Note: This is a reference cited in *AP 42, Compilation of Air Pollutant Emission Factors, Volume I Stationary Point and Area Sources.* AP42 is located on the EPA web site at www.epa.gov/ttn/chief/ap42/

The file name refers to the reference number, the AP42 chapter and section. The file name "ref02_c01s02.pdf" would mean the reference is from AP42 chapter 1 section 2. The reference may be from a previous version of the section and no longer cited. The primary source should always be checked.

AP-42 Section Number: 3.1

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Title: Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1991

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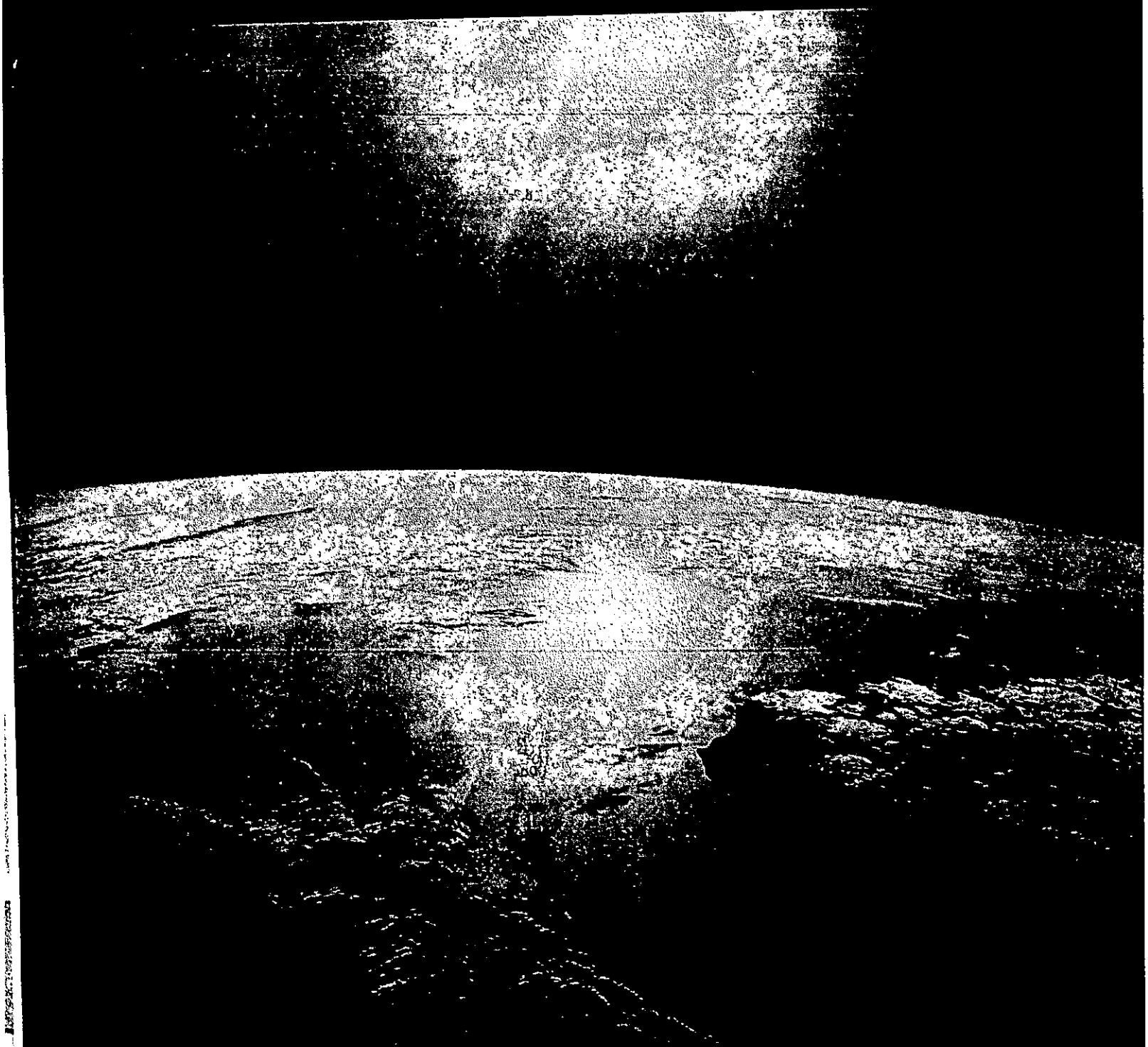
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1994



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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

APR 8 1996

OFFICE OF
POLICY, PLANNING AND EVALUATION

Dear Colleague,

I am pleased to announce the release of the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-1994*. The emissions estimates contained in this report, along with future updates, will be used to monitor and track the progress of the U.S. in meeting the U.S. commitment to return greenhouse gas emissions to 1990 levels by 2000. Decision 3/CP.1 under the Framework Convention on Climate Change (FCCC) states that Annex I Parties should submit "National inventory data on emissions by sources and removals by sinks ... should be provided annually on 15 April." In accordance with this decision, *Inventory of Greenhouse Gas Emissions and Sinks: 1990-1994* was prepared and is the second official U.S. submission to the The Framework Convention on Climate Change (FCCC). This report complies with the reporting guidelines established by the scientific and technical organizations that have been recommended to the Conference of Parties and is consistent with the reports from all Parties to the FCCC.

We greatly appreciate the efforts of the Energy Information Administration, The Department of Agriculture, and other EPA Offices for their strong cooperation and contributions to this document.

To obtain additional copies of this document, please FAX your requests to the National Center for Environmental Publications and Information (NCEPI) at (513) 489-8695. For other relevant EPA publications please refer to the list on the back of this page. If you have any questions or comments please call Wiley Barbour at (202) 260-6972.

Sincerely,

David Gardiner
Assistant Administrator

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Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1994

U.S. Environmental Protection Agency
Office of Policy, Planning and Evaluation
Washington, D.C., U.S.A.

November 1995

This document has undergone U.S. Environmental Protection Agency internal review, interagency review, and public review. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Table of Contents

Executive Summary ES-1

Introduction 1

Part I. Energy 9

Emissions from Fossil Fuel Consumption 10

Carbon Dioxide Emissions from Fossil Fuel Consumption 10

Other Greenhouse Gas Emissions from Stationary Fossil Fuel Combustion 18

Other Greenhouse Gas Emissions from Mobile Combustion 21

Fossil Fuel Production, Transport, Storage, and Distribution 24

Emissions from Coal Mining 24

Emissions from Natural Gas Production, Processing, Transport, and Distribution 26

Emissions from Production, Refining, Transportation, and Storage of Petroleum 28

Emissions from Biomass and Biomass-Based Fuel Consumption 32

Emissions from Wood Consumption 32

Emissions from Ethanol Consumption 33

Part II. Industrial Processes 35

Carbon Dioxide Emissions 36

Cement Production 36

Lime Manufacture 38

Limestone Use 40

Soda Ash Manufacture and Consumption 41

Carbon Dioxide Manufacture 42

Aluminum Production 43

Nitrous Oxide Emissions 44

Adipic Acid Production 44

Nitric Acid Production 45

Other Emissions 46
Emissions of Halogenated Compounds 46
Emissions of Criteria Pollutants: NO_X, NMVOCs and CO 51
Emissions of NF_3 51

Part III. Emissions from Solvent Use 53

Part IV. Emissions from Agriculture 55

Methane Emissions from Enteric Fermentation in Domestic Livestock 57
Methane Emissions from Cattle 58
Methane Emissions from Other Domestic Animals 60

Methane Emissions from Livestock Manure 60
Methodology 61
Methane Emissions Estimates from Livestock Manure 62

Methane Emissions from Rice Cultivation 62
Methodology 63
Methane Emissions from Rice Cultivation 64

Nitrous Oxide Emissions from Agricultural Soil Management 66
Methodology 67
Nitrous Oxide Emissions from Agricultural Soils 67

Emissions from Field Burning of Agricultural Wastes 69
Methodology 70
Emissions from Field Burning 70

Part V. Emissions from Land-Use Change and Forestry 75

Part VI. Emissions from Waste 79

Landfills 79

Wastewater 82

Waste Combustion 83

References

Annex A Method of Estimating Emissions of CO_2 from Fossil Energy Consumption

Annex B Emissions from Mobile Combustion

Annex C Emissions of HFCs, PFCs and SF_6

Annex D Estimation of Methane Emissions from Enteric Fermentation in Cattle and from Animal Manure Management

Annex E Methane Emissions from Landfills

Annex F Sulfur Dioxide: Effect on Radiative Forcing and Sources of Emissions

Annex G IPCC Reporting Tables

List of Boxes, Tables, and Figures

Boxes

Executive Summary

Box ES-1	The Global Warming Potential (GWP) Concept	ES-2
Box ES-2	Emissions of CFCs and Related Compounds	ES-15
Box ES-3	Sulfur Dioxide: Effects on Radiative Forcing and Sources of Emissions	ES-17

Introduction

Box 1	Greenhouse Gases and Other Photochemically Important Gases	2
Box 2	The Global Warming Potential (GWP) Concept	3

Part I

Box I-1	About Energy Data and Estimating Carbon Emissions	15

Part IV

Box IV-1	Estimating Nitrous Oxide Emissions Using the DNDC Model	68

Tables

Executive Summary

Table ES-1	Recent Trends in U.S. Greenhouse Gas Emissions: 1990-1994	ES-3
Table ES-2	Sources of CO_2 Emissions: 1994	ES-5
Table ES-3	Sources of CH_4 Emissions: 1994	ES-10
Table ES-4	Sources of N_2O Emissions: 1994	ES-13
Table ES-5	Emissions of HFCs, PFCs, and SF6: 1994	ES-14
Table ES-6	Emissions of CO, NO_x, and NMVOCs: 1994	ES-16

Introduction

Table 1	Recent Trends in U.S. Greenhouse Gas Emissions: 1990-1994	4

Part I

Table I-1	U.S. CO_2 Emissions from Energy Consumption by End-Use Sector and Fuel Type: 1990-1994	11
Table I-2	Key Assumptions for Estimating Carbon Dioxide Emissions	17
Table I-3	U.S. Greenhouse Gas Emissions from Stationary Combustion: 1990-1994	18

Table I-4	U.S. Greenhouse Gas Emissions from Stationary Combustion by Sector and Fuel Source: 1994	20
Table I-5	Ratio of CH_4 to NMVOCs Released During Combustion	21
Table I-6	U.S. Greenhouse Gas Emissions from Mobile Combustion: 1990-1994	22
Table I-7	U.S. Greenhouse Gas Emissions from Mobile Combustion by Vehicle Type: 1994	23
Table I-8	Coal Mine Methane Emissions Estimates	25
Table I-9	Methane Emissions from the U.S. Natural Gas Industry: 1990-1994	28
Table I-10	Methane Emissions from the Production and Refining of Petroleum Liquids: 1990-1994	29
Table I-11	CO_2 Emissions from Flaring of Natural Gas	31
Table I-12	NO_X, NMVOCs and CO Emissions from Oil and Gas Activities: 1990-1994	32
Table I-13	CO_2 Emissions from Wood Consumption by Sector: 1990-1994	33
Table I-14	Residential and Industrial Biomass Combustion: 1990-1994	33
Table I-15	U.S. CO_2 Emissions from Ethanol Consumption: 1990-1994	34
Part II		
Table II-1	Recent Trends in U.S. Greenhouse Gas Emissions from Industrial Sources: 1990-1994	36
Table II-2	CO_2 Emissions from U.S. Cement Production: 1990-1994	37
Table II-3	CO_2 Emissions from U.S. Lime Production: 1990-1994	39
Table II-4	CO_2 Emissions from U.S. Limestone Consumption: 1990-1994	40
Table II-5	Emissions of HFCs and PFCs: 1994	47
Table II-6	Emissions of ODSs: 1994	50
Table II-7	U.S. Emissions of NO_X, CO, and NMVOCs from Industrial Processes: 1990-1994	52
Part III		
Table III-1	Emissions of NMVOCs , NO_X and CO from Solvent Use: 1990-1994	54
Table III-2	U.S. Emissions of NMVOCs, NO_X, and CO by Category: 1994	54
Part IV		
Table IV-1	Recent Trends in U.S. Greenhouse Gas Emissions from Agricultural Sources: 1990-1994	56
Table IV-2	Methane Emissions from Animals: 1990-1994	59
Table IV-3	U.S. Animal Populations: 1990-1994	60
Table IV-4	Methane Emissions from Manure Management: 1990-1994	62
Table IV-5	Area Harvested and Flooding Season Length for Rice-Producing States	65
Table IV-6	CH_4 Emissions from Rice Cultivation in the U.S.: 1990-1994	65
Table IV-7	Fertilizer Consumption and N_2O Emissions in the U.S.: 1990-1994	69
Table IV-8	Key Assumptions for Estimating Emissions from Crop Waste Burning Using Annual Activity Data	71
Table IV-9	Annual Trace Gas Emissions from Field Burning: 1990-1994 Based on Annual Activity Data	72
Table IV-10	Key Assumptions for Estimating Emissions from Crop Waste Burning Using Three-year Averages of Activity Data	73
Table IV-11	Average Annual Trace Gas Emissions from Field Burning: 1990-1994 Based on Three-year Averages of Activity Data	74

Part V

Table V-1	U.S. Carbon Storage Estimates	77
Table V-2	Carbon Fluxes from U.S. Forests in 1990-1992	78

Part VI

Table VI-1	Recent Trends in U.S. Greenhouse Gas Emissions from Waste Sources: 1990-1994	80
Table VI-2	U.S. Methane Emissions from Landfills: 1990-1994	81
Table VI-3	U.S. Methane Emissions from Wastewater	83
Table VI-4	U.S. NMVOC, CO, and NO_X Emissions from Waste Incineration: 1990-1994	84
Table VI-5	U.S. NMVOC, CO, and NO_X Emissions from Waste Incineration by Source: 1994	84

Figures

Executive Summary

Figure ES-1	Total U.S. Emissions by Source: 1994	ES-1
Figure ES-2	Recent Trends in U.S. Greenhouse Gas Emissions	ES-4
Figure ES-3	Total U.S. Greenhouse Gas Emissions by Gas: 1994	ES-4
Figure ES-4	Primary Sources of Energy in the U.S.: 1994	ES-5
Figure ES-5	Carbon Dioxide Emissions from Fossil Fuel Combustion	ES-6
Figure ES-6	Sources of CH_4 Emissions: 1994	ES-10
Figure ES-7	CH_4 Emissions from Agriculture by Source: 1994	ES-10
Figure ES-8	Sources of N_2O Emissions: 1994	ES-13

Part I

Figure I-1	Primary Sources of Energy in the U.S.: 1994	10
Figure I-2	Change in Acquisition Price of Crude Oil	12
Figure I-3	Carbon Dioxide Emissions from Fossil Fuel Combustion by End-Use Sector: 1994	12
Figure I-4	Total Vehicle Miles Traveled by Major Vehicle Type: 1978-1994	13
Figure I-5	Carbon Dioxide Emissions from Fossil Fuel Combustion by Sector and Fuel Type: 1994	14

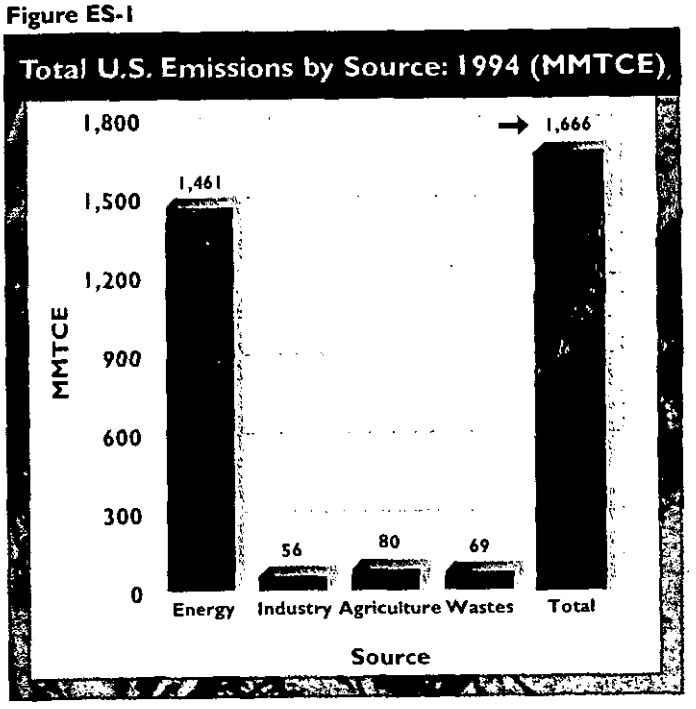
Part IV

Figure IV-1	Total U.S. Emissions by Source: 1994	55
Figure IV-2	U.S. Methane Emissions By Source: 1994	56
Figure IV-3	U.S. Nitrous Oxide Emissions By Source: 1994	56

Executive Summary

This document provides information on greenhouse gas sources and sinks, and estimates of emissions and removals for the United States for 1990-1994, as well as the methods used to calculate these estimates and the uncertainties associated with them. The emission estimates presented here were calculated using the *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA, 1995) to ensure that the greenhouse gas emission inventories prepared by the United States to meet its commitments under the Framework Convention on Climate Change are consistent and comparable across sectors and between nations. In order to fully comply with the *IPCC Guidelines,* the United States has provided a copy of the IPCC reporting tables in Annex G of this report. These tables include the data used to calculate emission estimates using the *IPCC Guidelines.* The United States has followed these guidelines, except where more detailed data or methodologies were available for major U.S. sources of emissions. In such cases, the United States expanded on the IPCC guidelines to provide a more comprehensive and accurate account of U.S. emissions. These instances have been documented, and explanations have been provided for diverging from the *IPCC Guidelines* (IPCC/OECD/IEA, 1995).

Figure ES-1



The Greenhouse Gases and Photochemically Important Gases

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Chlorofluorocarbons (CFCs) (a family of human-made compounds), its substitute hydrofluorocarbons (HFCs), and other compounds such as perfluorinated carbons (PFCs), are also greenhouse gases. In addition, other photochemically important gases — such as carbon monoxide (CO), oxides of nitrogen (NO_X), and nonmethane volatile organic compounds (NMVOCs) — are not greenhouse gases, but contribute indirectly to the greenhouse effect (see Box ES-1 for explanation).

These are commonly referred to as "tropospheric ozone precursors" because they influence the rate at which ozone and other gases are created and destroyed in the atmosphere. For convenience, all gases discussed in this summary are generically referred to as "greenhouse gases" (unless otherwise noted), although the reader should keep these distinctions in mind. In addition, emissions of sulfur dioxide (SO_2) are reported. Sulfur gases, primarily sulfur dioxide, are believed to contribute negatively to the greenhouse effect.

Recent Trends of U.S. Greenhouse Gas Emissions

Although CO_2, CH_4 and N_2O occur naturally in the atmosphere, their recent atmospheric buildup appears to be largely the result of anthropogenic activities. This growth has altered the composition of the Earth's atmosphere, and may affect future global climate. Since 1800, atmospheric concentrations of CO_2 have increased by more than 25 percent, CH_4 concentrations have more than doubled, and N_2O concentrations have risen approximately 8 percent (IPCC, 1992). From the 1950s until the mid-1980s, the use of CFCs increased by nearly 10 percent per year. Now that CFCs are being phased out under the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol), the use of CFC substitutes is expected to grow significantly.

The current U.S. greenhouse gas inventory for 1990-94 is summarized in Table ES-1 and Figures ES-1, ES-2, and ES-3. For 1994, total U.S. emissions were 1,666 MMTCE. To be consistent with the IPCC-recommended guidelines, this estimate excludes emissions of 23 MMTCE from international transport. Changes in CO_2 emissions from fossil fuel consumption had the greatest impact on U.S. emis-

Box ES-1

The Global Warming Potential (GWP) Concept

As mentioned, gases can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformation of the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The concept of Global Warming Potential (GWP) has been developed to allow scientists and policy makers to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. The GWP of a greenhouse gas is the ratio of global warming, or radiative forcing (both direct and indirect), from one kilogram of a greenhouse gas to one kilogram of carbon dioxide over a period of time. While any time period can be selected, the 100-year GWPs recommended by the IPCC are used in this report. Carbon dioxide was chosen as the "reference" gas to be consistent with IPCC guidelines. Carbon comprises 12/44 of carbon dioxide by weight. In order to convert emissions reported in million metric tonnes of a gas to MMTCE, the following equation is used:

MMTCE = (MMT of gas) (GWP of gas) (12/44),

where

MMTCE = million metric tonnes, carbon-equivalent,
MMT = million metric tonnes, full molecular weight,
GWP = global warming potential, and
(12/44) = carbon to carbon dioxide molecular weight ratio.

GWPs are not provided for the photochemically important gases CO, NO_x, NMVOCs, and SO_2 because there is no agreed-upon method to estimate their contribution to climate change. These gases only affect radiative forcing indirectly.

Gas	GWP[1] (100 Years)
Carbon dioxide	1
Methane*	24.5
Nitrous oxide	320
HFC-23	12,100
HFC-125	3,200
HFC-134a	1,300
HFC-152a	140
PFCs**	9,400
SF_6	24,900

** The methane GWP includes the direct effect and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.*

*** This figure is an average GWP for the two PFCs, CF_4 and C_2F_6. The GWP for CF_4 is 6,300 and the GWP for C_2F_6 is 12,500.*

[1] IPCC, 1994

Table ES-1

Recent Trends in U.S. Greenhouse Gas Emissions: 1990–1994

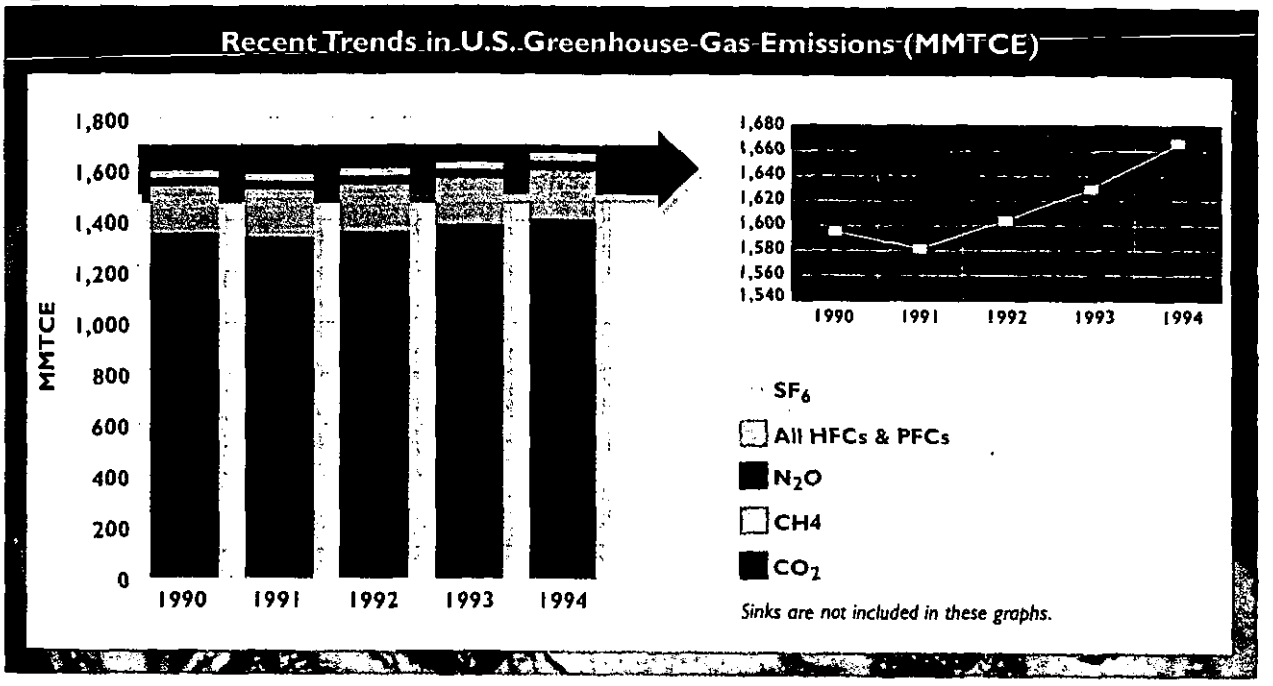
Gas/Source	Emissions (Full Molecular Weight)					Emissions (Direct and Indirect Effects; Carbon-Equivalent)				
	(Million Metric Tonnes)									
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
Greenhouse Gases										
Carbon Dioxide (CO_2)										
Fossil Fuel Combustion	4,899	4,839	4,914	5,020	5,098	1,336	1,320	1,340	1,369	1,390
Other	62	61	62	64	63	17	17	17	18	17
Total	4,961	4,901	4,976	5,084	5,161	1,353	1,336	1,357	1,387	1,408
Forests (sink)	(458)	(458)	(458)	NA	NA	(125)	(125)	(125)	NA	NA
Net Total	4,503	4,443	4,518	NA	NA	1,228	1,211	1,232	NA	NA
Methane (CH_4)										
Landfills	9.9	10.1	9.9	10.0	10.2	66	67	66	67	68
Agriculture	8.4	8.5	8.8	8.8	9.2	56	57	59	59	61
Coal Mining	4.4	4.3	4.1	3.7	4.3	29	28	27	24	29
Oil and Gas Systems	3.2	3.3	3.3	3.2	3.3	22	22	22	22	22
Other	0.9	1.0	1.0	0.9	0.9	6	7	7	6	6
Total	27.1	27.3	27.2	26.7	28.0	181	182	182	179	188
Nitrous Oxide (N_2O)										
Agriculture	0.2	0.2	0.2	0.2	0.2	16	17	17	17	19
Fossil Fuel Consumption	0.1	0.1	0.1	0.1	0.1	12	12	12	12	12
Industrial Processes	0.1	0.1	0.1	0.1	0.1	8	9	8	9	9
Total	0.4	0.4	0.4	0.4	0.5	37	37	37	38	41
HFCs and PFCs	*	*	*	*	*	18.8	19.3	21.1	19.8	23.5
SF_6	+	+	+	+	+	6.4	6.5	6.7	6.8	7.0
Photochemically Important Gases										
NO_x	20.6	20.4	20.6	21.0	21.2	–	–	–	–	–
NMVOC	18.7	18.3	18.2	18.2	18.6	–	–	–	–	–
CO	83.4	82.7	81.6	81.3	83.1	–	–	–	–	–
U.S. Emissions						1,595	1,582	1,604	1,630	1,666
Net, Including Sinks						1,470	1,457	1,479	NA	NA

** As this category contains multiple gases, an aggregate full molecular weight sum is not calculated.*
+ Total of this gas does not exceed 0.01 million metric tonnes.
NA = not available
Note: Totals may not equal the sum of the individual source categories due to independent rounding.

sions from 1990 to 1994. While these emissions of CO_2 in 1991 were approximately 1.2 percent lower than 1990 emission levels in the U.S., in 1992 they were about 1.5 percent over 1991 levels, thus returning emissions to slightly over 1990 levels. By 1993 CO_2 emissions from fossil fuel combustion were approximately 2.5 percent greater than 1990, with emissions in 1994 about 4 percent higher than 1990. This trend is largely attributable to changes in total energy consumption resulting from the economic slowdown in the U.S. during the early 1990s and the subsequent recovery, as can be clearly seen in Figure ES-2.

Methane, N_2O, and HFCs and PFCs represent a much smaller portion of total emissions than CO_2. In most cases, emissions of these gases remained relatively constant from 1990 to 1994. However, methane emissions from coal mining declined significantly in 1993, largely due to decreases in coal production as a result of labor unrest in 1993. As coal

Figure ES-2



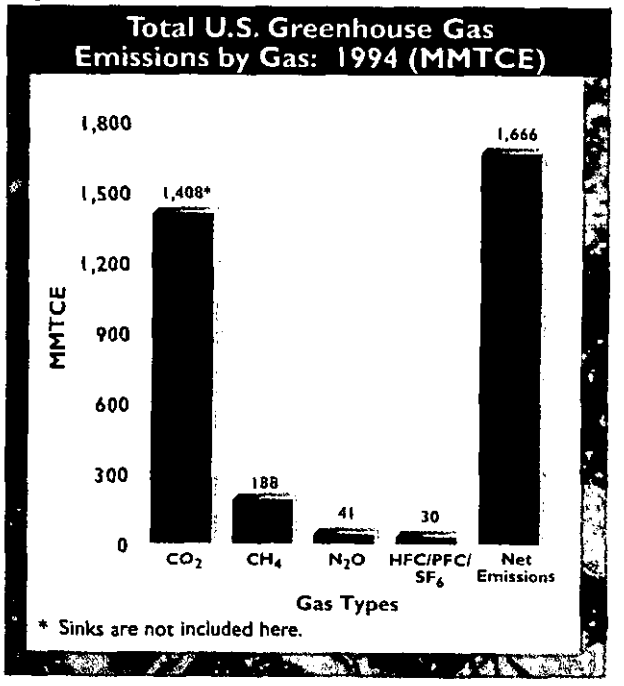
production has risen since the end of the strikes, emissions have increased commensurately. Also, emissions of HFCs and PFCs have fluctuated significantly in the 1990s, initially declining in response to lower CFC production. The use of these chemicals has begun to increase, however, as replacements for CFCs and other ozone-depleting compounds being phased out under the terms of the Montreal Protocol and Clean Air Act Amendments.

Figure ES-3 illustrates the relative contribution of the primary greenhouse gases to total U.S. emissions in 1994. Due largely to fossil fuel consumption, CO_2 emissions accounted for the largest share of U.S. emissions on a carbon equivalent basis — almost 85 percent. These emissions were partially offset by the sequestration that occurred on forested lands. Methane accounted for 11 percent of total emissions, including contributions from landfills and agricultural activities, among others.

The other gases contributed less to emissions, with N_2O emissions comprising about 2 percent of total U.S. emissions, HFCs accounting for just over one percent, PFCs about 0.2 percent, and SF_6 about 0.4 percent. Any gases covered under the Montreal Protocol are not included because their use is being phased out, and the *IPCC Guidelines* (IPCC/OECD/IEA, 1995) recommend excluding gases covered by the Montreal Protocol.

The following sections present the anthropogenic sources of greenhouse gas emissions, briefly discuss the emission pathways, summarize the emission estimates, and explain the relative importance of emissions from each source category.

Figure ES-3



Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Hundreds of billions of tons of carbon in the form of carbon dioxide (CO_2) are absorbed by oceans, trees, soil, and vegetative cover and are emitted to the atmosphere annually through natural processes. When in equilibrium, carbon flows between the various reservoirs roughly balance each other. Since the Industrial Revolution, however, atmospheric concentrations of carbon dioxide have risen more than 25 percent, principally because of the combustion of fossil fuels (IPCC, 1992). While the combustion of fossil fuels accounts for 99 percent of total U.S. carbon dioxide emissions, carbon dioxide emissions also result directly from industrial processes. Changes in land use and forestry activities both emit carbon dioxide (*e.g.*, as a result of forest clearing) and can act as a sink for carbon dioxide (*e.g.*, as a result of improved forest management activities).

Table ES-2 summarizes U.S. emissions of carbon dioxide for 1994, while the remainder of this section presents detailed information on the various anthropogenic sources and sinks of carbon dioxide in the United States.

Table ES-2

Sources of CO_2 Emissions by Source: 1994

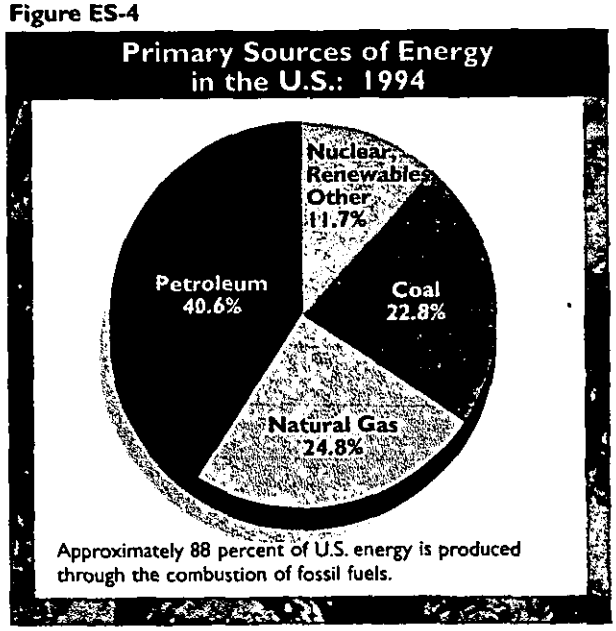
Source/Sink	CO_2 Emissions (Molecular Basis)	CO_2 Emissions (Carbon-Equivalent)
	(Million Metric Tonnes)	
Sources		
Fossil Fuel Consumption		
Residential	1,001	273
Commercial	798	218
Industrial	1,709	466
Transportation	1,553	424
U.S. Territories	36	10
Total	5,098	1,390
Fuel Production and Processing	5.0	1.4
Cement Production	35.5	9.7
Lime Production	12.7	3.5
Limestone Consumption	4.6	1.2
Soda Ash Production and Consumption	4.0	1.1
Carbon Dioxide Manufacture	1.3	0.4
Sinks	NA	NA
Total Emissions	5,161	1,408

Note: The totals provided here do not reflect emissions from bunker fuels used in international transport activities. The INC 9th Session instructed countries to report these emissions separately, and not to include them in national totals. U.S. emissions from bunker fuels were approximately 23 MMTCE in 1994.

Energy

Approximately 88 percent of U.S. energy is produced through the combustion of fossil fuels. The remaining 12 percent comes from renewable or other energy sources such as hydropower, biomass, and nuclear energy (see Figure ES-4). As they burn, fossil fuels emit carbon dioxide due to oxidation of the carbon contained in the fuel. The amount of carbon in fossil fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of energy, while petroleum has about 20 percent less carbon than coal, and natural gas has about 45 percent less.

Figure ES-4



Fossil Fuel Consumption

In 1994, the United States emitted a total of 1,390 MMTCE of carbon dioxide from fossil fuel combustion. (Bunker fuels, or fuels used in international transport, accounted for an additional 23 MMTCE.) The energy-related activities producing these emissions included heating in residential and commercial buildings, the generation of electricity,

steam production for industrial processes, and gasoline consumption in automobiles and other vehicles. Petroleum products across all sectors of the economy accounted for about 42 percent of total U.S. energy-related carbon dioxide emissions; coal, 36 percent; and natural gas, 22 percent.

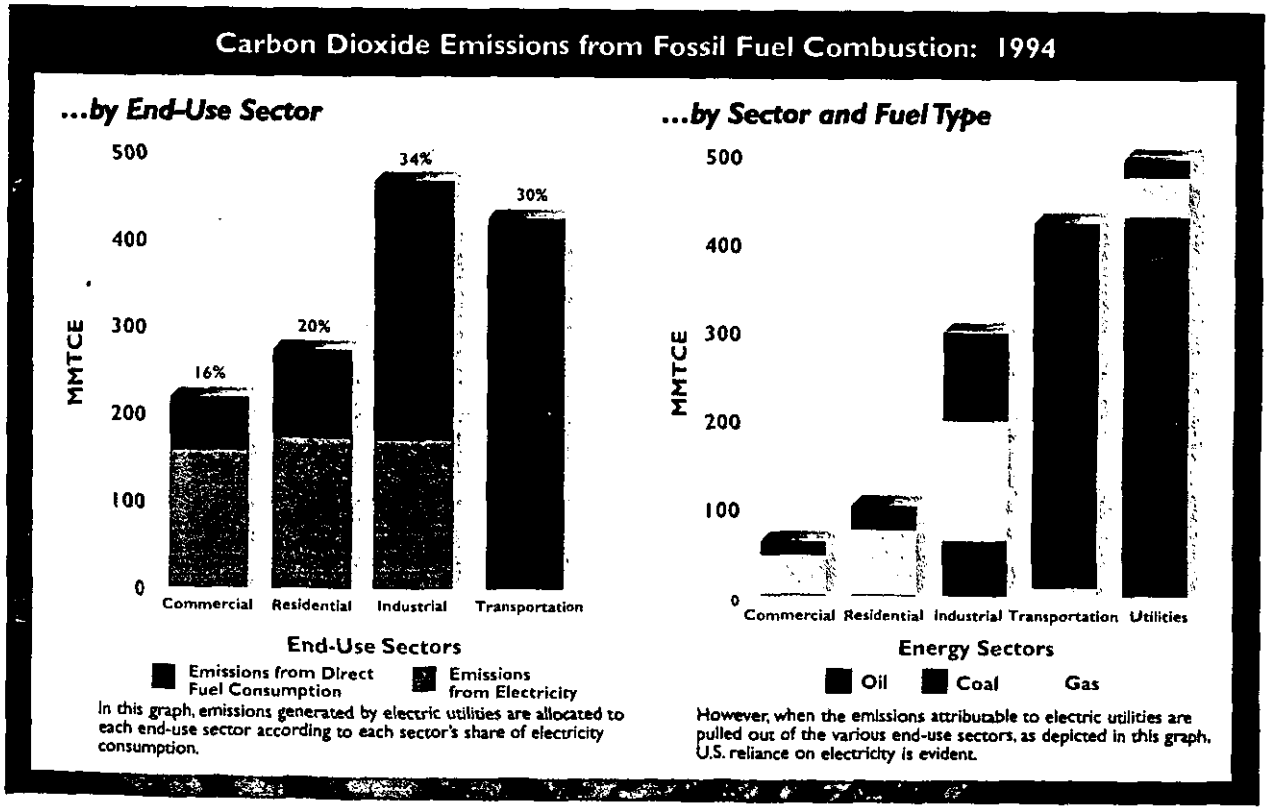
Industrial Sector. The industrial sector accounts for 34 percent of U.S. carbon dioxide emissions from fossil fuel consumption, making it the largest end-use source of carbon dioxide emissions (see Figure ES-5). About two-thirds of these emissions result from the direct consumption of fossil fuels in order to meet industrial demand for steam and process heat. The remaining one-third of industrial energy needs are met by electricity for such uses as motors, electric furnaces and ovens, and lighting.

The industrial sector is also the largest user of nonenergy applications of fossil fuels, which often store carbon. Fossil fuels used for producing fertilizers, plastics, asphalt, or lubricants can store carbon in products for very long periods. Asphalt used in road construction, for example, stores carbon indefinitely. Similarly, the fossil fuels used in the manufacture of materials like plastics also store carbon, releasing this carbon only if the product is incinerated.

Transportation Sector. The transportation sector is also a major source of carbon dioxide, accounting for just over 30 percent of U.S. emissions. Virtually all of the energy consumed in this sector comes from petroleum-based products. Nearly two-thirds of the emissions are the result of gasoline consumption in automobiles and other vehicles, with other uses, including diesel fuel for the trucking industry and jet fuel for aircraft, accounting for the remainder.

Residential and Commercial Sectors. The residential and commercial sectors account for about 20 and 16 percent, respectively, of carbon dioxide emissions from fuel consumption. Both sectors rely heavily on electricity for meeting energy needs, with about two-thirds to three-quarters of their emissions attributable to electricity consumption. End-use applications include lighting, heating, cooling, and operating appliances. The remaining emissions are largely due to the consumption of natural gas and oil, primarily for meeting heating and cooking needs.

Figure ES-5



Electric Utilities. The U.S. relies on electricity to meet a significant portion of its energy requirements. In fact, as the largest consumers of fossil fuels, electric utilities are collectively the largest producers of U.S. carbon dioxide emissions (see Figure ES-5). Electric utilities generate electricity for uses such as lighting, heating, electric motors, and air conditioning. Some of this electricity is generated with the lowest carbon dioxide-emitting energy technologies, particularly nonfossil options, such as nuclear energy, hydropower, or geothermal energy. However, electric utilities rely on coal for 55 percent of their total energy requirements and account for about 86 percent of all coal consumed in the United States.

Fuel Production and Processing

Carbon dioxide is produced via flaring activities at natural gas systems and oil wells. Typically, the methane that is trapped in a natural gas system or oil well is flared to relieve the pressure building in the system or to dispose of small quantities of gas that are not commercially marketable. As a result, the carbon contained in the methane becomes oxidized and forms carbon dioxide. In 1994, the amount of carbon dioxide from the flared gas was just over 1 MMTCE, or about 0.1 percent of total U.S. carbon dioxide emissions.

Biomass and Biomass-Based Fuel Consumption

Biomass fuel is used primarily by the industrial sector in the form of fuelwood and wood waste. Biomass-based fuel use, such as ethanol from corn or woody crops, occurs mainly in the transportation sector. Ethanol and ethanol blends, such as gasohol, are typically used to fuel public transport vehicles, such as buses or centrally fueled fleet vehicles.

Biomass, ethanol, and ethanol-blend fuels do release carbon dioxide. However, in the long run, the carbon dioxide they emit does not increase total atmospheric carbon dioxide because the biomass resources are consumed on a sustainable basis. For example, fuelwood burned one year but regrown the next only recycles carbon, rather than creating a net increase in total atmospheric carbon.

Carbon dioxide emissions from biomass consumption in 1994 were approximately 49 MMTCE, with the industrial sector accounting for 75 percent of the emissions and the residential sector 23 percent, the rest being made up of commercial and electric utility consumption. Carbon dioxide emissions from ethanol use in the United States have been increasing in recent years due to a number of factors, including the extension of Federal tax exemptions for ethanol production, the Clean Air Act Amendments mandating the reduction of mobile source emissions, and the Energy Policy Act of 1992 which established incentives to increase the use of alternative fuels and alternative-fueled vehicles. In 1994, total U.S. carbon dioxide emissions from ethanol were 1.85 MMTCE.

Industrial Processes

Emissions are often produced as a by-product of various nonenergy-related activities. For example, in the industrial sector raw materials are chemically transformed from one state to another. This transformation often releases such greenhouse gases as carbon dioxide. The production processes that emit carbon dioxide include cement production, lime production, limestone consumption (*e.g.*, in iron and steel production), soda ash production and use, and carbon dioxide manufacture. Total carbon dioxide emissions from these sources were approximately 16 MMTCE in 1994, accounting for about 1 percent of total U.S. carbon dioxide emissions.

Cement Production (9.6 MMTCE)

Carbon dioxide is produced primarily during the production of clinker, an intermediate product from which finished portland and masonry cement are made. Specifically, carbon dioxide is created when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime and carbon dioxide. This lime combines with other materials to produce clinker, while the carbon dioxide is released into the atmosphere. Since 1990, carbon dioxide emissions from cement production have increased about 8.4 percent, from 8.9 MMTCE in 1990 to 9.6 MMTCE in 1994.

Lime Production (3.5 MMTCE)

Lime is used in steel making, construction, pulp and paper manufacturing, and water and sewage treatment. It is manufactured by heating limestone (mostly calcium carbonate) in a kiln, creating calcium oxide (quicklime) and carbon dioxide, which is normally emitted to the atmosphere. Since 1990, carbon dioxide emissions from lime production have increased by approximately 7 percent, from 3.3 MMTCE in 1990 to 3.5 MMTCE in 1994.

Limestone Consumption (1.2 MMTCE)

Limestone is a basic raw material used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries. For example, limestone can be used as a purifier in refining metals, such as iron. In this case, limestone heated in a blast furnace reacts with impurities in the iron ore and fuels, generating carbon dioxide as a by-product. It is also used in flue gas desulfurization systems to remove sulfur dioxide from the exhaust gases. Since 1990, carbon dioxide emissions from limestone consumption have declined by about 10 percent, from 1.38 MMTCE in 1990 to 1.24 MMTCE in 1994.

Soda Ash Production and Consumption (1.1 MMTCE)

Commercial soda ash (sodium carbonate) is used in many consumer products, such as glass, soap and detergents, paper, textiles, and food. During the manufacturing of these products, natural sources of sodium carbonate are heated and transformed into a crude soda ash, in which carbon dioxide is generated as a by-product. In addition, carbon dioxide is released when the soda ash is consumed. Of the two states that produce natural soda ash, only Wyoming has net emissions of carbon dioxide, because producers in California recover the carbon dioxide and use it in other stages of production. U.S. carbon dioxide emissions from soda ash *production* were approximately 0.4 MMTCE in 1994, while U.S. soda ash *consumption* generated about 0.7 MMTCE. Since 1990, carbon dioxide emissions from soda ash manufacture and consumption have declined slightly, from 1.13 MMTCE in 1990 to 1.10 MMTCE in 1994.

Carbon Dioxide Manufacture (0.4 MMTCE)

Carbon dioxide is used in many segments of the economy, including food processing, beverage manufacturing, chemical processing, crude oil products, and a host of industrial and miscellaneous applications. For the most part, carbon dioxide used in these applications will eventually be released into the atmosphere. Since 1990, carbon dioxide emissions from carbon dioxide manufacture have increased slightly, from 0.33 MMTCE in 1990 to 0.37 MMTCE in 1994.

Forests and Land Use Change

When humans use and alter the biosphere through changes in land use and forest-management activities, they alter the natural balance of trace gas emissions and uptake. These activities include clearing an area of forest to create cropland or pasture, restocking a logged forest, draining a wetland, or allowing a pasture to revert to a grassland or forest. Forests, which cover about 737 million acres of U.S. land (Powell, *et al.*, 1993), are a potentially important terrestrial sink for carbon dioxide. Because approximately half the dry weight of wood is carbon, as trees add mass to trunks, limbs, and roots, carbon is stored in relatively long-lived trees instead of being released to the atmosphere. Soils and vegetative cover also provide a potential carbon sink.

Carbon fluxes can also be attributed to biomass that is harvested and used in wood products or disposed in landfills. The potential carbon flux associated with these biomass pools, however, is significantly smaller than the carbon flux associated with forests. Therefore, the majority of this discussion focuses on the carbon flux associated with land-use change and forest management activities.

In the United States, improved forest-management practices and the regeneration of previously cleared forest area have actually resulted in a net uptake (sequestration) of carbon on U.S. lands. This carbon uptake is an ongoing result of land-use changes in previous decades. For example, because of improved agricultural productivity and the widespread use of tractors, the rate of clearing forest land for crop cultivation and pasture slowed greatly in the

late 19th century, and by 1920 this practice had all but ceased. As farming expanded in the Midwest and West, large areas of previously cultivated land in the East were brought out of crop production, primarily between 1920 and 1950, and were allowed to revert to forest land or were actively reforested. The regeneration of forest land greatly increases carbon storage in both standing biomass and soils and the impacts of these land-use changes continue to affect forest carbon fluxes in the East. In addition to land-use changes in the early part of this century, forest carbon fluxes in the East are affected by a trend toward managed growth on private land in recent decades, resulting in a near doubling of the biomass density in eastern forests since the early 1950s. More recently, the 1970s and 1980s saw a resurgence of federally sponsored tree-planting programs (*e.g.*, the Forestry Incentive Program) and soil conservation programs (*e.g.*, the Conservation Reserve Program), which have focused on reforesting previously harvested lands, improving timber-management activities, combating soil erosion, and converting marginal cropland to forests.

The net carbon dioxide flux in 1990, 1991 and 1992 due to these activities is estimated to have been an uptake (sequestration) of 125 MMTCE per year. This carbon uptake represents an offset of about 9 percent of the average annual carbon dioxide emissions from energy-related activities during this period. Emission estimates are not yet available for 1993 and 1994 because the last national forest inventory was completed in 1992.

There are several major sources of uncertainty associated with the estimates of the total net carbon flux from U.S. forests. These sources are briefly described below:

- *The forest surveys used to compile these estimates are based on a statistical sampling instead of actual measurements.* The surveys are based on a statistical sample designed to represent a wide variety of growth conditions present over large territories. The actual values of carbon stored in forests, therefore, are represented by average values that are subject to sampling and estimation errors.
- *The impacts of forest management activities on soil carbon are quite uncertain.* Forest soils and forest floors contain over 60 percent of the total U.S. forest carbon. However, because of uncertainties associated with soil and forest floor carbon fluxes, these components are not included in the U.S. estimate at this time.
- *The current estimate does not include forest land in Alaska and Hawaii or reserved timber land.* However, forests in these states are believed to be in equilibrium, so their inclusion would not significantly affect the flux estimates presented here.
- *Forest management activities may also result in fluxes of other greenhouse and photochemically important gases.* Dry soils are an important sink for CH_4, a source of N_2O, both a sink and a source for CO, and vegetation is a source of several NMHCs (nonmethane hydrocarbons, a subset of NMVOCs). However, the effects of forestry activities on these gases are highly uncertain, and are therefore not included in the U.S. inventory at this time.
- *Estimates from wood products pools and landfills are based on limited data and subject to significant uncertainties.* Research continues on the potential magnitude of these sources.

Methane Emissions

Atmospheric methane (CH_4) is second only to carbon dioxide as an anthropogenic source of greenhouse gas emissions. Methane's overall contribution to global warming is large because it is 24.5 times more effective at trapping heat in the atmosphere than carbon dioxide over a 100-year time horizon, when the direct as well as most indirect effects are considered (IPCC, 1994). Furthermore, methane's concentration in the atmosphere has more than doubled over the last two centuries. Scientists have concluded that these atmospheric increases are largely due to increasing emissions from anthropogenic sources, such as landfills, agricultural activities, fossil fuel combustion, coal mining, the production and processing of natural gas and oil, and wastewater treatment (see Table ES-3 and Figure ES-6).

Landfills

Landfills are the largest single anthropogenic source of methane emissions in the United States. There are an estimated 6,000 methane-emitting landfills in the United States, with 1,300 of the largest landfills accounting for about half of the emissions.

In an environment where the oxygen content is low or nonexistent, organic materials, such as yard waste, household waste, food waste, and paper, are decomposed by bacteria to produce methane, carbon dioxide, and stabilized organic materials (materials that cannot be decomposed further). Methane emissions from landfills are affected by such factors as waste composition, moisture, and landfill size.

Methane emissions from U.S. landfills in 1994 were 68.2 MMTCE, or about 36 percent of total U.S. methane emissions. Emissions from U.S. municipal solid waste landfills, which received approximately 67 percent of the total solid waste generated in the United States, accounted for about 90 to 95 percent of total landfill emissions, while industrial landfills accounted for the remaining 5 to 10 percent. Currently, about 15 percent of the methane emitted is recovered for use as an energy source.

Table ES-3

Sources of CH_4 Emissions: 1994

Source	CH_4 (Molecular Basis) (Million Metric Tonnes)	CH_4 (Carbon-Equivalent; GWP=24.5) (Million Metric Tonnes)
Landfills	10.2	68.2
Agriculture	9.2	61.5
Coal Mining	4.3*	28.9*
Oil and Natural Gas Systems	3.3*	22.1*
Fossil Fuel Combustion	0.9*	6.0*
Wastewater Treatment	0.2	1.0
Total	28.0	187.7

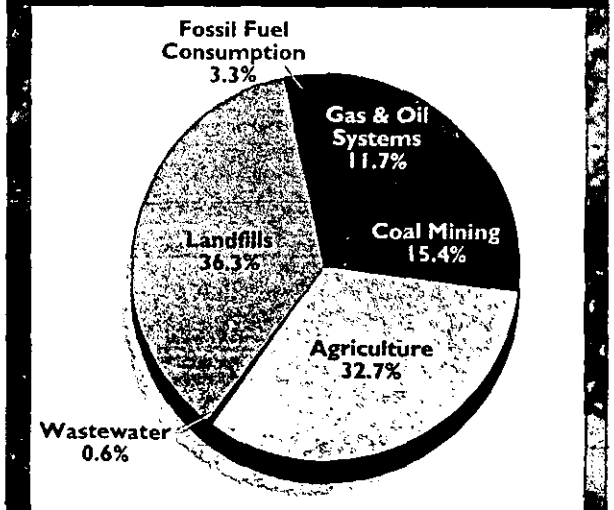
* *Preliminary estimate*

Agriculture

The agricultural sector accounted for approximately 33 percent of total U.S. methane emissions in 1994, with enteric fermentation in domestic livestock and manure management together accounting for the majority (see Figure ES-7). Other agricultural activities contributing directly to methane emissions include rice cultivation and field burning of agricultural crop wastes. Several other agricultural activities, such as irrigation and tillage practices, may contribute to methane emissions, but emissions from these sources are uncertain and believed to be small; therefore, the United States has not included them in the current inventory. Details on the emission pathways included in the inventory are presented below.

Figure ES-6

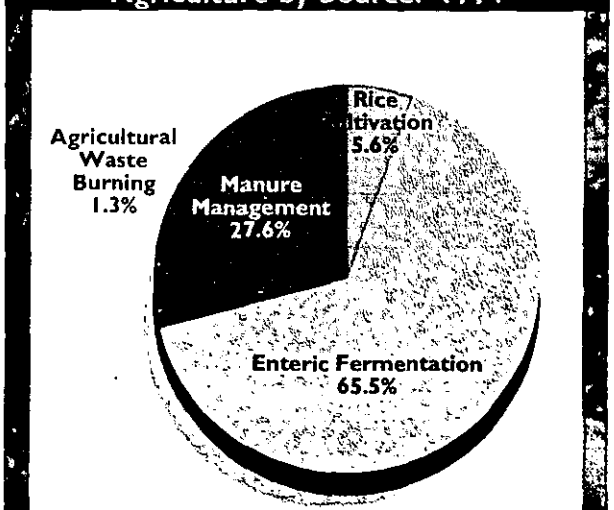
Sources of CH_4 Emissions: 1994



Landfills and agriculture are the largest sources of atmospheric methane in the United States.

Figure ES-7

CH_4 Emissions from Agriculture by Source: 1994



Enteric Fermentation in Domestic Livestock (40.2 MMTCE)

In 1994, enteric fermentation was the source of about 21 percent of total U.S. methane emissions, and about 65 percent of methane emissions from the agricultural sector. During animal digestion, methane is produced through enteric fermentation, a process in which microbes that reside in animal digestive systems break down the feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep, and goats, have the highest methane emissions among all animal types because they have a rumen, or large "fore-stomach," in which a significant amount of methane-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have much lower methane emissions than ruminants because much less methane-producing fermentation takes place in their digestive systems. The amount of methane produced and excreted by an individual animal also depends upon the amount and type of feed it consumes.

Manure Management (17.0 MMTCE)

The decomposition of organic animal waste in an anaerobic environment produces methane. The most important factor affecting the amount of methane produced is how the manure is managed, since certain types of storage and treatment systems promote an oxygen-free environment. In particular, liquid systems (*e.g.*, lagoons, ponds, tanks, or pits) tend to produce a significant quantity of methane. However, when manure is handled as a solid or when it is deposited on pastures and rangelands, it tends to decompose aerobically and produce little or no methane. Higher temperatures and moist climate conditions also promote methane production.

Emissions from manure management were about 9 percent of total U.S. methane emissions in 1994, and about 28 percent of methane emissions from the agricultural sector. Liquid-based manure management systems accounted for over 80 percent of total emissions from animal wastes.

Rice Cultivation (3.4 MMTCE)

Most of the world's rice, and all of the rice in the United States, is grown on flooded fields. When fields are flooded, anaerobic conditions in the soils develop, and methane is produced through anaerobic decomposition of soil organic matter. Methane is released primarily through the rice plants, which act as conduits from the soil to the atmosphere.

Rice cultivation is a very small source of methane in the United States. In 1994, methane emissions from this source were less than 2 percent of total U.S. methane emissions, and about 5.6 percent of U.S. methane emissions from agricultural sources.

Field Burning of Agricultural Wastes (0.8 MMTCE)

Large quantities of agricultural crop wastes are produced from farming systems. Disposal systems for these wastes include plowing them back into the field; composting, landfilling, or burning them in the field; using them as a biomass fuel; or selling them in supplemental feed markets. Burning crop residues releases a number of greenhouse gases, including carbon dioxide, methane, carbon monoxide, nitrous oxide, and oxides of nitrogen. Crop residue burning is not considered to be a net source of carbon dioxide emissions because the carbon dioxide released during burning is reabsorbed by crop regrowth during the next growing season. However, burning is a net source of emissions for the other gases. Because this practice is not common in the United States, it was responsible for only about 0.4 percent of total U.S. methane emissions in 1994, and 1.3 percent of emissions from the agricultural sector.

Coal Mining

Coal mining and post-mining activities, such as coal processing, transportation, and consumption, are the third largest source of methane emissions in the United States. Estimates of methane emissions from coal mining for 1994 were 28.9 MMTCE, which accounted for about 15 percent of total U.S. methane emissions.

Produced millions of years ago during the formation of coal, methane is trapped within coal seams and surrounding rock strata. When coal is mined, methane is released into the atmosphere. The amount of methane released from a coal mine depends pri-

marily upon the depth and type of coal, with deeper mines generally emitting more methane (U.S. EPA, 1993a). Methane from surface mines is emitted directly to the atmosphere as the rock strata overlying the coal seam are removed.

Methane is hazardous in underground mines because it is explosive at concentrations of 5 to 15 percent in air. Therefore, all underground mines are required to remove methane by circulating large quantities of air through the mine and venting this air into the atmosphere. At some mines, more advanced methane-recovery systems may be used to supplement the ventilation systems and ensure mine safety. The practice of using the recovered methane as an energy source has been increasing in recent years.

Oil and Natural Gas Production and Processing

Methane is also the major component of natural gas. Any leakage or emission during the production, processing, transmission, and distribution of natural gas emits methane directly to the atmosphere. Because natural gas is often found in conjunction with oil, leakage during the production of commercial quantities of gas from oil wells is also a source of emissions. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment condition. Fugitive emissions can occur at all stages of extraction, processing, and distribution. In 1994, emissions from the U.S. natural gas system were estimated to be 20.3 MMTCE, accounting for approximately 11 percent of total U.S. methane emissions.

Methane is also released as a result of oil production and processing activities, such as crude oil production, crude oil refining, transportation, and storage, when commercial gas production is not warranted due to the small quantities present. Emissions from these activities are generally released as a result of system leaks, disruptions, or routine maintenance. For 1994, methane emissions from oil production and processing facilities were 1.8 MMTCE, accounting for about 1 percent of total U.S. methane emissions.

Other Sources

Methane is also produced from several other sources in the United States, including energy-related combustion activities, wastewater treatment, industrial processes, and changes in land use. The sources included in the U.S. inventory are fossil fuel combustion and wastewater treatment. In 1994, 6.1 MMTCE of methane were emitted from fossil fuel combustion, which accounted for about 3.3 percent of total U.S. methane emissions. Approximately 1.1 MMTCE, or less than 1 percent of total U.S. methane emissions, were emitted due to wastewater treatment. Additional anthropogenic sources of methane in the United States, such as land use changes and ammonia, coke, iron, and steel production, are not included because little information on methane emissions from these sources is currently available.

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is a chemically and radiatively active greenhouse gas that is produced naturally from a wide variety of biological sources in soil and water. While actual emissions of nitrous oxide are much smaller than carbon dioxide emissions, nitrous oxide is approximately 320 times more powerful than carbon dioxide at trapping heat in the atmosphere over a 100-year time horizon.

Over the past two centuries, human activities have raised atmospheric concentrations of nitrous oxide by approximately 8 percent. The main anthropogenic activities producing nitrous oxide are soil management and fertilizer use for agriculture, fossil fuel combustion, adipic acid production, nitric acid production, and agricultural waste burning. The relative share of each of these activities to total U.S. nitrous oxide emissions is shown in Figure ES-8, and U.S. nitrous oxide emissions by source category for 1994 are provided in Table ES-4.

Agricultural Soil Management and Fertilizer Use

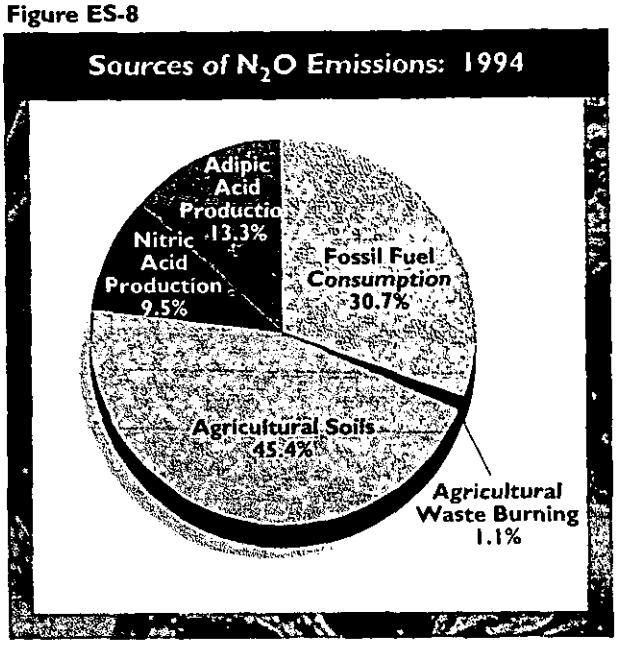
The primary sources of anthropogenic nitrous oxide emissions in the United States are fertilizer use and soil management activities. Synthetic nitrogen

Table ES-4

Sources of N_2O Emissions: 1994

Source	N_2O (Molecular Basis)	N_2O (Carbon-Equivalent; GWP=320)
	(Million Metric Tonnes)	
Agricultural Soil Management and Fertilizer Use	0.21	18.4
Fossil Fuel Consumption	0.14	12.4
Adipic Acid Production	0.06	5.4
Nitric Acid Production	0.04	3.8
Agricultural Waste Burning	0.005	0.4
Total	0.46	40.5

Figure ES-8



fertilizers and organic fertilizers add nitrogen to soils, and thereby increase emissions of nitrous oxide. Nitrous oxide emissions in 1994 due to consumption of synthetic and organic fertilizers were 18.4 MMTCE, or approximately 45 percent of total U.S. nitrous oxide emissions.

