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INTERNATIONAL ANTHROPOGENIC METHANE EMISSIONS:

ESTIMATES FOR 1990

REPORT TO CONGRESS

Editor: Michael J. Adler

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TABLE OF CONTENTS

Acknowledgements xiii

EXECUTIVE SUMMARY ES-1
ES.1 GLOBAL METHANE EMISSIONS AND THE U.S. NATIONAL ACTION PLAN ES-1
ES.2 KEY CONCLUSIONS OF THE REPORT ES-1
ES.3 OVERVIEW OF GLOBAL ANTHROPOGENIC CH_4 EMISSIONS ES-2
ES.4 CURRENT ESTIMATES OF GLOBAL ANTHROPOGENIC METHANE EMISSIONS ES-3
ES.4.1 Estimates by Source ES-3
ES.4.2 Regional Estimates ES-4
ES.4.3 Country Estimates ES-5
ES.5 REDUCING UNCERTAINTIES IN METHANE EMISSION ESTIMATES .. ES-7
ES.6 REFERENCES ES-7

1. INTRODUCTION 1-1
1.1 BACKGROUND 1-1
1.1.1 The Importance of Methane to Potential Greenhouse Warming 1-1
1.1.2 An Overview of Methane 1-2
1.1.3 The Atmospheric History and Geographic Distribution of Methane .. 1-4
1.1.4 The Role of Methane in Global Climate Change 1-8
1.1.5 The Methane Budget 1-10
1.1.6 Summary 1-12
1.2 OVERVIEW OF THIS REPORT 1-13
1.3 REFERENCES 1-14

2. METHANE EMISSIONS FROM THE DIGESTIVE PROCESSES OF LIVESTOCK 2-1
2.1 SUMMARY 2-1
2.2 BACKGROUND 2-1
2.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS. 2-4
2.3.1 Implementation of the Methodology 2-5
2.4 RESULTS 2-24
2.4.1 Cattle 2-24
2.4.2 Other Livestock 2-25
2.5 TRENDS 2-25
2.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES 2-29
2.7 CONCLUSIONS 2-29
2.8 REFERENCES 2-30
APPENDIX A: EMISSION FACTORS FOR BUFFALO 2-34
A.1 FEED INTAKES 2-34
A.2 METHANE EMISSION FACTORS 2-38
A.3 REFERENCES 2-40
APPENDIX B: DERIVATION OF THE RELATIONSHIP BETWEEN NE AND DE . 2-42
B.1 REFERENCES 2-44

TABLE OF CONTENTS (Continued)

3. METHANE EMISSIONS FROM RICE CULTIVATION 3-1
3.1 SUMMARY 3-1
3.2 BACKGROUND 3-1
3.2.1 Methane Emission Rates From Rice Fields 3-2
3.2.2 Factors Affecting Methane Emissions 3-3
3.2.3 Regional Estimates of Methane Emissions 3-13
3.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS 3-16
3.3.1 Summary of Recommended Method 3-17
3.4 RESULTS 3-20
3.5 TRENDS 3-20
3.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES 3-21
3.6.1 Specific Estimation Problems 3-21
3.6.2 Verification of Country Inventories 3-21
3.7 CONCLUSIONS 3-21
3.8 REFERENCES 3-25

4. METHANE EMISSIONS FROM ANTHROPOGENIC BIOMASS BURNING 4-1
4.1 SUMMARY 4-1
4.2 BACKGROUND 4-2
4.2.1 Introduction 4-2
4.2.2 Varieties of Biomass Burning 4-7
4.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS 4-16
4.3.1 Review of IPCC-OECD Methodology 4-16
4.3.2 Methodology Used in this Chapter 4-18
4.4 RESULTS 4-22
4.5 TRENDS 4-24
4.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES 4-25
4.7 CONCLUSIONS 4-27
4.8 REFERENCES 4-28

5. METHANE EMISSIONS FROM OIL AND NATURAL GAS SYSTEMS 5-1
5.1 SUMMARY 5-1
5.2 BACKGROUND 5-1
5.2.1 Overview of Oil and Natural Gas Systems 5-1
5.2.2 Sources of Methane Emissions in Oil and Natural Gas Systems 5-5
5.2.3 Emission Data 5-9
5.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS 5-10
5.3.1 Definition of Regions 5-14
5.3.2 Emission Factors 5-14
5.3.3 Activity Levels 5-18
5.4 RESULTS 5-20
5.5 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES 5-20
5.6 TRENDS 5-22
5.7 CONCLUSIONS 5-22
5.8 REFERENCES 5-23

TABLE OF CONTENTS (Continued)

APPENDIX A: DERIVATION OF NON-U.S. EMISSION FACTORS FOR FUEL COMBUSTION 5-25
APPENDIX B: EMISSION ESTIMATES BY REGION 5-28

6. METHANE EMISSIONS FROM THE COAL FUEL CYCLE 6-1
6.1 SUMMARY 6-1
6.2 BACKGROUND 6-3
6.2.1 Processes of Methane Generation and Emission in Coal 6-3
6.2.2 Key Emission Processes of the Coal Fuel Cycle 6-4
6.2.3 Previous Methane Emission Studies 6-5
6.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS 6-8
6.3.1 Underground Mining 6-8
6.3.2 Treatment of Methane Utilization 6-14
6.3.3 Surface Mining 6-15
6.3.4 Post-Mining Activities 6-18
6.3.5 Coal Combustion 6-21
6.3.6 Treatment of Other Coal Fuel Cycle Emissions 6-21
6.4 RESULTS 6-22
6.4.1 General Findings 6-22
6.4.2 Country-Specific Information 6-25
6.5 TRENDS 6-33
6.5.1 General Factors Influencing Emissions 6-33
6.5.2 National Trends 6-34
6.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES 6-37
6.6.1 Data Uncertainties 6-37
6.6.2 Methodological Uncertainties 6-38
6.6.3 Research Needs 6-40
6.7 CONCLUSIONS 6-41
6.8 REFERENCES 6-41

7. MINOR INDUSTRIAL SOURCES OF METHANE 7-1
7.1 SUMMARY 7-1
7.2 BACKGROUND 7-1
7.2.1 Recent Research 7-2
7.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS 7-6
7.3.1 Peat Mining and Geothermal Power Production 7-7
7.3.2 Coke Production and Iron-and-Steel Production Processes 7-7
7.3.3 Miscellaneous Industrial Processes 7-8
7.3.4 Paper and Printing Processes 7-8
7.3.5 Chemical Manufacturing Processes 7-8
7.4 RESULTS 7-8
7.5 TRENDS 7-10
7.6 CONCLUSIONS 7-12
7.7 REFERENCES 7-13

TABLE OF CONTENTS (Continued)

8. METHANE EMISSIONS FROM LANDFILLS AND OPEN DUMPS 8-1
8.1 SUMMARY 8-1
8.2 BACKGROUND 8-1
8.2.1 Methane Production from the Anaerobic Decomposition of Waste . . 8-1
8.2.2 Factors Affecting CH_4 Potential from Landfilled Waste 8-3
8.2.3 Determination of the CH_4 Potential of MSW 8-4
8.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS 8-5
8.3.1 Estimation of Waste-Generation Rates 8-5
8.3.2. AEERL Regression Model Methodology 8-11
8.3.3 Draft IPCC/OECD Methodology 8-12
8.4 RESULTS 8-13
8.5 TRENDS 8-13
8.5.1 Europe 8-14
8.5.2 United States and Canada 8-14
8.5.3 Asia 8-15
8.5.4 Latin America and the Caribbean Islands 8-15
8.5.5 Africa and Middle East 8-15
8.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES 8-15
8.6.1 Quantity and Composition of Waste-in-Place 8-15
8.6.2 CH_4 Production of Waste in Open Dumps and Industrial Landfills . 8-16
8.6.3 Quantity of CH_4 Emitted to the Atmosphere 8-16
8.7 CONCLUSIONS 8-17
8.8 REFERENCES 8-17

9. METHANE EMISSIONS FROM LIVESTOCK MANURE 9-1
9.1 SUMMARY 9-1
9.2 BACKGROUND 9-1
9.2.1 Characteristics of the Manure 9-2
9.2.2 Manure Management System 9-2
9.2.3 Climate 9-3
9.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS 9-3
9.3.1 Volatile Solids (VS) Production 9-5
9.3.2 Maximum Methane-Producing Capacity (B_o) 9-6
9.3.3 Descriptions of Manure Management Systems 9-7
9.3.4 Methane Conversion Factors (MCFs) 9-9
9.3.5 Livestock Manure Management System Usage (MS%) 9-10
9.4 RESULTS 9-14
9.5 TRENDS 9-14
9.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES 9-17
9.7 CONCLUSIONS 9-19
9.8 REFERENCES 9-20

10. METHANE EMISSIONS FROM WASTEWATER 10-1
10.1 SUMMARY 10-1
10.2 BACKGROUND 10-1

TABLE OF CONTENTS (Continued)

10.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS ... 10-3
10.3.1 Assumptions and Data Used to Estimate Emissions ... 10-4
10.4 RESULTS ... 10-11
10.5 TRENDS ... 10-11
10.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES ... 10-14
10.6.1 Activity Data: Quantities of Wastewater Flows ... 10-14
10.6.2 Methane Yield per Unit BOD Loading ... 10-15
10.6.3 Efficiency and Output of Wastewater Treatment Facilities ... 10-15
10.6.4 BOD Values and Other Physical and Chemical Data ... 10-15
10.7 CONCLUSIONS ... 10-16
10.8 REFERENCES ... 10-16

11. VERIFICATION OF METHANE EMISSIONS ... 11-1
11.1 INTRODUCTION ... 11-1
11.2 VERIFICATION METHODOLOGIES ... 11-3
11.2.1 Direct Verification ... 11-4
11.2.2 Indirect Verification ... 11-8
11.3 CONCLUSIONS ... 11-13
11.4 REFERENCES ... 11-14

LIST OF FIGURES

EXECUTIVE SUMMARY
FIGURE ES-1: GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY SOURCE ES-4
FIGURE ES-2: GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY REGION ES-5
FIGURE ES-3: METHANE EMISSIONS OF THE FIVE LARGEST EMITTING COUNTRIES ES-6

1. INTRODUCTION
FIGURE 1-1: MEASUREMENTS OF GLOBAL METHANE CONCENTRATIONS . 1-6
FIGURE 1-2: ATMOSPHERIC METHANE AND AIR TEMPERATURE RECORD DETERMINED FROM VOSTOK ICE CORE 1-7
FIGURE 1-3: SPATIAL AND TEMPORAL DISTRIBUTION OF ATMOSPHERIC METHANE 1-9

2. METHANE EMISSIONS FROM THE DIGESTIVE PROCESSES OF LIVESTOCK
FIGURE B-1: NRC NE:DE RELATIONSHIP 2-43
FIGURE B-2: LINEAR EXTRAPOLATION OF THE NRC NE:DE RELATIONSHIP 2-44

3. METHANE EMISSIONS FROM RICE CULTIVATION
FIGURE 3-1: SCHEME OF PRODUCTION, REOXIDATION, AND EMISSION OF CH_4 IN A PADDY FIELD 3-10
FIGURE 3-2: RELATIONSHIP BETWEEN THE FLUX AND SOIL TEMPERATURE IN A PADDY FIELD IN SICHUAN, CHINA 3-12
FIGURE 3-3: TIME SERIES OF GLOBAL CH_4 EMISSIONS FROM RICE AGRICULTURE 3-23
FIGURE 3-4: PER-CAPITA EMISSIONS OF METHANE (Tg CH_4 PER BILLION POPULATION (BP)) FROM RICE FIELDS IN CHINA DURING THE LAST CENTURY 3-24

4. METHANE EMISSIONS FROM ANTHROPOGENIC BIOMASS BURNING
FIGURE 4-1: CARBONACEOUS PRODUCTS OF BIOMASS BURNING 4-5
FIGURE 4-2: ESTIMATES OF METHANE EMISSIONS FROM GLOBAL BIOMASS BURNING 4-6
FIGURE 4-3: TYPES OF BIOMASS BURNING 4-8
FIGURE 4-4: ESTIMATING METHANE EMISSIONS FROM BIOMASS BURNING 4-17

5. METHANE EMISSIONS FROM OIL AND NATURAL GAS SYSTEMS
FIGURE 5-1: STAGES IN THE OIL & NATURAL GAS SYSTEM 5-2

LIST OF FIGURES (Continued)

6. METHANE EMISSIONS FROM THE COAL FUEL CYCLE
FIGURE 6-1: FLOW CHART FOR ESTIMATING METHANE EMISSION FROM THE COAL CYCLE 6-9
FIGURE 6-2: 1990 METHANE EMISSIONS FROM THE COAL FUEL CYCLE . . 6-26

10. METHANE EMISSIONS FROM WASTEWATER
FIGURE 10-1: WASTEWATER TREATMENT SYSTEMS AND METHANE PRODUCTION 10-2

LIST OF TABLES

ES. EXECUTIVE SUMMARY

TABLE ES-1: GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY SOURCE ES-9

TABLE ES-2: GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY REGION ES-10

TABLE ES-3: METHANE EMISSIONS OF THE FIVE LARGEST EMITTING COUNTRIES ES-11

1. INTRODUCTION

TABLE 1-1: SUMMARY OF ATMOSPHERIC PARAMETERS OF METHANE AND OTHER KEY GREENHOUSE GASES INFLUENCED BY HUMAN ACTIVITIES 1-3

TABLE 1-2: ESTIMATED SOURCES AND SINKS OF METHANE 1-5

2. METHANE EMISSIONS FROM THE DIGESTIVE PROCESSES OF LIVESTOCK

TABLE 2-1: CATTLE POPULATIONS: 1990 2-6

TABLE 2-2: REPRESENTATIVE CATTLE TYPES 2-7

TABLE 2-3: DATA ON REPRESENTATIVE CATTLE TYPES 2-11

TABLE 2-4: NET ENERGY REQUIREMENTS FOR REPRESENTATIVE CATTLE TYPES (MJ/day) 2-14

TABLE 2-5: GROSS ENERGY INTAKE FOR REPRESENTATIVE CATTLE TYPES 2-18

TABLE 2-6: METHANE EMISSION FACTORS FOR CATTLE 2-21

TABLE 2-7: EMISSION FACTORS FOR LIVESTOCK 2-23

TABLE 2-8: REGIONAL AND GLOBAL CATTLE EMISSIONS: 1990 2-26

TABLE 2-9: GLOBAL LIVESTOCK METHANE EMISSIONS 2-27

TABLE A-1: DATA ON BUFFALO SIZE 2-35

TABLE A-2: DATA ON REPRESENTATIVE BUFFALO TYPES 2-37

TABLE A-3: NET ENERGY REQUIREMENTS FOR REPRESENTATION BUFFALO TYPES (MJ/day) 2-37

TABLE A-4: GROSS ENERGY INTAKE FOR REPRESENTATIVE BUFFALO TYPES 2-39

TABLE A-5: METHANE EMISSION FACTORS FOR BUFFALO 2-39

3. METHANE EMISSIONS FROM RICE CULTIVATION

TABLE 3-1: METHANE FLUX MEASUREMENTS FROM RICE PADDIES 3-4

TABLE 3-2: SEASONAL FACTORS FOR METHANE EMISSIONS FROM RICE FIELDS 3-15

TABLE 3-3: ESTIMATES OF GLOBAL METHANE EMISSIONS FROM RICE AGRICULTURE 3-16

TABLE 3-4: ESTIMATES OF METHANE EMISSIONS BY COUNTRY FOR 1990 USING FOUR SETS OF ASSUMPTIONS (Tg CH_4/yr) 3-17

TABLE 3-5: RESULTS: AVERAGE ANNUAL (1990) METHANE EMISSION ESTIMATES AND AREA, SEASON, AND FLUX DATA FOR MAJOR RICE-PRODUCING COUNTRIES 3-22

LIST OF TABLES (Continued)

4. METHANE EMISSIONS FROM ANTHROPOGENIC BIOMASS BURNING

TABLE 4-1: ESTIMATES OF BIOMASS BURNED GLOBALLY (Pg dm/yr) 4-3
TABLE 4-2: BIOMASS-BURNING METHANE EMISSION FACTORS 4-20
TABLE 4-3: DEFAULT VALUES OF PARAMETERS FOR USE IN CALCULATING METHANE EMISSIONS FROM BIOMASS BURNING 4-21
TABLE 4-4: ESTIMATES OF METHANE EMISSIONS FROM ANTHROPOGENIC BIOMASS BURNING (Gg CH_4/year) 4-23

5. METHANE EMISSIONS FROM OIL AND NATURAL GAS SYSTEMS

TABLE 5-1: MAJOR OIL- AND GAS-PRODUCING AND OIL-REFINING COUNTRIES 5-3
TABLE 5-2: EMISSIONS FROM OIL AND NATURAL GAS SYSTEMS 5-8
TABLE 5-3: SUMMARY OF EMISSION FACTORS 5-11
TABLE 5-4: U.S. EMISSION FACTORS 5-15
TABLE 5-5: EASTERN EUROPE AND THE FORMER SOVIET UNION - EMISSION FACTORS 5-15
TABLE 5-6: WESTERN EUROPE - EMISSION FACTORS 5-16
TABLE 5-7: OTHER OIL-EXPORTING COUNTRIES - EMISSION FACTORS . 5-17
TABLE 5-8: REST OF THE WORLD - EMISSION FACTORS 5-18
TABLE 5-9: ACTIVITY LEVELS FOR OIL AND NATURAL GAS SYSTEMS IN 1990 (petajoules/yr) 5-19
TABLE 5-10: GLOBAL EMISSIONS BY REGION AND INDUSTRY SEGMENT (Tg of CH_4 in 1990) 5-21
TABLE 5-11: GLOBAL EMISSIONS BY KEY COUNTRIES (Tg of CH_4 in 1990) 5-21
TABLE A-1: DERIVATION OF STATIONARY-SOURCE, GAS-COMBUSTION EMISSION FACTORS 5-26
TABLE A-2: DERIVATION OF STATIONARY-SOURCE, OIL-COMBUSTION EMISSION FACTORS 5-27
TABLE B-1: U.S EMISSIONS 5-29
TABLE B-2: EMISSIONS FROM EASTERN EUROPE AND FORMER SOVIET UNION 5-30
TABLE B-3: EMISSIONS FROM WESTERN EUROPE 5-31
TABLE B-4: EMISSIONS FROM OTHER OIL EXPORTING COUNTRIES 5-32
TABLE B-5: EMISSIONS FROM THE REST OF THE WORLD 5-33
TABLE B-6: WORLD EMISSIONS 5-34

6. METHANE EMISSIONS FROM THE COAL FUEL CYCLE

TABLE 6-1: EMISSION ESTIMATES FROM SELECTED STUDIES 6-6
TABLE 6-2: 1990 COAL PRODUCTION AND CONSUMPTION DATA (million tonnes) 6-10
TABLE 6-3: ESTIMATED UNDERGROUND MINING EMISSION FACTORS FOR SELECTED COUNTRIES 6-13
TABLE 6-4: SELECTED COAL COMBUSTION EMISSION FACTORS, BY SOURCE (m^3/tonne of coal consumed) 6-21

LIST OF TABLES (Continued)

TABLE 6-5: ESTIMATED 1990 METHANE EMISSIONS FROM THE COAL FUEL CYCLE (Tg) 6-24
TABLE 6-6: 1990 ESTIMATED METHANE EMISSIONS FROM THE COAL FUEL CYCLE FOR THE TOP-10 EMITTING COUNTRIES 6-25
TABLE 6-7: METHANE RECOVERY BY DEGASIFICATION SYSTEMS FOR KEY COUNTRIES (Tg) 6-27
TABLE 6-8: SUMMARY OF GLOBAL AVERAGE EMISSION FACTORS FOR THE COAL FUEL CYCLE 6-38

7. MINOR INDUSTRIAL SOURCES OF METHANE
TABLE 7-1: RANKED LISTING OF SIGNIFICANT INDUSTRIAL SOURCES OF METHANE EMISSIONS IN THE UNITED STATES 7-3
TABLE 7-2: 1990 GLOBAL CH_4 EMISSIONS ESTIMATED FOR SELECTED MINOR SOURCES 7-5
TABLE 7-3: SELECTED MINOR SOURCE CATEGORIES AND EMISSION ESTIMATES 7-6
TABLE 7-4: METHANE EMISSIONS FROM SELECTED MINOR SOURCES (1,000 tonnes/yr) 7-9

8. METHANE EMISSIONS FROM LANDFILLS AND OPEN DUMPS
TABLE 8-1: TOTAL GLOBAL AND U.S. ESTIMATES OF METHANE EMISSIONS FROM LANDFILLS AND OPEN DUMPS, ACCORDING TO VARIOUS METHODS 8-2
TABLE 8-2: REFERENCES USED 8-6
TABLE 8-3: WASTE GENERATION RATES AND METHANE EMISSION ESTIMATES USING IPCC/OECD AND AEERL METHODS 8-7
TABLE 8-4: ESTIMATES OF METHANE EMISSIONS FROM LANDFILLS FROM OECD/IPCC AND EPA/AEERL METHODOLOGIES 8-17

9. METHANE EMISSIONS FROM LIVESTOCK MANURE
TABLE 9-1: LIVESTOCK MANURE PRODUCTION DATA FOR DEVELOPED COUNTRIES 9-6
TABLE 9-2: LIVESTOCK MANURE PRODUCTION DATA FOR DEVELOPING COUNTRIES 9-7
TABLE 9-3: B_o VALUES FOR DEVELOPED AND DEVELOPING COUNTRIES 9-8
TABLE 9-4: METHANE CONVERSION FACTORS (MCFs) FOR LIVESTOCK MANURE SYSTEMS 9-11
TABLE 9-5: LIVESTOCK MANURE SYSTEM USAGE 9-12
TABLE 9-6: METHANE EMISSIONS BY ANIMAL TYPE AND REGION FOR 1990 (Tg CH_4) 9-15
TABLE 9-7: METHANE EMISSIONS BY REGION AND SYSTEM FOR 1990 (Tg CH_4) 9-15
TABLE 9-8: METHANE EMISSIONS FOR MAJOR COUNTRIES FOR 1990 (Tg CH_4) 9-16

LIST OF TABLES (Continued)

TABLE 9-9: BASE-, HIGH-, AND LOW-CASE EMISSION ESTIMATE ASSUMPTIONS 9-18
TABLE 9-10: EMISSION ESTIMATE RANGES FOR 1990 (Tg CH_4) 9-19

10. METHANE EMISSIONS FROM WASTEWATER
TABLE 10-1: BIOCHEMICAL OXYGEN DEMAND (BOD) ESTIMATES FOR VARIOUS INDUSTRIAL WASTEWATERS 10-5
TABLE 10-2: SELECTED WASTEWATER TREATMENT METHODS IN THE UNITED STATES 10-11
TABLE 10-3: ESTIMATES OF GLOBAL AND COUNTRY-SPECIFIC METHANE EMISSIONS FROM DOMESTIC WASTEWATER, 1990 (Tg/yr) 10-12
TABLE 10-4: ESTIMATE OF GLOBAL METHANE EMISSIONS FROM INDUSTRIAL WASTEWATER 1990 (Tg/yr) 10-13

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Ming-Xing Wang (Inst. for Atmospheric Physics)
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D. J. Williams (CSIRO)
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EXECUTIVE SUMMARY

The Clean Air Act Amendments of 1990 (P.L. 101-549, Sec. 603) requires the U.S. Environmental Protection Agency to prepare five reports on methane (CH_4) emissions and mitigation options. The topics to be covered by these reports include domestic and global inventories of anthropogenic (Sec.603 b. and c.1) and natural sources (Sec.603 d.) of CH_4, and options for mitigating these emissions domestically and internationally (Sec.603 a. and c.2).

This report addresses the request for a global inventory of the key anthropogenic sources of CH_4. As stated in the Clean Air Act Amendments, U.S. EPA is to prepare "a report on methane emissions from countries other than the United States." (Sec. 603.c.1).

ES.1 GLOBAL METHANE EMISSIONS AND THE U.S. NATIONAL ACTION PLAN

On October 19, 1993, President Clinton issued the U.S. Climate Change Action Plan. The Action Plan initiates specific measures to reduce greenhouse gas (GHG) emissions, including methane, in the United States to 1990 levels by the year 2000. This report makes several contributions to the general goals of the Action Plan:

- The report provides information on inventory methods useful in measuring reductions in methane emissions achieved under the Climate Change Action Plan. Accurate information on inventory methods, including their limitations and research requirements, will enable the United States to respond with appropriate policies in the future.

- The report also provides a baseline with which to assess trends in methane emissions in other countries. Knowing where we stand in relation to other countries can help us provide leadership in efforts to reduce global emissions. Having the necessary tools allows us to track, analyze, and verify global emission data in the future.

- The report contributes to international emission reductions by building confidence in the state-of-the-art emission estimation methods. With more effective methods, countries can prepare better national GHG inventories, contributing, in turn, to ensuring that subsequent climate change actions plans are as effective as possible.

- The report identifies general areas of opportunity for reducing methane emissions by entities interested in joint implementation projects. It may also assist the International Negotiating Committee and the Global Environment Facility in identifying and targeting priority sources for financial support under the FCCC (Framework Convention on Climate Change).

ES.2 KEY CONCLUSIONS OF THE REPORT

This report reaches several conclusions pertinent to U.S. climate change policy:

- Total global emissions of CH_4 from anthropogenic sources were estimated to be slightly under 360 teragrams (Tg)[1] in 1990, the same as the best-guess value of the Intergovernmental Panel on Climate Change (IPCC, 1992). This is a favorable comparison, but the correspondence belies the many differences in specific source estimates.

- The United States, with about 8% of global anthropogenic methane emissions, is among the five countries with the highest emissions. The others are China (14%), the former Soviet Union (12%), India (8%), and Brazil (4%).

- The major sources of CH_4 globally are livestock (80 Tg), rice cultivation (65 Tg), natural gas and oil systems (51 Tg), and biomass burning (48 Tg), together contributing approximately 69% of total anthropogenic CH_4 emissions. Five sources, liquid wastes (35 Tg), coal (30 Tg), landfills (27 Tg), livestock manure (14 Tg), and minor industrial sources (4 Tg), comprise the remaining 31% of emissions.

- As the above figures indicate, energy and agricultural activities are thus the two key sources of global anthropogenic CH_4 emissions. Industrialized countries and countries with economies in transition are major emitters of energy-related CH_4 emissions, while developing countries are major emitters of agriculture-related emissions.

- Global anthropogenic CH_4 emissions are expected to continue growing in the foreseeable future largely because of population growth and economic development. However, according to U.S. EPA's report to Congress on Options for Reducing Methane Emissions Internationally (1993a), significantly slowing or halting the increase in methane concentrations in the atmosphere appears to be achievable, cost-effectively, over the next 10 years.

- Of the four largest sources of CH_4, natural gas and oil systems appear to have the largest emission reduction potentials in the near term. Higher emission reductions appear possible from the smaller sources, particularly landfills and coal mining. Large opportunities to achieve reductions in specific countries, such as the countries of the former Soviet Union, also exist (U.S. EPA, 1993a).

- The quality of CH_4 emission estimates varies considerably by source and by country. Therefore, to accurately review progress toward national reduction goals under the FCCC, the Conference of the Parties will need improved emission factors and activity levels, national inventories, and data verification processes.

ES.3 OVERVIEW OF GLOBAL ANTHROPOGENIC CH_4 EMISSIONS

Methane is a trace gas found in the atmosphere that results from various man-made and natural activities. The primary sources of CH_4 influenced by human activities ("anthropogenic" sources of CH_4) account for about 70% of global emissions (Fung et al., 1991; and IPCC, 1992). These sources include digestive processes of livestock, rice cultivation, biomass burning, oil and natural gas systems, the coal fuel cycle, minor industrial sources, landfills and open dumps, livestock manure, and waste water. Natural sources,

[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

which account for the remaining emissions, include wetlands, oceans and freshwater bodies, termites, wildfires, and CH_4 hydrates.

Methane concentrations are increasing roughly in parallel with world population growth and associated industrial and agricultural activities. Concentrations have more than doubled over the last 200 years and are currently rising by about 0.6% annually. In recent years, this rate of increase has slowed slightly, however, it is not certain whether this slowing trend will continue.

Increased CH_4 concentrations are cause for significant concern because methane is a potent greenhouse gas. Its direct radiative effect, averaged over a 100-year time frame, is at least 11 times more effective at trapping heat in the atmosphere than carbon dioxide, the most abundant greenhouse gas. When indirect effects[2] are included, CH_4 has approximately 20 times the global warming potential (GWP) of carbon dioxide (IPCC, 1992).[3] The contribution of anthropogenic CH_4 to potential global warming, including its direct and indirect effects, is approximately 18%. This share is uncertain, however, because of uncertainties in the contribution of other gases, particularly CFCs.

The atmospheric lifetime of CH_4 is relatively short, about 10 years (Lelieveld and Crutzen, 1993), compared with about 120 years for carbon dioxide (IPCC, 1990). This short lifetime means that programs and policies to reduce CH_4 can help to mitigate the rate of climate change faster than reductions in emission of carbon dioxide and other longer-lived greenhouse gases. However, the cost of such actions must still be compared with other options, such as energy-efficiency improvements to reduce carbon dioxide, to determine the most cost-effective approaches available.

ES.4 CURRENT ESTIMATES OF GLOBAL ANTHROPOGENIC METHANE EMISSIONS

This report's best estimate of 354 Tg of methane is, given the large range of uncertainty in the estimate (274-477 Tg/yr), essentially the same as the IPCC (1992) estimate of 360 Tg. The similar estimates, however, belie important differences in individual source categories. These are caused in part by different estimation methods and different source definitions. For example, rice cultivation and biomass burning are between 8 and 20 percent higher in this report than in the IPCC report. In the IPCC report, livestock manure, coal, and oil and natural gas are higher than in this report, 80% higher in the case of livestock and an uncertain but probably significant percent higher for the latter categories. In addition, the U.S. EPA report covers industrial waste water emissions, which the IPCC report does not.

ES.4.1 Estimates by Source

As shown in Figure ES-1 below, livestock (80 Tg), rice cultivation (65 Tg), natural gas and oil systems (51 Tg), and biomass burning (48 Tg) are the most significant sources of CH_4

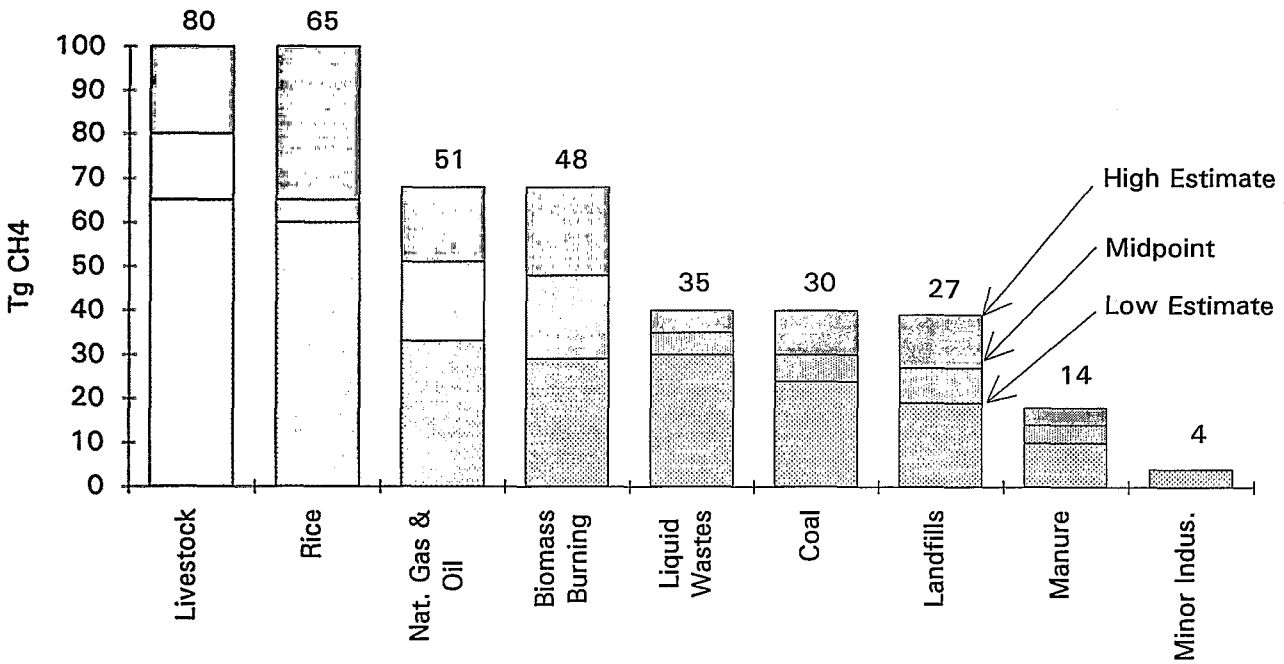
[2] The indirect effects of methane result from its role in atmospheric chemical reactions that increase the lifetimes and abundances of methane and other greenhouse gases.

[3] The GWP is a measure of the effect that one kilogram of methane would have on global warming, compared with an equivalent amount of carbon dioxide, over a specified period of time.

globally. Together they account for about 69% of total anthropogenic CH_4 emissions. The other five sources contribute about 110 Tg. (See Table ES-1 at end of executive summary.)

