therefore, it is more important to accurately determine the activity factors for reciprocating engines in production, processing, and transmission.

COMPRESSOR DRIVER ACTIVITY FACTORS FOR EACH INDUSTRY SEGMENT

Industry Segment	Installed Engine MMhp[a]	Installed Turbine MMhp[a]	Annual Hours Engine	Annual Hours Turbine	Engine MMHp · hr	Turbine MMHp·hr
Production	NA	NA	NA	NA	27,460 ± 200%	0
Processing	4.19 ± 132%[b]	5.19 ± 99.4%[b]	6626 ± 11.5%	6345 ± 48.4%	27,760 ± 133%	32,910 ± 121%
Transmission						
Compressor Drivers	10.2 ± 10.0%	4.55 ± 10.0%	3964 ± 13.8%	2118 ± 31.3%	40,380 ± 17.1%	9635 ± 33.0%
Generator Drivers	1.45 ± 23.3%	0.045 ± 166%	1352 ± 38.0%	474 ± 620%	1962 ± 45.4%	21.2 ± 1215%
Storage						
Compressor Drivers	1.33 ± 13.5%	0.59 ± 13.5%	3707 ± 23.1%	2917 ± 620%	4922 ± 26.9%	1729 ± 626%
Generator Drivers	0.085 ± 126%	0.057 ± 184%	191 ± 377%	36 ± 620%	16.3 ± 621%	2.05 ± 1312%

[a] Does not include horsepower associated with gas lift for oil recovery or with electric drivers.
[b] Average of two estimation methods.

AF DATA SOURCES:

1. The production segment horsepower is based on the total installed horsepower·hours for data provided by one company for 516 compressor drivers (all reciprocating engines). The horsepower·hours for the company was divided by their production before scaling to a national estimate. National horsepower·hour was calculated using the 1992 marketed production for the U.S. [*Natural Gas Annual 1992*, (3)].

2. The processing segment horsepower was determined by taking the average of two methods. Each of the methods uses site data for the 10 gas plants visited. The first method scales to a national estimate by multiplying the total U.S. gas plant throughput as of January 1, 1993 [46,510.7 MMcfd, *Oil & Gas Journal* (4)] by the total site visit horsepower per throughput (47.8 hp/MMcfd, engines and 59.2 hp/MMcfd, turbines). The second method scales to a national estimate by multiplying the total number of gas plants in the U.S. [726, *Oil & Gas Journal* (4)] by the total site visit horsepower per number of gas plants visited (10), which is a scale-up ratio of about 73. The annual operating hours are based on the 10 sites plus data from two companies for an additional 18 gas plants. An average of the average operating hours per site was calculated to get the processing segment operating hours (203 engines and 9 turbines).

3. The transmission segment compressor station horsepower for each compressor driver type is based on the GRI TRANSDAT database. Installed horsepower was taken from the Industry Database module of GRI TRANSDAT. The annual operating hours are based on information reported on FERC Form No. 2. FERC data does not distinguish between driver type. The FERC data were split between engines and turbines based on data in GRI TRANSDAT and data provided by one transmission company (524 engines and 89 turbines).

4. The storage segment horsepower came from *Gas Facts* (5) data for 1992 (1,920,441 hp). The split between engines and turbines was assumed to be the same as the engine and turbine splits found in GRI TRANSDAT (69.1%, engines and 30.9%, turbines). The annual operating hours are based on 11 storage stations (50 engines and 6 turbines). An average of the average operating hours per station was calculated to get the storage segment operating hours.

5. The generator driver horsepower (compressor stations) is based on the total installed horsepower for 7 of the transmission sites visited and company data for 34 transmission compressor stations. To scale to a national estimate, the total horsepower per station was multiplied by the total number of transmission compressor stations [1700, FERC Form No. 2 (6)] in the U.S. The annual operating hours are also based on data from the site visits and company data. An average of the average generator operating hours per station was calculated to get generator operating hours (87 engines and 1 turbine).

6. The generator driver horsepower (storage fields) is based on the total installed horsepower for 9 storage fields (one company). To scale to a national estimate, the total horsepower per field was multiplied by the total number of storage fields [475, *Gas Facts* (5)] in the United States. The annual operating hours are also based on the company data. An average of the average generator operating hours per field was calculated to get generator operating hours (3 engines and 1 turbine).