Other agricultural soil management practices, such as irrigation, tillage practices, or the fallowing of land, can also affect nitrous oxide fluxes to and from the soil. There is much uncertainty about the direction and magnitude of the effects of these other practices. Only emissions from fertilizer use and field burning of agricultural wastes are included in the U.S. inventory.

Fossil Fuel Combustion

Nitrous oxide is a product of the reaction that occurs between nitrogen and oxygen during fossil fuel combustion. Both mobile and stationary sources emit nitrous oxide. Emissions from mobile sources are more significant and are better understood than those from stationary sources. The amount of nitrous oxide emitted varies, depending upon fuel, technology type, and pollution control device. Emissions also vary with the size and vintage of the combustion technology, as well as maintenance and operation practices.

For example, catalytic converters installed to reduce air pollution resulting from motor vehicles have been proven to promote the formation of nitrous oxide. As catalytic converter-equipped vehicles have increased in the U.S. motor vehicle fleet, emissions of nitrous oxide from this source have also increased (EIA, 1994d). Mobile emissions totaled 9.3 MMTCE in 1994 (23 percent of total nitrous oxide emissions), with road transport accounting for approximately 95 percent of these nitrous oxide emissions. Nitrous oxide emissions from stationary sources were 3.2 MMTCE in 1994.

Adipic Acid Production

Nitrous oxide is emitted as a by-product of the production of adipic acid. Ninety percent of all adipic acid produced in the United States is used to produce nylon 6,6. It is also used to produce some low-temperature lubricants, and to provide foods with a "tangy" flavor. In 1994, U.S. adipic acid production generated 5.4 MMTCE of nitrous oxide, or 13 percent of total U.S. nitrous oxide emissions.

Nitric Acid Production

Production of nitric acid is another industrial source of nitrous oxide emissions. Nitric acid is a raw material used primarily to make synthetic commercial fertilizer, and is also a major component in the production of adipic acid and explosives. Virtually all of the nitric acid that is manufactured commercially in the United States is obtained by the oxidation of ammonia. During this process, nitrous oxide is formed and emitted to the atmosphere. Nitrous oxide

emissions from this source were about 3.8 MMTCE in 1994, accounting for about 9 percent of total U.S. nitrous oxide emissions.

Other Sources of Nitrous Oxide

Other activities that emit nitrous oxide include the burning of agricultural crop residues and changes in land use. Emissions from agricultural crop residue burning are extremely small relative to overall U.S. nitrous oxide emissions. Nitrous oxide emissions in 1994 from this source were approximately 0.4 MMTCE, or about 1 percent of total U.S. nitrous oxide emissions.

Forestry activities may also result in fluxes of nitrous oxide, since dry soils are a source of nitrous oxide emissions. However, the effects of forestry activities on fluxes of these gases are highly uncertain; therefore, they are not included in the inventory at this time. Similarly, the U.S. inventory does not account for several land-use changes because of uncertainties in their effects on trace gas fluxes, as well as poorly quantified land-use change statistics. These land-use changes include loss and reclamation of freshwater wetland areas, conversion of grasslands to pasture and cropland, and conversion of managed lands to grasslands.

Table ES-5

Emissions of HFCs, PFCs, and SF_6: 1994

Compound	Molecular Basis	GWP	Carbon Equivalent
		(Million Metric Tonnes)	
HFCs			
HFC-23	0.00418	12,100	13.80
HFC-125	0.00113	3,200	0.99
HFC-134a	0.01041	1,300	3.69
HFC-152a	0.00153	140	0.06
HFC-227	0.00089	3,300	0.80
PFCs			
CF_4	0.00200	6,300	3.43
C_2F_6	0.00020	12,500	0.68
SF_6	0.00103	24,900	6.96

Source: Abseck (1995)

In 1994, the use of substitutes for ODS was minimal. Thus, emissions of HFCs were quite small, and were largely the result of by-product emissions from the production of HCFC-22. PFC emissions were the result of aluminum smelting activities.

HFC, PFC, and SF_6 Emissions

Emissions of hydrofluorocarbon (HFC) and perfluorocarbon (PFC) chemicals occur for three reasons. First, these chemicals were introduced as alternatives to the ozone-depleting substances (ODS) under phaseout by the Montreal Protocol and Clean Air Act Amendments of 1990. Second, some of the HFCs and PFCs are emitted as by-products of industrial reactions. Third, some manufacturing procedures employ these chemicals intentionally.

As substitutes for ODSs, HFCs and PFCs do not directly harm the stratospheric ozone layer, but they are powerful greenhouse gases. In many cases, HFCs and PFCs absorb much more radiation than equivalent amounts of carbon dioxide. For this reason, their emissions are addressed by the Framework Convention on Climate Change (FCCC). An example of an ODS substitute with a high global warming potential (GWP) is HFC-134a, with a GWP of 1,300 over a 100 year time horizon. Emissions of HFC-134a reached 3.7 MMTCE in 1994. Other HFCs included in the *Inventory* are HFC-125, HFC-152a, and HFC-227; their emissions are listed in Table ES-5. From 1990 to 1994, the use of CFC substitutes has grown primarily due to HFC-134a use in automobile air conditioners. Emissions of HFCs and PFCs as ODS substitutes are expected to rise.

Emissions of HFCs and PFCs also occur as by-products of industrial reactions. HFC-23 is produced and emitted as a by-product of HCFC-22 production; 1994 HFC-23 emissions were estimated to be 13.8 MMTCE. The PFCs, CF_4 and C_2F_6, were emitted as by-products of aluminum smelting; 1994 CF_4 and C_2F_6 emissions reached 3.4 MMTCE and 0.7 MMTCE, respectively.

Sulfur hexafluoride (SF_6) use occurs primarily in electrical transmission and distribution systems where it serves as a dielectric and

Box ES-2

Emissions of CFCs and Related Compounds

Chlorofluorocarbons (CFCs) and other halogenated compounds were first emitted into the atmosphere this century. This family of man-made compounds includes chlorofluorocarbons, halons, methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). These substances are used in a variety of industrial applications, including foam production and refrigeration, air conditioning, solvent cleaning, sterilization, fire extinguishing, paints, coatings, other chemical intermediates, and miscellaneous uses (e.g., aerosols, propellants and other products).

Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances, or ODSs. In addition, they are important greenhouse gases because they block infrared radiation that would otherwise escape into space (IPCC, 1990).

Recognizing the harmful effects of these compounds on the atmosphere, in 1987 many governments signed the Montreal Protocol on Substances that Deplete the Ozone Layer to limit the production and consumption of a number of CFCs and other halogenated compounds. As of August 1995, 149 countries have signed the Montreal Protocol. The United States furthered its commitment to phase out these substances by signing and ratifying the Copenhagen Amendments to the Montreal Protocol in 1992. Under these amendments, the United States committed to eliminating the production of all halons by January 1, 1994, and all CFCs by January 1, 1996.

The *IPCC Guidelines* do not include reporting emissions of CFCs and related compounds because their use is being phased out by the Montreal Protocol. The United States believes that no inventory is complete without these emissions; therefore, emission estimates for several Class I and Class II ODSs are provided in the table below. Compounds are classified as "Class I" or "Class II" substances based on their ozone-depletion potential, and must adhere to a distinct set of phase out requirements under the Montreal Protocol. Class I compounds are the primary ODSs in use today; Class II compounds include partially halogenated chlorine compounds (known as HCFCs), some of which were developed as interim replacements for CFCs. Because these HCFC compounds are only partially halogenated, their hydrogen-carbon bonds are more vulnerable to oxidation in the troposphere, and therefore pose only about one-tenth to one-hundredth the threat to stratospheric ozone compared to CFCs. Also, it should be noted that the effects of these compounds on radiative forcing are not provided here. Although CFCs and related compounds have very large direct GWPs, their indirect effects are believed to be negative and, therefore, could significantly reduce the magnitude of their direct effects (IPCC, 1992). Given the uncertainties surrounding the net effect of these gases, they are reported here on a full molecular weight basis only.

U.S. Emissions of Ozone-Depleting Substances and Related Compounds: 1994

Compound	Emissions (Million Metric Tonnes; Molecular Weight)	Compound	Emissions (Million Metric Tonnes; Molecular Weight)
Class I ODSs		*Class II ODSs*	
CFC-11	0.037	HCFC-22	0.105
CFC-12	0.059	HCFC-123	0.002
CFC-113	0.017	HCFC-124	0.002
CFC-114	0.005	HCFC-141b	0.016
CFC-115	0.003	HCFC-142b	0.010
Carbon Tetrachloride	0.016		
Methyl Chloroform	0.078		
Halon-1211	0.001		
Halon-1301	0.002		

Source: Abseck (1995)

insulator in circuit breakers, gas-insulated substations, and related equipment. Emissions occur from this use due to older, leaky equipment, improper maintenance, or intentional venting of the gas. The metals industries also employ SF_6 in degassing and magnesium protection. For this latter use, SF_6 protects molten metal from catastrophic oxidation, a process which emits most or all of the chemical. Overall emissions will likely grow if the need for magnesium in alloys increases as expected. In 1994, emissions of SF_6 reached 7.0 MMTCE.

Chlorofluorocarbons (CFCs) and other halocarbons, which were emitted into the atmosphere for the first time this century, have been shown to deplete

stratospheric ozone, and thus are typically referred to as ozone-depleting substances, or ODSs. Emission estimates for several ODSs are provided in Box ES-2.

The growing semiconductor industry emits such greenhouse gases as CF_4, C_2F_6, NF_3, SF_6, C_3F_8, and HFC-23 due to use in plasma etching and chemical cleaning applications. Emissions of these gases in the semiconductor industry are expected to grow.

Criteria Pollutant Emissions

Carbon monoxide (CO), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2) are commonly referred to in the United States as "criteria pollutants".[1] Carbon monoxide is created when carbon-containing fuels are burned incompletely; oxides of nitrogen, NO and NO_2, are created from lightning, biomass fires, fossil-fuel combustion, and in the stratosphere from nitrous oxide (N_2O); NMVOCs include compounds such as propane, butane, and ethane, and are emitted primarily from transportation and industrial processes, as well as biomass burning, and nonindustrial consumption of organic solvents (U.S. EPA, 1990b); SO_2 can result from the combustion of fossil fuels, industrial processing (particularly in the metals industry), waste incineration, and biomass burning (U.S. EPA, 1993b).

Because of their contribution to the formation of urban smog, criteria pollutants are regulated under the 1970 Clean Air Act and successive amendments. These gases also have an impact on global climate, although their impact is limited because their radiative effects are indirect (*i.e.*, they do not directly act as greenhouse gases, but react with other chemical compounds in the atmosphere). It should be noted, however, that SO_2 emitted into the atmosphere affects the Earth's radiative budget negatively; therefore, it is discussed separately from the other criteria pollutants (see Box ES-3).

The most important of the indirect effects of the criteria pollutants — CO, NO_x and NMVOCs — is their role as *precursors* of tropospheric ozone. In this role, they contribute to ozone formation and alter the atmospheric lifetimes of other greenhouse gases. For example, CO interacts with the hydroxyl radical (OH) — the major atmospheric sink for CH_4 — to form CO_2. Therefore, increased atmospheric concentrations of CO limit the number of OH compounds available to destroy CH_4, thus increasing its atmospheric lifetime.

These criteria pollutants are generated through a variety of anthropogenic activities, including fossil fuel combustion, solid waste incineration, oil and gas production and processing, industrial processes and solvent use, and agricultural crop waste burning. Table ES-6 summarizes U.S. emissions from these sources for 1994. The United States has annually published estimates of criteria pollutants since 1970. Table ES-6 clearly shows that fuel consumption accounted for the majority of emissions of these gases. In fact, motor vehicles that burn fossil fuels comprise the single largest source of CO emissions in the United States, contributing nearly 90 percent of

Table ES-6

Emissions of CO, NO_x, and NMVOCs: 1994

Source	CO	NO_x	NMVOCs
	(Million Metric Tonnes)		
Fossil Fuel Combustion	74.04	20.27	8.56
Industrial Processes	4.56	0.64	3.48
Fossil Fuel Production, Distribution, and Storage	0.35	0.09	0.57
Waste Incineration	1.58	0.08	0.30
Agricultural Waste Burning	2.56	0.12	–
Solvent Use	0.002	0.003	5.73
Total	83.10	21.19	18.64

[1] The term criteria pollutant refers to those compounds for which attainment criteria have been established under the Clean Air Act Amendments of 1970. NO, NO_x, NMVOCs, and SO_2 all have air quality standards for which air quality criteria have been issued.

all U.S. CO emissions in 1994. Motor vehicles also emit about half of total U.S. NO_X and NMVOC emissions. Industrial processes, such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents, are also major sources of CO, NO_X and NMVOCs.

Box ES-3

Sulfur Dioxide: Effect on Radiative Forcing and Sources of Emissions

Sulfur dioxide (SO_2) emitted into the atmosphere through natural and anthropogenic processes affects the Earth's radiative budget through photochemical transformation into sulfate particles that 1) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; 2) possibly increase the number of cloud condensation nuclei, thereby potentially altering the physical characteristics of clouds, and 3) affect atmospheric chemical composition, e.g., stratospheric ozone, by providing surfaces for heterogeneous chemical processes. As a result of these activities, the effect of sulfur dioxide on radiative forcing may be negative (IPCC, 1992). Therefore, since its effects are uncertain and potentially opposite from the other criteria pollutants, emissions of SO_2 have been presented separately.

The major source of SO_2 emissions in the U.S. is the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also release significant quantities of SO_2. As a result, the largest contributor to overall U.S. emissions of SO_2 are electric utilities, accounting for about 70 percent. Coal combustion accounted for approximately 96 percent of SO_2 emissions from electric utilities. The second largest source is industrial fuel combustion, which produced about 14 percent of 1994 SO_2 emissions.

U.S. Emissions of SO_2: 1994

Source	Emissions (Million Metric Tonnes)
Fossil Fuel Combustion	17.31
Industrial Processes	1.43
Solvent Use	0.001
Waste Incineration	0.03
Fossil Fuel Production, Distribution and Storage	0.37
Total	19.16

Source: U.S. EPA, 1995b

Sulfur dioxide is important for reasons other than its effect on radiative forcing. It is a major contributor to the formation of urban smog and acid rain. As a contributor to urban smog, high concentrations of SO_2 can cause significant increases in acute and chronic respiratory diseases. In addition, once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to earth as the primary contributor to acid deposition, or acid rain. Acid rain has been found to accelerate the decay of building materials and paints, as well as cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the U.S. has regulated the emissions of SO_2 in the Clean Air Act of 1970 and in its amendments of 1990. The U.S. EPA has also developed a strategy to control these emissions via four programs: 1) the National Ambient Air Quality Program, which protects air quality and public health on the local level; 2) the New Source Performance Standards, which set emission limits for new sources; 3) the New Source Review/Prevention of Significant Deterioration Program, which protects air quality from deteriorating, especially in clean areas; and 4) the Acid Rain Program, which addresses regional environmental problems often associated with long-range transport of SO_2 and other pollutants.

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Introduction

The Earth naturally absorbs radiation from the sun, primarily at the surface, and reradiates this energy to space. A portion of this reradiated energy is absorbed or "trapped" by gases in the atmosphere. This "trapped" energy warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the Earth's temperature would average about 55°F lower than today.

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).[1] Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), a family of human-made compounds, their substitutes hydrofluorocarbons (HFCs), and other compounds such as perfluorocarbons (PFCs), are also greenhouse gases. In addition, there are other photochemically important gases such as carbon monoxide (CO), oxides of nitrogen (NO_X), and nonmethane volatile organic compounds (NMVOCs) that, although not greenhouse gases, contribute indirectly to the greenhouse effect. These are commonly referred to as tropospheric ozone precursors because they influence the rate at which ozone and other gases are created and destroyed in the atmosphere. Box 1 contains a brief description of these gases, their sources, and their roles in the atmosphere.[2] In addition, emissions of sulfur dioxide (SO_2) are provided in Annex F of this report. Sulfur gases, primarily sulfur dioxide, are believed to contribute negatively to the greenhouse effect. Therefore, the U.S. has discussed these emissions separately.

Although CO_2, CH_4 and N_2O occur naturally in the atmosphere, their recent atmospheric buildup appears to be largely the result of anthropogenic activities. This buildup has altered the composition of the Earth's atmosphere, and possibly will affect future global climate. Since 1800, atmospheric concentrations of CO_2 have increased more than 25 percent, CH_4 concentrations have more than doubled, and N_2O concentrations have risen approximately 8 percent (IPCC, 1992). And, from the 1950s until the mid-1980s, when international concern over CFCs grew, the use of these gases increased nearly 10 percent per year. The consumption of CFCs is declining quickly, however, as these gases are phased out under the Montreal Protocol. Use of CFC substitutes, in contrast, is expected to grow significantly.

[1] Ozone exists in the stratosphere and troposphere. In the stratosphere (about 20–50 km above the Earth's surface), ozone provides a protective layer shielding the Earth from ultraviolet radiation and subsequent harmful health effects on humans and the environment. In the troposphere (from the Earth's surface to about 10 km above), ozone is a chemical oxidant and major component of photochemical smog. Most ozone is found in the stratosphere, with some transport occurring to the troposphere (through the tropopause, *i.e.*, the transition zone separating the stratosphere and the troposphere) (IPCC, 1992).

[2] For convenience, all gases discussed in this inventory are generically referred to as "greenhouse gases," although the reader should keep in mind the distinction between actual greenhouse gases and other photochemically important trace gases.

Box 1

Greenhouse Gases and Other Photochemically Important Gases

The Greenhouse Gases

Carbon Dioxide (CO_2). The combustion of liquid, solid, and gaseous fossil fuels is the major anthropogenic source of carbon dioxide emissions. Some other non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide. Carbon dioxide emissions are also a product of forest clearing and biomass burning. Atmospheric concentrations of CO_2 have been increasing at a rate of approximately 0.5 percent per year (IPCC, 1992), although recent measurements suggest that this rate of growth may be moderating (Kerr, 1994).

In nature, CO_2 is cycled between various atmospheric, oceanic, land biotic, and marine biotic reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. While there is a small net addition of CO_2 to the atmosphere (*i.e.*, a net source of CO_2) from equatorial regions, oceanic and terrestrial biota in the Northern Hemisphere, and to a lesser extent in the Southern Hemisphere, act as a net sink of CO_2 (*i.e.*, remove more CO_2 from the atmosphere than they release) (IPCC, 1992).

Methane (CH_4). Methane is produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and oil, and is released as a by-product of coal production and incomplete fuel combustion. The atmospheric concentration of CH_4, which has been shown to be increasing at a rate of about 0.6 percent per year, may be stabilizing (Steele, *et al.*, 1992).

The major sink for CH_4 is its interaction with the hydroxyl radical (OH) in the troposphere. This interaction results in the chemical destruction of the CH_4 compound, as the hydrogen molecules in CH_4 combine with the oxygen in OH to form water vapor (H_2O) and CH_3. After a number of other chemical interactions, the remaining CH_3 turns into CO which itself reacts with OH to produce carbon dioxide (CO_2) and hydrogen (H).

Halocarbons. Halocarbons covered by the Montreal Protocol are human-made compounds that include chlorofluorocarbons (CFCs), halons, methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs). All of these compounds not only enhance the greenhouse effect, but also contribute to stratospheric ozone depletion. Under the Montreal Protocol, which controls the production and consumption of these chemicals, the U.S. will phase out the production and use of CFCs, HCFCs, and other ozone-depleting substances by December 31, 1995. Perfluorinated carbons (PFCs) and hydrofluorocarbons (HFCs), a family of CFC and HCFC replacements not covered under the Montreal Protocol, are also powerful greenhouse gases.

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, adipic (nylon) and nitric acid production, and biomass burning.

Ozone (O_3). Ozone is both produced and destroyed in the atmosphere through natural processes. Approximately 90 percent resides in the stratosphere, where it controls the absorption of solar ultraviolet radiation; the remaining 10 percent is found in the troposphere and could play a significant greenhouse role. Though O_3 is not emitted directly by human activity, anthropogenic emissions of several gases influence its concentration in the stratosphere and troposphere. Chlorine and bromine-containing chemicals, such as CFCs, deplete stratospheric O_3. However, as previously stated, under the Montreal Protocol, the U.S. will phase out the production and use of CFCs and other ozone-depleting substances by December 31, 1995.

Increased emissions of carbon monoxide (CO), nonmethane volatile organic compounds (NMVOCs), and oxides of nitrogen (NO_x) have contributed to the increased production of tropospheric ozone (otherwise known as urban smog). Emissions of these gases, known as criteria pollutants, are regulated under the Clean Air Act of 1970 and subsequent amendments.

Other Photochemically Important Gases

Carbon Monoxide (CO). Carbon monoxide is created when carbon-containing fuels are burned incompletely. Carbon monoxide elevates concentrations of CH_4 and tropospheric ozone through chemical reactions with atmospheric constituents (e.g., the hydroxyl radical) that would otherwise assist in destroying CH_4 and O_3. It eventually oxidizes to CO_2.

Oxides of Nitrogen (NO_x). Oxides of nitrogen, NO and NO_2, are created from lightning, biomass burning (both natural and anthropogenic fires), fossil fuel combustion, and in the stratosphere from N_2O. They play an important role in climate change processes due to their contribution to the formation of ozone.

Nonmethane Volatile Organic Compounds (NMVOCs). Nonmethane VOCs include compounds such as propane, butane, and ethane. These compounds participate along with NO_x in the formation of ground-level ozone and other photochemical oxidants. Nonmethane VOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents (U.S. EPA, 1990b).

The Inventory Process

Central to any study of climate change is the development of an emissions inventory that identifies and quantifies a country's primary sources and sinks of greenhouse gases. Developing and participating in the inventory process is important for two reasons: (1) it provides a basis for the ongoing development of a comprehensive and detailed methodology for estimating sources and sinks of greenhouse gases, and (2) it provides a common and consistent mechanism through which all signatory countries to the United Nations' Framework Convention on Climate Change (FCCC) can estimate emissions and compare the relative contribution of different emission sources and greenhouse gases to climate change. Moreover, systematically and consistently estimating emissions at the national and international levels is a prerequisite for evaluating the cost-effectiveness and feasibility of pursuing possible mitigation strategies and implementing emission reduction technologies.

This report presents estimates by the United States government of U.S. greenhouse gas emissions and sinks for 1990-1994. A summary of these estimates is provided in Table 1 by gas and source category. The remainder of this document discusses the methods and data used to calculate these emission estimates. The emission estimates in Table 1 are presented on both a full molecular basis and on a carbon-equivalent basis in order to show the relative contribution of each gas to total radiative forcing (see Box 2 for an explanation of how the relative contribution of each gas was calculated).

The U.S. views this submission as an opportunity to fulfill its commitment under Article 4-1 of the FCCC, which came into force on March 21, 1994, following ratification. As decided at the Ninth Session of the International Negotiating Committee

Box 2

The Global Warming Potential (GWP) Concept

As mentioned, gases can contribute to the greenhouse effect both directly and *indirectly*. *Direct effects occur when* the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformation of the original gas produces a gas or gases that are greenhouse gases, or when a gas influences the atmospheric lifetimes of other gases. The concept of Global Warming Potential (GWP) has been developed to allow scientists and policy makers to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. The GWP of a greenhouse gas is the ratio of global warming, or radiative forcing (both direct and indirect), from one kilogram of a greenhouse gas to one kilogram of carbon dioxide over a period of time. While any time period can be selected, the 100-year GWPs recommended by the IPCC are used in this report. Carbon dioxide was chosen as the "reference" gas to be consistent with IPCC *guidelines*. Carbon comprises 12/44 of carbon dioxide by weight. In order to convert emissions reported in million metric tonnes of a gas to MMTCE, the following equation is used:

MMTCE = (MMT of gas) (GWP of gas) (12/44),

where

MMTCE = million metric tonnes, carbon-equivalent,
MMT = million metric tonnes, full molecular weight,
GWP = global warming potential, and
(12/44) = carbon to carbon dioxide molecular weight ratio.

GWPs are not provided for the photochemically important gases CO, NO_x, NMVOCs, and SO_2 because there is no agreed-upon method to estimate their contribution to climate change. These gases only affect radiative forcing indirectly.

Gas	GWP[1] (100 Years)
Carbon dioxide	1
Methane*	24.5
Nitrous oxide	320
HFC-23	12,100
HFC-125	3,200
HFC-134a	1,300
HFC-152a	140
PFCs**	9,400
SF_6	24,900

* *The methane GWP includes the direct effect and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.*

** *This figure is an average GWP for the two PFCs, CF_4 and C_2F_6. The GWP for CF_4 is 6,300 and the GWP for C_2F_6 is 12,500.*

[1] IPCC, 1994

Table 1

Recent Trends in U.S. Greenhouse Gas Emissions: 1990–1994

Gas/Source	Emissions (Full Molecular Weight)					Emissions (Direct and Indirect Effects; Carbon-Equivalent)				
	(Million Metric Tonnes)									
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
Greenhouse Gases										
Carbon Dioxide (CO_2)										
Fossil Fuel Combustion	4,899	4,839	4,914	5,020	5,098	1,336	1,320	1,340	1,369	1,390
Other	62	61	62	64	63	17	17	17	18	17
Total	4,961	4,901	4,976	5,084	5,161	1,353	1,336	1,357	1,387	1,408
Forests (sink)	(458)	(458)	(458)	NA	NA	(125)	(125)	(125)	NA	NA
Net Total	4,503	4,443	4,518	NA	NA	1,228	1,211	1,232	NA	NA
Methane (CH_4)										
Landfills	9.9	10.1	9.9	10.0	10.2	66	67	66	67	68
Agriculture	8.4	8.5	8.8	8.8	9.2	56	57	59	59	61
Coal Mining	4.4	4.3	4.1	3.7	4.3	29	28	27	24	29
Oil and Gas Systems	3.2	3.3	3.3	3.2	3.3	22	22	22	22	22
Other	0.9	1.0	1.0	0.9	0.9	6	7	7	6	6
Total	27.1	27.3	27.2	26.7	28.0	181	182	182	179	188
Nitrous Oxide (N_2O)										
Agriculture	0.2	0.2	0.2	0.2	0.2	16	17	17	17	19
Fossil Fuel Consumption	0.1	0.1	0.1	0.1	0.1	12	12	12	12	12
Industrial Processes	0.1	0.1	0.1	0.1	0.1	8	9	8	9	9
Total	0.4	0.4	0.4	0.4	0.5	37	37	37	38	41
HFCs and PFCs	*	*	*	*	*	18.8	19.3	21.1	19.8	23.5
SF_6	+	+	+	+	+	6.4	6.5	6.7	6.8	7.0
Photochemically Important Gases										
NO_x	20.6	20.4	20.6	21.0	21.2	–	–	–	–	–
NMVOC	18.7	18.3	18.2	18.2	18.6	–	–	–	–	–
CO	83.4	82.7	81.6	81.3	83.1	–	–	–	–	–
U.S. Emissions						1,595	1,582	1,604	1,630	1,666
Net, Including Sinks						1,470	1,457	1,479	NA	NA

** As this category contains multiple gases, an aggregate full molecular weight sum is not calculated.*
+ Total of this gas does not exceed 0.01 million metric tonnes.
NA = not available
Note: Totals may not equal the sum of the individual source categories due to independent rounding.

(INC), emission estimates are to be estimated and presented in accordance with the *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA, 1995)[3] to ensure that the emission inventories submitted to the FCCC are consistent and comparable across sectors and between nations. The information provided in this inventory is presented in accordance with the *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA, 1995), unless otherwise noted.

Methodology and Data

Emissions of greenhouse gases from various

[3] Discussions of inventory methods can also be found in *Estimation of Greenhouse Gas Emissions and Sinks: Final Report from the OECD Experts Meeting, 18-21 February 1991* (August 1991). That report documents baseline inventory methodologies for a variety of source categories, which have subsequently been further refined based on recommendations provided at an IPCC-sponsored experts workshop held in Geneva, Switzerland in December 1991 and at an OECD/Netherlands-sponsored workshop in Amersfoort, Netherlands in February 1993. The proceedings from these meetings, the *Final Report* (OECD, 1991), as well as several other international meetings, form the basis for the current *IPCC Guidelines*.

sources are estimated using methodologies that are consistent with Volumes 1-3 of *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA, 1995). To the extent possible, the present U.S. inventory relies directly on published activity and emission factor data.[4] Inventory emission estimates from energy consumption and production activities are based primarily on the latest official information from the Energy Information Administration of the Department of Energy (DOE/EIA). Emission estimates for NO_X, CO, and NMVOCs are based directly on available U.S. Environmental Protection Agency (U.S. EPA) emissions data. These estimates are supplemented by calculations using the best available activity data from other agencies. Complete documentation of emission estimations can be found in the sources referenced throughout the text. In these supplementary calculations, attempts were made to adhere as closely as possible to IPCC methods. In many cases, the IPCC default methodologies have been followed. However, for emission sources considered to be *major* sources in the U.S., the IPCC default methodologies were expanded and more comprehensive methods used. These instances, including energy consumption, forest sinks, and some CH_4 sources are documented in the text, along with the reasons for diverging from the IPCC default methodologies.[5]

The majority of U.S. CH_4 emission estimates presented in this inventory are based on methods developed in the U.S. EPA report, *Anthropogenic Methane Emissions in the United States Estimates for 1990: Report to Congress* (U.S. EPA, 1993a). That U.S. EPA report provided 1990 U.S. CH_4 emissions for a variety of domestic sources, including natural gas systems, coal mining, landfills, domesticated livestock, manure management, rice cultivation, fuel combustion, and production and refining of petroleum liquids. The methodologies used to arrive at the emissions estimates in U.S. EPA (1993a) are conceptually similar to IPCC methodologies. Where the methodologies differ, information is provided in the text and/or appendices to ensure that the estimates presented are reproducible.

Emission estimates for NO_X, CO, and NMVOCs were taken directly, except where noted, from the U.S. EPA report, *Draft National Air Pollutant Emission Trends 1900–1994* (U.S. EPA, 1995b), which is an annual U.S. EPA publication that provides the latest estimates of regional and national emissions for criteria pollutants.[6] Emissions of these pollutants are estimated by the U.S. EPA based on statistical information about each source category, emission factor, and control efficiency. While the U.S. EPA's estimation methodologies are conceptually similar to the IPCC-recommended methodologies, the large number of sources EPA used in developing the estimates makes it difficult to reproduce the information from EPA (1995b) in this inventory document. In these instances, the sources containing the detailed documentation of the methods used are referenced for the interested reader.

Organization of the Inventory

In accordance with the IPCC guidelines for reporting contained in the *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA, 1995), this inventory is organized into six parts. These six parts correspond to the six major source categories below. In addition, annexes provide additional data on calculations which are not included in the main text. (Note: while the list below follows the IPCC's list of recommended source categories, emission sources that are not applicable to the U.S. are not included).

I. Part I covers emissions from all energy activities, including:
   A. Fuel Combustion Activities:
      1. Industry
      2. Transportation

[4] Depending on the emission source category, *activity data* can include fuel consumption or deliveries, vehicle- miles traveled, raw material processed, etc.; *emission factors* are factors that relate the quantity of emissions to the activity.

[5] In order to fully comply with the *IPCC Guidelines*, the United States has provided a copy of the IPCC reporting tables in Annex G.

[6] Criteria pollutants include carbon monoxide (CO), lead (Pb), nitrogen oxides (NO_X), particulate matter less than ten microns (PM-10), sulfur oxides (SO_X), total particulate matter (TP), and nonmethane volatile organic compounds (NMVOCs).

3. Residential
4. Commercial/Institutional
5. Electric Utilities

B. Fuel Production, Transmission, Storage, and Distribution:
1. Coal mining
2. Crude oil and natural gas

C. Biomass for Energy

II. Part II covers emissions from other industrial production processes

III. Part III covers emissions from solvent use

IV. Part IV covers emissions from agriculture, including:
A. Enteric Fermentation (in domestic animals)
B. Manure Management (for domestic animals)
C. Rice Cultivation
D. Agricultural Soils
E. Agricultural Crop Waste Burning

V. Part V covers emissions resulting from land-use change and forestry.

VI. Part VI covers emissions from wastes and waste-treatment processes, including:
A. Landfills
B. Wastewater Treatment
C. Waste Combustion

Uncertainty and Limitations of Emissions Estimates

While the current U.S. emissions inventory provides a solid foundation for the development of a more detailed and comprehensive national inventory, it has several strengths and weaknesses. First of all, this report by itself does not provide a complete picture of past or future emissions in the U.S.; it only provides an inventory of U.S. emissions for the years 1990–1994. However, the U.S. believes that common and consistent inventories taken over a period of time can and will contribute to understanding future emission trends. The U.S. plans to update this comprehensive inventory of greenhouse gas emissions and sinks on an annual basis and to use the information gained to track progress of commitments made under the U.S. *Climate Change Action Plan*. This report represents the second inventory compiled by the U.S for meeting its commitments under the FCCC. The methodologies used to estimate emissions will be periodically updated as methods and information improve, and as further guidance is received from the IPCC.

Secondly, there are uncertainties associated with the emissions estimates. Some of the current estimates, such as those for CO_2 emissions from energy-related activities and cement processing, are considered accurate. For other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated limit the scope or accuracy of the inventory. For certain categories, emission estimates are given as a specific range to reflect the associated uncertainty. Where applicable, specific factors affecting the accuracy of the estimates are also discussed in detail.

Finally, while the IPCC methodologies provided in the three volume IPCC/OECD/IEA report, *IPCC Guidelines for National Greenhouse Gas Inventories*, represent baseline methodologies for a variety of source categories, many of these methodologies are still being refined. The current U.S. inventory uses the IPCC methodologies where possible, and supplements with other available methodologies and data where needed. The U.S. realizes that not only are the methodologies still evolving, but that additional efforts are necessary to improve methodologies and data collection procedures. Specific areas requiring further research include:

- *Completing estimates for various source categories.* Quantitative estimates of some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities and industrial processes are not included in the inventory either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories.

- *Understanding the relationship between emissions and sources.* This is a crucial step in completing and refining existing methodologies and in developing methodologies for emission source cate-

gories where none currently exist. For example, a great deal of uncertainty exists in how nitrous oxide emissions are produced from energy-related activities and fertilizer consumption. As a consequence, the quality of emission factors and activity data for these categories are particularly weak.

- *Improving the accuracy of emission factors.* A substantial amount of research is underway that could improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors used to estimate emissions from surface coal mining is limited by a lack of available data. Emission factors for CH_4 from landfills are also currently undergoing revision. To more accurately assess CH_4 emissions from landfills, researchers are working to determine the relationship between moisture, climate, and waste composition and CH_4 generation rates. Emission factors used to estimate greenhouse gas emissions from biomass burning and land use are also being revised.

- *Providing appropriate activity data.* Although methodologies exist for estimating emissions for some source categories, problems arise in obtaining data that are compatible with methodology requirements. For example, the ability to estimate emissions from oil and gas systems is constrained by a lack of information on compressor type, amount of leakage, and emission control technology. In the agricultural sector, estimating emissions of animal wastes using the IPCC methodology is arduous because of the complexity of the data required. Obtaining information on animal weights, waste management systems, and feeding practices by animal type is difficult. Efforts need to be made to collect activity data appropriate for use in the IPCC methodologies.

The uncertainties and limitations associated with calculating greenhouse gas emissions are both qualitative and quantitative. Emissions calculated for the U.S. inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies and incomplete data. Efforts need to be made to improve existing methodologies and data collection activities, so that methodologies and data are consistent with one another and so that they allow both the U.S. and other countries to estimate emissions with greater ease, certainty, and consistency.

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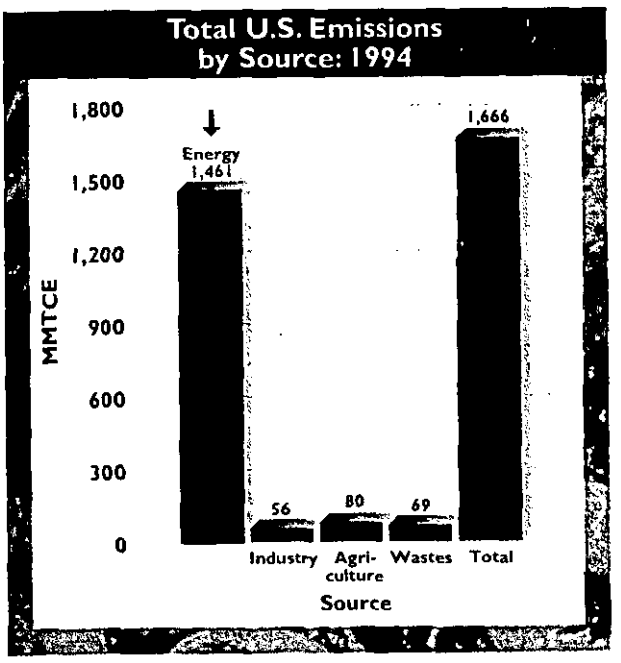
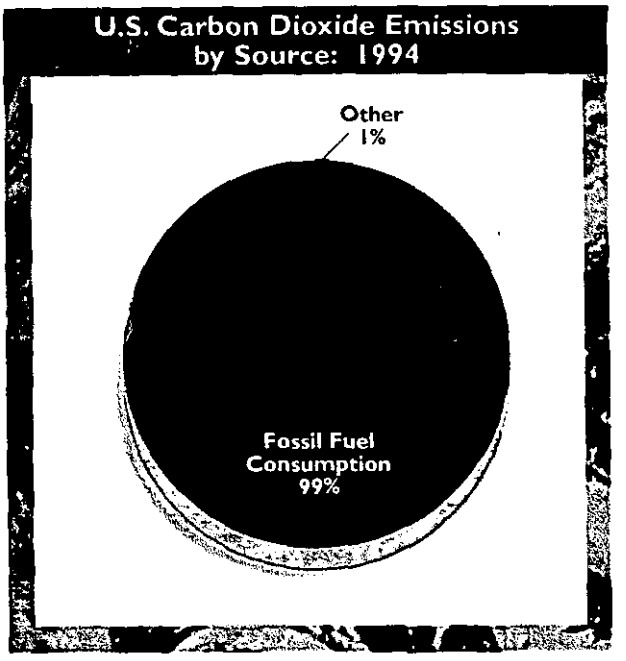
Part I: Energy

Energy-related activities are the most significant source of U.S. anthropogenic greenhouse gas emissions, accounting for roughly 88 percent of total U.S. emissions annually on a carbon equivalent basis. This includes almost 99 percent of carbon dioxide (CO_2) emissions and just under one third of the nation's methane (CH_4) and nitrous oxide (N_2O) emissions. Energy-related CO_2 emissions comprise close to 85 percent of total national emissions on a carbon equivalent basis, while the non-CO_2 emissions represent a much smaller portion of total national emissions (less than 5 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the main gas emitted. Due to the relative importance of combustion related CO_2, these emissions are considered separately from other emissions. Fossil fuel combustion also emits CH_4 and N_2O, as well as criteria pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).

Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of CH_4 from natural gas systems, oil production and refining, and coal mining. Smaller quantities of CO_2, CO, NMVOCs, and NO_x are also emitted.





The combustion of biomass and biomass-based fuels also emits greenhouse gases, although CO_2 emissions from these activities are not included in the U.S. total because biomass resources in the U.S. are used on a sustainable basis. That is, the carbon released when biomass is consumed is recycled as U.S. forests regenerate, causing no additional CO_2 to be added to the atmosphere. The net impact of land-use activities on the forest sector carbon cycle are accounted for in Part V of this document.

Overall, the energy sector was driven by a strengthening U.S. economy following an economic slowdown in 1991. This resulted in a general increase in the production and consumption of fossil fuels since 1990, with an associated increase in greenhouse gas emissions. Overall, emissions due to energy-related activities have increased nearly 4 percent from 1990 to 1994, rising from 1,408 MMTCE in 1990 to 1,461 MMTCE in 1994. This largely defines the trend in total U.S. anthropogenic greenhouse gas emissions, since energy-related emissions represent the vast majority of total emissions (about 88 percent). Discussion of specific energy sector trends is presented below.

EMISSIONS FROM FOSSIL FUEL CONSUMPTION

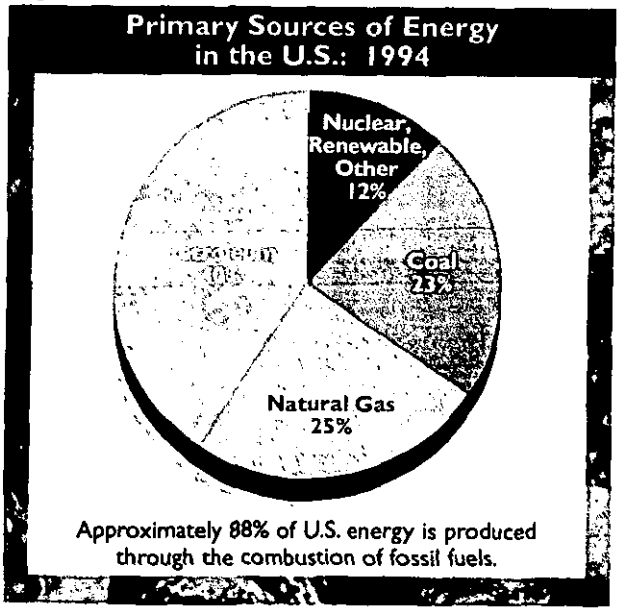
Carbon Dioxide Emissions from Fossil Fuel Consumption

Background and Overall Emissions

The majority of energy in the United States, approximately 88 percent, is produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure I-1). The remaining 12 percent comes from other sources such as nuclear energy, hydropower, and biomass fuels.

After 1990, during which carbon dioxide (CO_2) emissions from fossil fuel combustion were 1,336 MMTCE, there was a slight decline of emissions in 1991, followed by an increase to 1,390 MMTCE in 1994. These trends are directly attributable to increased economic activity since the economic downturn in the early 1990's. About 60 percent of the increase since 1990 has come from increased natural gas consumption, 30 percent from coal, and 10 percent from oil. Over two thirds of the increase from 1993 to 1994 was due to oil products, of which two thirds can be attributed to growth in the transportation sector (see Table I-1).

Figure I-1



As fossil fuels are combusted, the carbon stored in the fuels is emitted as CO_2 and smaller amounts of other gases, including CO, CH_4, and NMVOCs. These other gases are emitted as a by-product of incomplete fuel combustion. The amount of carbon in the fuel varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has about 80 percent of the carbon per unit of energy as compared to coal, and natural gas has only about 55 percent. Petroleum supplies the largest share of U.S. energy needs, accounting for just over 40 percent of total energy consumption on an annual basis (see Figure I-1). Natural gas and coal follow in order of importance, accounting for an average of 25 and 23 percent of total consumption, respectively. Most petroleum is consumed in the trans-

portation sector, while the vast majority of coal is used by electric utilities, and natural gas is consumed largely in the industrial and residential sectors.

Following just over a one percent decline in 1991, U.S. emissions of CO_2 from energy increased approximately two percent annually through 1994. The major factor behind this trend was the growing domestic economy, combined with relatively low energy prices and extreme weather conditions (EIA, 1994a).

Coal production fell in 1993 due primarily to a United Mine Workers strike, but consumption was largely unaffected as stocks were drawn down (EIA, 1994b). In fact, energy-related combustion of coal was up 3 percent in 1993 and leveled off in 1994, due almost exclusively to increased use by electric utilities.

Oil combustion increased by about 1 and 3 percent in 1993 and 1994, respectively. This was spurred largely by U.S. economic growth and lower petroleum prices (EIA, 1994a), which are shown in Figure I-2. A major portion of the increase was in the transportation sector, which accounted for almost two-thirds of the growth in petroleum demand during this period.

Natural gas combustion rose by about 3 percent and 2 percent, respectively, in 1993 and 1994, driven largely by heating uses in the residential and commercial sectors due to exceptionally cold winters. This consumption increase was accompanied by an increase in gas prices, production, imports, and storage as the nat-

Table I-1

U.S. CO_2 Emissions from Energy Consumption by End-Use Sector and Fuel Type: 1990–1994

Sector	1990	1991	1992	1993	1994
	(Million Tonnes of Carbon Equivalent)				
Residential					
Coal	141	142	141	150	150
Natural Gas	79	83	85	89	89
Petroleum	33	33	32	34	35
Total	253	259	257	273	273
Commercial					
Coal	129	128	129	135	138
Natural Gas	52	54	55	56	58
Petroleum	26	25	22	22	22
Total	207	208	206	213	218
Industrial					
Coal	211	204	208	209	209
Natural Gas	133	138	143	148	151
Petroleum	113	99	109	103	106
Total	457	442	460	459	466
Transportation					
Coal	1	1	1	1	1
Natural Gas	10	9	9	9	10
Petroleum	399	391	397	404	413
Total	410	401	407	414	424
U.S. Territories					
Coal	0.1	0.2	0.2	0.2	0.2
Natural Gas	0	0	0	0	0
Petroleum	9	11	10	10	10
Total	9	11	10	10	10
All Sectors					
Coal	482	476	479	495	497
Natural Gas	274	285	292	302	307
Petroleum	580	559	569	572	586
Total	1,336	1,320	1,340	1,369	1,390

Source: Based on energy consumption estimates from EIA (1995f, 1995b, 1994a, and 1995d), and carbon content coefficients from EIA (1995a) and IPCC (IPCC/OECD/IEA, 1995, Vols. 1-3). For complete references see Annex A.

Note: Totals may not equal the sum of components due to independent rounding.

Figure I-2

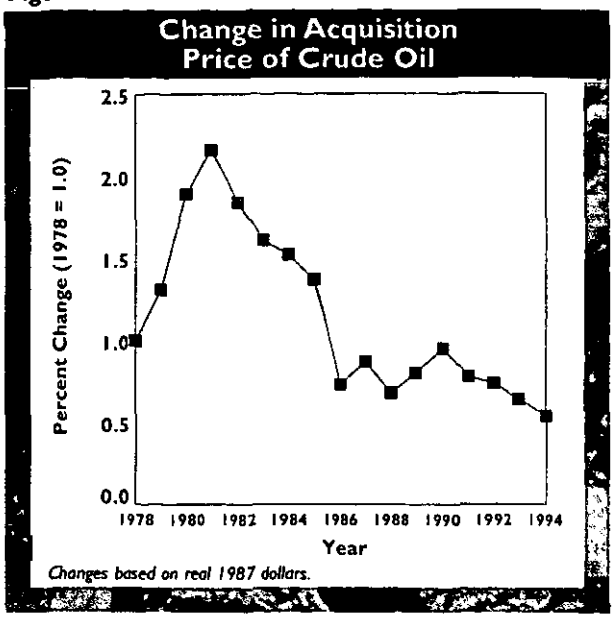
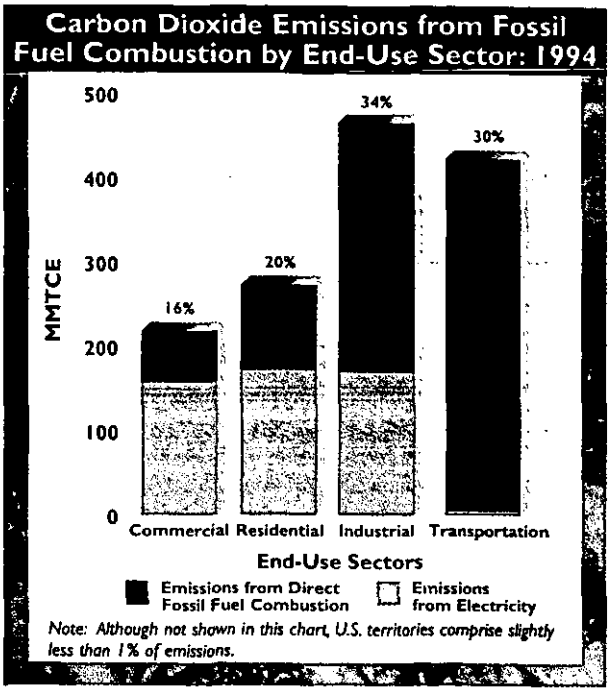


Figure I-3



ural gas industry responded to pressures placed on it by intense seasonal demands and adjustment to industry restructuring under Federal Energy Regulatory Commission (FERC) Order 636, which increased the complexity of natural gas service and heightened competition among gas providers (EIA, 1994h).

Sectoral Contributions

The four end-use sectors that contribute to CO_2 emissions from fossil fuel combustion include:

- industrial;
- transportation;
- residential; and
- commercial/institutional.

Electric utilities also emit CO_2, although these emissions are produced as they consume fossil fuel to generate electricity which is ultimately consumed by the four end-use sectors. For the discussion below, utility emissions have been distributed to the end-use sectors based on electricity consumption in those sectors. Emissions from utilities are addressed separately after the end-use sectors have been discussed.

Industrial Sector

From 1990 through 1994, the industrial sector accounted for just over one-third of U.S. CO_2 emissions from fossil fuel consumption (see Figure I-3). On average, nearly two-thirds of these emissions resulted from the direct consumption of fossil fuels in order to meet industrial demand for steam and process heat. The remaining one-third of industrial energy needs was met by electricity for uses such as motors, electric furnaces and ovens, and lighting.

Coal consumption by industry has remained relatively constant since 1992, with a slight increase in coal consumption for general industrial use offset by a drop in coal consumption at coke plants (EIA, 1994b). In comparison, industrial use of natural gas was up in 1993 due to overall sector growth, and leveled out in 1994 as the result of localized economic slowdowns in the Northeast and California (EIA, 1994h). The opposite trend occurred with petroleum consumption, which declined in 1993 and subsequently increased in 1994. This trend was largely driven by decreased 1993 demand for distillate fuel oil, LPG, and still gas, which rebounded in 1994.

The industrial sector is also the largest user of non-energy applications of fossil fuels. Fossil fuels used for producing fertilizers, plastics, asphalt, or lubricants can store carbon in products for very long periods. Asphalt used in road construction, for example, stores carbon indefinitely. Similarly, fossil fuels used in the manufacture of materials like plastics also store carbon, releasing this carbon only if the product is incinerated. Industrial non-fuel use rose about 22 percent between 1990 and 1994 (3,910 TBtu in 1990

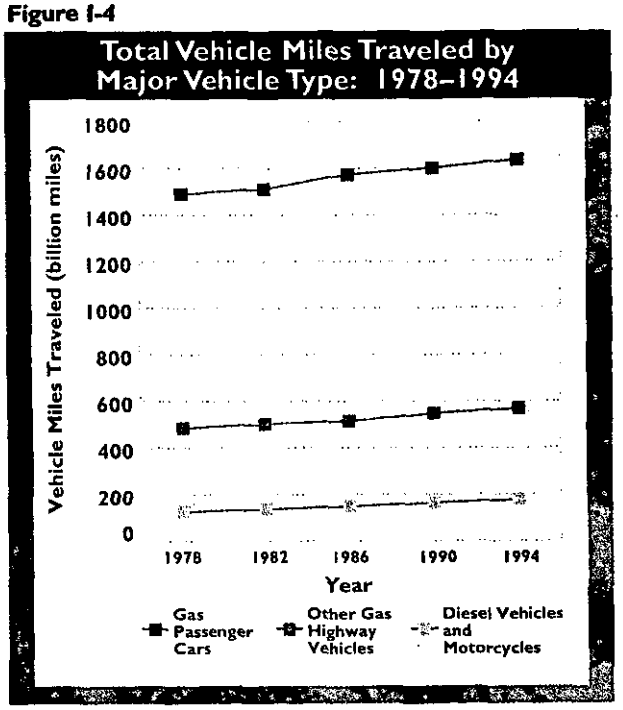
to 4,788 TBtu in 1994).[1] This increase, however, has a negligible effect on total U.S. emissions since non-fuel use comprises less than 7 percent of fossil fuel consumption and the annual change in non-fuel use is less than 0.3 percent of total consumption.

Transportation Sector

The transportation sector is also a major source of CO_2, accounting for slightly over 30 percent of U.S. combustion-related emissions on an annual basis. Virtually all of the energy consumed in this sector comes from petroleum-based products, with nearly two-thirds of the emissions resulting from gasoline consumption in automobiles and other vehicles. Other uses, including diesel fuel for the trucking industry and jet fuel for aircraft, account for the remainder.

Following the overall trend in U.S. energy consumption, fossil fuel combustion for transportation has grown steadily after declining in 1991, with associated increases in CO_2 emissions (410 MMTCE in 1990 to 424 MMTCE in 1994). From 1992 to 1994, petroleum consumption increased about 4 percent. This increase was caused by the rising consumption of motor gasoline, distillate fuel, and jet fuel, as travel increased. This was slightly offset by decreases in the consumption of residual fuel and liquefied petroleum gases, as well as a slight decline in the energy intensity of the U.S. passenger vehicle fleet. Declining petroleum prices during these years (see Figure I-2), combined with a stronger economy, was largely responsible for transportation growth, causing an overall increase in vehicle miles traveled by on-road vehicles, as shown in Figure I-4 (EIA, 1994a).

Figure I-4



Residential and Commercial Sectors

From 1990 to 1994, the residential and commercial sectors have, on average, accounted for about 19 and 16 percent, respectively, of CO_2 emissions from fossil fuel consumption. Unlike in other major U.S. sectors, residential and commercial emissions did not decline in 1991, but rather grew slowly during the entire period from 1990 to 1994. Both sectors are heavily reliant on electricity for meeting energy needs, with about two-thirds of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions are largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs.

Coal consumption is a small component of energy use in the residential and commercial sectors, but has increased slightly from 1990 to 1994 (accounting for about 1 percent of total residential consumption and 2 to 3 percent of total commercial consumption). Residential and commercial natural gas consumption increased slightly during both 1993 and 1994. This slow upward trend was primarily due to sectoral growth, a shift toward natural gas heat in new-home starts and old-home conversions, and abnormally cold winter months in these two years (EIA, 1994h). The majority of the annual increases are due to colder than normal weather patterns, which occurred in the eastern U.S. for the winters of 1993 and 1994. Specifically, the cold spell of March 1993 caused a combined 5 percent increase in residential/commercial consumption over 1992 levels, and the cold spell of January 1994 resulted in 18 percent higher residential deliveries and 30 percent higher commercial deliveries compared to those in January 1993. Oil consumption and related emis-

[1] Throughout this document, TBtu stands for trillion Btus, or 10^{12} Btus.

sions in these sectors remained relatively constant during this period, with only a slight increase in residential consumption and a slight decrease in commercial consumption. This static trend is largely caused by the offsetting factors of sectoral growth and a shift toward natural gas heating.

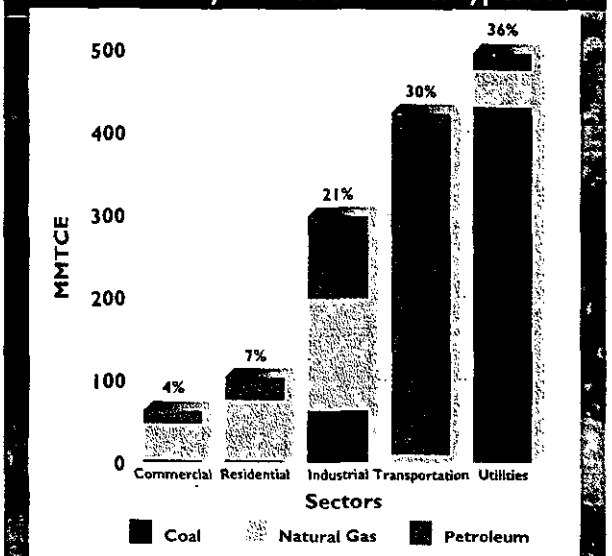
Electric Utilities

The U.S. relies on electricity to meet a significant portion of its energy requirements. In fact, as one of the largest consumers of fossil fuel in the U.S. (averaging 28 percent of total fossil fuel consumption on an energy basis), electric utilities are collectively the largest producers of U.S. CO_2 emissions (see Figure I-5). These emissions are produced as electricity is generated for such uses as lighting, heating, electric motors, and air conditioning in the industrial, residential, and commercial/institutional end-use sectors. Since electric utilities consume such a substantial portion of U.S. fuel to generate this electricity, the type of fuel they use has a significant effect on the total amount of CO_2 emitted. For example, some of this electricity is generated with the lowest CO_2-emitting energy technologies, particularly non-fossil options such as nuclear energy, hydropower, or geothermal energy. However, electric utilities rely on coal for over half of their total energy requirements and account for about 87 percent of all coal consumed in the U.S. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Due almost exclusively to an increase in utility consumption, coal-related emissions increased approximately 3 percent in 1993 over 1992 levels. This increase occurred despite a large drop in 1993 coal production due to a United Mine Workers strike, resulting in a substantial depletion of utility stockpiles (EIA, 1994b). There are three reasons for the consumption increase (EIA, 1994b). First, there was nearly a 4 percent increase in electricity demand caused by a hot 1993 summer following a relatively cool summer in 1992. Second, there was general growth in the U.S. economy accompanied by reduced imports of Canadian electricity. Third, compared to earlier years, coal constituted a slightly larger share of

Figure I-5

Carbon Dioxide Emissions from Fossil Fuel Combustion by Sector and Fuel Type: 1994



Note: Although not shown in this chart, U.S. territories comprise slightly less than 1% of emissions.

the electricity mix, primarily due to a reduction in nuclear power generation caused by plant outages in the Midwest and Southeast. A smaller increase in utility coal consumption occurred in 1994 as the U.S. economy continued to strengthen. This gain was partially offset by more moderate summer temperatures.

Utility consumption of natural gas declined in 1993 due to rising gas prices relative to coal and oil and a displacement of marginal production by hydroelectric generation following record levels of precipitation in the Midwest and West (EIA, 1994h and EIA, 1994i). Utility natural gas use increased slightly in 1994, as the natural gas industry stabilized following a series of cold winters and industry restructuring. Also, gas prices fell, making gas-based electricity production more economical.

Petroleum constitutes a relatively small portion of utility fossil fuel consumption (approximately 5 to 6 percent), mostly occurring in the eastern United States. Utility petroleum consumption increased slightly in 1993 and leveled off in 1994. This trend was due largely to a 1993 summer heat wave in the eastern U.S., combined with relatively low petroleum prices compared to natural gas through the first half of 1993. This was followed in 1994 by declining gas prices relative to petroleum, which encouraged gas consumption at the expense of petroleum use.

Methodology Used to Estimate Emissions

The methodology used by the U.S. for estimating CO_2 emissions from fossil fuel combustion is conceptually similar to the approach recommended by the IPCC for countries that intend to develop detailed, sectoral-based emission estimates (IPCC/OECD/EIA, 1995; Vol. 3). A detailed description of the U.S. methodology is presented in Annex A, and is characterized by the following five steps:

1. *Determine fuel consumption by fuel type and sector.* Fuel consumption data were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), which is responsible for the collection of all U.S. energy data. By aggregating consumption data by sector (*e.g.*, commercial, industrial, etc.), primary fuel type (*e.g.*, coal, oil, gas), and secondary fuel category (*e.g.*, gasoline, distillate fuel, etc.), EIA estimates total U.S. energy consumption for a particular year.[2] A discussion of the data sources and comparison of different methodological approaches can be found in Box I-1.

Box I-1

About Energy Data and Estimating Carbon Emissions

When fuels are burned, the carbon contained within them combines with atmospheric oxygen to form CO_2. In theory, if the carbon content of the fuel and the combusted quantity is known, the resulting volume of CO_2 can be estimated with a high degree of certainty. Therefore, energy-related CO_2 emissions can be estimated with a fairly high degree of precision using available energy data.

1. Data Availability

In the U.S., the organization responsible for reporting and maintaining annual energy statistics is the Energy Information Administration (EIA), an agency of the U.S. Department of Energy (U.S. DOE). EIA reports consumption statistics for the 50 U.S. states (e.g., the *State Energy Data Report*) and U.S. territories as well as international statistics. EIA is also responsible for reporting U.S. data to the IEA and U.N.

2. Data format

For consistency of reporting, the IPCC has recommended that national inventories report energy data (and emissions from energy) using the International Energy Agency (IEA) reporting convention and/or IEA data.

Data in the IEA format are presented "top down" — that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption."

The data collected in the U.S. by EIA are more of the "bottom up" nature, *i.e.*, they are collected through EIA surveys at the point of delivery or use and aggregated to determine national totals. In other words, the EIA data reflect the reported consumption quantities of fuel categories and types.

For reporting to IEA, EIA converts the data for the 50 states into IEA fuel categories and units, calculates "apparent consumption," and adjusts for production, imports, exports, and stock changes in U.S. territories and islands. The "converted" data are then submitted to the IEA, along with the conversion factors used and other relevant information.

Both of the above approaches have advantages and disadvantages. For example, while the "top down" approach more accurately captures fuel flow (and therefore the carbon flow) in most countries, the "bottom up" approach allows for more detailed information by end-use sectors and fuel types.

3. Estimating Carbon Emissions

Theoretically, both approaches should yield similar carbon emissions results. In reality, most countries' estimates will vary depending on the method used to estimate consumption totals, the definition and interpretation of data sources, the carbon coefficients used, and the assumptions regarding both the quantity of carbon stored in products and combustion efficiency. Both approaches are believed to produce highly accurate results in the U.S. For example, carbon emissions estimates for 1990 from the "bottom up" approach total 1,336 MMTCE, while the "top down" approach results in carbon emissions of 1,320 MMTCE.

[2] Fuel consumption by U.S. territories (*i.e.*, American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed about 10 MMTCE of emissions in 1993 and 1994.

2. *Determine the total carbon content of fuels consumed.* Total carbon is estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon were converted to CO_2. The carbon emission coefficients used by the U.S. are presented in Table I-2.