FIGURE ES-1

GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY SOURCE (1990)
(Midpoints of ranges given above bars)



(See notes for Table ES-1)

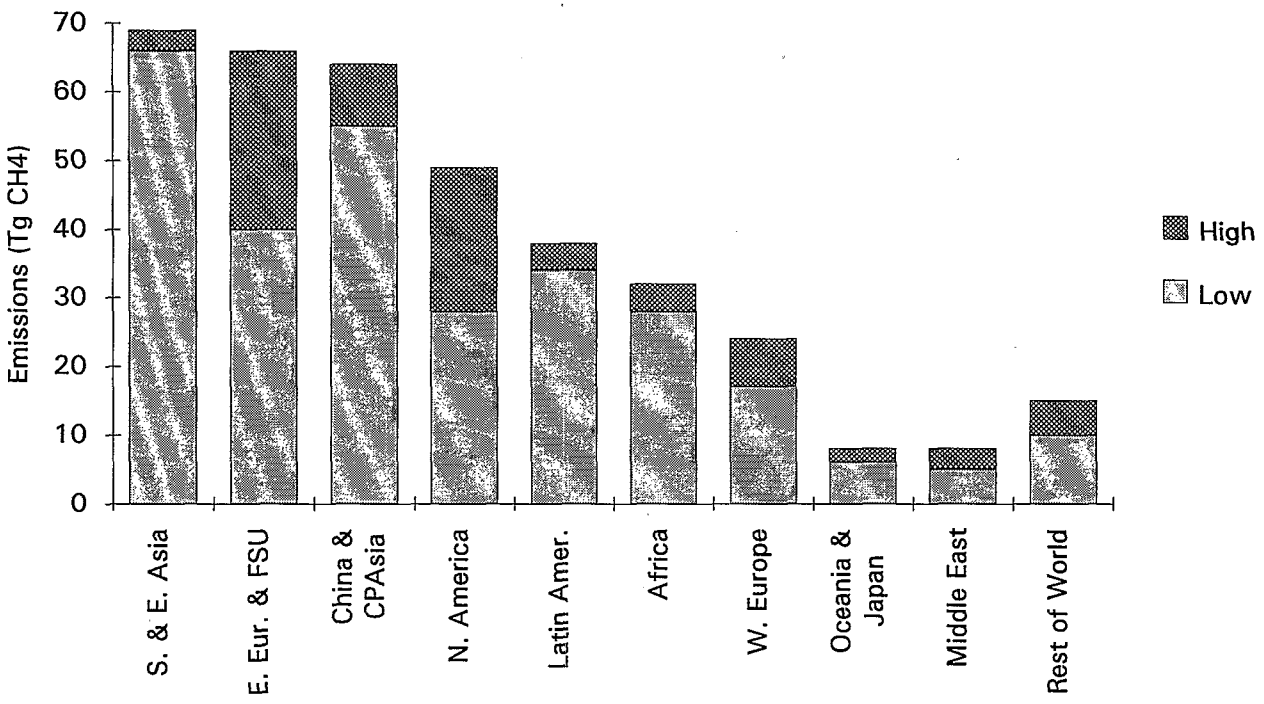
U.S. EPA (1993a) reports that significant global emission reductions are possible in oil and natural gas systems, coal mining, livestock, livestock manure, landfills, and wastewater treatment. The exact amount of possible reductions per source tend to be uncertain, however. They vary from as little as 20% to as much as 90% per source, depending on the availability of technology and capital, as well as other factors. Currently, the reduction potential for rice cultivation appears to be relatively low, and that of biomass burning is uncertain but also appears to be low.

ES.4.2 Regional Estimates

Regionally, CH_4 emissions are widely distributed, due in large part to the varied activities associated with CH_4 production. In industrial countries, energy production and waste management tend to be key sources. In developing countries, agricultural and land-use activities, such as livestock, rice cultivation and biomass burning, tend to dominate. Figure ES-2 presents anthropogenic CH_4 emissions by region. (See Table ES-2 at end of executive summary.)

FIGURE ES-2

GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY REGION (1990)



(See notes for Table ES-2)

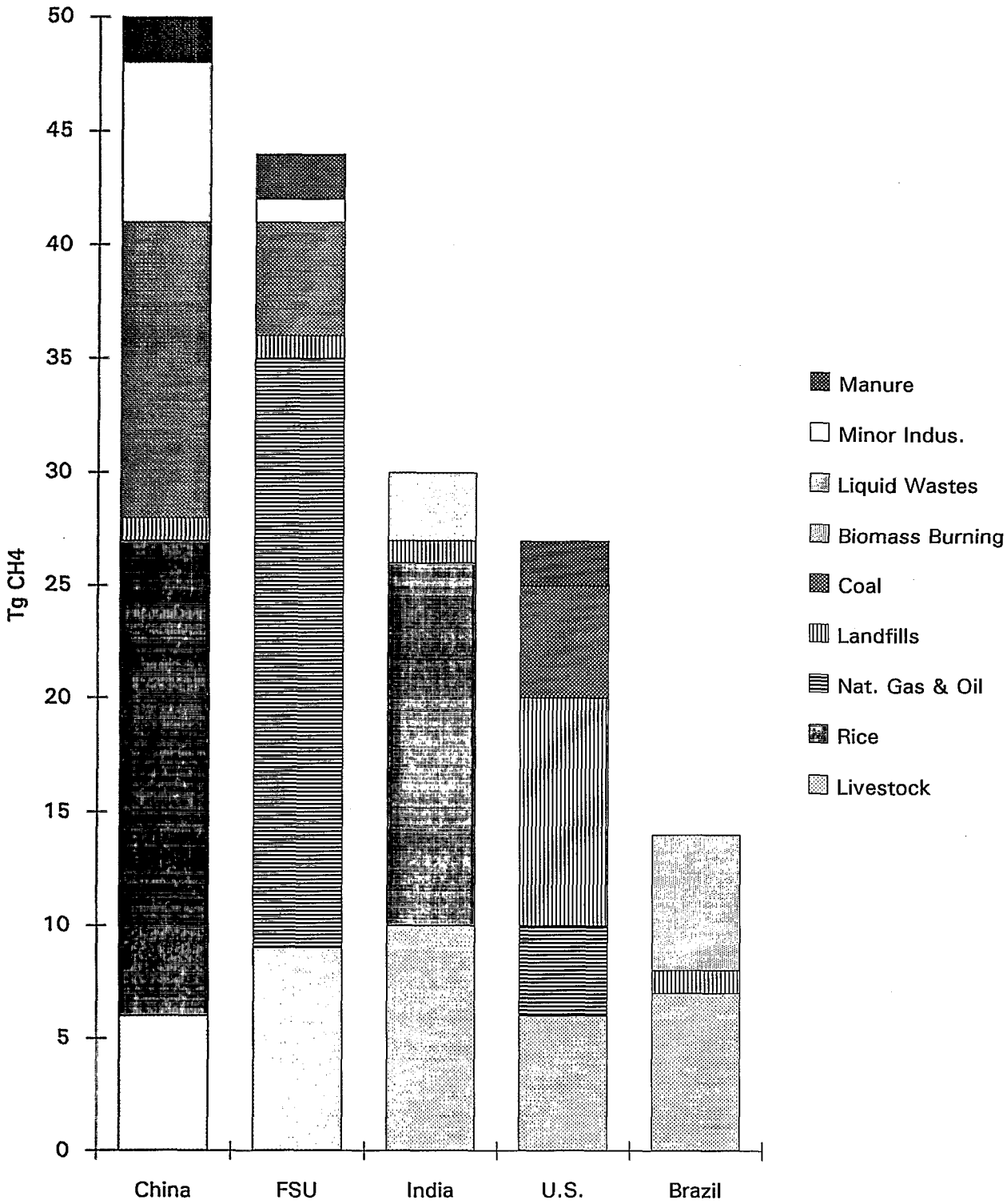
Developing countries and countries with economies in transition account for approximately 80% of anthropogenic CH_4 emissions. Countries in the Organization for Economic Cooperation and Development (OECD) account for the remaining 20%. The large contribution from non-OECD countries is due in part to the importance of agriculture and land-use changes in the formation of CH_4. These countries tend to be agriculturally based, with rice cultivation a large component in some countries. Also, a large part of deforestation, biofuels consumption, and other forms of biomass burning take place in those countries. Population size is another major factor. If measured on a per capita basis, the emissions of the non-OECD countries would be much closer to the OECD.

ES.4.3 Country Estimates

Five countries stand out as major emitters. These include, in order of importance, China, the former Soviet Union (dominated by Russia), India, the United States, and Brazil. *Together these top five countries are estimated to account for nearly half of all anthropogenic CH_4 emissions.* Among these, the United States leads in one source category, emissions from waste landfills, and is tied with China and the FSU in domestic livestock manure emissions. Figure ES-3 presents the key sources of CH_4 emissions for each of these countries.

FIGURE ES-3

METHANE EMISSIONS OF THE FIVE LARGEST EMITTING COUNTRIES (1990)



(See notes for Table ES-3)

U.S. EPA (1993a) examined the potential for reducing emissions in different countries for four sources: landfills, oil and natural gas, coal mining, and livestock (cattle and buffalo). The report found that significant emission reductions could be achieved cost-effectively among the five highest emitting countries. For example, 3-10 Tg of methane could be reduced per year in the near term from the oil and gas sector in the former Soviet Union, 4-6 Tg/yr from landfills in the United States, and 1.2-1.6 Tg/yr from coal mining in China.

ES.5 REDUCING UNCERTAINTIES IN METHANE EMISSION ESTIMATES

Resolving the relatively large uncertainties in global CH_4 emission estimates should be a priority of international cooperation on climate change issues. The accuracy of results is limited by several uncertainties. One is the need for better emission factors for certain categories, such as oil and natural gas production and use. Another is the need for better information on emission factors and output for CH_4-producing activities in developing countries. For example, more information is needed on the viability of using emission factors developed for industrialized-country activities to measure similar activities in developing countries.

There are many international research efforts underway that are helping to resolve these and other uncertainties in global GHG emission assessments. A key activity is the joint effort of the IPCC and the OECD. The IPCC/OECD effort is developing an emission inventory methods document. This document, when reviewed and adopted by the Conference of the Parties of the FCCC, will be used by countries to prepare or strengthen national GHG emission inventories, as required by the FCCC.

A number of bilateral and multilateral entities are directly assisting developing countries in preparing GHG inventories. One of these is the Global Environment Facility, which is funding GHG emission inventory assessments through the United Nations Development Program (UNDP) and the United Nations Environment Program (UNEP). Another is the United States Climate Country Study Program which is providing $25 million to developing countries to assist them with GHG inventories and development of national climate plans.

In addition, several research organizations in the United States, including U.S. EPA, the National Science Foundation, the Department of Energy, the National Aeronautic and Space Administration and others, are sponsoring research to improve understanding of the processes and activities leading to the production of methane from man-made sources.

ES.6 REFERENCES

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TABLE ES-1

GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY SOURCE FOR 1990

Category	Estimated Emissions ($Tg\ CH_4$) Low	High	Mid
Livestock	65	100	80
Rice Cultivation	60	100	65
Natural Gas and Oil Systems	33	68	51[a]
Biomass Burning	29	68	48
Liquid Wastes	30	40	35
Coal Fuel Cycle	24	40	30
Landfills	19	39	27
Livestock Manure	10	18	14
Minor Industrial Sources[b]	4	4	4
Total	274	477	354

a. This figure is a mid-point of the estimated range. A point estimate could not be determined with a reasonable degree of confidence. A mid-point is used here to help rank sources in their general order of importance.

b. A range estimate for this source was not available for this report.

TABLE ES-2

GLOBAL ANTHROPOGENIC METHANE EMISSIONS BY REGION FOR 1990

Region	Estimated Emissions ($Tg\ CH_4$) Low	High
South and East Asia	66	69
Eastern Europe and the Former Soviet Union	40	66
China and Centrally Planned Asia	55	64
North America	28	49
Latin America	34	38
Africa	28	32
Western Europe	17	24
Oceania (incl. Japan)	6	8
Middle East	5	8
Rest of World[a]	10	15
Regional Totals[b]	289	373

a. Applies only to minor industrial sources.

b. Totals differ from the world totals in Table ES-1 because regional estimates were not calculated for industrial liquid wastes.

TABLE ES-3

METHANE EMISSIONS OF THE FIVE LARGEST EMITTING COUNTRIES, 1990 ($Tg\ CH_4$)

Source Category	China	Former Soviet Union	United States	India	Brazil
Livestock	6	9	6	10	7
Rice Cultivation	21	ns	<1	16	<1
Natural Gas and Oil Systems[a]	<1	26	4	ns	ns
Landfills	1	1	10	1	1
Coal Fuel Cycle[a]	13	5	5	<1	ns
Biomass Burning	7	<1	<1	3	6
Liquid Wastes[b]	<1	<1	<1	ns	<0.1
Minor Industrial Sources	<1	1	<1	<1	<0.1
Livestock Manure	2	2	2	<1	<1
Total	50	44	27	30	14

a. Figures are mid-points of the estimated ranges and not accurate point estimates. Point estimates could not be determined with a reasonable degree of confidence. Mid-points are used to help rank sources in their general order of importance.

b. Includes domestic waste only.

ns Not significant -- little or no emissions from this source.

CHAPTER 1

INTRODUCTION

Section 603 of the Clean Air Act Amendments of 1990 (Public Law 101-549) requires the U.S. Environmental Protection Agency (U.S. EPA) to prepare and submit to Congress a series of reports on issues concerning methane emissions from anthropogenic (human-related) and natural sources. The topics for the five required reports are: (1) Anthropogenic Methane Emissions in the United States; (2) Options for Reducing Anthropogenic Methane Emissions in the United States; (3) International Anthropogenic Methane Emissions; (4) Options for Reducing International Anthropogenic Methane Emissions; and (5) Methane Emissions from Natural Sources. This report, which presents estimates of international anthropogenic methane emissions for the year 1990, fulfills the third requirement.

1.1 BACKGROUND

1.1.1 The Importance of Methane to Potential Greenhouse Warming

Methane (CH_4) is an important greenhouse gas whose concentration in the atmosphere is increasing, although its rate of increase has slowed in recent years. Second only to carbon dioxide (CO_2) in terms of its contribution to potential global warming, CH_4 is responsible for about 17% of the total contribution of all greenhouse gas emissions in 1990 to future warming.[1] The atmospheric concentration of CH_4 has more than doubled over the last 200 years (IPCC, 1992), but its rate of increase gradually slowed over the last decade or so, to about 0.6%/year, or approximately 30 teragrams (Tg)[2] CH_4/year in 1990 (Steele et al., 1992). This decline in growth rates could be due to a decrease in CH_4 emission rates, or an increase in CH_4 destruction rates, or a combination of the two. The atmospheric concentration of CO_2, in comparison, is currently increasing at about 0.5%/year, or approximately 14,000 Tg CO_2/year (IPCC, 1990 and 1992). Although the amount of CO_2 accumulating in the atmosphere each year is orders of magnitude larger than that of CH_4, each additional gram of CH_4 released to the atmosphere is as much as 22 times more effective in potentially warming the Earth's surface over a 100-year period than each additional gram of CO_2 (IPCC, 1992).

Compared with other greenhouse gases emitted by anthropogenic activities, CH_4 has a relatively short atmospheric lifetime. The lifetime of CH_4 (defined as its atmospheric content divided by its rate of removal) is approximately 10 years (Lelieveld and Crutzen, 1993),

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[1] This contribution to potential warming is based on converting 1990 emission estimates to a CO_2-equivalent basis using direct 100-year global warming potentials (GWPs) from IPCC (1992). When both direct and indirect effects are considered, each additional kilogram of CH_4 released to the atmosphere is as much as 22 times more effective in warming the Earth than each additional kilogram of CO_2. This estimate of CH_4's contribution to warming is quite uncertain because of scientific and methodological uncertainties associated with the GWPs, especially the indirect GWPs for CH_4 and other trace gases. The GWPs are continually being revised as these uncertainties are analyzed and debated.

[2] Teragram = 10^6 metric tonnes = 10^{12} grams.

whereas the atmospheric lifetime of CO_2 is approximately 120 years (IPCC, 1990).[3] A short atmospheric lifetime of a gas means that the atmosphere will adjust relatively rapidly to reductions in emissions. In other words, CH_4 emission reductions will result relatively rapidly in reductions in atmospheric concentrations of CH_4.

Because of CH_4's short lifetime and its potency as a greenhouse gas, reductions in emissions of CH_4 are a very effective means of mitigating future climate change. Reducing annual CH_4 emissions by 10-20% and holding emissions constant over the next century would cut projected global warming by about 1ºC (roughly 25% of the total) and might also result in reduced atmospheric concentrations of other greenhouse gases because of chemical feedbacks (Thompson et al., 1992). A number of technical options for reducing emissions from different anthropogenic source categories have been identified, and work is ongoing to better understand and implement these options (e.g., IPCC/RSWG, 1990; U.S. EPA, 1993).

Although total emissions of CH_4 are fairly well constrained by measurements of CH_4's atmospheric concentrations and knowledge of its atmospheric lifetime (see section 1.1.4 below), the magnitudes of individual sources of CH_4 are quite uncertain. Also, the biogeochemical and socioeconomic factors that control CH_4 emissions, and the geographic distribution of emissions by source category, are poorly understood and/or poorly quantified. Improving our understanding of the different sources of CH_4 is a critical step in designing appropriate and effective emission reduction strategies for the world. This report, by quantifying anthropogenic emissions by source and by nation and/or region, contributes to this understanding.

1.1.2 An Overview of Methane

Methane is a radiatively and chemically active atmospheric trace gas. It is called a "trace gas" because its atmospheric concentration, approximately 1.72 parts per million by volume (ppmv) in 1990 (IPCC, 1992), is minute in comparison with the atmospheric concentrations of the gases that make up most of the atmosphere: nitrogen and oxygen (78% and 21% by volume, respectively). Methane's atmospheric concentration lies within the broad range of concentrations of the other trace gases that are also important greenhouse gases (Table 1-1).

Methane is radiatively active in that it affects the radiative, or energy, balance of the Earth. The Earth's radiative balance is controlled by the difference between the energy absorbed by the Earth (from solar radiation) and the energy emitted by the Earth (in the form of long-wave, infrared energy). By absorbing outgoing, infrared radiation emitted by the Earth, and re-emitting some of that energy back toward the Earth, CH_4 and other "greenhouse gases" help to warm the Earth. This absorption of infrared radiation is called a "direct effect on radiative forcing."

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[3] Carbon dioxide does not have any real sinks, i.e., it is not destroyed by chemical or biological processes in the same manner as other trace gases, such as methane. Rather, CO_2 is circulated between its various reservoirs (the atmosphere, oceans, biota, and sediments). Therefore, the lifetime of CO_2 cannot be defined as its atmospheric content divided by its rate of removal. Instead, it is estimated here as the time necessary for the atmospheric concentration to decline to 1/*e*, i.e., to decrease by 63%, in the absence of further emissions (IPCC, 1990).

TABLE 1-1

SUMMARY OF ATMOSPHERIC PARAMETERS OF METHANE AND OTHER KEY GREENHOUSE GASES INFLUENCED BY HUMAN ACTIVITIES[a]

Parameters	CO_2	CH_4	N_2O	CFC-11	CFC-12
Preindustrial atmospheric concentration (1750-1800)	280 ppmv[b]	**0.8 ppmv**	288 ppbv[b]	0	0
Current atmospheric concentration (1990)[c]	353 ppmv	**1.72 ppmv**	310 ppbv	265 pptv[b]	470 pptv
Current rate of annual atmospheric accumulation	1.8 ppmv (0.5%)	**0.010 ppmv (0.6%)**	0.8 ppbv (0.25%)	9.5 pptv (4%)	16.5 pptv (4%)
Atmospheric lifetime[d] (years)	(50-200)	**11**	130	65	130

a. Ozone, which is also an important greenhouse gas that is influenced by human activities, has not been included in the table because of lack of precise data.

b. ppmv = parts per million by volume; ppbv = parts per billion by volume; pptv = parts per trillion by volume.

c. The current (1990) concentrations have been estimated based upon an extrapolation of measurements reported for earlier years, assuming that the recent trends remained approximately constant.

d. For each gas in the table, except CO_2, the "lifetime" is defined here as the ratio of the atmospheric content to the total rate of removal. This time scale also characterizes the rate of adjustment of the atmospheric concentrations if the emission rates are changed abruptly. Carbon dioxide is a special case since it has no real sinks, but is merely circulated between various reserves (atmosphere, ocean, biota, sediments). The "lifetime" of CO_2 given in the table is a rough indication of the time it would take for the CO_2 concentration to adjust to changes in the emissions.

Sources: IPCC, 1990 and 1992.

Methane also has an *indirect* effect on radiative forcing because it is a chemically active greenhouse gas. That is, CH_4 enters into chemical reactions that indirectly alter the Earth's radiative balance through increasing the lifetimes and abundances of CH_4 and other greenhouse gases. These positive feedbacks on the Earth's climate system augment CH_4's direct effect on radiative forcing, resulting in a greater total effect. (See section 1.1.4 of this chapter for further discussion of CH_4's direct and indirect impacts on radiative forcing.)

Methane is released to the atmosphere from a wide variety of anthropogenic and natural sources. Anthropogenic sources, which are responsible for about 70% of total emissions, include domestic livestock, rice cultivation, biomass burning, oil and natural gas systems, coal systems (especially mining), landfills, domestic livestock wastes, wastewater treatment, and a variety of minor industrial processes. Natural sources, responsible for about 30% of the total emissions from all sources (IPCC, 1992), include natural wetlands, termites, oceans and fresh waters, wildfires, and CH_4 hydrates.

The abundance of CH_4 in the atmosphere is determined by the difference between the rates of CH_4 production by its sources and the rates of CH_4 destruction by its sinks. The primary sink, or removal mechanism, for CH_4 is oxidation by hydroxyl (OH) radicals in the troposphere.[4] This chemical reaction, which accounts for about 90% of total CH_4 destruction (IPCC, 1992; Lelieveld and Crutzen, 1993), eventually yields carbon monoxide and water vapor. The carbon monoxide then reacts with OH radicals to produce CO_2. The remainder of CH_4 destruction occurs by chemical reactions in the stratosphere[5] and by biological oxidation in dry soils. Methane is destroyed in the stratosphere by reactions with OH, chlorine (Cl), and excited atomic oxygen ($O^1(D)$) radicals (Crutzen and Schmailzl, 1983). Reactions with OH radicals are responsible for about three-quarters of the stratospheric destruction (Lelieveld and Crutzen, 1993). The remaining sink is microbial oxidation of CH_4 in dry (aerated) soils (Born et al., 1990; Keller et al., 1983; Seiler et al., 1984; and Seiler and Conrad, 1987).

The current rate of increase in the atmospheric abundance of CH_4 indicates that the total rate of production by CH_4 sources exceeds the total rate of destruction by CH_4 sinks by approximately 30 Tg/year. Table 1-2 presents a summary of CH_4's sources and sinks.

1.1.3 The Atmospheric History and Geographic Distribution of Methane

Historic and paleo-atmospheric concentrations of CH_4 have been measured using various techniques, including direct atmospheric measurements, measurements of CH_4 in air extracted from air bubbles in polar ice cores, and analyses of solar infrared spectra. These measurements reveal that current concentrations of CH_4 and rates of growth over the last century are higher than at any time during the past 160,000 years (e.g., Chappellaz et al., 1990; Rasmussen and Khalil, 1984; Blake and Rowland, 1988; and Steele et al., 1992). Figure 1-1 summarizes the inferred evolution of global average CH_4 concentrations.

Analyses of air trapped in ice cores from Antarctica and Greenland (Raynaud et al., 1988; Chappellaz et al., 1990; and Stauffer et al., 1988) indicate that CH_4 levels in the atmosphere rose rapidly from minimums of about 0.35 ppmv during the last two glacial periods (about 150,000 and 18,000 years before present (YBP)) to maximums of about 0.65 ppmv during the subsequent interglacials (about 133,000 and 9,000 YBP). The highest measured rates of growth during these glacial/interglacial transitions were about 0.2-0.3 ppbv/year. Methane concentrations were fairly constant between about 3000 and 200 YBP, at about 0.7-0.8 ppmv, and began to increase rapidly between 100 and 180 years ago (Craig and Chou, 1982; Rasmussen and Khalil, 1984; Stauffer et al., 1985; and Pearman et al., 1986). Methane concentrations reached about 0.9 ppmv at the beginning of this century.

Analysis of the Vostok ice core from Antarctica (Chappellaz et al., 1990) indicates that not only are high and low paleo-atmospheric concentrations of CH_4 associated with interglacial and glacial periods, but also CH_4 concentrations closely follow higher-frequency fluctuations in surface air temperature (Figure 1-2). This positive correlation suggests that higher surface temperatures may increase the strength of CH_4 sources, and/or that higher atmospheric CH_4 levels may increase surface temperatures. Although it is uncertain which mechanism, or if

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[4] The "troposphere" is defined as the layer of the atmosphere immediately above the earth's surface where the temperature decreases with height. The maximum height of the troposphere varies from about 16 km near the equator to about 8 km near the poles.

[5] The "stratosphere" is defined as the atmospheric layer immediately above the troposphere where temperature increases with height. It is approximately 30-40 km thick.

both mechanisms, were operative over the past 160,000 years, the CH_4 concentration/-temperature correlation indicates a fundamental link between temperature and the CH_4 cycle.

TABLE 1-2

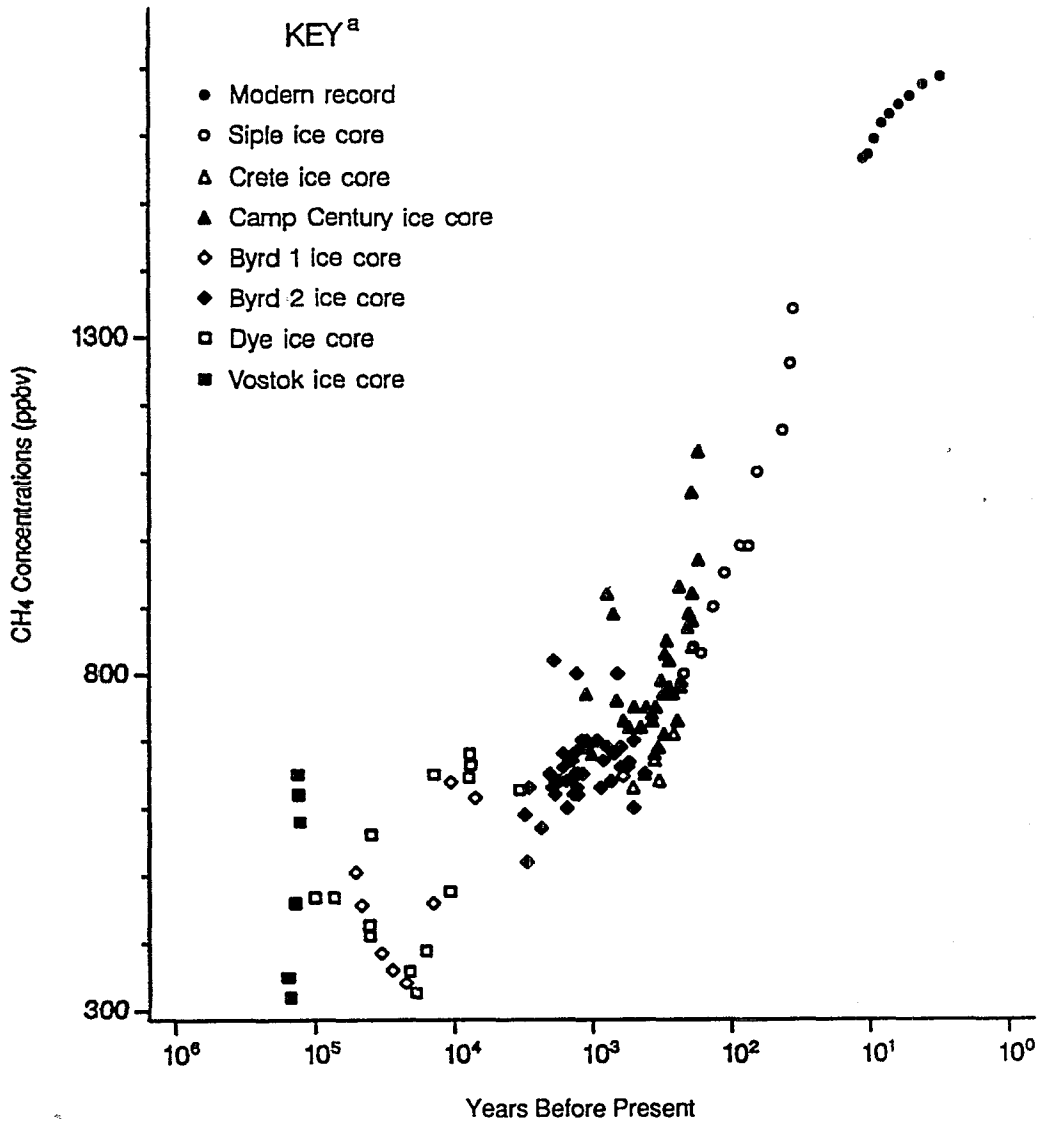
ESTIMATED SOURCES AND SINKS OF METHANE
(Tg CH_4 per year)

Sources/Sinks	Global Estimate	Global Range
Anthropogenic Sources:		
Rice	70	20 - 120
Domesticated Livestock	80	60 - 100
Oil/Gas Systems	80	35 - 125
Coal Mining	35	25 - 45
Biomass Burning	30	15 - 45
Landfills	40	15 - 65
Animal Wastes	25	15 - 35
Wastewater Treatment	25	15 - 35
Natural Sources:		
Wetlands	125	55 - 195
Termites	30	0 - 60
Oceans and Fresh Waters	15	5 - 25
Methane Hydrate Destabilization	5	0 - 10
Total Natural and Anthropogenic Sources:	560	470 - 650
Sinks:		
Reaction with OH in the Troposphere	455	405 - 505
Reactions with OH, Cl, and $O(^1D)$in the Stratosphere	45	35 - 55
Soil Absorption	30	5 - 55
Total Sinks:	530	445 - 615
Atmospheric Increase:	30	25 - 35

Source: Lelieveld and Crutzen, 1993.

FIGURE 1-1

MEASUREMENTS OF GLOBAL METHANE CONCENTRATIONS

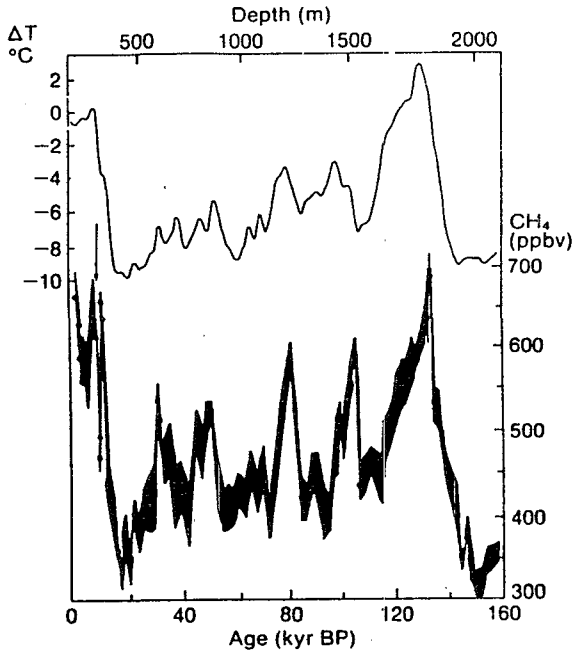


Annual atmospheric CH_4 concentrations during the past 160,000 years (derived from ice cores and the NOAA/CMDL flask sampling network).

Source: ORNL, 1991.

FIGURE 1-2

ATMOSPHERIC METHANE AND AIR TEMPERATURE RECORD DETERMINED FROM VOSTOK ICE CORE



Methane concentrations (bottom) and estimated temperature changes (top) during the past 160,000 years, as determined on the ice core from Vostok, Antarctica.

Sources: Chappellaz et al., 1990, as presented in IPCC, 1990.

Direct measurements of atmospheric CH_4, which began in 1978, indicate that the current global-average CH_4 concentration is 1.72 ppmv (equivalent to about 4,900 Tg CH_4) -- more than double the preindustrial concentration (IPCC, 1992). Both direct atmospheric measurements and analyses of solar spectra have documented that CH_4 levels increased at roughly 1%/year during the past 30-40 years (Blake and Rowland, 1986 and 1988; Ehhalt et al., 1983; Fraser et al., 1981; Rinsland et al., 1985; Khalil and Rasmussen, 1982; Steele et al., 1987; and Wallace and Livingston, 1990). Recent measurements, however, indicate that CH_4's rate of growth has slowed over the past decade or so, from about 18 ppbv/year during the late 1970s (about 1.2%/year), to about 12-13 ppbv/year in the mid-1980s (about 0.75%/per year), to 9.5 ppbv/year in 1990 (about 0.6%/year) (Blake and Rowland, 1986 and 1988; and Steele et al., 1992). The decrease in the growth rate of atmospheric CH_4 may be due to reductions in CH_4 emissions from natural or anthropogenic sources, increases in CH_4 sinks, or a combination of the two. An analysis of the trend in atmospheric concentrations of OH since 1978 indicates that increasing abundances of OH radicals may be largely responsible for this observed decrease in atmospheric CH_4 growth (Prinn et al., 1992). This inferred increase in OH radical abundance may have several causes, including increased short-wave (ultraviolet, or UV) radiation resulting from stratospheric ozone loss, and growing tropospheric concentrations of gases that contribute to OH radical formation (especially nitrogen oxides (NO_x), ozone (O_3), and water vapor) due to anthropogenic activities (Lelieveld and Crutzen,

1993). Most atmospheric chemistry models that compute OH, however, show OH concentrations decreasing, rather than increasing, since preindustrial times (Thompson, 1992). The reasons for CH_4's slowing growth rate remain unresolved.