AF ACCURACY:

Basis:
Errors were propagated from each of the following terms:

1. Production Hp·hr: The production Hp·hr accuracy is based upon an engineering analysis and set at ± 200%.
2. Transmission Hp·hr: The transmission Hp·hr accuracy is based upon an assigned estimated error of ± 10% for the horsepower data in the GRI TRANSDAT database and error propagation from the FERC operating hours.
3. Other segment Hp·hr: The accuracy of the site visit data for horsepower and operating hours was also propagated using the spread of the data, but from much smaller data sets. The accuracy of the horsepower·hour activity factors for each industry segment are calculated statistically using the individual terms for horsepower and operating hours.

ANNUAL EMISSIONS: (24.57 ± 65.1% Bscf, engines + 0.256 ± 97.8% Bscf, turbines)
The annual emissions were determined by multiplying an emission factor by the horsepower·hour activity factor for reciprocating engines and turbines and summing these values for each segment. The following table shows the resulting emissions for each industry segment and the overall national estimate.

ANNUAL COMPRESSOR EMISSIONS FOR THE NATURAL GAS INDUSTRY BY SEGMENT

Compressor	Production	Processing	Transmission	Storage	Generators	TOTAL
Engines, Bscf	6.58±200%	6.65±133%	9.68±17.9%	1.18±26.9%	0.474±45.6%	24.57±65.1%
Turbines, Bscf	0.00	0.186±129%	0.0546±45.7%	0.00979±654%	0.000132±1163%	0.256±97.8%

REFERENCES

1. Biederman, N. GRI TRANSDAT Database: Compressor Module. (prepared for Gas Research Institute). npb Associates with Tom Joyce and Associates, Chicago, IL, August 1991.

2. Jones, D.L., L.M. Campbell, C.E. Burklin, M. Gundappa, and R.A. Lott, "National Estimate of Methane Emissions from Compressors in the U.S. Natural Gas Industry." Radian Corporation and Gas Research Institute, Air & Waste Management Association Conference Proceedings, Paper # 92-142.02, Kansas City, MO, 1992.

3. U.S. Department of Energy/Energy Information Administration. *Natural Gas Annual*, 1992. DOE/EIA-0131 (92), Washington, DC, September 1992.

4. *Oil & Gas Journal*. 1992 Worldwide Gas Processing Survey Database, 1993.

5. *Gas Facts*: 1992 Data, American Gas Association, Arlington, VA, 1993.

5. Federal Energy Regulatory Commission (FERC) Form No. 2: Annual Report of Major Natural Gas Companies, 1992 database.

APPENDIX C

Production Segment Site Visit Results

Table C-1 shows the production segment data collected for each of the 28 sites visited and the data provided by one company for 25 gathering stations. The data have been grouped into four geographic areas so that a regional extrapolation can be conducted for this industry segment. The following four regions were selected based on differences in production rates and equipment populations: Pacific Mountain, Gulf Coast, Central Plains, and Atlantic & Great Lakes. Differences in onshore versus offshore production were not considered because of the lack of available site data. (This approach is described further in the *Methane Emissions from the Natural Gas Industry, Volume 5: Activity Factors*).[1]

No turbines were installed at any of the production facilities surveyed; therefore, the data shown in Table C-1 represent an engine/turbine horsepower split of 100%/0% for this segment. Excluding compressors used for gas lift and electrically driven compressors, the average horsepower per MMcfd was calculated for each region. The United States marketed natural gas production, by region, for 1992 was used to extrapolate from the regional ratios (hp/MMcfd) to a national estimate of compressor engine driver horsepower in the production segment of 3.61 MMhp (0 MMhp for turbine drivers).[2] The following equation describes the national extrapolation using the regional approach.

$$\text{Engine hp} = \sum_{\text{region 1}}^{\text{region 4}} \left(\text{Avg } \frac{\text{hp}}{\text{MMcfd}}\right)_{\text{region x}} \times \text{MMcfd}_{\text{region x}}$$

This estimate for the production segment is based on the total installed horsepower from the sites surveyed. Table C-2 shows the regional data used to extrapolate to the national horsepower estimate. The table also shows the 90% confidence intervals for each of the values used in the calculation. Confidence limits were calculated using the ratio method for each region's average hp/MMcfd and the total horsepower from the variation of the site data. The resulting uncertainty is $\pm$ 63.2%.

