United States
Environmental Protection
Agency

Research and Development

Air and Energy Engineering
Research Laboratory
Research Triangle Park NC 27711

EPA/600/S7-90/010 Aug. 1990

EPA

Project Summary

Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NO_x, N_2O, CH_4, CO, and CO_2

Stephen D. Piccot, Jennifer A. Buzun and H. Christopher Frey

Emission factors for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), and nitrous oxide (N_2O) were developed for about 80 globally significant combustion sources in 7 source categories - utility, industrial, fuel production, transportation, residential, commercial, and kilns/ovens/dryers. Because of the lack of adequate international data, the emission factors for most sources are based on U.S. performance cost, and emissions data. Data on CO_2, CO, and NO_x were available for over 90% of the sources studied; on CH_4, for about 80%; on N_2O, for only about 10%. Emission factor quality ratings were developed to indicate the overall adequacy of the supporting data. Quality ratings ranged from A to E, A the best. Except for N_2O, the emission factors for the gases covered the quality spectrum from A to E; all of the emission factors for N_2O were rated E. Evaluation of the emission factors for the seven source categories (taking the five gases as an aggregate for each category) showed that the kilns/ovens/dryers category had the lowest overall quality rating; no factors rated better than B. Emission factors for fuel production were somewhat better, but generally of lower quality than those for the remaining five source categories.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The U.S. EPA was asked by Congress under the National Climate Program Act to report on the environmental effects of global climate change and the options available to the global community to mitigate and adapt to potential global warming. The U.S. National Climate Program established by the National Climate Program Act involves several agencies and organizations engaged in interdisciplinary analysis of global climate and related issues. Within EPA, several programs have been established to perform the work necessary for supporting the National Climate Program and to provide the analysis and assessments necessary for the reports to Congress. EPA's Air and Energy Engineering Research Laboratory (AEERL) is supporting the technical effort required to estimate a global greenhouse gas emission inventory and to identify options to reduce these emissions. The technical effort includes development of emission, efficiency, and cost estimates for globally significant greenhouse gas emission sources and development of performance and cost estimates for emission control technologies.

Rapid expansion of global population and industrial activity has dramatically increased

creased the emissions of gases and pollutants that are referred to as greenhouse gases. Greenhouse gases transmit solar radiation and absorb infrared radiation, as does the glass in a greenhouse, and could result in significant increases in the global average surface temperature. In the report to Congress, several atmospheric trace gases are to be evaluated. The gases considered are CO_2, CO, CH_4, NO_x, and N_2O, which are considered greenhouse gases or are precursors of atmospheric chemical reactions that produce greenhouse gases. The concentrations of these five gases are currently increasing due to both anthropogenic and biogenic emission sources.

Anthropogenic emission sources include combustion and noncombustion sources. The combustion of fossil fuels is generally considered the major cause of increasing atmospheric CO_2 and CO concentrations. Fuel combustion is also responsible for significant emissions of NO_x, including both NO and NO_2. NO_2 and NO are not greenhouse gases, but they are precursors of the formation of ozone, an active greenhouse gas in the troposphere. Although the emissions of N_2O from combustion are small on a mass basis when compared to the emissions of CO_2, N_2O is over 250 times more effective than CO_2 in absorbing infrared radiation .

The purpose of this effort is to develop emission factor estimates and other data for combustion sources of greenhouse gases. The emission factors developed for this report are intended for use in estimating a global emission inventory of CO_2, CO, CH_4, NO_x, and N_2O. To provide options for stabilization and reduction of emissions of these gases, emission control technologies are identified for the combustion sources. The emission reduction capabilities of emission control technologies can be incorporated into developing a global emission inventory and into forecasting global emissions under various scenarios.

Scope

This project is limited to the evaluation of significant combustion sources of greenhouse gases. Only sources and controls for which data are readily available are included in this report. Performance and cost estimates for advanced combustion technologies and controls and for noncombustion sources and controls were not included in this study.