3. *Subtract the amount of carbon stored in products.* Non-fuel uses of fossil fuels can result in storage of some or all of the carbon contained in the fuel for some period of time, depending on the end-use. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon for extended periods of time, while other products, such as lubricants or plastics, lose or emit some carbon when they are used and/or are burned as waste after utilization. The amount of carbon sequestered or stored in non-energy uses of fossil fuels was based on the best available data on the end uses and ultimate fate of the various energy products. These non-energy uses occur in the industrial and transportation sectors. Carbon sequestered by these uses was estimated to be about 66 MMTCE in 1990, which rose to 79 MMTCE in 1994.

4. *Adjust for carbon that does not oxidize during combustion.* Because combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot or other byproducts of inefficient combustion. The estimated amount of carbon not oxidized due to inefficiencies during the combustion process range from 1 percent for oil and coal to 0.5 percent for natural gas (see Table I-2 for the assumptions used by the U.S.).

5. *Subtract emissions from international bunker fuels.* According to the IPCC guidelines (IPCC/OECD/IEA, 1995) emissions from international transport activities, or bunker fuels, should not be included in national totals. Therefore, since EIA consumption statistics include these bunker fuels (primarily residual oil) as part of consumption by the transportation sector, emissions from this source are calculated separately and subtracted from the transportation sector. The calculations for emissions from bunker fuel follow the same procedures used for emissions due to consumption of all fossil fuels (*i.e.*, estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized). Emissions from bunkers resulted in emissions of over 22 MMTCE in 1990, which rose to a peak of 25 MMTCE in 1992 and then declined to approximately 23 MMTCE in 1994.[3]

Uncertainty in the Carbon Dioxide Emission Estimates

Uncertainties exist for all of the emission estimates provided in this report. For estimates of CO_2 from energy consumption, in principle the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, carbon content of fossil fuels consumed, and consumption of products with long-term carbon storage would yield an accurate estimate of CO_2 emissions.

There are uncertainties, however, over the levels of detail, data sources, carbon content of fuels and products, and combustion efficiency. For example, given the same primary fuel type (*e.g.*, coal), the amount of carbon contained in the fuel per unit of useful energy can vary. Non-energy uses of the fuel can create situations where the carbon is not emitted to the atmosphere (*e.g.*, plastics, asphalt, etc.) or is emitted at a much delayed rate. The proportions of fuels used in these non-fuel production processes and their carbon content can also vary. Additionally, inefficiencies in the combustion process, which can result in ash or soot remaining unoxidized for long periods, can vary. These factors all contribute to the uncertainty in the CO_2 estimates. For the U.S., however, these uncertainties are believed to be relatively small.[4]

[3] 1994 estimates of emissions from bunker fuel consumption by the U.S. and its territories are preliminary estimates based on 1992 and 1993 data. Final estimates will be available in late 1995 or early 1996, when international data from EIA are published.

[4] U.S. CO_2 emission estimates from fossil fuel consumption are considered accurate within one or two percent. See, for example, Marland and Pippin, 1990 or EIA, 1993a.

Table I-2

Key Assumptions for Estimating Carbon Dioxide Emissions

Fuel	Carbon Content Coefficient (MMTCE/QBtu[5])	Fraction Oxidized	Fraction Sequestered
Residential Coal	[a]	0.99	-
Commercial Coal	[a]	0.99	-
Industrial Coking Coal	[a]	0.99	0.75
Industrial Other Coal	[a]	0.99	-
Coke Imports	27.85	0.99	-
Transportation Coal	NC	0.99	-
Utility Coal	[a]	0.99	-
U.S. Territory Coal (bit)	25.14	0.99	-
Natural Gas	14.47	0.995	1.00[d]
Asphalt & Road Oil	20.62	0.99	1.00
Aviation Gasoline	18.87	0.99	-
Distillate Fuel Oil	19.95	0.99	[b]
Jet Fuel	[a]	0.99	-
Kerosene	19.72	0.99	-
LPG	[a]	0.99	0.80
Lubricants	20.24	0.99	0.50
Motor Gasoline	[a]	0.99	-
Residual Fuel	21.49	0.99	[b]
Other Petroleum			
AvGas Blend Components	18.87	0.99	-
Crude Oil	20.29	0.99	-
MoGas Blend Components	19.41	0.99	-
Misc. Products	20.31	0.99	[b]
Naphtha (<401 deg. F)	18.14	0.99	[c]
Other Oil (>401 deg. F)	19.95	0.99	[c]
Pentanes Plus	18.24	0.99	-
Petrochemical Feedstocks	19.37	0.99	0.80
Petroleum Coke	27.85	0.99	0.00
Still Gas	17.51	0.99	-
Special Naphtha	19.86	0.99	0.00
Unfinished Oils	20.21	0.99	-
Waxes	19.81	0.99	[b]
Other Wax & Misc.	19.81	0.99	1.00

Sources: Carbon Coefficients from EIA (1995a). Stored Carbon from Marland and Pippen (1990) and Rypinski (1994). Combustion efficiency for coal from Bechtel (1993) and for oil and gas from IPCC /IPCC/OECD/IEA, 1995; Vol. 2).

Notes: NC = Not Calculated

[a] = These coefficients vary annually due to fluctuations in fuel quality. See Annex A for more information.

[b] = Non-fuel use values of distillate fuel, miscellaneous products, residual fuel, and waxes are reported in aggregate in the "Other Waxes & Misc." category.

[c] = Non-fuel use values of Naphtha (<401 deg. F) and Other Oil (>401 deg. F) are reported in aggregate in the "Petrochemical Feedstocks" category.

[d] = It is assumed that 100 percent of the carbon in natural gas used as a chemical feedstock is sequestered. (There are actually two major non-fuel uses for natural gas: 1. for ammonia production in nitrogenous fertilizer manufacture; and 2. as a chemical feedstock. The carbon in natural gas used for ammonia production oxidizes quickly.)

[5] One QBtu is one quadrillion Btu, or 10^{15} Btu. This unit is commonly referred to as a "Quad."

Other Greenhouse Gas Emissions from Stationary Fossil Fuel Combustion

Stationary combustion encompasses all fuel combustion activities except transportation (i.e., mobile combustion). Other than carbon dioxide (CO_2), which was addressed in the previous section, gases from stationary combustion include the greenhouse gases methane (CH_4) and nitrous oxide (N_2O) and the photochemically important gases such as nitrogen oxides (NO_X), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs), which are all products of incomplete combustion. The amount of emissions varies depending upon fuel, technology type, and pollution control equipment. Emissions also vary with the size and vintage of the combustion technology as well as maintenance and operational practices.

Stationary combustion is a significant source of NO_X and CO emissions. In 1994, emissions of NO_X from stationary combustion represented 50 percent of national NO_X emissions, while CO and NMVOC emissions from stationary combustion contributed 5 and 4 percent, respectively, to the national totals for the same year. Emissions of these criteria pollutants have declined from much higher levels in the past due to a combination of technological advances and more stringent emissions requirements. From 1990 to 1994, emissions of NO_X increased by about 2 percent, while emissions of CO and NMVOCs showed a slight decline (see Table I-3).[6]

Table I-3

U.S. Greenhouse Gas Emissions from Stationary Combustion: 1990–1994

Year	NO_x	NMVOCs	CO	CH_4	N_2O
	(Thousand Metric Tonnes)				
1990	10,414	834	4,594	708	35
1991	10,319	887	4,857	760	35
1992	10,358	926	5,079	802	35
1993	10,607	815	4,493	691	36
1994	10,636	804	4,431	678	36

Sources: 1. Criteria pollutant emissions estimates from U.S. EPA (1995b)
2. CH_4 emission estimates based on NMVOC emissions from U.S. EPA (1995b) and emission ratios from U.S. EPA (1993a).
3. N_2O emissions are based on IPCC emission factors for uncontrolled fossil fuel and wood fuel combustion (IPCC/OECD/IEA, 1995), and U.S. fossil fuel and wood fuel consumption data (EIA, 1995f, 1994a, and 1994c).

Stationary combustion is also a small source of CH_4 and N_2O. CH_4 emissions from stationary combustion in 1994 accounted for about 2 percent of total U.S. CH_4 emissions, while N_2O emissions from stationary combustion accounted for about 8 percent of all N_2O emissions. From 1990 levels, CH_4 emissions rose by almost 8 percent in 1991 and 6 percent in 1992, but dropped by more than 14 percent in 1993 and 2 percent in 1994. Despite slightly more than a 1 percent drop in 1991, N_2O emissions rose from the 1990 level of 35.2 thousand tonnes to 36.1 thousand tonnes in 1994 (an increase of nearly 3 percent).

Background and Overall Emissions

Nitrous oxide and NO_X emissions from stationary source combustion are closely related to air-fuel mixes and combustion temperatures, as well as pollution control equipment. Carbon monoxide emissions from stationary combustion are generally a function of the efficiency of combustion and emission controls, and are highest when there is less oxygen in the air-fuel mixtures than necessary for complete combustion. This is likely to occur during combustion stopping and starting, or switching of fuels (for example, the switching of coal grades at a coal-burning utility plant). Methane and NMVOC emissions from stationary combustion are believed to be a function of the CH_4 content of the fuel and post-combustion controls.

Methane emission estimates from stationary sources are highly uncertain, primarily due to major uncertainties in emissions from wood combustion (*e.g.*, fireplaces and wood stoves). The largest source of N_2O emissions comes from utility coal combustion, accounting for almost 38 percent of total N_2O emissions from stationary combustion over the period 1990 to 1994. It is important to note, however, that both of these gases are currently not regulated in the U.S., and therefore, their emission

[6] Tables in this document are generally reported in million metric tonnes or thousand metric tonnes, depending on the relative magnitude of the emissions being presented. When comparing information across tables, please note the units.

processes are not as well understood as emission processes for some criteria pollutants. The estimates of CH_4 and N_2O emissions presented here are based on broad indicators of emissions (*i.e.*, aggregate emissions ratios of CH_4 emitted to total NMVOCs and rate per amount of fuel used, respectively), rather than specific emission processes (*i.e.*, by combustion technology and type of emission control).

Greenhouse gas emissions from energy-related stationary combustion activities have been grouped into four sectors:

- industrial;
- commercial/institutional;
- residential; and
- electric utilities.

The major source categories included in this section are similar to those used by U.S. EPA (1995b): coal, fuel oil, natural gas, wood, other fuels (including bagasse, LPG, coke, coke oven gas, and others), and stationary internal combustion (which includes emissions from internal combustion engines that are not used in transportation). A summary of the emissions from stationary combustion sources in 1994 is provided in Table I-4.

The slight decline in CO and NMVOC emissions from 1990 to 1994 can largely be attributed to residential wood combustion, which is the most significant source of these pollutants in the energy sector (74 percent of CO and 77 percent of NMVOCs). As fossil fuel prices have decreased in the last several years, residential wood consumption for home heating has declined (EPA, 1995b). Overall, NO_X emissions from energy have increased largely due to an increase in emissions from electric utilities, which constitute over 66 percent of stationary NO_X emissions. However, utility emissions have increased more slowly than utility fuel consumption, due in large part to emission control systems in plants burning fossil fuel.

Like NMVOCs, emissions of CH_4 decreased over the period 1990 to 1994, due largely to the decline in residential wood use. Nitrous oxide emissions, on the other hand, increased slightly over this period as fossil fuel combustion increased (72,300 TBtu in 1990 to 76,200 TBtu in 1994). Like NO_X, the emission increase was due in large part to electric utility consumption, which grew at a faster rate than overall energy consumption.

Methodology Used to Estimate Emissions

Emissions estimates for NO_X, CO, and NMVOCs in this section were taken directly from the U.S. EPA's *Draft National Air Pollutant Emissions Trends: 1900–1994* (U.S. EPA, 1995b). U.S. EPA (1995b) estimates emissions of NO_X, NMVOCs, and CO by sector and fuel source using a "bottom-up" estimating procedure, *i.e.*, the emissions were calculated either for individual sources (*e.g.*, industrial boilers) or for many sources combined, using basic activity data (such as fuel consumption or deliveries, etc.) as indicators of emissions. The national activity data used to calculate the individual source categories were obtained from many different sources. Depending on the source category, these basic activity data may include fuel consumption or deliveries of fuel, tons of refuse burned, raw material processed, etc. Activity data are used in conjunction with emission factors, which relate the quantity of emissions to the activity. The basic "bottom-up" calculation procedure for most source categories presented in U.S. EPA (1995b) is represented by the following equation:

$$E_{p,s} = A_s \times EF_{p,s} \times (1 - C_{p,s}/100)$$

where

E = emissions
p = pollutant
s = source category
A = activity level
EF = emissions factor
C = percent control efficiency

Emission factors are generally available from the U.S. EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (U.S. EPA, 1995a), often referred to as AP-42 emission factors. The EPA currently derives the overall emission control efficiency of a source category from a variety of sources, including published reports, the 1985 NAPAP (National Acid Precipitation and Assessment Program) emissions inventory, and other EPA data bases. The U.S.

Table 1-4

U.S. Greenhouse Gas Emissions from Stationary Combustion by Sector and Fuel Source: 1994

Sector/Fuel Source	NO_x	NMVOCs	CO	CH_4	N_2O
		(Thousand Metric Tonnes)			
Electric Utilities					
Coal	6,355	26	223	14	14
Fuel Oil	137	4	13	+	1
Natural gas	528	2	48	NA	+
Wood	NA	NA	NA	NA	+
Other Fuels[a]	NA	NA	NA	NA	NA
Internal Combustion	50	1	11	+	NA
Total	7,070	33	295	14	15
Industrial					
Coal	515	6	73	3	3
Fuel Oil	288	15	45	1	5
Natural gas	1,482	55	248	NA	1
Wood	NA	NA	NA	NA	7
Other Fuels[a]	107	33	154	3	NA
Internal Combustion	514	14	89	1	NA
Total	2,907	123	609	9	17
Commercial/Institutional					
Coal	34	1	14	+	+
Fuel Oil	93	4	15	+	+
Natural gas	152	6	46	NA	+
Wood	NA	NA	NA	NA	+
Other Fuels[a]	10	4	47	+	NA
Internal Combustion	NA	NA	NA	NA	NA
Total	289	15	122	1	1
Residential					
Coal[c]	NA	NA	NA	NA	+
Fuel Oil[c]	NA	NA	NA	NA	1
Natural gas[c]	NA	NA	NA	NA	1
Wood	40	620	3,272	620	2
Other Fuels[a]	330	13	133	1	NA
Internal Combustion	NA	NA	NA	NA	NA
Total	370	633	3,405	622	4
STATIONARY COMBUSTION TOTAL	10,636	804	4,431	678[b]	36

Sources: NO_x, NMVOCs, and CO data are from U.S. EPA (1995b) (original data in short tons). CH_4 emissions were calculated from EPA (1995b) data using the midpoint of CH_4 to NMVOC ratios from U.S. EPA (1993a) (see text). N_2O emissions were calculated from EIA data and IPCC emission factors. (EIA 1995f; 1994a; 1994c and IPCC/OECD/IEA, 1995)

Notes: 1. Technically, of the gases listed in this table, only CH_4 and N_2O are greenhouse gases. See Box 1 in the Introduction for further explanation.

2. Components may not sum to totals due to independent rounding.

3. "+" Denotes negligible; and "NA" denotes Not Available.

a. When referring to criteria pollutants and CH_4, other fuels include: LPG, waste oil, coke oven gas, coke, and wood. For these pollutants wood has been disaggregated in the residential sector. For N_2O, wood has been disaggregated in all sectors. (U.S. EPA, 1995b)

b. This figure includes an additional 32 kt of CH_4 emissions from natural gas stationary sources, which was not distributed among the sectors in the rest of the table. This estimate was from U.S. EPA (1993a), and was not disaggregated, so it has been added to the total at the bottom of the CH_4 column.

c. Coal, fuel oil, and natural gas emission of NO_x, NMVOCs, CO, and CH_4 are included in "Other Fuels" (U.S. EPA, 1995b).

approach for estimating emissions of NO_X, CO, and NMVOCs from stationary combustion as described above is similar to the methodology recommended by the IPCC (IPCC/ OECD/IEA, 1995).

Methane emissions from stationary combustion of coal, fuel oil, and wood were calculated using

reported NMVOC emissions for each activity from U.S. EPA (1995b), and emission ratios of CH_4 to NMVOCs (U.S. EPA, 1993a) for these activities. The emission ratios used are provided in Table I-5. The estimates for emissions from natural gas consumption came from U.S. EPA (1993a).

The estimates of CH_4 emissions from stationary sources, other than gas-fired sources, are subject to considerable uncertainty due to the lack of accurate data regarding the technology type and the pollution control equipment in each of the other source categories (*e.g.*, coal, fuel oil, and especially wood).[7] As a result, estimates are based on broad estimates of the percentage of CH_4 emissions relative to NMVOC emissions — a methodology that results in very imprecise estimates. The estimates for gas-fired stationary combustion are more precise due to the greater level of disaggregation by sector and technology.

Nitrous oxide emissions were estimated using IPCC-recommended emission factors and U.S. fossil fuel and wood fuel consumption data. Estimates were obtained by multiplying the appropriate emission factors (by sectors and fuel types) by the appropriate U.S. energy data. The emission factors used were: 4.3 g N_2O/GJ of energy input for wood in all sectors; 0.1 g N_2O/GJ for gas use and 0.6 g N_2O/GJ for oil use in all sectors; and for coal use, 0.8 g N_2O/GJ for the utility sector and 1.4 g N_2O/GJ for the industrial, commercial, and residential sectors.[8]

Table I-5

Ratio of CH_4 to NMVOCs Released During Combustion

Activity (Source Category)	Ratio of CH_4 to NMVOCs (Low–High)
Coal Combustion	0.05 to 1.00
Fuel Oil Combustion	0.05 to 0.10
Wood Combustion (Industrial Use)	0.2
Wood Combustion (Residential Use)	2
Other	0.1

Source: U.S. EPA (1993a); except for "Other", where the upper end of the fuel oil category was used as an approximation.

Notes: Emissions ratios from wood-fired equipment are based on U.S. EPA (1995b). For industrial wood combustion, the mean CH_4 to NMVOC ratio is based on wood combustion in boilers. For residential wood combustion, the mean ratio is based on available emission factors for residential wood stoves.

Uncertainty in the Emission Estimates

Estimating emissions other than CO_2 from stationary combustion can be time consuming and complex. Moreover, the amount of gases emitted from these activities are not thought to be major contributors to climate change. The uncertainties associated with the emission estimates of these gases, especially CH_4 and N_2O estimates, are also much higher than the uncertainty associated with estimates of CO_2 from fossil fuel combustion. Uncertainties in the CH_4 estimates are due primarily to the fact that they are based on simple ratios of CH_4 to emitted NMVOCs and are derived from a limited number of emissions tests. Uncertainties in the N_2O estimates are due to the fact that emissions were estimated based on a limited set of emission factors. For the other gases, the uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, and the emission factors used.

Other Greenhouse Gas Emissions from Mobile Combustion

Mobile sources emit greenhouse gases other than CO_2, including methane (CH_4) and nitrous oxide (N_2O), and photochemically important gases, including carbon monoxide (CO), nitrogen oxides (NO_X), and non-methane volatile organic compounds (NMVOCs). Emissions of these trace gases are produced by the incomplete combustion of the fossil fuels used to power vehicles.

Fossil fueled motor vehicles comprise the single largest source of CO emissions in the United States as well as being a significant contributor of NO_X and NMVOC emissions (see Table I-6). In 1994, CO emissions from mobile sources contributed about 84 percent of all U.S. anthropogenic CO emissions and 46 and 42 percent of NO_X and NMVOC emissions, respectively. Mobile emissions are also a small source of CH_4 and N_2O in the U.S. Road transport accounts for the majority of mobile source emissions.

For the period 1990 to 1994, emissions of the criteria pollutants as a whole declined through 1992,

[7] Methane emissions from gas-fired sources were extensively researched and documented in U.S. EPA (1993a).

[8] GJ = Gigajoule = one billion joules. One joule = 0.9478 Btu.

after which there was an increase through 1994. The increase was caused by a drop in gasoline prices combined with a strengthening U.S. economy. These factors pushed the vehicle miles traveled (VMT) of road sources up, resulting in increased fuel consumption and higher pollutant emissions. Some of the increased activity was offset by increasing energy efficiency of highway vehicles and an increasing portion of the vehicle population meeting established emissions standards.

Methane and N_2O emissions have increased slightly over the period 1990 to 1994. As with criteria pollutants, this was driven largely by high economic growth and low oil prices. On-road vehicles accounted for nearly all of the increase.

Background and Overall Emissions

As in combustion in stationary sources, N_2O and NO_X emissions are closely related to air-fuel mixes and combustion temperatures, as well as pollution control equipment. Carbon monoxide emissions from mobile combustion are a function of the efficiency of combustion and post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. This occurs especially in idle, low speed and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of motor fuel, the amount of hydrocarbons passing unburnt through the engine, and any post-combustion control of hydrocarbon emissions, such as catalytic converters.

Table I-6

U.S. Greenhouse Gas Emissions from Mobile Combustion: 1990–1994

Year	NO_X	NMVOCs	CO	CH_4	N_2O
	(Thousand Metric Tonnes)				
1990	9,371	8,141	70,308	248	98
1991	9,226	7,821	69,559	250	100
1992	9,369	7,469	67,820	256	102
1993	9,521	7,535	68,469	262	104
1994	9,636	7,753	69,607	267	106

Sources: NO_X, NMVOCs, and CO emissions data are from U.S. EPA (1995b); CH_4 and N_2O emissions were calculated with data provided by the U.S. EPA and EIA (U.S. EPA (1995b), Brezinski, et al. (1992); Carlson (1994); Nizich (1994 and 1995); EIA (1994e); DOT (1994) and FAA (1994 and 1995)).

Emissions from mobile sources are estimated by major transport activity, (*i.e.*, road, air, rail, and ships), where several major fuel types, including gasoline, diesel fuel, jet fuel, aviation fuel, natural gas, liquefied petroleum gas (LPG), and residual fuel oil are considered. Road transport accounts for the majority of mobile source fuel consumption, and hence, the majority of mobile source emissions. Table I-7 summarizes the preliminary 1994 emissions from mobile sources by transport activity, vehicle type, and fuel type.[9]

Since 1990, emissions of CO and NMVOCs have decreased by 1 and 5 percent, while emissions of NO_X have increased by almost 3 percent. All criteria pollutants experienced a slight drop in emissions during 1991 and 1992, after which emissions have increased steadily. For NO_X this increase surpassed 1990 levels, due to increased vehicle miles traveled (VMT) for gasoline vehicles, as well as increased fuel consumption for non-road vehicles for which NO_X control measures are not yet in effect.

Methane and N_2O emissions increased from 1990 to 1994, rising from 1.67 and 8.58 MMTCE in 1990 to 1.79 and 9.29 MMTCE in 1994. The change was dominated by gasoline on-road vehicles, where CH_4 and N_2O emissions increased by 7 and 8 percent respectively, or 0.12 MMTCE for CH_4 and 0.71 MMTCE for N_2O, respectively.

Methodology used to Estimate Emissions

NO_X, NMVOCs, and CO

Emissions estimates for NO_X, NMVOCs, and CO (U.S. criteria pollutants) in this section were taken directly from U.S. EPA (1995b), except for emissions from bunker fuels (fuels delivered to marine vessels, including warships and fishing vessels, and aircraft for international transport), which were calculated based on U.S. EPA data. The U.S. EPA provided emission estimates for eight categories

[9] Annex B contains a description of the methodology and data sources used for these estimates. Estimates of CO_2 emissions from mobile combustion are provided as part of the transportation sector in the section titled "Carbon Dioxide Emissions from Fossil Fuel Consumption." These CO_2 estimates are not provided at the level of detail indicated in Table I-7, because fuel consumption data for each of these categories, which would be needed to complete calculations, are not readily available.

of highway vehicles,[10] aircraft,[11] and seven categories of off-highway vehicles.[12]

CH_4 and N_2O

Emission estimates of CH_4 and N_2O from mobile sources historically have not been calculated by the U.S. Emission estimates for these gases were calculated using the IPCC-recommended methodologies and emission factors (IPCC/OECD/IEA, 1995). Activity data were derived from U.S. EPA (1995b), Brezinski, *et al.* (1992); Carlson (1994); Nizich (1994 and 1995); EIA (1994e); DOT (1994) and FAA (1994 and 1995).

Uncertainty in the Emission Estimates

Estimating emissions from mobile combustion, as with stationary combustion, can be time consuming and complex. Also, the estimates can vary significantly due to many factors, including fuel type, technology type, extent of emission control equipment, equipment age, and operating and maintenance practices. However, compared to stationary sources, more detailed data are available on activity levels and emission factors by vehicle type.

Table 1-7

U.S. Greenhouse Gas Emissions from Mobile Combustion by Vehicle Type: 1994

Source Category	NO_x	NMVOCs	CO	CH_4[a]	N_2O[a]
	(Thousand Metric Tonnes)				
Gasoline Highway Vehicles					
Passenger Cars	3,390	3,524	35,481	126	74
Light-Duty Trucks	1,299	1,510	13,734	78	21
Heavy-Duty Vehicles	302	357	4,757	26	1
Motorcycles	11	33	174	4	+
Total	5,002	5,422	54,146	233	96
Diesel Highway Vehicles[c]					
Passenger Cars	36	13	31	+	+
Light-Duty Trucks	7	3	6	+	+
Heavy-Duty Vehicles	1,784	271	1,218	16	6
Total	1,827	287	1,256	16	6
Other Mobile Sources					
Aircraft	139	192	964	5	+
Locomotives	859	39	112	2	1
Vessels/Boats	189	444	1,197	3	2
Farm Equipment	241	54	250	5	1
Construction Equipment	980	155	958	1	+
Other Off-Highway	399	1,159	10,723	b	b
Total	2,807	2,044	14,205	17	5
TOTAL MOBILE SOURCES	9,636	7,753	69,607	267	106

Sources: NO_x, NMVOCs, and CO emissions data are from U.S. EPA (1995b); CH_4 and N_2O emissions were calculated with data provided by the U.S. EPA and EIA (U.S. EPA (1995b), Brezinski, et al. (1992); Carlson (1994); Nizich (1994 and 1995); EIA (1994e); DOT (1994) and FAA (1994 and 1995)).

Notes: 1. Totals may not equal the sum of components due to independent rounding.

2. "+" Denotes negligible (i.e., <0.5 Thousand MT).

a. Average of high and low estimates reported for diesel vehicles.

b. For CH_4 and N_2O, "Other Off-Highway" is included with "Construction Equipment".

c. Estimates carry an error range of ± 50 percent, of which these numbers are the midpoints.

[10] These categories include: gasoline powered automobiles, diesel powered automobiles, light duty gasoline trucks less than 6,000 pounds in weight, light duty gasoline trucks between 6,000 and 8,500 pounds in weight, light duty diesel trucks, heavy duty gasoline trucks and buses, heavy duty diesel trucks and buses, and motorcycles.

[11] Currently, emissions factors are not available for aircraft flying above 3000 feet. These emissions may be significant and do affect atmospheric chemistry, but sufficient information to calculate these emissions is unavailable at this time.

[12] These categories include: gasoline and diesel farm tractors, other gasoline and diesel farm machinery, gasoline and diesel construction equipment, snowmobiles, small gasoline utility engines, and heavy duty gasoline and diesel general utility engines.

FOSSIL FUEL PRODUCTION, TRANSPORT, STORAGE, AND DISTRIBUTION

Emissions from Coal Mining

The most significant emissions from coal mining are methane (CH_4). Emissions from coal mining are currently the third largest source of methane emissions in the U.S., behind landfills and domestic livestock, accounting for approximately 15 percent of national methane emissions. Estimates of methane emissions from coal mining for 1994 were about 28.9 MMTCE.

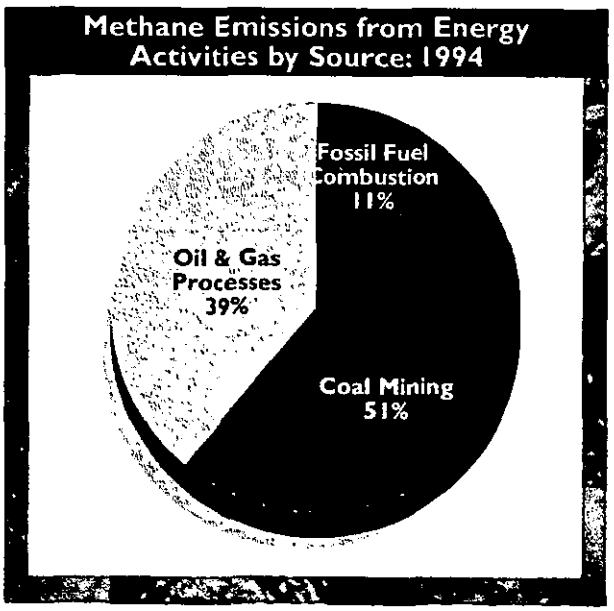
The amount of methane released during coal mining is primarily a function of coal rank and depth, although other factors, such as moisture, also affect the amount of methane released. In most underground coal mines, methane is removed by circulating large quantities of air through the mine and venting this air (typically containing a concentration of 1 percent methane or less) into the atmosphere. In some very gassy underground mines, however, more advanced methane recovery systems are used to supplement the ventilation systems and ensure mine safety. In surface mines, methane is emitted directly to the atmosphere as the strata overlying the coal seam are removed. In addition to emissions from underground and surface mining, a portion of the methane emitted from coal mining comes from post-mining activities such as coal processing, transportation, and consumption.

Background and Overall Emissions

The process of coal formation, commonly called coalification, inherently generates methane and other by-products. The degree of coalification (defined by the rank, *i.e.*, quality of the coal) determines the quantity of methane generated. Once generated, the amount of methane stored in coal is controlled by the pressure and temperature of the coal seam and other, less well-defined characteristics of the coal. The methane will remain stored in the coal until the pressure on the coal is reduced. This can occur through erosion of the overlying strata or through coal mining. Once the methane has been released from the coal seam, it flows through the coal toward a pressure sink (such as a coal mine) and methane is released into the atmosphere (U.S. EPA, 1990a).

Methane emissions from coal mining in 1994 ranged from 3,300,000 to 5,300,000 metric tonnes of methane (22.3 to 35.5 MMTCE), with a central estimate of approximately 4,300,000 metric tonnes (28.9 MMTCE). This is a decline of about 2 percent since 1990 (see Table I-8).

From 1990 through 1992, methane emissions from coal mining decreased by about 1 MMTCE per year (from 29.4 MMTCE in 1990 to 28.4 in 1991 to 27.4 in 1992). The decrease from 1990 to 1991 was caused by lower coal production levels in 1991, particularly for coal produced from underground mines. In 1992, total annual coal production for both underground and surface mines was very similar to 1991 production. However, coal production from underground mines in the Central Appalachian Basin decreased, while production from other, less gassy basins increased. An additional factor contributing to the reduced emissions levels was that a large methane recovery and utilization project, involving four extremely gassy Virginia mines, started during the second half of 1992.



While emissions declined gradually between

Table I-8

Coal Mine Methane Emissions Estimates

Year	Range	Point Estimate
	(Million Metric Tonnes)	
1990	3.4 - 5.4	4.40
1991	3.3 - 5.2	4.25
1992	3.2 - 5.0	4.10
1993	3.0 - 4.3	3.65
1994	3.3 - 5.3[a]	4.33

[a] *1994 estimates are preliminary as detailed production data and emissions from ventilation and degasification systems are not yet available.*

1990 and 1992, there was a substantial decrease between 1992 and 1993 — from 27.4 MMTCE in 1992 to 24.4 MMTCE in 1993. Two primary factors account for this decrease. First, a lengthy strike by the United Mine Workers of America against many large underground mines resulted in substantially lower coal production levels from underground mines (underground production decreased from 406 million tons in 1992 to 351 million tons in 1993). Second, the new methane recovery and utilization project in Virginia, which started producing in the second half of 1992, was in full operation throughout 1993. This one project alone accounted for emissions reductions of 1.2 MMTCE. During the time period between 1990 through 1993, the total quantity of methane liberated[13] per ton of coal mined remained fairly constant.

Methane emissions increased from 24.4 MMTCE in 1993 to 28.9 MMTCE in 1994. The 1994 estimate is preliminary as coal production data by basin and type and methane emissions estimates from underground ventilation systems are not yet available for that year. The increase in emissions is due to the increase in coal production from about 945 million short tons in 1993 to about 1,031 million short tons in 1994. In particular, production from gassy underground mines increased in 1994 because the strike against many large underground mines in the eastern U.S. was over by the start of 1994.

Methodology Used to Estimate Emissions

For 1990 and 1993, these estimates were based on detailed analysis of coal mine methane emissions from surface and underground mines and post-mining activities. Emissions were estimated for each major coal mining source, including both ventilation and degasification systems at underground mines, surface mines, and post mining operations. Detailed emissions data for underground mines were not available for 1991 and 1992. For 1991, 1992, and 1994, the 1990 emissions were adjusted to account for differences in coal production between 1990 and these subsequent years. Coal production levels for all basins for surface and underground mines were compared to coal production levels for 1990.

Detailed emissions data for 1994 are not yet available. Accordingly, for 1994, preliminary emissions estimates were based on 1990 emissions factors, adjusted for the increase in total coal production and the increase in the amount of methane recovered and used for pipeline sales. 1990 emissions factors, rather than 1993 emissions factors, were used to estimate 1994 emissions due to the impact of the strike on 1993 emissions estimates.

For 1990 and 1993, the following data were used to estimate emissions from underground mines:

- methane emissions from ventilation systems for all underground mines with methane emissions greater than 0.1 million cubic feet per day (measured by the Mine Safety and Health Administration and reported by the U.S. Bureau of Mines (Bureau of Mines, 1995i);
- estimated ventilation emissions from mines for which measurements were not available;
- reported emissions from degasification systems;
- estimated emissions from degasification systems from mines for which reported values were not available; and
- reported and estimated methane recovered from degasification systems that was sold to pipelines, rather than emitted to the atmosphere.

For all years, emissions from surface mines were

[13] Total methane liberated is the total quantity of methane released from the coal seams, which includes both methane emitted and methane recovered and used for energy purposes.

estimated using reported in-situ methane contents for the surface coals mined in each U.S. coal basin and by assuming that total emissions were from 1 to 3 times the in-situ content of the coal. Post-mining emissions from both underground mines and surface mines were estimated to be between 25 to 40 percent of the in-situ methane content of the coal mined in each basin. A more detailed discussion of emissions from each stage of the coal extraction process can be found in U.S. EPA (1993a).

Further research is being conducted into emissions from surface mines, post-mining emissions, and emissions from abandoned mines. This research will potentially make it possible to provide improved estimates of emissions from these sources in the future. A more detailed description of this recent research may be found in Piccot, *et al.* (1995).

Uncertainty in the Emission Estimates

The key uncertainties in these estimates arise from emissions for which measurements are not available. The most significant source of uncertainty stems from emissions from degasification systems at underground mines. While the EPA has developed a list of mines known or believed to have degasification systems in place, there is still some uncertainty regarding which mines have degasification systems. Furthermore, the quantity of methane that is emitted from these systems has not been reported and is not known for most mines. Accordingly, emissions from degasification systems must be estimated. For mines with unknown degasification emissions, it was assumed that mines generally emit between 35 to 65 percent of their total emissions from degasification systems. To the extent that the degasification strategy varies by mine or coal basin, emissions could be over- or underestimated.

Due to a combination of instrument error and sampling and aggregation errors, measured estimates of emissions from ventilation systems may have an uncertainty range of ±20 percent. Estimates for surface mining are less certain as these emissions are not measured by the Mine Safety and Health Administration. Surface mining emissions are estimated to range from 1 to 3 (and possibly as much as 5) times the amount of methane contained in the coal. As mentioned previously, recent research by EPA should help to clarify these emissions in the future.

Emissions from Natural Gas Production, Processing, Transport, and Distribution

The production, processing, transport, and distribution of natural gas produces methane emissions. These emissions from U.S. natural gas systems account for about 11 percent of total U.S. methane emissions. Between 1990 and 1994, methane emissions from natural gas systems have remained relatively constant at approximately 3 million tonnes (20 MMTCE). Although no emissions trend is discernable using the estimation method applied here, emissions reductions of nearly 0.1 million tonnes have been reported under the Natural Gas STAR program for 1993 and 1994. Future emissions estimates will need to develop an approach that considers the impact of this program.

In addition to not reflecting the impacts of the Natural Gas STAR program, the emissions estimates remain very uncertain because the basis for estimating emissions remains extremely weak. Currently, work is ongoing to improve the accuracy of the estimates, which may change the emissions estimates substantially as new information becomes available and new methods are developed.

Background and Overall Emissions

Emissions from the U.S. natural gas systems are generally process related. Normal operations of systems, routine maintenance, and system upsets all contribute to methane emissions. Emissions from normal operations include: emissions from the exhaust of engines and turbines that use natural gas as fuel, bleed and discharge emissions from pneumatic devices, and fugitive emissions from system components. Routine maintenance emissions are released from pipelines, equipment, and wells during repair and maintenance activities. System upset emissions originate from pressure surge relief systems and accidents. These sources of emissions exist throughout

the natural gas system, in different quantities and degrees in different stages and activities.

There are a variety of activities that exist and take place throughout the U.S. natural gas system. This complex system encompasses hundreds of thousands of wells, hundreds of processing facilities, hundreds of thousands of miles of transmission pipelines, and over a million miles of distribution pipeline. The system can be divided into six stages, each with different factors affecting methane emissions, as follows:

- *Field Production.* In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, treatment facilities, gathering pipelines, and process units such as dehydrators and separators. Fugitive emissions and emissions from pneumatic devices account for the majority of total methane emissions. Emissions from field production accounted for roughly one-third of total emissions from natural gas systems (U.S. EPA, 1993a).

- *Processing Plants.* At this stage, undesired constituents in the raw gas are removed before the gas is injected into the transmission system. Based on estimates from model plant analyses, emissions from the venting of glycol dehydrators account for a large portion of emissions, with compressor start/stops and fugitive emissions accounting for most of the remaining discharge (U.S. EPA, 1993a). Processing plants contribute less than five percent of the total emissions from natural gas systems.

- *Storage and Injection/Withdrawal Facilities.* Natural gas is injected and stored in underground formations during periods of low demand, and withdrawn, processed, and distributed during periods of high demand. From a 1990 analysis of five plants (Tilkicioglu, 1990), the only significant source of emissions originated from compressor start/stops and routine maintenance. Less than one percent of total emissions from natural gas systems can be attributed to these facilities.

- *Transmission Facilities.* These are high pressure, large diameter lines that transport gas long distances from sources of supply to distribution centers or large volume customers. In 1993, the transmission system consisted of approximately 272,200 miles of line. An additional 77,300 miles of field and gathering line also fall into this segment. Throughout the system, compressor stations pressurize the gas. The majority of emissions were found to arise from routine maintenance, fugitive emissions, and pneumatic devices. Methane emissions from the transmission sector accounted for approximately one-third of total emissions from natural gas systems.

- *Distribution Systems.* Distribution pipelines are low pressure pipelines used to deliver gas to customers. The distribution network consists of over 1.3 million miles of line (AGA, 1991). In U.S. EPA (1993a), emissions from distribution were shown to arise mostly from fugitive emissions from non-plastic pipe and gate stations. The distribution system accounts for roughly 10 percent of total emissions from natural gas systems.

- *Compressor Engines.* These engines, which are used throughout the entire industry, produce emissions in their exhaust. Reciprocating engines account for the majority of exhaust emissions, with turbines contributing a small amount. Compressor engines account for less than 15 percent of total emissions from the gas system.

Taking into account the high level of uncertainty in the calculation of emissions estimates, the small fluctuations in the emissions estimates from 1990 to 1994 are negligible (see Table I-9). Thus, during the period 1990 to 1994, estimates show that methane emissions from natural gas systems have remained virtually unchanged.

Methodology Used to Estimate Emissions

The methodology used to estimate methane emissions from the natural gas system, as described in the EPA report, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (U.S. EPA, 1993a), is as follows:

1. One or more model facilities were defined for each stage of the natural gas system. These model

Table 1-9

Methane Emissions from the U.S. Natural Gas Industry: 1990-1994

Segment	1990	1991	1992	1993	1994[a]
			(Million Metric Tonnes)		
Production	1.08	1.08	1.08	1.07	1.10
Processing	0.08	0.09	0.09	0.09	0.09
Storage	0.02	0.02	0.02	0.02	0.02
Transmission	1.04	1.05	1.06	1.01	1.04
Distribution	0.33	0.34	0.34	0.34	0.35
Compressor Engines	0.42	0.41	0.40	0.42	0.43
TOTAL	2.97	2.99	2.99	2.96	3.03

[a] *1994 data are preliminary.*

facilities were selected based on the extent to which they were representative of the system.

2. Emissions types were identified for each model facility based on detailed data describing the facility and the processes that lead to emissions.

3. Emissions factors for each model facility were estimated based on an appropriate measure of the facility's size (*e.g.*, throughput in ft^3/year or miles of pipeline).

4. Average emissions factors were estimated by averaging the emissions factors estimated for each of the model facilities in each stage of the industry.

5. National emissions were estimated by multiplying the average emissions factors for each stage by the total applicable size of the national system, such as billion cubic feet of throughput, number of wells, or miles of pipeline.

6. Total industry emissions were determined by adding the national segment emissions for each year.

Estimates of each emissions type within each segment of the industry were obtained by multiplying emissions factors with their corresponding activity levels. To estimate emissions for 1991 to 1993, the emissions factors developed for 1990 in the EPA report (U.S. EPA, 1993a) were multiplied with updated activity factors for 1991 to 1993. National aggregate activity factors were obtained from the AGA publication *Gas Facts* (AGA, 1994), and the *Natural Gas Annual* (EIA, 1994i). Since appropriate 1994 activity factors were unavailable, 1994 emissions were estimated by increasing 1993 emissions data based on the percent increase in national natural gas production (approximately 2.7 percent).

Uncertainty in the Emissions Estimates

Due to the complexity and size of the U.S. natural gas system, activity levels are uncertain. Similarly, extrapolating measurement data from a small number of "model" facilities to determine average emissions factors for the whole industry also becomes a large source of uncertainty. Recognizing the weaknesses in the bases for the estimates presented above, the U.S. EPA and the Gas Research Institute are conducting in-depth data collection and analysis to improve the basis for making emissions estimates (Kirchgessner, *et al.*, 1995). The ongoing work involves collecting field data to estimate the number of components in each stage of the natural gas system. These field data will then be extrapolated to estimate national activity factors. Additionally, detailed field measurements are being conducted to improve the emissions factors for each component type. The results of the ongoing work are anticipated in the coming year, at which time the emissions estimates will be updated.

Emissions from Production, Refining, Transportation, and Storage of Petroleum

The major gas emitted from the production and refining of petroleum products is methane (CH_4). The

activities that produce these emissions are production field treatment and separation; routine maintenance of production field equipment; crude oil storage; refinery processes; crude oil tanker loading and unloading; and venting and flaring. Together, these activities account for approximately one percent of total U.S. methane emissions. From 1990 to 1994, these emissions remained relatively constant at approximately 0.27 million tonnes per year (1.8 MMTCE). The emissions estimates remain very uncertain as the basis for estimating emissions remains weak due to the complexity of sources and factors affecting emissions. Work is ongoing to improve the accuracy of the estimates, which may change substantially as new information becomes available and sounder methods for characterizing the system are developed.

The flaring of gas from oil wells is also a small source of carbon dioxide (CO_2), while the above activities release small amounts of nitrogen oxides (NO_X), nonmethane volatile organic compounds (NMVOCs), and carbon monoxide (CO). Each of these sources, however, is a small portion of overall emissions. Emissions of CO_2, NO_X, and CO from petroleum production activities are all less than one percent of national totals, while NMVOC emissions are roughly three percent of national totals.

Methane: Background and Overall Emissions

Several activities during the production and refining of petroleum products produce methane emissions. Tilkicioglu and Winters (1989) identified the major emissions sources as:

- *Production Field Emissions.* Fugitive emissions from oil wells and related production field treatment and separation equipment are the primary source of field production emissions. From 1990 to 1994, these emissions accounted for about 60 percent of total emissions from petroleum production and refining (see Table I-10). Routine maintenance, which includes the repair and maintenance of valves, piping, and other equipment, accounted for less than 1 percent of total emissions from petroleum production and refining.

- *Crude Oil Storage Emissions.* Crude oil storage tanks emit methane during two general processes. When the tank is in use, roof seals and joints become a source for "breathing losses." When tanks are emptied and filled, the methane in the space above the liquid in the tank is often released; these emissions are referred to as "working losses." Also, piping and other equipment at storage facilities produce fugitive emissions. Between 1990 and 1994, crude oil storage emissions accounted for about 5 percent of total emissions

Table I-10

Methane Emissions from the Production and Refining of Petroleum Liquids: 1990-1994

Emissions Source	1990	1991	1992	1993	1994
			(Thousand Metric Tonnes)		
Production					
Fugitive Emissions	22.4	22.4	22.5	22.1	22.1
Routine Maintenance	0.05	0.05	0.05	0.05	0.05
Refining					
Waste Gas Streams	10.3	10.1	9.9	10.1	9.7
Storage					
Crude Oil Storage	1.8	1.8	1.8	1.9	1.9
Transportation					
Tankers	5.6	5.5	5.5	5.4	5.3
Total	40.1	39.9	39.7	39.4	39.0
Range	10.0 - 160.3	10.0 - 159.7	9.9 - 158.9	9.9 - 157.6	9.75-156.0
Venting and Flaring (V&F)	92.5 - 462	92.5 - 462	92.5 - 462	92.5 - 462	92.5 - 462
Range with V&F	102.5-622.3	102.5-621.7	102.4-620.9	102.4-619.6	102.2-618.0
POINT ESTIMATE (W/V&F)	271	271	270	270	270

from petroleum production and refining.

- *Refining: Waste Gas Streams.* Waste gas streams from refineries are a source of methane emissions. Based on Tilkicioglu and Winters (1989), which extrapolated waste gas stream emissions to national refinery capacity, emissions estimates from this source accounted for approximately 25 percent of total methane emissions from the production and refining of petroleum.

- *Transportation: Tanker Operations.* The loading and unloading of crude oil tankers releases methane. From 1990 to 1994, emissions from crude oil transportation on tankers accounted for roughly 14 percent of total emissions from petroleum production and refining activities.

- *Venting and Flaring.* Gas produced during oil production that cannot be contained or otherwise handled is released into the atmosphere or flared. Vented gas typically has a high methane content, and flaring does not always destroy all the methane in the gas. Venting and flaring can potentially account for up to 90 percent of emissions from the production and refining of petroleum, but there is a wide range of potential estimates for this category, which reflects the considerable uncertainty in the estimate for this emissions source.

Methane: Methodology used to Estimate Emissions

The methodology used for estimating emissions from each source is described as follows:

- *Production Field Emissions.* Fugitive emissions and routine maintenance emissions during production are driven by the size of the production system, *i.e.*, the number of oil wells. Emissions estimates are obtained by multiplying emissions factors (emissions per well) with their corresponding activity level (number of wells). To estimate emissions for 1990 to 1993, emissions factors developed for 1990, in the EPA report (U.S. EPA, 1993a) were multiplied with updated activity levels for 1990 to 1993. The updated activity levels were obtained from the *Oil and Gas Journal* ("Worldwide Look at Reserves and Production", 1994). Since no updated activity factors were available for 1994, 1993 values were used as preliminary estimates.

- *Crude Oil Storage Emissions.* There are significant uncertainties in estimating crude oil storage tank emissions because a good census of tank characteristics that influence emissions is not available. Tilkicioglu & Winters (1989) estimated crude oil storage emissions based on a model tank farm facility with fixed and floating roof tanks. Emissions factors developed for the model facility were applied to published crude oil storage data to estimate total emissions. Crude oil storage data for 1990 to 1993 were obtained from the Energy Information Administration (EIA, 1994k). Since no updated activity factors were available for 1994, 1993 values were used as preliminary estimates.

- *Refining: Waste Gas Streams.* Tilkicioglu & Winters (1989) estimated national methane emissions from waste gas streams based on measurements at 10 refineries. These data were extrapolated to total U.S. refinery capacity to estimate total emissions from waste gas streams for 1990. To estimate emissions for 1991 to 1994, the 1990 emissions estimates were scaled using updated data on U.S. refinery capacity. These data were obtained from the Energy Information Administration (EIA, 1994k).

- *Transportation: Tanker Operations.* Methane emissions from tanker operations are associated with: (1) the loading and unloading of domestically-produced crude oil transported by tanker; and (2) the unloading of foreign-produced crude transported by tanker. The quantity of domestic crude oil transported by tanker was estimated as Alaskan crude oil production less Alaskan refinery crude oil utilization, plus 10 percent of non-Alaskan crude oil production. Crude oil imports by tanker were estimated as total imports less imports from Canada. An emissions factor based on the methane content of hydrocarbon vapors emitted from crude oil was developed (Tilkicioglu & Winters, 1989). The emissions factor was multiplied by updated activity data to estimate total emissions for 1990 to

1994. Data on crude oil stocks, crude oil production, utilization, and imports was obtained from the Energy Information Administration (EIA, 1994k).

- *Venting and Flaring.* The basis for estimating emissions from venting and flaring is weak. Also, the data for estimating how much gas is vented and how much is flared are very poor. Because of this considerable uncertainty in estimating venting and flaring emissions, the 1990 estimates were used in the calculations of total estimates for the years 1991-1994. The range of emissions estimated in the EPA report (U.S. EPA, 1993a) for 1990 is 92.5 to 462 million kilograms.

Methane: Uncertainty in the Emissions Estimates

The first range in Table I-10 accounts for uncertainty in the emissions estimates excluding venting and flaring. Following the uncertainty range adopted in U.S. EPA (1993a), the range consists of one fourth to four times the total estimate. The venting and flaring estimates are those determined by Radian (1992b) and Barns and Edmonds (1990). The addition of venting and flaring results in a combined range of approximately 102 to 620 million kilograms of methane per year.

As the wide range reveals, considerable uncertainty is present in these emission estimates. Presently, sufficient national emissions data do not exist. Consequently, the emissions factors were determined based on measurements at several model facilities that may not encompass the range and diversity of factors that affect emissions. However, ongoing efforts to develop more precise assessments may significantly improve the emissions estimates.

Carbon Dioxide: Emissions, Methodology, and Uncertainty

Carbon dioxide emissions from oil and gas production come from the natural gas that is flared at the production site, which releases CO_2 as a by-product of the combustion process. Barns and Edmonds (1990) note that of total reported U.S. venting and flaring, approximately 20 percent is actually vented, with the remaining 80 percent flared. The amount of natural gas vented and flared was obtained from the *Natural Gas Monthly* (EIA, 1994j) and used to estimate the amount of CO_2 resulting from the flared gas. For 1994 these emissions were estimated to be approximately 5 million metric tonnes (1.4 MMTCE), which was down by approximately 23 percent from 1990 (see Table I-11).

Table I-11

CO_2 Emissions from Flaring of Natural Gas

Year	CO_2 (Million Metric Tonnes)
1990	6.5
1991	7.4
1992	7.3
1993	8.3
1994	5.0

Source: EIA (1994j)

The estimates were prepared using a conversion factor of 525 grams of carbon per cubic meter of flared gas, as determined by Marland and Rotty (1984), and an assumed flaring efficiency of 100 percent. The assumed uncertainty range is ±25 percent. The 20 percent vented as methane is accounted for in the above section on methane emissions from petroleum production, refining, transportation, and storage activities.

Nitrogen Oxides, NMVOCs, and CO: Emissions, Methodology, and Uncertainty

Criteria pollutant emissions from oil and gas production, transportation, and storage constitute a relatively small and stable portion of the overall U.S. emissions of these gases for the 1990 to 1994 period (see Table I-12).

The U.S. EPA (1995b) provided emission estimates for NO_X, NMVOCs, and CO from petroleum refining, petroleum product storage and transfer, and petroleum marketing operations. Included are gasoline, crude oil and distillate fuel oil storage and transfer operations, gasoline bulk terminal and bulk plants operations, and retail gasoline service stations operations. Emission estimates were determined using industry-published production data and applying

Table I-12

NO_x, NMVOCs, and CO Emissions from Oil and Gas Activities: 1990 -1994

Year	NO_x	NMVOCs	CO
	(Thousand Metric Tonnes)		
1990	91	583	395
1991	88	575	374
1992	87	579	372
1993	86	572	361
1994	86	572	354

Source: U.S. EPA (1995b).

average emission factors.

Due to the diverse nature of the various types of emissions and the fact that some emissions occur periodically or unexpectedly, precise measurements are not practical in many cases. As a result, the uncertainties associated with the emission estimates in this section vary, ranging anywhere from 25 to 50 percent.

EMISSIONS FROM BIOMASS AND BIOMASS-BASED FUEL CONSUMPTION

The combustion of biomass fuels (such as wood, charcoal, and wood waste) and biomass-based fuels (such as ethanol from corn or woody crops) produce carbon dioxide. However, the carbon dioxide (CO_2) emitted from biomass consumption in the long run does not increase total atmospheric carbon dioxide if this consumption is done on a sustainable basis (i.e., annual emissions of CO_2 due to consumption of biomass are completely offset by the annual uptake of CO_2 from regrowing biomass). As a result, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel-based emissions and are not included in the U.S. totals. Net carbon flux in the forest sector resulting from land-use activities and forest management practices are accounted for in Part V: Emissions from Land-Use Change and Forest Management.

Carbon dioxide emissions from stationary biomass fuel consumption were estimated to be about 49 MMTCE in 1994. Emissions from this source have increased 4 percent since 1990, primarily due to increases in biomass fuel consumption in the industrial sector in response to U.S. economic growth. Carbon dioxide emissions from ethanol fuel consumption were about 1.9 MMTCE, increasing about 19 percent from 1990 levels. This increase can be attributed to rising consumption of ethanol due to new legislation establishing incentives for ethanol fuel use.

Emissions from Wood Consumption

Background and Overall Emissions

In 1994, total CO_2 emissions due to burning of woody biomass within the electric utility, industrial, residential and commercial sectors were about 49 MMTCE (181 million metric tonnes CO_2) (See Table I-13). As the largest consumer of biomass fuels, the industrial sector was responsible for about 74 percent of the CO_2 emissions from biomass-based fuels. The residential sector was the second largest emitter of CO_2, making up about 24 percent of total emissions from biomass. The commercial and electric utility sectors accounted for the remainder.

Between 1990 and 1994, total emissions of CO_2 from biomass burning have increased about 4 percent despite a 5 percent decrease in biomass fuel use in the residential sector during this same time period (See Table I-14). This increase in total emissions is largely due to a 7 percent rise in industrial biomass fuel consumption between 1990 and 1994. Increases in industrial biomass use are directly due to growth in the U.S. economy. The 5 percent decline in biomass fuel use in the residential sector is attributable to both the rising cost of wood burning stoves and a falling number of households relying on wood as a primary heating source (Thompson, 1995). Consumption of

Table I-13

CO_2 Emissions from Wood Consumption by Sector: 1990–1994

Sector	1990	1991	1992	1993	1994
			(Million Metric Tonnes)		
Electric Utility	1.0	0.8	0.9	0.9	0.9
Industrial	124.8	122.1	127.3	129.4	133.5
Residential	46.4	49.0	51.5	43.9	43.9[a]
Commercial	2.4	2.4	2.4	2.4	2.4
Total	174.6	174.3	182.1	176.6	180.7

Sources: 1990-92 emissions estimates are based on biomass consumption estimates in trillion Btu from EIA (1994c). 1993-94 emissions estimates for the industrial, commercial, and electric utility sectors, and the 1993 emissions estimate for the residential sector are based on EIA unpublished biomass consumption estimates. See Table I-14 for industrial and residential biomass consumption estimates for 1990–1994.

Notes: 1. Components may not sum to total because of rounding.

2. Consumption estimates in trillion Btu were converted to short tons based on an average energy content of 17.2 million Btu per short ton of dry wood (EIA, 1994c).

3. Estimates carry an error range of ±25 percent.

4. According to EIA, commercial wood energy use is typically not reported because there are no accurate data sources to provide reliable estimates (EIA, 1994c). However, EIA's 1989 Nonresidential Building Energy Consumption Survey estimates that commercial sector use is about 20 to 40 trillion Btu. An average of 30 trillion Btu is used here.

[a] Data on residential wood consumption for 1994 were unavailable at the time this report was compiled. Emissions for 1993 have been used as a proxy until 1994 data becomes available.

biomass fuels within the commercial and electric utility sectors remained relatively stable and thus had little impact on changes in overall CO_2 emissions from biomass combustion.

Methodology and Uncertainty

Emissions estimates were calculated based on the methodology recommended by the IPCC. Emissions were estimated by first converting U.S. consumption data (in trillions of Btu) to tonnes of dry matter using EIA assumptions.[14] Once consumption data for each sector were converted to tonnes of dry matter, the carbon content of the dry fuel was estimated based on IPCC default values of 45 to 50 percent carbon in dry biomass. The amounts of carbon released from combustion were also estimated using IPCC-provided default values of 87 percent combustion efficiency. This is probably an underestimate of the efficiency of wood combustion processes in the U.S. The IPCC assumption has been used, however, since better data are not yet available.

Emissions from Ethanol Consumption

Background and Overall Emissions

Biomass-based fuel use in the U.S. consists mainly of ethanol use in the transportation sector. Ethanol is mostly produced from corn grown in the

Table I-14

Residential and Industrial Biomass Combustion: 1990-1994

Sector	1990	1991	1992	1993	1994
			(Trillion Btus)		
Industrial	1,562	1,528	1,593	1,619	1,671
Residential	581	613	645	550	550[a]

Sources: 1990-1992 biomass consumption estimates from EIA (1994c). 1993-94 biomass consumption estimates are preliminary and were obtained from an EIA database.

[a] Estimate for 1994 residential biomass consumption was not available at the time this report was compiled. 1993 biomass consumption data have been used as a proxy until 1994 data become available.

[14] Data for 1990-1992 are from the EIA report entitled *Estimates of U.S. Biomass Energy Consumption 1992*, published in May 1994. Preliminary data for 1993-1994 were obtained from an EIA database.

Table I-15

U.S. CO_2 Emissions from Ethanol Consumption: 1990–1994

	1990	1991	1992	1993	1994
Ethanol Consumption (trillion Btu)	82	65	79	88	98
CO_2 Emissions (million metric tonnes)	5.7	4.5	5.5	6.1	6.8

Sources: 1990-1992 biomass consumption estimates from EIA (1994c). 1993-94 biomass consumption estimates are preliminary and were obtained from an EIA database.

Midwest, and used primarily in the Midwest and South. Ethanol can be used directly, or mixed with gasoline as a supplement or an octane enhancing agent. The most common form is a 90 percent gasoline, 10 percent ethanol blend known as gasohol. Ethanol and ethanol blends are used to fuel public transport vehicles such as buses, or centrally-fueled fleet vehicles. Ethanol and ethanol blends are believed to burn "cleaner" than gasoline (lower in NO_X and other hydrocarbons), and are being tested in urban areas with poor air quality. However, because ethanol is a hydrocarbon fuel, its combustion releases CO_2.

Emissions of CO_2 in 1994 due to ethanol fuel burning were estimated to be approximately 1.9 MMTCE (6.8 million metric tonnes of CO_2) (See Table I-15). Between 1990 and 1991, emissions of CO_2 due to ethanol fuel consumption fell by about 21 percent. Since this decline, emissions from ethanol have steadily increased through 1994. Between 1991 and 1992, CO_2 emissions due to ethanol consumption increased about 22 percent. Increases in CO_2 emissions continued at an average annual rate of about 11 percent between 1992 and 1994. Emissions from ethanol consumption are not included in the U.S. total since the corn from which the ethanol is derived is produced on a sustainable basis.

Increases in CO_2 emissions from ethanol consumption between 1991 and 1994 can be attributed to several factors. In 1990, the Budget Reconciliation Act extended Federal tax exemptions for ethanol production through the year 2000 and the Clean Air Act Amendments mandated the reduction of mobile source emissions. In 1992, the Energy Policy Act established incentives to encourage an increase in the use of alternative fuels and alternative-fueled vehicles. Other factors also influencing ethanol consumption include prices of corn, gasoline, and other alternative fuels (EIA, 1994c).

Methodology

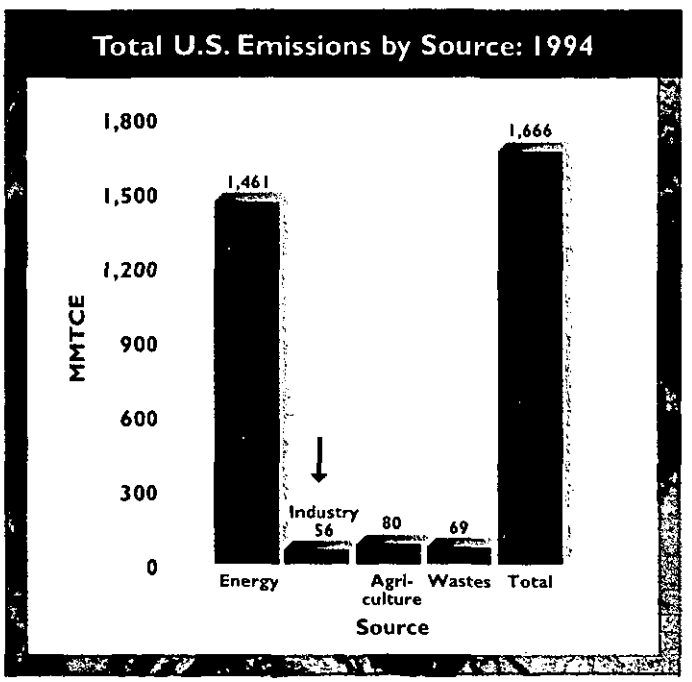
Emissions from ethanol were estimated based on EIA (1994c). In 1994, the U.S. consumed an estimated 98 trillion Btus of ethanol (1.3 billion gallons), mostly in the transportation sector. Using an ethanol carbon coefficient of 19 milligrams C/Btu (OTA, 1991), 1994 emissions of CO_2 from the use of ethanol were calculated to be about 6.8 million metric tonnes (1.85 MMTCE).