The spatial and temporal distribution of atmospheric CH_4 is not uniform (Figure 1-3), as it reflects geographic and seasonal differences in source and sink strengths (Fung et al., 1991). In the Southern Hemisphere, CH_4 concentrations are approximately uniform from mid to high latitudes and increase northward. The average concentration in the Northern Hemisphere is approximately 100 ppbv higher than in the Southern Hemisphere, a reflection of greater source strengths in the northern latitudes. The seasonal cycle in the Southern Hemisphere shows a minimum in February (the Southern Hemisphere summer) and a maximum in September/October, which is consistent with higher summer abundances of OH and temperature-dependent destruction rates.[6] The seasonal cycle is more complex in the Northern Hemisphere and appears to be a function of seasonal fluctuations in sources as well as sinks.

1.1.4 The Role of Methane in Global Climate Change

Increasing atmospheric concentrations of CH_4 have important implications for global climate change because CH_4 is a potent greenhouse gas. If CH_4's direct effect on radiative forcing alone is taken into account, then over a 20-year period each additional kilogram of CH_4 released to the atmosphere is about 35 times more effective in warming the Earth than each additional kilogram of CO_2. Over a 100-year period, CH_4 is about 11 times more effective per kilogram than CO_2 (IPCC, 1992; and Lelieveld et al., 1993). The effectiveness of CH_4 relative to CO_2 decreases as the time frame increases because of CH_4's shorter atmospheric lifetime (about 10 years, versus approximately 120 years for CO_2).

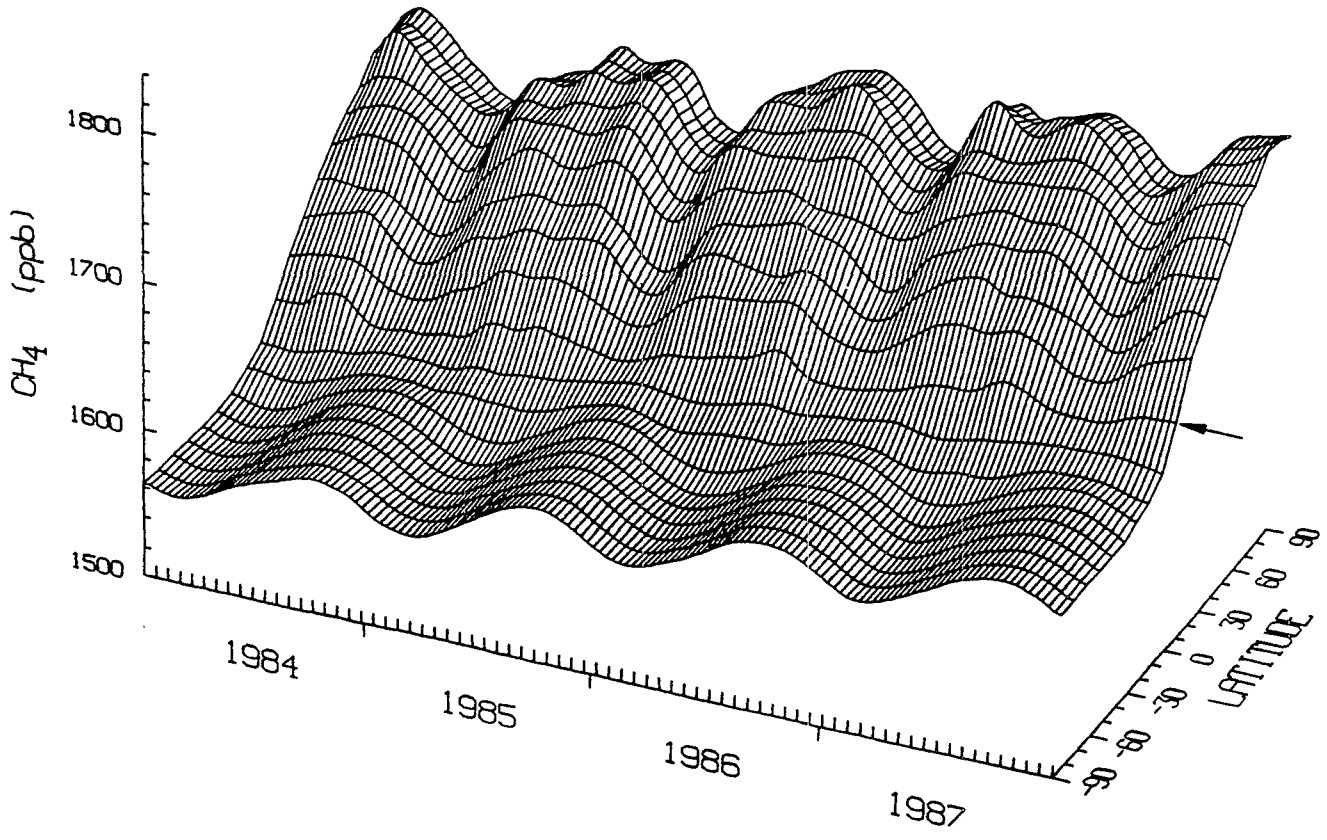
If indirect chemical effects on greenhouse gases are taken into account, then CH_4 is even more effective in contributing to global warming. Although these indirect effects are both positive and negative and are poorly quantified, the total indirect forcing of climate by CH_4 is positive and is likely to be comparable in magnitude to the direct effect (IPCC, 1992; and Lelieveld et al., 1993). Therefore, when both direct and indirect effects are considered, each additional kilogram of CH_4 released to the atmosphere is as much as 22 times more effective in warming the Earth than each additional kilogram of CO_2.

Through reaction with OH radicals, CH_4 influences the oxidizing capacity of the troposphere and may cause its own concentration to increase. Hydroxyl radicals are responsible for the oxidation of the majority of the gases emitted into the atmosphere, including CH_4, higher hydrocarbons, carbon monoxide, and hydrogenated CFCs. Therefore, the atmospheric concentration of OH determines the lifetime and, hence, the abundance of these gases. Since the oxidation of CH_4 by OH is a sink not only for CH_4, but also for OH (Thompson and Cicerone, 1986; and Isaksen and Hov, 1987), increases in atmospheric CH_4 may cause a depletion of OH in the troposphere. As OH is depleted, the lifetime of CH_4 increases, causing a consequent increase in the atmospheric concentration of CH_4. Depletion of OH may also increase the lifetimes and, therefore, the concentrations of other greenhouse gases that are oxidized by OH.

[6] The OH + CH_4 reaction rate is strongly dependent on temperature, increasing with increases in temperature (Vaghjiani and Ravishankara, 1991).

FIGURE 1-3

SPATIAL AND TEMPORAL DISTRIBUTION OF ATMOSPHERIC METHANE



Three-dimensional representation of the global distribution of atmospheric CH_4 derived from direct measurements. The arrow denotes the equator.

Source: Fung et al., 1991.

Increasing concentrations of CH_4 in environments with high levels of NO_x tend to increase the amount of O_3 in the troposphere and lower stratosphere, where O_3 acts as a greenhouse gas (Wuebbles and Tamaresis, 1993). High concentrations of NO_x are primarily found in the industrial regions of the Northern Hemisphere, since the major anthropogenic source of NO_x is fossil fuel combustion.

Oxidation of CH_4 by OH and $O^1(D)$ in the stratosphere results in the production of water vapor, which is also a greenhouse gas (Wuebbles and Tamaresis, 1993). An increase of water vapor in the lower stratosphere may enhance global warming significantly, as the low temperatures there augment the efficiency with which water vapor traps infrared energy. Increases in stratospheric water vapor concentrations may also enhance the formation of polar stratospheric clouds, which are thought to play an important role in the seasonal formation of the stratospheric ozone "hole" over Antarctica (WMO, 1991).

Methane emissions also contribute to the atmospheric burden of CO_2, since CH_4 ultimately oxidizes to CO_2. Only the fossil fuel-related CH_4 emissions (i.e., emissions from coal mining and from natural gas and oil systems), however, are net contributors to atmospheric CO_2, since biogenic CH_4 emissions (i.e., emissions from rice cultivation, livestock, solid and liquid wastes, and biomass burning) are recently recycled CO_2 (Lelieveld and Crutzen, 1992).

In sum, increased concentrations of CH_4 can indirectly increase radiative forcing by depleting tropospheric OH and by increasing tropospheric and lower stratospheric O_3, stratospheric water vapor, and CO_2.

1.1.5 The Methane Budget

Because of CH_4's significant role in global climate change, it is important to understand CH_4's atmospheric budget. Conservation of mass requires that CH_4's total annual source strength equal CH_4's total annual sink strength plus the annual increase in atmospheric concentrations of CH_4, i.e.:

$$E = S + dC/dt \qquad (1.1)$$

where:

E = total emissions, or total sink strength (Tg CH_4/yr)
S = total sink strength (Tg CH_4/yr)
C = global-average atmospheric concentration (Tg CH_4)

The total sink strength is equal to CH_4's atmospheric concentration divided by CH_4's lifetime. Therefore, equation (1.1) can be rewritten as follows:

$$E = C/L + dC/dt \qquad (1.2)$$

where:

L = atmospheric lifetime (yr)

The atmospheric concentration of CH_4 and its annual rate of increase are well known from high-precision atmospheric measurements. Because CH_4 oxidation by OH is by far the dominant sink for CH_4, the atmospheric lifetime of CH_4 is determined primarily by the reaction rate of this process and the amount of OH in the troposphere, where the bulk of CH_4 oxidation

occurs. There are significant uncertainties in the estimation of both these quantities. The other CH_4 sinks, oxidation in the stratosphere and removal by soils, must also be included in the calculations. By including these two other sinks, the calculated lifetime of CH_4 is decreased (i.e., a greater sink strength implies a shorter lifetime).

The reaction rate of CH_4 with OH has been determined by laboratory measurements, although the presence of impurities and the occurrence of secondary reactions in laboratory samples can result in significant errors in these measurements (DeMore et al., 1992). Recent measurements by Vaghjiani and Ravishankara (1991), in which impurities and secondary reactions were minimized, found that the CH_4-OH reaction rate was about 20% lower than indicated by preceding measurements. This lower reaction rate indicates that the atmospheric lifetime of CH_4 is longer than had been estimated previously.

Determining the global average distribution of OH in the troposphere by direct measurement is difficult. Because the concentration of OH is extremely low (about one part per 50 trillion), its measurement requires highly sensitive techniques. Also, because OH is so short-lived (about 1-2 seconds), it is highly variable both temporally and spatially. Therefore, indirect methods have been necessary to estimate OH concentrations. One method consists of measuring atmospheric concentrations of methyl chloroform (CH_3CCl_3), a compound of purely industrial origin whose sources are well known and whose major sink is reaction with OH. Using CH_3CCl_3 emission estimates (based on industry data), measured CH_3CCl_3 concentrations, and an experimentally determined CH_3CCl_3-OH reaction rate, scientists can infer the lifetime of CH_3CCl_3 and the atmospheric distribution of OH.[7] Using this method, Prinn et al. (1992) deduced a global-average tropospheric OH concentration of about 810,000 radicals per cubic centimeter. Laboratory measurements by Talukdar et al. (1992) indicate that the CH_3CCl_3-OH reaction rate used by Prinn et al. in their calculations was too high; scaling Prinn et al.'s estimated OH concentration upwards to account for this new reaction rate results in an OH abundance of approximately 930,000 radicals per cubic centimeter (Lelieveld and Crutzen, 1993).

Using their estimated global-average OH concentration and the CH_4-OH rate coefficient reported by Vaghjiani and Ravishankara (1991), Prinn et al. (1992) inferred a lifetime for atmospheric CH_4 of about 11.1 years. This estimate is likely about 10-15% too high because of the implication of Talukdar et al.'s (1992) work on the OH concentration. If CH_4 loss in the stratosphere and removal by soils are also considered, the global atmospheric lifetime of CH_4 reduces to about 9.5 years (Lelieveld and Crutzen, 1993). Inserting this lifetime into equation (1.2), with the current atmospheric CH_4 concentration (about 4,900 Tg) and annual rate of increase (about 30 Tg/yr) yields an estimated total source strength of about 545 Tg CH_4/yr. Uncertainties in measured reaction rates and estimated OH concentrations indicate that the estimated CH_4 lifetime has an uncertainty of about $\pm$ 25% (Fung et al., 1991). Therefore, the estimated CH_4 source strength ranges from approximately 450 to 750 Tg CH_4/yr.

The technique of deducing CH_4 emissions from the atmospheric lifetime and global-average concentrations of CH_4 can be used only to estimate total emissions; it cannot distinguish among individual source components. Although the major sources of CH_4 have

[7] Methyl chloroform has one other sink: oceanic consumption (Butler et al., 1991). Although this sink is minor, accounting for about 6% of the total sink strength, it must also be included in these calculations. Such inclusion increases estimates of OH abundance by about 7% (Prinn et al., 1992), which results in a lower inferred CH_4 lifetime.

been identified, their individual strengths are still highly uncertain. Estimates of individual source strengths are based on CH_4 flux measurements, which are highly variable, and activity data (e.g., global area of wetland rice cultivation), which in many cases are uncertain. Methane fluxes from an individual source can span several orders of magnitude, so extrapolation from individual flux measurements to a global budget is very difficult. Furthermore, emissions are controlled by a wide variety of both biogeochemical and socioeconomic factors, which are neither well understood nor well quantified. Additional information about individual source strengths can be obtained from isotopic composition measurements of atmospheric CH_4, but even with these additional constraints, CH_4 source estimates derived from estimated individual source strengths have uncertainties of ± 20-40% (e.g., Cicerone and Oremland, 1988; and IPCC, 1992). The total source strength estimated from sink strength and atmospheric concentrations (via Equation 1.2) is thus better constrained than that obtained by summing the contribution from individual sources.

Estimates of the strengths of individual CH_4 sources have also been derived using three-dimensional atmospheric chemistry models, with geographic and seasonal variations in atmospheric concentrations of CH_4 and other chemically active gases, as well as geographic and temporal variations in the isotopic composition of atmospheric CH_4 and in estimated CH_4 sources, as input data. As described more fully in Chapter 11 of this report, these input data place constraints on individual sources in the CH_4 budget, but there are numerous possible emission combinations that can satisfy these constraints (e.g., Fung et al., 1991; Taylor et al., 1991; and Tie et al., 1991). Although scientific understanding of the CH_4 budget has vastly improved over the last few years, there remain large discrepancies among various authors' estimates of the contributions of individual sources.

1.1.6 Summary

Methane is a radiatively and chemically important greenhouse gas, second only to CO_2 in its contribution to future warming. Methane helps to warm the Earth by absorbing and re-radiating outgoing energy from the Earth, and by entering into chemical reactions that increase the atmospheric lifetimes and abundances of CH_4 and other greenhouse gases. Each additional gram of CH_4 released to the atmosphere is as much as 22 times more effective in potentially warming the Earth's surface over a 100-year period than each additional gram of CO_2 (IPCC, 1992). Because of CH_4's potency as a greenhouse gas and its short lifetime (about 10 years), reductions in emissions of CH_4 are a very effective means of mitigating future climate change.

The current atmospheric concentration of CH_4 is greater than at any time during the past 160,000 years. Methane's concentration more than doubled over the past 200 years, although during the last decade or so, its rate of increase slowed from about 1%/year to about 0.6%/year (Steele et al., 1992). Since the atmospheric abundance of CH_4 is determined by the difference between rates of CH_4 production by its sources and rates of destruction by its sinks, this recent decline in atmospheric growth rates could be due to a decrease in emission rates, an increase in destruction rates, or a combination of the two.

Atmospheric measurements of CH_4 and information about its rate of destruction by its sinks indicate that current emissions of CH_4 range from approximately 450 to 750 Tg CH_4/year. Methane is released by both anthropogenic and natural sources, which are responsible for about 70% and 30%, respectively, of total emissions (IPCC, 1992). Estimates of individual source strengths, which are based on highly variable CH_4 flux measurements and, in some cases, inaccurate activity data, are very uncertain. Geographic and seasonal

variations in atmospheric concentrations of CH_4 and in isotopic composition data place constraints on some of the source strengths, but estimates of emissions from individual sources still vary by as much as an order of magnitude. Because of CH_4's importance as a greenhouse gas, improving our understanding of individual source strengths and their geographic distribution is a critical step in designing appropriate emission reduction strategies.

1.2 OVERVIEW OF THIS REPORT

This report estimates the current magnitude and geographic distribution of each anthropogenic source of CH_4, based on the latest flux measurements and current scientific understanding of the many factors that control emissions. In addition to estimating total emissions by source category, the report provides country- or region-specific emission estimates for each of the sources. Individual chapters on CH_4 sources include background information on the source (including a discussion of measured fluxes from the source, and the biogeochemical and socioeconomic factors that control emissions), describe the methodology used for estimating emissions, present estimates of 1990 national and/or regional CH_4 emissions, discuss trends that could affect future emission levels, and describe uncertainties associated with the emission estimates. These emission source chapters cover the following topics:

- Livestock Digestion: emissions from beef and dairy cattle and other domestic animals;
- Rice Cultivation: emissions from flooded rice fields;
- Biomass Burning: emissions from open and confined burning of biomass;
- Natural Gas and Oil Systems: emissions from oil and gas production; crude oil transportation and refining; natural gas processing, transportation, and distribution; and fuel combustion;
- Coal Fuel Cycle: emissions from surface and underground coal mining; processing, transport, and storage of extracted coal; and coal combustion;
- Minor Industrial Sources: emissions from coke and steel production, chemical manufacturing, and other miscellaneous sources;
- Landfills and Open Dumps: emissions associated with disposal of solid waste in landfills and dumps;
- Livestock Manure: emissions from solid and liquid waste management systems; and
- Wastewater: emissions from domestic and industrial wastewater treatment.

The final chapter of the report discusses verification of CH_4 emission inventories, particularly the constraints placed on inventories by the available socioeconomic, biogeochemical, and

atmospheric data, and how uncertainties associated with CH_4 emission estimates can be reduced.

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CHAPTER 2

METHANE EMISSIONS FROM THE DIGESTIVE PROCESSES OF LIVESTOCK

2.1 SUMMARY

Domesticated livestock are an important source of methane emissions, accounting for about 80 teragrams (Tg)[1] per year, or about 20-25% of global anthropogenic emissions. Methane is produced as a part of the normal digestive processes of ruminant animals (cattle, buffalo, sheep, goats, and camels), which account for nearly all the emissions from this source. Cattle are the largest single source, responsible for nearly 75% of the total. Five countries account for nearly 50% of the total emissions from livestock: India (13%), the former Soviet Union (11%), Brazil (9%), China (8%), and the United States (7%). In the future, emissions from livestock are expected to increase as animal populations and animal production continue to grow.

A firm scientific basis exists for estimating the rate of methane emissions from ruminant animals managed in temperate agricultural systems. Several decades of measurements are available that relate methane emission rates to various feeding and management practices. Very few measurements are available on the rate of rumen methanogenesis under tropical livestock management systems. Consequently, additional data are needed to verify the emission estimates that have been made to date. Additionally, improved data for estimating animal populations and levels of production would help reduce the uncertainty in the emission estimates for all regions. In particular, data are needed on numbers of animals classified by age groups and nutrition or feeding conditions for individual countries. Given the available data, the emission estimate is believed to be approximately ±25%, so that the total global emission estimate range is 80 ±20 Tg per year.

2.2 BACKGROUND

Methane (CH_4) is produced as part of the normal digestive processes of animals. Referred to as "enteric fermentation," these processes produce emissions that have been estimated to account for a significant portion of the global CH_4 budget, about 65-100 Tg annually (IPCC, 1992). Of domesticated animals, ruminant animals (cattle, buffalo, sheep, goats, and camels) are the major source of CH_4 emissions, with cattle being the most important source globally. Therefore, emissions from cattle are emphasized in this chapter.[2] Although wild ruminant animals, such as deer, and wild nonruminant herbivores, such as rabbits, also produce CH_4, they are not included because emissions from these animals are considered a natural source.

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[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

[2] Although nonruminant animals produce only a small quantity of methane from enteric fermentation as compared with ruminant animals, emissions from nonruminant animal wastes, especially swine wastes, may be significant. Methane emissions from domestic animal wastes are discussed in Chapter 9 of this report.

Ruminant animals have a large "fore-stomach," or rumen, within which microbial fermentation breaks down feed into soluble products that can be utilized by the animal. Approximately 200 species and strains of microorganisms are present in the anaerobic rumen environment, although only a small portion -- about 10 to 20 species -- is believed to play an important role in ruminant digestion (Baldwin and Allison, 1983). The microbial fermentation that occurs in the rumen enables ruminant animals to digest coarse plant material that monogastric animals,[3] including humans, cannot digest.

Methane is produced in the rumen by bacteria as a by-product of the fermentation process. This CH_4 is exhaled or eructated by the animal and accounts for the majority of emissions from ruminants. Methane also is produced in the large intestines of ruminants and is excreted. Nonruminant herbivores, such as horses, mules, rabbits, pigs, and guinea pigs, have a limited amount of fermentation in their large intestines or ceca. The CH_4 produced in this manner is quite small compared with the amount produced by ruminant animals.

A significant body of scientific literature exists that describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. This literature results from decades of research evaluating feeding practices for cattle and other ruminants.[4] Over the past 30 years, hundreds of CH_4 measurements have been performed on a wide variety of cattle and sheep diets typically found in the temperate countries of North America and Europe. The main purpose of these measurements was to develop scientifically based feeding standards for these animals. In the United States the standards are presented in a series of National Research Council publications (e.g., NRC, 1984 and 1989). In the United Kingdom, feeding standards are published in ARC (1980); other countries have developed similar publications.

Based on the scientific information available, a variety of factors affect CH_4 production in ruminant animals. These include the physical and chemical characteristics of the feed, the feeding level and schedule, the use of feed additives to promote production efficiency, and the activity and health of the animal. It has also been suggested that there may be genetic factors that affect CH_4 production. Of these factors, the feed characteristics and level have the most influence.

To describe the CH_4 production by ruminant animals, it is convenient to refer to the portion of feed energy intake that is converted to CH_4. Higher levels of conversion translate into higher emissions, given constant feed energy intake. Similarly, higher levels of intake translate into higher emissions, given constant conversion. There are, however, interactions between level of intake and conversion to CH_4, so these values are not independent. Blaxter and Clapperton (1965) developed a statistical relationship that correlates feed-intake level and

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[3] Monogastric animals have a mouth, esophagus, stomach, small intestines, large intestines, pancreas, and liver (Ensminger, 1983). Examples of monogastric animals include swine, dogs, monkeys, and humans.

[4] Calorimetry is the laboratory technique currently used to conduct in-depth evaluations of the performance of alternative feeding practices. This technique involves placing an animal in a chamber maintained under thermo-neutral conditions for two days and measuring levels of input to the chamber (oxygen and carbon dioxide) and output from the chamber (carbon dioxide, oxygen, and methane). Because methane is produced as part of the normal digestive process of ruminant animals, it is measured as part of this feed-evaluation technique. The technique is accompanied by a seven- to ten-day physical balance of feed nutrients consumed versus excreted (feces and urine) and product nutrient outputs from the animals.

feed digestibility (%)[5] with the level of feed-energy conversion to CH_4. This relationship captures the interdependent nature of these variables and may be used to evaluate the CH_4 conversion rates for diets that fall within the range of diets evaluated by Blaxter and Clapperton.

As a result of the various interrelationships among feed characteristics, feed intake, and conversion rates to CH_4, most well-fed ruminant animals in temperate agricultural systems will convert about 5.5-6.5% of their feed-energy intake to CH_4 (Johnson et al., 1991). With only one exception, this range of CH_4 production can be applied to the ruminant animals typically found throughout North America and Europe, as well as Australia and New Zealand. Given this range for the rate of CH_4 formation, CH_4 emissions can be estimated based on the feed energy consumed by the animals. Because feed energy intake is related to production level (e.g., weight gain or milk production), the feed energy intake can be estimated for these regions based on production statistics.

The important exception to this general range of 5.5-6.5% in temperate agricultural systems occurs when ruminant animals are fed diets comprised primarily of grains. In the United States, cattle are commonly fed high-grain diets during the final stage prior to slaughter. Similar systems are used in other countries, such as Canada, Australia, and France, although to a lesser extent. In the United States, numerous measurements have been conducted to estimate the conversion of feed energy to CH_4 for these high-grain diets, showing that CH_4 formation is generally lower, ranging between 2.5% and 4.5%. A typical value of 3.5% has been suggested (Johnson et al., 1991).[6]

Given the emission measurement data and the animal production data available for temperate agricultural systems, there is a solid foundation for estimating CH_4 emissions from ruminant animals in these regions. However, the basis for estimating emissions from tropical countries is less complete. Few measurements of CH_4 production have been performed for the types and levels of feeding found in many parts of Asia, the Indian subcontinent, Africa, and Latin America. The feeds used in these areas are often more fibrous and less digestible than the feeds typically encountered in temperate countries.

It has been suggested that CH_4 conversion rates will be higher for these tropical feeds, and a value of 7.5% has been suggested for situations in which feed quality and quantity are relatively poor (Leng, 1991). The Blaxter and Clapperton (1965) relationship also produces estimates in the range of 7-8% for feeding levels and feed digestibility commonly found in tropical countries. However, tropical diets were not included in the Blaxter and Clapperton data set, and the basis for the CH_4 conversion estimates for these conditions needs to be improved.

Margan et al. (1988) present measurements of CH_4 production from sheep for two tropical grasses typically found in Australia: *Setaria spacelata* and *Digitaria decumbens*.

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[5] The digestibility of energy in feed is defined as the proportion of energy in the feed that is not excreted in the feces. Digestibility is commonly expressed as a percentage (%).

[6] The value of 3.5% was chosen as representative of the 90% concentrate diets fed at 2.6 times maintenance at typical U.S. feedlots (maintenance feed intake is that necessary to support the animal without growth). The very high proportion of concentrate in the diet and the high feeding level combine to reduce the methane conversion rate.

Compared with two temperate forages (*Lolium perenne*[7] and *Trifolium resupinatum*[8]), these tropical forages converted more feed energy to CH_4 at both maintenance and *ad libitum* feeding levels. Although these estimates tend to support the thesis that tropical feeds have higher CH_4 conversion rates than temperate feeds, additional measurements are needed to evaluate the wide diversity of feeds used in tropical agricultural systems. In particular, the CH_4 conversion characteristics of crop by-products, such as rice straw, must be measured because they are important animal feeds in many countries (Huque and Stem, 1993; Devendra, 1989; and Winrock, 1978). Also, in the work described by Margan et al., the tropical forages were modified to remove part of the stems, whereas the temperate forages were fed whole. It is not known what effect this selected plant part removal had on the CH_4-producing properties of the species studied.

The uncertainty in the CH_4 emission estimates for tropical countries is due also to a lack of data on feed-intake levels, or typical animal-growth and milk-production rates. Improved characterizations of the animal populations in many tropical countries are needed to improve the emission estimates.

The rates of conversion of feed energy to CH_4 for the nonruminant animals are much lower than those for ruminants. For swine on good-quality grain diets, found mostly in developed countries, about 0.6% of feed consumed is converted to CH_4. For swine on lower-quality diets, found mostly in developing countries, about 1.3% is converted (Crutzen et al., 1986). For horses, mules, and asses that estimate is about 2.5%. While these estimates are also uncertain and are likely to vary among regions and countries, the global emissions from these species are much smaller than the emissions from ruminant animals. Consequently, the uncertainty in these values does not contribute significantly to the uncertainty in the estimates of total global CH_4 emissions from livestock digestion.

2.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

The general approach described in OECD (1991) is recommended for estimating CH_4 emissions from livestock. Each of the following steps may be performed for each animal species:

(1) Define representative animal types. For example, cattle could be divided into dairy cattle and beef cattle. Within these categories, further divisions by age (e.g., calves and mature animals) and production level should be considered.

(2) Estimate feed energy intake for each representative animal type. The feed requirements for each representative animal type should be calculated based on data about their size and production level. For example, large dairy cows with high levels of production require more feed than growing calves.

(3) Estimate the portion of feed-energy intake that is converted to CH_4 by the animal. As discussed above, a general range of 5.5-6.5% is applicable to most

[7] Ryegrass grown under the same conditions as the tropical grasses.

[8] Temperate clover hay grown under the same conditions as the tropical grasses.

well-fed ruminant animals in temperate agricultural systems. Special cases, such as cattle consuming high-grain diets, should use estimates that are tailored to their specific feed-intake conditions. The Blaxter and Clapperton (1965) relationship can be used to estimate this value in cases where diets fall within the range of observations used to generate the relationship.

(4) Estimate emission factors per head for each animal type. The feed intake, expressed in units of feed energy, is multiplied by the conversion percentage to estimate CH_4 energy produced per head. This value is then converted to kilograms (kg) of CH_4 per head per year, using a conversion of 55.65 megajoules (MJ) per 1,000 grams (g) of CH_4. Separate emission factors are estimated for each animal type.

(5) Multiply the emission factors by the appropriate animal populations. The total emissions are computed as the emission factor per head times the appropriate population of each animal type.[9]

The full implementation of this method requires detailed information about animal populations and their feed and production characteristics. Because these characteristics vary substantially for cattle among regions and countries, and even within countries, it is expected that emission factors also will vary significantly. Therefore, it is recommended that this method be implemented for cattle in as much detail as possible, given available data for those countries for which cattle are an important source of emissions.

With the exception of two broad and general differences between developed and developing countries (discussed below), the emission factors for the other animal species are not expected to vary as much by country as the emission factors for cattle. Additionally, emissions from the other species are not estimated to be a large portion of total CH_4 emissions from livestock, with only several notable exceptions (such as sheep emissions in New Zealand). Consequently, in general it is recommended that broadly representative emission factors be used to estimate emissions from these other species and that the full implementation of the detailed method is not necessary.

2.3.1 Implementation of the Methodology

Cattle

This section implements the methodology for cattle in nine regions of the world. These regions and the six countries with the largest cattle populations are listed in Table 2-1. As shown in the table, the total cattle population was about 1.3 billion in 1990, and the six countries with the largest populations accounted for about one-half of the total.

[9] The population of each animal type must reflect the time that an animal spends as that type. Although most animal categories are based on a complete year, some categories are based on shorter time periods (e.g., U.S. feedlots are based on a 140-day period).

TABLE 2-1

CATTLE POPULATIONS: 1990

Regions	Population (millions)
North America	110
Western Europe	100
Oceania	36
Eastern Europe	154
China and Centrally Planned Asia	87
Middle East	13
Africa	188
Latin America	314
South and East Asia	278
World Total	*1,279*

Key Countries	Population (millions)
India (71%)[a]	197
Brazil (45%)	140
Former Soviet Union (77%)	118
United States (89%)	98
China (89%)	77
Australia (64%)	23
Key Country Total (51%)[b]	*653*

a. Percentage of regional cattle population accounted for by this country.

b. Percentage of global cattle population accounted for by the key countries.

Source: FAO, 1991.

Information characterizing the cattle in each of the major countries was reviewed to estimate emission factors for those countries. These emission factors were used to estimate emissions from each of the regions. As discussed previously, the characteristics of cattle in many developing countries are not well documented. While the best readily available data were used, the estimates could be improved by collecting more detailed information for the countries with large cattle populations. Following are descriptions of each step of the method.

Step 1: Define Representative Animal Types

Developing precise estimates of emissions necessitates dividing cattle into categories of relatively homogeneous groups. For each category, a representative animal is chosen and characterized for purposes of estimating an emission factor. For purposes of this study, the definition of "categories" is limited by the availability of data for characterizing the animals in terms of the key variables needed to estimate an emission factor. This limitation is particularly severe for many developing countries and regions for which precise data were not readily identified. Consequently, a relatively aggregate analysis is presented here for those countries and regions. More detailed assessments performed by animal experts within the individual countries should be performed to improve these estimates.

Table 2-2 presents a set of representative animal types that are recommended for estimating emission factors for cattle. Two main categories, Mature Cattle and Young Cattle, are recommended as the minimum set of representative types. The subcategories listed should be used when data are available. In particular, the subpopulation of milking cows should be identified because the feed intake necessary to support milk production can be substantial. In the United States, the feedlot category is needed so that the implications of the high-grain diets can be incorporated.

TABLE 2-2

REPRESENTATIVE CATTLE TYPES

Main Categories	Subcategories		
Mature Animals	Mature Females:		
	--	Dairy Cows:	used principally for commercial milk production
	--	Beef Cows:	used principally for producing beef steers and heifers
	--	Multiple-Use Cows:	used for milk production, draft power, and other uses
	Mature Males:		
	--	Breeding Bulls:	used principally for breeding purposes
	--	Draft Bullocks:	used principally for draft power
Young Animals	Preweaned Calves		
	Growing Heifers, Steers/Bullocks and Bulls		
	Feedlot-Fed Steers and Heifers on High-Grain Diets		

Step 2: Estimate Feed Intake

Feed intake is estimated based on the feed-energy requirements of the representative animals, subject to feed-intake limitations. For this analysis, the net energy system described in NRC (1984 and 1989) is used. Because this system was developed for feeding conditions in temperate regions, several adjustments were made to avoid potential biases when applied to evaluate feed-energy intakes for tropical cattle (see Appendix B).