Anthropogenic Sources Included in the Study

An initial list (Table 1) of about 90 combustion sources was developed as a starting

Table 1. *Initial List of Combustion Sources of Greenhouse Gases*

Major Categories	*Subcategories*
Utilities	*Gas - boiler*
	Gas - combined cycle
	Gas turbines
	Residual oil
	Distillate oil
	Shale oil
	Municipal waste - mass feed
	Municipal waste - refuse-derived fuel
	Coal - spreader stoker
	Coal - fluid bed - combined cycle
	Coal - fluid bed - boiler
	Coal - pulverized coal - cyclone
	Coal - pulverized coal - tangential
	Coal - wall fired
	Wood
Industrial Boilers	*Wood*
	Gas - low thermal efficiency
	Gas - high thermal efficiency
	Residual - low thermal efficiency
	Residual - high thermal efficiency
	Distillate - low thermal efficiency
	Distillate - high thermal efficiency
	Municipal waste
	Refuse-derived fuel
	Coal - fluid bed
	Coal - spreader stoker - low thermal efficiency
	Coal - spreader stoker - high thermal efficiency
	Coal - pulverized coal
	Coal - mass stoker
	Bagasse/agricultural waste
Fuel Production	*Gas production & refining*
	Oil production & refining - w/CH_4 wastage
	Oil production & refining - w/o CH_4 wastage
	Coal production & cleaning
	Oil shale production & refining
	Coal gasification - current technology
	Coal gasification - advanced technology
	Coal liquefaction
	Charcoal production

Table 1. *(Continued)*

Major Categories	*Subcategories*
Transportation	*Rail*
	Jet aircraft
	Ships
	Aviation gasoline
	Gasoline - light duty - pre-control
	Gasoline - light duty - post-control
	Gasoline - heavy duty
	Gasoline - light duty
	Diesel -light duty
	Diesel - heavy duty
	Methanol - light duty
	Methane - light duty
	Internal combustion engines - diesel pipeline transportation
	Internal combustion engines - gas pipeline transportation
	Gas turbines
Residential/Commercial	*Direct fired - wood pits*
	Direct fired - wood fireplace
	Direct fired - wood stove - old/modern
	Direct fired - gas heater - old
	Direct fired - gas heater - modern (pulse)
	Direct fired - oil - old
	Direct fired - oil - modern
	Direct fired - coal fireplace
	Direct fired - coal stove
	Direct fired - coal central heat
	Direct fired - propane/butane
	Boilers - wood
	Boilers - gas
	Boilers - residual oil
	Boilers - distillate oil
	Boilers - municipal waste
	Boilers - coal
	Boilers - shale
	Waste reduction - open burning - municipal waste
	Waste reduction - open burning - agricultural
	Waste reduction - incineration - low efficiency
	Waste reduction - incineration - high efficiency
Heaters/Furnaces/Kilns/ Ovens/Dryers	*High temperature - distillate oil*
	High temperature - gas
	High temperature - residual oil
	High temperature - coal
	High temperature - shale oil
	Intermediate temperature - distillate oil
	Intermediate temperature - gas
	Intermediate temperature - residual oil
	Intermediate temperature - coal
	Intermediate temperature - shale oil
	Low temperature - distillate oil
	Low temperature - gas
	Low temperature - residual oil
	Low temperature - coal
	Low temperature - shale oil

point for the collection of emission and control technology data. After a review of the available literature and discussions with various experts, the list was revised to roughly 80 sources (Table 2).

The utility sources in Table 2 are the same as those in Table 1. The industrial boiler category was modified because data were not readily available for the population of high versus low efficiency boilers, nor were emission factors readily available for industrial boilers categorized based on efficiency. The different coal-fired industrial boiler technologies in Table 1 are represented by a single coal-fired industrial boiler category in Table 2. Distillate oil-fired boilers were not included in Table 2. Fired heaters were added as part of the fuel production category because they are an integral part of the petroleum refining process. The initial list of transportation sources is unchanged in the revised list except for deletion of post-control light duty vehicles; the effect of control technologies for light duty vehicles is