Part II: Industrial Processes

Emissions are often produced as a by-product of various non-energy related activities. That is, these emissions are produced directly from the process itself and are not a result of energy consumed during the process. For example, in the industrial sector raw materials are chemically transformed from one state to another. This transformation often results in the release of greenhouse gases such as carbon dioxide (CO_2). Other emissions result from use of greenhouse gases in manufacturing and subsequent emissions of the excess gas. The production processes addressed in this section include cement production, lime production, limestone use (*e.g.*, for iron and steel making, flue gas desulfurization, and glass manufacturing), soda ash production and use, CO_2 manufacture, aluminum production, adipic acid production, nitric acid production, and HCFC-22 production. Total CO_2 emissions from industrial processes were approximately 58.1 million metric tonnes (15.9 MMTCE) in 1994. This accounts for 1.1 percent of total U.S. CO_2 emissions. Nitrous oxide (N_2O) emissions from adipic acid and nitric acid production were about 105.8 thousand metric tonnes (9.2 MMTCE) in 1994, or 22.8 percent of total U.S. N_2O emissions. In the same year, emissions of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) combined for about 23.5 MMTCE, and emissions of sulfur hexafluoride (SF_6) were about 1 thousand metric tonnes (7.0 MMTCE). Table II-1 contains a summary of non-energy related greenhouse gas emissions from industrial processes in the U.S.

Greenhouse gases are also emitted from a number of industrial processes not covered in this section. For example, ammonia production is believed to be an industrial source of methane (CH_4) emissions, N_2O, and non-methane volatile organic compounds (NMVOCs). However, emissions for these sources have not been estimated at this time due to a lack of information on the emission processes, the manufacturing data, or both. As more information becomes available, emission estimates will be calculated and included in future greenhouse gas emission inventories.

The emission estimates presented here generally follow the IPCC-recommended guidelines, although the only processes for which the



IPCC provides a specific methodology for estimating emissions are cement, adipic acid, and nitric acid production. The IPCC has not provided specific details (*e.g.*, default emission factors) to calculate emissions from the other sources, but recommends a basic approach that can be followed for each source category. This involves multiplying production data for each process by an emission factor per unit of production. The methods used to estimate emissions in this section generally follow this basic approach. Most of the emission factors used below were derived using calculations that assume precise, efficient chemical reactions. As a result, uncertainties in the emission coefficients can be attributed to, among other things, impurities contained in the raw materials or to inefficiencies in the chemical reactions associated with each production process. Additional sources of uncertainty specific to an individual source category are discussed in the appropriate section.

Carbon Dioxide Emissions

Cement Production

Carbon dioxide (CO_2) emitted during the cement production process represents the most significant non-energy source of industrial CO_2 emissions. Cement is produced in most states and is used in all of them. Carbon dioxide is created when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime (calcium oxide or CaO) and CO_2. This lime combines with other materials to produce clinker (an intermediate product), while the CO_2 is released into the atmosphere. Clinker is then used to make portland and masonry cement. The production of masonry cement requires additional lime and thus results in additional CO_2 emissions. However, since this lime is already accounted for in the lime manufacture section of this chapter, the resulting emissions

Table II-1

Recent Trends in U.S. Greenhouse Gas Emissions from Industrial Sources: 1990–1994

Gas/Source	Emissions (Full Molecular Weight)					Emissions (Direct and Indirect Effects; Carbon-Equivalent)				
	(Million Metric Tonnes)									
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
CO_2										
CO_2 Manufacture	1.2	1.3	1.3	1.4	1.3	0.3	0.3	0.4	0.4	0.4
Cement Manufacture	32.6	31.9	32.1	33.9	35.4	8.9	8.7	8.8	9.3	9.6
Lime Manufacture	11.9	11.7	12.1	12.4	12.8	3.3	3.2	3.3	3.4	3.5
Limestone Use	5.1	4.9	4.5	4.1	4.6	1.4	1.3	1.4	1.1	1.2
Soda Ash Man. & Consumption	4.1	4.0	4.1	4.0	4.0	1.1	1.1	1.1	1.1	1.1
Aluminum Manufacture*	7.5	7.6	7.5	6.8	6.1	2.0	2.1	2.0	1.9	1.7
N_2O										
Nitric Acid Manufacture	0.04	0.04	0.04	0.04	0.04	3.5	3.5	3.5	3.6	3.8
Adipic Acid Manufacture	0.06	0.06	0.05	0.06	0.06	4.9	5.1	4.7	5.1	5.4
HFCs and PFCs										
HFC-23	+	+	+	+	+	13.7	14.1	14.8	13.1	13.8
HFC-125	na	na	na	na	+	na	na	na	na	1.0
HFC-134a	+	+	+	+	0.01	0.0	0.0	1.2	2.1	3.7
HFC-152a	+	+	+	+	+	0.01	0.01	0.04	0.04	0.06
HFC-227	na	na	na	na	+	na	na	na	na	0.8
CF_4	+	+	+	+	+	4.2	4.3	4.2	3.8	3.4
C_2F_6	+	+	+	+	+	0.8	0.9	0.8	0.8	0.7
Total						18.8	19.3	21.1	19.8	23.5
SF_6	+	+	+	+	+	6.4	6.5	6.7	6.8	7.0
U.S. Industrial Emissions						48.5	49.0	50.9	50.6	55.5

+ Total does not exceed 0.01 million metric tonnes.

** Emissions from aluminum manufacture are not included in the industry totals to avoid double-counting (see text).*

Note: Totals presented may not equal the sum of the individual source categories due to rounding.

are not counted towards the cement manufacturing emissions totals, although they are calculated here for informational purposes.

In 1994, U.S. clinker production totaled 69.79 million metric tonnes, and U.S. masonry cement production reached 3.28 million metric tonnes. As a result, CO_2 emissions from clinker production were estimated to be 9.65 MMTCE, or 0.7 percent of total U.S. CO_2 emissions (Table II-2).[1] Emissions from masonry production were estimated to be 0.02 MMTCE.

Carbon dioxide is produced during the production of clinker, an intermediate product from which finished portland and masonry cement are made. The quantity of the CO_2 released during cement production is directly proportional to the lime content of the clinker. During cement production, calcium carbonate ($CaCO_3$) from limestone, chalk, or other calcium-rich materials are heated in cement kilns to form lime (CaO) and CO_2:

$$CaCO_3 \rightarrow CaO + CO_2$$

This process is known as calcination or calcining. The lime is then combined with silica-containing materials (provided to the kiln as clays or shales) to form dicalcium or tricalcium silicates, two of the four major compounds in cement clinker (Griffin, 1987).

Carbon dioxide emissions were estimated by applying an emission factor, in tonnes of CO_2 released per tonne of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the fraction of lime used in the cement clinker and a constant reflecting the mass of CO_2 released per unit of lime. The emission factor was calculated as follows:

$$EF_{clinker} = fraction\ CaO \times \left(\frac{44.01\ g/mole\ CO_2}{56.08\ g/mole\ CaO}\right)$$

This analysis assumes an average lime fraction for clinker of 64.6 percent, which yields an emission factor of 0.507 tonnes of CO_2 per tonne of clinker produced.

Clinker production in the U.S. (including Puerto Rico) was reported as 70 million metric tonnes in 1994 (Solomon, 1995). Combined with the emissions factor derived above, CO_2 emissions from cement manufacturing in 1994 were estimated to be 35.4 million metric tonnes (9.65 MMTCE). Carbon dioxide emissions from U.S. clinker production reached 32.6 million metric tonnes in 1990, 31.9 million metric tonnes in 1991, 32.1 million metric tonnes in 1992, and 33.9 million metric tonnes in 1993 (see Table II-2).

Industrial CO_2 Emissions by Source: 1994

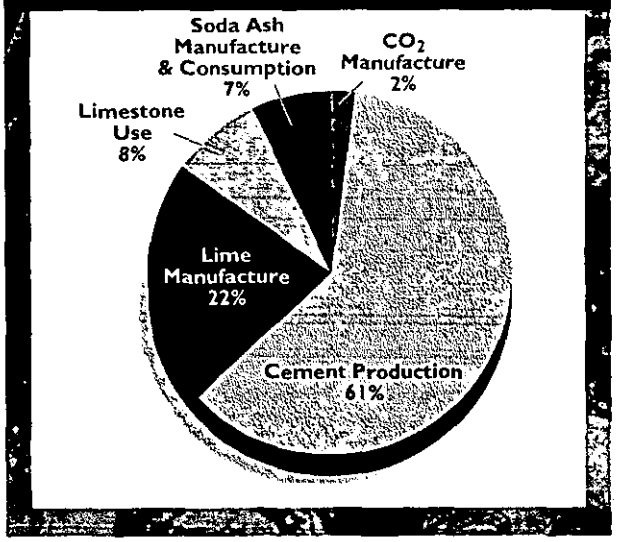


Table II-2

CO_2 Emissions from U.S. Cement Production: 1990–1994

Source	Cement Production (Thousand Metric Tonnes)					CO_2 Emissions (Thousand Metric Tonnes)				
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
Clinker	64,355	62,918	63,415	66,957	69,786	32,626	31,897	32,149	33,945	35,379
Masonry[a]	2,911	2,591	2,806	2,975	3,283	65	58	63	67	74

Source: Production data taken from the Bureau of Mines: 1990 (1992a); 1991 & 1992 (1994c); 1993 (1995a); 1994 (Solomon, 1995).

[a] Emissions from masonry cement production are not counted towards the cement manufacturing emissions totals.

[1] Please note that emissions in Table II-2 are expressed in thousand metric tonnes.

After falling by 8.3 percent from 1990 levels, U.S. cement production has grown every year since 1991, growing by 5.0 percent in 1992, 10.6 percent in 1993, and 7.3 percent in 1994. Demand outpaced production in 1994, causing imports to grow by 67 percent (totaling 11.8 million metric tonnes), due in part to shortages in some parts of the country. Despite the magnitude of this growth, imports were still shy of their all-time high (13.3 million metric tonnes, established in 1987). Consumption also grew in 1994, to its highest point of the decade (90.5 million metric tonnes), representing an 11.6 percent increase over the previous year. This consumption increase is attributed in large part to greater construction activity resulting from the economic recovery and the 1991 transportation bill (Bureau of Mines, 1995d).

Masonry cement requires additional lime over and above the lime used in clinker production. In particular, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by 5 percent. Lime accounts for approximately 60 percent of this added weight. Thus, the additional lime is equivalent to roughly 2.86 percent of the starting amount of the product, since

$$(0.6 * 0.05/1.05) = 0.0286.$$

An emission factor for this added lime can then be calculated by multiplying that percentage by the molecular weight ratio of CO_2 to CaO:

$$EF_{mas} =$$

$$\left(\frac{\text{fraction of weight added}}{1 + \text{fraction of weight added}}\right) \times \left(\begin{matrix}\text{fraction lime}\\ \text{in added}\\ \text{substance}\end{matrix}\right) \times \left(\frac{44.01 \text{ g/mole } CO_2}{56.08 \text{ g/mole } CaO}\right)$$

$$= \left(\frac{0.05}{1 + 0.05}\right) \times 0.06 \times 0.785$$

$$= 0.0286 \times 0.785$$

$$= 0.0224$$

Thus, 0.0224 tonnes of additional CO_2 are emitted for every tonne of masonry cement produced. Masonry cement production in the U.S. was reported to be 3.3 million metric tonnes in 1994 (Bureau of Mines, 1995b). Combined with the emissions factor derived above, this translates into 73.6 thousand metric tonnes (0.02 MMTCE) of CO_2 emitted. U.S. masonry production reached 2.9 million metric tonnes in 1990, 2.6 million metric tonnes in 1991, 2.8 million metric tonnes in 1992, and 3.0 million metric tonnes in 1993.

The CO_2 emissions from the additional lime added during masonry cement production are already accounted for in the section on CO_2 emissions from lime manufacture. Thus, these emissions are estimated in this chapter for informational purposes only, and are not included in the emission totals.

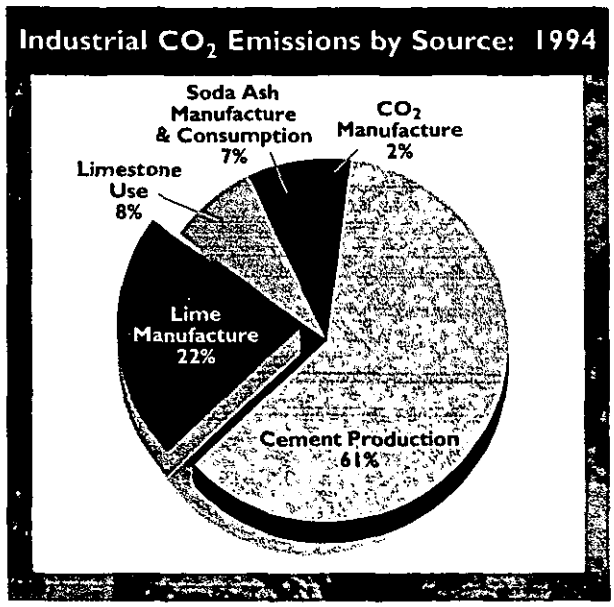
The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the amount of lime added to masonry cement. For example, the lime content of clinker varies from 64 to 66 percent. Also, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During the curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Since the amount of CO_2 reabsorbed is thought to be minimal, it is not included here.

Lime Manufacture

Lime, or calcium oxide (CaO), is a manufactured product with many chemical, industrial, and environmental uses. Lime has historically ranked fifth in total production of all chemicals in the United States. Its major uses are in steel making, construction, pulp and paper manufacturing, and water and sewage treatment. Lime is manufactured by heating limestone (mostly calcium carbonate — $CaCO_3$) in a kiln, creating calcium oxide (CaO) and carbon dioxide (CO_2). The CO_2 is driven off as a gas and is normally emitted to the atmosphere.

Lime production in the U.S. was estimated to be 17.4 million metric tonnes in 1994 (Miller, 1995). This resulted in CO_2 emissions of 3.5 MMTCE, or 0.25 percent of total U.S. CO_2 emissions.

Lime is an important chemical with a variety of industrial, chemical, and environmental applications



in the U.S. Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone (calcium carbonate or a combination of calcium and magnesium carbonate) or other calcium carbonate materials are roasted at high temperatures. This process is usually performed in either a rotary or vertical kiln, although there are a few other designs. Carbon dioxide is produced as a by-product of this process, just as CO_2 is released during clinker production (see previous section on cement production). The CO_2 is driven off as a gas and normally exits the system with the stack gas. The mass of CO_2 released per unit of lime produced can be calculated based on their molecular weights:

$$44.01 \text{ g/mole } CO_2 \div 56.08 \text{ g/mole CaO} = 0.785$$

Lime production in the U.S. was 17,400 thousand metric tonnes in 1994 (Miller, 1995). This results in *potential* CO_2 emissions of 13.66 million metric tonnes. Some of the CO_2 generated during the production process, however, is recovered for use in sugar refining and precipitated calcium carbonate (PCC) production. Combined lime production by these producers was 1.377 million metric tonnes in 1994, generating 1.081 million metric tonnes of CO_2. Approximately 80 percent of this CO_2 is recovered and not emitted, resulting in *net* CO_2 emissions of about 12.8 million metric tonnes (3.5 MMTCE) from U.S. lime production in 1994.

Domestic production has increased every year since 1991, when it declined by 1.0 percent from 1990 levels. Production grew by 3.4 percent in 1992, 3.5 percent in 1993, and 3.6 percent in 1994 (see Table II-3). This growth is attributed in part to growth in demand from environmental applications. For example, in 1993, the Environmental Protection Agency (EPA) completed regulations of the Clean Air Act concerning sulfur dioxide (SO_2) emissions caps for electric utilities. The initial phase of this legislation has already resulted in greater lime demand; for example, consumption for flue gas desulfurization increased by 16 percent in 1993 (Bureau of Mines, 1994b).

The term "lime" is actually a general term that includes various chemical and physical forms of this commodity. Uncertainties in the emission estimate can be attributed to slight differences in the chemical composition of these products. For example, although much care is taken to avoid contamination

Table II-3

CO_2 Emissions from U.S. Lime Production: 1990–1994

	Lime Production					CO_2 Emissions				
	(Thousand Metric Tonnes)									
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
Potential CO_2 from All Lime Producers	15,859	15,694	16,227	16,800	17,400	12,445	12,317	12,737	13,188	13,659
Recovered CO_2 from Sugar & PCC Manufacturers	826	964	1,023	1,310	1,377	519	605	642	823	865
Net Emissions						11,927	11,711	12,092	12,365	12,794

Sources: Production data taken from the Bureau of Mines: 1990 & 91 (1992b); 1992 (1994b). Data for 1993 & 1994, Miller (1995).

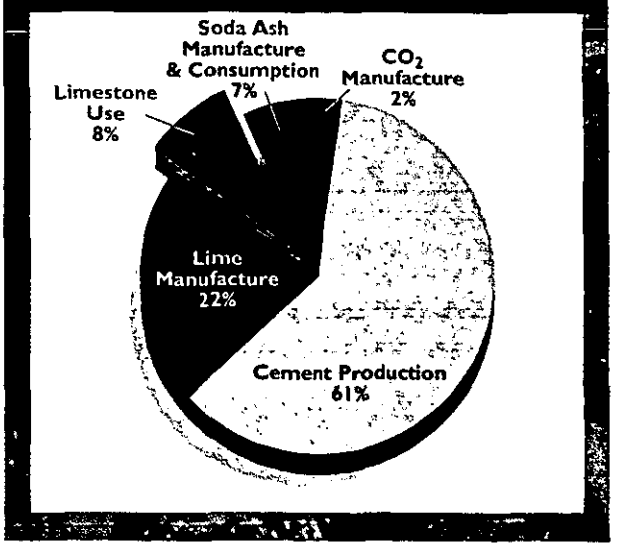
during the production process, lime typically contains trace amounts of impurities such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants manufacture lime with exactly the same properties.

A portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed. In most processes that use lime (*e.g.*, water softening), CO_2 reacts with the lime to create calcium carbonate. This is not necessarily true about lime consumption in the steel industry, however, which is the largest consumer of lime. A detailed accounting of lime use in the U.S. and further research into the associated processes are required to quantify the amount of CO_2 that will be reabsorbed. As more information becomes available, this emission estimate will be adjusted accordingly.

Limestone Use

Limestone is a basic raw material used by a wide variety of industries, including the construction, agriculture, chemical, and metallurgical industries. For example, limestone can be used as a flux or purifier in refining metals such as iron. In this case, limestone heated in a blast furnace reacts with impurities in the iron ore and fuels, generating carbon dioxide (CO_2) as a by-product. Limestone is also used for glass manufacturing and for sulfur dioxide (SO_2) removal from stack gases in utility and industrial plants.

Industrial CO_2 Emissions by Source: 1994



In 1994, approximately 3.9 million metric tonnes of limestone and 0.7 million metric tonnes of dolomite were used as flux stone in the chemical and metallurgical industries, in flue gas desulfurization systems, and for glass manufacturing. This results in total CO_2 emissions of 1.2 MMTCE, or 0.09 percent of total U.S. CO_2 emissions (see Table II-4).

Limestone is widely distributed throughout the world in deposits of varying sizes and degrees of purity. Deposits of limestone occur in nearly every state in the U.S., usually in tremendous amounts. Great quantities of limestone are extracted for commercial use. For example, limestone can be used as a

Table II-4

CO_2 Emissions from U.S. Limestone Consumption: 1990–1994

	Limestone Production* (Thousand Metric Tonnes)					CO_2 Emissions				
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
Flux Stone										
Limestone	5,776	5,213	4,422	3,631	3,984	2,541	2,294	1,946	1,597	1,753
Dolomite	929	838	735	632	694	444	400	351	301	331
Glass Making	428	386	504	622	683	188	170	222	274	300
SO_2 Removal	4,303	4,499	4,403	4,307	4,991	1,928	2,003	1,990	1,895	2,196
TOTAL						5,102	4,867	4,508	4,068	4,580

Source: Production data taken from the Bureau of Mines: 1991 (1993a), 1993 (1995c).

** Although the U.S. Bureau of Mines reports production of total crushed stone annually, limestone and dolomite production are provided for odd-numbered years only. Limestone consumption for 1992 was estimated by taking the average of the numbers reported in 1991 and 1993. Consumption figures for 1990 and 1994 were estimated by assuming that limestone and dolomite accounted for the same percentage of total crushed stone in those years as they did in 1991 and 1993.*

flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems in utility and industrial plants, or as a raw material in glass manufacturing. Limestone is heated during these processes, generating CO_2 as a by-product. Carbon emissions can be calculated by multiplying the amount of limestone consumed by the carbon content of the limestone (which is approximately 12 percent for calcite, 13 percent for dolomite).[2]

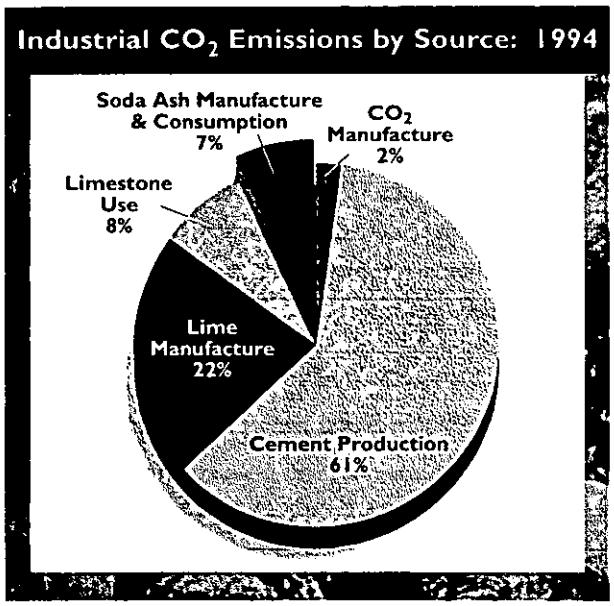
Using U.S. Bureau of Mines reports for 1990-93, it was estimated that approximately 3,984 thousand metric tonnes of limestone and 694 thousand metric tonnes of dolomite were used as flux stone in the chemical and metallurgical industries in 1994 (Bureau of Mines, 1995c and g).[3] Additionally, 683 thousand metric tonnes of limestone were used for glass manufacturing (Bureau of Mines, 1995c and g) and 4,991 thousand metric tonnes of limestone were used in FGD systems (EIA, 1994n, 1993b, 1992, 1991). Assuming that all of the carbon is released into the atmosphere, these applications result in total emissions of 1.2 MMTCE, or 4.6 million metric tonnes of CO_2 (see Table II-4).

Uncertainties in this estimate are due to variations in the chemical composition of limestone. In addition to calcite, limestone may contain smaller amounts of magnesia, silica, and sulfur. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process, the kind of ore processed, and the final use of the slag. Similarly, the quality of the limestone used for glass manufacturing will depend on the type of glass being manufactured. Uncertainties also exist in the activity data. Much of the limestone consumed in the U.S. is reported as "other unspecified uses." Furthermore, some of the limestone reported as "limestone" is actually dolomite (which has a higher carbon content than limestone).

Soda Ash Manufacture and Consumption

Commercial soda ash (sodium carbonate) is used in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. Internationally, two types of soda ash are produced — natural and synthetic; the U.S. produces only natural soda ash. During the production process, natural sources of sodium carbonate are heated and transformed into a crude soda ash that requires further refining. Carbon dioxide (CO_2) is generated as a by-product of this reaction, and is eventually emitted into the atmosphere. In addition, CO_2 is released when soda ash is consumed.

Only two states produce natural soda ash: Wyoming and California. Of these two states, only Wyoming has net emissions of CO_2. Because a different production process is used in California, those soda ash producers never actually release the CO_2 into the atmosphere. Instead, the CO_2 is recovered and used in other stages of production. U.S. CO_2 emissions from soda ash production in 1994 were



[2] Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

[3] Of the 723.5 million metric tonnes of limestone consumed in the U.S. in 1993, 213.1 million metric tonnes, or 29.5 percent, were reported as "unspecified uses," and only 2.6 million metric tonnes were reported as "flux stone." The Bureau of Mines recommends that when analyzing the industry, however, the quantity reported as unspecified should be distributed among the various reported uses. For example, limestone used as flux stone accounts for 0.5 percent of specified limestone uses. Assuming the same percentage of the unspecified limestone was actually used as flux stone, total limestone used would be (0.005 x 213.1) + 2.6 = 3.666 million metric tonnes. A similar calculation was applied for dolomite and glass manufacturing. 1994 consumption for SO_2 removal was calculated as the average of the 1992 and 1993 ratios of consumption for SO_2 removal to consumption for the other three end-uses (flux stone, dolomite, and glass manufacturing), multiplied by the 1994 total consumption for the flux stone, dolomite, and glass manufacturing end-uses.

approximately 0.39 MMTCE in 1994.

Soda ash consumption in the U.S. generated about 0.71 MMTCE of CO_2 in 1994. Annual soda ash consumption in the U.S. decreased slightly in 1991 and 1992, and recovered in 1993 before decreasing once again in 1994. Combined with production, which accounted for 0.39 MMTCE, total emissions from this source were about 1.1 MMTCE in 1994, or about 0.08 percent of total U.S. CO_2 emissions.

Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and is strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes. It is used primarily as an alkali, either in glass manufacturing or simply as a material that reacts with and neutralizes acids or acidic substances. About 75 percent of world production is synthetic ash made from sodium chloride; the remaining 25 percent is produced from natural sodium carbonate-bearing deposits. The U.S. produces only natural soda ash.

During the production process, trona (the principal ore from which natural soda ash is made) is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as a by-product of the calcination process. CO_2 emissions from the calcination of trona can be estimated based on the following chemical reaction:

$$\underset{\text{[trona]}}{2(Na_3H(CO_3)_2 \cdot 2H_2O)} \longrightarrow \underset{\text{[soda ash]}}{3Na_2CO_3} + 5H_2O + CO_2$$

Based on this formula, it takes approximately 10.27 metric tonnes of trona to generate 1 metric tonne of CO_2. Thus, the 14.6 million metric tonnes of trona mined in 1994 for soda ash production (Bureau of Mines, 1995f) resulted in CO_2 emissions of approximately 1.4 million metric tonnes (0.39 MMTCE).

Changes in production from 1990 to 1994 may be attributed in large part to European antidumping actions against the U.S. industry. In late 1990, an antidumping duty of 67.5 European Currency Units (ECUs) was rescinded on U.S. imports, but another investigation opened in mid-1993. Thus, the U.S. share of the European market jumped from 1 percent in 1990 to 11.3 percent in 1992, but then fell by about 35 percent in 1993 and again by 33 percent in 1994 (Bureau of Mines, 1993b, 1994c, & 1995h). Nevertheless, total U.S. soda ash exports hit an all-time high of 3.23 million metric tonnes in 1994 due to other favorable global economic trends, such as the global price increase for caustic soda, a substitute product (Bureau of Mines, 1995h).

An alternative method of natural soda ash production uses sodium carbonate-bearing brines. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which will precipitate under these conditions. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a by-product, the CO_2 is recovered and recycled for use in the carbonation stage and is never actually released.

Glass manufacture represented about 50 percent of domestic soda ash consumption, with smaller amounts used for chemical manufacture, soap and detergents, flue gas desulfurization, and other miscellaneous uses. In each of these applications, a mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 tonnes of carbon (or 0.415 tonnes of CO_2) is released for every tonne of soda ash consumed.

In 1994, U.S. consumption of soda ash was reported as 6.26 million metric tonnes (Bureau of Mines, 1995h). This generated about 2.6 million metric tonnes (0.71 MMTCE) of CO_2 for the year. Between the years 1990 and 1994, emissions from consumption were essentially static. However, the flat glass and fiberglass sectors had significant growth in the second half of 1994, primarily due to growth in the automotive and construction industries (Bureau of Mines, 1995h).

Carbon Dioxide Manufacture

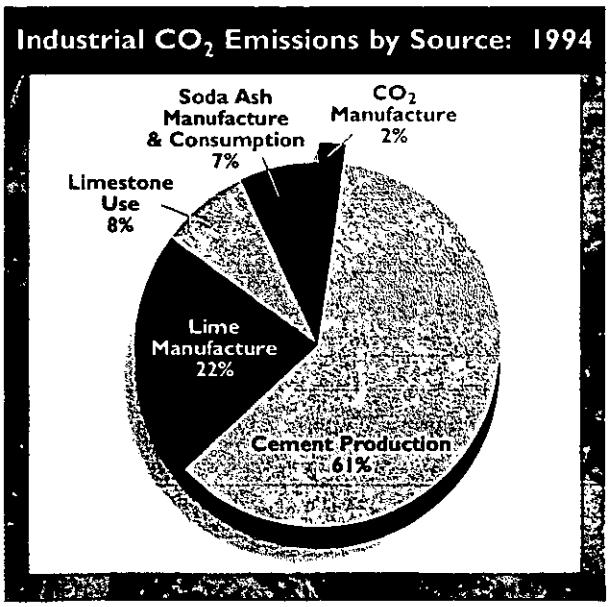
Carbon dioxide (CO_2) is used in many segments of the economy, including food processing, beverage manufacturing, chemical processing, crude oil products, and a host of industrial and miscellaneous

applications. For the most part, CO_2 used in these applications will eventually be released into the atmosphere.

Carbon dioxide emissions from this source were about 1.3 million metric tonnes in 1994. This translates to approximately 0.4 MMTCE, or 0.03 percent of total CO_2 emissions. Carbon dioxide demand in the merchant market is expected to expand 4.2 percent annually through 1998 (Freedonia Group, 1994).

Carbon dioxide is used for a variety of applications, including food processing, chemical production, carbonated beverages, and enhanced oil recovery (EOR). Carbon dioxide used for EOR is injected into the ground to increase reservoir pressure, and is therefore considered sequestered.[4] For the most part, however, CO_2 used in these applications will eventually enter the atmosphere.

With the exception of a few natural wells, CO_2 used in these applications is a by-product from the production of other chemicals (*e.g.*, ammonia), or obtained by separation from crude oil or natural gas. Depending on the raw materials that are used, the by-product CO_2 generated during these production processes may already be accounted for in the CO_2 emission estimates from fossil fuel consumption (either during combustion or from non-fuel use). For example, ammonia is manufactured using natural gas and naphtha as feedstocks. Carbon dioxide emissions from this process are included in the portion of carbon for non-fuel use that is not sequestered (see Part I), rather than in this section.



Carbon dioxide emissions were calculated by estimating the fraction of manufactured CO_2 that is not accounted for in these other emission sources. Carbon dioxide consumption for uses other than EOR was about 4.6 million metric tonnes in 1994 (Freedonia Group, 1994). Carbon dioxide wells, natural gas wells, and fermentation account for approximately 30 percent of total production capacity in the U.S. Assuming that the remaining 70 percent is accounted for in the CO_2 emission estimates from other categories (the most important being fossil fuel consumption), CO_2 emissions from industrial sources were approximately 1.35 million metric tonnes in 1994, or 0.37 MMTCE. This is 12 percent higher than CO_2 emissions in 1990, which totaled 1.20 million metric tonnes (0.33 MMTCE).

Aluminum Production

The production of aluminum results in emissions of several greenhouse gases, including carbon dioxide (CO_2) and two perfluorocarbons (PFCs), CF_4 and C_2F_6. Carbon dioxide is emitted as carbon contained in the anode and cathode of the electrolytic production cell is oxidized during the reduction of alumina to aluminum. Emissions of CO_2 from aluminum production in the U.S. were about 6.1 million metric tonnes (1.7 MMTCE) in 1994. However, the CO_2 emissions from this source are already accounted for in the non-fuel use portion of CO_2 emissions from fossil fuel consumption. Thus, to avoid double-counting, CO_2 emissions from aluminum production are not included in the industrial processes emission totals, although they are described here for informational purposes.

[4] It is unclear to what extent the CO_2 used for EOR will be re-released. For example, the CO_2 used for EOR is likely to show up at the wellhead after a few years of injection (Hangebrauk, *et al.*, 1992). This CO_2, however, is typically recovered and reinjected into the well. More research is required to determine the amount of CO_2 that in fact escapes. For the purposes of this analysis, it is assumed that all of the CO_2 remains sequestered.

The aluminum production industry is also thought to be the largest source of CF_4 and C_2F_6 emissions. Emissions of these two PFCs occur during the reduction of alumina in the primary smelting process. As with emissions of CO_2, the carbon is present in the anode and cathode material; the fluorine is present in the molten cryolite in which the reduction of alumina occurs. Total U.S. emissions of PFCs in 1994 were 3.4 MMTCE for CF_4 and 0.7 MMTCE for C_2F_6. A detailed description of these emissions may be found in the "Other Emissions" section of this chapter.

Carbon dioxide is emitted during the aluminum production process when alumina (aluminum oxide) is reduced to aluminum. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite. The reduction cells contain a carbon lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks. During reduction, some of this carbon is oxidized and released to the atmosphere as CO_2.

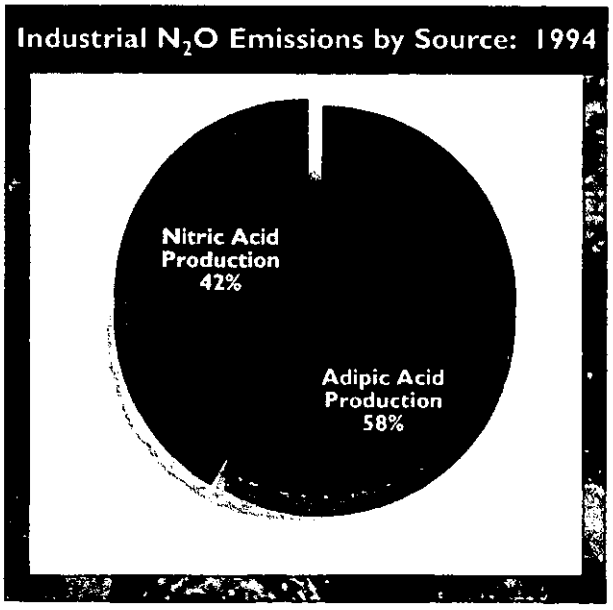
U.S. primary aluminum production fell to a seven-year low in 1994, continuing a decline since 1991. Production had increased by 2 percent in 1991 to 4,121 thousand metric tonnes, but then began to drop: by 2 percent in 1992, 9 percent in 1993, and 11 percent in 1994 (Bureau of Mines, 1995e). These declines were due in part to a continued increase in imports for consumption, primarily from the newly independent states and the former Soviet Union. For example, in 1994 these countries exported 60 percent more ingot (metal cast for easy transformation) to the U.S. than in 1993, pushing the total for aluminum imports to a record high of just under 3.4 million metric tonnes. However, the Bureau of Mines reports that due to the temporary nature of this supply surplus, a more normal global supply and demand equilibrium should return beginning in 1995. Indeed, through the first quarter of 1995, data already pointed to lower demand, more stable prices, and dramatically diminished world inventories (Bureau of Mines, 1995e).

Approximately 1.5 to 2.2 tonnes of CO_2 are emitted for each tonne of aluminum produced (Abrahamson, 1992). As a result, 1994 U.S. production yielded CO_2 emissions of approximately 6.1 million metric tonnes (1.7 MMTCE). The CO_2 emissions from this source are already accounted for in the non-fuel use portion of CO_2 emissions from fossil fuel consumption, which was estimated in Part I of the *Inventory* (*i.e.*, the carbon contained in the anode is considered a non-fuel use of petroleum coke). Thus, to avoid double-counting, CO_2 emissions from aluminum production are not included in the industrial processes emission totals. Aluminum production is also thought to be the largest source of two PFCs, CF_4 and C_2F_6. Emissions of these two potent greenhouse gases occur during the reduction of alumina in the primary smelting process. Emission estimates and a description of the estimation methodology are provided in the HFCs and PFCs section of this chapter.

Nitrous Oxide Emissions

Adipic Acid Production

Adipic acid production has been identified as a significant anthropogenic source of atmospheric nitrous oxide (N_2O). Adipic acid is a major component used in nylon production, as well as production of some low-temperature lubricants. It is also used to



provide foods with a "tangy" flavor. Estimates of 1994 U.S. adipic acid production were 815 thousand metric tonnes (C & EN, 1995). Nitrous oxide emissions from this source were 5.4 MMTCE for 1994, or 13.3 percent of total U.S. N_2O emissions.

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Ninety percent of all adipic acid produced in the United States is used in the production of nylon 6,6.

Adipic acid is produced through a two-stage process during which N_2O is generated in the second phase. The second stage involves the oxidation of ketone-alcohol with nitric acid. Nitrous oxide is generated as a by-product of this reaction and enters the waste gas stream. In the U.S., this waste gas is treated to remove NO_X and other regulated pollutants (and, in some cases, N_2O as well) and is then released into the atmosphere. There are currently four plants in the U.S. that produce adipic acid. Since 1990, two of these plants have employed emission control measures destroying about 98 percent of the N_2O before its release into the atmosphere (Radian, 1992a). By 1996, all adipic acid production plants will have N_2O emission controls in place as a result of a voluntary agreement among producers.

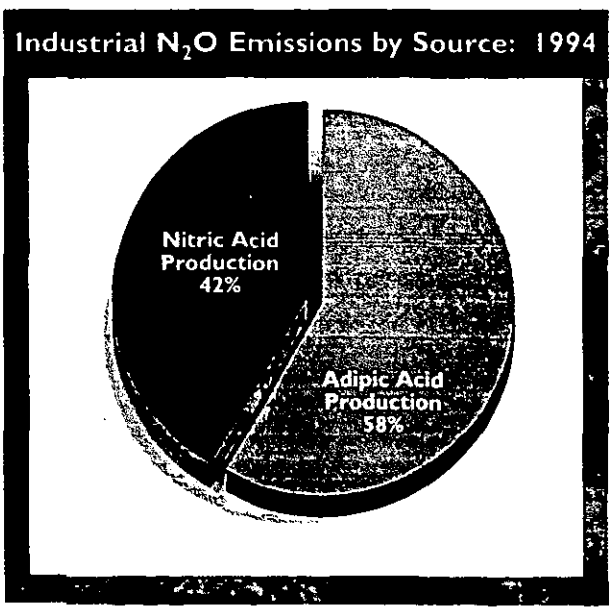
Since emissions of N_2O in the U.S. are not regulated, very little emissions data exist. However, based on the overall reaction stoichiometry for adipic acid, it is estimated that approximately 0.3 kg of N_2O is generated for every kilogram of adipic acid produced (Radian, 1992a). Estimates of 1994 U.S. adipic acid production were 815 thousand metric tonnes (C & EN, 1995). When combined with existing levels of control, this yields N_2O emissions from this source of 5.4 MMTCE for 1994.

Adipic acid production reached its highest level in ten years in 1994, growing 6.5 percent from the previous year. Production reached 735 thousand metric tonnes in 1990, grew to 771 thousand metric tonnes in 1991, dropped to 708 thousand metric tonnes in 1992, and rebounded to 765 thousand metric tonnes in 1993 (C&EN, 1992, 1993, 1994, 1995). However, emissions should follow a significantly lower path by 1996, due to the imminent increase in pollution control measures mentioned above.

Because N_2O emissions are controlled in some adipic acid production facilities, the amount of N_2O that is actually released will depend on the level of controls in place at a specific production plant. Thus, in order to calculate accurate emission estimates, it is necessary to have production data on a plant-specific basis. In most cases, however, these data are confidential. As a result, plant-specific production figures were estimated by disaggregating total adipic acid production using existing plant capacities. This created a significant degree of uncertainty in the adipic acid production data used to derive the emission estimates. The most accurate N_2O emissions estimates would be derived from actual production figures, if these data were reported by each plant.

Nitric Acid Production

The production of nitric acid (HNO_3) produces nitrous oxide (N_2O) as a by-product via the oxidation of ammonia. Nitric acid is a raw material used primarily to make synthetic commercial fertilizer. It is also a major component in the production of adipic acid (a feedstock for nylon) and explosives. In 1994 this inorganic chemical ranked 13th in total produc-



tion of all chemicals in the United States.

Nitric acid plants are in operation in all regions of the U.S., with a total annual operating capacity of 9.7 million metric tonnes in 1994 (SRI, 1994). Nitric acid production reached about 8.0 million metric tonnes in 1994. Based on an average emissions factor of 5.5 kg N_2O per metric tonne of nitric acid, N_2O emissions from this source were about 3.8 MMTCE, accounting for about 9.5 percent of total U.S. N_2O emissions.

Nitric acid is an inorganic compound used primarily as a feedstock for nitrate fertilizer production. It is also a raw material used in the production of adipic acid and explosives. Relatively small quantities of nitric acid are employed for stainless steel pickling, metal etching, rocket propellants, and nuclear-fuel processing. Virtually all of the nitric acid produced in the U.S. is manufactured by the catalytic oxidation of ammonia (U.S. EPA, 1995a). During this reaction, N_2O is formed as a by-product and is released from reactor vents into the atmosphere. While the waste gas stream may be cleaned of other pollutants such as nitrogen dioxide, there are currently no control measures aimed at eliminating N_2O.

Nitric acid production in the U.S. was approximately 8.0 million metric tonnes in 1994 (C & EN, 1995). Off-gas measurements at one nitric acid production facility have shown N_2O emission rates to be approximately 2-9 g N_2O per kg of nitric acid produced (Reimer, *et al.*, 1992). Using the midpoint of this emission factor range, 1994 N_2O emissions from nitric acid production were about 44.0 thousand metric tonnes (3.8 MMTCE). This represents a slight increase over the prior years of the decade, as production resulted in 39.9 thousand metric tonnes in 1990, 39.5 thousand metric tonnes in 1991, 40.1 thousand metric tonnes in 1992, and 41.2 thousand metric tonnes in 1993.

These emission estimates are highly uncertain because of insufficient information on manufacturing processes and emission controls. Although no abatement techniques are specifically directed at removing N_2O, existing control measures for other pollutants will have some effect on the N_2O contained in the gas stream. While the emission coefficients used here do account for these other abatement systems, there may be some variation between different production facilities depending on the existing level of pollution control at a given plant.

Other Emissions

Emissions of Halogenated Compounds

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used primarily as alternatives to the ozone depleting substances (ODSs) being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. ODSs, which include chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs,) are used in a variety of industrial applications, including refrigeration, solvent cleaning, foam production, sterilization, and fire extinguishing. Although the ODS replacements (i.e., HFCs and PFCs) are not harmful to the stratospheric ozone layer, they are powerful greenhouse gases. For example, HFC-134a is 1,300 times more heat absorbent than an equivalent amount of CO_2 by weight in the atmosphere.

In 1994, HFCs and PFCs were not used as widely as more common commercial chemicals. However, these gases were emitted from other industrial production processes. For example, HFC-23 was emitted as a by-product of HCFC-22 production, and CF_4 and C_2F_6 (two PFCs) were released during aluminum smelting. Emissions of these gases totaled approximately 23.5 MMTCE in 1994. The manufacture and emissions of HFCs and PFCs are expected to rise as their use as ODS replacements increases.

Sulfur hexafluoride (SF_6) is a gas used in the electrical and metals industries. In particular, it is primarily used as insulation in high voltage electrical equipment, as well as in aluminum degassing processes and as a protective atmosphere for casting of magnesium alloys. Emissions from the use of this gas have increased by about 2 percent annually for the period 1990 to 1994, when they totaled 1,030 metric tonnes (7.0 MMTCE).

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) were introduced as alternatives to the ozone depleting substances (ODSs) being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990 (see discussion on ODSs below). ODSs, which include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and related compounds, are used in several major end use sectors, including refrigeration, air conditioning, solvent cleaning, foam production, sterilization, fire extinguishing, paints, coatings, and other chemical intermediates, and miscellaneous uses (*e.g.*, aerosols, propellants, and other products). Because HFCs and PFCs are not harmful to the stratospheric ozone layer, they are not controlled by the Montreal Protocol. However, HFCs and PFCs are powerful greenhouse gases, and therefore are covered under the Framework Convention on Climate Change (FCCC). For example, HFC-134a has an estimated direct GWP of 1,300, which makes HFC-134a 1,300 times more heat absorbent than an equivalent amount by weight of carbon dioxide (CO_2) in the atmosphere. As a result, emission estimates for these gases have been included in the U.S. inventory and are provided in Table II-5. Emissions for the entire period 1990 to 1994 may be found in Annex C.

Because the use of CFC and HCFC substitutes was minimal in 1994, emissions of HFCs and PFCs were largely the result of by-product emissions from other production processes, and not the result of their use as CFC alternatives. For example, HFC-23 is a by-product emitted during HCFC-22 production, and PFCs (CF_4 and C_2F_6) are emitted during aluminum smelting. Emissions of HFCs and PFCs should continue to rise, however, as their use as ODS replacements increases.

Table II-5

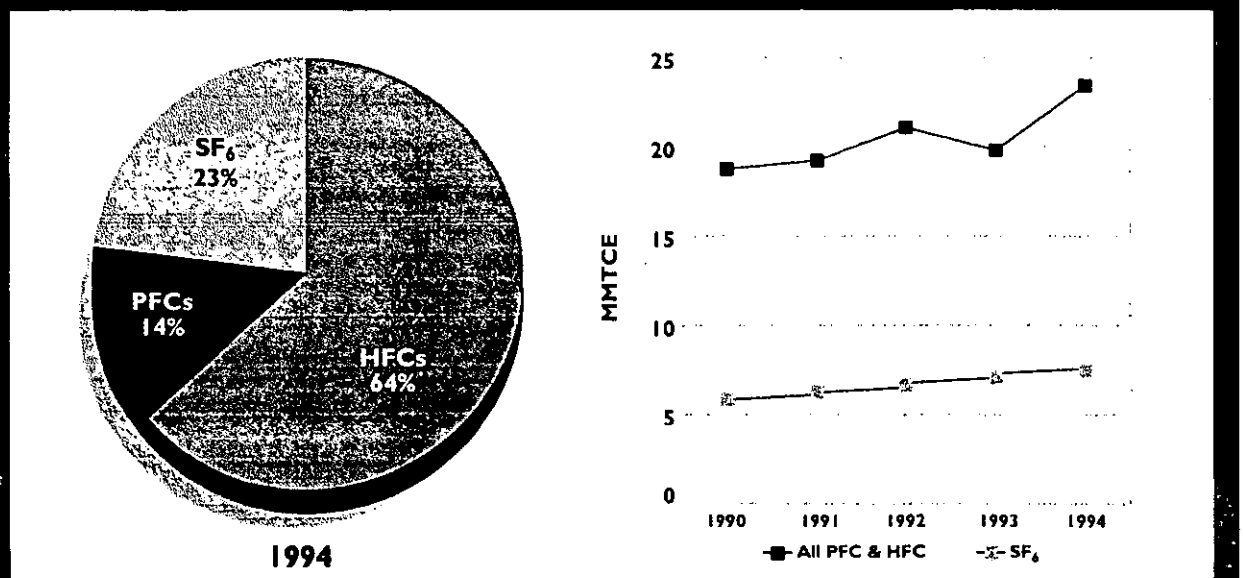
Emissions of HFCs and PFCs: 1994

Compound	Molecular Basis	GWP	Carbon-Equivalent
	(Million Metric Tonnes)		
HFCs			
HFC-23	0.00418	12,100	13.80
HFC-125	0.00113	3,200	0.99
HFC-134a	0.01041	1,300	3.69
HFC-152a	0.00153	140	0.06
HFC-227	0.00089	3,300	0.80
PFCs			
CF_4	0.00200	6,300	3.43
C_2F_6	0.00020	12,500	0.68

Source: Abseck (1995).

Hydrofluorocarbons (HFCs). Emission estimates were

Emissions of HFCs, PFCs, and SF_6



developed using the Vintaging Framework Model developed by EPA that estimates ODS emissions based on:

- a vintaging framework that generates results using information on the stock of equipment in each end use, chemical use per piece of equipment, equipment lifetimes, and emission rates from each piece of equipment, and
- substitution scenarios that describe when chemicals will replace ODSs as they are phased out under the Copenhagen Amendments to the Montreal Protocol. The scenarios are based on estimated market penetration and the number of years it may take to fully implement a substitute.

Because HFCs were not used widely as commercial chemicals in 1994, emissions of these compounds were relatively small, but are growing. Emissions of HFC-134a were close to zero in 1990 but grew to approximately 10,410 metric tonnes (3.7 MMTCE) in 1994. This was due to the introduction of HFC-134a as a substitute for CFC-12 and other refrigerants being phased out under the Montreal Protocol. Emissions of HFC-152a (a component of the refrigerant blend R-500) were estimated to be approximately 1,530 metric tonnes (0.06 MMTCE). Hydrofluorocarbons continue to be evaluated and introduced to the market as refrigerants, solvents, fire extinguishing agents, sterilizers, and foam blowing agents.

HFC-23 is currently emitted as a by-product of HCFC-22 production. Even after HCFC-22 is phased out under the Montreal Protocol, production of HCFC-22 as a polymer precursor will continue. By-product emissions of HFC-23 are assumed to be 3 percent of HCFC-22 production. HCFC-22 production was about 139 thousand metric tonnes in 1994, resulting in 4.2 thousand metric tonnes of HFC-23 (13.8 MMTCE). This represents a 5.5 percent increase over 1993 emissions, itself the low-point of the five-year period. Emissions grew by 2.8 percent in 1991 and 4.8 percent in 1992 before dropping by about 12 percent in 1993. HFC-125 and HFC-227 each came into production during 1994.

Perfluorocarbons (PFCs). The aluminum production industry is thought to be the largest source of emissions of two PFCs — CF_4 and C_2F_6. Emissions of these two potent greenhouse gases occur during the reduction of alumina in the primary smelting process. Aluminum is produced by the electrolytic reduction of alumina (Al_2O_3) in the Hall-Heroult reduction process, whereby alumina is dissolved in molten cryolite (Na_3AlF_6), which acts as the electrolyte and is the reaction medium. PFCs are formed during disruptions of the production process known as anode effects, which are characterized by a sharp rise in voltage across the production vessel. The PFCs can be produced through two mechanisms: direct reaction of fluorine with the carbon anode; and electrochemical formation. In both cases the fluorine originates from dissociation of the molten cryolite.

Because CF_4 and C_2F_6 are inert, and therefore pose no health or local environmental problems, there has been little study of the processes by which emissions occur and the important factors controlling the magnitude of emissions. In general, however, the magnitude of emissions for a given level of production depends on the frequency and duration of the anode effects during that production period. The more frequent and long-lasting the anode effects, the greater the emissions.

The methodology used to estimate emissions of PFCs from aluminum production first calculates a per unit production emissions factor as a function of several important operating variables, including average anode effect frequency and duration. Total annual emissions are then calculated based on reported annual production levels. The five components of the per unit production emissions factor are:

- the amount of CF_4 and C_2F_6 emitted during every minute of an anode effect, per kAmp of current;
- the average duration of anode effects, expressed in anode effect minutes per effect;
- the average frequency of anode effects, expressed in anode effects per day;
- the current efficiency for aluminum smelting (no units); and,
- the current required to produce a metric tonne of aluminum, assuming 100 percent efficiency.

Using currently available data for the U.S., this methodology yields a range in the emissions factor of 0.3 to 0.9 kg CF_4 per metric tonne of aluminum produced (Jacobs, 1994). The emissions factor for C_2F_6 is estimated to be an order of magnitude lower, and therefore ranges from 0.03 to 0.09 kg C_2F_6 per metric tonne of aluminum produced. Based on 1994 aluminum production of 3.299 million metric tonnes, total U.S. emissions of PFCs in 1994 averaged about 2 thousand metric tonnes of CF_4 (3.4 MMTCE) and 200 metric tonnes of C_2F_6 (0.7 MMTCE). U.S. aluminum production increased by 2 percent in 1991, but then began to drop: by 2 percent in 1992, 9 percent in 1993, and 11 percent in 1994 (Bureau of Mines, 1995e).

Because there has been relatively little study of emissions from this source, considerable uncertainty remains in several of the values used in the estimates presented here. In particular, the value for emissions per anode effect minute per kAmp is based on a single measurement study that may not be representative of the industry as a whole (U.S. EPA, 1993b). For example, this emissions factor may vary by smelter technology type, among other factors. The average duration of anode effects, according to preliminary results of ongoing research, may in fact be considerably shorter than the current values used. The average frequency of anode effects and the current efficiency are well documented, although they may change over time as operating efficiencies improve. Because recent studies indicate that the values for the important variables used in developing the emission coefficient may actually be lower than previously thought, the estimates presented here are likely to be conservatively high. Annex C contains a more detailed description of the calculations regarding these gases and their emissions.

SF_6. Sulfur hexafluoride (SF_6) is a gas used in the electrical and metals industries. In particular, it is used as insulation in high voltage electrical equipment, as well as in aluminum degassing processes and as a protective atmosphere for the casting of magnesium alloys. Sulfur hexafluoride production in the United States was estimated to be approximately 6.0 million pounds, or 2.7 thousand metric tonnes annually for the period 1990 to 1994. This translates to emissions of about 1,000 metric tonnes of SF_6 per year. About 80 percent of SF_6 use is attributed to the electrical industry. When SF_6 is sealed in such equipment, it leaks at about 1 percent per year, so there is a significant difference between production and emissions. For SF_6 used in the metals industry, most or all of the chemical is emitted during use. Emissions from production and leakage combined for an annual increase of about 2 percent from 1990 to 1994, reaching 1,030 metric tonnes in 1994 (7.0 MMTCE). Annex C contains a more detailed description of the calculations regarding this gas and its emissions.

Emissions of CFCs and Related Compounds. Chlorofluorocarbons (CFCs) and other halocarbons, which were emitted into the atmosphere for the first time this century, are a family of man-made compounds used in a variety of industrial applications, including foam blowing, refrigeration, and solvent cleaning. These compounds, which contain chlorine and bromine, have been shown to deplete stratospheric ozone, and thus are typically referred to as ozone-depleting substances, or ODSs. In addition, they are important greenhouse gases because they block infrared radiation that would otherwise escape into space (EIA, 1993a). Unlike other greenhouse gases, however, these compounds do not occur naturally in the atmosphere. ODSs include the following substances: chlorofluorocarbons, halons, methyl chloroform, carbon tetrachloride, methyl bromide, and partially halogenated fluorocarbons (HCFCs).

Many governments, recognizing the harmful effects of these compounds on the atmosphere, signed the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987 to limit the production and consumption of a number of CFCs and other halogenated compounds. The U.S. furthered its commitment to phase-out these substances by signing and ratifying the Copenhagen Amendments to the Montreal Protocol in 1992. Under these amendments, the U.S. committed to eliminating the production of all halons by January 1, 1994 and all CFCs by January 1, 1996.

Under the Clean Air Act (CAA), which developed the U.S. phaseout schedule for the Montreal Protocol, ODSs were categorized based on their ozone depletion potential. Compounds are classified as "Class I" or "Class II" substances, and must adhere to a distinct set of phase-out requirements.

- Class I ODSs include fully halogenated CFCs, halons, tetrachlorocarbon (commonly known as carbon tetrachloride), and 1,1,1 trichloroethane (a.k.a. methyl chloroform). Fully halogenated compounds have no hydrogen atoms in their makeup and are so called because they contain chlorine, fluorine, or bromine atoms (elements belonging to the halogen family). Of the elements in the halogen family, chlorine and bromine are thought to be ozone-depleting agents, while fluorine is believed to be a potent greenhouse gas. Halon compounds contain bromine atoms instead of chlorine atoms, while methyl chloroform is actually a partially halogenated compound (the only one to be included in this Class). These compounds are the primary ODSs in use today.
- Class II ODSs include hydrochlorofluorocarbons (HCFCs), some of which were developed as interim replacements for CFCs. Because these HCFC compounds are only partially-halogenated, their hydrogen-carbon bonds are more vulnerable to oxidation in the troposphere, and therefore pose only about one-tenth to one-hundredth the threat to stratospheric ozone compared to CFCs. Although HCFCs pose less of a threat to the Earth's stratospheric ozone layer, they are still powerful greenhouse gases, with GWPs several orders of magnitude larger than CO_2 (for example, HCFC-22 has an estimated direct GWP of 1,700, which makes HCFC-22 1,700 times more heat absorbent than an equivalent amount by weight of CO_2 in the atmosphere).

The production and use of Class I and Class II substances in the U.S. are being phased out in accordance with the Montreal Protocol and the 1990 Clean Air Act. Under these measures, the production of Class I substances in the U.S. will cease by January 1996, while the production of Class II substances will be gradually phased out between 2003 and 2030. Another group of partially-halogenated compounds that do not contain chlorine, known as HFCs, are being developed as long-term replacements for Class I and Class II substances.

Although the IPCC emission inventory guidelines do not include reporting emissions of CFCs and related compounds, the U.S. believes that no inventory is complete without the inclusion of these emissions; therefore, emission estimates for several Class I and Class II ozone-depleting substances are provided in Table II-6. It should be noted that the use of these compounds is declining as the U.S. fulfills its obligations under the Montreal Protocol. Also, the effects of these compounds on radiative forcing are not provided here. Although CFCs and related compounds have very large direct GWPs, their indirect effects are believed to be negative, possibly equal in magnitude to their direct effects. Given the uncertainties surrounding the net effect of these gases, they are reported here on a full molecular basis only.

Emissions of ODSs were estimated by the U.S. EPA using the Atmospheric and Health Effects Framework (AHEF) model. The EPA model starts

Table II-6

Emissions of ODSs: 1994

Compound	Emissions (Million Metric Tonnes; Molecular Basis)
Class I	
CFC-11	0.037
CFC-12	0.059
CFC-113	0.017
CFC-114	0.005
CFC-115	0.003
Carbon Tetrachloride	0.016
Methyl Chloroform	0.078
Halon-1211	0.001
Halon-1301	0.002
Class II	
HCFC-22	0.105
HCFC-123	0.002
HCFC-124	0.002
HCFC-141b	0.016
HCFC-142b	0.010

Source: Abseck (1995).

with global production forecasts for each compound and estimates U.S. consumption based on forecasted regional shares. These data are further divided by end-use.

With the exception of aerosols and solvents, emissions from CFCs and related compounds are not instantaneous, but instead occur gradually over time, *i.e.*, emissions in a given year are the result of both CFC and related compound use in that year and their use in previous years. Each end-use has a certain release profile, which gives the percentage of the compound that is released to the atmosphere each year until all releases have occurred.

The emission estimates provided here account for ODS use in both the current year and in previous years. Uncertainties exist over the levels of production, data sources, and emissions profiles that are used by the model to estimate yearly emissions for each compound.

Emissions of CFC-12, HCFC-22, and methyl chloroform were three of the most prevalent ODS emissions in 1994. An estimated 59 thousand metric tonnes of CFC-12 were emitted into the atmosphere, along with an estimated 105 thousand metric tonnes of HCFC-22, and an estimated 78 thousand metric tonnes of methyl chloroform.

Emissions of Criteria Pollutants: NO_x, NMVOCs and CO

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of criteria air pollutants. Total U.S. emissions of nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOCs), and carbon monoxide (CO) from non-energy industrial processes from 1990-1994 are reported by detailed source category in Table II-7. The emission estimates in this section were taken directly from the U.S. EPA's *Draft National Air Pollutant Emissions Trends, 1900-1994* (U.S. EPA, 1995b). This EPA report provided emission estimates of these gases by sector, using a "top down" estimating procedure: the emissions were calculated either for individual sources or for many sources combined, using basic activity data (*e.g.*, the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data are used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the U.S. EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (U.S. EPA, 1995a). The EPA currently derives the overall emission control efficiency of a source category from a variety of sources, including published reports, the 1985 NAPAP (National Acid Precipitation and Assessment Program) emissions inventory, or other EPA data bases.

Emissions of NF_3

Nitrogen trifluoride (NF_3) is a gas used in plasma etching applications in the semiconductor industry. A range of lifetimes are reported for NF_3, from 50 to 740 years. These estimates vary due to different destruction pathway assumptions, with the high end estimate assuming photolysis and the low end estimate considering ferrous ions present in water droplets in the atmosphere. The global warming potential (GWP) of NF_3 relative to CO_2 is estimated for both lifetime extremes. The 100 year GWP of NF_3 based on a 50 year lifetime is estimated to be 6,300; for a lifetime of 740 years, the GWP is estimated to be 13,100. Although the concentration of NF_3 in the atmosphere to date has not yet been determined, experts have found that if all the NF_3 produced in the U.S. over the past 15 years were released into the atmosphere, the temperature rise would be less than 1×10^{-60} degrees Celsius (Maroulis, 1994). Because of the uncertainties surrounding its contribution to the greenhouse gas effect, NF_3 is not included in this inventory. However, as the understanding of this gas increases, NF_3 may be included in future inventories.