The net energy system specifies the amount of feed-energy required for the physiological functions of cattle, including maintenance, growth, and lactation. Feed-energy requirements for work have also been estimated and are included in this analysis for the draft animals in developing countries. Energy requirements for pregnancy have also been added for the portion of cows that give birth in each year. The following information is required to estimate feed-energy intakes:

- Maintenance. Maintenance refers to the apparent feed energy required to keep the animal in energy equilibrium, i.e., there is no gain or loss of energy in the body tissues (Jurgens, 1988). For cattle, net energy for maintenance (NE_m) has been estimated to be a function of the weight of the animal raised to the 0.75 power (NRC, 1984):

$$NE_m(MJ/day) = 0.322 \times (weight\ in\ kg)^{0.75} \qquad (2.1)$$

NRC (1989) recommends that lactating dairy cows be allowed a slightly higher maintenance allowance:

$$NE_m(MJ/day) = 0.335 \times (weight\ in\ kg)^{0.75} \quad \{dairycows\} \qquad (2.1^*)$$

Consequently, the *weight* of the animal is needed to estimate maintenance requirements in megajoules per day (MJ/day). It has also been suggested that additional energy is required for animals to obtain their food. Grazing animals require more energy for this activity than do stall-fed animals. The following energy requirements are added for this activity:[10]

  - Confined animals (pens and stalls): no additional NE_m;
  - Animals grazing good-quality pasture: 17% of NE_m; and
  - Animals grazing over very large areas: 37% of NE_m.

- Growth. The energy requirements for growth can be estimated as a function of the weight of the animal and the rate of weight gain. NRC (1989) presents formulae for large- and small-frame males and females. The equations for large-frame females and small-frame males produce about the same values for energy requirements per unit of weight gain. The equation for large-frame males produces values about 25% lower per unit of weight gain, and the equation for small-frame females produces values about 25% higher. For this

[10] OECD (1991) recommends slightly higher energy additions. These revised figures are based on newly published information in AAC (1990).

analysis, the equation for large-frame females is used, which is about the average for the four types:

$$NE_g(MJ/day) = 4.18 \times (0.035 W^{0.75} \times WG^{1.119} + WG) \quad (2.2)$$

where:

W = animal weight in kilograms (kg); and
WG = weight gain in kg per day.

The relationships for NE_g were developed for temperate agricultural conditions, and may overestimate energy requirements for tropical conditions, particularly for draft animals that may have a lower fat content in their weight gain (Graham, 1985). However, no data are available for improving the estimates at this time.

Lactation. Net energy for lactation has been expressed as a function of the amount of milk produced and its fat content (NRC, 1989):

$$NE_l(MJ/day) = kg\ of\ milk/day \times (1.47 + 0.40 \times Fat\%) \quad (2.3)$$

At 4.0% fat, the NE_l in MJ/day is about 3.1 x kg of milk per day.

Draft Power. Various authors have summarized the energy intake requirements for providing draft power (e.g., Lawrence, 1985; Bamualim and Kartiarso, 1985; and Ibrahim, 1985). The strenuousness of the work performed by the animal influences the energy requirements; consequently, a wide range of energy requirements has been estimated. The values by Bamualim and Kartiarso show that about 10% of NE_m requirements are required per hour of typical work for draft animals. This value is used in this analysis.

Pregnancy. Daily energy requirements for pregnancy are presented in NRC (1984). Integrating these requirements over a 281-day gestation period yields the following equation:

$$NE_{pregnancy}(MJ/281\text{-}day\ period) = 28 \times calf\ birth\ weight\ in\ kg \quad (2.4)$$

The following equation can be used to estimate the approximate calf birth weight as a function of the cow's weight:[11]

$$Calf\ birth\ weight\ (kg) = 0.266 \times (cow\ weight\ in\ kg)^{0.79} \quad (2.5)$$

Manipulating equations 2.4 and 2.5, in conjunction with equation 2.1, shows that the NE required for pregnancy is about 7.5% of NE_m for the range of cow sizes considered in this analysis. Therefore, a factor of 7.5% of NE_m is added

[11] This species-specific equation from Robbins and Robbins (1979) was adjusted to the mean cow and calf weight of a typical beef breed of cattle. This adjustment increases the coefficient in the equation from 0.214 to 0.266.

to account for the energy required for pregnancy for the portion of cows giving birth each year.

Based on these equations, the following information is needed to estimate the net energy intakes of the representative animal types: weight in kilograms; feeding situation (stall- or pen-fed, grazing good pasture, or grazing over very large areas); weight gain per day in kilograms; milk production in kilograms of 4% fat-corrected milk; number of hours of work performed per day; and portion that give birth. Table 2-3 presents estimates of these values for the representative animal types in each of the six key countries (equation 2.1* is used only for mature dairy cows). Additionally, Table 2-3 (and subsequent tables) includes representative cattle types for Africa and the Middle East and Western Europe.

As shown in Table 2-3, four to eight representative animal types are defined for each country or region. The data on animal weights come from a variety of sources.[12] Because data on cattle in developing countries are less available, judgment is required in some cases to make the estimates. In many cases the estimates are based on case studies conducted in individual regions or countries. Generally, the cattle in developing countries are smaller at all ages than the cattle in developed countries.

The feeding situations for the animal types are assigned based on the types of animal-production systems employed. For example, in India, due to limitations on the availability of grazing land, nearly all animals are stall-fed to some degree. Alternatively, in Brazil, nearly all the animals graze, some over large areas. In the United States, dairy cows and feedlot cattle are stall- or pen-fed, while most other cattle graze. With the exception of Brazil, it was assumed that all dairy cows are primarily stall-fed. Also, all draft animals were assumed to be stall-fed. In China and Africa, separate animal types were defined to represent that some cattle principally graze, while others are principally stall-fed.

Weight gain is estimated based on the mature weights of the animals and the approximate age of maturity. For example, young cattle in India have three to four years to gain about 50-200 kg. The average daily weight gain would be about 0.05-0.14 kg per day (kg/day), and a middle value of 0.10 kg/day is used.[13] Mature animals are assumed to have a constant weight; consequently, no weight gain is reported.[14]

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[12] Estimates of cattle weights were developed from Reuss et al. (1990) and sources identified therein, including: Pathak and Jakhomola (1983); Simpson and Farris (1982); CIAT (1975 and 1979); Simpson (1988); Rong Yi (1983); Gryseels et al. (1988); Doppler (1980); and ADETEF (1982).

[13] 50 kg ÷ (365 days x 3 years) = 0.05 kg/day. 200 kg ÷ (365 days x 4 years) = 0.14 kg/day.

[14] Even mature animals gain and lose weight during the year. In some cases, weight change between the wet and dry seasons can be large. Reflecting these fluctuations in weight during the year would tend to increase the estimate of the feed-energy intake requirements of the animals by a small amount. However, insufficient data are available to quantify this effect for most regions.

TABLE 2-3

DATA ON REPRESENTATIVE CATTLE TYPES

Animal Type	Animal Category	Weight (kg)	Feeding Situation	Weight Gain (kg/day)	Milk (kg/day)	Work (hrs/day)	Percent Pregnant
			India				
Mature Females	Dairy Cows	275	Stall Fed	0.00	2.5	0.00	50%
Mature Females	Other Cows	125	Stall Fed	0.00	0.6	0.00	33%
Mature Males	Draft Bullocks	200	Stall Fed	0.00	0.0	2.74	0%
Young	All	80	Stall Fed	0.10	0.0	0.00	0%
			Brazil				
Mature Females	Dairy Cows	400	Pasture/Range	0.00	2.2	0.00	80%
Mature Females	Other Cows	400	Large Areas	0.00	1.1	0.00	67%
Mature Males	Bulls	450	Large Areas	0.00	0.0	0.00	0%
Young	All	230	Large Areas	0.30	0.0	0.00	0%
			Former Soviet Union				
Mature Females	Dairy Cows	550	Stall Fed	0.00	7.0	0.00	80%
Mature Females	Other Cows	500	Pasture/Range	0.00	3.3	0.00	67%
Mature Males	Bulls	600	Pasture/Range	0.00	0.0	0.00	0%
Young	All	230	Pasture/Range	0.40	0.0	0.00	0%
			United States				
Mature Females	Dairy Cows	600	Stall Fed	0.00	18.4	0.00	90%
Mature Females	Other Cows	500	Pasture/Range	0.00	3.3	0.00	80%
Mature Males	Bulls	800	Pasture/Range	0.00	0.0	0.00	0%
Young	Calves on Milk	100	Pasture/Range	0.90	0.0	0.00	0%
Young	Calves on Forage	185	Pasture/Range	0.90	0.0	0.00	0%
Young	Growing Heifers/Steers	265	Pasture/Range	0.70	0.0	0.00	0%
Young	Replacements	375	Pasture/Range	0.40	0.0	0.00	0%
Feedlot	All	415	Stall Fed	1.30	0.0	0.00	0%

(continued)

TABLE 2-3

DATA ON REPRESENTATIVE CATTLE TYPES (Continued)

Animal Type	Animal Category	Weight (kg)	Feeding Situation	Weight Gain (kg/day)	Milk (kg/day)	Work (hrs/day)	Percent Pregnant
			China				
Mature Females	Dairy Cows	350	Stall Fed	0.00	4.5	0.00	80%
Mature Females	Farming Region	325	Stall Fed	0.00	1.1	0.55	33%
Mature Females	Grazing Region	300	Pasture/Range	0.00	1.1	0.00	50%
Mature Males	Farming Region	450	Stall Fed	0.00	0.0	1.37	0%
Mature Males	Grazing Region	400	Pasture/Range	0.00	0.0	0.00	0%
Young	All	200	Pasture/Range	0.20	0.0	0.00	0%
			Australia				
Mature Females	Dairy Cows	500	Stall Fed	0.00	4.7	0.00	80%
Mature Females	Other Cows	400	Pasture/Range	0.00	2.4	0.00	67%
Mature Males	Bulls	450	Pasture/Range	0.00	0.0	0.00	0%
Young	All	200	Pasture/Range	0.30	0.0	0.00	0%
			Africa/Middle East				
Mature Females	Dairy Cows	275	Stall Fed	0.00	1.3	0.00	67%
Mature Females	Other Cows	200	Stall Fed	0.00	0.3	0.55	33%
Mature Males	Draft Bullocks	275	Stall Fed	0.00	0.0	1.37	0%
Mature Females	Other Cows: Grazing	200	Large Areas	0.00	0.3	0.00	33%
Mature Males	Bulls: Grazing	275	Large Areas	0.00	0.0	0.00	0%
Young	All	75	Pasture/Range	0.10	0.0	0.00	0%
			Western Europe				
Mature Females	Dairy Cows	550	Stall Fed	0.00	11.5	0.00	90%
Mature Males	Bulls	600	Pasture/Range	0.00	0.0	0.00	0%
Young	Replacement/ Growing	400	Pasture/Range	0.40	0.0	0.00	0%
Young	Calves on Milk	100	Pasture/Range	0.30	0.0	0.00	0%
Young	Calves on Forage	230	Pasture/Range	0.30	0.0	0.00	0%

Milk production is estimated for dairy cows and other mature females. Milk production per dairy cow is taken from FAO (1991). Milk production for other mature females is estimated as follows: for developing countries, milk production is assumed to be 25% of the dairy cow value in the country; and for developed countries and Brazil (Latin America), milk production is assumed to be 50% of the dairy cow value, up to a maximum of 1,200 kg of milk per year per cow.[15]

Only draft bullocks and other mature females (nondairy cows) in developing countries are estimated to perform work. In Asia and Africa, draft bullocks are estimated to work five hours per day for 100 days a year, for a total of 500 hours per year, or 1.4 hours per day on average. Other mature females are assumed to work for two hours per day for 100 days, for an average of 0.55 hours per day for the entire year. In the Indian subcontinent, draft bullocks are estimated to work for 10 hours per day for 100 days (2.7 hours per day on average), and other mature females are assumed to perform no work at all. While it is true that the duration and strenuousness of work vary, these values are believed to be broadly representative of the work provided by these animals in the various regions.

Based on the data presented in Table 2-3, the net energy requirement of each of the representative animal types was estimated, as shown in Table 2-4. As expected, the larger, more productive cattle have higher feed-energy requirements.

These net energy requirements must be translated into gross energy intakes. Gross energy-intake estimates also allow the net energy estimates to be checked for reasonableness against expected ranges of feed intake as a percentage of animal weight. Estimating gross energy intake requires considering the relationship between the net and gross energy values of different feeds. This relationship can be summarized briefly as follows:

Digestible Energy	=	Gross Energy - Fecal Losses
Metabolizable Energy	=	Digestible Energy - Urinary and Combustible Gas Losses
Net Energy	=	Metabolizable Energy - Heat Increment
Net Energy	=	Gross Energy - Fecal Losses - Urinary and Combustible Gas Losses - Heat Increment

The quantitative relationship among these energy values varies among feed types. Additionally, the values depend on how the feeds are prepared and fed, and the level at which they are fed. For purposes of this analysis, simplifying assumptions are used to produce a reasonably representative relationship for the range of diets typically fed to cattle.

[15] The value of 1,200 kg is typical for the milk production of a U.S. beef cow per lactation. Milk production for nursing a calf is unlikely to exceed this level. Milk production in developing countries is expected to be lower due to poorer feed resources.

TABLE 2-4

NET ENERGY REQUIREMENTS FOR REPRESENTATIVE CATTLE TYPES (MJ/day)

Animal Type	Animal Category	NE_m	NE_{feed}	NE_g	NE_l	NE_w	NE_p
		India					
Mature Females	Dairy Cows	22.6	0.0	0.0	7.8	0.0	0.8
Mature Females	Other Cows	12.0	0.0	0.0	1.9	0.0	0.3
Mature Males	Draft Bullocks	17.1	0.0	0.0	0.0	4.7	0.0
Young	All	8.6	0.0	0.7	0.0	0.0	0.0
		Brazil					
Mature Females	Dairy Cows	30.0	5.1	0.0	6.8	0.0	1.8
Mature Females	Other Cows	28.8	10.7	0.0	3.4	0.0	1.4
Mature Males	Bulls	31.5	11.6	0.0	0.0	0.0	0.0
Young	All	19.0	7.0	3.5	0.0	0.0	0.0
		Former Soviet Union					
Mature Females	Dairy Cows	38.0	0.0	0.0	21.7	0.0	2.3
Mature Females	Other Cows	34.0	5.8	0.0	10.2	0.0	1.7
Mature Males	Bulls	39.0	6.6	0.0	0.0	0.0	0.0
Young	All	19.0	3.2	4.8	0.0	0.0	0.0
		United States					
Mature Females	Dairy Cows	40.6	0.0	0.0	57.0	0.0	2.7
Mature Females	Other Cows	34.0	5.8	0.0	10.2	0.0	2.0
Mature Males	Bulls	48.4	8.2	0.0	0.0	0.0	0.0
Young	Calves on Milk	10.2	1.7	7.9	0.0	0.0	0.0
Young	Calves on Forage	16.2	2.7	10.3	0.0	0.0	0.0
Young	Growing Heifers/Steers	21.1	3.6	9.4	0.0	0.0	0.0
Young	Replacements	27.4	4.7	6.1	0.0	0.0	0.0
Feedlot	All	29.6	0.0	23.5	0.0	0.0	0.0
		China					
Mature Females	Dairy Cows	26.8	0.0	0.0	14.0	0.0	1.6
Mature Females	Farming Region	24.6	0.0	0.0	3.4	1.4	0.6
Mature Females	Grazing Region	23.2	3.9	0.0	3.4	0.0	0.9

(continued)

TABLE 2-4

NET ENERGY REQUIREMENTS FOR REPRESENTATIVE CATTLE TYPES (MJ/day) (continued)

Animal Type	Animal Category	NE_m	NE_{feed}	NE_g	NE_l	NE_w	NE_p
		China (continued)					
Mature Males	Farming Region	31.5	0.0	0.0	0.0	4.3	0.0
Mature Males	Grazing Region	28.8	4.9	0.0	0.0	0.0	0.0
Young	All	17.1	2.9	2.1	0.0	0.0	0.0
		Australia					
Mature Females	Dairy Cows	35.4	0.0	0.0	14.6	0.0	2.1
Mature Females	Other Cows	28.8	4.9	0.0	7.4	0.0	1.4
Mature Males	Bulls	31.5	5.3	0.0	0.0	0.0	0.0
Young	All	17.1	2.9	3.3	0.0	0.0	0.0
		Africa/Middle East					
Mature Females	Dairy Cows	22.6	0.0	0.0	4.0	0.0	1.1
Mature Females	Other Cows	17.1	0.0	0.0	0.9	0.9	0.4
Mature Males	Draft Bullocks	21.7	0.0	0.0	0.0	3.0	0.0
Mature Females	Other Cows: Grazing	17.1	6.3	0.0	0.9	0.0	0.4
Mature Males	Bulls: Grazing	21.7	8.0	0.0	0.0	0.0	0.0
Young	All	8.2	1.4	0.7	0.0	0.0	0.0
		Western Europe					
Mature Females	Dairy Cows	38.0	0.0	0.0	35.7	0.0	2.6
Mature Males	Bulls	39.0	6.6	0.0	0.0	0.0	0.0
Young	Replacement/Growing	28.8	4.9	6.4	0.0	0.0	0.0
Young	Calves on Milk	19.0	3.2	3.5	0.0	0.0	0.0
Young	Calves on Forage	19.0	3.2	3.5	0.0	0.0	0.0

NE_m = net energy for maintenance.

NE_{feed} = net energy for obtaining feed; stall fed, grazing, or grazing over very large areas.

NE_g = net energy for growth.

NE_l = net energy for lactation (milk production).

NE_w = net energy for work.

NE_p = net energy for pregnancy.

Given the above relationship between net and gross energy, the digestibility of feeds consumed by cattle was assigned to each of the key countries and regions by animal type as follows:

- Dairy cows generally get the best available feeds. Consequently, they have feeds with high digestibilities. A value of 60% was assigned for all dairy cows, except for India (where large amounts of crop by-products are fed) and the United States (where grains are fed). An estimate of 55% is used for dairy cows in India, and an estimate of 65% is used for dairy cows in the United States.

- Most of the grazing animals were assumed to consume feed with a digestibility of 60%. Young cattle were assumed to have a higher digestibility (65%) because they are nursing for a period of time, are often supplemented, and preferentially consume forages with higher digestibilities. Because the digestibilities of grazing resources in Africa were assumed to be of lower quality, a 55% digestibility was assumed.

- Stall-fed animals subsisting on crop by-products were assumed to have a digestibility of 55%, except in India, where 50% was assumed. Feedlot cattle in the United States that consume large amounts of grain were estimated to have an 82% digestibility.

Given the digestibility of the feed, a general relationship between digestible energy and metabolizable energy can be used as follows (NRC, 1984):

$$\textit{Metabolizable Energy } (ME) = 0.82 \times \textit{Digestible Energy } (DE) \qquad (2.6)$$

Equation 2.6 is a simplified relationship; larger (smaller) CH_4 conversion rates would tend to reduce (increase) the coefficient to values below (above) 0.82.

NRC (1984) presents a quantitative relationship between metabolizable energy and net energy. Separate relationships are presented for net energy used for growth versus net energy used for other functions. However, the NRC (1984) relationships were developed based on diets with digestibilities that are higher than most of the digestibilities discussed previously. Consequently, the NRC (1984) relationship (which is nonlinear) may not be appropriate for all of the digestibility values used in this analysis.

Other energy systems (e.g., ARC, 1980) use linear relationships between metabolizable energy and net energy values for feeds. The nonlinear nature of the NRC (1984) relationship could bias the estimates of feed intake upward, particularly for low-digestibility feeds. Such an upward bias could also bias the emission estimate upward. Consequently, as described in Appendix B, a linear relationship was adopted. The following equations define the ratio of net energy to metabolizable energy when digestibility is 65% or lower:

$$NE/ME = 0.364 + 0.00499 \times ME\%$$

$$NE_g/ME = -0.044 + 0.00796 \times ME\%$$

where:

NE/ME	=	the ratio for net energy consumed for maintenance, lactation, work, and pregnancy;
NE_g/ME	=	the ratio for net energy consumed for growth; and
ME%	=	the metabolizable energy as a percentage of gross energy, expressed in percent (e.g., 50%).

For example, for a digestibility of 60%, ME% equals 49.2%, NE/ME equals 0.61, and NE_g/ME equals 0.35.

Based on equation 2.6, these linear relationships can be expressed as a function of digestible energy as follows:

$$NE/DE = 0.298 + 0.00335 \times DE\% \quad (2.7)$$

$$NE_g/DE = -0.036 + 0.00535 \times DE\% \quad (2.8)$$

For example, at DE% of 60%, NE/DE equals 0.50, and NE_g/DE equals 0.28.

Given the estimates for feed digestibility and equations 2.7 and 2.8, the gross energy intake (GE in MJ/day) can be estimated as follows:

$$GE = [(NE_m + NE_{feed} + NE_l + NE_w + NE_p) \div \{NE/DE\} + (NE_g \div \{NE_g/DE\})] \div (DE\%/100) \quad (2.9)$$

where:

{NE/DE} is computed from equation 2.7;
{NE_g/DE} is computed from equation 2.8; and
DE% is digestibility in percent (e.g., 60%).

Using equation 2.9 for the cases in which digestible energy is 65% or lower (which is nearly all the cases), and the nonlinear NRC relationships for the case in which digestibility exceeds 65%, Table 2-5 lists the estimated gross energy intakes and intakes as a percentage of body weight. Nearly all of the estimated daily intakes are between 1.5% and 3.0% of body weight, a reasonable range for the diverse cattle management conditions found globally.

These intake estimates also are consistent with previous estimates. For example, the energy requirements and intakes listed in Tables 2-4 and 2-5 imply an average metabolizable energy (ME) intake for Indian cattle of about 10,000 MJ per year. Winrock (1978) estimates the average ME requirements for Indian cattle at 10,600 MJ per year. Similarly, the values implied for the U.S. dairy and beef cows are 58,000 MJ and 31,000 MJ per year, respectively, which are similar to the respective estimates of 62,000 MJ and 31,700 MJ derived in U.S. EPA (1993). Consequently, for the diverse set of conditions represented in the analysis, the

TABLE 2-5

GROSS ENERGY INTAKE FOR REPRESENTATIVE CATTLE TYPES

Animal Type	Animal Category	Digest (%)[a]	GE[b]	Percent BW[c]
		India		
Mature Females	Dairy Cows	55	117.7	2.3%
Mature Females	Other Cows	50	61.0	2.6%
Mature Males	Draft Bullocks	50	93.7	2.5%
Young	All	50	43.2	2.9%
		Brazil		
Mature Females	Dairy Cows	60	145.9	2.0%
Mature Females	Other Cows	60	148.0	2.0%
Mature Males	Bulls	60	144.0	1.7%
Young	All	60	107.5	2.5%
		Former Soviet Union		
Mature Females	Dairy Cows	60	207.2	2.0%
Mature Females	Other Cows	60	172.9	1.9%
Mature Males	Bulls	60	152.5	1.4%
Young	All	60	102.2	2.4%
		United States		
Mature Females	Dairy Cows	65	299.5	2.7%
Mature Females	Other Cows	60	174.0	1.9%
Mature Males	Bulls	60	189.9	1.3%
Young	Calves on Milk	NA	NA	NA
Young	Calves on Forage	65	107.2	3.1%
Young	Growing Heifers/Steers	65	120.1	2.5%
Young	Replacements	60	143.2	2.1%
Feedlot	All	75	161.8	2.1%
		China		
Mature Females	Dairy Cows	60	141.6	2.2%
Mature Females	Farming Region	55	113.2	1.9%
Mature Females	Grazing Region	60	105.0	1.9%

(continued)

TABLE 2-5

GROSS ENERGY INTAKE FOR REPRESENTATIVE CATTLE TYPES (Continued)

Animal Type	Animal Category	Digest (%)[a]	GE[b]	Percent BW[c]
	China (continued)			
Mature Males	Farming Region	55	134.9	1.6%
Mature Males	Grazing Region	60	112.5	1.5%
Young	All	60	79.3	2.1%
	Australia			
Mature Females	Dairy Cows	60	174.1	1.9%
Mature Females	Other Cows	55	160.5	2.2%
Mature Males	Bulls	55	138.8	1.7%
Young	All	55	98.6	2.7%
	Africa/Middle East			
Mature Females	Dairy Cows	60	92.8	1.8%
Mature Females	Other Cows	55	73.2	2.0%
Mature Males	Draft Bullocks	55	93.2	1.8%
Mature Females	Other Cows: Grazing	55	93.6	2.5%
Mature Males	Bulls: Grazing	55	112.3	2.2%
Young	All	60	36.2	2.6%
	Western Europe			
Mature Females	Dairy Cows	60	254.7	2.5%
Mature Males	Bulls	60	152.5	1.4%
Young	Replacement/Growing	60	149.8	2.0%
Young	Calves on Milk	NA	NA	NA
Young	Calves on Forage	65	83.7	2.0%

a. Digestibility in percentage on an energy basis.

b. Gross-energy intake, MJ/day.

c. Dry-matter intake as a percentage of body weight. Energy density of feed estimated at 18.45 MJ/kilogram.

NA = values not estimated for nursing calves.

intake estimates correspond to reasonably expected ranges and previously published estimates.

Step 3: Estimate Conversion of Feed to Methane

As discussed previously, the rate of conversion of feed energy to CH_4 is relatively constant across most feeding and management situations. The following estimates were adopted for this analysis:

- Developed Countries. A 6.0% conversion rate was assumed for all cattle in developed countries, except for feedlot cattle in the United States, where a 3.5% rate was used.

- Developing Countries. Several assumptions were made for different animal management situations in developing countries:

  -- All dairy cows and young cattle were assumed to have a conversion rate of 6.0%. These cattle are generally the best-fed cattle in these regions.
  -- All nondairy, nonyoung stall-fed animals consuming low-quality crop by-products were assumed to have a conversion rate of 6.5%, except the cattle in India, which were assigned a conversion rate of 7.5%, because feed resources are particularly poor in many cases in this region.
  -- All grazing cattle were assumed to have a conversion rate of 6.0%, except for grazing cattle in Africa, which were assigned a rate of 7.5% because of the forage characteristics found in many portions of tropical Africa.

Step 4: Develop Emission Factors

Methane emission factors per head were developed for each of the representative animal types by using the feed-intake and CH_4-conversion-rate estimates. First, the daily feed-energy intake was multiplied by the CH_4 conversion rate for each animal type. Then, the daily CH_4 emission rate was estimated using the conversion factor of 55.65 MJ per 1,000 g of CH_4. The resulting daily estimates, shown in Table 2-6, vary from 0 g per day (for nursing calves) to over 300 g per day across the animal types.

Other Livestock

Table 2-7 lists emission factors that may be used for the noncattle species. While some variation is expected in the level of feed-energy intake among countries, the average values reported are reasonable for most situations. For two species, buffalo and camels, the estimates of the CH_4 conversion rates are particularly uncertain because measurements are not available for the types of diets they typically consume. Crutzen et al. (1986) assumed a CH_4 conversion rate of 9.0% for these animals. In this analysis, lower rates were used because the poor-quality diets generally consumed by these animals would not likely support a 9.0% conversion to CH_4. For buffalo, a 7.5% rate was used, consistent with Leng (1991).

A recent report by Carmean et al. (1992) with the llama, a close relative of the camel, found a 7.1% CH_4 conversion rate with a mixed concentrate-forage diet fed at restricted levels near maintenance. The significance of this result for choosing a CH_4 conversion rate for

TABLE 2-6

METHANE EMISSION FACTORS FOR CATTLE

Animal Type	Animal Category	CH_4 Percent	CH_4 (g/day)	CH_4 (kg/head/yr)[a]	Population Mix (%)	Average Emission Factor (kg/head/yr)
			India			
Mature Females	Dairy Cows	6.0%	127	46.3	15%	
Mature Females	Other Cows	7.5%	82	30.0	34%	
Mature Males	Draft Bullocks	7.5%	126	46.1	9%	
Young	All	6.0%	47	17.0	43%	28.3
			Brazil			
Mature Females	Dairy Cows	6.0%	157	57.4	13%	
Mature Females	Other Cows	6.0%	160	58.2	32%	
Mature Males	Bulls	6.0%	155	56.7	5%	
Young	All	6.0%	116	42.3	50%	50.1
			Former Soviet Union			
Mature Females	Dairy Cows	6.0%	223	81.5	30%	
Mature Females	Other Cows	6.5%	202	73.7	21%	
Mature Males	Bulls	6.5%	178	65.0	15%	
Young	All	6.0%	110	40.2	34%	63.4
			United States			
Mature Females	Dairy Cows	6.0%	323	117.9	10%	
Mature Females	Other Cows	6.0%	188	68.5	32%	
Mature Males	Bulls	6.0%	204	74.5	2%	
Young	Calves on Milk	0.0%	0	0.0[b]	14%	
Young	Calves on Forage	6.0%	116	8.1[c]	7%	
Young	Growing Heifers/Steers	6.0%	130	19.4	15%	
Young	Replacements	6.0%	154	56.3	10%	
Feedlot	All	3.5%	102	14.3[b]	10%	54.2

(continued)

TABLE 2-6

METHANE EMISSION FACTORS FOR CATTLE (Continued)

Animal Type	Animal Category	CH_4 Percent	CH_4 (g/day)	CH_4 (kg/head/yr)[a]	Population Mix (%)	Average Emission Factor (kg/head/yr)
			China			
Mature Females	Dairy Cows	6.0%	153	55.7	3%	
Mature Females	Farming Region	6.5%	132	48.3	26%	
Mature Females	Grazing Region	6.0%	113	41.3	9%	
Mature Males	Farming Region	6.5%	158	57.5	23%	
Mature Males	Grazing Region	6.0%	121	44.3	8%	
Young	All	6.0%	86	31.2	31%	44.5
			Australia			
Mature Females	Dairy Cows	6.0%	188	68.5	7%	
Mature Females	Other Cows	6.0%	173	63.2	48%	
Mature Males	Bulls	6.0%	150	54.6	10%	
Young	All	6.0%	106	38.8	35%	54.2
			Africa/Middle East			
Mature Females	Dairy Cows	6.0%	100	36.5	20%	
Mature Females	Other Cows	6.5%	86	31.2	10%	
Mature Males	Draft Bullocks	6.5%	109	39.7	10%	
Mature Females	Other Cows: Grazing	7.5%	126	46.0	5%	
Mature Males	Bulls: Grazing	7.5%	151	55.2	20%	
Young	All	6.0%	39	14.2	35%	32.7
			Western Europe			
Mature Females	Dairy Cows	6.0%	275	100.2	31%	
Mature Males	Bulls	6.0%	164	60.0	15%	
Young	Replacement/Growing	6.0%	162	84.0	38%	
Young	Calves on Milk	0.0%	0	0.0[c]	11%	
Young	Calves on Forage	6.0%	90	6.3[d]	5%	64.2

a. Estimates based on 365 days of feeding, unless otherwise noted.

b. Based on 140 days of feeding.

c. Based on 70 days of feeding.

d. Based on 150 days of feeding.

TABLE 2-7

EMISSION FACTORS FOR LIVESTOCK

Animal	Gross Energy Intake (MJ/day)	Energy Intake Released as Methane (%)	Emission Factor (kg/head/yr)
Buffalo[a]			
India	108	7.5[b]	53.0
Other Countries	119	7.5[b]	58.0
Sheep			
Developed Countries	20	6.0	8.0
Developing Countries	13	6.0	5.0
Goats	14	6.0	5.0
Camels	100	7.0[c]	46.0[d]
Pigs			
Developed Countries	38	0.6	1.5
Developing Countries	13	1.3	1.0
Horses	110	2.5	18.0
Mules and Asses	60	2.5	10.0

a. The derivation of the feed-energy intake for buffalo is described in Appendix A. The value of 85 MJ/day used by Crutzen et al. was found to be too low based on the information reviewed for this study.

b. Crutzen et al. assume that the developing country emission factor for sheep is appropriate to use for Australia and New Zealand. In this analysis, the developed country emission factor for sheep was found to be more representative of the emission rate for sheep in these countries.

c. The CH_4 conversion rates for buffalo and camels were reduced from the 9.0% reported by Crutzen et al. Although available measurements are sparse, a 9.0% conversion rate to CH_4 is unlikely to be supported on the poor-quality feeds typically consumed by buffalo and camels.

d. The emission factor was reduced to 46 from the 58 reported by Crutzen et al., to be consistent with the 7.0% CH_4 conversion rate in this analysis.

MJ = megajoules.

Source: Crutzen et al., 1986.

camels is difficult to assess for two reasons: camels will typically be fed above maintenance so they can provide draft power, and camels will not typically be fed concentrates. In the absence of better information, an assumption of 7% was used in this analysis.

Based on a review of available data, the feed-energy intake levels assumed for buffalo by Crutzen et al. (1986) appear to be underestimates. Consequently, the feed-intake levels and emission factors for buffalo are derived separately in Appendix A. As discussed in the appendix, the average feed-energy intake requirements for buffalo were calculated using data and certain assumptions about their size, feeding situation, weight gain, lactation, and typical work hours. The feed-energy-intake estimates are on the order of 90-150 MJ per day, with the averages reported in the table. In comparison with Crutzen et al., the buffalo feed-energy intake level is higher in this study, and the CH_4 conversion rate is lower. These two differences offset each other to a large extent, so that the emission factors for buffalo listed in Table 2-7 are quite similar to the 50 kg/head/yr reported by Crutzen et al.

The 6.0% CH_4 conversion rate used for the sheep and goats falls within the 5.5-6.5% range discussed previously. Sheep and goats in developing countries are assumed to have this conversion rate, despite the relatively poorer-quality feeds found in this region because sheep and possibly, to some extent, goats are less able to digest poor-quality forages as contrasted with cattle (Terada et al., 1987; and Minson, 1990). The reduced digestibility, and thus, reduced fermentation of these forages appear to be associated with the faster rate of passage of the particles through the digestive tract of sheep (Poppi et al., 1981).