Table 2. *Revised List of Combustion Related Emission Sources*

UTILITY

- *Natural Gas Boilers*
- *Gas Turbine Combined Cycle - Natural Gas*
- *Gas Turbine Simple Cycle - Natural Gas*
- *Residual Oil Boilers*
- *Distillate Oil Boilers*
- *Shale Oil Boilers*
- *Municipal Solid Waste - Mass Feed*
- *Municipal Solid Waste - Refuse Derived Fuel*
- *Coal - Spreader Stoker*
- *Coal - Fluidized Bed Combined Cycle*
- *Coal - Fluidized Bed*
- *Coal - Pulverized Coal Cyclone Furnace*
- *Coal - Pulverized Coal Tangential Fired*
- *Coal - Pulverized Coal Wall Fired*
- *Wood-Fired-Boilers*

INDUSTRIAL

- *Coal-Fired Boilers*
- *Residual Oil-Fired Boilers*
- *Natural Gas-Fired Boilers*
- *Wood-Fired Boilers*
- *Bagasse/Agricultural Waste-Fired Boilers*
- *Municipal Solid Waste - Mass burn*
- *Municipal Solid Waste - Small modular*

FUEL PRODUCTION

- *Natural Gas Refining*
- *Catalyst Regeneration*
- *Refinery - Natural Gas Waste Flared*
- *Refinery - Natural Gas Waste Used*
- *Coal Dryer*
- *Oil Shale - Surface Retorting*
- *Oil Shale - In-Situ Retorting*
- *Lurgi Coal Gasification*
- *Coal Liquefaction - Acid Gas*
- *Charcoal Production*
- *Waste Flare - Pure Methane*
- *Waste Flare - Natural Gas*
- *Fired Heater - Natural Gas*
- *Fired Heater - Process Gas*
- *Fired Heater - Distillate Oil*
- *Fired Heater - Residual Oil*

TRANSPORTATION

- *Rail*
- *Jet Aircraft*
- *Aviation- Gasoline*
- *Ships*
- *Light Duty Gasoline Vehicle*
- *Heavy Duty Gasoline Vehicle*
- *Light Duty Diesel Vehicle*
- *Heavy Duty Diesel Vehicle*
- *Light Duty Methanol Vehicle*
- *Light Duty Compressed Natural Gas Vehicle*
- *Internal Combustion Engine-Diesel (Pipeline)*
- *Internal Combustion Engine- Natural Gas (Pipeline)*
- *Gas Turbine - Natural Gas (Pipeline)*

RESIDENTIAL

- *Wood Pits*
- *Wood Fireplaces*
- *Wood Stoves*
- *Propane/Butane Furnace*
- *Coal Hot Water Heater*
- *Coal Furnaces*
- *Coal Stoves*
- *Distillate Oil Furnaces*
- *Natural Gas Heaters*

COMMERCIAL

- *Wood Boilers*
- *Natural Gas Boilers*
- *Residual Oil Boilers*
- *Distillate Oil Boilers*
- *Municipal Solid Waste Boilers*
- *Coal Boilers*
- *Shale Oil Boilers*
- *Open Burning - Municipal Solid Waste*
- *Open Burning - Agricultural*
- *Incinerator - Multistage*
- *Incinerator - Single Chamber*

KILNS/OVENS/DRYERS

- *Kilns - Natural Gas (Cement or Lime Kiln)*
- *Kilns - Oil (Cement or Lime Kiln)*
- *Kilns - Coal (Cement or Lime Kiln)*
- *Coke Oven - Coke Oven Gas*
- *Dryer - Natural Gas*
- *Dryer - Oil*
- *Dryer - Coal*

estimated as part of the control technology performance estimates. The original residential and commercial category was divided. Sources within these categories for the original list are included in the revised list; however, no data were readily available to distinguish the performance of old from modern residential sources, so this distinction is not made in the revised table. Insufficient data were readily available to justify the subdivision of kilns, ovens, and dryers based on operating temperature, and no data were readily available from which to estimate emissions of these sources from the combustion of shale oil.