Table C-3 shows the "operating hours" for the compressors at the sites surveyed. For the production segment, annual operating hours were not available for most of the sites visited; therefore, the compressors that were running during the site visit were assigned annual operating hours of 8760. Compressors that were idle were assigned annual operating hours of 0. This approach was used for 9 of the sites visited. Actual operating hours were available for two of the 2 sites visited and for the 25 gathering stations surveyed (one company). Operating hours for the remaining sites were not included in this analysis since compressors were either used for gas lift, had electric drivers, or were not found at the site. The operating hours listed for these sites are the average hours for all of the drivers at the site. This table also reflects the fact that no turbines were surveyed in the production industry segment. Confidence limits were calculated for the operating hours estimate from the variation of the data. The resulting uncertainty is $\pm$ 9.7% (90% confidence limits).

Activity factors based on the site data presented here are 23,820 MMhp·hr for engines and 0 MMhp·hr for turbines. Confidence limits were calculated for the engine driver activity factor to be $\pm$ 64.3%. This activity factor is within the error bounds of the activity factor calculated using the company database for horsepower-hours (Section 4.1). This database provided one data point for turbine drivers in the production segment, thus affirming their presence in production. However, the number of these drivers is assumed to be very small and not significant for this estimate.

REFERENCE

1. Stapper, B.E. *Methane Emissions from the Natural Gas Industry, Volume 5: Activity Factors*, Final Report, GRI-94/0257.22 and EPA-600/R-96-080e. Gas Research Institute and U.S. Environmental Protection Agency, June 1996.

2. U.S. Department of Energy/Energy Information Administration. *Natural Gas Annual*, 1992. DOE/EIA-0131 (92), Washington, DC, September 1992.

TABLE C-1. GATHERING COMPRESSOR DATA FROM PRODUCTION SEGMENT SITE VISITS

Site	Installed hp [a]	MMcfd	Avg hp/MMcfd
Pacific Mountain			
PM1	37941 (112000)	104	
PM2	1650	4.5	
PM3	0 (200 [b])	12	
Total [f]	39591	120.5	328.6
Gulf Coast			
GC1	0 (NA [c])	4.5	
GC2	7467 [d]	23	
GC3	4950	25.5	
GC4	700 [d]	112	
GC5	0 [d]	12	
GC6	8878	54	
GC7	0	18	
GC8	625	250	
GC9	0 (NA [c])	0.50	
Total [f]	22620	499.5	45.3
Central Plains			
CP1	6000	180	
CP2	4650	42.7	
CP3	4480	240	
CP4 [e]	72192	542	
Total [f]	87322	1004.7	86.9
Atlantic & Great Lakes			
AG1	0	24	
AG2	0	0.18	
AG3	0	0.18	
AG4	0	0.17	
AG5	0	0.39	
AG6	0	0.37	

Continued

TABLE C-1. (CONTINUED)

Site	Installed hp [a]	MMcfd	Avg hp/MMcfd
AG7	50 [d]	0.37	
AG8	0	0.18	
AG9	0	0.23	
AG10	0	0.30	
AG11	0	0.35	
AG12	0	0.13	
AG13	0	0.35	
Total [f]	50	27.2	1.84

[a] Total site horsepower (including gas lift for oil recovery) is shown in parentheses.
[b] Horsepower associated with electric drivers.
[c] Not available.
[d] Estimated.
[e] Total for 25 gathering stations; peak production rate.
[f] Excludes gas lift and electric drivers.