Table II-7

U.S. Emissions of NO_x, CO, and NMVOCs from Industrial Processes: 1990–1994

Source	1990	1991	1992	1993	1994
			(Thousand Metric Tonnes) NO_x		
Chemical & Allied Product Manufacturing	250	252	258	259	264
Metals Processing	73	71	73	73	76
Other Industrial Processes	278	269	277	286	298
Storage and Transport	2	2	3	3	3
TOTAL[a]	603	594	610	621	640
			CO		
Chemical & Allied Product Manufacturing	1,760	1,764	1,782	1,813	1,858
Metals Processing	1,887	1,807	1,854	1,897	1,965
Other Industrial Processes	650	644	652	664	681
Storage and Transport	50	49	50	51	53
TOTAL[a]	4,347	4,264	4,338	4,424	4,557
			NMVOCs		
Chemical & Allied Product Manufacturing	1,384	1,391	1,403	1,412	1,431
Metals Processing	65	63	65	67	70
Other Industrial Processes	364	361	366	368	373
Storage and Transport	1,596	1,560	1,583	1,594	1,608
TOTAL[a]	3,409	3,375	3,416	3,442	3,482

[a] *Totals may not equal the sum of individual source categories due to independent rounding.*

Source: U.S EPA, 1995a

Part III: Emissions from Solvent Use

The use of solvents and other chemical products can result in emissions of various photochemically important trace gases. Nonmethane VOCs (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based solvents, along with small amounts of carbon monoxide (CO) and oxides of nitrogen (NO_X). While these gases are not greenhouse gases, they are photochemically important gases, and so contribute indirectly to the greenhouse effect.

Emissions from solvent use in the U.S. consist mainly of NMVOCs, along with trace amounts of CO and NO_X. NMVOC emissions from solvent use increased nearly 6 percent from 1990 to 1994, while emissions of NO_X increased by 50 percent and CO emissions remained constant (Table III-1). Surface coatings accounted for the majority of NMVOC emissions from solvent use (over 40 percent), while "non-industrial" uses accounted for about 32 percent and dry cleaning for slightly over 3 percent of NMVOC emissions during the same period. Overall, solvent use accounted for approximately 31 percent of total U.S. 1994 emissions of NMVOCs.

Although a comparatively minor source category in the U.S., emissions from solvent use have been reported separately by the U.S. to be consistent with the reporting guidelines recommended by the IPCC. These guidelines identify solvent use as one of the major source categories for which countries should report emissions. In the U.S. emissions from solvents are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The evaporation process varies depending on different solvent uses and solvent types. The major categories of solvents use include:

- Degreasing;
- Graphic arts;
- Surface coating;
- Other industrial uses of solvents (*i.e.*, electronics, etc.);
- Dry cleaning; and
- Non-industrial uses (*i.e.*, uses of paint thinner, etc.).

U.S. NMVOC Emissions by Source: 1994

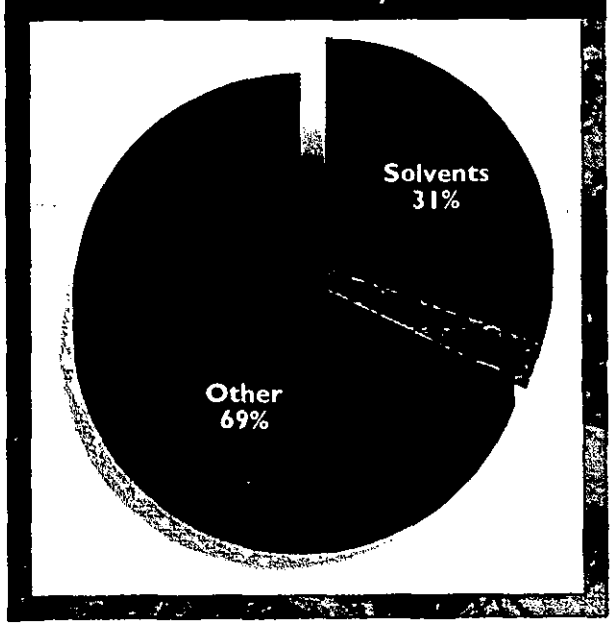


Table III-2 contains detailed 1994 emission estimates from solvents by major source category.[1]

Estimates of emissions from solvents came from U.S. EPA (1995b), which estimated emissions based on a "bottom up" process. This process involves aggregating solvent use data based on information relating to solvent uses from different sectors such as degreasing, graphic arts, etc. Emission factors for each consumption category are then applied to the data to estimate emissions. For example, emissions from surface coatings are mostly due to solvent evaporation as the coatings solidify. By applying the appropriate solvent emission factors to the type of solvents used for surface coatings, an estimate of emissions can be obtained.

Table III-1

Emissions of NMVOCs, NO_x and CO from Solvent Use: 1990–1994

(Thousand Metric Tonnes)

Gas	1990	1991	1992	1993	1994
NMVOC	5,420	5,369	5,471	5,585	5,727
NO_x	2	2	3	3	3
CO	2	2	2	2	2

Source: U.S. EPA (1995b)

Table III-2

U.S. Emissions of NMVOCs, NO_x and CO by Category: 1994

(Thousand Metric Tonnes)

Source	NMVOCs	NO_x	CO
Degreasing	712	+	1
Graphic Arts	359	+	+
Surface Coating	2,516	2	1
Other Industrial	115	+	+
Dry Cleaning	200	na	na
Non-Industrial	1,824	na	na
Total[a]	5,727	3	2

Source: U.S. EPA (1995b)

Note: "+" Denotes less than 453.5 metric tonnes (500 short tons).

a The totals provided may not equal the sum of the individual source categories presented due to independent rounding.

[1] Please note that emissions in Tables III-1 and III-2 are expressed in thousand metric tonnes.

Part IV: Emissions from Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of different processes. This part of the U.S. inventory presents emission estimates for five types of agricultural activities: management of domestic livestock, management of the manure of domestic livestock and poultry, cultivation of rice, fertilizer use, and field burning of agricultural crop wastes. Several other agricultural activities, such as irrigation and tillage practices, may contribute to greenhouse gas emissions; however, due to uncertainty surrounding the impact of these practices, emissions from these sources are not included in the inventory.[1] Agriculture-related land-use change activities, such as conversion of grassland to cultivated land, are discussed in part V of this inventory.

In 1994, agricultural activities were responsible for emissions of 80 MMTCE, or approximately 5 percent of total U.S. GHG emissions (see Figure IV-1). Methane (CH_4) is the most significant gas emitted by agricultural activities, accounting for 61 MMTCE. Domestic livestock, manure management, rice cultivation, and field burning of agricultural crop wastes are all sources of CH_4. Methane emissions from domestic livestock enteric fermentation and manure management represent about 21 percent and 9 percent of total CH_4 emissions from all anthropogenic activities in the U.S. (see Figure IV-2). Together, emissions from these sources make up 93 percent of CH_4 emissions from agricultural activities. Of all domestic animal types, beef and dairy cattle are by far the largest emitters of CH_4. Rice cultivation and agricultural crop waste burning are minor sources of CH_4, comprising about 2 percent and 0.4 percent of total CH_4 emissions in the U.S., respectively. These sources together account for about 5 percent of U.S. CH_4 emissions from agriculture.

Figure IV-1

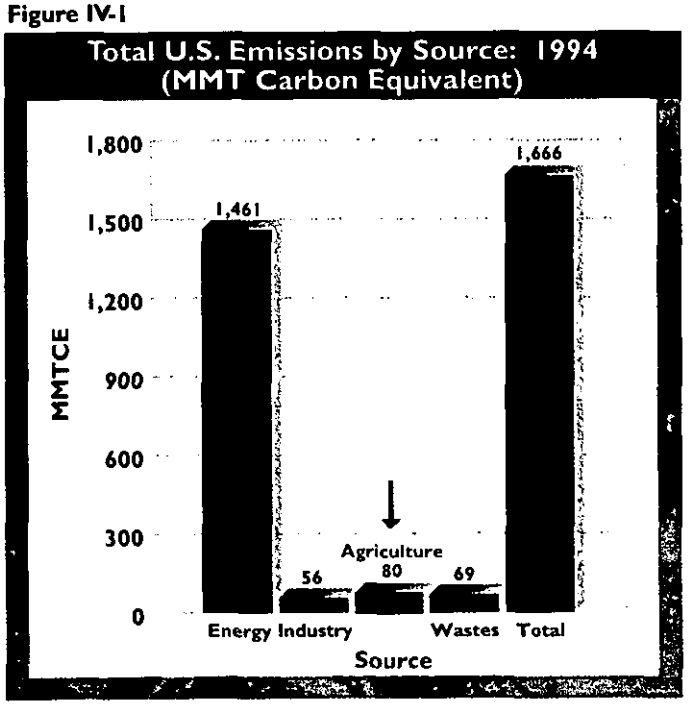


Table IV-1 presents emissions estimates for the agriculture sector between 1990 and 1994. Between 1990 and 1994, CH_4 emissions from domestic livestock enteric fermentation and manure management increased about 6 percent

[1] Irrigation associated with rice cultivation is included in this inventory.

Figure IV-2

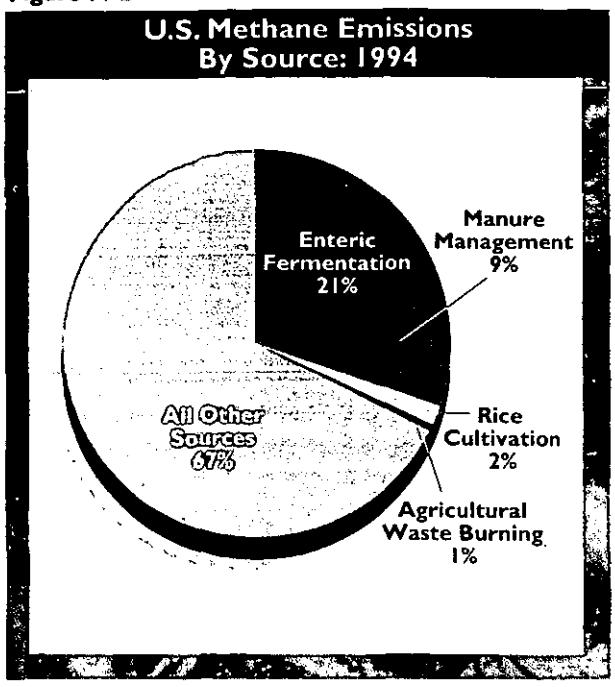
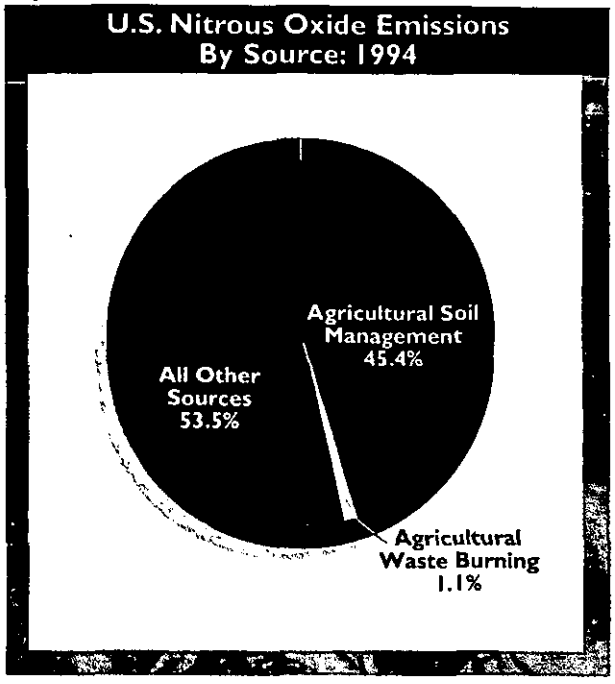


Figure IV-3



and 15 percent, respectively. During the same time period, CH_4 emissions from rice cultivation increased about 21 percent, while emissions from agricultural waste burning rose about 16 percent.

In addition to CH_4, agricultural activities are a source of nitrous oxide (N_2O), carbon monoxide (CO) and nitrogen oxides (NO_x). Fertilizer use on agricultural soils is a major contributor to total N_2O emissions, responsible for about 45 percent of total U.S. emissions (see Figure IV-3). Emissions of N_2O from this source increased about 14 percent between 1990 and 1994. Agricultural crop waste burning is a source of

Table IV-1

Recent Trends in U.S. Greenhouse Gas Emissions from Agricultural Sources: 1990–1994

Gas/Source	Emissions (Full Molecular Weight) (Million Metric Tonnes)					Emissions (Direct and Indirect Effects; Carbon-Equivalent) (Million Metric Tonnes)				
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
CH_4										
Enteric Fermentation										
Cattle	5.4	5.4	5.5	5.6	5.8	36.2	36.3	36.8	37.4	38.4
Other	0.3	0.3	0.3	0.3	0.3	1.8	1.9	1.9	1.8	1.8
Manure Management	2.2	2.3	2.4	2.4	2.5	14.8	15.2	15.8	16.0	17.0
Rice Cultivation	0.4	0.4	0.5	0.4	0.5	2.9	2.9	3.2	3.0	3.4
Field Burning	0.1	0.1	0.1	0.1	0.1	0.7	0.7	0.8	0.6	0.8
N_2O										
Soil Management	0.2	0.2	0.2	0.2	0.2	16.1	16.4	16.7	16.6	18.4
Field Burning	†	†	†	†	†	0.3	0.3	0.4	0.3	0.4
NO_x										
Field Burning	0.1	0.1	0.1	0.1	0.1					
CO										
Field Burning	2.2	2.1	2.5	1.9	2.6					
U.S. Emissions						72.9	73.7	75.6	75.6	80.3

† Emissions of these gases do not exceed 0.01 million metric tonnes.

Note: Totals presented in the summary tables in this chapter may not equal the sum of the individual source categories due to rounding.

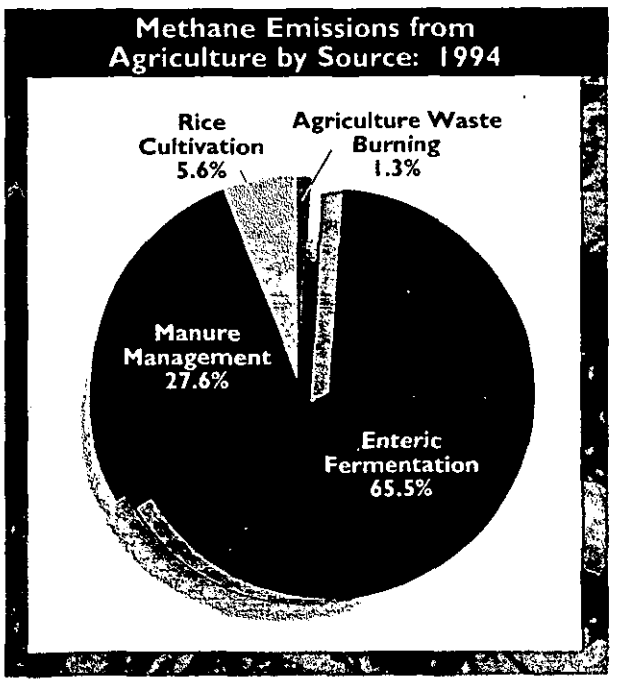
N_2O, CO and NO_X, in addition to CH_4. However, agricultural crop waste burning accounts for only about 1 percent or less of total U.S. emissions of each gas.

Methane Emissions from Enteric Fermentation in Domestic Livestock

Methane is a natural by-product of animal digestion. During digestion, methane is produced through a process referred to as enteric fermentation in which microbes that reside in animal digestive systems break down feed consumed by the animal. Ruminants, which include cattle, buffalo, sheep and goats, have the highest methane emissions among all animal types because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which a significant amount of methane-producing fermentation occurs. Non-ruminant domestic animals, such as pigs and horses, have lower methane emissions than ruminants because much less methane-producing fermentation takes place in their digestive systems. The amount of methane produced and excreted by an individual animal depends upon its digestive system (i.e., whether or not it possesses a rumen), and the amount and type of feed it consumes.

Enteric fermentation in domestic livestock is a major source of methane in the U.S. Methane emissions from enteric fermentation in the U.S. amounted to 5.7 million metric tonnes (38.1 MMTCE) in 1990, rising to 6.0 million metric tonnes (40.2 MMTCE) in 1994. Of all domestic livestock, cattle are by far the largest source of methane. In 1994, cattle accounted for 96 percent of total emissions from enteric fermentation in domestic livestock. Of total cattle emissions in 1994, beef cattle accounted for about 70 percent, while dairy cattle accounted for the rest.

Increases in methane emissions from enteric fermentation in livestock are primarily due to increasing beef cattle populations. Between 1990 and 1994, the total beef cattle population increased by about 8 percent. The population of dairy cattle, on the other hand, decreased by about 2.8 percent between 1990 and 1994. Despite this decrease in dairy cattle population, methane emissions from dairy cattle increased by 0.7 percent because feed intake per cow increased as milk production per cow increased.



Methane is produced during the normal digestive processes of animals. During digestion, microbes resident in the digestive system ferment feed consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces methane as a by-product, which is exhaled or eructed by the animal. The amount of methane produced and excreted by an individual animal depends primarily upon the animal's digestive system and the amount and type of feed it consumes.

Among animal types, the ruminant animals (*i.e.*, cattle, buffalo, sheep, goats, and camels) are the major emitters of methane because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down consumed feed into soluble products that can be utilized by the animal. The microbial fermentation that occurs in the rumen enables ruminants to digest coarse plant material that non-ruminant animals cannot digest. Ruminant animals have the highest methane emissions among all animal types because a significant amount of methane-producing fermentation occurs within the rumen.

Non-ruminant domestic animals, such as pigs, horses, mules, rabbits, and guinea pigs, also produce

methane through enteric fermentation, although this microbial fermentation occurs in the large intestine. The non-ruminants have much lower methane emissions than ruminants because much less methane-producing fermentation takes place in their digestive systems.

In addition to the type of digestive system that an animal possesses, its feed intake also affects the amount of methane produced and excreted. In general, the higher the feed intake, the higher the methane emissions. Feed intake is positively related to animal size, growth rate and production (*i.e.*, milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

This section presents estimates of methane emissions resulting from enteric fermentation in domestic livestock. Only animals managed by humans for production of animal products, including meat, milk, hides and fiber, and draft power are included.[2] Although methane emissions from non-ruminants are significantly less than those for ruminants, both animal types are included in order to produce a complete inventory.

The emission estimates for all domestic livestock were determined using the emission factors developed in U.S. EPA (1993a). To derive emissions estimates, emission factors were multiplied by the applicable animal populations. The resulting emissions by animal type were summed over all animal types to estimate total annual methane emissions for all domestic livestock. Emission estimates for 1990 to 1994 were derived using annual animal population statistics from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS).

The principal uncertainty in estimates of methane emissions from livestock digestion results from the large diversity of animal management practices found in the U.S., all of which cannot be precisely characterized and evaluated. Also, the methodological assumptions used to derive emission factors are only as accurate as the experimental data upon which they are based. Nevertheless, significant scientific literature exists that describes the quantity of methane produced by individual ruminant animals, particularly cattle. Also, cattle production systems in the U.S. are well characterized compared to other livestock management systems in the U.S.

Methane Emissions from Cattle

With the availability of cattle management data, it is possible to estimate methane emissions from cattle in the U.S. using fairly detailed analyses of feeding practices and production characteristics. Also, due to their large population, large size, and particular digestive characteristics, cattle account for the majority of methane emissions from livestock in the U.S. Thus, a model can be constructed to determine estimates of emissions from cattle. The estimates presented in Table IV-2 are based on a detailed analysis that accounts for regional differences in sizes, ages, feeding systems, and management systems among cattle subgroups.

In order to derive emission factors representative of the diverse types of cattle found in the U.S., U.S. EPA (1993a) applied a mechanistic model of rumen digestion and animal production (Baldwin, *et al.*, 1987) to 32 different diets and nine different cattle types.[3] The cattle types were defined to represent the different sizes, ages, feeding systems and management systems that are typically found in the U.S. (see Table IV-2). Representative diets were defined for each category of animal, reflecting the diverse feeds and forages consumed by different types of cattle in different regions of the U.S. Using the mechanistic model, an emission factor was derived for each combination of animal type and representative diet. Based upon the extent to which each diet is used in each of five regions of the U.S., regional average emission factors for each of the nine cattle types were derived.[4]

[2] Wild animals also produce methane emissions. The principal wild animals that contribute to U.S. emissions are ruminant animals such as antelope, caribou, deer, elk, and moose. Termites have also been identified as a potentially important source of methane emissions and are generally examined separately from other wild animals. These sources are not included in the U.S. inventory because they are not considered anthropogenic.

[3] The basic model of Baldwin, *et al.* (1987) was revised somewhat to allow for evaluations of a greater range of animal types and diets. See U.S. EPA (1993a) for more detail.

[4] Feed intake of bulls does not vary significantly by region, so only a national emissions factor was derived for this cattle type.

For each cattle type, except dairy cows, emission estimates for 1990 to 1994 were obtained using the nationally weighted-average emission factors from U.S. EPA (1993a) and national population data from the USDA National Agricultural Statistics Service (NASS),[5] (USDA, 1995a-d, 1994a). The emission factors were multiplied by the applicable animal populations in each region, and the results were summed over all cattle types to produce the total emissions estimate for U.S. cattle. Dairy cow emission factors from U.S. EPA (1993a) were modified to reflect increasing milk production per cow. The following factors should be considered when assessing these emission estimates:

- Because all estimates except for dairy cows were done nationally (rather than regionally), regional shifts in these populations were not considered.
- Dairy cow emission factors were developed regionally, and reflect both increasing milk production per cow by region and the shift in dairy cows away from the North Central region to the West (see Annex D for detail). The regional estimates were summed to determine a national emissions estimate.
- Emission factors for mature dairy cattle were increased to reflect the higher feed intakes required to achieve the increases in milk production per cow.
- The mix of Weanling and Yearling slaughters was kept constant (see Annex D for detail). Despite indications of a shift toward more Weanling slaughters, this change has not been quantified.

Table IV-2 presents emissions estimates for each animal category for the years 1990 to 1994. Emissions from beef cattle increased by 8 percent, from 3.95 million metric tonnes to 4.27 million metric tonnes, reflecting increases in the beef cattle population (see Table IV-3). Emissions from dairy cattle were relatively static, despite a declining population as emissions per head increased due to higher milk production per cow.

There are a variety of factors that make the emissions estimates uncertain. First, animal population and production statistics, particularly for range fed cattle, are uncertain. Second, the diets analyzed using the rumen digestion model are broad representations of the types of feed consumed within each region, so the full diversity of feeding strategies is not represented. And last, the rumen digestion model is itself uncertain since it was validated using uncertain experimental data. Together, these sources of uncertainty result in an overall uncertainty of about 20 per-

Table IV-2

Methane Emissions from Animals: 1990–1994

Cattle Types	Emissions (Million Metric Tonnes)					Emissions Factor (kg/head/yr)
	1990	1991	1992	1993	1994	
Dairy	1.47	1.46	1.47	1.47	1.48	
Cows	1.15	1.14	1.15	1.15	1.16	a
Replacements 0-12	0.08	0.08	0.08	0.08	0.08	19.6
Replacements 12-24	0.24	0.24	0.24	0.24	0.24	58.8
Beef	3.95	3.98	4.04	4.12	4.27	
Cows	2.18	2.20	2.23	2.28	2.36	66.7
Replacements 0-12	0.11	0.12	0.13	0.13	0.14	22.3
Replacements 12-24	0.33	0.35	0.37	0.38	0.40	65.0
Slaughter-Weanlings	0.12	0.12	0.12	0.12	0.12	23.1
Slaughter-Yearlings	0.98	0.98	0.97	0.98	1.02	47.3
Bulls	0.22	0.22	0.22	0.22	0.23	100.0
Other	0.27	0.28	0.28	0.27	0.27	
Sheep	0.09	0.09	0.09	0.08	0.08	8.0
Goats	0.01	0.01	0.01	0.01	0.01	5.0
Horses	0.09	0.09	0.09	0.09	0.09	18.0
Hogs	0.08	0.08	0.09	0.09	0.09	1.5
U.S. Total	5.70	5.72	5.79	5.86	6.02	

[a] Emissions from dairy cows are estimated using regional emissions factors. See Annex D, Table D-1

[5] USDA annual population data from 1990 through 1993 were revised. Due to these revisions, emissions estimates for 1990 through 1993 are also revised.

cent in the emission estimate (U.S. EPA, 1993a).

Methane Emissions from Other Domestic Animals

Methane emissions from other animals (*i.e.*, sheep, goats, pigs, and horses) account for a very small fraction of total methane emissions from livestock in the U.S. Also, the variability in emission factors for each of these other animal types (*e.g.*, variability by age, production system and feeding practice within each animal type) is much smaller than for cattle. Therefore, emissions from each of these other animal types are derived using a more simple analysis that is based on average emission factors representative of entire populations of each animal type.

Table IV-3

U.S. Animal Populations: 1990–1994

Cattle Types	Population (thousand head)				
	1990	1991	1992	1993	1994
Dairy					
Cows	10,007	9,883	9,714	9,679	9,614
Replacements 0-12	4,135	4,097	4,116	4,088	4,072
Replacements 12-24	4,135	4,097	4,116	4,088	4,072
Beef					
Cows	32,677	32,960	33,453	34,132	35,325
Replacements 0-12	5,141	5,321	5,621	5,896	6,133
Replacements 12-24	5,141	5,321	5,621	5,896	6,133
Slaughter-Weanlings	5,199	5,160	5,150	5,198	5,408
Slaughter-Yearlings	20,794	20,639	20,600	20,794	21,632
Bulls	2,180	2,198	2,220	2,239	2,304
Other					
Sheep	11,356	11,174	10,797	10,201	9,742
Goats	2,545	2,475	2,645	2,605	2,595
Horses	5,215	5,215	5,215	5,215	5,215
Hogs	53,807	56,535	58,553	56,919	60,028

Sources: USDA 1995a, 1995b, 1995c, 1995d, 1995g, 1995h, 1995m, 1994a, 1994c, and 1994d.

[a] For a more complete description of the derivation of population figures, see Annex D.

Methane emissions from other domestic animals were estimated by using emission factors from Crutzen, *et al.* (1986), utilized in U.S. EPA (1993a) and population data from NASS data sets (USDA, 1995h,m, and 1994c-d).[6] These emission factors are representative of typical animal sizes, feed intakes and feed characteristics in developed countries. The methodology employed in U.S. EPA (1993a) is the same as the method recommended by the IPCC (IPCC/OECD/IEA, 1995).

In 1994, total methane emissions from other animals are estimated to be 270 thousand metric tonnes CH_4 (1.8 MMTCE). The uncertainty in this estimate is probably greater than that for the cattle emissions estimate because a less detailed analysis was performed. However, since cattle account for over 95 percent of the emissions from all domestic livestock, the uncertainty in the cattle estimates drives the overall uncertainty for all livestock. Therefore, the same uncertainty range that was applied to cattle (20 percent) has been applied to other animals (U.S. EPA, 1993a). This results in low and high estimates of 200 and 350 thousand metric tonnes CH_4 (1.3 to 2.3 MMTCE).

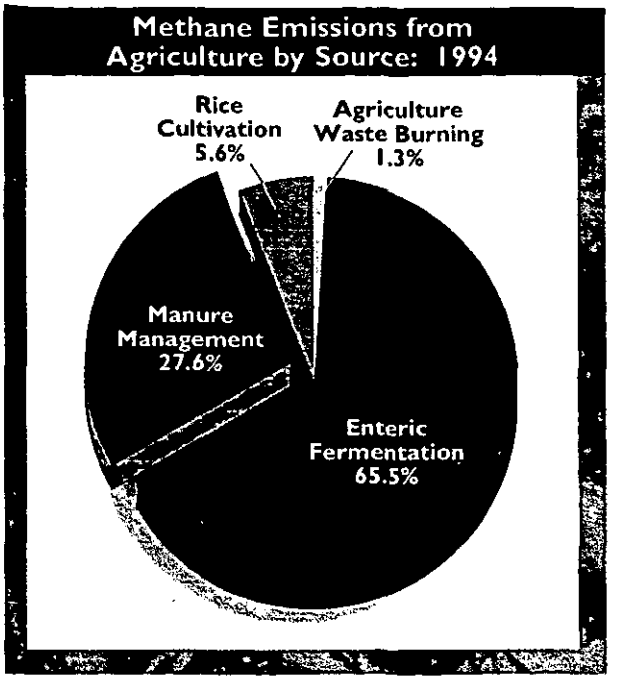
Enteric fermentation emissions from other animals changed little from 1990 to 1994. This is a reflection of very slight fluctuations in these animal populations and the small magnitude of the emission source.

Methane Emissions from Livestock Manure

Anaerobic decomposition of the organic material in livestock and poultry manure produces methane. In particular, liquid manure management systems, e.g., lagoons, ponds, tanks, or pits, tend to produce a significant quantity of methane. Higher temperatures and moist climatic conditions promote methane production. Although the majority of manure is handled as a solid, producing little methane, the general trend in manure management is towards an increase in usage of higher methane producing liquid systems.

Emission quantities are broken down by animal categories representing the major methane producing groups. Total methane emissions for 1994 are esti-

[6] Population data for horses were not readily available for 1991–1994. These emissions are small and were assumed to be constant.



mated to have been 2.54 million metric tonnes (16.97 MMTCE). Between 1990 and 1994, methane emissions from manure management increased about 15 percent. The largest increases occurred between 1991 and 1992, when the emissions level increased by 3.9 percent, and between 1993 and 1994, where there was a 6.3 percent rise. Emissions for each category of animal except "other" have increased annually. Animals in the "other" category, representing those that produce negligible amounts of methane from manure, exhibited no change in their total methane emissions from manure.

These increases in methane emissions reflect changes in animal populations in the beef, swine and poultry categories, and shifts in dairy and swine manure management towards lagoon management systems. Additionally, the increases reflect the regional redistribution of dairies to the Southwest, as well as a small increase in feed consumption by dairy cows.

Livestock manure is primarily composed of organic material and water. When manure decomposes in an anaerobic environment (*i.e.*, in the absence of oxygen), the organic material is broken down by methanogenic bacteria. Methane, carbon dioxide and stabilized organic material are produced as end products.

The principal factors that affect the amount of methane produced during decomposition are the way in which the manure is managed and the climatic environment in which the manure decomposes. Methane production will only occur under anaerobic conditions. Therefore, when manure is stored or treated in systems that promote an oxygen free environment (*e.g.*, as a liquid in lagoons, ponds, tanks, or pits), the manure tends to produce a significant quantity of methane. When manure is handled as a solid (*e.g.*, in stacks or pits) or when it is deposited on pastures and rangelands, it tends to decompose aerobically and produce little or no methane. Air temperature and moisture also affect the amount of methane produced since they influence the growth of the bacteria responsible for methane formation. Methane production generally increases with rising temperature. Also, for non-liquid based manure systems, moist conditions (which are a function of rainfall and humidity) favor methane production.

The composition of the manure also affects the amount of methane produced. Manure composition depends on the composition and digestibility of the animal diet. The greater the energy content and digestibility of the feed, the greater the amount of methane that potentially could be produced by the resulting manure. For example, feedlot cattle fed a high energy grain diet produce manure with a high methane-producing capacity. Range cattle feeding on a low energy forage diet produce manure with only half the methane-producing capacity of feedlot cattle manure. However, as described above, in either case the amount of methane that is actually produced and emitted to the atmosphere depends largely on the way that the manure is managed.

Methodology

Using annual livestock population data obtained from the USDA National Agricultural Statistics Service (NASS), the methods used in U.S. EPA (1993a) were applied to derive methane emission estimates for manure management in each state for the year 1990. For 1991-1994, state methane emissions for each animal subcategory were estimated by multiplying the corresponding 1990 emissions by the per-

cent change in population between each respective year and 1990. To incorporate shifts in manure management practices, changes in the methane conversion factor (MCF) were estimated for seven states for 1992 and after. Additionally, to reflect changes in the feed intake of dairy cows, a yearly volatile solids change factor was applied to each state.

Methane Emissions Estimates from Livestock Manure

From 1990 to 1994, methane emissions from manure management increased from about 2.21 to 2.54 million metric tonnes of methane, or 15 percent (see Table IV-4). A variety of factors contributed to these changes in emission levels, including changes in total animal populations, manure management systems, animal diets, and regional shifts in the dairy industry:

Populations. The increases in emissions reflect a general increase in animal populations in all categories, except dairy cows, heifers and the other minor animals populations. These population increases are primarily due to increases in demand.

Manure Management. Emission levels have increased with the general shift in swine and dairy management from dry storage to lagoon storage and treatment, the latter method producing higher quantities of methane. The increased use of anaerobic lagoon manure management systems is primarily a result of larger herd sizes that warrant the use of cost effective, automated (liquid) manure management systems. Increased concern over the effect of improper manure management is also encouraging such conversions.

Table IV-4

Methane Emissions from Manure Management: 1990–1994

	(Million Metric Tonnes)				
	1990	1991	1992	1993	1994
Dairy Cattle	0.75	0.75	0.79	0.80	0.84
Beef Cattle	0.20	0.20	0.21	0.21	0.22
Swine	0.95	0.99	1.04	1.03	1.14
Poultry	0.26	0.27	0.28	0.28	0.29
Other	0.06	0.06	0.06	0.06	0.06
Total	2.21	2.28	2.37	2.39	2.54

Source: The emissions data used above are derived from population numbers quoted in USDA (1995a-e, g-m, o)

Diet. The decrease in dairy cow and heifer populations was accompanied by increases in emissions from these animals. Increases in milk production per cow result in increased feed intake, leading to increased manure production per cow.

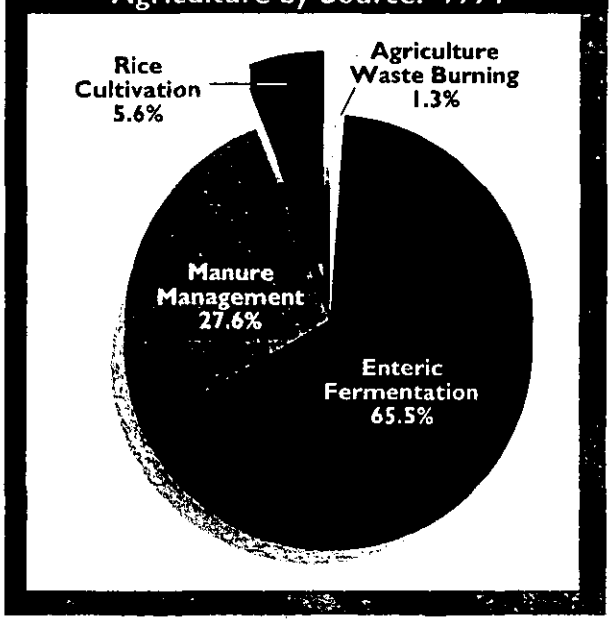
Regional Shifts. State emissions data have indicated a shift in dairy operations to states where wastes were more likely to produce methane. This is due largely to the types of waste management systems in use in these states; factors such as climate and rainfall are secondary.

Methane Emissions from Rice Cultivation

Most of the world's rice, and all rice in the U.S., is grown on flooded fields. When fields are flooded, anaerobic conditions in the soil develop, and methane is produced through anaerobic decomposition of soil organic matter. Methane is released primarily through the rice plants, which act as conduits from the soil to the atmosphere.

Rice cultivation is a very small source of methane in the U.S. Emissions from this source are estimated to

Methane Emissions from Agriculture by Source: 1994



have been approximately 0.9 - 6.0 MMTCE in 1994, accounting for about 1 percent of U.S. methane emissions from all sources and about 6 percent of U.S. methane emissions from agricultural sources. Seven states grow rice: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas. Emissions from Arkansas accounted for over 35 percent of total U.S. emissions from 1990 through 1994, primarily because it has the largest area of rice fields harvested. Louisiana, which has a longer growing season, has the second highest level of emissions, accounting for more than 20 percent of the national total.

Between 1990 and 1994 methane emissions from rice cultivation increased about 21 percent. While emissions remained relatively constant between 1990 and 1991, they increased about 13 percent between 1991 and 1992, due primarily to the relatively large areas harvested for most states in 1992. Emissions decreased about 9 percent in 1993 as a result of reductions in the total area harvested for that year. In 1994, emissions increased approximately 16 percent as total area harvested increased again in each state.

Most of the world's rice is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and floodwater causing anaerobic conditions in the soil to develop. Methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. However, not all of the methane that is produced is released into the atmosphere. As much as 60 to 90 percent of the produced methane is oxidized by aerobic methanotrophic bacteria in the soil (Holzapfel-Pschorn, *et al.*, 1985; Sass, *et al.*, 1990). Some of the methane is also leached away as dissolved methane in floodwater that percolates from the field. The remaining non-oxidized methane is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Some methane also escapes from the soil via diffusion and bubbling through the floodwaters.

The water management system under which rice is grown is one of the most important factors affecting methane emissions. Upland rice fields are not flooded, and therefore are not believed to produce methane. In deepwater rice fields (*i.e.*, fields with flooding depths greater than 1 meter), lower stems and roots of the rice plants are dead, and thus effectively block the primary CH_4 transport pathway to the atmosphere. Therefore, while deepwater rice growing areas are believed to emit methane, the quantities released are likely to be significantly less than the quantities released from areas with more shallow flooding depths. Also, some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, methane emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil methane to oxidize but also inhibits further methane production in soils.

Other factors that influence methane emissions from flooded rice fields include soil temperature, soil type, fertilization practices, cultivar selection, and other cultivation practices (*e.g.*, tillage, seeding and weeding practices). Many studies have found, for example, that methane emissions increase as soil temperature increases. Several studies have indicated that some types of nitrogen fertilizer inhibit methane generation, while organic fertilizers enhance methane emissions. However, while it is generally acknowledged that these factors influence methane emissions, the extent of the influence of these factors individually or in combination has not been well quantified.

Methodology

Estimates of methane emissions from rice cultivation in the U.S. are based on the IPCC methodology (IPCC/OECD/IEA, 1995), using emission factors that slightly vary from recommended values. The IPCC Guidelines suggest that the "growing" season be used to calculate emissions assuming that emission factors are based on measurements over the whole growing season rather than just the flooding season. Applying this assumption to the U.S., however, would result in an overestimate of emissions because the emission factors developed for the U.S. are based on measurements over the flooding rather than the

growing season. Therefore, the method used here is based on the number of days of flooding during the growing season and a daily emission factor, which is multiplied by the harvested area. Agricultural statisticians in each of the seven states in the U.S. that produce rice were contacted to determine water management practices and flooding season lengths in each state, and all reported that U.S. rice growing areas are continually flooded and that none are either upland or deepwater. Because flooding season lengths varied considerably among states, the IPCC method was applied to each of the seven states separately to calculate total emissions.

Daily methane emission factors were taken from results of field studies performed in California (Cicerone, *et al.*, 1983), Texas (Sass, *et al.*, 1990, 1991a, 1991b, 1992) and Louisiana (Lindau, *et al.*, 1991; Lindau and Bollich, 1993). Based on the maximal and minimal estimates of the emission rates measured in these studies, a range of 0.1065 to 0.5639 g/m^2/day was applied to the harvested areas and flooding season lengths in each state.[7] Since these measurements were taken in rice growing areas, they are representative of soil temperatures, and water and fertilizer management practices typical of the U.S.

The climatic conditions of southwest Louisiana, Texas and Florida allow for a second, or ratoon, rice crop. This second rice crop is produced from regrowth on the stubble after the first crop has been harvested. The emission estimates presented here account for this additional harvested area. Acreage for a second cropping cycle, or ratoon cropping, was estimated to account for about 30 percent of the primary crop in Louisiana, 40 percent in Texas (Lindau and Bollich, 1993) and 50 percent in Florida (Schudeman, 1995).

Rice fields for the second crop typically remain flooded for a shorter period of time than for the first crop. Recent studies indicate, however, that the methane emission rate of the second crop may be significantly higher than that of the first crop. The rice straw produced during the first harvest has been shown to dramatically increase methane emissions during the ratoon cropping season (Lindau and Bollich, 1993). It is not clear to what extent the shorter season length and higher emission rates offset each other. As scientific understanding improves, these emission estimates can be adjusted to better reflect these variables.

Since the number of days that the rice fields remain permanently flooded varies considerably with planting system and cultivar type, a range for the flooding season length was adopted for each state. The harvested areas and flooding season lengths for each state are presented in Table IV-5. Arkansas and Louisiana have the largest harvested areas, accounting for approximately 40 and 20 percent of the U.S. total, respectively. The flooding season lasts the longest in California (138 days), Louisiana (105 days) and Florida (105 days).

Methane Emissions from Rice Cultivation

Table IV-6[8] presents annual emission estimates based on the actual area harvested in each state between 1990 and 1994. Emissions for the U.S. from 1990 to 1994 increased 21 percent, from about 112-744 thousand metric tonnes (0.75-4.97 MMTCE) to 131-900 thousand metric tonnes (0.88-6.02 MMTCE), largely due to increases in rice production during this time period. Emissions from Arkansas account for over 35 percent of total emissions, primarily because it has the largest rice area harvested. Louisiana, because of its relatively large rice area and long growing season, has the second highest level of emissions, accounting for over 20 percent of the national total.

For comparison, Table IV-6 also presents national emission estimates based on three year averages of the area harvested for each state — a

[7] Two measurements from these studies were excluded when determining the emission coefficient range. A low seasonal average flux of 0.0595 g/m^2/day in Sass, *et al.* (1990) was excluded because this site experienced a mid-season accidental drainage of floodwater, after which methane emissions declined substantially and did not recover for about two weeks. Also, the high seasonal average flux of 2.041 g/m^2/day in Lindau and Bollich (1993) was excluded since this emission rate is unusually high, compared to other flux measurements in the U.S., as well as in Europe and Asia (see IPCC/OECD/IEA, 1995).

[8] Please note that emissions in Table IV-6 are expressed in thousand metric tonnes.

methodology recommended by the IPCC to avoid unrepresentative results due to fluctuations in economic or climatic conditions. The U.S. believes that annual data should be used, particularly as year-by-year estimates are developed as they are in this document.

Table IV-5

Area Harvested and Flooding Season Length for Rice-Producing States

State	Area Harvested (ha)						Flooding Season Length (days)	
	1989	1990	1991	1992	1993	1994	low	high
Arkansas	461,352	485,633	509,915	558,478	497,774	574,666	75	100
California	165,925	159,854	141,643	159,450	176,851	196,277	123	153
Florida[a]								
primary	5,585	4,978	8,580	8,944	8,449	8,902	90	120
ratoon	2,792	2,489	4,290	4,472	4,225	4,451		
Louisiana[a]								
primary	196,277	220,558	206,394	250,911	214,488	250,911	90	120
ratoon	58,883	66,168	61,918	75,273	64,346	75,273		
Mississippi	95,103	101,174	89,033	111,291	99,150	126,669	75	82
Missouri	31,971	32,376	37,232	45,326	37,637	50,182	80	100
Texas[a]								
primary	136,787	142,857	138,810	142,048	120,599	143,262	60	80
ratoon	54,715	57,143	55,524	56,819	48,240	57,305		
Total[b]	1,209,389	1,273,229	1,253,339	1,413,011	1,271,759	1,487,897		

Source: Area harvested data taken from Jett and Bequet, 1995; Lindau and Bollich, 1993; and Schudeman, 1995.

[a] These states have a second, or "ratoon", cropping cycle which may have a shorter flooding season than the one listed in the table.

[b] Totals may not add due to rounding.

Table IV-6

CH_4 Emissions from Rice Cultivation in the U.S.: 1990–1994

State	Annual Emissions (using annual data on harvested areas)[a] (Thousand Metric Tonnes)									
	1990		1991		1992		1993		1994	
	low	high	low	high	low	high	low	high	low	high
Arkansas	38.8	273.8	40.7	287.5	44.6	314.9	39.8	280.7	45.9	324.1
California	20.9	143.2	18.6	122.2	20.9	137.6	23.2	152.6	25.7	169.3
Florida	0.7	5.7	1.2	8.7	1.3	9.1	1.2	8.6	1.3	9.0
Louisiana	27.4	172.6	25.7	181.6	31.2	220.7	26.8	188.6	31.2	220.7
Mississippi	8.1	44.0	7.1	41.2	8.9	51.5	7.9	45.8	10.1	58.6
Missouri	2.8	18.0	3.2	21.0	3.9	25.6	3.2	21.2	4.3	28.3
Texas	12.8	86.4	12.4	87.6	12.7	89.7	10.8	76.2	12.9	90.5
Total	111.5	743.7	108.9	749.8	123.5	849.0	112.8	773.8	131.4	900.5
Annual Emissions (using three-year averaging method)[a,b]										
Total	109.0	748.7	114.7	788.3	115.1	790.9	122.6	841.1	122.1	837.1

Source: Based on: Cicerone, et al., 1983; Sass, et al., 1990, 1991a, 1991b, 1992; Lindau, et al., 1991; and Lindau and Bollich, 1993.

[a] Emission Factor: 0.1065 - 0.5639 (g $CH_4/m^2/day$)

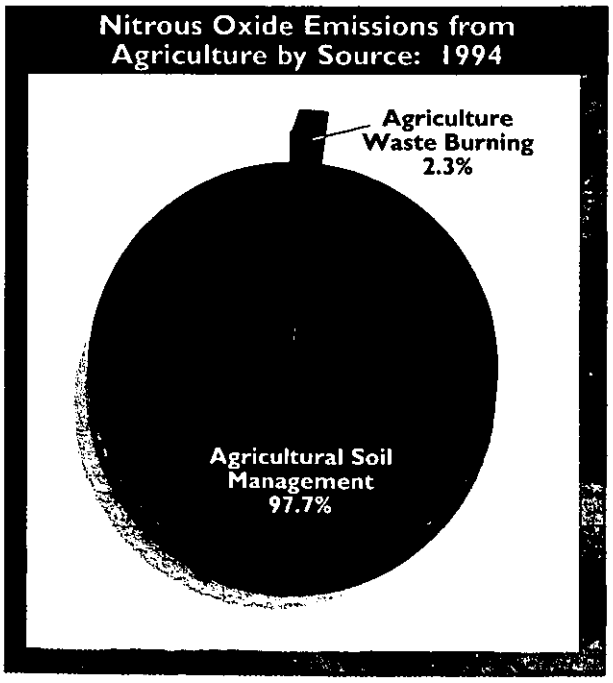
[b] Emission estimates for 1994 are based on two-year averages for harvested area (i.e., 1993 and 1994).

Nitrous Oxide Emissions from Agricultural Soil Management

Various agricultural soil management practices contribute to greenhouse gas emissions. The use of synthetic and organic fertilizers adds nitrogen to soils, thereby increasing natural emissions of nitrous oxide (N_2O). Other agricultural soil management practices such as irrigation, tillage practices, or the fallowing of land can also affect trace gas fluxes to and from the soil since soils are both a source and a sink for carbon dioxide (CO_2) and carbon monoxide (CO), a sink for methane (CH_4) and a source of nitrous oxide (NO_X). However, there is much uncertainty about the direction and magnitude of the effects of cropping and other soil management practices on GHG fluxes to and from soils. Due to these uncertainties, only N_2O emissions due to fertilizer consumption are included in the U.S. Inventory at this time.

Fertilizer use is a significant source of N_2O in the U.S. Consumption of organic and synthetic fertilizers (both multi-nutrient and nitrogen) increased about 3 percent between 1990 and 1992. While fertilizer use declined slightly between 1992 and 1993, heavy flooding in the North Central region in 1993 led to an 11 percent increase in fertilizer application in 1994 to replace depleted nitrogen in affected cropland soils. Total increases in fertilizer consumption between 1990 and 1994 caused emissions of N_2O to expand from about 16 MMTCE to about 18.4 MMTCE. Fertilizer emissions in 1994 represent approximately 45 percent of total U.S. N_2O emissions, and about 98 percent of N_2O emissions from all agricultural sources.

In 1994, the North Central region was responsible for approximately 55 percent of the total amount of fertilizer consumed in the U.S., while the South Central region consumed about 20 percent. Between 1990 and 1994, fertilizer consumption within each region, as a percentage of total U.S. fertilizer consumption, remained constant.



Nitrous oxide is produced naturally in soils through the microbial processes of denitrification and nitrification.[9] A number of anthropogenic activities add nitrogen to soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities include cropping practices, such as application of fertilizers, irrigation and tillage, acid deposition, and cultivation of nitrogen-fixing crops. This section focuses the discussion on emissions of N_2O due to fertilizer use (organic and synthetic nitrogen and multi-nutrient fertilizers). Other factors impacting N_2O emissions are also discussed such as tillage and irrigation practices, local climate, rainfall, and soil properties. Emissions due to atmospheric deposition and nitrogen-fixing crops are not included for two reasons: these emission sources are highly uncertain, and activity data are not readily available.

Research has shown that a number of factors affect nitrification and denitrification rates in soils, including: water content, which regulates oxygen supply; temperature, an important factor in microbial activity; nitrogen concentration, in particular nitrate and ammonium concentration; available organic car-

[9] Denitrification is the process by which nitrates or nitrites are reduced by bacteria, which results in the escape of nitrogen into the air. Nitrification is the process by which bacteria and other microorganisms oxidize ammonium salts to nitrites, and further oxidize nitrites to nitrates.

bon for microbial activity; and soil pH. These conditions vary greatly by soil type, crop type, management regime, and fertilizer application. Moreover, the interaction of these conditions and their combined effect on the processes leading to nitrous oxide emissions are not fully understood.

Scientific knowledge regarding N_2O production and emissions from fertilized soils is limited. Significant uncertainties exist regarding the agricultural practices, soil properties, climatic conditions, and biogenic processes that determine how much fertilizer nitrogen various crops absorb, how much remains in soils after fertilizer application, and in what ways the remaining nitrogen either evolves into N_2O or into gaseous nitrogen and other nitrogen compounds.

A major difficulty in estimating the magnitude of N_2O from soil has been the relative lack of emissions measurement data across a suitably wide variety of controlled conditions, making it difficult to develop statistically valid estimates of emission factors. Several attempts have been made to develop emission factors for the purpose of developing national emissions inventories. However, the accuracy of these emission factors has been questioned. For example, while some studies indicate that N_2O emission rates are higher for ammonium-based fertilizers than for nitrate, other studies show no particular trend in N_2O emissions related to fertilizer types (see Eichner, 1990; and Bouwman, 1990 for reviews of the literature). Therefore, it is possible that fertilizer type is not the most important factor in determining emissions. One study suggests that N_2O emissions from the nitrification of fertilizers may be more closely related to soil properties than to the type of fertilizer applied (Byrnes, *et al.*, 1990). Other factors, such as tillage and irrigation practices, local climate and crop type impact the production of N_2O in soils. By linking these factors through modeling, several studies estimate N_2O emissions from both crop and pasture lands (Li, *et al.*, 1992a, 1994, 1995) (See Box IV-1).

Agricultural practices not only affect atmospheric fluxes of N_2O, but also impact oxidation and uptake of CH_4 in soils. In addition, various land use changes affect fluxes of both N_2O and CH_4. A study assessing the impact of land use and management changes on soil as a CH_4 sink in temperate forest and grassland ecosystems indicates that intensive land cover changes and increased use of nitrogen fertilizers reduced soil uptake of CH_4 about 30 percent over the past 150 years (Ojima, *et al.*, 1993). Another study provides evidence that cultivation of former grasslands between the spring and late fall of 1990 decreased soil uptake of CH_4 and increased N_2O production (Mosier, *et al.*, 1991).

Due to the uncertainty surrounding the variety of possible emission factors, the IPCC recommends that countries estimate emissions from soil based on fertilizer use only, assuming 1 percent of nitrogen applied as fertilizer is released into the atmosphere (IPCC/OECD/IEA, 1995).

Methodology

Nitrous oxide emissions from fertilizer use have been estimated using the IPCC methodology, although with a slightly higher emission coefficient. The emission coefficient used (1.17 percent) is based on research done by the USDA (CAST, 1992). The amount of fertilizer consumed (synthetic nitrogen, multiple-nutrient and organic fertilizer, measured in mass units of nitrogen) was multiplied by this emission coefficient. Fertilizer data for the U.S. were obtained from the Tennessee Valley Authority's (TVA) National Fertilizer and Environmental Research Center (TVA, 1994).[10] Nitrous oxide emissions from fertilizer use were calculated as follows:

$$N_2O \text{ Emissions} = \text{Fertilizer Consumption (tonnes N)} \times 0.0117 \times {}^{44}/_{28}$$

Nitrous Oxide Emissions from Agricultural Soils

Between 1990 and 1994, total fertilizer consumption (multiple nutrient, synthetic nitrogen and organic) increased approximately 14 percent, largely reflecting the increase in fertilizer use after flooding in 1993. Fertilizer use increased at a 2 percent average

[10] Fertilizer consumption data may be underestimated since they do not include organic fertilizers that do not enter the commercial market.

Box IV-1

Estimating Nitrous Oxide Emissions Using the DNDC Model

To more fully understand and quantify sources of nitrous oxide within soils and to estimate emissions from agricultural lands, the Denitrification-Decomposition (DNDC) model was developed. This model links the decomposition and denitrification processes and uses data on soil properties, climate and agricultural practices to simulate processes that impact nitrous oxide production in soils. These processes include soil heat flux and moisture flows, decomposition of soil residues, denitrification rates, plant growth, and nitrogen uptake (Li, *et al.*, 1992a and 1994).

The DNDC model estimates emissions of nitrous oxide from both crop and pasture lands resulting from different soil properties, climate, crop type, fertilizer applications, and tillage and irrigation practices (Li, *et al.*, 1992a). Nitrous oxide emissions from a variety of agricultural lands simulated by the DNDC model have proven to be consistent with actual field measurements of emissions (Li, *et al.*, 1995, 1994, 1992b).

In light of uncertainty surrounding the validity of the IPCC methodology for determining nitrous oxide emissions from soils, emissions estimates based on DNDC model criteria may offer new and important insights into nitrous oxide emissions from agricultural lands. Using the DNDC model, estimates of nitrous oxide emissions in 1990 due to fertilizer consumption ranged between 110 thousand metric tonnes (9.6 MMTCE) and 126 thousand metric tonnes (11 MMTCE). While this estimate is lower than the 1990 emissions estimate based on the IPCC methodology (185 thousand metric tonnes, or 16 MMTCE), once differences in fertilizer consumption data used to calculate the two emissions estimates are reconciled, the IPCC and DNDC emissions estimates are more consistent.[a]

Like fertilizer consumption, cropping practices such as tillage and irrigation, local climate, crop type and soil properties are important factors affecting production of nitrous oxide in soils. By simulating the effects of factors other than fertilizer consumption through the DNDC model, emissions of nitrous oxide from both pasture and croplands were estimated to range between 1,226 and 1,807 thousand metric tonnes (107 and 158 MMTCE) in 1990. According to DNDC model estimates, nitrous oxide emissions from cropland make up about 60 percent of total nitrous oxide emissions from agricultural lands, while emissions from pasture land account for the remaining 40 percent (Li, *et al.*, 1995).

The DNDC model expands on the IPCC methodology estimates of nitrous oxide emissions by assessing both crop and pasture lands as sources of nitrous oxide and by examining emissions factors beyond fertilizer consumption. However, by incorporating a wide variety of emissions factors to estimate nitrous oxide emissions from soil, the DNDC model measures nitrous oxide emissions that may be unrelated to different land uses and farming practices. As soil is a natural source of nitrous oxide, the DNDC model may provide an overestimation of nitrous oxide emissions due to anthropogenic activities.

[a] The DNDC model estimate of 1990 nitrous oxide emissions due to fertilizer use is based on consumption of 8,100 thousand metric tonnes of fertilizer (data from TVA, 1989). The IPCC emissions estimate is based on consumption of 10,048 thousand metric tonnes of fertilizer, a more recent estimate of U.S. fertilizer consumption in 1990 (TVA, 1994). To make the emissions estimates more compatible, the IPCC method estimate was re-calculated using the same fertilizer consumption data as the DNDC model estimate. This changes the IPCC estimate for 1990 to 149 thousand metric tonnes, a figure closer to the DNDC model estimate.

annual rate between 1990 and 1992. Due to severe flooding of cropland in the North Central region and low total acreage harvested in 1993, fertilizer consumption decreased 0.5 percent and cropland yield declined about 20 percent. In response to low cropland productivity in 1993, total acreage planted in 1994 increased about 8 percent (USDA, 1995f; Dowdy, 1995). Fertilizer consumption increased about 11 percent in 1994 (TVA, 1994) due to both the increase in acres planted and efforts to restore nitrogen to cropland soil depleted by the heavy rainfall and flooding in 1993 (Taylor, 1995).

Regional fertilizer use, as a percent of total U.S. fertilizer consumption, has remained fairly constant between 1990 and 1994 for all regions with the exception of the North Central region between 1993 and 1994. From 1990 to 1992, the North Central region made up about 55 percent of total fertilizer consumption in the U.S. While fertilizer use within this region began to decline in 1993, it again stabilized at 55 percent of total U.S. fertilizer consumption in 1994, following cropland flooding in 1993. The South Central, West, South East, and North East regions remained constant from 1990 to 1994, making up approximately 20 percent, 15 percent, 10 percent and 5 percent of total U.S. fertilizer consumption, respectively (TVA, 1993; TVA, 1994).[11]

[11] Regional percentages of total U.S. fertilizer consumption are approximations. Therefore, the sum of percentages for each region will not equal 100. North East, South East, North Central, South Central, and West are defined as the following: *North East:* Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, Maryland, and West Virginia. *South East:* Virginia, North Carolina, South Carolina, Georgia, and Florida. *North Central:* Ohio, Indiana, Illinois, Minnesota, Wisconsin, Iowa, Missouri, North Dakota, South Dakota, Nebraska, and Kansas. *South Central:* Kentucky, Tennessee, Alabama, Mississippi, Arkansas, Louisiana, Oklahoma, and Texas. *West:* Montana, Idaho, Wyoming, Colorado, New Mexico, Arizona, Utah, Nevada, California, Washington, and Oregon. For 1993 and 1994, fertilizer consumption data on Georgia as part of the South East region are unavailable.

Based on annual fertilizer consumption statistics, emissions of N_2O from agricultural soils have been estimated from 1990 through 1994 (see Table IV-7)[12]. In 1994, emissions of N_2O were estimated to be about 211 thousand metric tonnes (18.4 MMTCE). After increasing at an average rate of about 2 percent between 1990 and 1992, N_2O emissions declined about 0.5 percent from 1992 to 1993. Due to the dramatic increase in fertilizer use following cropland flooding in 1993, emissions of N_2O from agricultural lands increased approximately 11 percent in 1994. Because agricultural activities fluctuate from year to year due to economic, climatic and other variables, the IPCC recommends that emissions are estimated based on three year averages of fertilizer consumption data. While the U.S. believes that annual data should be used to calculate emissions, estimates based on three year averages are also presented in Table IV-7.

Estimates using the IPCC methodology are highly uncertain due to the large degree of uncertainty associated with the emission factor. A survey of the current scientific literature on field N_2O flux provides a rather broad range for the emission coefficient — greater than 0.001 and less than 0.1 (CAST, 1992). Also, the emission coefficient used (1.17 percent) is probably too low for organic fertilizers and, as mentioned earlier, organic fertilizer consumption may be underestimated since the statistics only include fertilizers that enter the commercial market. Uncertainty is also introduced due to the variable nitrogen content of organic fertilizers. Nitrogen content varies by type of organic fertilizer as well as within individual types, and average values are used to estimate total organic fertilizer nitrogen consumed.

Emissions from Field Burning of Agricultural Wastes

In some parts of the U.S., agricultural crop wastes are burned in the field to clear remaining straw and stubble after harvest and to prepare the field for the next cropping cycle. When crop residues are burned, a number of greenhouse gases are released, including carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and oxides of nitrogen (NO_X). However, crop residue burning is not thought to be a net source of CO_2 because the CO_2 released during burning is reabsorbed by crop regrowth during the next growing season.

Field burning of crop residues is not a common method of agricultural waste disposal in the U.S., so emissions from this source are minor. Annual emissions from this source over the period 1990-1994 averaged approximately 107 thousand metric tonnes of CH_4 (0.7 MMTCE), 2,247 thousand metric tonnes of CO, 4 thousand metric tonnes of N_2O (0.4 MMTCE), and 98 thousand metric tonnes of NO_X. These estimates are highly uncertain because data on the amounts of residues burned each year are not available. The average annual emission estimates for field burning of crop residues over the 1990-1994 time period represent less than 1 percent of total U.S. emissions of CH_4 and NO_X, around 3 percent of total U.S. CO emissions, and less than 1 percent of total U.S. emissions of N_2O. Cereal crops (e.g., wheat, corn and sorghum) account for about 75 percent of the CH_4 and CO released and 50 percent of the N_2O and NO_X released.

Emissions decreased on average about 4 percent

Table IV-7

Fertilizer Consumption and N_2O Emissions in the U.S.: 1990–1994

	1990	1991	1992	1993	1994
Fertilizer Use (10^3 t N)	10048.1	10239.4	10384.1	10335.2	11469.5
N_2O Emissions(10^3 t N_2O)	184.7	188.3	190.9	190.0	210.9
3-Year Average[a] of Fertilizer Use(10^3 t N)	9965.7	10223.9	10319.6	10729.6	10902.3
3-Year Average[a] of N_2O Emissions (10^3 t N_2O)	183.2	188.0	189.7	197.3	200.4

Notes: Fertilizer consumption data obtained from TVA, 1994.
[a] Emission estimates for 1994 are based on two-year averages for harvested area (i.e., 1993 and 1994).

[12] Please note that emissions in Table IV-7 are expressed in thousand metric tonnes.

between 1990 and 1991, increased about 18 percent between 1991 and 1992, decreased about 21 percent between 1992 and 1993, and then increased by approximately 34 percent between 1993 and 1994. These fluctuations in emissions estimates reflect annual fluctuations in the amount of crops produced.