Type of Data Collected

Table 3 shows the format of the source performance and cost data presented in the report. The data for each of the emission sources includes the energy conversion efficiency for utility, industrial boiler, residential, commercial, fuel production, and kilns/ovens/dryers. Plant costs were developed for utility and industrial boiler sources, and were levelized on an energy input or energy output basis depending on the availability of an efficiency estimate. Emission factors were developed on an energy output basis for utility, industrial boiler, and commercial sources, and for some other sources where applicable efficiency data were available. Emission factors for the remaining sources were developed on an energy input basis, except for some fuel production sources, for which emission factors were developed based on crude oil production. All of the combustion technologies considered in this project are currently available.

For each emission source in Table 2, an effort was made to identify applicable emission control technologies. Most of the control technologies included in the report are currently available. However, some advanced control technologies were included in this study to provide an option for more stringent control of a specific greenhouse gas or, as for advanced utility controls for CO_2, to provide an option for controlling a gas that cannot be reduced by current methods.

The general format of the control technology performance and cost data is shown in Table 4. For control technologies, an efficiency penalty on the combustion technology was estimated, as was the removal efficiency for the five greenhouse gases considered in this study. Emission control costs were developed on an energy input or energy output basis, depending on the basis for the combustion technology cost. For each control technology, an availability date was estimated.

The emission factors developed in the report represent sources without control technologies. To calculate the baseline global emission inventory for the regions of the world, appropriate controls can be applied to specific source categories to represent the current application of control technologies in some countries. The report does not identify controls to be applied to represent current control levels in different parts of the world.

Data Quality

For each emission factor, a data quality rating was assigned to indicate the relative quality of the emission factors within the database. The data quality ratings can also be used to identify areas that could benefit from additional research. A few of the factors that affect the quality of an emission factor are the quality of the emission data, (typically available on the basis of mass of pollutant emitted per mass of fuel burned), the quality of the fuel properties used to convert the emission factor to an energy basis, and the quality of efficiency estimates used to convert the emission factor to an end-use energy basis. The emission data may be subject to variability due to variations in the design, operation, and maintenance at specific sources. These factors were taken into consideration when assigning emission factor ratings.

Summary of Results

For this study, performance and cost estimates were developed for globally significant combustion sources of CO_2, CO, CH_4, NO_x, and N_2O and for applicable emission control technologies. Although the intent of this work was to develop globally representative estimates, international performance and cost data were not readily available for most of the sources and controls. In many cases, data were not available from which to estimate the emission factors of all five of the gases for a given source; in particular, few data are available from which to estimate emission factors for N_2O. The emission factors for CO_2 were generally calculated from a carbon balance.

For most sources and control technologies, the performance and costs are based on U.S. data. The emission data developed under various EPA projects represent the most extensive, highest quality, and most accessible information available from which to calculate emission factors, efficiency, cost, and emission control removal efficiency, efficiency penalty, and cost. Although data are available from the United Nations to estimate global fuel consumption and in some cases energy conversion efficiency, the data readily available from the United Nations Statistical Office and Environment Programme are not suitable for a disaggregated analysis (i.e., few data are available for specific combustion technologies). However, the United Nations data can be used to estimate, for example, the overall energy conversion efficiency of

Table 3. *Combustion Emission Source Data Format*

Emission Source Technology	*Efficiency (%)*	*Cost ($/joule)*	*Emissions (kg/joule)*					*Applicable Control Technology Codes*
			CO_2	*CO*	*CH_4*	*N_2O*	*NO_X*	
	Utility eff. = fuel heat value/electricity delivered to user.	*Joule = energy delivered to user.*	*Joule = energy delivered to user except transportation and kiln/oven/dryer where joule is fuel heating value. Emissions = uncontrolled emissions.*					
	Industrial and residential eff. = fuel energy in/energy delivered to user.	*$ = cost in 1985 excluding fuel costs.*						

Table 4. *Emission Control Technology Data Format*

Control Technology	*Device Code*	*Efficiency Penalty*[a] *(%)*	*Cost ($/joule)*	*Availability (date)*	*Performance (% reduction)*				
					CO_2	*CO*	*CH_4*	*N_2O*	*NO_X*
		Expressed as % of combustion device efficiency	*Cost = 1985 $*						

[a] *May be a benefit in some cases.*

all utility sources in various geopolitical regions of the world. The Organization for Economic Cooperation and Development (OECD) has addressed global fuel consumption and environmental issues, but again the data available from the OECD do not directly support the development of source specific emission factors. The use of source-specific U.S. data was generally required due to the absence of readily available data from international sources; however, in many cases the U.S. data may be globally representative of the energy-specific emissions of the five greenhouse gases considered in this study.