TABLE C-2. REGIONAL DATA FOR PRODUCTION SEGMENT HORSEPOWER EXTRAPOLATION

Region	Site Avg hp/MMcfd	Site Avg 90% Limit	National Marketed Production MMcfd	Engine MMhp
Pacific Mountain	328.6	± 48.2%	2696	0.886
Gulf Coast	45.3	± 132%	31544	1.43
Central Plains	86.9	± 94.6%	14860	1.29
Atlantic & Great Lakes	1.84	± 244%	2166	0.00398
Total U.S.			51265	3.61
90% Limit			---	± 63.2%

TABLE C-3. ANNUAL OPERATING HOURS FOR PRODUCTION SEGMENT

Site	No. of Engines [a]	Average Operating Hours
PM1 [b]	19 (56)	8760
PM2	17	7884
PM3	0 (9)[c,g]	--
GC1	0 (14)	--
GC2 [b]	12	8030
GC3 [b]	4	8760
GC4 [b]	1	8760
GC5 [b]	0 (1)[c]	--
GC6 [b]	37	8523
GC7	0	--
GC8	25 [g]	4380
GC9	0 (1)	--
CP1 [b]	50 [d]	8760
CP2 [b]	31	8195
CP3 [b]	64	8760
CP4-1	1	5924
CP4-2	1	8364
CP4-3	2	4753
CP5-4	1	0
CP4-5	1	6884
CP4-6	18	5193
CP4-7	1	7631
CP4-8	1	7309
CP4-9	3	6953
CP4-10	2	5833
CP4-11	5	6386
CP4-12	1	5505
CP4-13	1	7235
CP4-14	1	7333

Continued

TABLE C-3. (CONTINUED)

Site	No. of Engines [a]	Average Operating Hours
CP4-15	2	8031
CP4-16	1	6841
CP4-17	1	7607
CP4-18	2	6303
CP4-19	1	6946
CP4-20	2	6340
CP4-21	7	748
CP4-22	1	7384
CP4-23	2	6908
CP4-24	2	7176
CP4-25	1	579
AG1	1	--
AG2	0	--
AG3	0	--
AG4	0	--
AG5	0	--
AG6	0	--
AG7	2	NA [e]
AG8	0	--
AG9	0	--
AG10	0	--
AG11	0	--
AG12	0	--
AG13	0	--
TOTAL AVERAGE [f] **90% LIMIT [f]**	315	6599 ± 9.7%

[a] Total number of compressors (including gas lift for oil recovery) is shown in parentheses.
[b] Based on active (8760 hrs) versus idle (0 hrs).
[c] Electric drivers.
[d] Estimated.
[e] Not available.
[f] Based on site averages.
[g] Includes vapor recovery.

APPENDIX D

Transmission Compressor Station Site Visit Results

Data were collected during site visits and company surveys for 51 transmission compressor stations. The compressor horsepower is related to the gas throughput and the pressure. Throughput is available for most of the sites surveyed, but a national figure is not available. Pressure data are not available for any of the sites surveyed or nationally. As a result, the only extrapolation method currently available for this industry segment is based on the number of compressor stations.

Table D-1 shows the number of compressors, installed horsepower, and gas throughput for each of the sites surveyed in the transmission segment. The engine/turbine horsepower split for this segment is 63.8% engines and 36.2% turbines (compared to 69.1% for engines and 30.9% for turbines in TRANSDAT). Using the average site horsepower per station and the total number of transmission compressor stations in the United States for 1992 from the FERC Form No. 2, the site data were scaled up to give a national estimate of compressor horsepower in transmission compressor stations of about 11.1 MMhp for engines and 6.3 MMhp for turbines.

$$\text{Engine hp} = \frac{\text{Total hp}}{\text{No. Stations}} \times \text{No. U.S. Stations}$$

$$= \frac{334240\ \text{hp}}{51\ \text{Stations}} \times 1700\ \text{Stations}$$

$$= 11.1\ \text{MMhp}$$

$$\text{Turbine hp} = \frac{190030\ \text{hp}}{51\ \text{Stations}} \times 1700\ \text{Stations}$$

$$= 6.33\ \text{MMhp}$$

Confidence limits were calculated for the horsepower from the variation of the data. The uncertainty calculated for the compressor station estimate used to scale up the site visit horsepower is $\pm$ 10%. The resulting uncertainties for the national horsepower estimates for this industry segment are $\pm$ 22.0% for engines and $\pm$ 44.9% for turbines.