Large quantities of agricultural crop wastes are produced from farming systems. There are a variety of ways to dispose of these wastes. For example, agricultural residues can be plowed back into the field, composted, landfilled, or burned in the field. Alternatively, they can be collected and used as a biomass fuel or sold in supplemental feed markets. This section addresses field burning of agricultural crop wastes. Field burning of crop wastes is not thought to be a net source of CO_2 because the carbon released to the atmosphere during burning is reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, CO, N_2O, and NO_X, which are released during combustion. In addition, field burning may result in enhanced emissions of N_2O and NO_X many days after burning (Anderson, *et al.*, 1988; Levine, *et al.*, 1988), although this process is highly uncertain and will not be accounted for in this section.

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural wastes is based on the amount of carbon burned, emission ratios of CH_4 and CO to CO_2 measured in the smoke of biomass fires, and emission ratios of N_2O and NO_X to the nitrogen content of the fuel. The methodology is the same as the IPCC methodology (IPCC/OECD/IEA, 1995).

The first step in estimating emissions from agricultural waste burning is to estimate the amounts of carbon and nitrogen released during burning:

Carbon Released =
Annual Crop Production x Residue/Crop Product Ratio x Fraction of Residues Burned *in situ* x Dry Matter content of the Residue x Burning Efficiency x Carbon Content of the Residue x Combustion Efficiency[13]

Nitrogen Released =
Annual Crop Production x Residue/Crop Product Ratio x Fraction of Residues Burned *in situ* x Dry Matter Content of the Residue x Burning Efficiency x Nitrogen Content of the Residue x Combustion Efficiency[13]

Estimates of the amounts of crop residues burned in situ, or in the field, are not readily available. Therefore, the default value of 10 percent, recommended by the IPCC for developed countries, was used. However, this default value, based on Crutzen and Andreae (1990), may be an overestimate for the U.S. because open burning is banned in many states.

Emissions of carbon as CH_4 and CO are calculated by multiplying the amount of carbon released by the appropriate emission ratio (*i.e.*, CH_4/C or CO/C). Similarly, N_2O and NO_X emissions are calculated by multiplying the amount of nitrogen released by the appropriate emission ratio (*i.e.*, N_2O/N or NO_X/N). The specific values used in this inventory and the results are presented in Tables IV-8 and IV-9.[14]

Emissions from Field Burning

Estimates of emissions based on each year's activity data have been calculated for the years 1990 through 1994. Field burning of agricultural wastes was estimated to release an average of approximately 107 thousand metric tonnes CH_4 (0.7 MMTCE), 2,247 thousand metric tonnes CO, 4 thousand metric tonnes N_2O (0.4 MMTCE), and 98 thousand metric tonnes NO_X annually from 1990 through 1994. Cereal crops account for about 75 percent of the carbon released and 50 percent of the nitrogen released.

Emissions from field burning of agricultural

[13] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" is added to the calculations.

[14] Please note that emissions in Tables IV-8 and IV-9 are expressed in Thousand Metric Tonnes.

Table IV-8

Key Assumptions for Estimating Emissions from Crop Waste Burning Using Annual Activity Data

Crop Type	Annual Production (Thousand Metric Tonnes) 1990	1991	1992	1993	1994	res/crop ratio[a]	dry matter (%)	fraction carbon	fraction nitrogen
Cereals									
Wheat	74,473	53,918	67,135	65,220	63,157	1.3	85.0	0.4853	0.003
Barley	9,192	10,110	9,908	8,666	8,162	1.2	85.0	0.4567	0.004
Corn[d]	201,534	189,886	240,719	160,954	256,629	1.0	78.0	0.4709	0.0081
Oats	5,189	3,534	4,271	3,001	3,336	1.3	90.4	0.4853	0.007
Rye	258	248	291	263	283	1.6	90.0	0.4853	0.007
Rice	7,080	7,142	8,149	7,081	8,971	1.4	85.0	0.4144	0.0067
Millet[b]	180	180	180	180	180	1.4	88.5	0.4853	0.007*
Sorghum	14,563	14,856	22,227	13,569	16,638	1.4	88.0	0.4853	0.0085*
Pulse									
Soya	52,416	54,065	59,612	50,919	69,626	2.1	86.7	0.45	0.023*
Beans	1,469	1,532	1,026	994	1,324	2.1	85.4	0.45	0.023*
Peas	155	217	115	149	102	1.5	90.2	0.45	0.023*
Lentils	40	76	71	91	84	2.1	86.7	0.45	0.023*
Tuber and Root									
Sugarbeet	24,959	25,585	26,438	23,812	29,037	0.3	90.0	0.4072	0.0228
Artichoke[c]	56	56	56	46	55	0.8	90.0	0.4226	0.011
Peanut	1,634	2,235	1,943	1,539	1,934	1.0	90.1	0.4226	0.011
Potatoes	18,239	18,943	19,294	19,445	20,835	0.4	86.7	0.4226	0.011
Other	574	511	548	504	596	0.4	86.7	0.4226	0.011
Sugarcane	25,525	27,444	27,545	28,214	28,863	0.8	90.0	0.4695	0.003

Sources: Data on annual crop production were taken from USDA (1991a, 1993b, 1994b, 1995f), FAO (1994) and McFarland (1995). Residue/crop ratios, dry matter contents, and carbon contents were taken from Strehler and Stützle (1987) and University of California (1977). Nitrogen contents were also taken from Strehler and Stützle (1987) except where indicated by an asterisk (*). These data were taken from Bernard (1990). The percent of produced residue that is burned is based on Crutzen and Andreae (1990).

[a] The percent of crop residue burned is assumed to be 10 percent.

[b] Because millet is such a small commodity relative to other crops, the USDA no longer tracks its production. These production estimates were taken from the FAO (1993, 1994).

[c] Total artichoke production was estimated by assuming that California accounted for 90% of the entire market. Artichoke production data for California are based on McFarland (1995).

[d] Corn refers to maize.

wastes decreased 1 to 7 percent between 1990 and 1991 and then increased 15 to 20 percent in 1992. A similar pattern again followed between 1992 and 1993, with a 20 to 21 percent decrease in 1993, and then a 31 to 37 percent increase in 1994. Total emissions are based on actual crop production figures and reflect general crop production trends. Production for most crops decreased between 1990 and 1991, increased from 1991 to 1992, decreased from 1992 to 1993, and then increased from 1993 to 1994. The large decrease in 1993 relative to 1992 and 1994 is due, in part, to the decrease in area harvested in 1993 (USDA, 1994c) that was partially caused by flooding (Dowdy, 1995).

For the 1990-1994 time period, 1994 had the highest emissions. Emissions for that year included 122 thousand tonnes of CH_4 (0.8 MMTCE), 2,562 thousand tonnes of CO, 5 thousand tonnes of N_2O (0.4 MMTCE), and 116 thousand tonnes of NO_X. Emissions estimates for 1993 were the lowest for the period 1990-1994.

To avoid effects of fluctuations in economic or climatic conditions on estimates of emissions from burning of agricultural wastes, the IPCC recommends using a three-year average for crop production centered around the year in question. This method was used to estimate emissions for the years 1990, 1991, 1992, 1993, and 1994. The data and results are con-

Table IV-9

Annual Trace Gas Emissions from Field Burning: 1990–1994 Based on Annual Activity Data

Gas/Crop Type	Carbon or Nitrogen Released (Thousand Metric Tonnes)					Emission Conversion Ratio	Emission Conversion Factor	Emissions (Thousand Metric Tonnes)[b]				
	1990	1991	1992	1993	1994			1990	1991	1992	1993	1994
CH_4												
Cereals	10,941	9,663	12,201	9,145	12,154	0.005	16/12	73	64	81	61	81
Pulse	3,622	3,742	4,075	3,493	4,767	0.005	16/12	24	25	27	23	32
Tuber & Root	503	535	538	503	580	0.005	16/12	3	4	4	3	4
Sugarcane	706	759	762	781	799	0.005	16/12	5	5	5	5	5
TOTAL[a]	15,772	14,699	17,576	13,921	18,299	0.005	16/12	105	98	117	92	122
CO												
Cereals	10,941	9,663	12,201	9,145	12,154	0.006	28/12	1,532	1,353	1,708	1,280	1,702
Pulse	3,622	3,742	4,075	3,493	4,767	0.006	28/12	507	524	571	489	667
Tuber & Root	503	535	538	503	580	0.006	28/12	70	75	75	70	81
Sugarcane	706	759	762	781	799	0.006	28/12	99	106	107	109	112
TOTAL[a]	15,772	14,699	17,576	13,921	18,299	0.006	28/12	2,208	2,058	2,461	1,949	2,562
N_2O												
Cereals	147	136	173	122	174	0.007	44/28	2	1	2	1	2
Pulse	185	191	208	179	244	0.007	44/28	2	2	2	2	3
Tuber & Root	20	21	21	20	23	0.007	44/28	0.2	0.2	0.2	0.2	0.3
Sugarcane	5	5	5	5	5	0.007	44/28	0.05	0.05	0.05	0.05	0.06
TOTAL[a]	357	353	407	325	446	0.007	44/28	4	4	4	4	5
NO_x[c]												
Cereals	147	136	173	122	174	0.121	30/14	38	35	45	32	45
Pulse	185	191	208	179	244	0.121	30/14	48	50	54	46	63
Tuber & Root	20	21	21	20	23	0.121	30/14	5	5	5	5	6
Sugarcane	5	5	5	5	5	0.121	30/14	1	1	1	1	1
TOTAL[a]	357	353	407	325	446	0.121	30/14	93	91	106	84	116

[a] *Totals may not add due to rounding.*

[b] *Burning efficiency (the fraction of dry biomass exposed to burning that actually burns) was assumed to be 93 percent and combustion efficiency (the fraction of carbon in the fire that is oxidized completely to CO_2) was assumed to be 88 percent (U.S. EPA, 1994a).*

[c] *The source for the factor to convert NO_x to full molecular weight is Andreae (1990). The ratio of 30/14 was used because NO is the primary form of NO_x emitted during biomass combustion.*

tained in Tables IV-10 and IV-11 and generate a trend counterintuitive to that reflected by results using the annual activity data. Emissions based on a three-year average increased approximately 6 to 7 percent from 1990 to 1991, decreased about 3 to 4 percent between 1991 and 1992, increased 8 to 9 percent from 1992 to 1993, and decreased about 2 to 3 percent between 1993 and 1994. Since these trends run counter to the results obtained using annual data, annual activity data, rather than three-year averages, were used in this Inventory to produce annual emission estimates.

Table IV-10

Key Assumptions for Estimating Emissions from Crop Waste Burning Using Three-year Averages of Activity Data

Crop Type	3 Yr. Avg. Production (Thousand Metric Tonnes)					res/crop ratio	dry matter	fraction carbon	fraction nitrogen
	1990	1991	1992	1993	1994[a]		(%)		
Cereals									
Wheat	61,273	65,175	62,091	65,171	64,189	1.3	85.0	0.4853	0.003
Barley	9,367	9,737	9,561	8,912	8,414	1.2	85.0	0.4567	0.004
Corn[d]	194,192	210,713	197,186	219,434	208,791	1.0	78.0	0.4709	0.0081
Oats	4,715	4,331	3,602	3,536	3,169	1.3	90.4	0.4853	0.007
Rye	284	266	267	279	273	1.6	90.0	0.4853	0.007
Rice	7,077	7,457	7,457	8,067	8,026	1.4	85.0	0.4144	0.0067
Millet[b]	183	180	180	180	180	1.4	88.5	0.4853	0.007*
Sorghum	15,017	17,215	16,884	17,478	15,103	1.4	88.0	0.4853	0.0085*
Pulse									
Soya	52,945	55,364	54,865	60,052	60,273	2.1	86.7	0.45	0.023*
Beans	1,359	1,342	1,184	1,115	1,159	2.1	85.4	0.45	0.023*
Peas	204	162	160	122	126	1.5	90.2	0.45	0.023*
Lentils	56	62	79	82	88	2.1	86.7	0.45	0.023*
Tuber and Root									
Sugarbeet	24,448	25,661	25,279	26,429	26,425	0.3	90.0	0.4072	0.0228
Artichoke[c]	59	56	52	52	50	0.8	90.0	0.4226	0.011
Peanut	1,893	1,937	1,906	1,806	1,737	1.0	90.1	0.4226	0.011
Potatoes	17,995	18,826	19,228	19,858	20,140	0.4	86.7	0.4226	0.011
Other	534	544	521	549	550	0.4	86.7	0.4226	0.011
Sugarcane	26,555	26,838	27,734	28,207	28,539	0.8	90.0	0.4695	0.003

Sources: Data on annual crop production were taken from USDA (1991a, 1993b, 1994b, 1995f), FAO (1994) and McFarland (1995). Residue/crop ratios, dry matter contents and carbon contents, were taken from Strehler and Stützle (1987) and University of California (1977). Nitrogen contents were also taken from Strehler and Stützle (1987) except where indicated by an asterisk (*). These data were taken from Barnard (1990). The percent of produced residue that is burned is based on Crutzen and Andreae (1990).

[a] Crop production for 1994 are two-year averages (i.e., 1993 and 1994).

[b] Because millet is such a small commodity relative to other crops, the USDA no longer tracks its production. These production estimates were taken from FAO (1993, 1994).

[c] Total artichoke production was estimated by assuming that California accounted for 90 percent of the entire market. Artichoke production data for California are based on McFarland (1995).

[d] Corn refers to maize.

[e] The percentage of crop residue burned is assumed to be 10 percent.

Table IV-11

Average Annual Trace Gas Emissions from Field Burning: 1990-1994 Based on Three-year Averages of Activity Data

Gas/Crop Type	Carbon or Nitrogen Released (Thousand Metric Tonnes)					Emission Conversion Ratio	Emission Conversion Factor	Emissions (Thousand Metric Tonnes)[b]				
	1990	1991	1992	1993	1994			1990	1991	1992	1993	1994
CH_4												
cereals	10,149	10,935	10,336	11,167	10,649	0.005	16/12	68	73	69	74	71
pulse	3,654	3,813	3,770	4,112	4,130	0.005	16/12	24	25	25	27	28
tuber/root	503	525	525	540	541	0.005	16/12	3	3	3	4	4
sugarcane	735	742	767	780	790	0.005	16/12	5	5	5	5	5
TOTAL[a]	15,040	16,016	15,399	16,599	16,110	0.005	16/12	100	107	103	111	107
CO												
cereals	10,149	10,935	10,336	11,167	10,649	0.006	28/12	1,421	1,531	1,447	1,563	1,491
pulse	3,654	3,813	3,770	4,112	4,130	0.006	28/12	512	534	528	576	578
tuber/root	503	525	525	540	541	0.006	28/12	70	73	73	76	76
sugarcane	735	742	767	780	790	0.006	28/12	103	104	107	109	111
TOTAL[a]	15,040	16,016	15,399	16,599	16,110	0.006	28/12	2,106	2,242	2,156	2,324	2,255
N_2O												
cereals	140	152	143	156	148	0.007	44/28	2	2	2	2	2
pulse	187	195	193	210	211	0.007	44/28	2	2	2	2	2
tuber/root	20	21	20	21	21	0.007	44/28	0.2	0.2	0.2	0.2	0.2
sugarcane	5	5	5	5	5	0.007	44/28	0.05	0.05	0.05	0.05	0.05
TOTAL[a]	352	372	361	393	385	0.007	44/28	4	4	4	4	4
NO_x[c]												
cereals	140	152	143	156	148	0.121	30/14	36	39	37	41	38
pulse	187	195	193	210	211	0.121	30/14	48	51	50	54	55
tuber/root	20	21	20	21	21	0.121	30/14	5	5	5	5	6
sugarcane	5	5	5	5	5	0.121	30/14	1	1	1	1	1
TOTAL[a]	352	372	361	393	385	0.121	30/14	91	97	94	102	100

[a] *Totals may not add due to rounding.*

[b] *Burning efficiency (the fraction of dry biomass exposed to burning that actually burns) was assumed to be 93 percent and combustion efficiency (the fraction of carbon in the fire that is oxidized completely to CO_2) was assumed to be 88 percent (U.S. EPA, 1994a).*

[c] *The source for the factor to convert NO_x to full molecular weight is Andreae (1990). The ratio of 30/14 was used because NO is the primary form of NO_x emitted during biomass combustion.*

Part V: Emissions from Land-Use Change and Forestry

The biosphere emits and absorbs a wide variety of carbon and nitrogen trace gases, including carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), oxides of nitrogen (NO_X), and non-methane hydrocarbons (NMHCs).[1] When humans impact the biosphere through land-use change and forest management activities, such as clearing an area of forest to create cropland, restocking a logged forest, draining a wetland, or allowing a pasture to revert to a grassland, the natural balance of these trace gas emissions and uptake is altered and their atmospheric concentrations adjust. Globally, the most important human activity that affects the biosphere is deforestation, particularly the clearing of tropical forests for agricultural use. Deforestation is estimated to be responsible for about 20 percent of the current annual global emissions of CO_2 from anthropogenic activities (IPCC, 1992).

In the U.S., however, forest management activities and the regeneration of previously cleared forest area are believed to be the primary factors affecting current greenhouse gas fluxes from land-use change and forestry, as the amount of forest land has remained fairly constant over recent decades. The net CO_2 flux in 1990, 1991 and 1992 due to these activities is estimated to have been an uptake (sequestration) of 125 MMTCE. This carbon uptake represents an offset of about 9 percent of the average annual CO_2 emissions from energy-related activities during this period. Emission estimates are not yet available for 1993 and 1994 because the last national forest inventory was completed in 1992.

The U.S. land area is roughly 2,263 million acres, of which 33 percent, or 737 million acres, is forest land (Powell, *et al.*, 1993). The amount of forest land has remained fairly constant over recent decades, declining by approximately 5 million acres between 1977 and 1987 (USFS, 1990; Waddell, *et al.*, 1989), and increasing by about 0.5 million acres between 1987 and 1992 (Powell, *et al.*, 1993). These changes represent fluctuations of well under 1 percent of the forest land area, or on average, about 0.1 percent per year. Other major land uses in the U.S. include range and pasture lands (36 percent), cropland (18 percent), urban uses (3 percent), and other lands (10 percent) (Daugherty, 1991).[2] Urban lands are the fastest growing land use. Given that U.S. forest land area changed by only about 0.1 percent per year over the last 15 years, the major influences on the net carbon flux from forest land are management activities and ongoing impacts of previous land-use changes. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems. For example, intensified management of forests can increase both the rate of growth and the eventual biomass density[3] of the forest, thereby

[1] Nonmethane hydrocarbons (NMHCs) are a subset of nonmethane volatile organic compounds.

[2] Other lands include farmsteads, transportation uses, marshes, swamps, deserts, tundra, and miscellaneous other lands.

[3] Biomass density, or the amount of biomass in a given land area, includes all the living and dead organic material, both above and below the ground surface.

increasing the uptake of carbon. The reversion of cropland to forest land through natural regeneration also will, over decades, result in increased carbon storage in biomass and soils (*i.e.*, in general, forests contain more carbon than cropland).

Forests are complex ecosystems with several interrelated components, each of which acts as a carbon storage pool, including:

- trees (*i.e.*, living trees, standing dead trees, roots, stems, branches, and foliage);
- soil;
- the forest floor (*i.e.*, woody debris and tree litter); and
- understory vegetation (*i.e.*, shrubs and bushes).

As a result of biological processes (*e.g.*, growth and mortality) and anthropogenic activities (*e.g.*, harvesting, thinning, and replanting), carbon is continuously cycled through these ecosystem components, as well as between the forest ecosystem and the atmosphere. For example, the growth of trees results in the uptake of carbon from the atmosphere and storage in living biomass. As trees age, they continue to accumulate carbon until they reach maturity, at which point they are relatively constant carbon stores. As trees die and otherwise deposit litter and debris on the forest floor, decay processes release carbon to the atmosphere and also increase soil carbon. The net change in forest carbon is the sum of the net changes in the total amount of carbon stored in each of the forest carbon pools over time.

The net change in forest carbon, however, is not likely to be equivalent to the net flux between forests and the atmosphere. Because most of the timber that is harvested and removed from U.S. forests is used in wood products, removals may not always result in an immediate flux of carbon to the atmosphere. Harvesting in effect transfers carbon from one of the "forest pools" to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 through either combustion or decay,[4] although the exact rate of emission varies considerably between different product pools and may in fact result in effective long-term carbon storage. For example, if timber is harvested and subsequently used as lumber in a house, it may be many decades or even centuries before the lumber is allowed to decay and carbon is released to the atmosphere. If timber is harvested for energy use, subsequent combustion results in an immediate release of carbon. Paper production may result in emissions over years or decades.

The U.S. forest carbon flux estimates for the period from 1990 to 1992 presented in this inventory are based on historical changes in forest carbon stocks and projected changes in forest product pools. Forest carbon stock estimates are derived for two years, 1987 and 1992, based on forest surveys conducted for those years. The derived forest stock estimates only include carbon contained in biomass of trees and understory vegetation. Soil and forest floor carbon stocks have not been included at this time due to methodological uncertainties associated with their estimation. The annual net carbon flux from forest growth in 1990, 1991, and 1992 was assumed to be equal to the average net annual flux during the period between 1987 and 1992. Carbon fluxes associated with changes in sizes of product pools were derived using the estimated pool sizes in 1980 and 2000. It was assumed that the product pool fluxes in 1990, 1991, and 1992 were equal to the average annual flux during the 1980–2000 period. The total annual carbon flux from forests was obtained by summing the carbon flux associated with forest growth and the flux associated with changes in product pools.

The inventory methodology described above differs somewhat from that recommended by the IPCC (IPCC/OECD/IEA, 1995). Instead of directly inventorying carbon stocks and changes in stocks over time, the IPCC methodology uses average annual statistics on land-use change and forest management activities, and applies carbon density and flux rate data to these

[4] Actually, if timber undergoes combustion, some small portion of the carbon - as much as 10 percent of the total carbon released - will be emitted as CO and CH_4 rather than CO_2. In addition, if timber products are placed in landfills, about 50 percent of the carbon that eventually decomposes is oxidized to CO_2 and about 50 percent is released as CH_4. However, eventually both CO and CH_4 oxidize to CO_2 in the atmosphere.

activity estimates to derive total flux values. In addition, the IPCC assumes that harvested biomass replaces biomass in existing product pools that decays in the inventory year (*i.e.*, that product pool sizes do not change over time), while the U.S. inventory accounts for changes in the amount of carbon stored in product pools. The IPCC has adopted a methodology that utilizes average land-use change statistics and does not include fluxes associated with product pools because the majority of the world's countries do not have detailed time-series of forest inventory statistics and information on product pool sizes, such as are available in the U.S. and have been used in preparing this inventory. Although there are large uncertainties associated with the data used to develop the emission estimates presented here, the use of direct measurements from forest surveys and of product pool size estimates is likely to have resulted in more accurate flux estimates than if the basic IPCC methodology had been employed.

The estimates of forest carbon and product carbon stocks used in this inventory to derive carbon fluxes were provided by Birdsey and Heath (1995). These estimates are based on a variety of data sources. The amount of carbon in trees and understory vegetation in 1987 and 1992 was estimated based on empirical data collected by the U.S. Forest Service (USFS) (Waddell, *et al.*,1989; Powell, *et al.*, 1993). The data include estimates of timber volume by tree species, size class, and other categories. Although the surveys cover only timberland, which is a subset of the forest land base, they capture the most productive and intensively managed forest lands.[5] The amount of carbon in aboveground and below ground tree biomass in forests was calculated by multiplying timber volume by conversion factors derived from a national biomass inventory (Cost, *et al.*, 1990). Carbon storage in understory vegetation was estimated based on simple models (Vogt, *et al.*, 1986)

Table V-1

U.S. Carbon Storage Estimates

Year	Carbon in Forests	Carbon in Landfills	Carbon in Wood Products
	(Million Metric Tonnes)		
1980	–	1,236	1,272
1987	13,567	–	–
1992	14,057	–	–
2000	–	1,533	1,520

Source: (Birdsey and Heath, 1995)

and review of numerous intensive ecosystem studies (Birdsey, 1992). The total biomass carbon was estimated as a sum of carbon contained in individual pools. Carbon stored annually in harvested biomass was assumed to be equal to a sum of the net amount of carbon deposited in landfills and the net increase in carbon contained in durable wood products. The average values of these fluxes were obtained using the 1980 and 2000 sizes of landfill and wood product pools (Row and Phelps, 1991).

The total amounts of biomass carbon in U.S. forests in 1987 and 1992 are given in Table V-1. The increase in forest carbon stocks over time indicates that, during the examined periods, forests on average functioned as net sinks of carbon.

The annual net carbon flux in forests in 1990, 1991, and 1992 was estimated by dividing the difference in total forest carbon storage in 1987 and 1992 by the number of years between the two surveys (Table V-2):

$$\frac{(14{,}057 - 13{,}567)}{5} = 98 \text{ million tonnes of carbon/year}$$

Net carbon fluxes associated with biomass accumulated in landfills and in wood products were estimated based on corresponding pool sizes in 1980 and 2000 (Table V-1). The annual average net fluxes for these pools were estimated by dividing the difference between 1980 and 2000 pool sizes by 20 (Table V-2).

[5] Forest land in the U.S. includes all land that is at least 10 percent stocked with trees of any size. Timberlands are the most productive of these forest lands, growing at a rate of 20 cubic feet per acre per year or more. In 1992 there were about 490 million acres of Timberlands, which represented 66 percent of all forest lands (Powell, *et al.*, 1993). Forest land classified as Timberlands is unreserved forest land that is producing or is capable of producing crops of industrial wood. The remaining 34 percent of forest land is classified as Productive Reserved Forest Land, which is withdrawn from timber use by a statute or regulation, or Other Forest Land, which includes unreserved and reserved unproductive forest land. While this inventory does not quantify the carbon flux on Productive Reserved or Other Forest Lands, this missing flux is assumed to be relatively minor because trees on these lands grow slowly and the standing stock of trees is not managed intensively.

The annual total net carbon fluxes from U.S. forests were estimated by summing the fluxes from forests, wood products, and landfills (Table V-2).[6]

There are considerable uncertainties associated with the estimates of the net carbon flux from U.S. forests in the present inventory. The first source of uncertainty is due to the probabilistic rather than the deterministic nature of forest surveys. These surveys are based on a statistical sample designed to represent a wide variety of growth conditions present over large territories. Therefore, the actual values of carbon stored in forests are represented by average values that are subject to sampling and estimation errors. However, according to Birdsey and Heath (1995), these errors are likely to be relatively small.

The second source of uncertainty results from incomplete accounting of wood products. Only biomass removed from private timberland was used to assess net carbon fluxes from landfill and wood product pools. Inclusion of biomass removed from other timberland would likely increase the estimated net sequestered carbon.

The third source of uncertainty is associated with the fact that the carbon content of the understory vegetation pool was evaluated using independent ecosystem studies. In order to extrapolate results of these studies to all forest lands, it was assumed that they adequately describe regional or national averages. This assumption can potentially lead to the following errors: bias from applying data from studies that inadequately represent average forest conditions, modeling errors (erroneous assumptions), and errors in converting estimates from one reporting unit to another (Birdsey and Heath, 1995).

It should be noted that the current inventory does not include estimates of soil and forest floor carbon fluxes. The main reason for excluding these fluxes is that impacts of forest management activities, including harvest, on soil and forest floor carbon are not well understood. For example, Moore, *et al.* (1981) found that harvest may lead to a 20 percent loss of soil carbon, while little or no net change in soil carbon following harvest was reported in another study (Johnson, 1992). Since forest soils and floors contain over 60 percent of the total stored forest carbon in the U.S., this difference can have a large impact on flux estimates.

The current inventory also does not address emissions of greenhouse gases other than CO_2. It is known that forest management activities result in fluxes of other radiatively important gases, such as CH_4, N_2O, CO, and several NMHCs. However, the effects of forestry activities on fluxes of these gases are highly uncertain. Similarly, there are several land-use changes that are not accounted for in the inventory due to uncertainties in their effects on trace gas fluxes as well as poorly quantified land-use change statistics. These land-use changes include loss and reclamation of freshwater wetland areas, conversion of grasslands to pasture and cropland, and conversion of managed lands to grasslands and other unmanaged, non-forest dryland types.

Table V-2

Carbon Fluxes from U.S. Forests in 1990–1992

Year	Forest Flux	Wood Products Flux	Landfill Carbon Flux	Total Carbon Flux	Total CO_2 Flux
			(Million Metric Tonnes)		
1990	98	12	15	125	458
1991	98	12	15	125	458
1992	98	12	15	125	458

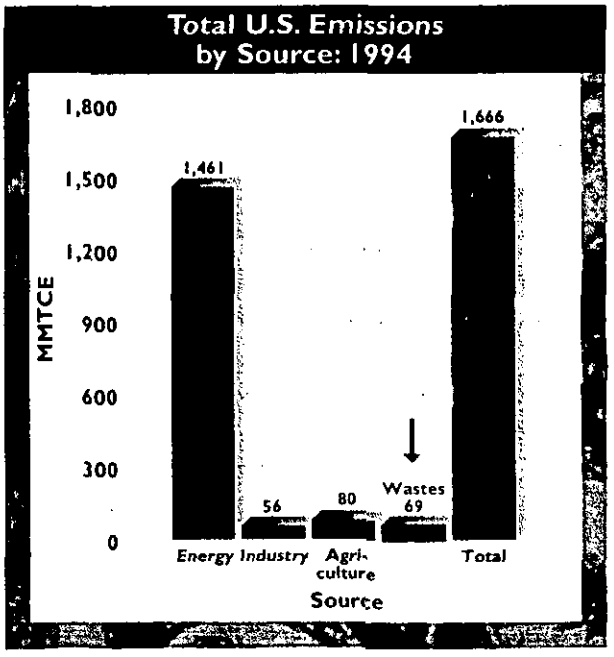
[6] The new estimates of the net flux associated with forest growth from 1990–1992 are lower than those provided in the 1994 U.S. Inventory (U.S. EPA, 1994b) because the forest floor flux was not included in the current inventory. Also, in addition to forest carbon stock changes between 1987 and 1992, the previous estimates were based on stock changes between 1977 and 1987. Estimates of changes in carbon stocks prior to 1987 were not used in the current inventory to calculate fluxes because it is believed that this would add extra uncertainty to the final flux estimates. The total net carbon fluxes in the current inventory exceed those presented in 1994 due to inclusion of fluxes associated with accumulation of harvested biomass in wood product and landfill pools.

Part VI: Emissions from Waste

Anaerobic decomposition of organic materials by bacteria in landfills can result in emissions of methane (CH_4), carbon dioxide (CO_2), and other greenhouse and photochemically important gases. Currently, methane emissions from landfills are the largest single anthropogenic source of methane in the U.S., contributing about 36 percent of total U.S. methane emissions. Large quantities of methane can be also emitted as a result of anaerobic decomposition processes in wastewater streams with high organic material content. In addition, the combustion of waste, both in incinerators and by open burning, is also a source of many greenhouse and photochemically important gases. This section covers methane emissions from U.S. landfills and wastewater streams, and criteria pollutant emissions from waste incineration. Emissions from each of these sources from 1990 to 1994 are presented in Table VI-1.

Landfills

Organic landfill materials such as yard waste, household garbage, food waste, and paper can decompose and produce methane. This decomposition process is a natural mechanism through which microorganisms derive energy for growth. Methane production typically begins one or two years after waste placement in a landfill and may last from 10 to 60 years. Methane emissions from landfills are the



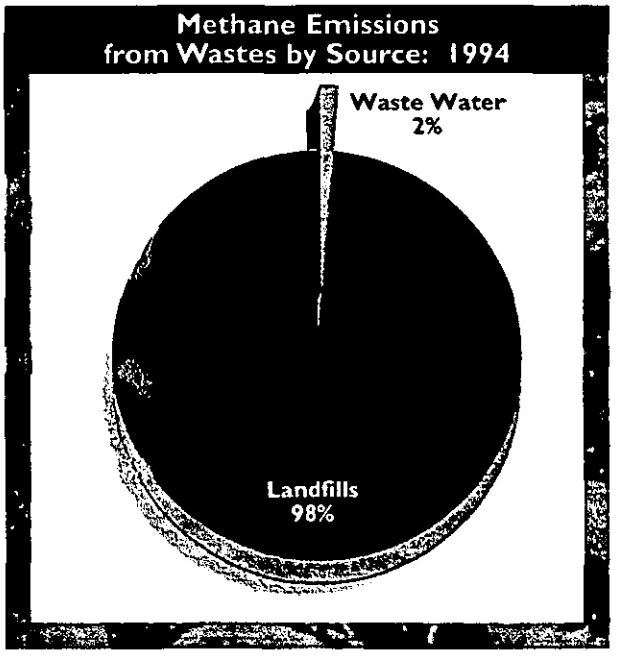


Table VI-1

Recent Trends in U.S. Greenhouse Gas Emissions from Waste Sources: 1990–1994

Gas/Source	Emissions (Full Molecular Weight)					Emissions (Direct and Indirect Effects; Carbon-Equivalent)				
	(Million Metric Tonnes)									
	1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
CH_4										
Landfills	9.9	10.1	9.9	10.0	10.2	66.2	67.5	66.2	66.8	68.2
Wastewater	0.2	0.2	0.2	0.2	0.2	1.0	1.0	1.0	1.0	1.1
NMVOC										
Waste Combustion	0.3	0.3	0.3	0.3	0.3	–	–	–	–	–
CO										
Waste Combustion	1.5	1.5	1.6	1.6	1.6	–	–	–	–	–
NO_x										
Waste Combustion	0.1	0.1	0.1	0.1	0.1	–	–	–	–	–
Total U.S. GHG Emissions						67.2	68.5	67.2	67.9	69.2

Note: Totals presented in the summary tables in this chapter may not equal the sum of the individual source categories due to rounding.

largest single anthropogenic source of methane in the U.S. In 1994, methane emissions from U.S. landfills totaled approximately 10.2 million tonnes (68.2 MMTCE), or about 36 percent of total U.S. methane emissions. Emissions from U.S. municipal solid waste (MSW) landfills, which received about 67 percent of the total solid waste generated in the U.S., account for about 90 to 95 percent of the total landfill emissions, while industrial landfills account for the remaining 5 to 10 percent. There are over 6,000 landfills in the U.S., with 1,300 of the largest landfills generating almost all the methane and receiving almost all the waste.

Between 1990 and 1994, estimates of methane emissions from landfills remained essentially unchanged. The relatively constant emissions estimates for the period are actually the result of two countervailing factors: (1) an increase in the amount of MSW in landfills contributing to methane emissions (thereby increasing the potential for emissions); and (2) an increase in the amount of landfill gas collected and combusted (thereby reducing emissions).

Methane emissions from landfills are a function of several factors, including the total amount of MSW landfilled over the last 30 years; composition of the waste in place; the amount of methane that is recovered and either flared or used for energy purposes; and the amount of methane oxidized in landfills before being released into the atmosphere. The estimated total quantity of waste in place contributing to emissions increased from about 4,708 million metric tons in 1990 to 4,971 million metric tonnes in 1994, an increase of 5.6 percent. During this same period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1.5 million tonnes of methane were recovered and combusted (*i.e.*, used for energy or flared) from landfills. In 1992, the estimated quantity of methane recovered and combusted increased to 1.8 million metric tonnes. While 1994 data are unavailable, the amount of methane recovered and combusted from landfills was expected to have continued increasing, resulting in relatively constant emissions estimates between 1990 and 1994.

Over the next several years, the total amount of MSW generated is anticipated to continue to increase. The percentage of waste landfilled, however, may decrease due to increased recycling and composting practices. While the percentage of waste landfilled could decrease, the composition of the waste being landfilled could include a higher proportion of organic material, thereby increasing methane generation per unit of waste in place (U.S. EPA, 1993a).

Conversely, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a new regulation that will require large landfills to collect and combust landfill gas in the future.[1] The impact of such shifts in activity on emissions cannot be fully assessed at this time.

After being placed in a landfill, organic waste first decomposes aerobically (in the presence of oxygen) and is then attacked by anaerobic bacteria which convert organic material to simpler forms like cellulose, amino acids, and sugars. These simple substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for methanogenic bacteria. Methane producing bacteria then convert these fermentation products into stabilized organic materials and a biogas consisting of approximately 50 percent carbon dioxide and 50 percent methane by volume. The percentage of carbon dioxide in the biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen, 1987).

Emissions of methane into the atmosphere will equal total methane production from municipal landfills adjusted for the methane produced by industrial landfills, the methane recovered, and the methane oxidized before being released into the atmosphere. These adjustments can be described as follows:

Methane Emissions =

	municipal landfill methane generation
plus	industrial landfill methane generation
minus	methane recovery
minus	methane oxidation

Further detail on the methodology used here can be found in Annex E.

In 1994, landfills in the U.S. were estimated to have emitted between 8.3 million metric tonnes to 12.0 million metric tonnes, with a central estimate of 10.2 million metric tonnes of methane (68.2 MMTCE; see Table VI-2). This amount represents about 36 percent of total U.S. methane emissions. Based on this analysis, landfills are by far the largest anthropogenic source of methane emissions in the U.S. Table VI-2 presents the estimates of landfill methane emissions and uncertainty ranges for 1990 through 1994.

Methane emissions estimates from 1990 to 1994 have remained essentially unchanged. The data indicate a slight increase in emissions from 1990 to 1994 (3 percent), but the uncertainties in the data available

Table VI-2

U.S. Methane Emissions from Landfills: 1990–1994

Source	Number	1990[a]	1991	1992	1993	1994
		(Million Metric Tonnes)				
Large Landfills	152	3.0-3.8	3.0-3.8	2.8-3.6	2.9-3.7	2.9-3.8
Medium Landfills	1,137	3.5-5.9	3.6-5.9	3.6-5.9	3.6-6.0	3.6-6.0
Small Landfills	4,744	1.0-1.3	1.0-1.3	1.0-1.3	1.0-1.3	1.1-1.4
Industrial	N/A	0.6-0.9	0.6-0.9	0.6-0.9	0.6-0.9	0.6-0.9
Total[b,c]	6,033[d]	8.1-11.8	8.2-11.9	8.0-11.8	8.2-11.9	8.3-12.0
Mean		9.9	10.1	9.9	10.0	10.2

[a] *The ranges presented for emissions by landfill category for 1990 have been revised from earlier estimates using updated emissions coefficients which better reflect actual landfill conditions.*

[b] *The totals may not equal the sum of the individual categories as each is treated independently, with its own mean and variance.*

[c] *In 1990, an estimated 1.5 million tonnes of methane was recovered for energy use or flared; this estimate was used for 1991 also, due to lack of data. In 1992, an estimated 1.8 million tonnes of methane was recovered for energy use or flared. Also, the amount of methane produced by industrial landfills is estimated to be 7 percent of municipal landfill methane generation (U.S. EPA, 1993a).*

[1] The primary regulation affecting landfill gas generation and recovery rates is the proposed rule "Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfills" [Federal Register, May 30, 1991, pp. 24467-24528].

make it difficult to precisely define trends. However, the estimates clearly indicate that larger landfills in the U.S. contribute more to overall methane emissions than smaller landfills. In 1994 "large" landfills accounted for only 2.5 percent of all landfills, but over 30 percent of total landfill methane emissions, while a far greater number of small landfills (79 percent) accounted for only about 12 percent of these emissions (see Table VI-2). Moreover, these percentages have remained essentially unchanged between 1990 and 1994.

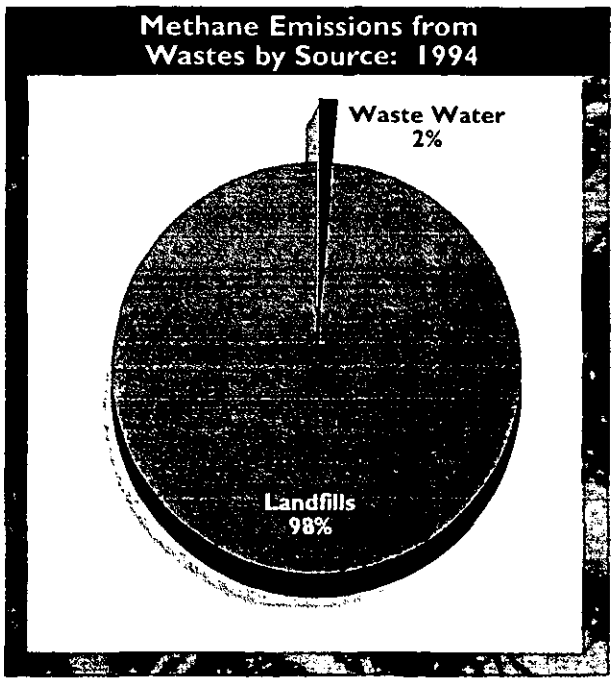
There are several uncertainties associated with the estimates provided for methane emissions from landfills. The primary uncertainty surrounding the estimates is the lack of comprehensive information regarding the characterization of landfills, in terms of acres landfilled, moisture content, waste composition, operating practices at the landfill, and total waste in place (the fundamental factors affecting methane production). In addition, there is very little information on the quantity of methane that is currently flared at non-energy related projects. Finally, the statistical model used to estimate emissions is based on methane generation at landfill facilities that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of all U.S. landfills. To the degree that emission data and inputs for the model are not representative of landfills as a whole, error may be introduced.

In addition to methane, carbon dioxide is also released from landfills. However, carbon dioxide from landfills is believed to come mainly from organic materials. Since these materials are assumed to absorb a similar amount of carbon during the growing cycle, the net contribution of landfills to the global carbon dioxide budget is assumed to be zero, and therefore is not included in the emissions totals. The same is not true for the methane that may be produced, however, since the methane is typically only produced as a by-product of the landfilling process. For the same reason, carbon dioxide released during methane combustion is also not counted.

Wastewater

Wastewater can be treated using aerobic and/or anaerobic technologies, or if untreated, can degrade under either aerobic or anaerobic conditions. Methane is produced when organic material in treated and untreated wastewater degrades anaerobically, i.e., without the presence of oxygen. Based on available data, methane emissions from municipal wastewater in the U.S. were about 1.1 MMTCE in 1994, or about 0.6 percent of total U.S. methane emissions. Emissions over the period from 1990 through 1994 have remained relatively constant, increasing only slightly due to a growing volume of municipal wastewater caused by a rising U.S. population. This estimate is based on rough assumptions of the U.S. municipal wastewater stream drawn from U.S. EPA (1994a), and at this time data are not sufficient to estimate methane emissions from industrial wastewater streams. Further research is ongoing at the U.S. EPA to better quantify emissions from this source.[2]

Highly organic wastewater streams such as waste streams from food processing or pulp and paper



[2] EPA's Atmospheric Pollution Prevention Division is currently conducting research to better quantify methane emissions from the U.S. wastewater stream. The results of this analysis should be available in early 1996.

plants rapidly deplete available oxygen in the water stream as their organic matter decomposes. The organic content, otherwise known as "loading" of these wastewater streams, is expressed in terms of biochemical oxygen demand, or "BOD." BOD represents the amounts of oxygen taken up by the organic matter in the wastewater during decomposition. Under the same conditions, wastewater with higher BOD concentrations will produce more methane than wastewater with relatively lower BOD concentrations. Most industrial wastewater has a low BOD content, while food processing facilities such as fruit, sugar, meat processing plants, and breweries can produce untreated waste streams with high BOD content.

Although IPCC-recommended methodologies for estimating municipal and industrial wastewater methane emissions exist, the data required by these methodologies are not easily obtained, especially industrial wastewater data. Estimates of municipal wastewater methane for the U.S. provided in this section are based on methods outlined in U.S. EPA (1994a). That report's methodologies, which are similar to the proposed IPCC methodologies, are based on BOD loading in the municipal wastewater flow in the U.S., resulting in the following equation:

$$\frac{kgCH_4}{yr} = \text{Population} \times \frac{kgBOD_5}{capita/day} \times \frac{365\ days}{yr} \times \frac{0.22kgCH_4}{kgBOD_5} \times (\text{Fraction Anaerobically Digested})$$

As shown in Table VI-3, applying this equation with U.S. population statistics and available waste stream data results in estimated methane emissions from municipal wastewater of about 150,000 metric tonnes (1.0 MMTCE) in 1990. This value increased slightly to about 160,000 metric tonnes (1.1 MMTCE) in 1994, which was about 0.6 percent of total U.S. methane emissions in that year. This small increase was due to an increase in U.S. population resulting in an increased flow of municipal wastewater.

Table VI-3

U.S. Methane Emissions from Wastewater

Year	Methane Emissions (molecular weight)	Methane Emissions (carbon equivalent)
	(Million Metric Tonnes)	
1990	0.151	1.0
1991	0.152	1.0
1992	0.154	1.0
1993	0.156	1.0
1994	0.157	1.1

There is uncertainty in these estimates due to a lack of data characterizing wastewater management practices, the quantities of wastewater that are subject to anaerobic conditions, the extent to which methane is emitted under anaerobic conditions, and flaring or utilization practices.

Waste Combustion

Similar to other types of combustion, waste combustion, whether in incinerators or out in the open, can be a source of CO_2, NO_X, CO, and NMVOCs. Waste combustion is also a source of CH_4 and N_2O, but emissions pathways are still highly uncertain.

In 1994, emissions of NMVOCs, CO, and NO_X from waste incineration constituted about 3 percent, 2 percent and 0.3 percent of total U.S. emissions of each of these criteria pollutants, respectively. Between 1990 and 1994, U.S. emissions of NMVOCs and CO from waste incineration increased by about 3.5 percent, while NO_X emissions from this source rose about 4 percent (see Table VI-4). Open burning contributes the majority of criteria pollutant emissions from waste combustion, constituting about 82 percent, 61 percent and 50 percent of total NMVOC, NO_X, and CO emissions, respectively, from this source in 1994 (see Table VI-5).

Criteria pollutants from waste combustion are inventoried annually by the U.S. EPA. Emissions of criteria pollutants from waste incineration were reported in *National Air Pollutant Emission Trends, 1900–1994*, (U.S. EPA, 1995b). The U.S. EPA esti-

mated emissions from waste combustion by applying activity emission factors (from MSW incineration or open burning) to collected or estimated local and regional activities to obtain local and regional emissions, which were then aggregated to obtain national emissions.

At present, net carbon dioxide emissions from waste incineration are not included in this inventory because a large fraction of the carbon in combusted waste (*e.g.*, food waste) is quickly recycled, typically on an annual basis as crops regrow or trees are replanted. Combusted wastes can also contain plastics or other fossil-fuel based products that contribute to net carbon dioxide emissions. At this time, however, carbon emissions from the incineration of fossil-based products are not estimated.

Table VI-4

U.S. NMVOC, CO, & NO_x Emissions from Waste Incineration: 1990–1994

Source	1990	1991	1992	1993	1994
	(Million Metric Tonnes)				
NMVOCs	0.290	0.292	0.296	0.298	0.300
CO	1.530	1.543	1.558	1.571	1.584
NO_x	0.074	0.075	0.075	0.076	0.077

Source: U.S. EPA (1995b)

Table VI-5

U.S. NMVOC, CO, & NO_x Emissions from Waste Incineration by Source: 1994

Source	NMVOCs	CO	NO_x
	(Million Metric Tonnes)		
Municipal Waste Incineration	0.054	0.797	0.029
Open-Burning	0.247	0.787	0.047
Total	0.300	1.584	0.077

Source: U.S. EPA (1995b)

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ANNEX A
METHOD OF ESTIMATING EMISSIONS OF CO_2 FROM FOSSIL ENERGY CONSUMPTION

The "bottom-up" methodology is characterized by six basic steps, which are described below. This discussion focuses on emission estimates for the year 1994, with the relevant data presented in Tables A-1 through A-6. Emissions estimates for other years were performed using the same methodology. Relevant data sources and notations are outlined at the end of this discussion.

METHODOLOGY

Step 1. Determine energy consumption by energy type and sector.

The bottom-up methodology used by the U.S. for estimating CO_2 emissions from fossil energy consumption is conceptually similar to the approach recommended by the IPCC for countries that intend to develop detailed, sectoral-based emission estimates (IPCC/OECD/IEA, 1995). Basic consumption data are presented in Columns 2 - 8 of Table A-1, with totals by energy type in Column 8 and totals by sector in the last row. Fuel consumption data for the bottom-up approach were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy, which is responsible for the collection of all U.S. energy data. All the EIA data were collected through surveys at the point of delivery or use, so they reflect the reported consumption of fuel by sector and fuel type. Individual data elements came from a variety of sources within EIA (see below for exact sources). Most information is from published reports, although some data have been drawn from unpublished energy studies and databases maintained by EIA.

By aggregating consumption data by sector (*i.e.*, residential, commercial, industrial, transportation, electric utilities, and U.S. territories), primary fuel type (*e.g.*, bituminous coal, natural gas, and petroleum), and secondary fuel type (*e.g.*, gasoline, distillate fuel, etc.), one can estimate total U.S. energy consumption for a particular year. The 1994 total energy consumption across all sectors, including territories, and energy types is 76,216 trillion Btu, as indicated in the last entry of Column 8 in Table A-1. This total includes fuel used for non-fuel purposes and fuel consumed as international bunkers, both of which are deducted in later steps.

There are three modifications made to consumption in this report that may cause consumption information herein to differ from figures given in the cited literature. These are the consideration of unmetered natural gas consumption, synthetic natural gas production, and ethanol added to motor gasoline. Unmetered natural gas is part of the "balancing item" found in most EIA gas statistics. This item represents unaccounted for differences between calculated

supply and consumption, including processes leaks, accounting and reporting problems, and other data errors. It is assumed that a fraction of this "balancing item" is actually combusted, despite not appearing in consumption figures. In this report, this additional unmetered portion is added to each sector's natural gas consumption in proportion to its total gas consumption, making the numbers reported herein slightly larger than in most EIA sources.

A portion of industrial coal accounted for in EIA combustion figures is actually used to make "synthetic natural gas" via coal gasification. The energy in this gas enters the natural gas stream, and is accounted for in natural gas consumption statistics. Since this energy is already accounted for as natural gas, it is deducted from industrial coal consumption to avoid double counting. This makes the figure for other industrial coal consumption in this report slightly lower than most EIA sources.

Ethanol has been add to the motor gasoline stream for several years, but prior to 1993 this addition was not captured in EIA motor gasoline statistics. Starting in 1993 this ethanol was included in the gasoline statistics. However, since ethanol is a biofuel which is assumed not to result in net carbon dioxide emissions to the atmosphere, the amount of ethanol added is subtracted from total gasoline consumption so as not to include the associated carbon dioxide emissions. Thus, motor gasoline consumption statistics given in this report may be slightly lower than in EIA sources.

There are three basic differences between the consumption figures presented in Table A-1 and those recommended in the IPCC emission inventory methodology. First, all consumption data in the U.S. inventory are presented using higher heating values (HHV) rather than the lower heating values (LHV) reflected in the IPCC emission inventory methodology. This convention is followed because all data obtained from EIA are based on HHV.

Second, while EIA's energy use data for the U.S. includes only the 50 U.S. states and the District of Columbia, the data reported for the U.S. by international agencies, such as the International Energy Agency (IEA), includes consumption in the U.S. territories. To make the inventory estimates comparable with these statistics, consumption estimates for U.S. territories were added to domestic consumption of fossil fuel. Energy consumption data from U.S. territories are presented in Column 7 of Table A-1. It is reported separately from domestic sectoral consumption, because it is collected separately by EIA with no sectoral disaggregation.

Third, the domestic sectoral consumption figures in Table A-1 include bunker fuels and non-fuel uses of energy. The IPCC recommends that countries estimate emissions from bunker fuels separately and exclude these emissions from national totals, so bunker fuel emissions have been estimated in Table A-2 and deducted from national estimates (see Step 4). Similarly, fossil fuels used to produce non-energy products that store carbon rather than release it to the atmosphere are calculated in Table A-3 and deducted from national emission estimates (see Step 3). The carbon content values of bunker fuels and carbon stored in products are reported as

"Adjustments" in Columns 17 through 19. The calculation if these adjustments is further described in Steps 3 and 4 below.

Step 2. Determine the carbon content of all fuels.

Total carbon contained in the energy consumed was estimated by multiplying energy consumption (Columns 2 through 8 of Table A-1) by fuel specific carbon content coefficients (Table A-6a, A-6b, and Column 9 of Table A-1) that reflected the amount of carbon per unit of energy for each fuel. The resulting carbon contents (Columns 10 through 16) are sometimes referred to as potential emissions, or the maximum amount of carbon that could potentially be released to the atmosphere if all carbon in the fuels were converted to CO_2. Fuel specific and sectoral totals are given in Column 16 and the last row of Table A-1, respectively. The carbon content coefficients used in the U.S. inventory were derived by EIA from detailed fuel information and are similar to the carbon content coefficients contained in the IPCC's default methodology (IPCC/OECD/IEA, 1995), with modifications reflecting fuel qualities specific to the U.S.

Step 3. Adjust for the amount of carbon stored in products.

Depending on the end use, non-fuel uses of fossil energy can result in storage of some or all of the carbon contained in the energy for some period of time. For example, asphalt made from petroleum can sequester up to 100 percent of the carbon contained in the petroleum feedstock for extended periods of time. Other non-fuel products, such as lubricants or plastics, also store carbon, but can lose or emit some of this carbon when they are used and/or burned as waste after utilization.

The amount of carbon sequestered or stored in non-fuel uses of fossil fuel energy products was based on data concerning the end uses and ultimate fate of various energy products, with all non-fuel use attributed to the industrial and transportation sectors. This non-fuel consumption is presented in Columns 2 and 3 of Table A-3. Non-fuel consumption was then multiplied by fuel specific carbon content coefficients (Tables A-6a and A-6b, and Column 4 of Table A-3) to obtain the carbon content of the fuel, or the maximum amount of carbon that could potentially be sequestered if all the carbon in the fuel were stored in non-fuel products (Columns 5 and 6 of Table A-3). This carbon content was then multiplied by the fraction of carbon actually sequestered in products (Table A-6a and Column 7 of Table A-3), resulting in the final estimates of carbon stored by sector and fuel type, which are presented in Columns 8 through 10 of Table A-3. The portions of carbon sequestered were based on IPCC data (IPCC/OECD/IEA, 1995) and U.S. specific estimates based on information provided by EIA (Rypinski, 1994).

Step 4. Subtract carbon from bunker fuels.

According to the decision reached at INC-9, emissions from international transport activities, or bunker fuel consumption, should not be included in national totals. There is international disagreement as to which countries are responsible for these emissions, and until this issue is resolved, countries are to report these emissions separately. However, EIA data includes bunker fuels (primarily residual oil) as part of consumption by the transportation sector. To compensate for this, bunker fuel emissions were calculated separately (Table A-2) and the carbon content of these fuels was subtracted from the transportation sector (Column 17 of Table A-1). This deduction, together with that of carbon stored in products, resulted in the net carbon content, or carbon content with adjustments, as presented in Columns 20 through 25 of Table A-1. The calculations of bunker fuel emissions followed the same procedures used for emissions due to consumption of all fossil fuels in the U.S. (*i.e.*, estimation of consumption, determination of carbon content, and adjustment for the fraction of carbon not oxidized).

Step 5. Account for carbon that does not oxidize during combustion.

Since combustion processes are not 100 percent efficient, some of the carbon contained in fuels is not emitted to the atmosphere. Rather, it remains behind as soot, particulate matter, or other byproducts of inefficient combustion. The estimated fraction of carbon not oxidized in U.S. energy conversion processes due to inefficiencies during combustion ranges from 0.5 percent for natural gas to one percent for oil and coal. Except for coal these assumptions are consistent with the default values recommended by the IPCC (IPCC/OECD/IEA, 1995). In the U.S. unoxidized carbon from coal combustion was estimated to be no more than one percent (Bechtel, 1993). Column 26 of Table A-1 presents fractions oxidized by fuel type, which are multiplied by the net carbon content of the combusted energy to give final emissions estimates (Columns 27 - 33 of Table A-1).

Step 6. Summarize emission estimates.

Table A-4 summarizes actual CO_2 emissions in the U.S. by major consuming sector (*i.e.*, residential, commercial, industrial, transportation, and electric utilities) and major fuel type (*i.e.*, coal, natural gas, and petroleum products). Adjustments for bunker fuels and carbon sequestered in products have been made, as shown in Table A-1. Emissions in Table A-4 are expressed in terms of million metric tons of carbon equivalent (MMTCE), except in the last column and row, which shows carbon dioxide emissions on a full molecular weight basis.

Table A-5 summarizes U.S. carbon dioxide emissions by end-use sector. To determine these estimates, emissions from the electric utility sector were distributed over the four end use sectors according to their share of electricity consumed. Column 2 presents the fraction of total

U.S. electricity consumed by each of the four end-use sectors. This fraction was then multiplied by total emissions by fuel type from the utility sector (Columns 2 - 4 of Table A-4), resulting in the portion of utility emissions attributable to each end-use sector. These end use emissions from electricity consumption were then added to the non-utility emission estimates taken from Table A-4 (Columns 2 - 4), resulting in total emissions from each of the four end-use sectors (Column 3 - 5 of Table A-5).

REFERENCES BY SUBJECT

Some of the major sources used in estimating CO_2 emissions from energy consumption are listed below. They have been grouped by subject for ease of reference and are included alphabetically with other sources in the reference section of this document. These sources are often annual or monthly publications. The citations given reflect only the most current issues at the time of data compilation. Where necessary, data were also taken from previous installments of the reports.

Consumption Data

General

EIA, 1995. *State Energy Data Report 1993*, unpublished full table presentations, DOE/EIA-0214(93)-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA, 1995. *Petroleum Supply Annual 1994*, DOE/EIA-0340(94)1&2-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA, 1995. *Petroleum Supply Monthly*, DOE/EIA-0109(95)-monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC.

Non-Fuel Use

EIA, 1994. *Annual Energy Review 1993*, DOE/EIA-0384(93)-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA, 1995. *Monthly Energy Review*, DOE/EIA-0035(94)-monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC.

Bunker Fuels

EIA, 1995. *International Energy Annual*, unpublished full table presentations, DOE/EIA-0219(93)-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA, 1993. *Fuel Oil and Kerosene Sales 1993*. Report DOE/EIA-0535(94)-annual. Energy Information Administration, U.S. Department of Energy, Washington, DC.

FAA, 1994. *Fuel Cost and Consumption*, monthly reports, DAI-10, Federal Aviation Administration, U.S. Department of Transportation, Washington, DC.

ORNL, 1994. *Transportation Energy Data Book*, ORNL-6798, Edition 14, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Prepared for Office of Transportation Technologies, U.S. Department of Energy, Washington, DC.

Unmetered and Synthetic Natural Gas

EIA, 1994. *Natural Gas Annual: 1993*, DOE/EIA-O131(93)-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA, 1995. *Natural Gas Monthly*, DOE/EIA-0130(95)-monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC.

Additional Information

Rypinski, 1994. Memorandum from Arthur Rypinski of the Energy Information Administration to Bill Hohenstein of U.S. EPA regarding "Unpublished Data for Inventory," July 27, 1994.

Carbon Content Coefficients and Thermal Conversion Factors

IPCC/OECD/IEA, 1995. *IPCC Guidelines for National Greenhouse Gas Inventories*, 3 volumes: Vol. 1, Reporting Instructions; Vol. 2, Workbook; Vol. 3, Reference Manual. United Nations Environment Programme, Intergovernmental Panel on Climate Change, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

EIA, 1995. *Draft Emissions of Greenhouse Gases In the United States 1989 - 1994*, DOE/EIA-0573-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC. In Press.

EIA, 1995. *State Energy Data Report 1993*, DOE/EIA-0214(93)-annual, Energy Information Administration, U.S. Department of Energy, Washington, DC.

Percents Sequestered

IPCC/OECD/IEA, 1995. *IPCC Guidelines for National Greenhouse Gas Inventories*, 3 volumes: Vol. 1, Reporting Instructions; Vol. 2, Workbook; Vol. 3, Reference Manual. United Nations Environment Programme, Intergovernmental Panel on Climate Change, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Rypinski, 1994. Memorandum from Arthur Rypinski of the Energy Information Administration to Bill Hohenstein of U.S. EPA regarding "Unpublished Data for Inventory," July 27, 1994.

Marland, G. and A. Pippin, 1990. "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, 14(4):323.

Fraction Oxidized

IPCC/OECD/IEA, 1995. *IPCC Guidelines for National Greenhouse Gas Inventories*, 3 volumes: Vol. 1, Reporting Instructions; Vol. 2, Workbook; Vol. 3, Reference Manual. United Nations Environment Programme, Intergovernmental Panel on Climate Change, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Bechtel, 1993. *A Modified EPRI Class II Estimate for Low NO_x Burner Technology Retrofit*, Prepared for Radian Corporation by Bechtel Power, Gaithersburg, Maryland. April, 1993.