The emission factor quality ratings are summarized in Figures 1 through 4 to indicate the overall quality of this emission factor database. The emission factors were given quality ratings from A to E, with an A being the best. Figure 1 shows that the distribution of the ratings is fairly even; roughly 35% of all emission factors are rated B or higher, while about 39% are rated D or lower.

Figure 2 shows the percentage of the total number of emission factors for each of the five gases for which data were not readily available. It shows that, in general, data were readily available for NO_x and CO. For nearly all sources it was possible to calculate CO_2 emission factors using a carbon balance. The carbon balance generally accounts for the conversion of carbon in the fuel to CO_2, CO, and CH_4. In many cases, the emission factors for CO_2 are orders of magnitude greater than for any other carbonaceous species. Therefore, it was possible to estimate with reasonable accuracy CO_2 emission factors for many sources for which CO and/or CH_4 emission factors were not available. For this reason, the percent of CO_2 emission factors for which data were not readily available is less than the percent of CO and CH_4 emission factors for which data were not readily available.

Only limited data were readily available from which to estimate N_2O emission factors. For about 90% of the sources included in this study, data were not available from which to estimate an N_2O emission factor.

Figure 3 indicates the overall quality of the available emission factors for each of the five gases. The rating of E for all N_2O emission factors reflects the lack of sufficient test data from which to develop high quality emission factors. The emission factors for CH_4, many of which were estimated based on a percentage of total hydrocarbon emissions, generally have lower ratings than CO and NO_x emission factors. The emission factors for CH_4 tend to be lower than NO_x or CO emission factors. The distributions of ratings for NO_x and CO emission factors are fairly uniform. The emission factors for CO_2 were generally rated higher than the other four gases, even though CO_2 emission factors were generally calculated from a carbon balance. CO_2 represents the largest carbonaceous species emitted by most combustion processes by several orders of magnitude; therefore, uncertainty associated with the emissions of CO, CH_4, or other carbonaceous species as gases or solids generally has a negligible impact on the CO_2 emission factor estimate and rating.

Figure 4 shows the distribution of emission factor ratings for all gases for each source category. Overall, the source categories with the best emission factor ratings are also the most significant emission sources. Utility and industrial boiler sources have the best overall ratings. N_2O emission factors account for most of the E ratings for these two sources. NO_x and CO emission factors in these two categories are generally rated A and B. Most of the transportation sources CH_4 and N_2O emission factors are rated D or lower. Kilns, ovens, and dryers noticeably are rated the lowest overall; only CO_2 emission factors are rated as high as B and C in the kilns category. The emission factors for fuel production sources are also generally of lower quality than for other sources; ratings of C and D are evenly distributed for CO_2, NO_x, CO, and CH_4 emission factors.