Table D-2 shows the operating hours for the compressors at the 9 sites surveyed and for one company that provided data for 39 transmission compressor stations. The operating hours listed are the average hours for all of the drivers at each of the sites. Confidence limits were calculated for the operating hours estimate from the variation of the average site data. The resulting uncertainty is $\pm$ 25.0% for engines and $\pm$ 48.1% for turbines (90% confidence limits).

Activity factors based on site visit data alone are 26,100 MMhp·hr for engines and 13,460 MMhp·hr for turbines. The uncertainties for these activity factors are $\pm$ 33.7% for engines and $\pm$ 69.2% for turbines. These activity factors are within the error bounds of the activity factors calculated using TRANSDAT (horsepower) and FERC (operating hours). However, the TRANSDAT database and the FERC database are much more representative of the transmission industry segment and were used in the overall emissions estimates.

TABLE D-1. COMPRESSOR DRIVER DATA FROM TRANSMISSION SEGMENT SITE VISITS

Site	No. of Engines	Installed Engine hp	No. of Turbines	Installed Turbine hp	MMcfd
TS1	13	32650	0	---	843
TS2	0	0	2	6900	200
TS3	0	0	2	6900	37.5
TS4	2	800	0	---	50
TS5	10	14560	2	20090	NA
TS6	12	17570	1	12090	NA
TS7	0	0	1	40000	NA
TS8	4	14000	2	26500	4.9
TS9	7	14000	3	37500	4.9
TS10-1	4	6900	0	---	NA
TS10-2	4	8000	0	---	NA
TS10-3	5	1340	0	---	NA
TS10-4	3	815	0	---	NA
TS10-5	4	8400	0	---	NA
TS10-6	2	1200	0	---	NA
TS10-7	1	2400	0	---	NA
TS10-8	2	4000	0	---	NA
TS10-9	2	1320	0	---	NA
TS10-10	3	2475	0	---	NA
TS10-11	3	4050	0	---	NA
TS10-12	0	--	1	1000	NA
TS10-13	10	13000	0	---	NA
TS10-14	7	11200	0	---	NA
TS10-15	2	4800	0	---	NA
TS10-16	8	10600	0	---	NA
TS10-17	2	1200	0	---	NA
TS10-18	1	2400	0	---	NA
TS10-19	19	32800	0	---	NA
TS10-20	0	---	1	9300	NA
TS10-21	5	850	0	---	NA

Continued

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TABLE D-1.
(CONTINUED)

Site	No. of Engines	Installed Engine hp	No. of Turbines	Installed Turbine hp	MMcfd
TS10-22	1	2400	0	---	NA
TS10-23	1	2400	0	---	NA
TS10-24	3	6000	0	---	NA
TS10-25	1	2400	0	---	NA
TS10-26	1	2400	0	---	NA
TS10-27	7	7000	2	8500	NA
TS10-28	2	2700	0	---	NA
TS10-29	0	---	1	4250	NA
TS10-30	2	4800	0	---	NA
TS10-31	2	3350	1	4250	NA
TS10-32	1	2400	0	---	NA
TS10-33	3	6000	0	---	NA
TS10-34	7	7510	0	---	NA
TS10-35	2	4000	0	---	NA
TS10-36	1	2400	0	---	NA
TS10-37	1	270	0	---	NA
TS10-38	11	12380	3	12750	NA
TS10-39	1	2400	0	---	NA
TS11	6	16900	0	---	NA
TS12	7	10400	0	0	140
TS13	13	24800	0	0	NA
TOTAL AVERAGE[a]	**208**	**334240 6554**	**22**	**190030 3726**	**1409.5**