The values for the nonruminant animals are broadly representative. The nonruminant animals do not contribute significantly to total emissions. Consequently, further refinement of the estimates is not considered vital. The CH_4 emissions for these species for a given country are estimated by multiplying the emission factors in Table 2-7 by the animal populations. The animal population data are reported by the Food and Agriculture Organization (FAO) in the Production Yearbook series (FAO, 1991).

2.4 RESULTS

2.4.1 Cattle

The total cattle population and the dairy cow population for each country and region were taken from FAO (1991). The makeup of the nondairy cow populations for each country or region was developed from a variety of sources.[16] These data were used to estimate an average emission factor per head for each country and region that reflects the mix of animal types within that country or region, as well as the number of days that animals spend in each animal category in a year (Table 2-6). For example, the average emission factor for India was estimated to be 28.3 kg per head per year (kg/h/yr). This value is lower than the emission factor reported by Crutzen et al. (1986) for developing countries. Western Europe and the former Soviet Union have relatively higher emission factors because a large portion of the

[16] The population estimates for India were developed from Vaidyanathan (1988), which presented detailed breakdowns of cattle populations by age and sex based on the national agriculture census. Sources for other regions were Reuss et al. (1990) and sources listed therein, including: Copland (1985); Ward et al. (1986); CIAT (1979); Swann (1987); Gryseels et al. (1988); and Politiek and Bakker (1982).

cattle in these regions consists of dairy cows, which tend to have higher emissions per head. The average emission factor for the United States, 54.2 kg/h/yr, is similar to the value developed in greater detail in U.S. EPA (1993) and is slightly below the value implied by the estimates in Johnson et al. (1991).

The emission factors for each country and region were applied to the total cattle population in each region, as reported by FAO (1991), to estimate regional and global CH_4 emissions from cattle. Table 2-8 presents the estimates by region and for the key countries. As shown in the table, total emissions are estimated at about 58 Tg for 1990. The regions with the largest emissions are Latin America (15.7 Tg) and Eastern Europe (9.8 Tg), which includes the former Soviet Union. The former Soviet Union and Brazil are the countries with the largest emissions, followed by India and the United States.

2.4.2 Other Livestock

Table 2-9 lists the emissions for the other livestock by region. Cattle estimates also are shown for completeness. Both the animal populations and the emission estimates (in Tg per year) are reported. As shown in the table, buffalo and sheep are the second and third largest sources of emissions, each contributing about 10% of the total emission estimate. The emissions from the remaining livestock are relatively small, accounting for less than 10% of total emissions. The table also lists the top 10 countries in terms of emissions. These countries account for an estimated 49.1 Tg of emissions, or about 60% of the total.

2.5 TRENDS

Future CH_4 emissions from livestock will be driven by future production levels and practices. With increasing human population, the trend of increased production of milk, meat, and hides from livestock is expected to continue. Because this trend is contingent on continued economic growth, it may be influenced by a variety of factors. For example, Parikh et al. (1988) project a 1.6% annual increase in milk and bovine/ovine meat production through the year 2000. Growth rates are expected to be larger among developing countries because of more rapid population increases and because of the high income elasticities of demand for these products among the relatively poorer populations of most developing countries.

U.S. EPA (1989) also developed a scenario of future milk and meat production as part of its evaluation of policies for stabilizing global climate. This scenario, based on the results of an international agricultural model that incorporates demand and supply functions for the major agricultural commodities (including grains, meat, and milk products), trade policies, and domestic agricultural pricing and supply policies, projects slightly lower rates of increases in production over the next 20 years.

Some have questioned whether developing countries can achieve the increases in animal production projected by such studies as Parikh et al. (1988) and U.S. EPA (1989) because feed availability may impose a constraint on future production increases. Parikh et al. address this issue and expect feed costs to increase as supplies tighten in some regions. However, assuming that economic development continues, the prices for animal products are also expected to increase, substantially offsetting the increased cost of feed.

TABLE 2-8

REGIONAL AND GLOBAL CATTLE EMISSIONS: 1990

Region/Country	Population (millions)	Emission Factor (kg/h/yr)	Emissions (Tg/yr)
	Regions		
North America	110	54.2	6.0
Western Europe	100	64.2	6.4
Oceania	36	54.2	2.0
Eastern Europe	154	63.4	9.8
China and Centrally Planned Asia	87	44.5	3.9
Middle East[a]	13	32.7	0.4
Africa	188	32.7	6.1
Latin America	314	50.1	15.7
South and East Asia	278	28.3	7.9
World Total	*1,279*	*45.4*	*58.1*
	Key Countries		
India (71%)[b]	197	28.3	5.6
Brazil (45%)	140	50.1	7.0
Former Soviet Union (77%)	118	63.4	7.5
United States (89%)	98	54.2	5.3
China (89%)	77	44.5	3.4
Australia (64%)	23	54.2	1.2
Key Country Total (52%)[c]	*653*	*46.0*	*30.0*

a. Emissions estimated using the emission factor for Africa.

b. Percentage of regional emissions accounted for by this country.

c. Percentage of global emissions accounted for by the key countries.

Source: Population data from FAO (1991).

TABLE 2-9

GLOBAL LIVESTOCK METHANE EMISSIONS

Region/Country	Cattle	Buffalo	Sheep	Goats	Camels	Swine	Horses	Mules/ Asses	Total
				Livestock Populations (000s)					
North America	110,449	0	12,123	1,927	0	64,384	5,630	56	N/A
Western Europe	99,831	653	141,043	25,771	3	111,835	2,455	2,342	N/A
Oceania	36,024	0	226,149	1,996	0	17,155	519	9	N/A
Eastern Europe	154,171	682	179,672	9,257	300	148,972	8,283	797	N/A
China and CP Asia	86,986	26,119	128,193	103,660	1,035	379,152	12,742	16,532	N/A
Middle East	12,646	379	72,711	25,895	899	446	395	3,383	N/A
Africa	187,771	2,500	205,094	173,944	14,509	13,585	4,987	14,445	N/A
Latin America	313,502	1,209	119,731	35,302	0	80,060	22,828	14,613	N/A
South and East Asia	277,877	109,216	105,784	179,278	2,704	41,174	3,081	6,219	N/A
World Total	*1,279,257*	*140,758*	*1,190,500*	*557,030*	*19,450*	*856,763*	*60,920*	*58,396*	*N/A*
				1990 Emissions (Tg/yr)					
North America	6.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	6.3
Western Europe	6.4	0.0	1.1	0.1	0.0	0.2	0.0	0.0	7.9
Oceania	2.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0	3.8
Eastern Europe	9.8	0.0	1.4	0.0	0.0	0.2	0.1	0.0	11.7
China and CP Asia	3.9	1.5	0.6	0.5	0.0	0.4	0.2	0.2	7.4
Middle East	0.4	0.0	0.4	0.1	0.0	0.0	0.0	0.0	1.0
Africa	6.1	0.1	1.0	0.9	0.7	0.0	0.1	0.1	9.1
Latin America	15.7	0.1	0.6	0.2	0.0	0.1	0.4	0.1	17.2
South and East Asia	7.9	5.8	0.5	0.9	0.1	0.0	0.1	0.1	15.4
World Total	*58.1*	*7.7*	*7.6*	*2.8*	*0.9*	*1.0*	*1.1*	*0.6*	*79.8*

(continued)

TABLE 2-9

GLOBAL LIVESTOCK METHANE EMISSIONS (continued)

Region/Country	Cattle	Buffalo	Sheep	Goats	Camels	Swine	Horses	Mules/ Asses	Total
				1990 Emissions for the Top 10 Countries (Tg/yr)					
India	5.59	4.00	0.27	0.55	0.07	0.01	0.02	0.02	10.52
Former Soviet Union	7.50	0.02	1.10	0.03	0.01	0.12	0.11	0.00	8.90
Brazil	7.01	0.07	0.11	0.06	0.00	0.03	0.11	0.03	7.42
China	3.42	1.25	0.57	0.49	0.02	0.36	0.19	0.17	6.47
United States	5.32	0.00	0.09	0.01	0.00	0.08	0.09	0.00	5.60
Argentina	2.53	0.00	0.14	0.02	0.00	0.00	0.05	0.00	2.75
Australia	1.22	0.00	1.34	0.00	0.00	0.00	0.01	0.00	2.58
Pakistan	0.50	0.78	0.15	0.18	0.05	0.00	0.01	0.03	1.69
Mexico	1.41	0.00	0.03	0.05	0.00	0.02	0.11	0.06	1.68
France	1.36	0.00	0.10	0.01	0.00	0.02	0.00	0.00	1.49

N/A = Not applicable.

Sources: Population data from FAO (1991). Emission estimates for cattle described above. Emission factors for buffalo are derived in Appendix A. Emission factors for camels based on a 7.0% CH_4 conversion rate. Emission factors for all other noncattle livestock taken from Crutzen et al. (1986).

If production practices were to remain constant, emissions from animals involved in the production of meat, milk, and hides would be expected to increase at the same rate as the increase in production. However, several factors must be considered:

- Improved animal management and breeding practices are continuing to increase animal productivity in developed and developing countries. Increased productivity tends to reduce CH_4 emissions per unit of product produced. This point is emphasized by the fact that in 1990 nearly 80% of the emissions from cattle was estimated to be associated with animal *maintenance*, so that only 20% was associated with feed intake required for *production*. Because improved productivity can have a substantial impact on emissions per unit of product produced, emissions will increase more slowly than the increase in production, and could actually decline.

- Because of changes in animal productivity, emissions do not track trends in animal populations. As shown previously, emission factors per head for cattle vary substantially among countries. These factors increase over time as production levels per animal increase. Therefore, emissions can increase more

rapidly than the rate of increase in animal populations. Additionally, emissions can increase as production increases, even if animal populations remain unchanged or decline.

The projections of milk and meat production do not allow for the fact that a substantial number of cattle, buffalo, and camels are used as draft animals. The number of draft animals used is driven by a range of interrelated and complex factors, including the size of landholdings (smaller landholdings tend to have a higher number of draft animals per unit area), the availability and mechanization of irrigation systems, the cost and availability of feed resources, and the types of crops grown (Vaidyanathan, 1988). Projections of global draft animal requirements are not available at this time.

Based on these observations, it is likely that CH_4 emissions from livestock will continue to increase in the future, although at a rate less than the rate of increase in meat and milk production.

2.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

The CH_4 emission estimates are uncertain for a variety of reasons. First, more detailed analyses of feed energy requirements could be conducted to improve the precision of the estimates for particular countries. A more detailed analysis would require better data to characterize the production levels and management conditions of the animals. Second, better descriptions of the feed characteristics would improve the estimates. In particular, data describing the energy, protein, and other characteristics of crop by-products would help improve the basis for making the estimates.

Third, measurements are required to provide a basis for estimating the CH_4 conversion rates for feed types and feeding levels typically encountered in tropical developing countries. While limited data and simple models indicate that the CH_4 production rates for typical tropical production systems may be higher than the rate measured for temperate systems, this difference must be verified. If a 6.0% conversion rate were assumed for all cattle, including all cattle in tropical management systems, the global emission estimate for cattle for 1990 would be reduced from 58.1 Tg to 56.2 Tg.

Based on the available data, the global emissions estimate is likely to be within a range of about ±25% of the central estimate. This range accounts for the uncertainty in the animal populations as well as the emission rates for the wide variety of animal management conditions that exist. The overall range for CH_4 emissions from the digestive processes of livestock is, therefore, about 60 to 100 Tg per year.

2.7 CONCLUSIONS

The amount of CH_4 emitted by domesticated livestock is estimated to be about 80 Tg per year, which is consistent with previous estimates. Cattle are the largest single source, accounting for 75% of the total. Buffalo and sheep are the second and third largest sources, accounting for about 10% each. Emissions from domesticated livestock are likely to increase in the future as the production of animal products continues to increase.

These emission estimates were developed using the general approach defined in OECD (1991); adjustments were made to several assumptions to improve the estimates. National inventories of emissions from this source are possible, given the available data and understanding of the physical processes that control CH_4 emissions from livestock. The estimates presented here can be improved by incorporating additional country-specific information.

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APPENDIX A

EMISSION FACTORS FOR BUFFALO

This appendix summarizes the derivation of CH_4 emission factors for buffalo. Crutzen et al. (1986) estimated an emission factor of 50 kg of CH_4 per animal per year based on a gross energy intake of 85 MJ per animal per day (Pandey, 1981) and a CH_4 yield of 9.0%. Alternative emission factors for buffalo are presented here, using different estimates of feed intake and a CH_4 conversion rate of 7.5%.

A.1 FEED INTAKES

A.1.1 Buffalo Characteristics

As with cattle, the feed intakes for buffalo are driven by size (weight in kg), growth rate, lactation, and work performed. Among these factors, size is by far the most important. Table A-1 shows the data collected on buffalo weights for various types throughout the world. The majority of these data are based on case studies of buffalo in specific countries or regions of countries. For purposes of this study, the following weight ranges are used to estimate feed intakes:

- Adult Males: 350-550 kg;
- Adult Females: 250-450 kg; and
- Young: 100-300 kg.

The upper ends of these ranges represent the higher values listed in Table A-1. The lower values of the ranges may be found in some areas with relatively small animals and poor feed resources.

The estimates of weight gain for young buffalo are based on the adult weight of buffalo and the approximate age of maturity, which is about three to four years. The rate of weight gain for young is estimated at about 0.15 kg/day.[17] Mature buffalo are assumed to have a constant weight; consequently, no weight gain is reported.

Milk production per female buffalo is estimated from total commercial buffalo milk production, reported in FAO (1990), and from estimates of the female buffalo population. Two representative countries were used for the estimates: India, with about 75 million buffalo, and China, with about 21 million. Together, these two countries have nearly 70% of all buffalo. For India, the adult female population is assumed to be about 40% of the total buffalo population (Agricultural Statistics Division, 1977); for China, the estimate is 45% (Reuss et al., 1990). The resulting estimates of milk production per adult female are about 2.7 kg/day for India and 0.65 kg/day for China. These values are used to represent milk production of buffalo in the Indian Subcontinent and Other Countries, respectively.

As with cattle, draft male buffalo are estimated to work 5 hours per day for 100 days a year, for a total of 500 hours per year, or 1.37 hours per day on average. Draft female buffalo

[17] Growth rate estimated as: 150 kg ÷ 3 years = 0.14 kg/day to 250 kg ÷ 4 years = 0.17 kg/day.

TABLE A-1

DATA ON BUFFALO SIZE

Region	Category	Weight (kg)	Weight Source
Indian Subcontinent	Adult Males	550	Bangladesh/Foik (1988)
	Adult Females	450	Bangladesh/Foik (1988)
	Young	300	Bangladesh/Foik (1988) and Pathak and Jakhmola (1983)
	Dry Dairy	350	Pathak and Jakhmola (1983)
	Milk Dairy	350	Pathak and Jakhmola (1983)
Southeast Asia	Adult Males	540	Thailand/Chantalakhana (1985)
		525	Copland (1985)
	Bullocks	525	Thailand/Chantalakhana (1985)
	Adult Females	395	Copland (1985)
		400	Thailand/Chantalakhana (1985)
	All Adults	435	Malaysia/Liang et al. (1989)
		530	Philippines/Eusebio (1984)
		500	Devendra (1989)
		637	Thailand/Bunyavejchewin et al. (1985)
	Young	98	Thailand/Chantalakhana (1985)
		170	Copland (1985)
		305	Malaysia/Liang et al. (1989)
		360	Philippines/Eusebio (1984)
North Africa & Middle East	All Adults	500	FAO (1977)
	Young	300	FAO (1977)
Tropical America	All Adults	700	FAO (1977)
	Young	385	FAO (1977)
Eastern Europe & the Former Soviet Union	All Adults	530	FAO (1977)
	Young	115	FAO (1977)
China, Mongolia, Korea	Adult Males	515	FAO (1977)
	Adult Females	410	FAO (1977)

are assumed to work 2 hours per day for 100 days a year, for an average of 0.55 hours per day for the entire year. These buffalo characteristics are summarized in Table A-2.

A.1.2 Energy Requirements

Based on the buffalo characteristics in Table A-2, the energy intake requirements of the representative animal types were estimated (Table A-3). The energy relationships described in the main text for cattle are applied here for buffalo.

Maintenance

Net energy for maintenance (NE_m) for cattle is estimated as a function of the weight of the animal. Table A-3 presents the estimates for NE_m for the various animal sizes. The range is from about 10 MJ/day for small young to about 37 MJ/day for large adult males. The net energy required to obtain food is assumed to be zero for stall- and pen-fed animals.

Growth

The energy requirements for growth are estimated as a function of the weight of the animal and the rate of weight gain. The NRC (1989) equation for large-frame female cattle, as described in Section 2.4, is used to estimate the net energy requirement for growth (NE_g). As shown in Table A-3, the energy requirements for growth are relatively small compared with the maintenance requirements because the animals grow very slowly. Consequently, these estimates of energy requirements for growth do not have an important influence on the final emission estimates.

Lactation

Net energy for lactation (NE_l) is expressed as a function of the amount of milk produced and its fat content (NRC, 1989). At 4.0% fat, the NE_l in MJ/day is about 3.1 x kg of milk produced per day. Although buffalo milk generally has a higher fat content than that of cow milk, a 4% fat content is assumed for this analysis. The resulting NE_l estimates range from about 2.0 MJ/day to 8.4 MJ/day.

Draft Power

The values by Bamualin and Kartiarso (1985) show that about 10% of NE_m requirements are required per hour of typical work for draft animals. This value is used for estimating the net energy required for work (NE_w) for buffalo, as shown in Table A-3. As with energy for growth, these values are relatively small compared with those for maintenance requirements.

Pregnancy

Net energy for pregnancy (NE_p) is computed as described for cattle in the main text. One-third of mature female buffalo in India are assumed to give birth each year, and one-fourth is the portion assumed for other countries. The resulting energy estimates for pregnancy are small and do not have a significant influence on the emission estimates.

TABLE A-2

DATA ON REPRESENTATIVE BUFFALO TYPES

Region	Category	Weight (kg)	Wt. Gain (kg/day)	Milk (kg/day)	Work (hrs/day)
Indian Subcontinent	Adult Males	350 - 550	0.00	0.00	1.37
	Adult Females	250 - 450	0.00	2.70	0.55
	Young	100 - 300	0.15	0.00	0.00
Other Countries	Adult Males	350 - 550	0.00	0.00	1.37
	Adult Females	250 - 450	0.00	0.65	0.55
	Young	100 - 300	0.15	0.00	0.00

TABLE A-3

NET ENERGY REQUIREMENTS FOR REPRESENTATIVE BUFFALO TYPES (MJ/day)

Region	Category	NE_m	NE_g	NE_l	NE_w	NE_p
Indian Subcontinent	Adult Males	26.1 - 36.6	0.0	0.0	3.6 - 5.0	0.0
	Adult Females	20.2 - 31.5	0.0	8.4	1.1 - 1.7	0.5 - 0.8
	Young	10.2 - 23.2	1.2 - 1.9	0.0	0.0	0.0
Other Countries	Adult Males	26.1 - 36.6	0.0	0.0	3.6 - 5.0	0.0
	Adult Females	20.2 - 31.5	0.0	2.0	1.1 - 1.7	0.4 - 0.6
	Young	10.2 - 23.2	1.2 - 1.9	0.0	0.0	0.0

NE_m = net energy for maintenance.

NE_g = net energy for growth.

NE_l = net energy for lactation.

NE_w = net energy for work.

NE_p = net energy for pregnancy.

Gross Energy Intake

As with cattle, the gross energy (GE) intakes of the buffalo are estimated and compared to the weights of the representative animals. Because buffalo are almost entirely found in developing countries where they subsist on crop by-products, a digestibility of 55% is assumed. The resulting GE estimates are shown in Table A-4. All the GE estimates are between 1.5% and 2.5% of body weight, which is reasonable.

A.2 METHANE EMISSION FACTORS

The CH_4 conversion rate adopted for this analysis is 7.5%. Based on the feed-intake and CH_4 conversion rate estimates, CH_4 emission factors per head are developed for each of the representative buffalo types. First, the daily feed-energy intake is multiplied by the CH_4 conversion rate of 7.5%. Then, the daily CH_4 emission rate is estimated using the conversion factor of 55.65 MJ per 1,000 g of CH_4. The resulting daily estimates are shown in Table A-5. Then the daily rates are converted to annual rates by multiplying them by 365.

As shown in the table, annual emission rates for the buffalo in the Indian Subcontinent range from about 23 kg/yr for small young to about 80 kg/yr for large adult females. A similar range is shown for Other Countries.

Average emission factors are estimated for the Indian Subcontinent and Other Countries by taking into account the mix of animal types within the population of each region. Based on the population mixes in India and China, the average emission factors per head for the two regions are estimated at about 41-66 kg and 47-70 kg, respectively. The mid-points of these range estimates are used as the emission factors for buffalo in Tables 2-7 and 2-9 of the main text.

TABLE A-4

GROSS ENERGY INTAKE FOR REPRESENTATIVE BUFFALO TYPES

Region	Category	Digest. (percent)[a]	GE (MJ/day)[b]	Percent BW[c]
Indian Subcontinent	Adult Males	55	112 - 157	1.5 - 1.7
	Adult Females	55	116 - 162	2.0 - 2.5
	Young	55	47 - 101	1.8 - 2.5
Other Countries	Adult Males	55	112 - 157	1.5 - 1.7
	Adult Females	55	91 - 137	1.6 - 2.0
	Young	55	47 - 101	1.8 - 2.5

a. Digestibility in percent on an energy basis.

b. Gross energy intake.

c. Daily dry-matter intake as a percent of body weight. Energy density of feed estimated at 18.45 MJ/kg.

TABLE A-5

METHANE EMISSION FACTORS FOR BUFFALO

Region	Category	CH_4 (%)	CH_4 (g/day)	CH_4 (kg/head/yr)[a]	Population Mix (%)	Average Emission Factor (kg/head/yr)
Indian Subcontinent	Adult Males	7.5	150 - 211	54.9 - 77.1	14%	
	Adult Females	7.5	156 - 219	56.9 - 79.8	40%	41.0 - 65.5
	Young	7.5	63 - 136	23.0 - 49.6	46%	
Other Countries	Adult Males	7.5	150 - 211	54.9 - 77.1	45%	
	Adult Females	7.5	122 - 184	44.6 - 67.2	45%	47.1 - 69.9
	Young	7.5	63 - 136	23.0 - 49.6	10%	

a. Estimates based on 365 days of feeding.

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APPENDIX B

DERIVATION OF THE RELATIONSHIP BETWEEN NE AND DE

This appendix summarizes the derivation of the relationship between net energy (NE) and digestible energy (DE) that is used to estimate total feed-intake requirements for cattle. As described in the main text, the relationship among the energy values of feed consumed by cattle can be summarized as follows:

Digestible Energy	= Gross Energy - Fecal Losses
Metabolizable Energy	= Digestible Energy - Urinary and Combustible Gas Losses
Net Energy	= Metabolizable Energy - Heat Increment
Net Energy	= Gross Energy - Fecal Losses - Urinary and Combustible Gas Losses - Heat Increment

NRC (1984) presents the following quantitative relationships among these energy values:

$$ME = 0.82 \times DE \quad \text{(B.1)}$$

$$NE_m = 1.37 \times ME - 0.138 \times ME^2 + -0.0105 \times ME^3 - 1.12 \quad \text{(B.2)}$$

$$NE_g = 1.42 \times ME - 0.174 \times ME^2 + 0.0122 \times ME^3 - 1.65 \quad \text{(B.3)}$$

where:

DE = digestible energy in Mcal/kg (dry-matter basis);
ME = metabolizable energy in Mcal/kg (dry-matter basis);
NE_m = net energy for maintenance in Mcal/kg (dry-matter basis); and
NE_g = net energy for growth in Mcal/kg (dry-matter basis).

The ratio of NE_m and NE_g to ME or DE can be estimated by using these relationships. Figure B-1 shows that the ratio of NE to DE is nonlinear, with an increasing slope with decreasing DE. These relationships imply that at lower values of DE, cattle can recover a decreasing portion of the energy to use for maintenance or growth.

For purposes of estimating CH_4 emissions from cattle, it was decided that applying these relationships to cattle consuming relatively low-quality feeds (such as cattle in many tropical countries) may be inappropriate because the relationships were developed based on analyses of the higher-quality feeds typically found in the U.S. temperate agricultural system. Consequently, the experimental basis for extrapolating the nonlinear relationships to low levels of DE is not very strong.

An examination of other energy systems indicates that the rate of net energy retention declines at lower values of digestible energy. Unlike the NRC system, however, many other energy systems imply a *linear* relationship between NE and DE. The U.K. energy system (ARC, 1980), which is typical of the energy systems used in Europe, has a slope for the linear

NE_m:DE relationship that is similar to the slope of the nonlinear NRC relationship in the range of 65-70% digestibility. Similarly, the slope of the U.K. NE_g:DE relationship is similar to the slope of the nonlinear NRC relationship in the range of 60-65% digestibility.

To avoid possible biases in estimating feed-intake requirements in this study, the relationships were extrapolated linearly for DE values below 65%, using the average slopes of the NRC relationships between 60% and 70% DE. Figure B-2 shows the extrapolated linear relationships along with the nonlinear estimates. As expected, the linear extrapolations fall *above* the original nonlinear estimates.

The implication of making this adjustment to the NRC (1984) relationship for the global emissions estimate is relatively minor. Using the nonlinear relationship for the entire analysis increases the 1990 emissions estimate for cattle by 1 Tg, from 58.1 Tg to 59.1 Tg. Considering the wide range of factors that contribute to uncertainty in the estimates, including characterization of animal populations, this adjustment has a minor influence on the estimates.

FIGURE B-1

NRC NE:DE RELATIONSHIP

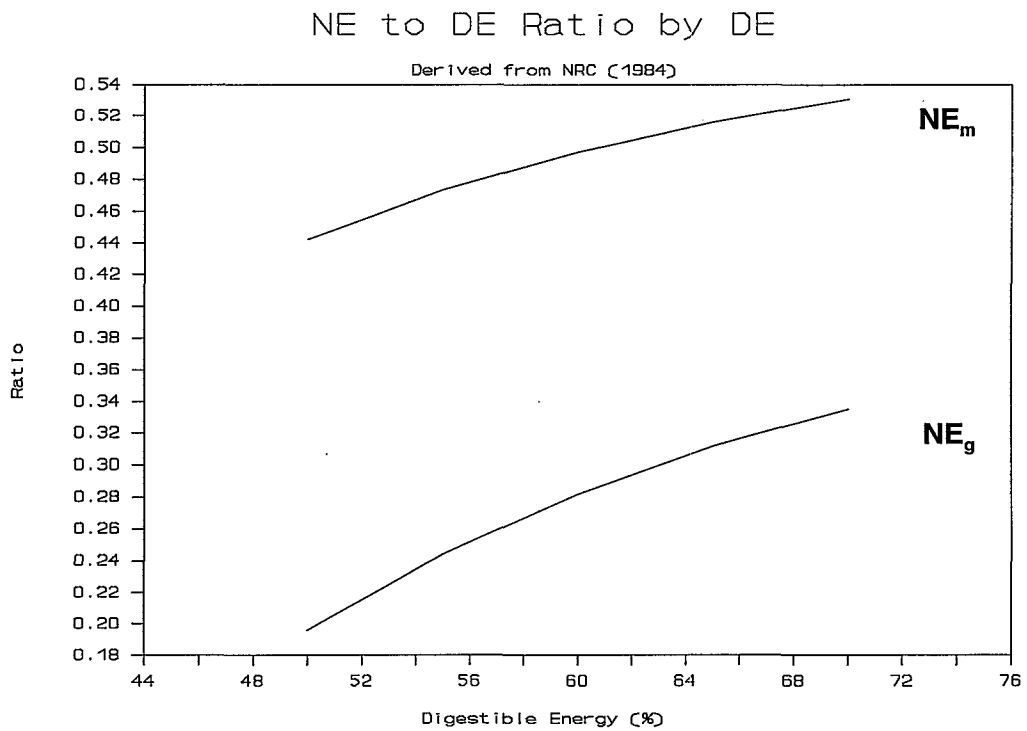
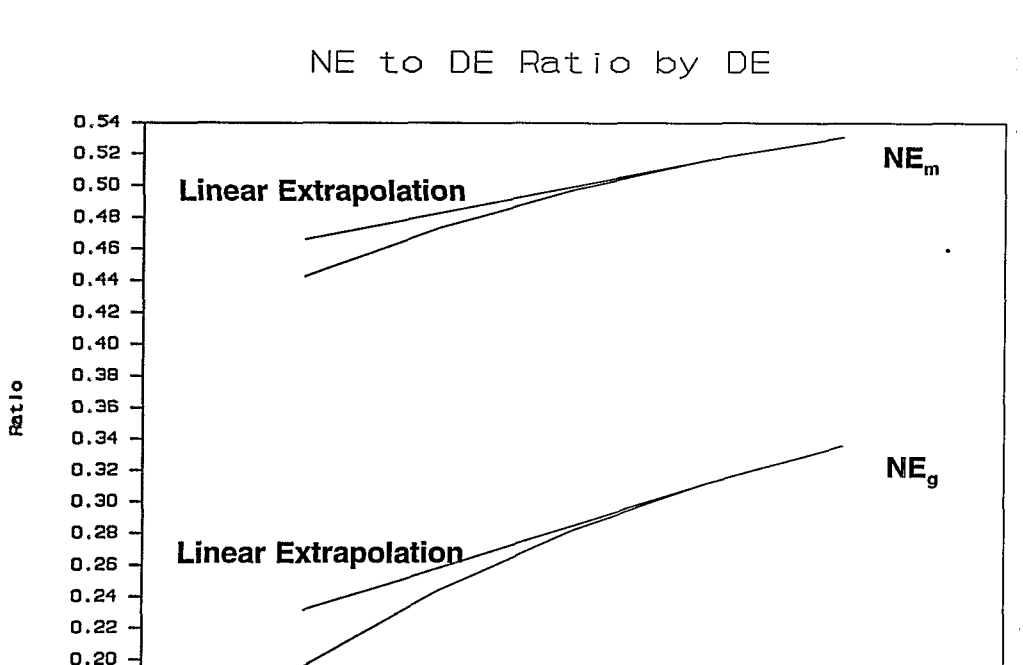


FIGURE B-2

LINEAR EXTRAPOLATION OF THE NRC NE:DE RELATIONSHIP



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CHAPTER 3

METHANE EMISSIONS FROM RICE CULTIVATION

3.1 SUMMARY

Rice cultivation is one of the major anthropogenic sources of methane. Rice has been grown for millennia in Asia; it is the primary grain eaten by a third of the world's population. Over 140 million hectares of rice were harvested in 1990, much of it from traditional flooded rice fields. These artificial wetlands provide the habitat for methanogenic bacteria and conditions that produce and emit methane at rates that greatly exceed fluxes from natural wetland ecosystems. The increase in rice cultivation was probably one of the main contributors to the growth in atmospheric methane concentration during the last century.

Current estimates of global methane emissions from rice cultivation range from 60 to 100 teragrams (Tg)[1]. Global estimates are made by summing regional estimates; regional estimates are made by multiplying a seasonal average methane flux factor by the season length and the area planted to rice. Because of the limited number and location of seasonal flux measurements, correctly associating an average flux with a particular area and growing season is the greatest uncertainty in making regional and global estimates. Soil temperature, soil type, soil microbiology, soil redox (oxidation-reduction) potential, day length, rice variety, fertilization, and irrigation all affect the methane flux from a particular area. This report estimates that in 1990 the global methane emissions from rice cultivation were about 65 Tg.

Rice area harvested increased rapidly in the 1950s, and estimated methane emissions from rice agriculture increased with it. In the last decade, the increase in area planted to rice has slowed greatly. The two major rice-planting countries, India and China, have apparently reached practical and economic limits of the available area for rice paddies. Per-capita rice area harvested in China has been decreasing since the 1960s. During the same period, rice yield has been increasing. Efforts to increase rice yield without increasing the area of rice harvested, through irrigation, fertilizers, and high-yield rice cultivars, will affect the future methane emissions from rice paddies.

3.2 BACKGROUND

Rice cultivation has long been recognized as a major source of methane (CH_4). Global budgets of CH_4 have generally included emissions of about 100 Tg/yr from rice cultivation (with a range of 50-300 Tg/yr), constituting about 20% of emissions from all sources (range 14-40%) (Ehhalt and Schmidt, 1978; Donahue, 1979; Khalil and Rasmussen, 1983; Blake, 1984; Bolle et al., 1986; Bingemer and Crutzen, 1987; Cicerone and Oremland, 1988; and Khalil and Rasmussen, 1990b). The Intergovernmental Panel on Climate Change (IPCC, 1992) estimates a source of 60 Tg/yr (range 20-150 Tg/yr). Increases of atmospheric CH_4 were first reported by Rasmussen and Khalil (1981a and 1981b) and later by many other authors (see Khalil and Rasmussen, 1983; Fraser et al., 1984; Blake and Rowland, 1986; Steele et al., 1987; and Khalil and Rasmussen, 1990a). Rice cultivation is estimated to contribute some 230 ppbv (parts per billion by volume) to the 1990 atmospheric burden of

[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

1,635 ppbv CH_4, and may be responsible for some 20-30% of the increase of CH_4 during the last century (Khalil and Rasmussen, 1991).