Table A-1: Emission Calculations For Energy Combustion: 1994

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)
Fuel	Consumption (TBtu)							Carbon Content Coefficient (MMTCE/QBtu)	Carbon Content (MMTCE)							Adjustments (MMTCE)			Net Carbon Content (MMTCE)						Fraction Oxidized	Emissions (MMTCE)						Total Emission
	Res	Comm	Ind	Trans	Utility	U.S. Territories	Total Cons		Res	Comm	Ind	Trans	Utility	U.S. Terr	Total Content	Carbon Content of Bunker Fuels	Carbon Stored Ind	Carbon Stored Trans	Res	Comm	Ind	Trans	Utility	U.S. Terr		Res	Comm	Ind	Trans	Utility	U.S. Terr	
Residential Coal	58.9						58.9	25.97	1.5						1.5				1.5						0.99	1.5						1.5
Commercial Coal		85.0					85.0	25.97		2.2					2.2					2.2					0.99		2.2					2.2
Industrial Coking Coal			850.6				850.6	25.51			21.7				21.7		0.4				21.3				0.99			21.1				21.1
Industrial Other Coal			1,588.8				1,588.8	25.61			41.4				41.4						41.4				0.99			41.0				41.0
Coke Imports			23.6				23.6	27.85			0.7				0.7						0.7				0.99			0.7				0.7
Transportation Coal				0.0			0.0	NC				0.0			0.0							0.0			0.99				0.0			0.0
Utility Coal					16,910.1		16,910.1	25.71					434.8		434.8								434.8		0.99					430.4		430.4
US Territory Coal (bit)						7.7	7.7	25.14						0.2	0.2									0.2	0.99						0.2	0.2
Total Coal	58.9	85.0	2,461.0	0.0	16,910.1	7.7	19,520.9		1.5	2.2	63.6	0.0	434.8	0.2	502.4	0.0	0.4	0.0	1.5	2.2	63.4	0.0	434.8	0.2		1.5	2.2	62.8	0.0	430.4	0.2	497.0
Natural Gas	5,088.0	3,070.4	9,688.2	865.4	3,099.8	NA	21,809.7	14.47	73.6	44.4	140.2	9.8	44.8	NA	312.7		3.9		73.6	44.4	136.3	9.8	44.8	NA	0.995	73.2	44.2	135.6	9.6	44.6	NA	307.2
Asphalt & Road Oil	0.0	0.0	1,172.9	0.0	0.0		1,172.9	20.62	0.0	0.0	24.2	0.0	0.0		24.2		24.1		0.0	0.0	0.1	0.0	0.0		0.99	0.0	0.0	0.1	0.0	0.0	0.0	0.1
Aviation Gasoline	0.0	0.0	0.0	38.1	0.0		38.1	18.87	0.0	0.0	0.0	0.7	0.0		0.7				0.0	0.0	0.0	0.7	0.0		0.99	0.0	0.0	0.0	0.7	0.0	0.0	0.7
Distillate Fuel Oil	949.9	481.6	1,128.9	4,067.7	95.2	78.7	6,802.0	19.95	19.0	9.6	22.5	81.2	1.9	1.6	135.7	2.1	[a]		19.0	9.6	22.5	79.1	1.9	1.6	0.99	18.8	9.5	22.3	78.3	1.9	1.6	132.3
Jet Fuel	0.0	0.0	0.0	3,154.5	0.0	62.1	3,216.6	19.34	0.0	0.0	0.0	61.0	0.0	1.2	62.2	5.6			0.0	0.0	0.0	55.4	0.0	1.2	0.99	0.0	0.0	0.0	54.9	0.0	1.2	56.1
Kerosene	74.8	13.8	12.9	0.0	0.0		101.3	19.72	1.5	0.3	0.3	0.0	0.0		2.0				1.5	0.3	0.3	0.0	0.0		0.99	1.5	0.3	0.3	0.0	0.0	0.0	2.0
LPG	435.2	76.6	1,961.3	20.7	0.0	9.9	2,503.6	17.02	7.4	1.3	33.4	0.4	0.0	0.2	42.6		23.5		7.4	1.3	9.9	0.4	0.0	0.2	0.99	7.3	1.3	9.8	0.3	0.0	0.2	18.9
Lubricants	0.0	0.0	180.9	170.8	0.0	0.0	351.7	20.24	0.0	0.0	3.7	3.5	0.0	0.0	7.1		1.8	1.7	0.0	0.0	1.8	1.7	0.0	0.0	0.99	0.0	0.0	1.8	1.7	0.0	0.0	3.5
Motor Gasoline	0.0	30.0	182.5	14,219.8	0.0	115.0	14,547.3	19.43	0.0	0.6	3.5	276.3	0.0	2.2	282.7				0.0	0.6	3.5	276.3	0.0	2.2	0.99	0.0	0.6	3.5	273.5	0.0	2.2	279.8
Residual Fuel	0.0	177.6	417.6	900.6	646.6	156.0	2,498.5	21.49	0.0	3.6	9.0	19.4	16.2	3.4	53.7	15.4	[a]		0.0	3.6	9.0	3.9	16.2	3.4	0.99	0.0	3.6	8.9	3.9	16.0	3.3	37.9
Other Petroleum						59.2	59.2	20.31						1.2	1.2						0.0	0.0		1.2	0.99	0.0	0.0	0.0	0.0	0.0	1.2	1.2
AvGas Blend Components			8.1				8.1	18.87			0.1				0.1						0.1	0.0			0.99	0.0	0.0	0.1	0.0	0.0	0.0	0.1
Crude Oil			18.7				18.7	20.21			0.4				0.4						0.4	0.0			0.99	0.0	0.0	0.4	0.0	0.0	0.0	0.4
MoGas Blend Components			0.0				0.0	19.41			0.0				0.0						0.0	0.0			0.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Misc. Products			105.9				105.9	20.31			2.1				2.1						2.1	0.0			0.99	0.0	0.0	2.1	0.0	0.0	0.0	2.1
Naphtha (<401 deg. F)			398.3				398.3	18.14			7.2				7.2						7.2	0.0			0.99	0.0	0.0	7.2	0.0	0.0	0.0	7.2
Other Oil (>401 deg. F)			838.6				838.6	19.95			16.7				16.7						16.7	0.0			0.99	0.0	0.0	16.6	0.0	0.0	0.0	16.6
Pentanes Plus			338.7				338.7	18.24			6.2				6.2						6.2	0.0			0.99	0.0	0.0	6.1	0.0	0.0	0.0	6.1
Petrochemical Feedstocks			0.0				0.0	19.37			0.0				0.0		19.2				-19.2	0.0			0.99	0.0	0.0	-19.0	0.0	0.0	0.0	-19.0
Petroleum Coke			793.0		26.3		819.4	27.85			22.1		0.7		22.8		0.0				22.1	0.0	0.7		0.99	0.0	0.0	21.9	0.0	0.7	0.0	22.6
Still Gas			1,439.4				1,439.4	17.51			25.2				25.2						25.2	0.0			0.99	0.0	0.0	25.0	0.0	0.0	0.0	25.0
Special Naphtha			81.1				81.1	19.86			1.6				1.6		0.0				1.6	0.0			0.99	0.0	0.0	1.6	0.0	0.0	0.0	1.6
Unfinished Oils			-279.2				-279.2	20.21			-5.6				-5.6						-5.6	0.0			0.99	0.0	0.0	-5.6	0.0	0.0	0.0	-5.6
Waxes			40.6				40.6	19.81			0.8				0.8						0.8	0.0			0.99	0.0	0.0	0.8	0.0	0.0	0.0	0.8
Other Wax & Misc.			0.0				0.0	19.81			0.0				0.0		4.3				-4.3	0.0			0.99	0.0	0.0	-4.2	0.0	0.0	0.0	-4.2
Total Petroleum	1,459.7	779.8	8,838.2	22,572.3	968.2	480.9	35,099.0		27.8	15.6	173.4	442.3	20.8	9.7	689.7	23.1	72.9	1.7	27.8	15.6	100.4	417.5	20.8	9.7		27.5	15.4	99.4	413.4	20.6	9.6	586.0
TOTAL (All Fuels)	6,602.5	3,935.3	20,987.4	23,237.6	20,977.1	488.6	76,229.5		102.9	62.2	377.3	452.0	500.4	9.9	1,504.8	23.1	77.2	1.7	102.9	62.2	300.1	427.2	500.4	9.9		102.2	61.8	297.8	422.9	495.6	9.6	1,390.3

Table A-2: Emissions From International Bunker Fuel Consumption: 1994

(1)	(2)	(3)	(4)	(5)	(6)
Fuel	Bunker Fuel Consumption (TBtu)	Carbon Content Coeffcient (MMTCE/QBtu)	Carbon Content (MMTCE)	Fraction Oxidized	Emissions (MMTCE)
Distillate Fuel	104	19.95	2	0.99	2
Jet Fuel	289	19.34	6	0.99	6
Residual Fuel	718	21.49	15	0.99	15
Total	*1,111*		*23.1*		*22.9*

Table A-3: Carbon Stored In Products: 1994

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Fuel	Non-Fuel Use (TBtu)		Carbon Content Coefficient (MMTCE/QBtu)	Carbon Content (MMTCE)		Fraction Sequestered	Carbon Stored (MMTCE)		
	Ind	Trans		Ind	Trans		Ind	Trans	Total
Industrial Coking Coal	20		25.51	0.5	0.0	0.75	0.4	0.0	0.4
Natural Gas	270		14.47	4	0	1.00	4	0	4
Asphalt & Road Oil	1,170		20.62	24	0	1.00	24	0	24
Distillate Fuel Oil	[a]		19.95	0	0	[a]	[a]	[a]	[a]
LPG	1,727		17.02	29	0	0.80	24	0	24
Lubricants	181	169	20.24	4	3	0.50	2	2	4
Residual Fuel	[a]		21.49	0	0	[a]	[a]	[a]	[a]
Naphtha (<401 deg. F)	[b]		18.14	0	0	[b]	[b]	[b]	[b]
Other Oil (>401 deg. F)	[b]		19.95	0	0	[b]	[b]	[b]	[b]
Petrochemical Feedstocks	1,239		19.37	24	0	0.80	19	0	19
Petroleum Coke	179		27.85	5	0	0.00	0	0	0
Special Naphtha	77		19.86	2	0	0.00	0	0	0
Other Wax & Misc.	215		19.81	4	0	1.00	4	0	4
Total	*4,788*	*169*		*92*	*3*		*77.2*	*1.7*	*78.9*

Notes:
[a] Non-fuel use values of distillate fuel and residual fuel are relatively small and included in the "Other Waxes and Misc." category.
[b] Non-fuel use values of Naphtha (<401 deg. F) and Other Oil (>401 deg. F) are reported in the "Petrochemical Feedstocks" category.

Table A-4: Summary Of U.S. Emissions By Sector And Gas: 1994

(1)	(2)	(3)	(4)	(5)	(6)
Sector	Coal (MMTCE)	Natural Gas (MMTCE)	Petroleum (MMTCE)	Total (MMTCE)	Total (MMTCO2)
Residential	1	73	28	102	375
Commercial	2	44	15	62	227
Industrial	63	136	99	298	1,092
Transportation	0	10	413	423	1,551
Utilities	430	45	21	496	1,817
U.S. Territories	0	NA	10	10	36
TOTAL	*497*	*307*	*586*	*1,390*	*5,098*
TOTAL (MMTCO2)	1,822	1,127	2,149		

Table A-5: Summary Of U.S. Emissions By End-Use Sector And Fuel: 1994

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Sector	% Elect. Consumption	Coal (MMTCE)	Natural Gas (MMTCE)	Petroleum (MMTCE)	Total (MMTCE)	Total (MMTCO2)
Residential	34.44%	149.7	88.6	34.6	272.9	1,000.7
Commercial	31.46%	137.6	58.2	21.9	217.7	798.3
Industrial	33.98%	209.0	150.8	106.4	466.2	1,709.5
Transportation	0.13%	0.6	9.6	413.4	423.6	1,553.2
U.S. Territories	0.00%	0.2	0.0	9.6	9.8	36.0
Total Emissions		*497.0*	*307.2*	*586.0*	*1,390.3*	*5,097.7*
TOTAL (MMTCO2)		1,822.5	1,126.5	2,148.7		

Table A-6a: Key Assumptions for Estimating Carbon Dioxide Emissions

Fuel	Carbon Content Coefficient (MMTCE/QBtu)	Fraction Oxidized	Fraction Sequestered
Residential Coal	[a]	0.99	-
Commercial Coal	[a]	0.99	-
Industrial Coking Coal	[a]	0.99	0.75
Industrial Other Coal	[a]	0.99	-
Coke Imports	27.85	0.99	-
Transportation Coal	NC	0.99	-
Utility Coal	[a]	0.99	-
U.S. Territory Coal (bit)	25.14	0.99	-
Natural Gas	14.47	0.995	1.00[d]
Asphalt & Road Oil	20.62	0.99	1.00
Aviation Gasoline	18.87	0.99	-
Distillate Fuel Oil	19.95	0.99	[b]
Jet Fuel	[a]	0.99	-
Kerosene	19.72	0.99	-
LPG	[a]	0.99	0.80
Lubricants	20.24	0.99	0.50
Motor Gasoline	[a]	0.99	-
Residual Fuel	21.49	0.99	[b]
Other Petroleum			
AvGas Blend Components	18.87	0.99	-
Crude Oil	[a]	0.99	-
MoGas Blend Components	19.41	0.99	-
Misc. Products	20.31	0.99	[b]
Naphtha (<401 deg. F)	18.14	0.99	[c]
Other Oil (>401 deg. F)	19.95	0.99	[c]
Pentanes Plus	18.24	0.99	-
Petrochemical Feedstocks	19.37	0.99	0.80
Petroleum Coke	27.85	0.99	0.00
Still Gas	17.51	0.99	-
Special Naphtha	19.86	0.99	0.00
Unfinished Oils	20.21	0.99	-
Waxes	19.81	0.99	[b]
Other Wax & Misc.	19.81	0.99	1.00

Sources: Carbon Coefficients from EIA (1995a). Stored Carbon from Marland and Pippen (1990) and Rypinski (1994). Combustion efficiency for coal from Bechtel (1993) and for oil and gas from IPCC (IPCC/OECD/IEA, 1995).

Notes: NC = Not Calculated

[a] =These coefficients vary annually due to fluxuations in fuel quality. See Table A-6b for more information.

[b] = Non-fuel use values of distillate fuel, miscellaneous products, residual fuel, and waxes are reported in aggregate in the "Other Waxes & Misc." category.

[c] = Non-fuel use values of Naphtha (<401 deg. F) and Other Oil (>401 deg. F) are reported in aggregate in the "Petrochemical Feedstocks" category.

[d] = There are two major non-fuel uses of natural gas: 1. ammonia production in nitrogenous fertilizer manufacture; and 2. chemical feedstocks. It is assumed that 100 percent of the carbon in natural gas used as a chemical feedstock is sequestered, while the carbon in that used for ammonia production is oxidized quickly.

Table A-6b: Variation in Carbon Content Coefficients by Year (MMTCE / QBtu)

Fuel Type	1990	1991	1992	1993	1994
Residential Coal	25.92	26.00	26.13	25.97	25.97
Commercial Coal	25.92	26.00	26.13	25.97	25.97
Industrial Coking Coal	25.51	25.51	25.51	25.51	25.51
Industrial Other Coal	25.58	25.60	25.62	25.61	25.61
Utility Coal	25.68	25.69	25.69	25.71	25.71
LPG	17.00	16.99	17.00	16.98	17.02
Motor Gasoline	19.41	19.41	19.42	19.43	19.43
Jet Fuel	19.40	19.40	19.39	19.37	19.34
Crude Oil	20.16	20.18	20.22	20.23	20.21

Sources: Carbon Coefficients from EIA (1995a).

ANNEX B
EMISSIONS FROM MOBILE COMBUSTION

Greenhouse gas emissions from mobile sources are reported by transport mode (*i.e.*, road, rail, air), vehicle type, and fuel type. The emissions estimates for NO_x, NMVOCs, and CO (U.S. criteria pollutants) were taken directly from the U.S. EPA's *Draft National Air Pollutant Emissions Trends, 1900 - 1994* (U.S. EPA, 1995b). This EPA report provides emission estimates for these gases by sector and fuel type using a "top down" estimating procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions.

Estimates for CH_4 and N_2O emissions from mobile combustion were calculated by multiplying the appropriate emission factors provided in IPCC/OECD/IEA (1995) by measures of activity for each source category. National activity data for the source categories were obtained from a number of U.S. government agency publications. Depending on the category, these basic activity data included such information as fuel consumption, fuel deliveries, or vehicle miles traveled (VMT).

Estimates of NMVOCs, NO_x, and CO Emissions From Mobile Combustion

Estimates of NMVOCs, NO_x, and CO emissions from gasoline and diesel-powered highway vehicles are reported by U.S. EPA (1995b) and based on annual VMT and distance based emission factors. The annual VMT data was obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as noted in U.S. EPA (1995b). The emission factors were calculated using MOBILE5a, a model used by U.S. EPA to estimate exhaust and running loss emissions from highway vehicles. The MOBILE5a model uses information on ambient temperature, vehicle speeds, national vehicle registration distributions, gasoline volatility, and other variables in order to produce these factors (U.S. EPA, 1995b).

Emissions of NMVOCs, NO_x, and CO from aircraft, marine vessels, railroads, and other non-highway vehicles are also reported by U.S. EPA (1995b). These values were grown from emissions calculated in the 1985 National Acid Precipitation Assessment Program (NAPAP) Inventory, based on E-GAS growth factors obtained by Bureau of Labor Statistics codes (U.S. EPA, 1995b).

Estimates of CH_4 and N_2O Emissions From Mobile Combustion

Since EPA does not systematically track emissions of CH_4 and N_2O, estimates of these gases were determined using a methodology conceptually similar to that outlined by the IPCC in which activity data for each source category was multiplied by the appropriate emission factors provided in the *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA, 1995). The emission factors were derived in part from data used in MOBILE4, a somewhat earlier version of EPA's MOBILE5a mobile source emissions model, while activity data was derived from information provided by various government agencies as noted below.

The 1990 activity data for highway vehicles entailed estimates of VMT by vehicle type and control technology obtained from U.S. EPA's National Vehicle and Fuel Emissions Laboratory (Brezinski, et al., 1992; Carlson, 1994; Nizich, 1994; U.S. DOT, 1994; and U.S. EPA, 1995b). For 1991 through 1994, aggregate VMT data were used to adjust the 1990 emissions estimates (Nizich, 1995 and U.S. EPA, 1995b). Activity data for gasoline highway vehicles are presented in Table B-1, while the breakdown by control technology (assumed roughly constant for the period 1990 to 1994) is presented in Table B-2. Given the uncertainty underlying these estimates, an arbitrary uncertainty range of ± 50 percent was assigned to the resulting emission totals, which are presented in Part I.

Because the travel fraction and control technology data for diesel highway vehicles and motorcycles were not available from U.S. EPA, emissions estimates for these vehicle types were conducted in a slightly different manner than gasoline highway vehicles. Rather than determining a point estimate, they were calculated as a range of values by multiplying the total VMT by the high (uncontrolled) and low (advanced) emission factors provided for each category (IPCC/OECD/IEA, 1995). The emission estimates reported in the inventory for diesel vehicles and motorcycles are the midpoint of these ranges. The data used are included in Table B-3.

Activity data for off-highway vehicles generally took the form of annual fuel consumption broken down by transportation mode and fuel type. Consumption of distillate (diesel) and residual fuel oil by marine bunkers, boats, construction equipment, farm equipment, and locomotives, as well as coal consumption by locomotives, was obtained from EIA (1994e and 1995e). Aircraft consumption of jet fuel and aviation gasoline was obtained from FAA (1995 and 1994). Consumption of motor gasoline by boats, construction equipment, farm equipment, and locomotives was drawn from FHWA (1994). The activity data used for off-highway vehicles are included in Table B-4.

Table B-1 . Vehicle Miles Traveled for Gasoline Highway Vehicles (10^9 Miles)

Year	Passenger Cars	Light Duty Vehicles	Heavy Duty Vehicles
1990	1492.6	462.3	43.3
1991	1512.7	468.9	43.6
1992	1574.6	472.9	43.4
1993	1602.3	493.2	46.0
1994	1636.4	504.1	47.1

Source: VMT data are the same as those used in U.S. EPA (1995b) as reported by Nizich (1995).

Table B-2 . Control Technology Breakdown for Gasoline Highway Vehicles (percent of total vehicles)

Data Category	Passenger Cars	Light Duty Trucks 1	Light Duty Trucks 2	Heavy Duty Vehicles
3-Way Catalyst	45%	36%	30%	6%
Oxi-3-Way Catalyst	32%	17%	15%	0%
Oxi-Catalyst	18%	14%	14%	9%
Non-Catalyst	2%	2%	3%	35%
Uncontrolled	4%	31%	39%	50%

Source: Distribution of control technologies are calculated from U.S. EPA data (Brezinski, 1992).

Table B-3. Vehicle Miles Traveled for Diesel Highway Vehicles and Motorcycles (10^6 Miles)

Year	Diesel	Light Duty	Heavy Duty	Motorcycles
1990	20.60	3.80	112.2	9.57
1991	20.90	3.80	112.90	9.20
1992	21.70	3.90	1115.00	9.55
1993	22.09	4.08	119.61	9.89
1994	22.56	4.18	122.77	10.12

Source: VMT data are the same as those used in U.S. EPA (1995b) as reported by Nizich (1995).

Table B-4. Activity Data for Non-Highway Vehicles

Fuel Category	Fuel Quantity (U.S. gallons unless otherwise noted)			
	Residual	Diesel	Jet Fuel	Other
Aircraft [a]				
1990	NA	NA	12,986,111,661	353,100,000
1991	NA	NA	11,995,880,426	353,600,000
1992	NA	NA	12,279,912,686	314,000,000
1993	NA	NA	12,326,549,428	268,400,000
1994	NA	NA	12,838,425,825	268,400,000
Marine Bunkers				
1990	4,686,071,250	549,251,000	NA	NA
1991	5,089,541,250	541,910,000	NA	NA
1992	5,399,308,500	560,042,500	NA	NA
1993	4,702,411,500	510,936,250	NA	NA
1994	4,702,411,500	510,936,250	NA	NA
Boats [b]				
1990	1,562,023,750	1,647,753,000	NA	1,300,400,000
1991	1,696,513,750	1,625,730,000	NA	1,709,700,000
1992	1,799,769,500	1,680,127,500	NA	1,316,170,000
1993	1,567,470,500	1,532,808,750	NA	873,687,000
1994	1,567,470,500	1,532,808,750	NA	873,687,000
Construction Equip. [c]				
1990	NA	2,508,300,000	NA	1,523,600,000
1991	NA	2,447,400,000	NA	1,384,900,000
1992	NA	2,287,642,000	NA	1,492,200,000
1993	NA	2,323,183,000	NA	1,464,599,000
1994	NA	2,323,183,000	NA	1,464,599,000
Farm Equip.				
1990	NA	3,164,200,000	NA	812,800,000
1991	NA	3,144,200,000	NA	776,200,000
1992	NA	3,274,811,000	NA	805,500,000
1993	NA	3,077,122,000	NA	845,320,000
1994	NA	3,077,122,000	NA	845,320,000
Locomotives [d]				
1990	25,422	3,210,111,000	NA	28,000
1991	6,845	3,026,292,000	NA	17,000
1992	8,343	3,217,231,000	NA	42,000
1993	4,065	2,906,998,000	NA	18,000
1994	4,065	2,906,998,000	NA	42,000

"NA" denotes not applicable.

Sources: FWHA, 1994; EIA, 1994e; EIA, 1995e; FAA, 1994, and FAA, 1995.

Notes: [a] Other Fuel = Aviation Gasoline.
[b] Other Fuel = Motor Gasoline
[c] Construction Equipment includes snowmobiles. Other Fuel = Motor Gasoline
[d] Other Fuel = Coal (in short tons)

ANNEX C
EMISSIONS OF HFCs, PFCs AND SF_6

This annex describes the assumptions and methodologies behind the United States emissions calculations of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) from 1990 to 1994. The spreadsheets used to generate the emissions figures follow the descriptions.

HFCs:

- HFC-23 emissions were assumed to equal three percent of HCFC-22 production. U.S. HCFC-22 production (Kozel, 1995) was as follows:

  - 1990 138,823 metric tonnes
  - 1991 142,641
  - 1992 149,526
  - 1993 132,165
  - 1994 139,444 (preliminary)

- Emissions of HFC-125, HFC-134a, HFC-152a, and HFC-227 were taken from the latest available information in the U.S. EPA's Vintaging Framework computer model. Values for HFC-125 and HFC-227 prior to 1994 were not available because these chemicals were not assumed to enter the market as substitutes until 1994.

PFCs:

- CF_4 and C_2F_6 emissions are primarily by-products of aluminum production. The respective emission factor ranges were estimated to be 0.01 to 1.2 kg CF_4 per metric tonne of aluminum produced and 0.001 to 0.12 kg C_2F_6 per metric tonne of aluminum produced (Jacobs, 1994). For this analysis, estimates were provided for the low, high and average emission factors for each chemical. U.S. aluminum production (Bureau of Mines, 1995e) was as follows:

  - 1990 4.048 million metric tonnes
  - 1991 4.121
  - 1992 4.042
  - 1993 3.695
  - 1994 3.299

SF_6:

- U.S. production of SF_6 was estimated to be 6,000,000 lbs annually for the period 1990 to 1994 (Wagner, 1994). U.S. production was assumed to equal U.S. consumption, *i.e.*, no imports or exports. Eighty percent of SF_6 consumption was assumed to be used in heavy electrical equipment, while the remaining 20 percent was assumed to be used in metal industries, *e.g.*, aluminum degassing, magnesium casting (Wagner, 1994). Emissions from electrical equipment were set at 1 percent of existing stock annually (Norwegian Institute for Air Research (NIAR), 1993). While leakage rates may be higher for older equipment, the 1 percent rate has been assumed for all equipment at this time. EPA is currently conducting additional research on this matter; estimates will be updated as new information becomes available. All SF_6 used in the metal industries was assumed to be emitted in the year of production. This assumption, too, may change as further research is conducted. Use of SF_6 in electrical equipment was assumed to begin in 1973 (NIAR, 1993). The GWP of 24,900 corresponds to a 100 year time horizon.

Emissions of HFCs and PFCs in the U.S. - 1990 through 1994

(Million Metric Tonnes)

Compound	GWP	1990		1991		1992		1993		1994	
		Molecular Basis	Carbon-Equivalent	Molecular Basis	Carbon-Equivalent	Molecular Basis	Carbon-Equivalent	Molecular Basis	Carbon-Equivalent	Molecular Basis	Carbon-Equivalent
HFCs											
HFC-23	12,100	0.00416	13.74	0.00428	14.12	0.00449	14.80	0.00396	13.08	0.00418	13.80
HFC-125	3,200	0.00000	0.00	0.00000	0.00	0.00000	0.00	0.00000	0.00	0.00113	0.99
HFC-134a	1,300	0.00000	0.00	0.00000	0.00	0.00347	1.23	0.00592	2.10	0.01041	3.69
HFC-152a	140	0.00017	0.01	0.00018	0.01	0.00103	0.04	0.00104	0.04	0.00153	0.06
HFC-227	3,300	0.00000	0.00	0.00000	0.00	0.00000	0.00	0.00000	0.00	0.00089	0.80
PFCs											
CF4 (Low)	6,300	0.00004	0.07	0.00004	0.07	0.00004	0.07	0.00004	0.06	0.00003	0.06
CF4 (High)	6,300	0.00486	8.35	0.00495	8.50	0.00485	8.33	0.00443	7.62	0.00396	6.80
C2F6 (Low)	12,500	0.000004	0.01	0.000004	0.01	0.000004	0.01	0.000004	0.01	0.000003	0.01
C2F6 (High)	12,500	0.000486	1.66	0.000495	1.69	0.000485	1.65	0.000443	1.51	0.000396	1.35
CF4 (Average)	6,300	0.00245	4.21	0.00249	4.28	0.00245	4.20	0.00224	3.84	0.00200	3.43
C2F6 (Average)	12,500	0.00024	0.83	0.00025	0.85	0.00024	0.83	0.00022	0.76	0.00020	0.68

Year	Aluminum Production (MMTs)	CF4 Emissions	C2F6 Emissions	
1990	4.048	4.048E-05	4.048E-06	(Low estimate)
		0.0048576	0.00048576	(High estimate)
1991	4.121	4.121E-05	4.121E-06	(Low estimate)
		0.0049452	0.00049452	(High estimate)
1992	4.042	4.042E-05	4.042E-06	(Low estimate)
		0.0048504	0.00048504	(High estimate)
1993	3.695	3.695E-05	3.695E-06	(Low estimate)
		0.004434	0.0004434	(High estimate)
1994	3.299	3.299E-05	3.299E-06	(Low estimate)
		0.0039588	0.00039588	(High estimate)

CF4 Emission Factor (kg PFC/kg Al)	Low:	1E-05	C2F6 Emission Factor (kg PFC/kg Al)	Low: 1E-06
	High:	0.0012		High: 0.00012

Note:

–Emissions factors divided by 1000 so that the units accord (i.e., kg PFC/kg aluminum).

HCFC-22 Production (in metric tonnes)

Percent of HCFC-22 production emitted as HFC-23: **3.0%**

Year	HCFC-22		HFC-23	GWP	Carbon-Equivalent
1990	138,823		0.00416	12,100	13.74
1991	142,641		0.00428	12,100	14.12
1992	149,526		0.00449	12,100	14.80
1993	132,165		0.00396	12,100	13.08
1994	139,444	Note: 1994 number is preliminary	0.00418	12,100	13.80

Emissions of Sulfur Hexafluoride (SF6) in the U.S. - 1990 through 1994

(Million Metric Tonnes)

1990			1991			1992			1993			1994		
Emissions	GWP	Carbon-Equivalent	Emissions	GWP	Carbon-Equivalent	Emissions	GWP	Carbon-Equivalent	Emissions	GWP	Carbon-Equivalent	Emissions	GWP	Carbon-Equivalent
0.00094	24,900	6.37	0.00096	24,900	6.52	0.00098	24,900	6.67	0.00100	24,900	6.82	0.00103	24,900	6.96

Total U.S. annual production:	6,000,000	pounds
Percent used in electrical equipment:	80%	
Percent used in metal industries:	20%	
Average lifetime of electrical equipment:	30	years
Average annual leakage rate from equipment:	1%	

ANNEX D
ESTIMATION OF METHANE EMISSIONS FROM ENTERIC FERMENTATION IN CATTLE AND FROM ANIMAL MANURE MANAGEMENT

This annex presents a detailed explanation of the methodologies and data used to estimate methane emissions from enteric fermentation in cattle and from animal manure management. This information is provided in order to enable the reader to verify the emission estimates presented in Part 4 of the inventory. Emissions estimates are based on the analysis presented in U.S. EPA (1993a). Information from U.S. EPA (1993a and 1994b) is included in this annex to serve as a reference point for the updated emissions estimates presented in this report.

Methane Emissions From Enteric Fermentation in Cattle

To estimate methane emissions from enteric fermentation in cattle, detailed analyses of rumen digestion and animal production were performed using a mechanistic model of cattle digestion. This model, originally described in Baldwin *et al.* (1987), explicitly models the fermentation of feed within the rumen, and estimates the amount of methane formed and emitted as a result. Since the original model of Baldwin *et al.* was developed for application to lactating cows, it was revised to enable evaluations of a wider range of animal types, sizes, and stages of maturity, as well as a wider range of diets.

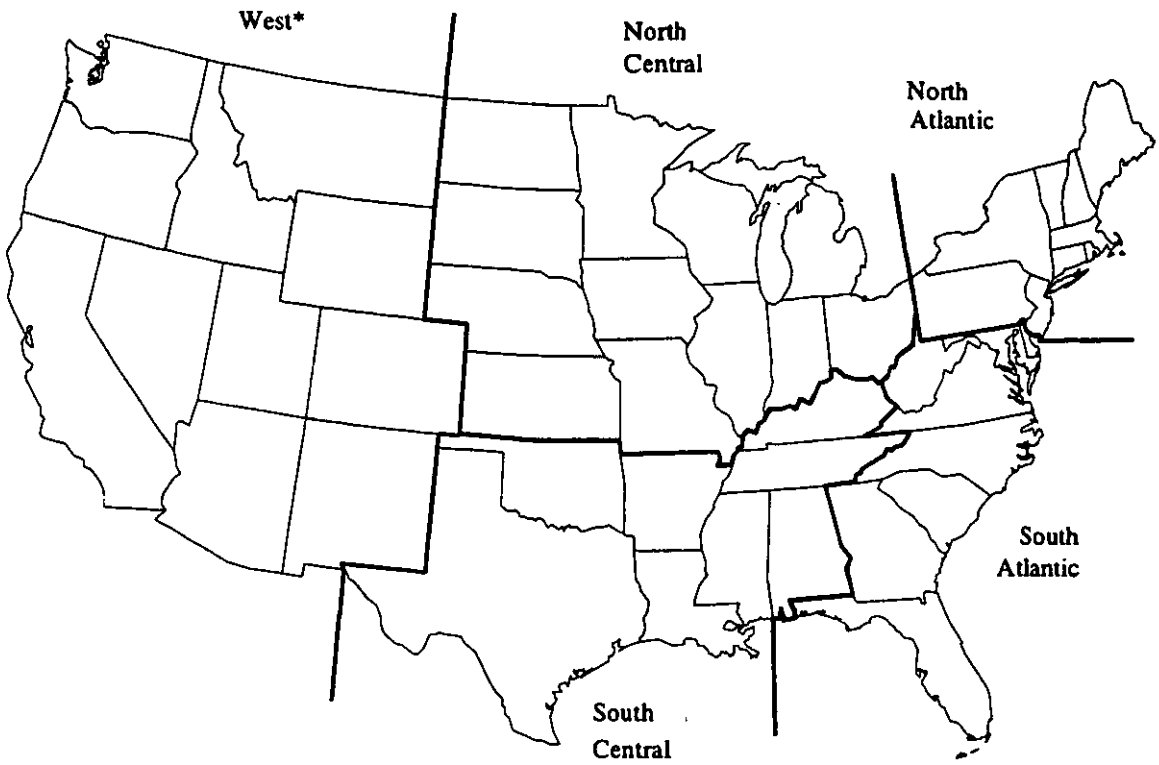
To apply the model, representative cattle types and diets for five geographic regions of the U.S. were defined. The cattle type categories represent the different sizes, ages, feeding systems, and management systems that are typically found in the U.S. Representative diets were defined for each category of cattle, reflecting the diversity of diets that are found in each of the five regions (Figure D-1). Each cattle type within each region was evaluated using the model, resulting in emission factors (kilograms CH_4/head/year) for each type in each region.

The following animal types were defined for the cattle population:

Dairy Animal Types
- Replacement heifers 0-12 months of age[1]
- Replacement heifers 12-24 months of age
- Mature dairy cows (over 24 months of age)

[1] "Replacements" are the offspring that are retained to replace mature cows that die or are removed from the herd (culled) each year.

Figure D-1: Geographic Regions Used in the Analysis



* Includes Alaska and Hawaii

Source: U.S. EPA (1993a)

Beef Animal Types

- Replacement heifers 0-12 months of age
- Replacement heifers 12-24 months of age
- Mature beef cows (over 24 months of age)
- Weanling system heifers and steers[2]
- Yearling system heifers and steers[3]
- Mature bulls

[2] In "weanling systems", calves are moved directly from weaning to confined feeding programs. This system represents a very fast movement of cattle through to marketing for slaughter. Weanling system cattle are marketed at about 420 days of age (14 months).

[3] "Yearling systems" represent a relatively slow movement of cattle through to marketing for slaughter. These systems include a wintering over, followed by a summer of grazing on pasture. Yearling system cattle are marketed at 565 days of age (18.8 months).

Due to their small number, mature dairy bulls were not evaluated. Dairy calves that are not kept as replacements are generally fed for slaughter. Therefore, these animals were included in the total for weanling and yearling system heifers and steers (*i.e.*, heifers and steers grown for slaughter). Tables D-1 and D-2 summarize the size, age, and production characteristics used to simulate each of the representative animal types.

A total of 32 different diets were defined to represent the diverse feeds and forages consumed by cattle in the U.S. Fourteen diets were defined for dairy cattle: six for dairy cows and four each for replacement heifers 0-12 months and 12-24 months. Eighteen diets were defined for beef cattle: three each for beef cows, replacements 0-12 months, weanling system heifers and steers, and yearling system heifers and steers; four for replacements 12-24 months; and two for beef bulls.

Table D-1. Representative Animal Characteristics: Heifers and Cattle Fed for Slaughter

Animal Type	Initial Weight (kg)[a]	Final Weight (kg)	Initial Age (days)	Final Age (days)	Other
Replacement Heifers					
Dairy Replacement Heifers: 0-12 months	170	285	165	365	--
Dairy Replacement Heifers: 12-24 months	285	460	365	730	Pregnant
Beef Replacement Heifers: 0-12 months	165	270	165	365	--
Beef Replacement Heifers: 12-24 months	270	390	365	730	Pregnant
Feedlot Fed Cattle for Slaughter					
Yearling System[b]	170	480	165	565	fed to 26-27% carcass fat
Weanling System[c]	170	480	165	422	fed to 29-30% carcass fat

[a] All weights reported as empty body weight.
[b] Includes 260 day stocker period principally on forages and a 140 day feedlot period with a high grain ration.
[c] Includes a 257 day feeding period, initially at 30 to 50 percent concentrate (125 days), followed by 132 days of a high grain ration.

Source: U.S. EPA (1993a)

Table D-2. Representative Animal Characteristics: Dairy Cows and Beef Cows

Animal Type	Initial and Final Weight (kg)[a]	Lactation/Dry Periods (days)	Milk Production/ Lactation (kg)	Other
Dairy Cows	550	305/60	5,570-7,190[b]	Pregnant
Beef Cows	450	205/160	1,400	Pregnant
Beef Bulls	650	NA	NA	NA

[a] All weights reported as empty body weight.
[b] Milk production per lactation varies by region.

Source: U.S. EPA (1993a)

Table D-3. Dairy Cow Diet Descriptions

	Lactating Cow Diets					
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Diet 6
Description	50% alfalfa hay, 50% corn-SBM[a] concen-trate	60% alfalfa hay, 40% corn-cotton-seed meal concen-trate (15% CP)[b]	69% corn silage, 16% corn meal, 14% SBM	50% alfalfa hay, 50% barley-SBM concentrate	40% timothy hay, 45% corn meal, 15% SBM- cane mo-lasses concen-trate	Early timothy hay supple-mented to 14.5% CP
ME (Mcal/kg)	2.61	2.56	2.65	2.57	2.69	2.41
Regional Distribution of Diets[c]						
North Atlantic	33%		33%		33%	
South Atlantic	40%				30%	30%
North Central	50%		50%			
South Central		33%			33%	33%
West		75%		25%		

[a] SBM = soybean meal
[b] CP = crude protein
[c] Regional distributions show the extent to which each diet is simulated to be used in each region. The percentages for each region sum to 100 percent.

Source: U.S. EPA (1993a)

To derive emission factors for each of the cattle types in each region, the extent to which each diet is used in each region was specified for each cattle type. For example, in the North Atlantic region, it was estimated that one third of the mature dairy cows are fed Dairy Cow Diet 1, one third Dairy Cow Diet 3, and one third Dairy Cow Diet 5 (Table D-3). The specification of the regional diet mixes was based on comments from cattle experts in different regions throughout the U.S. and on data on regional feed availability.

Estimates of methane emissions from enteric fermentation presented in this report and in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993* (U.S. EPA 1994b) are derived using the methodology developed in EPA 1993a, however emissions estimates discussed in this report are based on revised dairy cow emission factors and animal population data. To provide a reference point for the updated emissions estimates, a discussion of previous emission estimates is provided in Box D-1.

To update emission estimates for 1990 through 1993, and to calculate 1994 emissions, the "national" emissions factors developed in the EPA report were multiplied by the applicable "national" animal populations and the resulting emissions by animal type were summed across animal types to estimate total annual methane emissions. The above method was adopted for all animal types except dairy cows. For dairy cows, regional emissions factors were developed to reflect increasing milk production per cow. The regional emissions factors were applied to the regional animal populations to estimate total dairy cow emissions. Regional emission factors and updated estimates of emissions from dairy cows for 1990 through 1994 are presented in Table D-4.

Unlike the EPA report, the update does not account for regional shifts in animal populations (except dairy cows). Dairy cow populations for the 5 regions defined in the EPA report were used to determine total emissions from dairy cows. The data reflects a shift in dairy cows away from North Central and toward the West. Since the publication of U.S. EPA 1994b, USDA has revised all animal population data for 1990 to 1994. The emissions estimates for 1990 to 1994 presented in Part 4 of this report reflect these revisions.

Box D-1: Reference Point for Updated Emission Estimates

While estimates of emissions from enteric fermentation discussed in this report are based on revised dairy cow emission factors and more recent animal population data, emissions estimates and relevant statistics presented in U.S. EPA 1994b serve as a valuable reference point for the analysis of updated emissions estimates.

Emissions estimates in U.S. EPA 1994b were calculated using the methodology developed in EPA (1993a). The regional emission factors for mature dairy cows were estimated by applying the cattle digestion model to the average diet and the average annual milk production per head in each region (Table D-5). For the other dairy cattle types and all of the beef cattle types, emission factors were simulated for each of the defined diet types, and then using the diet percentages assigned for each region, weighted average emission factors were calculated for each animal type in each region. The statistics used in these simulations, and the resultant regional emission factors are summarized in Tables D-6 through D-12.

To estimate national emissions for each cattle type, the regional emission factors were multiplied by regional populations of each type (Tables D-13 and D-14). For all but the feedlot cattle, the average 1990 regional populations were taken from published statistics (Schoeff and Castaldo, 1991; USDA, 1992a). Emission factors for the feedlot fed cattle (*i.e.*, for yearling system and weanling system cattle) are based on the entire model simulation period, which is greater than 365 days for both systems. Therefore, the yearling system and weanling system cattle populations were derived from 1990 slaughter statistics (USDA, 1992b; CF Resources, 1991). National emissions from the entire cattle population were estimated by summing the emission estimates for all cattle types.

Table D-4. Dairy Cow Data and Estimates[a]: By Region and US Total

Region: U.S. Total	1990	1991	1992	1993	1994
Milk Prod (10^6 lbs):	147,722	147,695	150,884	150,594	153,622
Population (000's):	10,007	9,883	9,714	9,679	9,614
Prodn./Cow (lbs/yr):	14,761	14,945	5,532	15,559	15,979
Prodn./Cow (kg/day):	18.34	18.57	19.30	9.34	19.86
Emissions Factor:	114.8	115.7	118.3	118.5	120.4
Total Emissions(Tg):	**1.15**	**1.14**	**1.15**	**1.15**	**1.16**
Region: North Atlantic	**1990**	**1991**	**1992**	**1993**	**1994**
Milk Prod (10^6 lbs):	5,727	26,060	26,819	26,504	26,410
Population(000's):	1,775	1,729	1,716	1,704	1,692
Prodn./Cow (lbs/yr):	14,493	15,072	15,630	15,553	15,605
Prodn./Cow (kg/day):	18.01	18.73	19.42	19.33	19.39
Emissions Factor:	116.2	118.8	121.3	121.0	121.2
Total Emissions(Tg):	**0.206**	**0.205**	**0.208**	**0.206**	**0.205**
Region: South Atlantic	**1990**	**1991**	**1992**	**1993**	**1994**
Milk Prod (10^6 lbs):	9,705	9,752	9,957	9,826	9,758
Population (000's):	708	702	682	674	659
Prodn./Cow (lbs/yr):	13,698	13,889	14,599	14,569	14,810
Prodn./Cow (kg/day):	7.02	17.26	18.14	18.10	18.40
Emissions Factor:	127.7	128.7	132.3	132.2	133.4
Total Emissions (Tg):	**0.090**	**0.090**	**0.090**	**0.089**	**0.088**
Region: North Central	**1990**	**1991**	**1992**	**1993**	**1994**
Milk Prod (10^6 lbs):	61,605	60,570	60,722	59,036	57,980
Population (000's):	4,412	,284	4,148	4,041	3,913
Prodn./Cow (lbs/yr):	13,964	14,138	14,639	14,610	14,817
Prodn./Cow (kg/day):	17.35	17.57	18.19	18.16	18.41
Emissions Factor:	104.8	105.6	107.7	107.6	108.4
Total Emissions (Tg):	**0.462**	**0.452**	**0.447**	**0.435**	**0.424**
Region: South Central	**1990**	**1991**	**1992**	**1993**	**1994**
Milk Prod (10^6 lbs):	14,081	13,800	13,945	14,207	14,370
Population (000's):	1,121	1,101	1,081	1,078	1,082
Prodn./Cow (lbs/yr):	12,559	12,537	12,895	13,175	13,285
Prodn./Cow (kg/day):	15.61	15.58	16.02	16.37	16.51
Emissions Factor:	116.2	116.1	117.8	119.2	119.8
Total Emissions (Tg):	**0.130**	**0.128**	**0.127**	**0.129**	**0.130**
Region: West	**1990**	**1991**	**1992**	**1993**	**1994**
Milk Prod (10^6 lbs):	36,604	37,513	39,441	41,021	45,104
Population (000's):	1,991	2,067	2,087	2,181	2,268
Prodn./Cow (lbs/yr):	18,385	18,150	18,900	18,805	19,887
Prodn./Cow (kg/day):	22.85	22.56	23.49	23.37	24.71
Emissions Factor:	130.5	129.4	132.7	132.3	137.1
Total Emissions (Tg):	**0.260**	**0.267**	**0.277**	**0.289**	**0.311**

[a] Dairy milk production data for 1990-1994 from: USDA Economic Research Service, Dairy Outlook, February 27, 1995; Dairy cow population data from NASS data-sets.

Table D-5. Regional Estimates of Methane Emissions from Mature Dairy Cows Statistics for the Average Animal Modeled

	N. Atlantic	S. Atlantic	N. Central	S. Central	West
Feed consumed per year (kg DM)	5735	5460	5805	5182	6032
ME[a] consumed per year (Mcal)	15,224	13,421	15,012	12,975	15,190
Diet ME (Mcal/kg)	2.65	2.46	2.59	2.50	2.52
Average feed digestibility (%)[b]	68	66	66	64	66
Methane emissions per year (kg/cow)	116.2	127.7	104.8	116.2	130.5
Milk Production per cow per year (kg)	6574	6213	6334	5696	8339
Methane emissions per kg of milk produced (g/kg)	17.8	20.56	16.55	20.40	15.65

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1). Regional diets are weighted averages of the diets shown in Table D-3.

[a] ME = metabolizable energy
[b] Digestibility is reported as simulated digestible energy divided by gross energy intake.

Source: U.S. EPA (1993a)

Table D-6. Regional Estimates of Emissions from Dairy Replacement Heifers: 0-12 Months
Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	Diet 4	
Diet Description	Alfalfa hay	75% alfalfa hay, 25% concen.[a]	High quality grass forage (CP=18%)[b]	Corn silage with protein to 14% CP	
Feed consumed per year (kg DM)	1116	1080	967	904	
ME[c] consumed (Mcal)	2623	2684	2613	2432	
Diet ME (Mcal/kg)	2.35	2.48	2.70	2.69	
Average feed digestibility (%)[d]	62	65	67	69	
Methane emissions (kg/head/yr)	21.4	20.0	20.1	14	
Regional Distribution of Diets (%)[e]					**Emissions (kg/head/yr)**
North Atlantic	25%		60%	15%	19.5
South Atlantic	33%		67%		20.5
North Central	25%		50%	25%	18.9
South Central	15%		85%		20.3
West	50%	25%	25%		20.7

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] Concentrate of corn meal and soybean meal
[b] CP = crude protein
[c] ME = metabolizable energy
[d] Digestibility is reported as simulated digestible energy divided by gross energy intake.
[e] Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table D-7. Regional Estimates of Emissions from Dairy Replacement Heifers: 12-24 Months Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	Diet 4	
Diet Description	Alfalfa hay	75% alfalfa hay, 25% concen.[a]	Grass forage of declining quality[b]	Corn silage with protein to 14% CP[c]	
Feed consumed per year (kg DM)	3184	3018	3172	2540	
ME[c] consumed (Mcal)	7419	7437	7183	6801	
Diet ME (Mcal/kg)	2.33	2.46	2.25	2.68	
Average feed digestibility (%)[d]	62	64	58	67	
Methane emissions (kg/head/yr)	63.0	57.3	61.4	47.9	
Regional Distribution of Diets (%)[f]					**Emissions (kg/head/yr)**
North Atlantic	25%		50%	25%	58.4
South Atlantic	25%	10%	45%	20%	58.7
North Central	33%		33%	33%	57.4
South Central	20%		80%		61.7
West	50%	25%	25%		61.2

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] Concentrate of corn and cottonseed meal
[b] High quality grass forage for 100 days (ME=2.8 Mcal/kg). Intermediate quality grass forage for 100 days (ME=2.5 Mcal/kg). Lower quality grass forage for 165 days (ME=2.1 Mcal/kg).
[c] CP = crude protein
[d] ME = metabolizable energy
[e] Digestibility is reported as simulated digestible energy divided by gross energy intake.
[f] Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table D-8. Regional Estimates of Methane Emissions from Beef Cows Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	
Diet Description	Pasture for 7 mos; mixed hay for 5 mos[a]	Pasture of varying quality[b]	Pasture with 4 mos of supplement[c]	
Feed consumed per year (kg DM)	3029	3172	2700	
ME[d] consumed (Mcal)	7370	7731	7047	
Diet ME (Mcal/kg)	2.43	2.44	2.61	
Average feed digestibility (%)[e]	63	63	65	
Methane emissions (kg/head/yr)	63.4	71.7	53.7	
Regional Distribution of Diets (%)[f]				**Emissions (kg/head/yr)**
North Atlantic	80%		20%	60.5
South Atlantic	20%	80%		70.0
North Central	60%		40%	59.5
South Central	10%	90%		70.9
West	10%	80%	10%	69.1

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] Seven months of pasture declining in quality as the seasons progress. Five months of mixed hay, grass with some legumes.
[b] Pasture quality varies with the seasons.
[c] Pasture with four months of supplementation using a mixed forage (80 percent) and concentrate (20 percent) supplement.
[d] ME = metabolizable energy
[e] Digestibility is reported as simulated digestible energy divided by gross energy intake.
[f] Regional distribution of diets shows the extent to which each of the three diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table D-9. Regional Estimates of Emissions from Beef Replacements: 0-12 Months Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	
Diet Description	Legume pasture with supplement[a]	Very high quality grass (18% CP)[b]	Corn silage supplemented to 14% CP	
Feed consumed per year (kg DM)	984	1011	922	
ME[c] consumed (Mcal)	2443	2614	2454	
Diet ME (Mcal/kg)	2.48	2.58	2.66	
Average feed digestibility (%)[d]	65	68	68	
Methane emissions (kg/head/yr)	18.1	27.2	15.8	
Regional Distribution of Diets (%)[e]				**Emissions (kg/head/yr)**
North Atlantic	50%	20%	30%	19.2
South Atlantic	50%	50%		22.7
North Central	33%	33%	33%	20.4
South Central	40%	60%		23.6
West	50%	50%		22.7

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] Concentrate = 25 percent of ration
[b] CP = Crude protein
[c] ME = metabolizable energy
[d] Digestibility is reported as simulated digestible energy divided by gross energy intake.
[e] Regional distribution of diets shows the extent to which each of the three diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table D-10. Regional Estimates of Emissions from Beef Replacement Heifers: 12-24 Months Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	Diet 4	
Diet Description	Varying quality grass forage[a]	Varying quality grass forage[b]	Varying quality grass with winter supplement[c]	Varying quality grass with winter supplement[d]	
Feed consumed per year (kg DM)	2454	2675	2359	2305	
ME[e] consumed (Mcal)	6356	6524	5990	6000	
Diet ME (Mcal/kg)	2.59	2.49	2.54	2.60	
Average feed digestibility (%)[f]	67	66	66	67	
Methane emissions (kg/head/yr)	66.9	71.0	56.5	54.8	
Regional Distribution of Diets (%)[g]					**Emissions (kg/head/yr)**
North Atlantic		50%	50%		63.8
South Atlantic	50%	40%	10%		67.5
North Central		33%	33%	33%	60.8
South Central	80%	20%			67.7
West	33%	33%	33%		64.8

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] 165 days of high quality grass followed by 200 days of intermediate quality grass.
[b] 120 days of high quality grass followed by 125 days of intermediate quality grass -- grass hay provided for 120 days during winter
[c] 120 days of high quality grass followed by 125 days of intermediate quality grass -- medium quality alfalfa with a corn:soybean meal concentrate (25 percent) provided for 120 days during winter
[d] 120 days of high quality grass followed by 125 days of intermediate quality grass -- corn silage supplemented to 14 percent CP provided for 120 days during winter
[e] ME = metabolizable energy
[f] Digestibility is reported as simulated digestible energy divided by gross energy intake.
[g] Regional distribution of diets shows the extent to which each of the three diets is used in each region. The emissions estimates are the weighted average emissions using these percentages.

Source: U.S. EPA (1993a)

Table D-11. Regional Estimates of Emissions from Feedlot Fed Cattle: Yearling System Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	
Diet Description	All diets include forages during the stocker phase followed by high grain diets during feedlot feeding[a]			
Feed consumed per year (kg DM)	2865	2775	2755	
ME[b] consumed (Mcal)	7588	7383	7366	
Diet ME (Mcal/kg)	2.65	2.66	2.67	
Average feed digestibility (%)[c]	67	67	68	
Methane emissions (kg/head/yr)	50.0	54.1	52.9	
Adjustment for ionophores and hormone implants	90%	90%	90%	
Methane emissions (kg/head/yr)	45.0	48.7	47.6	
Regional Distribution of Diets (%)[d]				**Emissions (kg/head/yr)**
North Central	30%	20%	50%	47.0
South Central			100%	47.6
West	20%	50%	30%	47.6

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] All three diets include a high quality mixed hay (legume and grass) for the first winter (90 days). The three diets then include:

Diet 1: mixed pasture (legume and grass) to 425 days of age; 50 percent alfalfa:50 percent concentrate for 40 days; 10 percent alfalfa:90 percent concentrate for 100 days.

Diet 2: grass pasture to 425 days of age; 50 percent alfalfa:50 percent concentrate for 40 days; 10 percent alfalfa:90 percent concentrate for 100 days.

Diet 3: grass pasture to 425 days of age; 70 percent corn silage:30 percent concentrate for 40 days; 10 percent alfalfa:90 percent concentrate for 100 days.

[b] ME = metabolizable energy

[c] Digestibility is reported as simulated digestible energy divided by gross energy intake.

[d] Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages. Only the three regions with feedlots are shown.

Source: U.S. EPA (1993a)

Table D-12. Regional Estimates of Emissions from Feedlot Fed Cattle: Weanling System Statistics for the Average Animal Modeled

	Diet 1	Diet 2	Diet 3	
Diet Description	All diets include mixed rations with increasing amounts of high grain concentrates[a]			
Feed consumed per year (kg DM)	1935	1763	1742	
ME[b] consumed (Mcal)	5232	5184	5059	
Diet ME (Mcal/kg)	2.70	2.94	2.90	
Average feed digestibility (%)[c]	68	71	71	
Methane emissions (kg/head/yr)	31.2	25.3	25.4	
Adjustment for ionophores and hormone implants	85%	85%	85%	
Methane emissions (kg/head/yr)	26.5	21.5	21.6	
Regional Distribution of Diets (%)[d]				**Emissions (kg/head/yr)**
North Central	20%	20%	60%	22.6
South Central	50%	50%		24.0
West	40%	30%	30%	23.5

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] The following diets were simulated:

Diet 1: 60 percent alfalfa:40 percent concentrate for 125 days; 10 percent alfalfa:90 percent concentrate for 132 days.

Diet 2: 50 percent alfalfa:50 percent concentrate for 125 days; 10 percent alfalfa:90 percent concentrate for 132 days.

Diet 3: 69 percent corn silage:31 percent concentrate for 125 days; 10 percent alfalfa:90 percent concentrate for 132 days.

[b] ME = metabolizable energy

[c] Digestibility is reported as simulated digestible energy divided by gross energy intake.

[d] Regional distribution of diets shows the extent to which each of the four diets is used in each region. The emissions estimates are the weighted average emissions using these percentages. Only the three regions with feedlots are shown.

Source: U.S. EPA (1993a)

Table D-13. Methane Emissions From Enteric Fermentation in U.S. Dairy Cattle

Region/Animal Type	Emissions Factor (kg/head/yr)	Population (000 Head)	Emissions (Tg/yr)
North Atlantic			
Replacements 0-12 months	19.5	712	0.014
Replacements 12-24 months	58.4	712	0.042
Mature Cows	117.5	1,795	0.211
South Atlantic			
Replacements 0-12 months	20.5	268	0.005
Replacements 12-24 months	58.7	268	0.016
Mature Cows	126.5	710	0.090
North Central			
Replacements 0-12 months	18.9	1,987	0.038
Replacements 12-24 months	57.4	1,987	0.114
Mature Cows	109.4	4,497	0.492
South Central			
Replacements 0-12 months	20.3	405	0.008
Replacements 12-24 months	61.7	405	0.025
Mature Cows	114.8	1,156	0.133
West			
Replacements 0-12 months	20.7	833	0.017
Replacements 12-24 months	61.2	833	0.051
Mature Cows	119.3	1,972	0.235
National Total			
Replacements 0-12 months	19.6	4,205	0.082
Replacements 12-24 months	58.8	4,205	0.247
Mature Cows	114.6	10,130	1.161
Total	80.4	18,540	1.490

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

Source: U.S. EPA (1993a)

Table D-14. Methane Emissions From Enteric Fermentation in U.S. Beef Cattle

Region/Animal Type	Emissions Factor (kg/head/yr)	Population (000 Head)[a]	Emissions (Tg/yr)
North Atlantic			
Replacements 0-12 months	19.2	87	0.002
Replacements 12-24 months	63.8	87	0.006
Mature Cows	61.5	337	0.021
South Atlantic			
Replacements 0-12 months	22.7	594	0.013
Replacements 12-24 months	67.5	594	0.040
Mature Cows	70.0	3,418	0.239
North Central			
Replacements 0-12 months	20.4	1,546	0.032
Replacements 12-24 months	60.8	1,546	0.094
Mature Cows	59.5	10,592	0.630
Weanling System Steers/Heifers[b]	22.6	2,963	0.067
Yearling System Steers/Heifers	47.0	11,852	0.557
South Central			
Replacements 0-12 months	23.6	2,079	0.049
Replacements 12-24 months	67.7	2,079	0.141
Mature Cows	70.9	12,359	0.876
Weanling System Steers/Heifers	24.0	1,164	0.028
Yearling System Steers/Heifers	47.6	4,656	0.222
West			
Replacements 0-12 months	22.7	1,229	0.028
Replacements 12-24 months	64.8	1,229	0.080
Mature Cows	69.1	6,772	0.468
Weanling System Steers/Heifers	23.5	1,133	0.027
Yearling System Steers/Heifers	47.6	4,532	0.216
Bulls: Nationally	100.0	2,200	0.220
National Total			
Replacements 0-12 months	22.3	5,535	0.124
Replacements 12-24 months	65.0	5,535	0.360
Mature Cows	66.7	33,478	2.234
Weanling System Steers/Heifers	23.1	5,260	0.122
Yearling System Steers/Heifers	47.3	21,040	0.994
Bulls	100.0	2,200	0.220
Total[d]	47.5	85,398[c]	4.054

Note: Statistics and emissions estimates presented in this table are from U.S. EPA 1994b and serve as a reference point for updated emissions estimates in this report (See Box D-1).

[a] Population for slaughter steers and heifers in each region is the number slaughtered annually.
[b] The emissions from Yearling and Weanling System steers and heifers are assigned to the regions in which they are managed in feedlots.
[c] The national population is estimated using the average annual population of Yearling and Weanling System cattle: 38.65 million. See text.
[d] Total may not add due to rounding.

Source: U.S. EPA (1993a)

METHANE EMISSIONS FROM ANIMAL MANURE MANAGEMENT

Estimates of 1990 methane emissions from animal manure management were derived using the approach of Safley *et al.* (1992a). This approach is as follows:

(1) Estimate annual methane emissions for each animal type *i* and manure system *j* in each state *k*:

$$TM_{ijk} = N_{ik} \times TAM_i \times vs_i \times B_{0i} \times MCF_{jk} \times WS\%_{ijk}$$

Where TM_{ijk} = annual methane emissions for each animal type *i* and manure management system *j* in each state *k*

N_{ik} = number of animals of type *i* in state *k*

TAM_i = typical animal mass of animal *i*

vs_i = average annual volatile solids production per unit of animal mass for animal *i*

B_{0i} = maximum methane producing capacity of the manure of animal *i*

MCF_{jk} = the methane conversion factor of the manure system *j* in the state *k*

$WS\%_{ijk}$ = the percent of animal *i*'s manure managed in manure system *j* in state *k*

(2) Estimate total annual methane emissions for animal *i* by summing annual emissions over all applicable manure management systems *j* and states *k*.

(3) Estimate total annual methane emissions from all animals by summing over all animal types *i*.

Emissions estimates in this study differ slightly from previous estimates (EPA 1993a, EPA 1994b) because of the following:

- 1990 animal population data used to calculate point estimates of emissions in EPA 1993a were approximated based on 1987 population data and growth rates.

- In the current estimate, data was taken from the USDA National Agricultural Statistics Service (NASS) data sets to calculate 1990 emissions. The population numbers published by the NASS differ from those approximated in EPA 1993a. This produced different emissions values than those presented in EPA 1994b, which used the emissions data from EPA 1993a. The contrasting population numbers are presented in Table D-15.

- The updated population numbers, along with revised MCFs, have also produced new emissions estimates for the years 1991 to 1993.

Table D-15. 1990 Animal Population Estimates: Projected levels vs. Actual levels

	1990 Populations (projected)[a] (1000 head)	1990 Populations (actual)[b] (1000 head)
Dairy Cattle	14,335	14,143
Beef Cattle	89,293	86,065
Swine	55,299	53,807
Poultry	1,368,166	1,703,037
Other	15,444	19,116

[a] Source: U.S. EPA 1993a
[b] Source: USDA, 1994a,c,d

Table D-16 presents the annual increases in the national census of beef cattle, swine, and poultry, along with the respective emission levels for each for each year of the study. The total population of animals in the "other" category decreased over the five year span, without an effect on emissions.