The cost estimates are sensitive to the assumptions made regarding capacity fac-

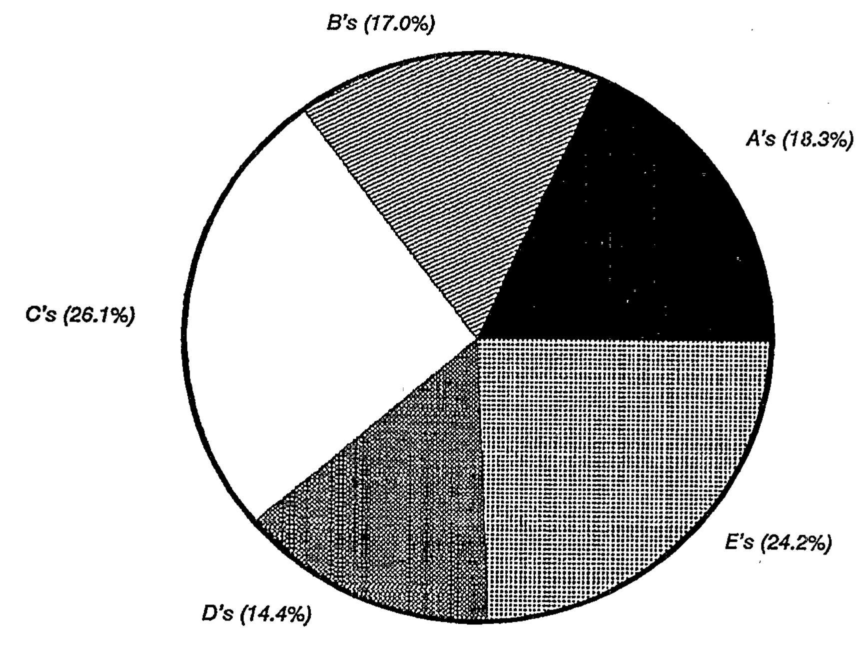

Figure 1. *Distribution of all emission factor quality ratings.*

tor when calculating annualized cost on an energy basis. Costs are also sensitive to the size of the facility being costed. When possible, reasonably representative source capacities were selected. However, in many cases, cost information was readily available for only a single source capacity. Globally, costs vary considerably due to differences in labor costs, financing methods, inflation, taxes, and regulations. The cost estimates should be regarded as rough estimates that indicate the relative cost of one technology to another.

The emission factor quality ratings identify some areas that could benefit from additional research. Many more test data are required before N_2O emission factors can be developed for any sources with good confidence. The applicability of U.S. data to develop globally representative emission factors, such as assuming that the design and operation of source technologies in the U.S. are the same as in other regions of the world, requires further study. The identification of significant differences in cost or performance for emission sources from one region of the world to another would indicate that emission source parameters should be estimated independently for different regions of the world. Additional study, and possibly source testing, may be required to fill gaps in the emission database and to improve the quality of emission factors. The impact of control technologies on N_2O emissions requires more testing.

Specific tasks for further development of this database could include additional literature search, consultation with experts in the U.S. and internationally, and source testing, including the impact of control technologies on N_2O. Data from these activities could be used to improve the accuracy of current estimates, provide data where data are currently not included, and develop new emission source and control categories to account for regional differences in performance and cost.