Estimating the flux of CH_4 from rice fields in various parts of the world requires knowledge of two factors: the emission rates and the regional or global extrapolating factor (extrapolant). The emission rate or flux depends on several internal and external variables. Internal variables include soil characteristics, rice variety, and soil microbiology. External factors include soil temperature, which is driven by solar radiation; meteorological conditions; water level, which is affected by rainfall, availability of irrigation, and water management; and treatments, such as the type and amount of fertilizers and organic amendments applied. The global flux, F_G, is usually calculated by equation 3.1:

$$F_G = \sum_R \phi_R \, T_R \, A_R \qquad (3.1)$$

where ϕ_R (g/m^2/day) is the average daily emission rate measured over the entire growing season from a region R; A_R (m^2) is the area of the region, presumably with similar characteristics, so that ϕ_R is an accurate representation of flux for the entire area; and T_R is the growing season (days/year). The global extrapolant is $A_R \, T_R$. Any smaller region, such as a country, may also be subdivided into similar regions, and the flux of CH_4 from rice cultivation from the country can be calculated based on an equation analogous to equation 3.1.

3.2.1 Methane Emission Rates From Rice Fields

Direct flux measurements over the entire growing period provide precise and accurate values for ϕ_R. Usually, A_R and T_R are determined from agricultural statistics and are also well known. Problems with the extrapolation arise in associating a measured flux at a specific site with an appropriate area and growing season and in the assumption that the measured flux is representative of the associated area and season. This empirical approach requires whole-season measurements of CH_4 emission rates from as many regions as possible so that the large variations of emissions from one region to another can be properly included in the estimate of global or regional emissions.

Alternative approaches to global extrapolation also exist and are based on the knowledge of the processes or factors that control emission rates. At present there are insufficient data for such approaches to produce reliable estimates of global or regional emissions.

Flux Measurements

During the last decade, a number of systematic experiments have been reported on CH_4 emissions from rice fields. All are based on static chamber methods. While there are many variants, the method consists of enclosing a small part (0.1-100 m^2) of the rice fields within a chamber and taking periodic air samples. The samples are analyzed for CH_4 content usually by gas chromatography using flame-ionization detectors (GC/FID). Methane, emitted from the enclosed area of the rice field, builds up in the chamber. The rate of accumulation is directly proportional to the flux or the rate of emission from the area covered by the chamber.

It is usually assumed that there are no losses of CH_4 from the chamber during the experiment, which is usually short (< 15 minutes). Methane may be lost if the chamber is not sealed, or by dissolving into the paddy water. The relationship is:

$$\phi = \frac{\rho M V}{N_A A} \times 10^{-6} \frac{dC}{dt} \qquad (3.2)$$

where ϕ is the flux, ρ is the density of air (molecules/m^3), M is the molecular weight of CH_4, V is the volume of the chamber (m^3), A is the area covered by the chamber (m^2), N_A is Avogadro's number, C is the concentration of CH_4 (ppbv), and dC/dt is in ppbv/hr. The most common units for reporting fluxes are mg/m^2/hr.

The advantages of chamber methods are: they are inexpensive, they are easy to use in remote locations, and they are coupled to a highly sensitive and precise measurement method using GC/FID. Since the fluxes of CH_4 are quite large, the plants need not be exposed to the unnatural conditions of the chamber environment for very long; often 10-minute exposures are sufficient. This fact also makes chamber methods suitable for CH_4 measurements, even though they may not be convenient for other gases.

One disadvantage is that placing the chamber can disturb the soil and release abnormal amounts of CH_4. Several methods have been devised to reduce, if not overcome, this problem. In the studies of Khalil et al. (1991), a permanent aluminum base is installed in the soil at the time rice is planted, and chambers fit into grooves in this base. In studies reported by Schütz et al. (1989a and 1990), a large permanent chamber is used that has a lid that opens and closes, but the chamber itself is not removed until the rice is harvested. Both these methods create some feedbacks that may affect flux estimates. The chambers also affect the immediate environment of the rice plant by causing heating and a buildup of carbon dioxide, which may affect emissions of CH_4. Finally, since most chambers are small, the extrapolation of direct flux measurements to large regions may be unreliable because of heterogeneities within fields, within local regions, and within different parts of the same country.

In recent years, experiments have been designed to measure the flux throughout the growing season. The earliest experiments of this type made it clear that there are large systematic changes in CH_4 emissions during the growing cycle. Such changes are driven by several factors, including the growth of root mass, maturation process for the plants, availability of nutrients and fertilization, and the seasonal change of temperature and length of day (Schütz et al., 1989a; Yagi and Minami, 1990; and Khalil et al., 1991).

Direct flux measurements are summarized in Table 3-1, with a description of the nature of the experiments. These studies were originally designed to measure the flux of CH_4 from rice paddies; later, to establish which factors affect CH_4 emissions; and most recently, to investigate treatments that may reduce CH_4 emissions.

3.2.2 Factors Affecting Methane Emissions

Methane emissions from rice cultivation result from a combination of three processes: CH_4 production in the paddy soil, CH_4 oxidation in the root zone and at the soil surface, and CH_4 transport from the soil to the atmosphere by diffusion through the floodwater, ebullition, and plant-mediated transport.

TABLE 3-1

METHANE FLUX MEASUREMENTS FROM RICE PADDIES

(From Shearer and Khalil, 1993; reprinted by permission of the authors.)

Study	Location	Rice Cultivar	Soil Type	Treatment	Flux ($mg/m^2/hr$)	Emission Season[a] (days)
Cicerone et al., 1983 1982 growing season	California, United States	M101	Vertisol, Capay Clay	Am. phosphate-Am. sulfate + Urea: 113 kg N/ha	10.4	100
Cicerone et al., 1992 1983 growing season	California, United States	Not given	Capay Silty Clay	Preplant: 36 kg N/ha + top dressing after planting: 78 kg N/ha	4.0	111
1985 growing season (Only data from plots with rice plants given here)		Not given	Sacramento Clay	No treatment	0.5	128 (approximate)
				2.5 t/ha ground rice straw	6.4	
				5 t/ha ground rice straw	18.9	
				78 kg N/ha (Urea, preplant fertilization)	0.9	
				78 kg N/ha + 2.5 t/ha rice straw	3.0	
				78 kg N/ha + 5 t/ha rice straw	13.9	
Seiler et al., 1984	Andalusia, Spain	Bahía	Not Given	Urea (before seeding): 160 kgN/ha; Am. nitrate (at tillering): 40 kg N/ha	4.0	125
Schütz et al., 1989a	Vercelli, Italy	Roma	Sandy Loam	Unfertilized	11.7	114
Data reported from 1984 to 1986; includes data from Holzapfel-Pschorn and Seiler, 1986.			(60% sand, 25% silt, 12% clay, 2.5% organic C)	Rice straw: average flux	17.6	
				5 t/ha	24.2	118
				3 t/ha	9.6	105
				6 t/ha	13.5	109
				12 t/ha	22.1	110
				24 t/ha	18.8	113
				Compost: 60 t/ha	27.5	113
				$CaCN_2$: 200 kg N/ha	12.5	118
				Urea: average flux	10.7	
				200 kg N/ha, raked	9.6	118
				100 kg N/ha, raked	9.6	118
				200 kg N/ha, incorporated	7.9	113
				200 kg N/ha, surface	15.8	113

(continued)

TABLE 3-1

METHANE FLUX MEASUREMENTS FROM RICE PADDIES (Continued)

Study	Location	Rice Cultivar	Soil Type	Treatment	Flux ($mg/m^2/hr$)	Emission Season[a] (days)
Schütz et al., 1989a (continued)	Vercelli, Italy	Roma	Sandy Loam	Straw + Urea: average flux	22.5	
				6 t/ha + 200 kg N/ha	20.0	113
				12 t/ha + 200 kg N/ha	25.0	113
				Ammonium sulfate: average flux	8.2	
				200 kg N/ha, raked	6.7	118
				200 kg N/ha, incorporated	5.6	109
				100 kg N/ha, incorporated	8.8	105
				50 kg N/ha, incorporated	7.5	105
				200 kg N/ha, surface	12.5	113
				Straw + $CaCN_2$: average flux	16.8	
				2.5 t/ha + 37.5 kg N/ha	11.7	118
				5 t/ha + 75 kg N/ha	17.9	118
				12 t/ha + 200 kg N/ha	20.6	109
Yagi and Minami, 1990	Ibaraki Prefecture, Japan	Koshihikari	Ryugasaki: Gley Soil (Eutric Gleysols)	Non-nitrogen (0:60:30)[b]	2.8	119
				Mineral (60+30:60:30)	2.9	118
				Compost: 12 t/ha + Mineral (above)	3.8	112
				Rice straw: 6 t/ha + Mineral (above)	9.6	117
			Kawachi: Peat Soil (Dystric Histosols)	Rice straw: 6 t/ha + Mineral (60+25:60:60+25)	16.3	115
			Mito: Humic Andosol	Non-nitrogen (0:120:80+30)	1.4	122
				Mineral (50+30:120:80+30)	1.2	125
				Compost: 12 t/ha	1.9	129
				Rice straw: 6 t/ha	3.2	128
				9 t/ha	4.1	128
			Tsukuba: Light Colored Andosol (volcanic ash soil)	Mineral (70+30:100:70+30)	0.2	125
				Rice straw: 6 t/ha + Mineral (above)	0.4	115

(continued)

TABLE 3-1

METHANE FLUX MEASUREMENTS FROM RICE PADDIES (Continued)

Study	Location	Rice Cultivar	Soil Type	Treatment	Flux ($mg/m^2/hr$)	Emission Season[a] (days)
Dai, 1988; and Schütz et al., 1990	Hangzhou, China	Not given	Not given	Late rice, average flux	26.4[c]	62
				Early rice, average flux	6.6[c]	70
Khalil et al., 1991	Sichuan, China	Local and Hybrid	"Purple Soil"	Organic	36.6	120
Sass et al., 1990, 1991a 1989 and 1990 data averaged for Lake Charles and Beaumont fertilized sites.	Texas, United States	Jasmine 85	Lk. Charles clay (Typic Pelludert)	Urea: 149 kg N/ha	8.7	85
				Rice straw: 12 t/ha + Urea: 102 kg N/ha	15.2	86
			Beaumont clay (Entic Pelludert)	Urea: 190 kg N/ha	2.5	85
				Rice straw: 8 t/ha + Urea: 102 kg N/ha	5.6	86
Sass et al., 1991b	Texas, United States	Jasmine 85	Verland silty clay loam (Vertic Ochraqualf)	All sites, Urea: 190 kg N/ha		
				Planted April 9		
				Straw: 6 t/ha	23.5	85
				w/o straw	18.3	
				Planted May 18		
				Straw: 6 t/ha	18.3	81
				w/o straw	11.8	
				Planted June 15		
				Straw: 6 t/ha	12.7	76
				w/o straw	12.0	
Sass et al., 1992	Texas, United States	Jasmine 85	Verland silty clay loam	All sites, Urea: 165 kg N/ha total		
				Normal flood irrigation (control)	4.4	87
				Mid-season aeration	2.3	87
				Multiple aeration (3 drained periods)	0.6	87
				Late season flood irrigation	6.3	99

(continued)

TABLE 3-1

METHANE FLUX MEASUREMENTS FROM RICE PADDIES (Continued)

Study	Location	Rice Cultivar	Soil Type	Treatment	Flux ($mg/m^2/hr$)	Emission Season[a] (days)
Chen et al., 1993	Beijing, China	Huang jinguang	Sandy Loam 1.33% organic matter	610 kg/ha NH_4HCO_3 + 15 t/ha horse manure: II[d]	14.6	79
				900 kg/ha NH_4HCO_3: F	17.5	
				610 kg/ha NH_4HCO_3 + 15 t/ha horse manure: F	35.9	
				710 kg/ha NH_4HCO_3 + 30 t/ha horse manure: F	48.9	
				610 kg/ha NH_4HCO_3 + 15 t/ha horse manure: D	~0.0	
	Nanjing, China	Shanyou 63	"yellow-brown earth" 2.29% organic matter	190 kg/ha Urea + 15 t/ha barnyard manure: L	10.8	101
				45 t/ha barnyard manure: II	9.5	
				600 kg/ha Ammonium Sulfate: F	2.6	
				190 kg/ha Urea + 3 t/ha rapestraw: M	14.3	
				190 kg/ha Urea + 15 t/ha barnyard manure: Semi-arid	6.6	
National Physical Laboratory, New Delhi, India, 1992.	New Delhi	P-615	Alluvial Sandy Loam	Intermittent Irrigation[f]	0.2	106
A.P. Mitra, ed.[e] Kharif season (Sept.-Dec.)	Gargacha, Garia	Fine	Not given	Rainfed, flooded	11.8	110

(continued)

TABLE 3-1

METHANE FLUX MEASUREMENTS FROM RICE PADDIES (Continued)

Study	Location	Rice Cultivar	Soil Type	Treatment	Flux ($mg/m^2/hr$)	Emission Season[a] (days)
Partial Studies: Studies where measurements were not taken for a full season or are not yet reported in full. Ranges of emissions are shown.						
Cicerone and Shetter (1981)	California, United States				1.3 - 7.8	
Khalil et al. (1990)	Sichuan, China				1 - 50	
Parashar et al. (1991)	New Delhi, Karnal, Dehradun, and Hyderabad, India				0.07 - 80.0	
Wassman et al. (1993)	Zheijian, China			no fertilizer	7.4 - 47.0	
				694 kg/ha K_2SO_4/KCl	7.7 - 35.4	
				694 kg/ha K_2SO_4/KCl + 1042 kg/ha rapeseed cake	7.9 - 44.0	
				1042 kg/ha rapeseed cake	6.0 - 50.6	

a. Number of days that CH_4 was actually emitted from the rice paddies.

b. ($N:P_2O_5:K_2O$) in kg/ha; rates of mineral fertilizer are expressed as basal + supplementary applications.

c. Values for Schütz et al. (1990) were digitized from the figures.

d. F: flood irrigation; II: intermittent irrigation; D: dry culture.

e. Measurements were taken at 18 sites during the 1991 Kharif season in this study. Both systematic CH_4 flux and water-level measurements for ≥ 70% of the growing season were published for the New Delhi and Gargacha sites only. Fertilization data are not available.

f. Irrigated field where water level was 0 at least once during the growing season.

Methane is produced in saturated soils by anaerobic bacteria (methanogens), which use compounds from the decay of organic matter as their food source and produce CH_4 as a by-product. This process takes place only where oxygen is not available, such as in flooded paddy fields and wetlands (Bouwman, 1991; Boone, 1993; and Neue and Roger, 1993). Temperature, water regime, nutrient availability, and soil factors (such as pH and redox potential) may affect the growth and metabolic activity of the methanogen populations and ultimately the CH_4 flux from the paddy fields.

Experiments to measure the production and emission of CH_4 from paddy soils have shown that not all CH_4 produced in the soil is emitted to the atmosphere (Holzapfel-Pschorn et al., 1985; Schütz et al., 1989b; and Sass et al., 1992). Laboratory studies of paddy soil indicate that 50-90% of the CH_4 produced in the soil can be oxidized before it reaches the surface (summarized in Neue and Roger, 1993). Strains of bacteria that consume CH_4 (methanotrophs) are believed to live in both soil and water. They oxidize the carbon in CH_4 and produce CO_2 as a by-product. This reaction can take place even in the low-oxygen environment of a paddy soil. Air transported to the roots of the rice plant creates an oxygenated zone around the roots (Nouchi et al., 1990). There the methanotrophs can break down CH_4 before it is pumped out of the soil by the air circulation system of the plant.

In the same experiments, the pathways of CH_4 emission to the atmosphere throughout the growing season were also measured. Most of the CH_4 (up to 90%) was found to be transported through the intercellular spaces in the plant. About 10% of the CH_4 was transported in bubbles from the soil, while less than 1% of the CH_4 diffused through the soil and water to the atmosphere (see Figure 3-1). At the beginning of the growing season all the CH_4 was emitted through ebullition; as the rice plants developed, an increasing amount was transported through the plant. Whether the numbers are representative of the world's rice fields is not known.

Internal Factors

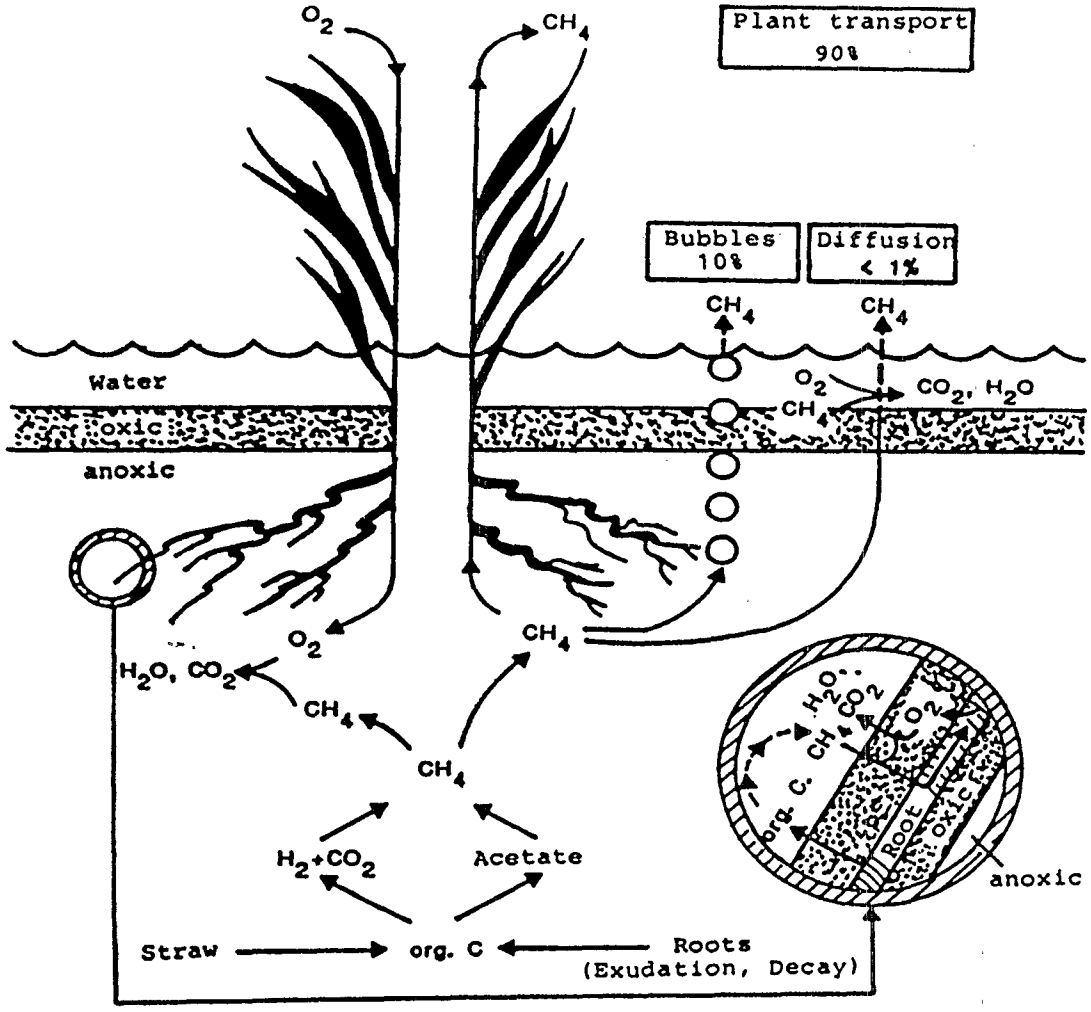
The "internal factors" of soil microbiology, soil properties, and different rice cultivars are at present the most difficult to incorporate into the global estimate of CH_4 flux from rice paddies. While the life cycle of methanogens is understood (see Boone, 1993, for a summary), predicting the population fluctuations in rice fields is not yet possible. Methanogens do not directly break down organic matter but require other bacteria to produce the substrates they need for food. The population dynamics of the various interdependent strains of bacteria may account for year-to-year variation found in field studies where all other variables are nearly the same. Organic compounds exuded from the root system of the plants may also influence the growth of methanogens or competing bacteria populations (Neue and Roger, 1993).

The soil properties most important in affecting CH_4 production are soil texture, mineralogy, and Eh/pH buffer systems (Neue et al., 1990). Several experiments have directly measured the effect of different soil textures during the same growing season (Yagi and Minami, 1990; Sass et al., 1990 and 1991a; and Chen et al., 1993). The differences in fluxes between the soil types may reflect the ability of the soils to sustain a reducing environment. In laboratory tests of paddy soils, a soil redox level of -150 mV was necessary for CH_4 emission to begin (Mariko et al., 1991; and Masscheleyn et al., 1993).

Most of the CH_4 emitted from rice paddies passes through the stems of the rice plant (Schütz et al., 1989b). Different rice cultivars may have different capacities for gas transport,

FIGURE 3-1

SCHEME OF PRODUCTION, REOXIDATION, AND EMISSION OF CH_4 IN A PADDY FIELD



Source: Schütz et al., 1989b; Reprinted by permission of the authors.

though this has not been established. The only published study using two different cultivars in the same environment for flux measurements found no significant differences between the two rice varieties (Khalil et al., 1991). The length of the growing seasons of different rice cultivars also vary, requiring different periods of standing water in the paddies. While most studies report the cultivar used, there is not enough information at present to relate cultivar type to variations in CH_4 flux.

External Factors

External factors affecting the flux of CH_4 from rice paddies may be the result of the weather, including solar radiation, which influences soil temperature, and rainfall; or agricultural practices, such as irrigation and fertilization. The former are mainly factors that change with season or stage of growth; the latter vary with geographic location, depending on availability of water and mineral fertilizers, traditional agricultural methods, and local economics.

There is a positive correlation between soil temperature and daily CH_4 flux, which changes slightly throughout the growing season with a Q_{10} of about 2 to 4 (see Figure 3-2)[2] (Schütz et al., 1989a; and Khalil et al., 1991). Temperature relationships may also vary from season to season at the same site (Khalil et al., 1991). The relationship between CH_4 flux and temperature only holds within an optimum range of soil temperatures. Parashar et al. (1993) tested the CH_4 emission response to temperature by placing heating coils in a rice field. They found that CH_4 emissions increased rapidly at temperatures above 24°C, reaching a maximum at 34.5°C. Higher temperatures inhibited production.

Changes in flux over the growing season have been found in every experiment (Schütz et al., 1989a; Yagi and Minami, 1990; and Khalil et al., 1991). Planting date determines which stage of the crop occurs during the longest and warmest days of the growing season. Schütz et al. (1990) found significant differences between average fluxes for early and late rice crops in Hangzhou, China. Sass et al. (1991b) compared the differences in flux over a planting season by planting a crop at one-month intervals. The later plantings ripened more quickly, and were irrigated for a shorter period, and differences in CH_4 fluxes between the fertilizer treatments decreased.

Rice cultivation may be divided into wetland and dryland (or upland) culture (Grist, 1986; and Neue et al., 1990). In wetland culture, the soil is prepared by puddling[3] to reduce water loss, and dikes or levees are built to contain the water. Wetland culture may be separated into irrigated and rain-fed rice. While rain-fed rice is planted during the wet season, all water is provided by rainfall, and dry spells decrease CH_4 fluxes. Dryland rice culture is generally a low-yield, subsistence agriculture, highly susceptible to drought, where no special preparations are made to retain water in the fields (De Datta, 1975). Dryland rice may not be a source of CH_4 at all, as the soil is not saturated long enough for methanogen populations to build up.

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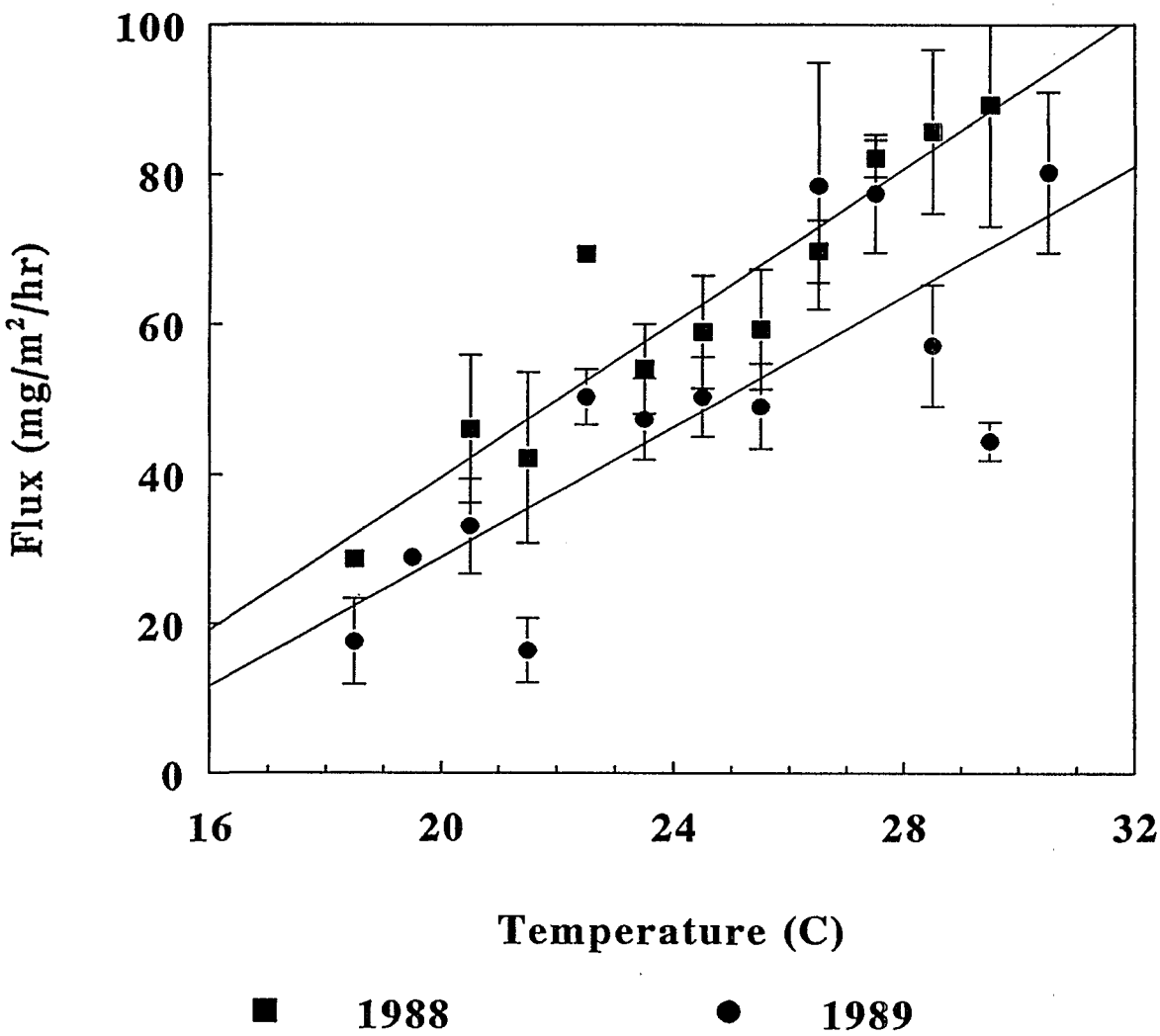
[2] Q_{10} is an experimentally-derived temperature coefficient which is the ratio of (1) the flux at a temperature 10°C above the base temperature, to (2) the flux at the base temperature.

[3] Puddling is a rice cultivation practice in which saturated and flooded soils are repeatedly plowed so that large soil aggregates are broken down into finer fractions that are well mixed with the water. Puddled soil holds more water than if it were in its natural state.

FIGURE 3-2

RELATIONSHIP BETWEEN THE FLUX AND SOIL TEMPERATURE IN A PADDY FIELD IN SICHUAN, CHINA



Source: Khalil et al., 1991; Reprinted by permission of the authors.

Most of the studies in Table 3-1 were carried out where flood irrigation is used. However, studies of water-management schemes where the soil surface is allowed to dry at least once during the season show much lower average CH_4 fluxes (Sass et al., 1992; and Chen et al., 1993). Field measurements on wetlands and on tropical soils (Harriss et al., 1982; and Keller et al., 1986) show that CH_4 flux stops and all CH_4 is oxidized once the soil dries out. Fallow rice fields where the soils are still saturated continue to have low CH_4 emissions, but emissions stop from paddy soils allowed to dry at harvest (Khalil et al., 1990). Intermittent flooding may have undesirable side effects, however. Allowing the soils to dry during some stages of plant growth, especially heading and flowering, leads to drastically reduced yields (see summaries in Grist, 1986; and Bouwman, 1991). Sass et al. (1992) compared normal flooding with both single- and multiple-aeration irrigation schemes; while the multiple-aeration regime produced the least CH_4, it used the most water.

Whether the crop is directly seeded or is transplanted may affect the length of time the crop is kept flooded and may thus affect the total CH_4 emissions over the growing season. The Khalil et al. (1991) data were obtained from a region where the rice was transplanted to the fields, then standing water was maintained in the fields until harvest about 120 days later. In the study by Sass et al. (1991a), the crop was seeded into nonflooded soil and was permanently flooded after the young plants were established. Out of a growing season of 140 days, the crop was flooded for only 85 days.

Fertilizer treatments have also been found to affect CH_4 flux. The addition of rice straw, manure, compost, and other organic fertilizers appears to enhance CH_4 production, probably by providing a food supply for the methanogens (Schütz et al., 1989a and 1990; Yagi and Minami, 1990; Sass et al., 1991a; Bouwman, 1991; Cicerone et al., 1992; and Chen et al., 1993). Nitrogen fertilizers, especially ammonium sulfate, may inhibit CH_4 production, possibly by chemical competition (reviewed in Bouwman, 1991). Use of mineral fertilizers in rice fields has been increasing globally (Neue et al., 1990); however, there are still large regions where they are unavailable or not economic. In particular, organic manures are still widely used in Asia and may result in higher fluxes for the largest rice-growing areas.

3.2.3 Regional Estimates of Methane Emissions

Four recent studies have included estimates of regional emissions from rice cultivation. Two of these studies were undertaken to provide data for global transport-chemistry models for CH_4; they concentrated on different variables, and the authors made different types of information available (Aselmann and Crutzen, 1989; and Matthews et al., 1991). Bachelet and Neue (1993) estimated emissions from rice-growing countries in Asia, modifying the estimates by soil and organic matter data. The study by Khalil and Shearer (1993) emphasized emissions by water-management level.

Aselmann and Crutzen (1989) provided detailed tables of the percent of the global rice-growing area in 2.5° latitude by 5° longitude boxes. The percentages reflect the area in rain-fed and irrigated rice only for Asia (no dryland rice was included) but show total area for Africa, Central America, and South America. Matthews et al. (1991) published detailed rice crop calendars, indicating the months of possible cultivation of rice by country, each Indian state, and each province of China. Area was allocated by 1° latitude by 1° longitude cells. Khalil and Shearer (1993) developed an inventory of direct flux measurements and modified the information from Matthews et al. on growing seasons to estimate global and regional annual emission rates.

Estimates of global emissions of rice cultivation usually focus on regions in South and East Asia, where 90% of the area planted to rice is located (FAO, 1991), and where agricultural practices are most likely to favor CH_4 production in rice paddies. Nine of the top ten rice-growing countries are in Asia (by 1990 area: India, China, Bangladesh, Indonesia, Thailand, Viet Nam, Myanmar, Brazil, Philippines, and Pakistan). Of the four non-Asian countries in the top 20 rice-planting countries, three (Brazil, Madagascar, and Nigeria) have 60-80% of their total area planted in dryland rice (Grist, 1986); the fourth country (the United States), uses cultivation practices different from most other large rice-growing countries.

The flux of CH_4 from rice fields is usually calculated by estimating the length of the season of CH_4 emission, the area in rice (irrigated and rain-fed), and the flux of CH_4 ($mg/m^2/hr$) averaged over the entire growing season (see equation 3.1). Each of these main variables is discussed separately.

Season Length

The estimate of the season length from the literature may be confused by whether "season" refers to the season of CH_4 emission, the rice-growing season (from seeding to harvest), or the total growing season (the frost-free period). For example, in the study of Sass et al. (1991a), the total growing season was about 245 days, the rice-growing season was 140 days from planting to harvest, while CH_4 was emitted during only 85 days (i.e., during the flood-irrigated period). Because the number of areas where the CH_4 emission season has actually been measured is quite limited, some other variable must be used to approximate it.

Matthews et al. (1991) used crop calendars to estimate the months of the rice-growing season by country; autumn, winter, and summer crops by Indian state; and early rice, double/late crop rice, and single (mid-season) crop rice by Chinese province. Table 3-2 compares the growing season and season of CH_4 emission reported in the literature with the growing season estimated from crop calendars by Matthews et al. With the exception of Italy, the difference between the growing season estimated using crop calendars and season of CH_4 emission is about 40-50 days.

Methane Flux Factors

Ideally, each rice-growing region would have an average CH_4 flux factor associated with it that uniquely reflects the soil, climate, and cultivation practices of the area. Practically, estimators must rely on the information that is available and their best judgment to apply measured fluxes from one region to another where data are not available.

Aselmann and Crutzen (1989) calculated fluxes from the work of Holzapfel-Pschorn and Seiler (1986) in Italy, with a base rate of 300 $mg/m^2/day$ (12.5 $mg/m^2/hr$) for average soil temperatures of 20°C and below, and assumed a linear relationship between flux and temperature up to 1,000 $mg/m^2/day$ (42 $mg/m^2/hr$) for soil temperatures of 30°C. Matthews et al. (1991) used a flux rate of 500 $mg/m^2/day$ (21 $mg/m^2/hr$) for all areas, since the emphasis of their study was to delineate the global distribution of rice cultivation rather than to estimate fluxes.