To estimate methane emissions from manure, twenty types of animals were defined for the U.S., and data were collected on the populations of each animal type in each state, their typical animal mass, and their average annual volatile solids production per unit of animal mass. The cattle populations and weights are equal to those used in the previous section of this annex to estimate emissions from enteric fermentation.[4]

The maximum amount of methane that can be produced per kilogram of volatile solids, or the maximum methane producing capacity of each animal's manure (B_0), varies by animal type and diet. Appropriate B_0 values were chosen from the scientific literature depending on the typical diet of each animal type. For animal types without B_0 measurements, the B_0 was estimated based on similarities with other animals and the experience of the authors of Safley *et al.* (1992a). Table D-18 lists the values selected for the analysis.

The extent to which the maximum methane producing capacity of each animal's manure is realized, or the methane conversion factor (MCF), depends upon the management system and climate conditions in which the manure is managed. Ten categories of manure management systems were identified for the U.S., and based upon estimates in the scientific literature and research sponsored by U.S. EPA, MCFs for each system were identified (Table D-19). The MCF for each management system in each state was calculated by:

- estimating the average monthly temperature in each climate division of each state;[5]
- estimating the MCF value for each month using the average temperature data and the MCF values listed in Table D-19;
- estimating the annual MCF by averaging the monthly division estimates; and

[4] Tables D-1 and D-2 (in the enteric fermentation section) list weights on an empty body weight basis. These values were converted to live weight for purposes of estimating emissions from animal manure management.

[5] The average temperature in each climate division of each state was calculated for the normal period of 1951 to 1980 using the National Climatic Data Center time-bias corrected Historical Climatological Series Divisional Data (NCDC, 1991).

- estimating the state-wide MCF by weighting the average MCF for each division by the fraction of the state's dairy population represented in each division.[6]

Table D-20 summarizes the resultant MCF estimates by management system for each state.

Livestock manure management system usage in the U.S. was determined by obtaining information from Extension Service personnel in each state. The U.S. was divided into eleven geographic regions based on similarities of climate and livestock production. For states that did not provide information, the regional average manure system usage was assumed. The results are summarized in Table D-21.

Shifts in Manure management practices in seven states also impact methane emissions. These changes are presented in Table D-22. These factors are derived from the change in total weighted MCFs for these states, calculated by multiplying the state MCF factor for a given management system by the degree to which that system is utilized. From this compilation of state data, national figures were calculated.

Information on shifts in manure management, particularly towards lagoon manure management, was ascertained based on analyses of the industry trends towards larger confinement facilities, which necessitate automated management systems. Discussions with industry experts and facility owners supplemented this information.

[6] The dairy populations in each climate division were estimated using the dairy population in each county (Bureau of the Census, 1987) and detailed county and climate division maps (NCDC, 1991). Using the dairy population as a weighting factor may slightly over or underestimate the MCFs for other livestock populations.

Table D-16. Methane Emissions from Manure Management: 1990-1994

	1990 Population (1,000 head)	1990 Emissions (Tg)	1991 Population (1,000 head)	1991 Emissions (Tg)	1992 Population (1,000 head)	1992 Emissions (Tg)	1993 Population (1,000 head)	1993 Emissions (Tg)	1994 Population (1,000 head)	1994 Emissions (Tg)
Dairy	**14,143**	**0.75**	**13,980**	**0.75**	**13,830**	**0.79**	**13,767**	**0.80**	**13,686**	**0.84**
Dairy Cows	10,007	0.58	9,883	0.59	9,714	0.62	9,679	0.63	9,614	0.66
Dairy Heifers	4,135	0.17	4,097	0.16	4,116	0.17	4,088	0.17	4,072	0.17
Beef	**86,065**	**0.20**	**87,267**	**0.20**	**88,548**	**0.21**	**90,321**	**0.21**	**92,623**	**0.22**
Feedlot Steers	7,336	0.03	7,976	0.03	7,617	0.03	8,032	0.03	8,223	0.03
Feedlot Heifers	3,458	0.02	3,841	0.02	3,608	0.02	3,878	0.02	3,938	0.02
Feedlot Cows/other	90	0.00	102	0.00	96	0.00	101	0.00	100	0.00
NOF Bulls	2,103	0.01	2,099	0.01	2,132	0.01	2,146	0.01	2,218	0.01
NOF Calves	23,621	0.02	23,665	0.02	24,067	0.02	24,369	0.02	24,145	0.02
NOF Heifers	10,326	0.02	10,356	0.02	10,728	0.02	10,868	0.02	10,999	0.02
NOF Steers	7,287	0.01	7,206	0.01	7,523	0.01	7,464	0.01	7,604	0.01
NOF Cows	31,844	0.10	32,022	0.10	32,776	0.10	33,464	0.11	34,396	0.11
Swine	**53,807**	**0.95**	**56,535**	**0.99**	**58,553**	**1.04**	**56,919**	**1.03**	**60,028**	**1.14**
Breeding pigs	6,883	0.31	7,239	0.32	7,269	0.33	7,212	0.32	7,594	0.36
Markets < 60 lbs	18,372	0.08	19,320	0.09	19,948	0.09	18,426	0.08	19,525	0.09
Markets 60-119 lbs	11,661	0.15	12,348	0.16	12,823	0.16	12,758	0.16	13,403	0.18
Markets 120-179lbs	9,367	0.19	9,778	0.20	10,180	0.21	10,323	0.22	10,850	0.24
Markets 180+ lbs	7,523	0.22	7,850	0.23	8,334	0.24	8,201	0.24	8,656	0.27
Poultry	**1,703,037**	**0.26**	**1,767,513**	**0.27**	**1,832,308**	**0.27**	**1,895,851**	**0.28**	**1,971,404**	**0.29**
Hens > 1 yr	119,551	0.05	117,178	0.05	121,103	0.06	131,688	0.06	134,876	0.06
Pullets laying	153,916	0.06	162,943	0.06	163,397	0.06	158,938	0.06	163,628	0.06
Pullets > 3 mo.	34,222	0.01	34,272	0.01	34,710	0.01	33,833	0.01	32,808	0.01
Pullets < 3 mo.	38,945	0.01	42,344	0.01	45,160	0.01	47,941	0.01	44,875	0.01
Chickens	6,546	0.00	6,857	0.00	7,113	0.00	7,240	0.00	7,319	0.00
Broilers	1,172,830	0.10	1,227,430	0.10	1,280,498	0.11	1,338,862	0.11	1,403,508	0.12
Other (Lost)	6,971	0.00	7,278	0.00	7,025	0.00	6,992	0.00	12,744	0.00
Other (Sold)	41,672	0.01	39,707	0.01	41,538	0.01	39,606	0.01	40,272	0.01
Turkeys	128,384	0.03	129,505	0.03	131,764	0.03	130,750	0.03	131,375	0.03
Other	**19,116**	**0.06**	**18,864**	**0.06**	**18,657**	**0.06**	**18,021**	**0.06**	**17,552**	**0.04**
Ewes > 1 yr	7,961	0.00	7,799	0.00	7,556	0.00	7,140	0.00	6,775	0.00
Rams/Weth > 1 yr	369	0.00	361	0.00	350	0.00	331	0.00	314	0.00
Ewes < 1 yr	1,491	0.00	1,464	0.00	1,432	0.00	1,349	0.00	1,277	0.00
Rams/Weth < 1 yr	381	0.00	373	0.00	366	0.00	348	0.00	332	0.00
Sheep on Feed	1,154	0.00	1,177	0.00	1,093	0.00	1,032	0.00	1,044	0.00
Goats	2,545	0.03	2,475	0.03	2,645	0.03	2,605	0.00	2,595	0.03
Horses	5,215	0.03	5,215	0.03	5,215	0.03	5,215	0.03	5,215	0.03
Total		***2.21***		***2.28***		***2.37***		***2.39***		***0***

Table D-17. U.S. Animal Populations, Average Size, and VS Production

Animal Type		Population[a,b] N_i	Typical Animal Mass $(TAM_i)^c$ Kg	Manure per day[d] (kg/day per 1000 kg mass)	
				Total Manure	Volatile Solids vs_i
Feedlot Beef Cattle	Steers/Heifers	10,088,000	415	58	7.2
Other Beef Cattle	Calves	36,040,000	180	58	7.2
	Heifers	5,535,0000	360	58	7.2
	Steers	2,162,000	360	58	7.2
	Cows	33,478,000	500	58	7.2
	Bulls	2,200,000	720	58	7.2
	Total	79,205,000			
Dairy Cattle	Heifers	4,205,000	410	86	10
	Cows	10,130,000	610	86	10
	Total	14,335,000			
Swine	Market	48,259,000	46	84	8.5
	Breeding	7,040,000	181	84	8.5
	Total	55,299,000			
Poultry[c]	Layers	355,469,000	1.6	64	12
	Broilers	951,914,000	0.7	85	17
	Ducks	7,000,000	1.4	107	18.5
	Turkeys	53,783,000	3.4	47	9.1
Other	Sheep	10,639,000	70	40	9.2
	Goats	2,396,000	64	41	9.5
	Donkeys	4,000	300	51	10
	Horses and Mules	2,405,000	450	51	10

[a] Population data for swine, poultry, and sheep from USDA (1989a-f). Goat and horse population data from Bureau of Census (1987). Population data for cattle are the same as those used to estimate emissions from enteric fermentation in cattle in 1990. Population data as of January 1, 1988 for poultry, and sheep and as of December 1, 1987 for swine, goats, and horses. Cattle populations represent an average for 1990.

[b] Broiler/turkey populations estimated yearly based on number of flocks per year (North 1978; Carter 1989).

[c] Source: Taiganides and Stroshine (1971).

[d] Source: ASAE (1988).

Source: U.S. EPA (1993a)

Table D-18. Maximum Methane Producing Capacity Adopted For U.S. Estimates

Animal Type, Category		Maximum Potential Emissions (B_o)	Reference
Cattle:	Beef in Feedlots	0.33	Hashimoto *et al.* (1981)
	Beef Not in Feedlots	0.17	Hashimoto *et al.* (1981)
	Dairy	0.24	Morris (1976)
Swine:	Breeder	0.36	Summers & Bousfield (1980)
	Market	0.47	Chen (1983)
Poultry:	Layers	0.34	Hill (1982 & 1984)
	Broilers	0.30	Safley *et al.* (1992a)
	Turkeys	0.30	Safley *et al.* (1992a)
	Ducks	0.32	Safley *et al.* (1992a)
Sheep:	In Feedlots	0.36	Safley *et al.* (1992a)
	Not in Feedlots	0.19	Safley *et al.* (1992a)
Goats:		0.17	Safley *et al.* (1992a)
Horses, Mules, and Donkeys:		0.33	Ghosh (1984)

Source: U.S. EPA (1993a)

Table D-19. Methane Conversion Factors for U.S. Livestock Manure Systems

MCFs based on laboratory measurement	MCF at 30°C	MCF at 20°C	MCF at 10°C
Pasture, Range, Paddocks[a]	2 %	1.5 %	1 %
Liquid/Slurry[a]	65 %	35 %	10 %
Pit Storage < 30 days[a]	33 %	18 %	5 %
Pit Storage > 30 days[a]	65 %	35 %	10 %
Drylot[b]	5 %	1.5%	1 %
Solid Storage[a]	2 %	1.5 %	1 %
Daily Spread[a]	1 %	0.5 %	0.1 %
MCF measured by long term field monitoring		**Average Annual MCF**	
Anaerobic Lagoons[c]		90 %	
MCFs estimated by Safley *et al.*		**Average Annual MCF**	
Litter[d]		10 %	
Deep Pit Stacking[d]		5 %	

Source: U.S. EPA (1993a)

[a] Hashimoto (1992)
[b] Based on Hashimoto (1992).
[c] Safley *et al.* (1992a) and Safley and Westerman (1992b).
[d] Safley *et al.* (1992a).

Table D-20. Methane Conversion Factors for U.S. Livestock Manure Systems

State	Pasture, Range & Paddocks	Drylot	Solid Storage	Daily Spread	Liquid/ Slurry
Alabama	1.4%	1.9%	1.4%	0.4%	29.0%
Arizona	1.4%	1.9%	1.4%	0.4%	28.9%
Arkansas	1.3%	1.8%	1.3%	0.4%	27.6%
California	1.2%	1.4%	1.2%	0.3%	21.9%
Colorado	0.9%	1.0%	0.9%	0.2%	18.2%
Connecticut	0.9%	1.0%	0.9%	0.2%	18.5%
Delaware	1.2%	1.4%	1.2%	0.3%	22.6%
Florida	1.5%	2.4%	1.5%	0.6%	38.6%
Georgia	1.4%	1.8%	1.4%	0.4%	29.0%
Idaho	0.8%	0.8%	0.8%	0.2%	15.5%
Illinois	1.1%	1.3%	1.1%	0.3%	22.8%
Indiana	1.0%	1.2%	1.0%	0.3%	21.5%
Iowa	0.9%	1.1%	0.9%	0.2%	20.7%
Kansas	1.1%	1.5%	1.1%	0.3%	24.7%
Kentucky	1.2%	1.5%	1.2%	0.3%	23.8%
Louisiana	1.4%	2.1%	1.4%	0.5%	32.5%
Maine	0.8%	0.8%	0.8%	0.2%	15.5%
Maryland	1.1%	1.2%	1.1%	0.3%	21.0%
Massachusetts	0.9%	1.0%	0.9%	0.2%	18.1%
Michigan	0.8%	0.9%	0.8%	0.2%	17.0%
Minnesota	0.8%	0.8%	0.8%	0.2%	18.0%
Mississippi	1.4%	1.9%	1.4%	0.4%	29.3%
Missouri	1.1%	1.4%	1.1%	0.3%	24.1%
Montana	0.7%	0.8%	0.7%	0.2%	15.8%
Nebraska	1.0%	1.1%	1.0%	0.2%	20.8%
Nevada	1.2%	1.4%	1.2%	0.3%	22.1%
New Hampshire	0.8%	0.8%	0.8%	0.2%	16.3%
New Jersey	1.0%	1.1%	1.0%	0.3%	20.6%
New Mexico	1.2%	1.3%	1.2%	0.3%	21.3%
New York	0.9%	0.9%	0.9%	0.2%	18.1%
North Carolina	1.3%	1.5%	1.3%	0.3%	24.5%
North Dakota	0.7%	0.7%	0.7%	0.2%	16.8%
Ohio	1.0%	1.1%	1.0%	0.2%	20.2%
Oklahoma	1.4%	1.9%	1.4%	0.4%	28.7%
Oregon	1.1%	1.1%	1.1%	0.2%	16.2%
Pennsylvania	0.9%	1.0%	0.9%	0.2%	18.7%
Rhode Island	1.0%	1.1%	1.0%	0.2%	18.7%
South Carolina	1.3%	1.7%	1.3%	0.4%	27.3%
South Dakota	0.8%	0.9%	0.8%	0.2%	19.1%
Tennessee	1.3%	1.6%	1.3%	0.3%	24.8%
Texas	1.4%	2.1%	1.4%	0.5%	31.7%
Utah	0.9%	1.0%	0.9%	0.2%	17.4%
Vermont	0.8%	0.8%	0.8%	0.2%	16.6%
Virginia	1.2%	1.4%	1.2%	0.3%	22.5%
Washington	1.0%	1.0%	1.0%	0.2%	15.5%
West Virginia	1.2%	1.3%	1.2%	0.3%	21.4%
Wisconsin	0.8%	0.8%	0.8%	0.2%	17.0%
Wyoming	0.8%	0.8%	0.8%	0.2%	15.9%

Other Systems: Pit Storage for less than 30 days is assumed to have an MCF equal to 50 percent of the MCF for Liquid/Slurry. Pit Storage for more than 30 days is assumed to have an MCF equal to liquid/slurry. Anaerobic lagoons are assumed to have an MCF of 90 percent; litter and deep pit stacks an MCF of 10 percent.

Source: U.S. EPA (1993a)

Table D-21. Livestock Manure System Usage for the U.S.

Animal	Anaerobic Lagoons	Liquid/Slurry and Pit Storage	Daily Spread	Solid Storage & Drylot	Pasture, Range & Paddock	Litter, Deep Pit Stacks and Other
Non-Dairy Cattle	<1%	<1%	0%	10%	89%	0%
Dairy	11%	21%	41%	18%	0%	8%
Poultry[b]	4%	3%	0%	0%	<1%	93%
Sheep	0%	0%	0%	0%	92%	8%
Swine	29%	44%	0%	20%	0%	7%
Other Animals[c]	0%	0%	0%	0%	89%	11%

Note: Totals may not add due to rounding.

[a] Includes liquid/slurry storage and pit storage.
[b] Includes chickens, turkeys, and ducks.
[c] Includes goats, horses, mules, and donkeys.

Source: Safley *et al.* (1992a).

Table D-22. Methane Conversion Factor Changes from 1990 to 1992

DAIRY State		Lagoon	Liquid Slurry	Daily Spread	Solid Storage	Other	Weighted MCF*WS	Change Factor
AZ	1990,1991	10%	0%	0%	0%	90%	0.0990	**4.60**
	1992+	50%	0%	0%	0%	50%	0.46	
	MCF	90.0%	24.0%	0.4%	1.4%	1.0%		
FL	1990,1991	2%	0%	10%	0%	88%	0.0274	**10.09**
	1992+	30%	0%	10%	0%	60%	0.28	
	MCF	90%	36.9%	0.6%	1.5%	1.0%		
NV	1990,1991	1%	1%	8%	90%	0%	0.0213	**17.76**
	1992+	40%	10%	0%	50%	0%	0.38	
	MCF	90.0%	13.0%	0.3%	1.2%	0.0%		
NC	1990,1991	5%	35%	50%	10%	0%	0.1189	**1.88**
	1992+	20%	20%	50%	10%	0%	0.22	
	MCF	90.0%	20.3%	0.3%	1.3%	0.0%		
ND	1990,1991	0%	20%	10%	70%	0%	0.0251	**0.66**
	1992	1%	1%	8%	90%	0%	0.02	
	MCF	90.0%	10.0%	0.2%	0.7%	0.0%		
TX	1990,1991	25%	60%	15%	0%	0%	0.4022	**0.65**
	1992+	25%	10%	15%	50%	0%	0.26	
	MCF	90.0%	29.4%	0.5%	1.4%	0.0%		
	SWINE State	Lagoon	Dry Lot	Pit St. <1 mnth	Pit St. >1 mnth	Other	Weighted MCF*WS	**Change Factor**
TX	1990,1991	35%	20%	15%	30%	0%	0.43	**1.08**
	1992+	45%	30%	15%	10%	0%	0.46	
	MCF	90.0%	2.1%	14.7%	29.4%	20.0%		
UT	1990,1991	25%	75%	0%	0%	0%	0.23	**2.91**
	1992+	75%	25%	0%	0%	0%	0.68	
	MCF	90.0%	1.0%	5.4%	10.8%	0.0%		

Point estimates of emissions were calculated using the previously described data. Emissions were estimated for each animal type by summing annual emissions over all applicable manure management systems and states. Total annual methane emissions from all animals were estimated by summing over all animal types.

Uncertainties in the point estimates result from uncertainties in the data used to make these estimates, in particular:

- The estimated MCF values for pasture, range, drylots, solid storage, and paddocks are based on dry manure. This may underestimate the MCFs for regions with significant rainfall. Because a large fraction of animal manure is managed in these systems; total emissions may be underestimated.

- The methane producing potential of liquid/slurry and pit storage manure systems may be greater than assumed. These systems are widespread, so total emissions may be underestimated.

The greatest uncertainty results from the MCF assumptions. Therefore, "high" and "low" case emission estimates were defined based on varying the MCFs used for the various manure management systems in the base case:

- High Case. The MCFs for liquid/slurry, pit storage, litter, and deep pit stacking systems were assumed to be double the base case. The MCFs for solid systems (except litter and deep stack pits) were assumed to be five times the base case. The MCFs for anaerobic lagoons were the same as the base case.

- Low Case. The MCFs for each of the major solid systems (pasture/range, solid storage, and drylots) were assumed to be 80 percent of the base case. The MCFs for liquid/slurry and pit storage were assumed to be 90 percent of the base case. The MCFs for litter and deep pits were assumed to be half the base case. The MCFs for anaerobic lagoons, estimated using a lagoon methanogenesis model prepared for U.S. EPA[7], were 40 to 100 percent of the base case.

These assumptions are summarized in Table D-23.

Table D-23. Base, High, and Low Case Emission Estimate Assumptions

Management System	MCF	
	High Case	Low Case
Pasture, Range, Paddock, Drylot, Daily Spread	Five Times Base Case	80 percent of Base Case
Liquid/Slurry, Pit Storage	Two Times Base Case	90 percent of Base Case
Litter, Deep Pits	Two Times Base Case	50 percent of Base Case
Anaerobic Lagoons	Same as Base Case	Model Estimates 40 to 100 percent of Base Case

Source: U.S. EPA (1993a)

[7] The model estimates methane production based on loading rates, lagoon characteristics, and climate. The model estimates are "conservative" because the model focuses on the amount of methane that can be recovered reliably for use as an energy source.

ANNEX E
METHANE EMISSIONS FROM LANDFILLS

Municipal Solid Waste Landfill Methane Generation

Municipal solid waste (MSW) landfill methane generation is estimated by the Waste In Place - 30 (WIP-30) model developed by U.S. EPA (henceforth known as the EPA model), which uses statistical relationships between landfill gas (LFG) recovery rates and landfill waste quantities (U.S. EPA, 1993a). The model coefficients are based on measured methane recovery rates at approximately 100 LFG energy recovery projects in the U.S. The total waste in place was divided into 7 landfill size classes and point estimates of emissions from each landfill size class were derived using regression coefficients developed in the model.

The EPA model assumes that the methane producing lifetime of waste is 30 years. Therefore, the estimate of total waste landfilled over the last 30 years is used as the quantity of MSW contributing to methane emissions. For example, in 1990, the total MSW contributing to methane emissions would be the total MSW landfilled for the period 1961 to 1990. Therefore, for 1994, total MSW contributing to methane emissions is the total MSW landfilled for the period 1965 to 1994. The amount of MSW landfilled in 1994 is estimated to be 195 million tonnes. Using these estimates, the EPA model gives a 30 year waste in place estimate of 4,971 million tonnes for 1994 (see Table E-1).

Table E-1. Municipal Solid Waste Contributing to Methane Emissions: 1990-1994 (Million Tonnes of Waste)

	1990	1991	1992	1993	1994
Total MSW Generated[a]	264	255	265	278	290
Percent of MSW Landfilled[a]	71%	76%	72%	71%	67%
Total MSW Landfilled	189	194	190	197	195
MSW Contributing to CH_4 Emissions[b]	4,708	4,771	4,838	4,901	4,971

[a] Source: Biocycle 1991, 1992, 1993, 1994, and 1995. The data, originally reported in short tons, have been converted to metric tons.
[b] These are estimates of MSW in place for the past 30 years (U.S. EPA, 1993a).

For the purposes of analyzing methane emissions from landfills in the U.S., the population of landfills was characterized in terms of size (i.e., waste in place) and climate (arid and non-arid[1]).

- **Size**. The EPA model defined 7 landfill size classes based on the amount of waste in place, with class 7 having the largest amount of waste in place, and class 1, the smallest. In this analysis, the different landfill classes were grouped as large, medium, and small. Classes 5, 6, and 7 were grouped as "large" landfills, classes 3 and 4 represented "medium" landfills, and class 2 was defined as "small" landfills. Approximately 3000 Class 1 landfills were excluded from this analysis as the quantity of waste in place contained in these landfills were a negligible fraction of total waste in place.

- **Climate**. The analyses indicate that about 13 percent of the waste in landfills can be considered to be in arid climates (U.S. EPA, 1993a). The methane emissions estimates reflect that the emissions from waste in arid climates are lower than waste in non-arid climates. Moisture can facilitate faster methane generation.

Industrial Landfill Methane Generation

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. Since there is no information available on methane generation at industrial landfills, the approached used is to assume that industrial methane generation equals about 7 percent of municipal landfill methane generation (U.S. EPA, 1993a).

Methane Recovery

To estimate LFG recovered per year in the U.S., data on current and planned LFG energy recovery projects in the U.S. were obtained from Government Advisory Associates (GAA). The GAA database, considered to be the most comprehensive source of information on LFG energy recovery in the U.S., contains 1990 and 1992 estimates for LFG energy recovery. The data set used in this analysis indicates that 1,200 and 1,440 thousand tonnes of methane were recovered nationally by MSW landfills in 1990 and 1992, respectively. In addition, a number of landfills are believed to recover and flare methane without energy recovery and were not included in the GAA database. To account for the amount methane flared without energy recovery, the estimate of gas recovered is increased by 25 percent (U.S. EPA, 1993a). Therefore, net methane recovery from landfills is assumed to equal 1,500 thousand tonnes in 1990 and 1,800 thousand tonnes in 1992. The 1990 estimate of methane recovered is used for 1991 and the 1992 estimate, presented in Table E-2, is used for 1992 through 1994.

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[1] A comprehensive census of landfills in the U.S. does not exist, making the landfill characterization somewhat uncertain. See EPA (1993a) for a description of the landfill population data used in the analysis.

Methane Oxidation

Methane migrating through the top layer of the soil over the landfill can be oxidized by micro-organisms. Landfills that recover methane practically eliminate migration of methane through the soil, thereby minimizing the amount of methane that is oxidized. The amount of oxidation that occurs is uncertain and depends on the characteristics of the soil and the environment. For purposes of this analysis, it is assumed that 10 percent of the methane produced is oxidized in the soil.

Table E-2. Landfill Gas Recovered Per Year: 1992-1994

LFG Recovered[a] (ft^3/day)	Methane Recovered[b] (10^3 tonnes/yr)	Other Recovery[c] (10^3 tonnes/yr)	Total Methane Recovered (10^3 tonnes/yr)
A	B	C	D
	$B=Ax19.2x0.5x365x10^{-9}$	C=Bx0.25	D=B+C
410,823,840	1,440	360	1,800

[a] Landfill gas recovered is estimated by aggregating total landfill gas processed for operational landfills which utilize gas for energy recovery (GAA, 1994).

[b] Conversion of LFG recovered from ft^3/day to 10^3 tonnes/yr assumes a methane density of 19.2 g/ft^3 and a methane concentration of 50%.

[c] The GAA data used to estimate LFG recovered does not include all landfills in the U.S. A small number of landfills are believed to recover and flare methane without energy recovery which are not included in the GAA data set. An estimated 25% of the estimated landfill gas recovered for energy use is assumed to be recovered and flared without energy recovery (U.S. EPA, 1993a).

ANNEX F
SULFUR DIOXIDE: EFFECT ON RADIATIVE FORCING AND SOURCES OF EMISSIONS

Sulfur dioxide emitted into the atmosphere through natural and anthropogenic processes affects the Earth's radiative budget through photochemical transformation into sulfate particles that (I) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; (ii) possibly increase the number of cloud condensation nuclei, thereby potentially altering the physical characteristics of clouds; and (iii) affect atmospheric chemical composition (*e.g.*, stratospheric ozone, by providing surfaces for heterogeneous chemical processes). As a result of these activities, the effect of SO_2 on radiative forcing may be negative (IPCC, 1992). Additionally, since SO_2 is short-lived, it may make no long-term contribution to radiative forcing (IPCC, 1994). Because the effects of SO_2 are uncertain and potentially opposite from the other criteria pollutants, SO_2 emissions have been presented separately below in Tables F-1 and F-2.

The major source of SO_2 emissions in the U.S. is the burning of sulfur containing fuels, mainly coal.. Metal smelting and other industrial processes also release significant quantities of SO_2. As a result, the largest contributor to overall U.S. emissions of SO_2 are electric utilities, accounting for about 70 percent in 1994. Coal combustion accounted for approximately 96 percent of SO_2 emissions from electric utilities in the same year. The second largest source is industrial fuel combustion, which produced about 14 percent of 1994 SO_2 emissions. Table F-2 provides SO_2 emissions disaggregated by fuel source.

Sulfur dioxide is important for reasons other than its effect on radiative forcing. It is a major contributor to the formation of urban smog and acid rain. As a contributor to urban smog, high concentrations of SO_2 can cause significant increases in acute and chronic respiratory diseases. In addition, once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to earth as the primary contributor to acid deposition, or acid rain. Acid rain has been found to accelerate the decay of building materials and paints, as well as cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the U.S. has regulated the emissions of SO_2 in the Clean Air Act of 1970 and in the amendments of 1990. The U.S. EPA has also developed a strategy to control these emissions via four programs: (1) the National Ambient Air Quality Program, which protects air quality and public health on the local level; (2) New Source Performance Standards, which set emission limits for new sources; (3) the New Source Review/Prevention of Significant Deterioration Program, which protects air quality from deteriorating, especially in clean areas; and (4) the Acid Rain Program, which addressees regional environmental problems often associated with long-range transport of SO_2 and other pollutants.

Table F-1. Emissions of Sulfur Dioxide: 1990 (Million Metric Tonnes)

Source	Emissions				
	1990	1991	1992	1993	1994
Fossil Fuel Combustion	**18.55**	**18.27**	**18.03**	**17.72**	**17.31**
Electric Utilities	14.42	14.32	13.99	13.78	13.49
Industrial	2.82	2.64	2.72	2.67	2.75
Commercial	0.37	0.37	0.38	0.38	0.38
Residential	0.17	0.17	0.17	0.17	0.17
Transportation	0.76	0.76	0.77	0.72	0.52
Industrial Processes	**1.360**	**1.330**	**1.360**	**1.390**	**1.430**
Metals Processing	0.600	0.570	0.590	0.610	0.630
Chemical and Allied Manufacturing	0.400	0.400	0.410	0.410	0.410
Asphalt Manufacturing	0.001	0.001	0.001	0.001	0.001
Agriculture, Food, Kindred Products	0.002	0.002	0.002	0.002	0.002
Wood, Pulp, Paper, and Publishing	0.120	0.120	0.130	0.130	0.130
Mineral Products	0.230	0.220	0.240	0.240	0.250
Solvent Use	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
Waste Incineration	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Fossil Fuel Production, Distribution and Storage	**0.40**	**0.39**	**0.38**	**0.38**	**0.37**
Total	**20.35**	**20.02**	**19.81**	**19.52**	**19.16**

Source: U.S. EPA, 1995b
Note: Totals may not add to the sum of the individual source categories due to independent rounding.

Table F-2. Emissions of SO_2 from Fossil Fuel Combustion by Fuel Source: 1990 (Million Metric Tonnes)

Fuel Source	Emissions				
	1990	1991	1992	1993	1994
Coal	15.672	15.285	15.205	14.880	14.715
Fuel Oil	2.179	2.295	2.133	2.144	1.893
Natural Gas	0.322	0.322	0.318	0.317	0.316
Wood[a]	0.006	0.006	0.006	0.006	0.006
Internal Combustion	0.033	0.037	0.034	0.034	0.036
Other Fuels[b]	0.336	0.330	0.337	0.340	0.350
Total	**18.548**	**18.275**	**18.033**	**17.721**	**17.316**

Source: U.S. EPA (1995b)
Notes: Totals may not add to the sum of the independent source categories due to independent rounding.
[a] Residential sector only.
[b] Other fuels include: LPG, waste oil, coke oven gas, coke, and wood from sectors other than the residential sector.

ANNEX G
IPCC REPORTING TABLES

This annex contains a series of tables which summarize the emissions and activity data discussed in the body of this report. These tables conform to guidelines established by the IPCC (IPCC/OECD/IEA, 1995; Vol. 1) for consistent international reporting of greenhouse gas emissions inventories. The format of these tables does not always correspond directly with the calculations discussed the body of the report. In these instances, the data have been reorganized to conform to the IPCC tables. As a result, a few slight differences may exist between the figures presented in the IPCC tables and those in the body of the report. These differences are merely an artifact of the variation in format and total U.S. emissions are unaffected.

Minimum Data Tables 1 A Energy: 1994

SOURCE AND SINKS	ACTIVITY DATA		EMISSIONS ESTIMATES						AGGREGATE EMISSION FACTORS					
Sector Specific Data (TBtu)	A Consumption [a]		B (Gg of full mass)						C (kg pollutant /GJ) C = B/A					
	(TBtu)	(PJ)	CO2	CH4 [c]	N20	NOx	CO	NMVOC	CO2	CH4	N20	NOx	CO	NMVOC
1-A-1 Energy & Transformation Activities														
(Electric Utilities)	20,977	22,133	1,818,000	14	15	7,070	295	33	82.14	6.40E-04	6.55E-04	3.19E-01	1.33E-02	1.48E-03
Oil	968	1,022	76,000	-	-	-	-	-	74.40	-	-	-	-	-
Gas	3,099	3,270	164,000	-	-	-	-	-	50.16	-	-	-	-	-
Coal	16,910	17,842	1,578,000	-	-	-	-	-	88.44	-	-	-	-	-
1-A-2 Industry (ISIC)	20,987	22,144	1,092,000	9	17	2,907	609	123	49.31	4.12E-04	7.65E-04	1.31E-01	2.75E-02	5.57E-03
Oil	8,838	9,325	365,000	-	-	-	-	-	39.14	-	-	-	-	-
Gas	9,688	10,222	497,000	-	-	-	-	-	48.62	-	-	-	-	-
Coal	2,461	2,597	230,000	-	-	-	-	-	88.58	-	-	-	-	-
1-A-3 Transportation	23,238	24,518	1,551,000	267	106	9,636	69,607	7,753	63.26	1.09E-02	4.34E-03	3.93E-01	2.84E+00	3.16E-01
Oil	22,572	23,816	1,516,000	-	-	-	-	-	63.65	-	-	-	-	-
Gas	665	702	35,000	-	-	-	-	-	49.86	-	-	-	-	-
Coal	0	0	0	-	-	-	-	-	NE	-	-	-	-	-
1-A-4 Commercial	3,935	4,152	227,000	1	1	289	122	15	54.67	2.68E-04	2.35E-04	6.97E-02	2.95E-02	3.50E-03
Oil	780	823	57,000	-	-	-	-	-	69.28	-	-	-	-	-
Gas	3,070	3,240	162,000	-	-	-	-	-	50.01	-	-	-	-	-
Coal	85	90	8,000	-	-	-	-	-	89.16	-	-	-	-	-
1- A-5 Residential	6,602	6,966	374,000	622	4	370	3,405	633	53.69	8.92E-02	5.35E-04	5.31E-02	4.89E-01	9.09E-02
Oil	1,460	1,540	101,000	-	-	-	-	-	65.58	-	-	-	-	-
Gas	5,086	5,366	268,000	-	-	-	-	-	49.94	-	-	-	-	-
Coal	57	60	5,000	-	-	-	-	-	83.35	-	-	-	-	-
1-A-6 Agriculture / Forestry	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Oil	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Gas	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Coal	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
1-A-8 Territories	489	516	36,000	NE	NE	NE	NE	NE	69.83	NE	NE	NE	NE	NE
Oil	481	507	35,000	NE	NE	NE	NE	NE	68.97	NE	NE	NE	NE	NE
Gas	NA	NA	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Coal	8	8	1,000	NE	NE	NE	NE	NE	123.31	NE	NE	NE	NE	NE
1-A-8 Biomass [b]	2,335	2,463	185,500	[b]	[b]	[b]	[b]	[b]	75.30	NE	NE	NE	NE	NE
Wood	2,237	2,360	178,700	[b]	[b]	[b]	[b]	[b]	75.71	NE	NE	NE	NE	NE
Ethanol	98	103	6,800	[b]	[b]	[b]	[b]	[b]	65.90	NE	NE	NE	NE	NE
TOTAL	**76,228**	**80,429**	**5,098,000**	**945**	**143**	**20,273**	**74,037**	**8,556**						

NA = Not Available; NE = Not Estimated; NO = Not Occurring
"-" = Value is not estimated separately, but included in an aggregate figure.
Note: Totals may not equal sum of components due to independent rounding.
[a] Estimates other than CO2 were often calculated via methodologies other than the IPCC default and do not necessarily use the activity data listed in this table. For CO2 calculations a detailed bottom-up approach was implemented using activity data disaggregated by sector and fuel type.
[b] CO2 emissions estimates from biomass consumption are from commercial, industrial, residential, transportation, and electric power production applications. They are provided for informational purposes only and are not included in national totals. Estimates of non-CO2 emissions from these sources were calculated via U.S. EPA methodologies and are incorporated in sectoral estimates of stationary and mobile combustion.
[c] Total methane emissions include 32 Gg from natural gas consumption which was not sector specific.

1 B 1 Fugitive Emissions (Oil and Gas)

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES		AGGREGATE EMISSIONS FACTORS	
	Fuel Quantity (PJ)	CH4 (Gg)	CO2 (Gg)	CH4 (g/GJ)	CO2 (kg/GJ)
1 B 1 a Crude Oil (Total)	**NA**	**270**	**NA**		
i Production [a] (no. of wells drilled)	306,298 [b]	253 [i]	NA	0.83	NA
ii Transportation	4,801 [c]	5	NA	1.04	NA
iii Refined [d]	33,817	12	NA	0.34	NA
1 B 1 b Natural Gas (Total)	**37,539**	**3,030**	**5,000**		
i Production [e]	18,299 [g]	1,410	5,000 [h]	77.05	273.24
ii Consumption [f]	19,240 [g]	1,620	NA	84.20	NA

NA = Not Applicable; NE = Not Estimated

Note: Totals may not equal sum of components due to independent rounding.

[a] Fugitive, routine maintenance, and venting and flaring emissions from oil production.

[b] Activity data represents the 1993 count for active oil wells attributed to crude oil emissions. The 1993 number was used to calculate the preliminary emissions estimate for 1994 because 1994 data was unavailable. The number is reported in "Worldwide Look at Reserves and Production," Oil and Gas Journal, December 1994, and represents 52% of active oil wells in the U.S. for 1993. 48% are attributed to natural gas emissions (USEPA, 1993a).

[c] Activity data represents the sum of domestic and imported oil tankered (EIA, 1994k).

[d] Activity data represents the amount of domestic and imported crude oil refined and stored in the U.S. (EIA 1994k).

[e] All emissions from gas production and processing facilities, not including fugitive emissions from gas producing oil wells. Also, emissions from compressor engines are not included.

[f] Emissions from natural gas transmission, distribution, and storage.

[g] The activity data are taken from Natural Gas Annual 1993 (EIA, 1994i).

[h] Consists exclusively of flared natural gas.

[i] This includes 22.3 Gg of fugitive emissions from oil wells, 0.05 Gg of routine maintenance emissions, and 231 Gg of venting and flaring emissions. Venting and flaring emissions were estimated by Radian (1992) at about 4% of total venting and flaring reported each year, or 92.5 Gg. Barns and Edmonds (1990) estimated venting and flaring emissions at 29% of total venting and flaring reported each year, or 462 Gg. A point estimate of 10%, or 231 Gg, is used in this report.

1 B 2 Fugitive Emissions (Coal Mining)

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES			AGGREGATE EMISSIONS FACTORS [c]	
	Production [a] (MMT)	Total CH4 (Gg)	Production (Gg)	Post Processing (Gg)	Production (Gg CH4 / MMT)	Post Processing (Gg CH4 / MMT)
1 B 2 Coal Mining (Total) [b]	**937**	**4,330**	**[b]**	**[b]**		
a Surface	[b]	[b]	[b]	[b]	NA	NA
b Underground	[b]	[b]	[b]	[b]	NA	NA

NA= Not Available

Note: Totals may not equal sum of components due to independent rounding.

[a] Production figures are preliminary 1994 EIA estimates.

[b] Only aggregate estimates are given since detailed figures (i.e. surface vs. underground and production vs. post processing) will not be available from EIA until December 1995.

[c] Emission factors are given as Gg CH4 per million metric tonnes of coal produced.

Minimum Data Tables 2 Industrial Processes

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES (shaded boxes not applicable)						AGGREGATE EMISSION FACTORS (shaded boxes not applicable)					
Sector Specific Data	A Production Quantity	B Full Mass of Pollutant (Gg)						C (kg pollutant per tonne of product) C = B/A					
	(Gg)	CO	CO2	CH4	N2O	NOx	NMVOC	CO	CO2	CH4	N2O	NOx	NMVOC
2 INDUSTRIAL PROCESSES (Total)		**4,557**	**23,084**	**NE**	**0**	**640**	**3,482**						
A Iron and Steel	NE	[a]	NE	NE	[a]		[a]	[a]	NE	NE	NE		[a]
B Non-Ferrous Metals													
Aluminum Production [b]	3,299	[a]	0		NE		[a]	[a]	0.00		NE		[a]
C Inorganic Chemicals (excluding. solvents)													
Nitric Acid	8,005				0.0						0.00		
Fertilizer Production	NE				NE	[a]					NE	[a]	
Carbon Dioxide Production	4,488	[a]	3,842		NE	[a]		[a]	0.86		NE	[a]	
D Organic Chemicals													
Adipic Acid	815				0.0		[a]				0.00		[a]
E Non-Metallic Mineral Products													
Cement	73,069	[a]	0	NE				[a]	0.00	NE			
Lime	17,400	[a]	9,649	NE				[a]	0.55	NE			
Soda Ash Production	14,600	[a]	6,103	NE				[a]	0.42	NE			
Soda Ash Use	6,260	[a]	0	NE				[a]	0.00	NE			
Limestone Use	10,351	[a]	3,489	NE				[a]	0.34	NE			
F Other Industry [c]													
Chemical & Allied Products	NE	1,858				264	1,431	NE				NE	NE
Metals Processing	NE	1,965				76	70	NE				NE	NE
Other Industrial	NE	681				298	373	NE				NE	NE
Storage and Transport	NE	53				3	1,608	NE				NE	NE

NA = Not Available; NE = Not Estimated

Note: Totals may not equal sum of components due to independent rounding.

[a] These estimates are encompassed in 2 F, "Other Industry" (see [b]).

[b] CO2 emissions from aluminum production are included in this table for informational purposes, but is not included in the national total in order to prevent double counting these emissions, which are included under non-fuel industrial uses in the Energy section.

[c] The "Other Industry" category is used to report NOx, CO, and NMVOC emissions for industry. Since these emissions estimates were taken directly from another report, no activity data or aggregate emissions factors are presented.

Minimum Data Tables 3 Solvents

SOURCE AND SINK CATEGORIES	ACTIVITY DATA	EMISSIONS ESTIMATES (shaded boxes not applicable)			AGGREGATE EMISSION FACTORS		
Sector Specific Data	A Quantity Consumed (kt)	B Full Mass of Pollutant (Gg)			C Tonne of pollutant per tonne of product (kg pollutant /GJ) C = B/A		
		CO	NMVOC	NOx	CO	NMVOC	NOx
3 Solvents (Total)	**NA**	**2**	**5,727**	**3**	**NA**	**NA**	**NA**
A. Degreasing	NA	1	712	-	NA	NA	NA
B. Dry Cleaning	NA	NA	200	NA	NA	NA	NA
C. Graphic Arts	NA	-	359	-	NA	NA	NA
D. Surface Coating (including. Paint)	NA	1	2,516	2	NA	NA	NA
E. Other Industrial	NA	-	115	-	NA	NA	NA
F. Non-Industrial	NA		1,824			NA	

NA = Not Available.
"-" = less than 0.0004535 Gg (453.5 metric tonnes).
Note: Totals may not equal sum of components due to independent rounding.

Minimum Data Tables 4 Agriculture
4 A & B Enteric Fermentation and Manure Management

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSIONS ESTIMATES		AGGREGATE EMISSIONS FACTOR	
	A		B		C	
Sector Specific Data	Number of Animals [b]					
	Enteric Fermentation	Manure Management	Enteric Fermentation	Manure Management	Enteric Fermentation	Manure Management
	(1000 head)		(Gg CH4)		(kg CH4 per animal) C = (B/A) X 1000	
4 Agriculture						
A & B Enteric Fermentation & Manure Management (Total)	**185,025**	**2,156,429**	**6,020**	**2,538**		
1.i Beef Cattle	89,687	89,687	4,270	215	47.6	2.4
1.ii Dairy Cattle [a]	17,758	17,758	1,480	839	83.3	47.2
2. Goats	2,595	2,595	10	27	3.9	10.4
3. Sheep	9,742	9,742	80	3	8.2	0.3
4. Pigs	60,028	60,028	90	1,135	1.5	18.9
5. Horses/Mules/Asses	5,215	5,215	90	27	17.3	5.2
6. Buffalo	NE	NE	NE	NE	NA	NA
7. Camels and Llamas	NO	NO	NO	NO	NA	NA
8. Poultry	NA	1,971,404	NA	292	NA	0.1

NA = Not Applicable; NE = Not Estimated; NO = Not Occurring

Note: Totals may not equal sum of components due to independent rounding.

[a] It is assumed that the number of dairy calves is equal to the number of dairy cattle replacements (= 4,135)

[b] Population figures are based on USDA data (1995a-d, 1995g, 1995h, 1995m, 1994a, 1994c-d).
For a more complete description of the derivation of the population figures, see Annex D.

4 C Rice Cultivation

SOURCE AND SINK CATEGORIES	ACTIVITY DATA [a]		EMISSION ESTIMATES	AGGREGATE EMISSIONS FACTOR
Sector Specific Data	A Area Harvested (Mha)	B Hectare-Days of Cultivation [a] (Mha-days)	C Emissions of Methane [a] (Gg CH4)	D Average Emission Factor [a] (kg CH4 per ha-day) D = C/B
C Rice Cultivation (Total)	**1.488**	**154.131**	**515.9**	**3.35**
1. Flooded Regime (Total)	1.488	154.131	515.9	3.35
Arkansas	0.575	50.313	185.0	3.68
California	0.196	27.048	97.5	3.60
Florida: primary	0.089	9.345	3.4	0.37
rantoon [b]	0.045	4.725	1.7	0.36
Louisiana: primary	0.251	26.355	96.5	3.66
rantoon [b]	0.075	7.875	29.5	3.75
Mississippi	0.127	9.970	34.4	3.45
Missouri	0.050	4.500	16.3	3.62
Texas: primary	0.143	10.010	36.9	3.69
rantoon [b]	0.057	3.990	14.8	3.71
2. Intermittent Regime	NO	NO	NO	NO
3. Dry Regime	NO	NO	NO	NO

NO = Not occurring in the U.S.
Note: Totals may not equal sum of components due to independent rounding.
[a] Numbers are based on average flooding season length.
[b] Ratoon cropping is estimated to account for about 30% of the primary crop in Louisiana, 40% in Texas (Lindau and Bollich, 1993), and 50% in Florida (Schudeman, 1995).

4 D Agricultural Soils

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSION ESTIMATES	AGGREGATE EMISSIONS FACTORS	
Sector Specific Data	A Amount of Nitrogen Applied in Fertilizer and Manure (tonnes N)	B Area Cultivated [a] (ha)	C (Gg N2O)	D Nitrous Oxide Released per tonne Nitrogen Applied (g N2O/ g N) D = C/A	E Amount of Biological Fixation of Nitrogen (tonnes N)
D Agricultural Soils					
1. Fertilizer Use	11,469,500	NE	210.9	0.0184	NE

[a] Since the estimate was made directly from the total amount of nitrogen applied, the area cultivated was not calculated.

4 E Agricultural Waste Burning

SOURCE AND SINK CATEGORIES	ACTIVITY DATA			EMISSION ESTIMATE				AGGREGATE EMISSION FACTORS			
Sector Specific Data	A Annual Burning of Crop Residues [a]	B Carbon Fraction	B Nitrogen Fraction	C Full Mass of Pollutant (Gg)				D Pollutant per tonne of dry matter (kg / t dm) D = C/A x 1,000			
	(Gg dm)	(t C / t dm)	(t N / t dm)	CH4	N20	NOx	CO	CH4	N20	NOx	CO
E Agricultural Waste Burning (Total)	**39,388**			**122.3**	**5.4**	**116.0**	**2,561.8**	**3.11**	**0.14**	**2.95**	**65.04**
1. Cereals (Total)	25,698			81.0	2.0	45.0	1,702.0	3.15	0.08	1.75	66.23
Wheat	5,711	0.4853	0.003	18.5	0.2	4.4	388.0	3.24	0.03	0.78	67.94
Barley	681	0.4567	0.004	2.1	+	0.7	43.5	3.04	0.00	1.04	63.94
Maize	16,382	0.4709	0.0081	51.4	1.5	34.4	1,080.0	3.14	0.09	2.10	65.93
Oats	321	0.4853	0.007	1.0	+	0.6	21.8	3.24	0.00	1.82	67.94
Rye	33	0.4853	0.007	0.1	+	0.1	2.2	3.24	0.00	1.82	67.94
Rice	874	0.4144	0.0067	2.4	0.1	1.5	50.7	2.76	0.07	1.74	58.02
Millet	18	0.4853	0.007	0.1	+	+	1.2	3.24	0.00	0.00	67.94
Sorghum	1,678	0.4853	0.0085	5.4	0.2	3.7	114.0	3.24	0.09	2.20	67.94
2. Pulse (Total)	10,593			32.0	3.0	63.0	667.0	3.02	0.28	5.95	62.97
Soya	10,375	0.45	0.023	31.1	2.6	61.9	653.6	3.00	0.25	5.96	63.00
Beans	194	0.45	0.023	0.6	+	1.2	12.2	3.00	0.00	5.96	63.00
Peas	11	0.45	0.023	+	+	0.1	0.7	0.00	0.00	5.96	63.00
Lentils	13	0.45	0.023	+	+	0.1	0.8	0.00	0.00	5.96	63.00
3. Tubers / Roots (Total)	1,396			4.0	0.3	6.0	81.0	2.87	0.21	4.30	58.02
Sugarbeet	642	0.4072	0.0228	1.7	0.2	3.8	36.6	2.71	0.25	5.91	57.01
Artichoke	3	0.4226	0.011	+	+	+	0.2	0.00	0.00	0.00	59.16
Peanut	143	0.4226	0.011	0.4	+	0.4	8.5	2.82	0.00	2.85	59.16
Potatoes	591	0.4226	0.011	1.7	0.1	1.7	35.0	2.82	0.12	2.85	59.16
Other	17	0.4226	0.011	+	+	+	1.0	0.00	0.00	0.00	59.16
4. Sugar Cane (Total)	1,701	0.4695	0.003	5.3	0.1	1.3	111.8	3.13	0.03	0.78	65.73

"+" = value less than 0.05.

Note: Totals may not equal sum of components due to independent rounding.

[a] "Annual Burning of Crop Residues," or total biomass burned as given in Column H, Sheet A, Worksheet 4-4, in the IPCC Workbook (IPCC/OECD, 1995) is computed by multiplying crop production by the residue to crop ratio, the dry matter content, the fraction burned in the field, the burning efficiency, and the combustion efficiency.

5 D 3 Managed Forests: Net Emissions/Removals [a]

SOURCE AND SINK CATEGORIES	EMISSIONS / REMOVALS [b]
	(Gg CO2)
Total Growth Increment	NE
Total Harvest	NE
Net Emissions (+) or Removals (-)	NE

NE = Not Estimated

[a] No emission estimates were calculated for forestry and land-use change in 1994, since the latest timber inventory was in 1992 and the uncertainty of the estimation procedure precludes extrapolation of the data to 1994.

[b] The methodology used by the U.S. determines net emissions and removals via direct timber inventory, so growth increment and harvest are not calculated.

Minimum Data Tables 6 Waste
6 A Waste: Landfills

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSION ESTIMATES	AGGREGATE REMOVAL FACTORS	
	A Total MSW [a] (kg per year)	B MSW Landfilled [a] (kg)	C Methane Emissions (kg)	D Emission Factor (kg CH4 / kg MSW Landfilled) D = C/B	E Quantity of CH4 recovered [b] (kg CH4)
A Landfills	2.90E+05	1.95E+05	1.02E+10	52307.692	1.80E+09

[a] Source: Biocycle, 1995.
[b] Recovered methane is flared or used for energy production.

6 B Wastewater (Sewage Treatment)

SOURCE AND SINK CATEGORIES	ACTIVITY DATA		EMISSION ESTIMATES	AGGREGATE EMISSIONS FACTORS	
	A Quantity BOD5 in Wastewater (kg BOD5)	B Quantity of BOD5 anaerobically digested (kg BOD5)	C CH4 Emissions Emissions (kg)	D Emission Factor (kg CH4 / kg BOD5) [a] D = C/B	E Quantity of CH4 recovered (kg CH4)
B Wastewater					
Municipal	4.76E+09	7.14E+08	6.82E+10	95.45	NE
Industrial	NE	NE	NE	NE	NE

[a] The Emissions factor is given as kg of CH4 emitted per kg of BOD5 anaerobically digested.

Table 7 A Summary Report for National Greenhouse Gas Inventories 1994

(Part I)

Summary Report for National Greenhouse Gas Inventories (Gg)						
Greenhouse Gas Source and Sink Categories	CO2	CH4 [e]	N2O	NOx	CO	NMVOC
Total (Net) National Emission [h]	**5,126,084**	**96,126**	**359**	**21,032**	**81,158**	**17,765**
1 All Energy (Fuel Combustion + Fugitives)	**5,103,000**	**8,575**	**143**	**20,273**	**74,037**	**8,556**
A Fuel Combustion	5,098,000	945	143	20,273	74,037	8,556
Energy & Transformation Industrie	1,818,000	14	15	7,070	295	33
Industry (ISIC)	1,092,000	9	17	2,907	609	123
Transport	1,551,000	267	106	9,636	69,607	7,753
Commercial/Institutional	227,000	1	1	289	122	15
Residential	374,000	622	4	370	3,405	633
Agriculture/Forestry	NE	NE	NE	NE	NE	NE
U.S. Territories	36,000	NE	NE	NE	NE	NE
Biomass Burned for Energy	185,500	[b]	[b]	[b]	[b]	[b]
B Fugitive Fuel Emission	5,000	7,630	-	-	-	-
Oil and Natural Gas Activities	5,000	3,300	-	-	-	-
Coal Mining	-	4,330	-	-	-	-
2 Industrial Processes (Total)	**58,191**	**NE**	**106**	**640**	**4,557**	**3,482**
A Iron and Steel	NE	NE	-	[d]	[d]	[d]
B Non-Ferrous Metals [f]	0	-	NE	[d]	[d]	[d]
C Inorganic Chemicals (excluding solvent	3,842	-	0.0	[d]	[d]	[d]
D Organic Chemicals	-	-	0.0	[d]	[d]	[d]
E Non-Metallic Mineral Products	19,241	NE	-	[d]	[d]	[d]
F Other Industry [c]	-	-	-	640	4,557	3,482
3 Solvent and Other Product Use (Total)	**-**	**-**	**-**	**3**	**2**	**5,727**
A Degreasing	-	-	-	-	1	712
B Dry Cleaning	-	-	-	NA	NA	200
C Graphic Arts	-	-	-	-	-	359
D Surface Coating (including paint)	-	-	-	2	1	2,516
E Other Industrial	-	-	-	-	-	115
F Non-Industrial	-	-	-	0	0	1,824

Table 7 A Summary Report for National Greenhouse Gas Inventories 1994
(Part 2)

Summary Report for National Greenhouse Gas Inventories (Gg)						
Greenhouse Gas Source and Sink Categories	CO2	CH4	N2O	NOx	CO	NMVO
4 Agriculture (Total)	-	**9,196**	**216**	**116**	**2,562**	-
A Enteric Fermentation	-	6,020	-	-	-	-
B Manure Management	-	2,538	-	-	-	-
C Rice Cultivation	-	516	-	-	-	-
D Agricultural Soils	-	-	211	-	-	-
E Agricultural Waste Burning	-	122	5	116	2,562	-
F Savannah Burning	NO	NO	NO	NO	NO	NO
5 Land Use Change and Forestry [g]	NE	NE	NE	NE	NE	NE
A Forest Clearing & On Site Burning	NE	NE	NE	NE	NE	NE
of Cleared Forests	NE	NE	NE	NE	NE	NE
B Grassland Conversion	NE	NE	NE	NE	NE	NE
C Abandonment of Managed Lands	NE	NE	NE	NE	NE	NE
D Managed Forests	NE	NE	NE	NE	NE	NE
6 Waste	-	**78,355**	-	-	-	-
A Landfills	-	10,200	-	-	-	-
B Wastewater	-	68,155	-	-	-	-
C Incineration	-	-	-	-	-	-

NA = Not Available; NE = Not Estimated; NO = Not Occurring
"-" = Information not applicable.
Note: Totals may not equal sum of components due to independent rounding.
[a] Reserved for future use.
[b] CO2 emissions estimates from biomass consumption are from commercial, industrial, residential, transportation, and electric power production applications. They are provided for informational purposes only and are not included in national totals. Estimates of non-CO2 emissions from these sources were calculated via U.S. EPA methodologies and are incorporated in sectoral estimates of stationary and mobile combustion.
[c] The "Other Industry" category is used to report NOx, CO, and NMVOC emissions for industry.
[d] These estimates are included in the category 2 F: Other Industry, as noted in footnote [c].
[e] Total methane emissions from energy include 32 Gg from natural gas consumption which is not sector specific.
[f] The non-ferrous metals category consists exclusively of aluminum production. Emissions of CO2 from aluminum production are reported in this table for informational purposes, but are not counted in the national total, because they are included under non-fuel industrial use in the Energy section.
[g] Due to the unique nature of forestry in the U.S., it is believed that the only significant area of forest related carbon flux occurs as a result of forest management practices. Flux due to forest managment was not estimated in 1994, but is likely to be a sink of the same magnitude as earlier years (532,000 Gg CO2 for 1992).
[h] Please note that total CO2 is abnormally high since carbon dioxide sequestration from land use change and forestry was not estimated in 1994.

Table 7 B Short Summary Report for National Greenhouse Gas Inventories 1994

Short Summary Report for National Greenhouse Gas Inventories (Gg)						
Greenhouse Gas Source and Sink Categories	CO2	CH4	N2O	NOx	CO	NMVOC
Total National Sources and Sinks	**5,126,084**	**96,126**	**359**	**21,032**	**81,158**	**17,765**
Total National Sources	5,126,084	96,126	359	21,032	81,158	17,765
Total National Sinks	NE	0	0	0	0	0
1 All Energy (Fuel Combustion + Fugitives)	5,103,000	8,575	143	20,273	74,037	8,556
A Fuel Combustion	5,098,000	945	143	20,273	74,037	8,556
B Fugitive Fuel Emission	5,000	7,630	-	-	-	-
2 Industrial Processes	23,084	NE	0	640	4,557	3,482
3 Solvent and Other Product Use	-	-	-	3	2	5,727
4 Agriculture (Total)	-	9,196	216	116	2,562	0
A Enteric Fermentation	-	6,020	-	-	-	-
B Manure Management	-	2,538	-	-	-	-
C Rice Cultivation	-	516	-	-	-	-
D Agricultural Soils	-	-	211	-	-	-
E Agricultural Waste Burning	-	122	5	116	2,562	-
F Savannah Burning	NO	NO	NO	NO	NO	NO
5 Land Use Change and Forestry	NE	-	-	-	-	-
6 Waste	-	78,355	-	-	-	-

NA = Not Available; NE = Not Estimated; NO = Not Occurring;
"-" = Information not applicable.
Note: Totals may not equal sum of components due to independent rounding.

Table 8 A Overview Table for National Greenhouse Gas Inventories

OVERVIEW TABLE															
GREENHOUSE GAS SOURCE AND SINK CATEGORIES	CO2		CH4		N2O		NOx		CO		NMVOC		Documen-tation	Dissaggre-gation	Footnotes
	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality	Estimate	Quality			
1 All Energy (Fuel Combustion + Fugitive)															
A Fuel Combustion	ALL	H	ALL	M	ALL	L	ALL	M	ALL	M	ALL	M	H	2	[a]
B Fugitive															
1 Coal Production	-	-	ALL	H	-	-	-	-	-	-	-	-	H	3	
2 Oil and Gas Systems	ALL	M	ALL	L	-	-	All	M	All	M	All	M	M	3	
2 Industrial Processes	ALL	H	-	-	ALL	H	All	M	All	M	All	M	M	3	
3 Solvent Use and Other Product Use	-	-	-	-	-	-	All	M	All	M	All	M	L	3	
4 Agriculture															
A Enteric Fermentation	-	-	ALL	M	-	-	-	-	-	-	-	-	H	3	
B Manure Management	-	-	ALL	M	-	-	-	-	-	-	-	-	H	3	
C Rice Cultivation	-	-	ALL	M	-	-	-	-	-	-	-	-	H	3	
D Agricultural Soils	-	-	-	-	PART	L	-	-	-	-	-	-	M	1	
E Agricultural Waste Burning	-	-	ALL	L	ALL	L	ALL	L	ALL	L	NE	-	H	3	
F Savannah Burning	-	-	NO	-	NO	-	NO	-	NO	-	NO	-			
5 Land Use Change and Forestry	PART	L	-	-	-	-	-	-	-	-	-	-	M	1	[b]
6 Waste	-	-	-	-	-	-	-	-	-	-	-	-			
A Landfills	-	-	ALL	M	-	-	-	-	-	-	-	-	H	3	
B Wastewater	-	-	PART	L	-	-	-	-	-	-	-	-	H	2	

[a] Some of the combustion calculations are based on currently unpublished data, which will in early 1996.

[b] No emission estimates were calculated for forestry and land-use change in 1994 due to lack of data. When calculated for earlier years, soil carbon flux was not included.

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