NA = Not Available
[a] Based on site averages

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TABLE D-2. ANNUAL OPERATING HOURS FOR TRANSMISSION SEGMENT

Site	No. of Engines	Average Operating Hours	No. of Turbines	Average Operating Hours
TS1	13	3303	0	--
TS2	0	--	2	3066
TS3	0	--	2	1139
TS4	2	7884	0	--
TS5	10	4066	2	3420
TS6	12	2082	1	6314
TS7	0	--	1	0
TS8	4	6366	2	4517
TS9	7	6813	3	4698
TS10-1	4	5019	0	--
TS10-2	4	3020	0	--
TS10-3	5	2343	0	--
TS10-4	3	0	0	--
TS10-5	4	4310	0	--
TS10-6	2	0	0	--
TS10-7	1	5914	0	--
TS10-8	2	3150	0	--
TS10-9	2	35	0	--
TS10-10	3	1574	0	--
TS10-11	3	2307	0	--
TS10-12	0	--	1	0
TS10-13	10	3653	0	--
TS10-14	7	52	0	--
TS10-15	2	158	0	--
TS10-16	8	2179	0	--
TS10-17	2	1351	0	--
TS10-18	1	4576	0	--
TS10-19	19	6117	0	--
TS10-20	0	--	1	579
TS10-21	5	470	0	--
TS10-22	1	5695	0	--

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TABLE D-2.
(CONTINUED)

Site	No. of Engines	Average Operating Hours	No. of Turbines	Average Operating Hours
TS10-23	1	2747	0	--
TS10-24	3	570.5	0	--
TS10-25	1	502.9	0	--
TS10-26	1	688.5	0	--
TS10-27	7	557	2	557
TS10-28	2	99	0	--
TS10-29	0	--	1	1823
TS10-30	2	615	0	--
TS10-31	2	1015	1	1015
TS10-32	1	497	0	--
TS10-33	3	4769	0	--
TS10-34	7	509	0	--
TS10-35	2	736	0	--
TS10-36	1	474.5	0	--
TS10-37	1	360	0	--
TS10-38	11	1240	3	497
TS10-39	1	586.9	0	--
TOTAL **AVERAGE** [a] **90% LIMIT** [a]	182	2343 ± 25.0%	22	2125 ± 48.1%

[a] Based on site averages.

APPENDIX E

Conversion Table

Unit Conversion Table

English to Metric Conversions

1 scf methane	=	19.23 g methane
1 Bscf methane	=	0.01923 Tg methane
1 Bscf methane	=	19,230 metric tonnes methane
1 Bscf	=	28.32 million standard cubic meters
1 short ton (ton)	=	907.2 kg
1 lb	=	0.4536 kg
1 ft^3	=	0.02832 m^3
1 ft^3	=	28.32 liters
1 gallon	=	3.785 liters
1 barrel (bbl)	=	158.97 liters
1 inch	=	2.540 cm
1 ft	=	0.3048 m
1 mile	=	1.609 km
1 hp	=	0.7457 kW
1 hp-hr	=	0.7457 kW-hr
1 Btu	=	1055 joules
1 MMBtu	=	293 kW-hr
1 lb/MMBtu	=	430 g/GJ
T (°F)	=	1.8 T (°C) + 32
1 psi	=	51.71 mm Hg

Global Warming Conversions

Calculating carbon equivalents of any gas:

$$\text{MMTCE} = (\text{MMT of gas}) \times \left(\frac{\text{MW, carbon}}{\text{MW, gas}}\right) \times (\text{GWP})$$

Calculating CO_2 equivalents for methane:

$$\text{MMT of } CO_2 \text{ equiv.} = (\text{MMT } CH_4) \times \left(\frac{\text{MW, } CO_2}{\text{MW, } CH_4}\right) \times (\text{GWP})$$

where MW (molecular weight) of CO_2 = 44, MW carbon = 12, and MW CH_4 = 16.

Notes

scf	=	Standard cubic feet. Standard conditions are at 14.73 psia and 60°F.
Bscf	=	Billion standard cubic feet (10^9 scf).
MMscf	=	Million standard cubic feet.
Mscf	=	Thousand standard cubic feet.
Tg	=	Teragram (10^{12} g).
Giga (G)	=	Same as billion (10^9).
Metric tonnes	=	1000 kg.
psig	=	Gauge pressure.
psia	=	Absolute pressure (note psia = psig + atmospheric pressure).
GWP	=	Global Warming Potential of a particular greenhouse gas for a given time period.
MMT	=	Million metric tonnes of a gas.
MMTCE	=	Million metric tonnes, carbon equivalent.
MMT of CO_2 eq.	=	Million metric tonnes, carbon dioxide equivalent.