Khalil and Shearer (1993) used averaged fluxes from the studies listed in Table 3-1 for the major seasonal divisions of Chinese and Indian rice, for other countries where fluxes have been measured, and to estimate fluxes for other rice-growing countries. Flux rates were reduced by 40% for areas of rain-fed rice, approximately the reduction in flux found by Chen

TABLE 3-2

SEASONAL FACTORS FOR METHANE EMISSIONS FROM RICE FIELDS

References	Rice Growing Season (Days)	CH_4 Emission Period (Days)	Crop Calendar Season (Days[a])
Cicerone et al. (1983): United States	145	100	152
Holzapfel-Pschorn and Seiler (1986): Italy	147	126	122
Yagi and Minami (1990): Japan	140	115	152
Sass et al. (1991a): United States	140	85	152
Khalil et al. (1991): Sichuan, China	120	120	168
Chen et al. (1993): Beijing, China	100	87	137

a. Estimated from Matthews et al. (1991). See text.

et al. (1993) for their intermittent irrigation regime. The flux from dryland rice was assumed to be zero in this study.

Area Planted to Rice

Estimates of rice-growing area are usually taken from published agricultural statistics of rice area harvested supplied by the United Nations (U.N.), the International Rice Research Institute (IRRI), or the agricultural agencies of individual countries (see, for example: FAO *Production Yearbook*; IRRI, 1990; *China Agriculture Yearbook*). For convenience, agricultural statistics are reported by political or administrative subdivisions.

Aselmann and Crutzen (1989) and Matthews et al. (1991) did careful global rice area allocations, described earlier. Khalil and Shearer (1993) reduced the total areas for each country by the percentage of dryland rice grown. Estimates of the percentages were taken from tables in De Datta (1975), Huke (1982), Morris et al. (1984), and Grist (1986).

Global Emissions

Three recent estimates of the global source of CH_4 from rice cultivation are shown in Table 3-3. (Matthews et al. (1991) assumed a global source of 100 Tg.)

The major difference between the first two estimates is probably in the way a weighted average flux rate is calculated. The Khalil and Shearer estimate takes a seasonally averaged flux, based on the field studies shown in Table 3-1, and applies it to the seasonal area in wetland rice culture. The Aselmann and Crutzen estimate uses temperature-adjusted fluxes, as described earlier. The IPCC estimate is essentially based on a review and assessment of the scientific literature.

TABLE 3-3

ESTIMATES OF GLOBAL METHANE EMISSIONS FROM RICE AGRICULTURE

	Khalil and Shearer (1993)	Aselmann and Crutzen (1989)	IPCC (1992)
Tg/year	65	92 (53[a])	60
Year	1990	1985	Not given

a. Number in parentheses assumes a constant flux of 13 mg/m^2/hr.

Regional Emissions

Estimates of CH_4 emissions by country are shown in Table 3-4, comparing the countries of South and East Asia by three estimation techniques. These countries produce about 90% of the estimated CH_4 from rice cultivation. The countries with the largest estimated CH_4 source from wetland rice paddies are all in Asia and are shown in the table. The estimates by Khalil and Shearer (1993) have been described earlier. Bachelet and Neue (1993) calculated a range of 40-80 Tg/yr as the rice source for South and East Asia, making different assumptions about the effects on CH_4 emissions of soil type, rice yield, temperature, and organic matter incorporated in the soil. Two of their estimates are presented in Table 3-4.

3.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

The estimates of the global source discussed in section 3.2.3 range from 50 to 100 Tg per year. Source estimates by country vary greatly due to assumptions made on the importance of different factors that affect the CH_4 flux, and the availability of information on these factors for individual countries. A recommended methodology must focus on the factors for which there is sufficient information on both the emission factors and the extrapolants. Including the available information in the present estimates of country-by-country emissions may improve the accuracy, but at present it is not certain which factors have the greatest effect on emissions.

The factors clearly identified by field experiments are (1) water level and its history during the growing season, (2) fertilizer applications and amendments of organic matter, (3) soil type, (4) soil temperature, and (5) agricultural practices that affect the length of the CH_4 emission season, such as direct seeding or transplanting. Different rice cultivars may influence the amount of CH_4 emitted from rice fields, but this is not yet documented. Data show that higher temperatures, continuously flooded fields, and some types of organic fertilizers lead to higher emissions compared to rice grown at lower temperatures, with intermittent or managed irrigation in which the fields are not continuously inundated, and with the use of chemical fertilizers.

TABLE 3-4

ESTIMATES OF METHANE EMISSIONS BY COUNTRY FOR 1990 USING FOUR SETS OF ASSUMPTIONS ($Tg\ CH_4/yr$)

Country	Khalil and Shearer (1993)	Bachelet and Neue: Yield[a] (1993)	Bachelet and Neue: Soil[b] (1993)
Bangladesh	3.6	4.1	4.0
Cambodia	0.9	0.4	0.4
China	21.4	21.3	14.7
India	15.8	18.5	14.5
Indonesia	5.0	4.5	3.5
Japan	0.2	1.0	0.8
N. Korea	0.3	0.5	0.4
S. Korea	0.8	0.8	0.6
Laos	0.2	0.2	0.1
Malaysia	0.3	0.3	0.2
Myanmar[c]	1.3	2.0	1.4
Nepal	0.2	0.3	0.2
Pakistan	0.7	0.8	0.4
Philippines	1.3	1.2	0.8
Sri Lanka	0.4	0.4	0.3
Taiwan	0.4	0.4	0.4
Thailand	4.9	3.8	2.2
Viet Nam	3.2	2.7	1.8
Total	61	63	47

a. Estimates made by Bachelet and Neue (1993) using IRRI rice yield data, and regional estimates of incorporated organic matter.

b. The Bachelet and Neue (1993) estimate modified using the FAO soil map, and authors' best judgement on the CH_4 potential of different soil types.

c. Formerly Burma.

At present there are insufficient data to incorporate most of these factors. Nonetheless, there are sufficient data to allow for incorporation of current knowledge on the effects of water levels and temperature. For some countries, the effects of organic and mineral fertilizer can also be included. Inclusion of the remaining factors may become feasible in the future.

3.3.1 Summary of Recommended Method

The recommended methodology follows the draft IPCC-OECD methodology (OECD, 1991), in which the area harvested is multiplied by a season length and an emission coefficient (see equation 3.1, above). Three significant refinements to the draft IPCC-OECD methodology, however, have been made here. First, the definition of "season length" has

been changed from length of cultivation season (or growing season) to length of emission season (or flooding season). This change in meaning results in many cases in a shorter season length and, therefore, a lower emission estimate. The second refinement is a distinction between "continuously flooded" and "intermittently flooded" areas. In the methodology described in this section, these two water-management regimes are assigned different emission factors, and annual emission estimates for the two regimes are summed. This also results in a lower emission estimate, as intermittently flooded areas are assigned lower emission coefficients than continuously flooded areas. (Dryland, or upland, rice areas are assumed to emit no CH_4 in this methodology, as in OECD (1991).)

The last refinement to the draft IPCC-OECD methodology is the recommendation that annual emissions be estimated for three contiguous years and then averaged, rather than averaging three years of harvested area and multiplying the average area by a season length and emission coefficient. The draft IPCC-OECD methodology only incorporated interannual changes in area harvested. This change allows for incorporation of interannual changes in season length and emission coefficients, where such data exist.

The steps in the recommended methodology are as follows:

(1) For each of three contiguous years, estimate annual emissions.
   (i) Estimate annual emissions from flooded fields:

$$Flux(flooded) = \sum_{s=1}^{n} \phi_s(flooded) \cdot A_s(flooded) \cdot T_s(flooded)$$

where:

ϕ(flooded)	=	emission factor for flooded conditions in Tg/m^2/day;
A(flooded)	=	area of rice agriculture under flooded regime in m^2;
T(flooded)	=	number of days under cultivation when flooded (days/growing season);
n	=	number of growing season(s) per year when flooded conditions are present in the rice field; and
s	=	year.

Emission factors should be based on local measurements or, if not available, on measurements from a similar climatic zone. If measurements from a different climatic zone must be used, correct flux for soil temperature effect:

$$multiply\ by\ [Q_{10}]^{(T-T_b)/10^\circ C}$$

Q_{10} is the ratio of the flux at a soil temperature 10°C above the base temperature to the flux at the base temperature, T is the soil temperature, and T_b is the base temperature.

(ii) Estimate annual emissions from intermittently flooded fields:

$$Flux(intermittent) = \sum_{s=1}^{n} \phi_s(intermittent) \cdot A_s(intermittent) \quad T_s(intermittent)$$

(iii) Sum the annual emission estimates to obtain the total annual flux:

$$Annual\ Flux = F = Flux(flooded) + Flux(intermittent)$$

The procedure is described by the following general formula:

$$F = \sum_i \phi_i A_i T_i \tag{3.3}$$

where i represents water-management regimes -- flooded and intermittent.

(2) Average three annual emission estimates to obtain annual average:

$$\overline{F} = \frac{1}{3} \sum_y \left(\sum_i \phi_i A_i T_i \right)$$

where y represents one of three inventory years.

Other factors can be added where data are available. For example, where the effects of fertilizer use on emission coefficients have been measured, and areas and season lengths under different management regimes are known, fertilizer use can be incorporated into the calculations as follows:

$$Flux(flooded) = Flux(flooded, organic) + Flux(flooded, chemical)$$

where Flux (flooded, organic) is calculated according to step (i), above, using the areas, emission factors, length of flooding season, and temperatures applicable to the amount of rice grown under flooded conditions using organic fertilizers. Flux(flooded, chemical) is calculated analogously. Flux(intermittent) is also calculated as in (i), and again, the flooded and intermittent fluxes are summed to yield a total annual flux.

Adding fertilizer effect:

$$\phi_i A_i T_i = \sum_j \phi_{ij} A_{ij} T_{ij} \tag{3.4}$$

where j represents different fertilizer types. Each component of equation 3.3 is calculated by equation 3.4.

Additional factors can be added in the same way, for example:

$$\phi_{ij} A_{ij} T_{ij} = \sum_{k} \phi_{ijk} A_{ijk} T_{ijk} \quad (3.5)$$

where k represents different soil types. Each component of equation 3.4 is calculated from 3.5 and then each component of equation 3.3 is calculated from equation 3.4. The process may be continued for more factors.

3.4 RESULTS

Applying the methodology discussed in section 3.3 through equation 3.3 results in an average global emission estimate of 65 Tg CH_4/year. This estimate is based on three years of data, centered on 1990, and incorporates the effects of water-management regime and temperature on flux. Some of the daily fluxes implicitly incorporate information on organic vs. mineral fertilizers, depending on the flux data available for a given region.

Together, China and India account for over half of the estimated global CH_4 emissions from rice cultivation. Six countries -- China, India, Indonesia, Thailand, Bangladesh, and Viet Nam -- account for over 80% of the estimated global emissions. Table 3-5 summarizes the global distribution of emissions by country, as well as area, season length, and flux data.

3.5 TRENDS

Rice paddies played an important role in the growth of atmospheric CH_4, particularly from the middle of this century to the present. However, the rate of increase in atmospheric CH_4 has slowed in the last decade. Predicting future emissions from rice cultivation using either the trend of past emissions or population-area relationships will probably lead to large overestimates (Khalil and Rasmussen, 1990a; and Khalil et al., 1993). The increase in rice cultivation was likely one of the main contributors to the increase of CH_4 during the last century (Figure 3-3). However, factors that were important causes of the increase in the past are changing and probably will not be as important in the future. The time series of global CH_4 emissions from rice estimated by Khalil and Shearer (1993) is largely influenced by the tremendous increase in area planted to rice in the last four decades. By the early 1980s, this growth in area had slowed significantly.

Figure 3-4 shows a time series of per-capita rice field CH_4 emissions for China (Khalil et al., 1993). Except for a brief period in the 1950s, per-capita emissions have steadily declined, despite the increase in area planted (nearly 10 million hectares). These data illustrate the difficulties associated with using historical population-area relationships and population projections to predict future CH_4 emissions from rice-growing countries. Efforts to increase rice yield without increasing the area planted, such as irrigation, fertilizers, and high-yield rice cultivars, will affect the future CH_4 emissions from rice paddies.

3.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

Uncertainty still exists in the estimate of global emissions, and there are substantial uncertainties in estimates of regional fluxes of CH_4 from rice cultivation. The principal uncertainties still are in the association of a measured, seasonal flux with a specific region; the length of the CH_4 emission season in a specific region; and the effects of specific factors of climate and management on the seasonal flux.

3.6.1 Specific Estimation Problems

Table 3-1 lists the areas where CH_4 fluxes from rice cultivation have been measured. The most comprehensive controlled studies are from the United States and Europe, which do not represent the most important rice-planting areas. Systematic seasonal measurements have been made in three locations in China but only preliminary data are available for India (National Physical Laboratory, 1992), with the largest rice-growing area in the world. No seasonal measurements have been made for the tropical rice-growing areas of Southeast Asia or for the continents of Africa and South America. The uncertainties are particularly large for Brazil, Nigeria, and Madagascar, countries that have large areas planted to rice but that lack accurate data on the fractions of the area under different water-management regimes.

The assumption that dryland rice is not a significant source of CH_4 uses the best information currently available, but it has never been tested. The difficulties in estimating the season of CH_4 emission from the growing season for rice were demonstrated in Table 3-2. Except for the limited number of areas where sampling has been done, the season of CH_4 emission must be estimated from the growing season. Using the growing season without adjustments will probably overestimate the CH_4 emission season.

3.6.2 Verification of Country Inventories

In all cases, an emission inventory must be fully documented. The documentation has two aspects. First, the method of calculation must be specified as in equation 3.5. Emission factors and extrapolants, such as area or yield, must be delineated. Second, all data and original sources must be referenced if not included explicitly as part of the inventory report. It is desirable in all cases to rely on published information, whether from the country's government, an international organization (such as the U.N. Food and Agriculture Organization or the International Rice Research Institute), or the scientific literature. The final data sets must be scrutinized by the scientific community and published in the open scientific literature, according to long-established traditions of scientific evaluation and publication.

3.7 CONCLUSIONS

Rice cultivation is one of the most important anthropogenic sources of CH_4. The main factors that control emissions from rice fields are now fairly well understood, though the effects of these factors are not well quantified.

Global estimates of CH_4 emissions from rice fields are roughly constrained by the lifetime of CH_4 in the atmosphere, isotopic measurements, and measurements from ice cores. Recent estimates of global emissions range from 50 to 100 Tg/year. There are no constraints on emissions for smaller regions, geographical or political. Estimates for smaller regions tend

TABLE 3-5

RESULTS: AVERAGE ANNUAL (1990) METHANE EMISSION ESTIMATES AND AREA, SEASON, AND FLUX DATA FOR MAJOR RICE-PRODUCING COUNTRIES

Country	Annual Methane Emissions[a] ($Tg\ CH_4/yr$)	Harvested Area[b] (10^3 ha)	Average Season (days)	Average Flux (mg/m^2-hr)	Effective Flux[c] (mg/m^2-hr)	Percent Dry Land	Percent Rain-fed
India	15.8	42,321	106	19.1	15.8	15.3	32.5
China	21.4	33,265	117	25.1	22.9	1.6	5.2
Indonesia	5.0	10,403	110	22.3	18.4	15.2	7.2
Bangladesh	3.6	10,303	123	17.4	11.8	14.3	71.5
Thailand	4.8	9,878	123	26.7	16.4	12.3	65.7
Viet Nam	3.2	6,069	119	22.4	18.3	7.3	27.8
Myanmar	1.3	4,774	139	11.7	7.9	14.9	43.1
Brazil	0.5	4,450	101	18.1	4.2	77.0	N/A
Philippines	1.3	3,413	98	22.1	16.4	11.8	34.3
Pakistan	0.7	2,093	103	13.4	13.4	0.0	0.0
Japan	0.2	2,073	123	4.0	3.8	4.0	0.0
Cambodia	0.9	1,800	134	27.3	15.6	27.3	39.0
Nigeria	0.2	1,567	103	11.7	4.4	62.0	N/A
Nepal	0.2	1,440	90	8.9	7.2	4.0	67.2
S. Korea	0.8	1,237	103	26.7	25.6	1.0	8.0
Madagascar	0.1	1,135	167	11.7	2.9	75.0	N/A
United States	0.3	1,114	123	9.2	9.2	0.0	0.0
Sri Lanka	0.4	793	122	21.4	17.6	6.8	27.6
Taiwan	0.4	700	119	22.4	21.8	3.0	0.0
N. Korea	0.3	673	103	21.6	17.0	13.3	20.0
Malaysia	0.3	640	109	19.6	15.7	12.9	23.5
Laos	0.2	625	123	36.3	12.6	49.2	39.9
Rest of World	3.0						
Global Total	*65*						

a. These emission estimates are averages of estimates for 1989 through 1991. The number of significant digits shown is not an indicator of precision; see discussion of uncertainties in the text.

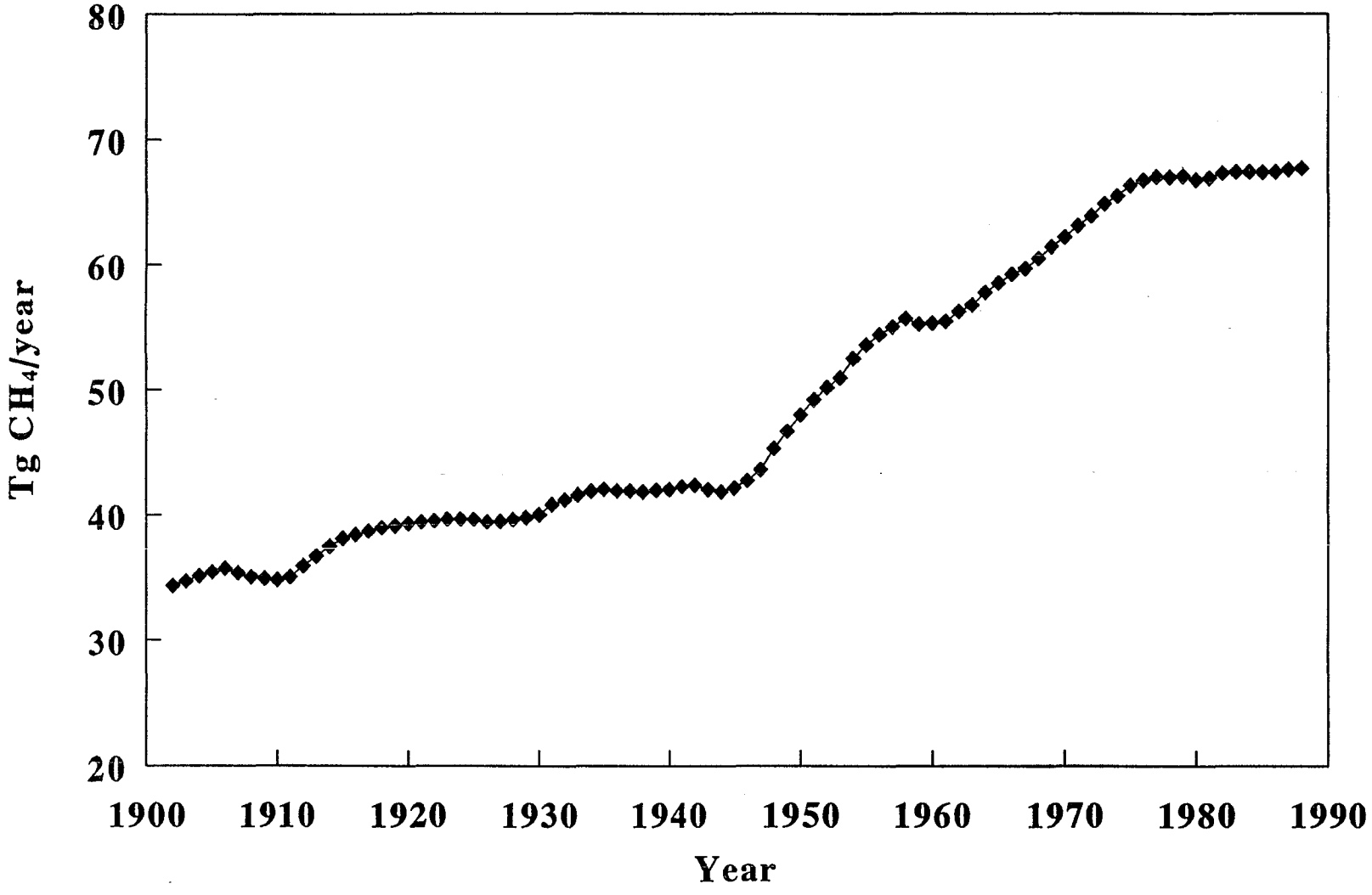
b. Harvested area is annual average, using 1989 to 1991 data (FAO, 1992). This statistic includes double and triple cropping.

c. Effective flux is the average flux adjusted for the percent area in dryland rice (flux = 0) and percent area in shallow rain-fed rice (flux = 60% of seasonal average). Fluxes are weighted averages by season and area; some rounding errors may result.

N/A = No data available.

FIGURE 3-3

TIME SERIES OF GLOBAL CH_4 EMISSIONS FROM RICE AGRICULTURE

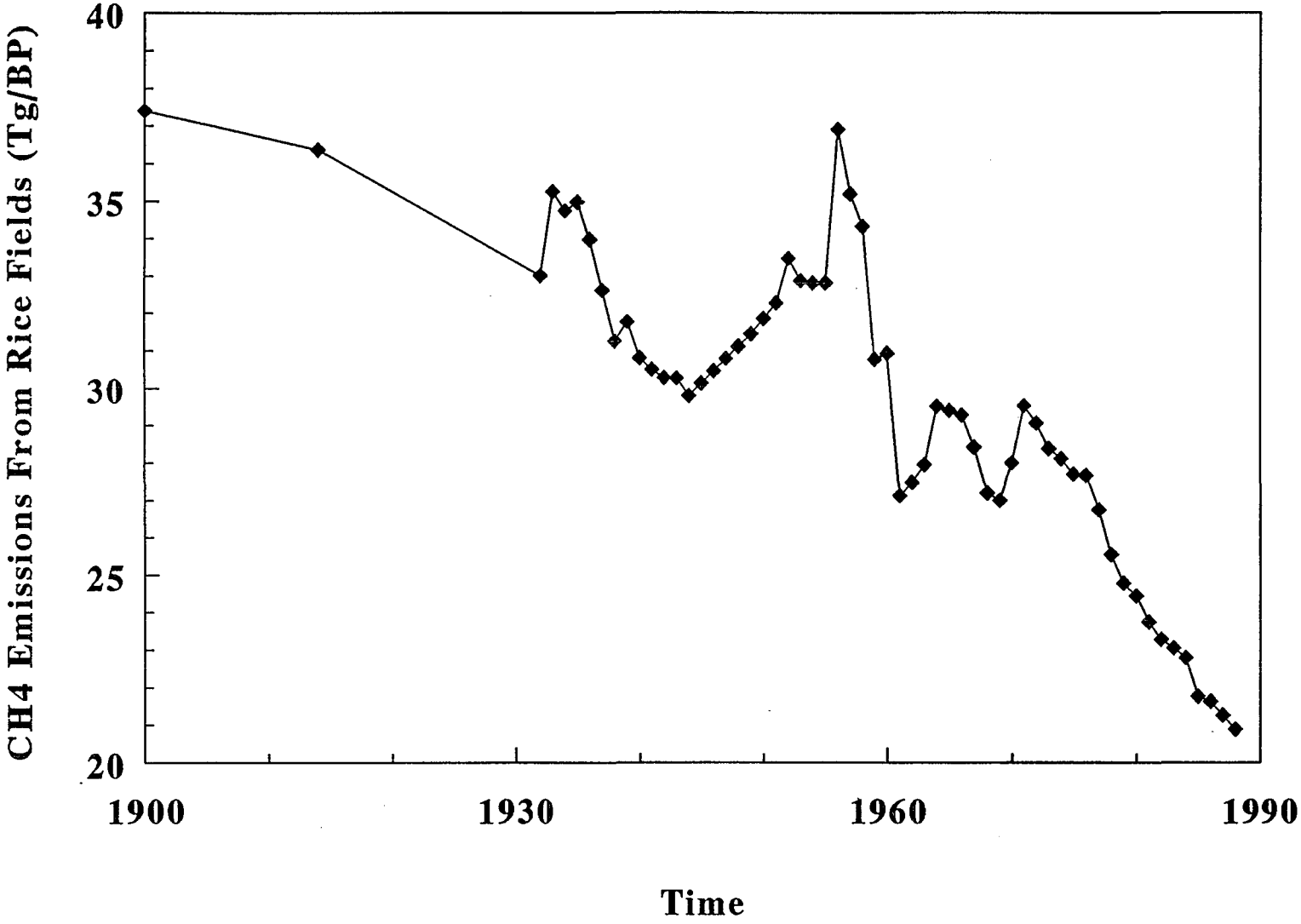


Source: Khalil and Shearer, 1993; Reprinted by permission of the authors.

FIGURE 3-4

PER-CAPITA EMISSIONS OF METHANE (Tg CH_4 PER BILLION POPULATION (BP)) FROM RICE FIELDS IN CHINA DURING THE LAST CENTURY

(The Per-Capita Emissions Have Declined by 35% From the 1930s to the 1980s)



Source: Khalil et al., 1993; Reprinted by permission of the authors.

to be much more variable. For some countries, even the area planted to rice is not accurately known, and there are no local flux measurements. Unless it is one of the few areas where measurements have been made, the smaller the region, the more uncertain the estimate. This report estimates 1990 emissions from rice cultivation at 65 Tg CH_4.

Although the growth in area harvested during the last century is believed to have caused a concurrent growth in CH_4 emissions from rice cultivation, future emissions are likely to be controlled in large part by other factors that are now changing. Chemical fertilizers are replacing traditional organic fertilizers in many areas of the world, new high-yield varieties of rice have been developed, and irrigation systems make possible multiple crops of rice. These factors will influence CH_4 emissions from rice cultivation in the next few decades, making it difficult to make credible estimates of future global emissions based on current knowledge.

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CHAPTER 4

METHANE EMISSIONS FROM ANTHROPOGENIC BIOMASS BURNING

4.1 SUMMARY

Biomass burning has been recognized as a significant source of atmospheric methane at least since the late 1970s. Like most other sources of methane, it has both natural and anthropogenic causes, although anthropogenic causes now predominate. Most of the estimates of methane emissions from biomass burning in the past have relied on a uniform emission factor for all types of burning. This results in the share of trace-gas emissions for different types of burning being the same as the amounts of biomass burned in those types. In fact, the emission factors for various types of burning differ by a factor of 15. This chapter estimates global emissions of methane from biomass burning based on an approach followed for Africa by Delmas et al. (1991). Several recent papers also attempt the same estimation (see e.g., Levine et al., 1993; Andreae and Warneck, 1993; and Hao and Ward, 1993).

This chapter estimates that anthropogenically caused biomass fires account for approximately one-seventh of the anthropogenic methane from all sources. Excluding emissions from prescribed forest burning and certain other minor categories for which data are sparse, this number is estimated to be ~ 49 teragrams (Tg)[1] CH_4/yr, with rough confidence limits of ± 40%. Confined burning of biofuels, such as firewood and charcoal, agricultural residues, and cattle dung, accounts for 38% (of all) biomass burned and 43% (of anthropogenic) methane emissions from biomass burning. Savanna burning accounts for 21% of the biomass burned, but only for 12% of methane emissions because of the nature of the biomass that burns. In contrast, deforestation for land-use change, although accounting for 11% of the biomass burned, contributes 17% of anthropogenic methane emissions. Sixteen countries, all in the developing world, account for almost two-thirds of the total anthropogenic methane emissions from biomass burning. By far, the largest emitters are China and Brazil, followed by Indonesia, India, Zaire, Nigeria, and Mexico.

Much of the uncertainty in estimating emissions from biomass burning comes from the uncertainty in the amounts burned. A large source of uncertainty is information about biofuel use. A compilation of country-specific consumption based on household surveys would help reduce this uncertainty.

When prescribed forest burning, wildfires and other sources that are not included in this chapter for lack of published information are included, and when some of the uncertainties are removed, the contribution of biomass burning could be close to that indicated by isotopic studies--i.e., 58 Tg/yr.

It is difficult to forecast trends in methane emissions from biomass burning. Each type of biomass burning is influenced by a different constellation of forces--among them, population pressure, the need for agricultural land, economic development, and the availability of alternatives. Future biomass use also will be determined by the shifts in the mix of energy sources in response to the threat of global warming. Though biomass usage and burning are

[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

likely to increase in the future, it should be possible to hold down methane emissions as newer technologies for burning biofuels will be more efficient than those in use today.

4.2 BACKGROUND

4.2.1 Introduction

Biomass burning must have existed on earth soon after land plants evolved 350 to 400 million years ago (Andreae, 1991). There is more certainty of large fires that occurred approximately 66 million years ago (Anders et al., 1991). Natural fires can be triggered by any one of several causes, such as lightning or meteorite strikes, volcanic eruptions, and even constant rubbing of bamboo plants (Kaul, 1991). The capture of fire by early hominids 1.5 million years ago (Pyne, 1991) changed the etiology of fire on earth. Since then, most fires have been of anthropogenic origin.

Burning of some type of biomass is connected intimately with human life in all societies; the more traditional a society, the more culturally entrenched the practice is likely to be. Fire is used for land management, for deriving energy, for waste disposal, and for personal, aesthetic, or religious reasons. Often the motivation is a mixture of two or more of the above reasons. Prescribed burning of savannas, agricultural residues, or forests can be considered as examples of land or waste management. Open-dump burning of municipal solid wastes in developing countries is purely a waste disposal activity, but the burning of the same wastes in incinerators is associated sometimes with energy recovery. Cooking energy is derived from biomass burned in stoves, which because of their copious production of smoke, also have multiple uses in insect control and in thatch and food preservation. Space heat is derived from wood stoves, steam and electricity from boilers, and gaseous fuels from gasifiers. Wood burning in a well-designed fireplace provides both energy and a feeling of warmth. In many cultures, fire is a witness at all religious ceremonies and a vehicle for the disposal of the dead. Tobacco smoking, too, is a form of biomass burning. Some reasons have become less important than they used to be, and some activities have disappeared from some continents altogether, such as burning of grasslands to drive game for hunting.

There are more types of biomass burned than there are reasons for burning them. Whole tree trunks are burned in boilers in electricity generating stations in Minnesota, and bark chips in Vermont. In many areas of developing countries where the cooking energy situation is bleak, any available combustible material is burned, including dried leaves, roots, and cattle dung. Just as varied as the types of biomass consumed are the conditions under which burning occurs. These range from completely unconfined burning to a rudimentary three-stone fire to carefully optimized efficient modern boilers.

It is difficult to estimate how much biomass is burned worldwide annually, given the multitudinous settings in which it is burned. Estimates range from 5 to 13 petagrams (Pg) of dry matter per year (Crutzen and Andreae, 1990; and Andreae, 1991). As shown in Section 4.2.2 and in Table 4-1, an overwhelming fraction, close to 95%, of biomass burned is from anthropogenic causes.

Since biomass is composed essentially of cellulose and lignin--which are carbohydrates consisting of carbon, hydrogen, and oxygen--the products of its complete

TABLE 4-1

ESTIMATES OF BIOMASS BURNED GLOBALLY
(Pg dm/yr)

TYPE	NATURAL		ANTHROPOGENIC				TOTAL
	Open		Open		Confined		
	Low	High	Low	High	Low	High	
Savannah--unintentional	(small?)		(small?)		x		(small?)
Savannah--prescribed	x		0.7[2]	3.7[1]			0.7-3.7
Forests--unintentional	0.27	0.47	?				0.33-0.67[2]
Forests--prescribed	x		0.06	0.20			
Forests--shifting cultivation			1.1[2]	2.2[2]			1.1-2.2
Forests--land-use change			0.44[2]	1.56[2]			0.44-1.56
Urban park wastes			Not estimated				Not estimated
Urban MSW			Not estimated		Not estimated		Not estimated
Agricultural residues			0.47[2]		0.64	1.55	1.1[2]-2.02[1]
Fuelwood			x		1.3[2]	2.7[2]	1.3-2.7
Animal dung					0.09[3]-0.40[4]		0.09-0.4
Charcoal					0.02[1]		0.02
Other processed biofuels					Not estimated		Not estimated
TOTAL	**0.3**	**0.5**	**2.8**	**8.1**	**2.1**	**4.4**	**5-13**

Sources: Andreae, 1991; Crutzen and Andreae, 1990; Meyers and Leach, 1989; and Armitage and Schramm, 1989.

combustion are carbon dioxide (CO_2) and water vapor, as the following simplified equation shows:

$$4(C_6H_9O_4)_n + 25O_2 = 24nCO_2\uparrow + 18nH_2O\uparrow \quad (3.1)$$

For a variety of reasons, an uncontrolled combustion process is never fully complete. The insufficiency of oxygen or a drop in fire temperature could prevent some carbon in biomass from being oxidized to CO_2. Consequently, burning generates several carbonaceous products of incomplete combustion. Some of these are particulates and some gaseous, as Figure 4-1 shows schematically. Scientists have identified hundreds, if not thousands, of chemical compounds in biomass smoke (Cooper, 1980). Methane (CH_4) is one such gaseous product of incomplete combustion of biomass and also the major hydrocarbon. While CO_2 is the largest constituent in all cases, the emissions of the products of incomplete combustion vary by over an order of magnitude, depending upon the type of fire.