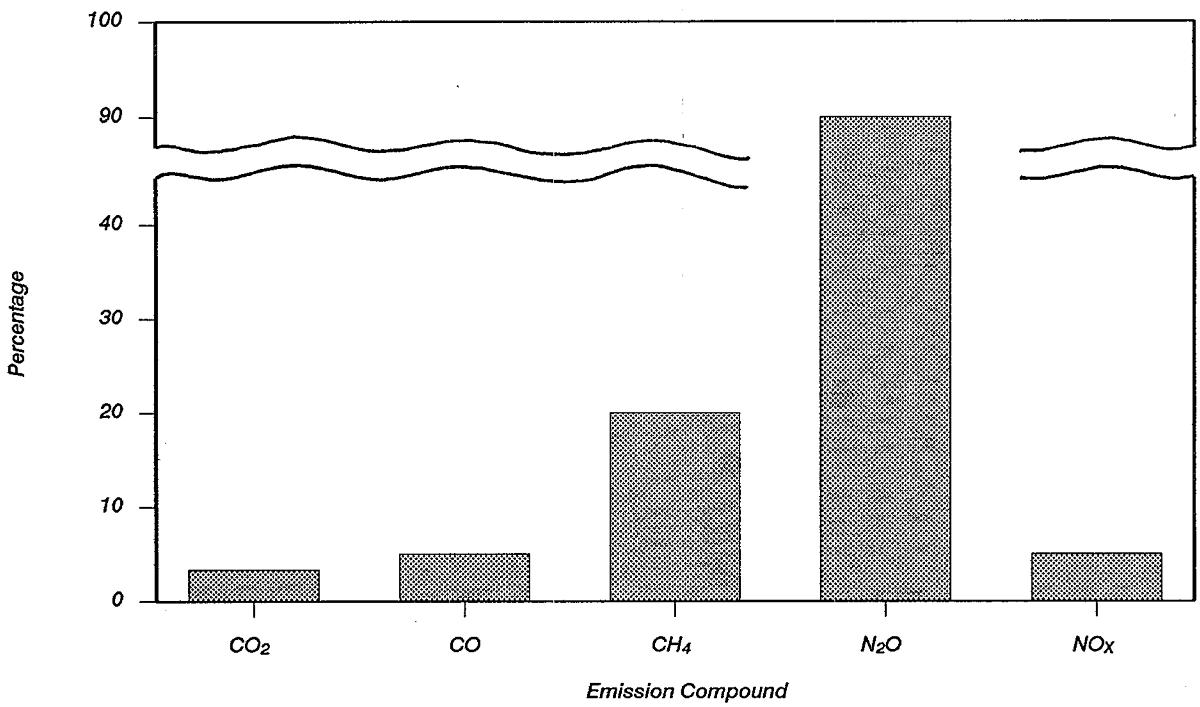

Figure 2. *Percent of emission factors for each gas for which data were not readily available.*

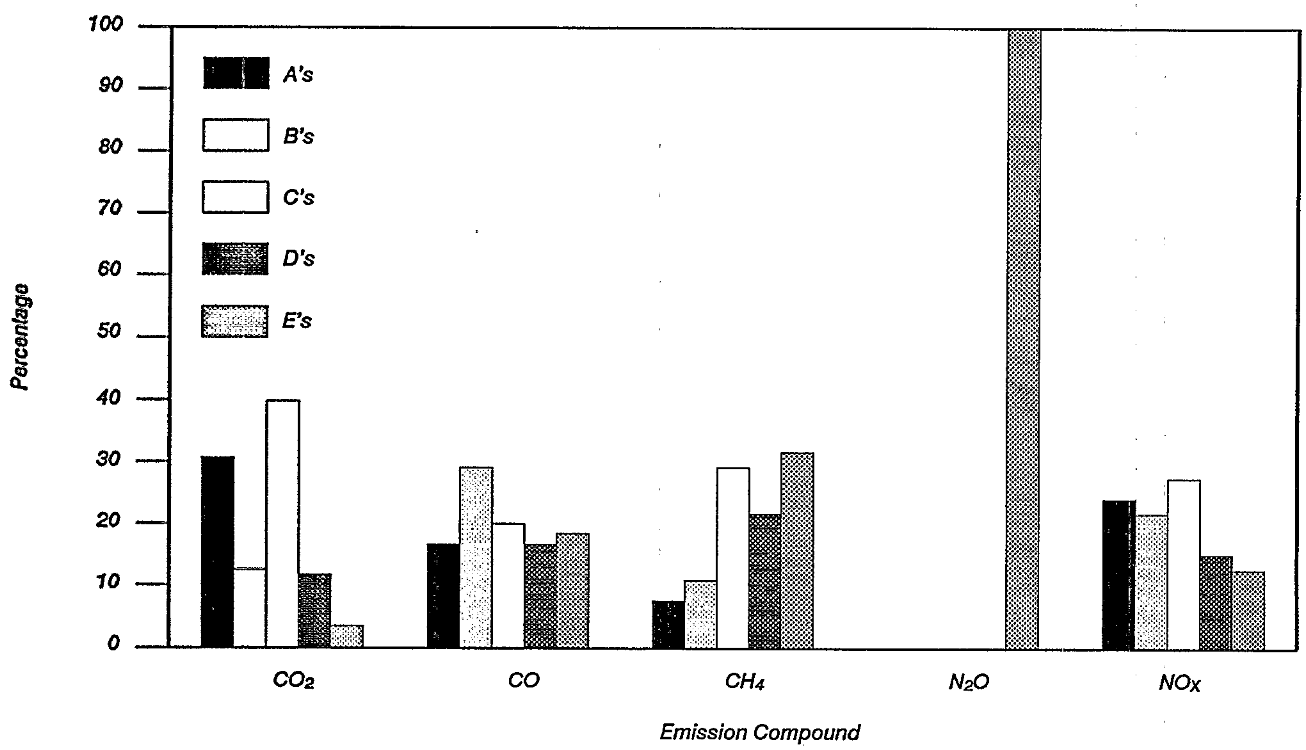

Figure 3. *Distribution of emission factor ratings by gas.*

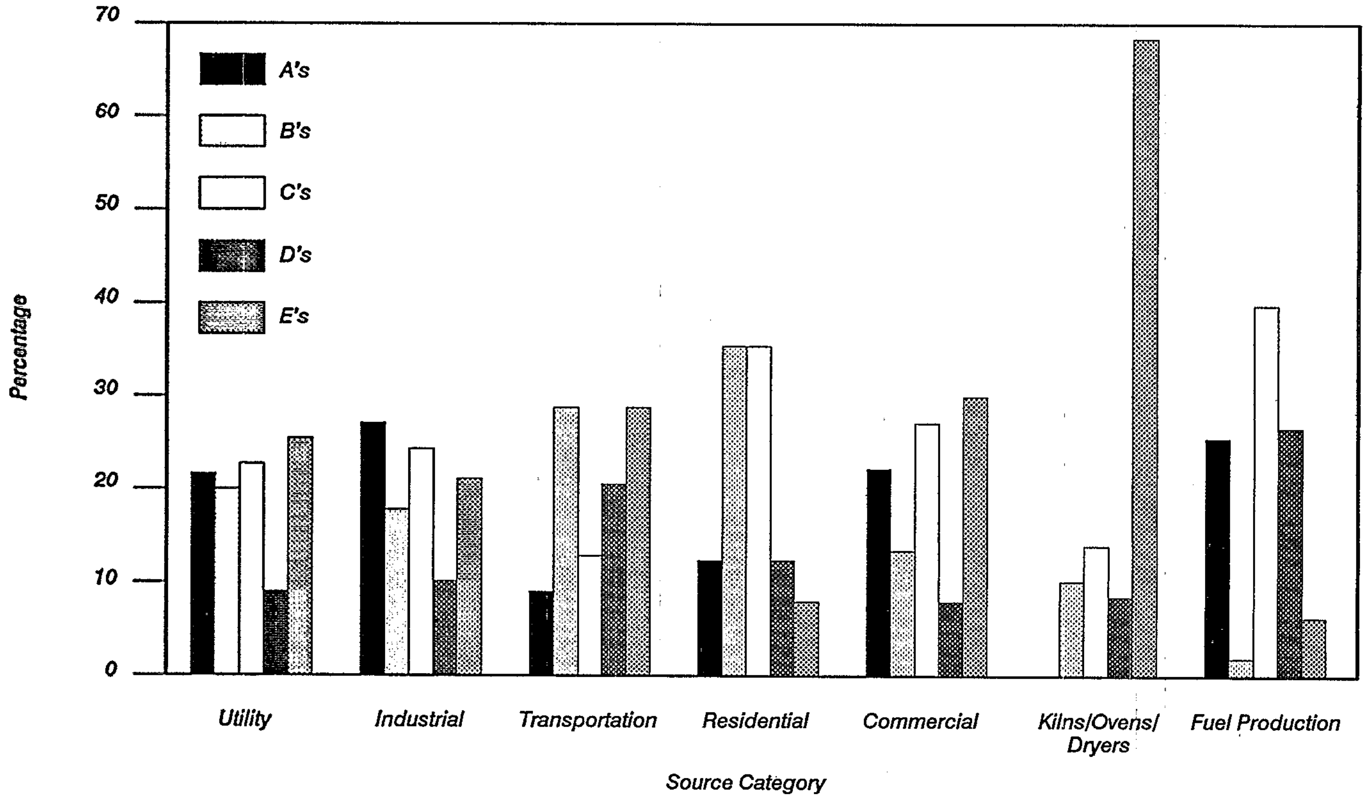

Figure 4. *Distribution of emission factor ratings by source.*

S. Piccot, J. Buzun, and C. Frey are with Radian Corporation, Research Triangle Park, NC 27709

***Julian W. Jones** is the EPA Project Officer (see below)*

The complete report, entitled "Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NO_x, N_2O, CH_4, CO, and CO_2," (Order No. PB 90-216 433/AS; Cost: $23.00, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Official Business
Penalty for Private Use $300

EPA/600/S7-90/010