Several investigators have estimated amounts of CH_4 emitted globally from biomass burning. Figure 4-2 shows the most likely point estimates and ranges. While a downward trend is indicated by this figure, this does not mean necessarily that CH_4 emissions from biomass burning are decreasing; on the contrary, they may be increasing. It is just that estimates are improving with more information on the levels of burning activities and on activity-specific emission factors. So while early central estimates[2] were roughly 60 Tg CH_4/yr (e.g., Crutzen et al., 1979), many current best central estimates are also between 50 and 60 Tg CH_4/yr (e.g., Quay et al., 1988; and Andreae, 1991). The early ranges were wide, from 25 to 110 Tg CH_4/yr. Now, while estimates of the lower limit (~25 Tg CH_4/yr) have not changed much, the upper-range limit is thought to be 80 Tg CH_4/yr (IPCC, 1992).

Every biomass fire is comprised of four phases of combustion: flaming, pyrolysis, smoldering, and glowing. These phases are chemically different processes and coexist in different proportions during the fire. Fuel characteristics and combustion conditions decide their relative durations and magnitudes. The differences in the relative durations and amounts of gases and particulates emitted during these phases make for the enormous variety of products from fires (Ward and Hardy, 1991).

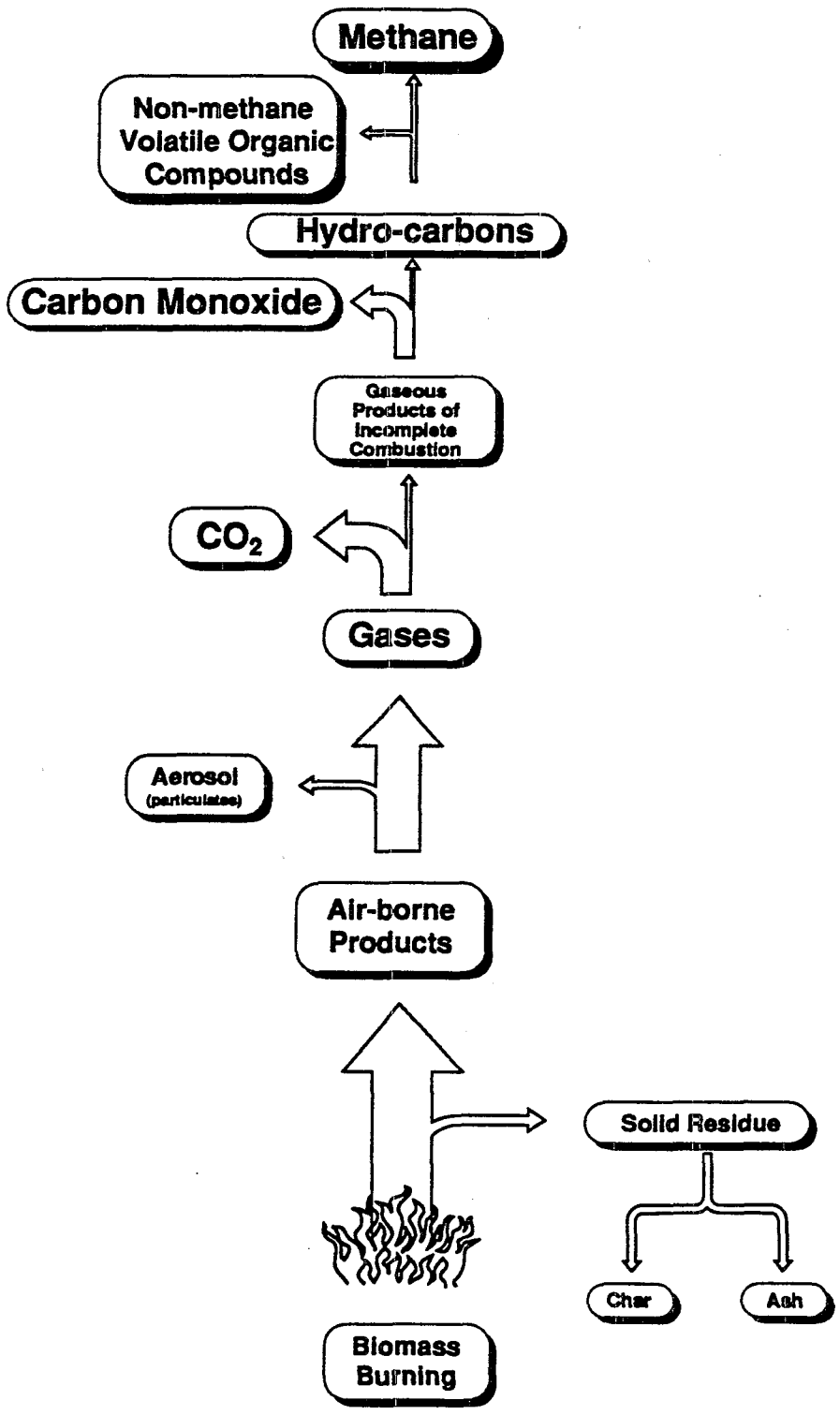
Flaming dominates the start of a fire. Surface materials supply the volatile hydrocarbons needed to sustain it. The heat from the flame initiates the thermal breakdown (pyrolysis) of cellulosic- and lignin-containing materials and provides fuel gases, including CH_4, that sustain the visible flaming process.

In the smoldering phase, carbon begins to build on the solid-fuel surfaces, and the pyrolytic reactions no longer produce sufficient fuel gases to maintain the flame envelope. The process ultimately leads to the production of charcoal, where the only combustion occurring is of the glowing type. This is a surface reaction of oxygen with carbon (Ward, 1990) and differs from smoldering in that it is not accompanied by appreciable emissions of volatile compounds.

[2] All numbers for trace-gas weights in this chapter are in the full molecular weight basis.

FIGURE 4-1

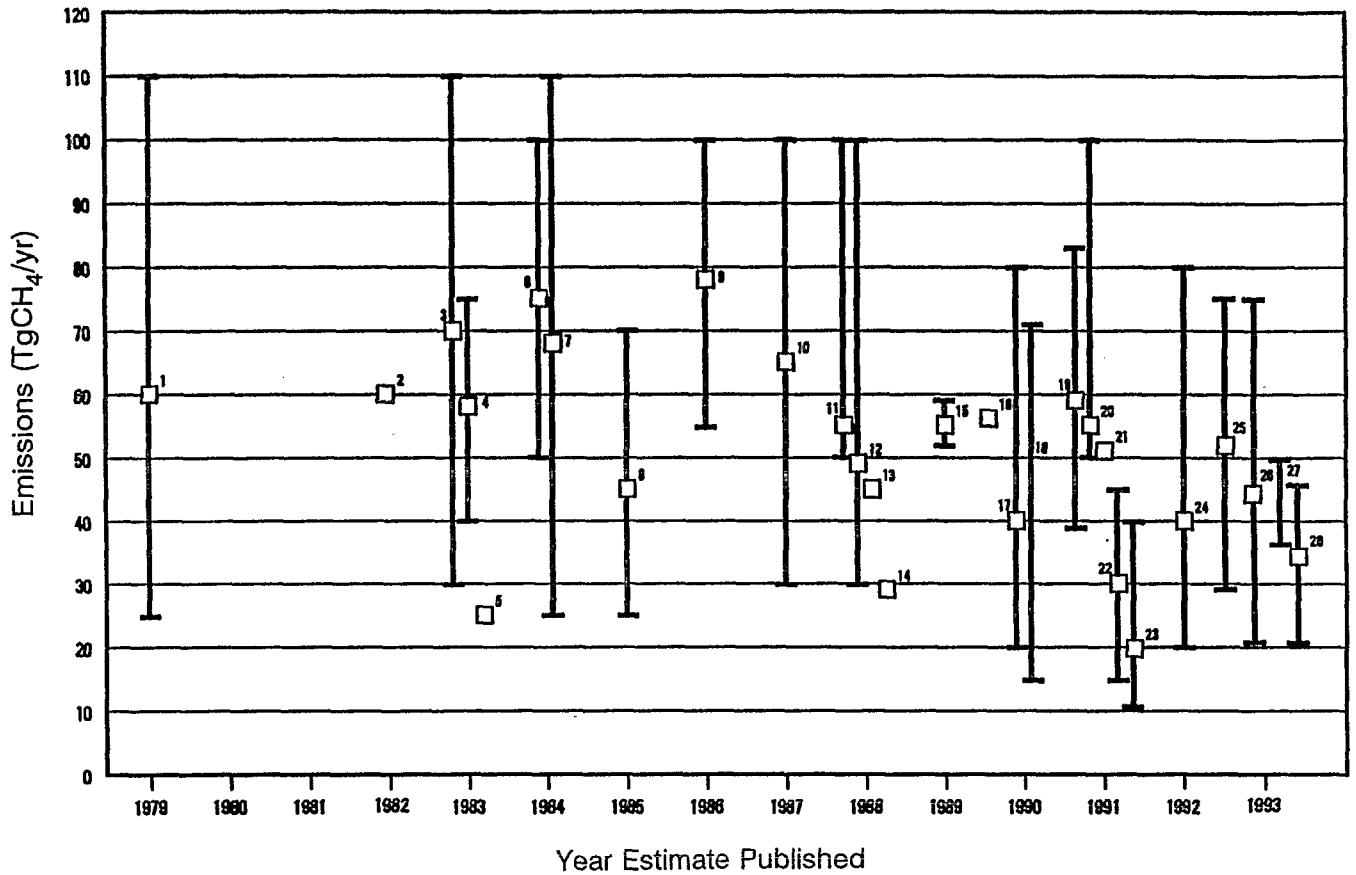
CARBONACEOUS PRODUCTS OF BIOMASS BURNING



Note: Arrows are not drawn to scale

FIGURE 4-2

ESTIMATES OF METHANE EMISSIONS FROM GLOBAL BIOMASS BURNING



Note: The superscripts are references to the following publications.

1. Crutzen et al., 1979
2. Sheppard et al., 1982
3. Crutzen, 1983
4. Cicerone, 1983
5. Khalil and Rasmussen, 1983
6. Seiler, 1984
7. Blake, 1984
8. Crutzen, 1987
9. Bolle et al., 1986
10. Bingemer and Crutzen, 1987
11. Cicerone and Oremland, 1988
12. Craig et al., 1988
13. Stevens and Engelkemeir, 1988
14. Quay et al., 1988
15. Wahlen et al., 1989
16. IPCC, 1991
17. IPCC, 1990
18. Crutzen and Andreae, 1990
19. Quay et al., 1991
20. Fung et al., 1991
21. Andreae, 1991
22. Crutzen, 1991
23. Lobert et al., 1991
24. IPCC, 1992
25. Levine et al., 1992
26. Andreae and Warneck, 1993.
27. Stevens, 1993
28. Delmas, 1993

It has been reported that CH_4 is *produced* in much larger quantity during the smoldering phase than in the flaming phase, with emission factors that are 2-3 times greater (Ward, 1990; and Lobert et al., 1991). It is possible that it may not be the production but the *release* of CH_4 that is greater during smoldering because it is oxidized to a smaller degree in the flame. Since combustion efficiency is invariably higher during the flaming phase than it is during the smoldering phase (Ward, 1990), the emissions of products of incomplete combustion will be greater, and the emissions of CO_2 smaller, during smoldering than during flaming.

Any factor that influences pyrolysis and, therefore, the production of CH_4 or its subsequent combustion in the flame will affect the emissions of CH_4 from biomass burning. Thus, the type of biomass and its chemical composition, its moisture content, the fuel geometry, size distribution, and combustion conditions--turbulence, availability of oxygen, etc.--influence emissions. During the burning of dung, the smoldering phase dominates; therefore, this type of burning is expected to have a high CH_4 emission factor. Conversely, burning of crop residues and grasses is mostly flaming combustion and can be expected to have lower emission rates. Up to a point, turbulence promotes flaming and lowers emissions, but excessive turbulence can cause the products of pyrolysis to escape before being consumed in the flames. Finally, since charcoal burning is mostly glowing, it too should be associated with lower emission factors.

The preceding discussion brings up the importance of considering the entire fuel cycle when evaluating emissions from different technologies that use biomass as a fuel. For example, although CH_4 emissions from charcoal-burning stoves may be less than those from wood-burning cook stoves, this does not imply necessarily that charcoal-burning stoves are preferable from the perspective of greenhouse gas emissions. Substantial amounts of CH_4 emissions associated with charcoal use occur during pyrolysis in charcoal making. Similarly, if one were to compare emissions from biogas combustion with those from dung burning, one must consider also the leakages from the digestor dome and connecting pipes (Figure 4-3).

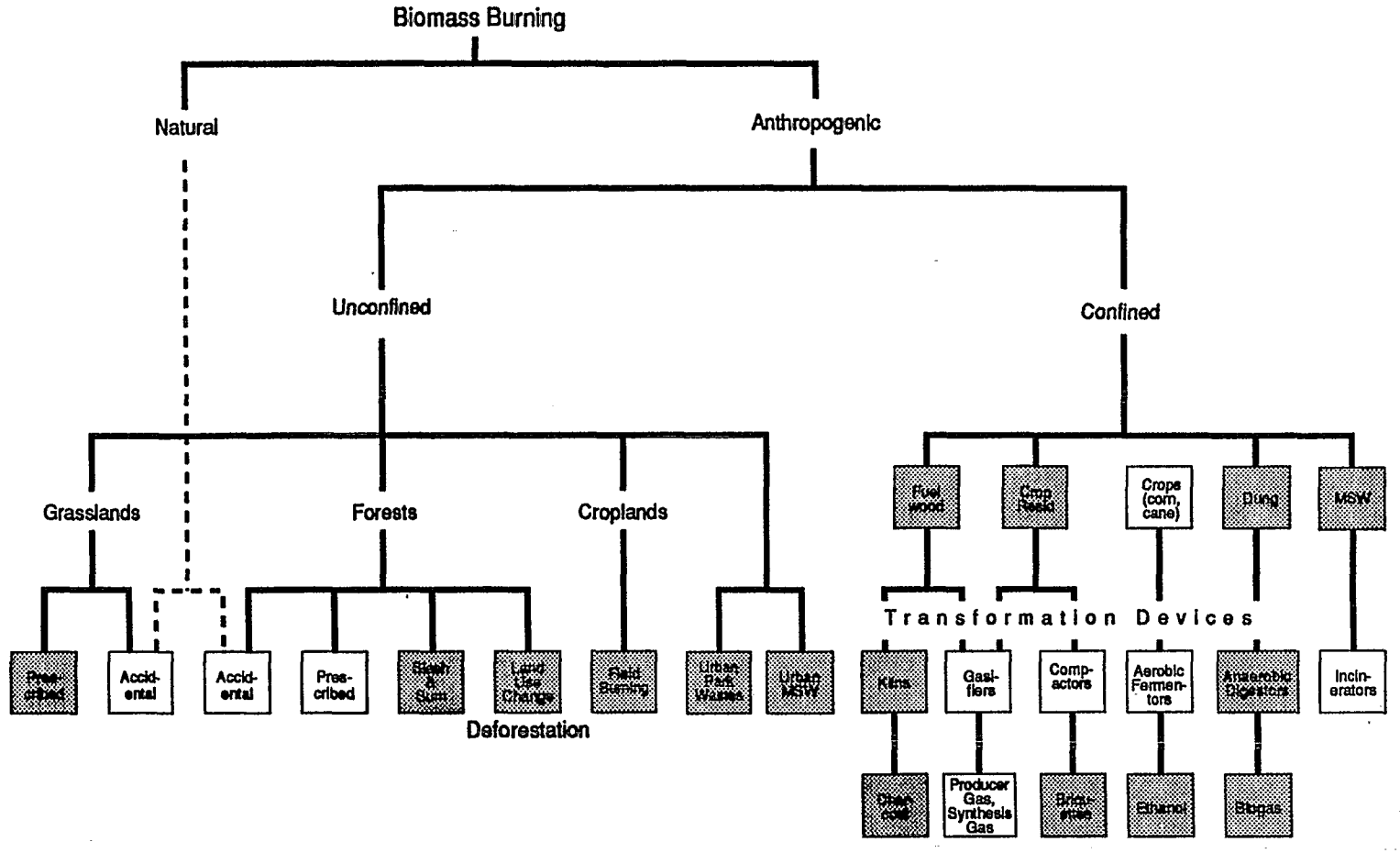
4.2.2 Varieties of Biomass Burning

Regional emissions of CH_4 are estimated by multiplying the emission factors associated with a burning activity by its extent and summing these subsectoral emissions over all activities. Since the emission factors for burning a particular type of biomass under a particular set of conditions are unlikely to vary geographically, the differences in CH_4 emissions between regions depend on the relative mix of the types of burning activity. Methane emissions from biomass burning in Africa, therefore, are determined largely by savanna burning, while in South America, they are determined by deforestation, and in Asia, by biofuel use.

This section describes briefly the different biomass burning activities. Figure 4-3 provides a synoptic view of the different activities. Wherever appropriate, distinctions are made between natural and anthropogenic, open and confined, and intentional and accidental burning--the first of these distinctions being required by the Framework Convention on Climate Change.

FIGURE 4-3

TYPES OF BIOMASS BURNING



Notes: 1. Subcategories possible within shaded boxes (e.g., land-use change occurring from open vs. closed forests).
2. For each fuel category, information may be available for residential (cooking and space heating), industrial, and commercial uses.

Open Burning

Savanna Burning

Savannas are tropical and subtropical ecosystems consisting mainly of grasses with varying amounts of shrubs and trees. They have alternating wet and dry seasons and high average annual temperatures. An annual rainfall of 700 mm divides arid savannas from humid savannas (Lanly, 1982). Humid savannas have almost a continuous grass cover that makes them susceptible to fire transmission during the dry season. Patchy covers exacerbated by a high density of herbivores limit fire propagation in arid regions.

There is evidence of lightning-induced fires in West Africa from geologic times (Menaut et al., 1991). Natural fires still occur, but they are rare and difficult to identify unequivocally. There also have been some instances of spontaneous combustion occurring in the wet season following fermentation in thick herbaceous litters.

Human beings have increased the frequency of savanna fires tremendously, especially after the transition from hunting-gathering to farming 10,000 years ago (Menaut et al., 1991). Wherever grazing of animals is an important activity, savanna burning is undertaken to remove unpalatable stubble and to promote the regrowth of new grasses and succulent shoots (Hao et al., 1990; and Menaut et al., 1991). While eliminating dead grasses and litter accumulation, burning also gets rid of weeds, shrubs, and tree seedlings and reduces the population of pests, insects, and snakes. Setting fire also helps drive game out of hiding. This may have been one of the earliest uses of fire by man (Andreae, 1991). Other reasons for setting fire to savannas include clearing the ground for agriculture, establishing fire breaks around settlements, and improving communications. While it is likely that burning recycles phosphorus and some micronutrients, the belief that burning stimulates the recycling of nitrogen, or that burning is desirable for maintaining the long-run productivity of grasslands, might be fallacious (Andreae, 1991), since fixed nitrogen is lost through pyro-denitrification when the burn temperature is high.

Most savanna fires are surface fires, rather than ground or crown fires (Menaut et al., 1991). Recent tree litter and grasses burn almost completely. Savanna trees seldom burn, as they have evolved to fire regimes by having a low terpene content, and so have a low degree of flammability.

Savannas, grasslands, and shrublands are found on all continents, except for Antarctica, and are still burned in Africa, Australia, South America, and Asia. Estimates of areal extent range from 1300 (Hao et al., 1990) to 1900 million hectares (mha) (Bolin et al., 1979)--60% of which is thought to be humid savannas subjected to periodic burning, and the remainder is arid. The interval between burnings varies from place to place. In the Brazilian *cerrado*, it is 1-2 years. Approximately 75% of the African humid savannas burns every year (Hao et al., 1990). Though in localized instances savannas in Africa burn twice a year, almost all savanna lands burn no more than every three years (Menaut et al., 1991). Burning the bush is an integral part of land management in northern Australia, happening typically every third year (Howden et al., 1992a). Burning of grazing lands is the predominant biomass burning activity in Australia.

The global amount of dry matter (dm) biomass (i.e., corrected for moisture content) that is burned annually in grassland fires has been estimated to be 0.7-3.6 Pg dm/yr (Hao et al., 1990; and Crutzen and Andreae, 1990).

Because of the periodic nature of grassland burning, all the carbon that is emitted to the atmosphere each year as carbon dioxide is reabsorbed by the new growth that occurs in the wet season. However, all the emissions of CH_4 are net additions to the atmosphere.[3] Since much of the combustion that occurs in savanna burning is flaming, CH_4 emissions per unit amount of dry-matter biomass burned are believed to be low. But if strong winds were to accompany burning, the emissions could increase, if capture in the flames is reduced.

There is a factor of 2-5 uncertainty in the published estimates of biomass burned globally in the savannas and so at least that much also in the emissions of CH_4 from this activity. A part of the uncertainty comes from not all lands classified as savanna being used in the way expected. Thus, some areas so classified may be under permanent agriculture or under shifting agriculture. Another part stems from the paucity of data on densities of above-ground biomass exposed to fires. The relative proportions of dead and living biomass (i.e., the distribution of moisture contents) at the time of the fire vary from year to year but are known only for a few regions. This, too, will have implications for uncertainties associated with estimating emissions.

Shifting Cultivation

Shifting cultivation is a name given to a cyclical sequence of subsistence farming events by which a mixture of crops is grown by rotation on different fields. The process begins by slashing vegetation on a plot of land, allowing the vegetation to dry, isolating the plot by cutting a fire line, burning the vegetation on the plot one or more times, cultivating the land until its fertility declines, and finally abandoning the plot and leaving it fallow while moving on to another plot. The cycle restarts when a cultivator returns to the first plot. In different parts of the world, the cycle goes by different names: swidden agriculture, field-forest rotation, bush fallowing, and, in India, as *jhum* agriculture. The duration of cultivation on a plot is typically three to five years but could be as short as one year (Hao et al., 1990; and Kaul, 1991). Slash-and-burn agriculture differs from shifting cultivation in that the farmer does not return to reuse the plot in the former case (Fearnside, 1993). The fallow period is 10-20 years (Hao et al., 1990).

Shifting cultivation is a legacy from the neolithic times: the practice dates back 10,000 years. It is a part of the cultural ethos of many tribal communities (Kaul, 1991). Often, although not always, it is practiced on hill slopes, which are often unsuitable for terraced farming. If performed on sparsely distributed, small plots with long enough fallow periods, it is an agronomically sustainable practice.

Estimates of the extent of shifting cultivation, according to Kaul (1991), are mostly educated guesses. It is thought to be practiced by some 500 million people worldwide (as of 1980) (Lanly, 1982) on some 300-500 mha (million hectares) with an annual clearing of 20-60 mha (Seiler and Crutzen, 1980; and Andreae, 1993). Not all standing biomass is burned. As in savanna burning, larger trees survive many burn cycles. Besides, some useful biomass, such as bamboo, may be extracted before the first burn. Seiler and Crutzen (1980) estimated that 0.9 to 2.5 Pg dm are burned every year--75% in tropical secondary forests, and the remaining in humid savannas. The more recent estimates narrow this range: Hao et al. (1990) estimate 1.2-1.5 Pg dm are burned, and Crutzen and Andreae (1990) estimate this to

[3] Also, there could be soil changes due to burning that could cause changes in soil methane uptake over some post-burn duration.

be between 1.1 and 2.2 Pg dm/yr. Crutzen and Andreae (1990) also estimate that perhaps an equal amount of standing biomass is exposed to the fire but escapes burning.

Because a greater mixture of various biomass types with a wider size distribution are burned during shifting cultivation than when savannas are burned, higher CH_4 emission factors are believed to be associated with shifting cultivation. Some amount of smoldering must take place as not everything burns on the first try. There is an uncertainty factor of at least 2 in the amounts burned, and a comparable level of uncertainty in the emission factors.

Burning of Forests for Permanent Land-Use Change

The permanent conversion of forests to pasture or to cropland begins with the initial cutting of undergrowth and felling of trees in a dry season. In some areas where biomass is scarce, such as in India, and the land-use change is for agriculture, all usable biomass is removed, and the remainder is set on fire after drying (Kaul, 1991). Where pasture is the end use, tree trunks are left on the ground and often are not consumed in the first burn. Tree trunks burn completely only after multiple burns. Ranchers in Brazil burn pastures at two- to three-year intervals to combat the invasion of woody vegetation. Subsequent fires consume progressively charred logs left over from previous burns, but do not affect charcoal incorporated in the soil.

Conversion of forests to pasture and agricultural lands has been going on for centuries, ever since agriculture became prominent. Europe was deforested extensively in the 13th century to make way for agriculture, and more recently, North America was deforested in the 19th century. Current deforestation is confined mainly to tropical and subtropical regions in Central and South America, Asia, and Africa.

Population pressure and related demand for agricultural and pastoral land have been historically the most significant reason for deforestation. Although they are still the most important reasons, many other reasons characterize modern times: submergence by hydro-electric reservoirs; construction of electricity transmission lines, roads, industries, and townships for human settlements; extraction of timber and other forest products for paper manufacture; etc. For a long time, government incentives promoted deforestation in some countries.

Because the estimate of amount of land area deforested is subject to much uncertainty, the estimates of amounts burned are subject to even greater uncertainty. Recent estimates (see Hao et al., 1990; and Andreae, 1991) put the current extent of forest conversion at between 4 and 5 mha/yr in primary forests and another 10 mha in secondary forests. Not all biomass is consumed in the fires. Fearnside (1991) estimates that 28% of the initial above-ground biomass burns on the first burn in Amazonia, but with three burnings, this rises to 40%. Crutzen and Andreae (1990) assume that only 40-50% in all is released through combustion; the rest decays or is decomposed by termites. They estimate that about 1.1-3.1 Pg dm/yr of biomass are exposed to the fire, resulting in burning of 0.4-1.6 Pg dm and immediate emissions of 0.7-2.6 Pg CO_2/yr. Results from a recent study coordinated by Lawrence Berkeley Laboratory (Makundi and Sathaye, 1992) fall within this range. The study estimates that in seven countries the emissions of carbon dioxide from deforestation burning are 1.3 Pg CO_2/yr. Together these countries account for approximately two-thirds of the annual prompt emissions from deforestation in developing countries (Makundi and Sathaye, 1992).

Aircraft observations over Amazonia forest fires show that a substantial portion of burning is in the smoldering phase (Andreae et al., 1988). The presence of prolonged smoldering implies higher emissions of CH_4 from burning of forests than from burning of savanna. Logs consumed in reburns are burned primarily through smoldering rather than flaming (Fearnside, 1992), though it is possible that some smaller charcoal pieces created in earlier fires would burn in the glowing phase.

To the extent that deforestation rates remain constant, current CH_4 emissions from subsequent burns in areas deforested in previous years will be equal to future releases from areas being cleared now (Fearnside, 1992). Burning brings about a whole host of other changes as well. N_2O emissions from soils, as well as CH_4 uptake by soils, change in the post-burn period (OECD, 1991). The sudden appearance of huge quantities of dead wood also increases termite attacks on the material left after a burn, but if they are fungal termites, they do not produce any more CH_4 (OECD, 1991). Little is known about these processes to allow their quantification in current national budgets.

Prescribed Open Burning in Forests

Prescribed open burning is a method of forest management by which combustible debris in limited areas is burned intentionally to reduce biomass accumulation and thereby reduce extensive natural fires. In the last century, many countries have gone from indiscriminate burning, to aggressive fire suppression, to now a mixture of fire control and fire use (Pyne, 1990). Generally, these ground fires consume mostly litter, grasses, shrubs, and undergrowth. Often fire lanes also are burned periodically to keep them free of biomass.

Forestry practices vary from place to place. Besides its use in fire conservancy, open burning is used to clear weeds and undergrowth before establishing new plantations and for the propagation and regeneration of certain species, like teak and some varieties of pine (Kaul, 1991). Besides natural fires and prescribed burns, many wildfires are caused unintentionally and accidentally by human activity. In boreal forests, especially in Canada, China, and Russia, emissions from these fires can be large.

Extensive prescribed burning is confined largely to North American temperate and boreal forests. Undisturbed moist tropical forests do not burn easily, but prescribed burning also occurs in the subtropical and dry tropical forests in India and Australia. Stocks (1990) estimates that 8 mha are subjected to natural wildfires in temperate and boreal regions. Crutzen and Andreae (1990) estimate that 2-3 mha are subjected to prescribed burning; further, with wildfires, 0.33-0.67 Pg dm/yr are burned. If this amount is apportioned in the ratio of areas involved, estimates of the amount of biomass burned as dry matter globally in prescribed burns would lie in the range of 0.06-0.2 Pg dm/yr. Since prescribed fires should be expected to consume less material than natural wildfires, estimates more close to the lower end of this range would be attributable to prescribed burns.

Prescribed burning in boreal and temperate forests is an anthropogenic replacement for what would occur naturally. Its objective is to reduce the total amount of combustible material available to a future natural fire; therefore, emissions will reduce as well. Thus, over a period (several decades to a century), CH_4 emissions from prescribed burning do not add to--and perhaps subtract from--what would have occurred naturally. Therefore, the IPCC-OECD (OECD, 1991) methodology does not include them in the national inventories, and they are not discussed further, since the intent of this report is to estimate anthropogenic emissions. Should one decide to include them, however, the methodology for estimating emissions would

be similar to that for estimating emissions from shifting agriculture or deforestation for land-use change, as described in section 4.3.2 of this chapter. What happens to soil fluxes (N_2O emissions, CH_4 sinks) because of these prescribed burns is a more complex and unresolved question (see Moore, 1992).

Open Burning of Agricultural Residues

Agricultural residues are by-products of agricultural production and associated processing activities. Traditionally, after a harvest, the field is prepared for the next sowing by burning the straw and the stubble remaining on the field. Similarly, outside rice mills, husk may be disposed of by burning.

Agricultural residues have multiple uses and disposal routes. They are used for fuel, fodder, mulch, fertilizer, building materials, and as raw materials for cottage industries and handicrafts. The by-products are valued sometimes more than the crop itself (Barnard, 1990). Traditional farming communities in areas of high population density are often very frugal in their use of biomass resources. Open burning in the field is generally a last option. Only when there are no alternate uses, or when it is too difficult to plough the residues back into the soil, as on non-mechanized farms, is burning resorted to for disposal.[4] With residues from cotton and tobacco plants, there is an increased risk of pest infestation and plant diseases if the residues are left in the field without being properly incorporated into the ground. In wetland farming systems with multiple annual croppings (some fields grow three rice crops in a year) because the next crop is to be sown immediately after the harvest of the previous one, the advantage of being quick and easy favors burning as the preferred disposal option (Barnard, 1990). In the case of rice cultivation, incorporation of residues in the soil may enhance CH_4 emissions from anaerobic bacterial decomposition.

Information on the types of residues that different countries burn is difficult to obtain. We know that rice, sugarcane, cotton, tea, coffee, and tobacco residues are burned. Sugarcane fields are burned before harvests (Howden et al., 1992a) and after harvests (Joshi, 1991). The use of agricultural residues, such as bagasse, for energy purposes is discussed in the following section on confined combustion. Similarly, when rice husks are left to smolder outside factory gates (Barnard, 1990), they should be accounted for here, but when they are used in specially designed stoves and boilers, they should be accounted for in the section on confined combustion.

The amount of agricultural residues produced is difficult to quantify because, unlike crops, residues do not enter markets, and no records are collected. Besides, annual production is large. Cereal crops produce 0.7 to 2.5 tonnes of straw per tonne of grain, and approximately 3.1 Pg are produced each year from food crops alone (Barnard, 1990). Of this, 50-60% is produced in developing countries, and 40-50% in the developed countries (Barnard, 1990; and Crutzen and Andreae, 1990). One recent estimate puts the annual amounts produced in both groups of countries at 1.7 Pg dm each (Crutzen and Andreae, 1990, quoting Barnard, 1990).

The fraction of residues burned in the fields is also not known precisely. Rice straw makes up 31% of agricultural residues produced in developing countries, and at least in

[4] Even in developed countries, when plowing is not cost-effective, farmers burn fields every year, as in Corvallis Valley, Oregon, in August-October (Andrasko, 1992).

Southeast Asia, burning is the preferred method of disposal. Another 11% is sugarcane residues (including bagasse), which are also burned. Crutzen and Andreae (1990) estimate that about 25% of the residues produced in developing countries is burned in the fields, amounting to 425 Tg dm/yr. About 10% is thought to be disposed off similarly in the developed countries. Their estimate for *total* burning of agricultural residues is between 1.1 and 1.8 Pg dm/yr. Other estimates are 1.7-2.1 Pg dm/yr (Seiler and Crutzen, 1980) and 2.02 Pg dm/yr (Andreae, 1991).

The uncertainty in estimating CH_4 emissions from open burning of agricultural residues stems from our ignorance of (1) the amounts produced and then disposed of in the different routes and (2) emission factors. The amounts of residues produced in different countries will vary because of the differences in crops grown and in management systems. Agricultural residues being dry and thin can burn rapidly with predominantly flaming combustion. Methane emission factors, therefore, are believed to be relatively low, just as for savanna burning, unless strong winds accompany burning. Although no measurements exist, open burning of rice husks is predominantly smoldering and, therefore, should be associated with higher emission factors.

Other Miscellaneous Sources

There are several other instances of open burning in developing countries--burning practices that vary from country to country. In garbage dumps around large cities in developing countries, smoldering spontaneous combustion and intentional burning by scavenger communities to recover metals are common sights (Smith and Thorneloe, 1992). Park wastes (mostly fallen leaves) in some cities are often collected and set on fire. This practice was also prevalent in the now developed countries until two decades ago, when it was discontinued to improve local air quality. Very little information exists on the amounts of park wastes or of urban solid wastes that are burned. Compared with the other sources, these amounts can be expected to be small, but since the type of burning is predominantly smoldering, emission factors can be high. Lack of sufficient information precludes their estimation in this report, but as more information becomes available, these sources, if significant, should be added to national inventories.

Confined Burning

Direct Burning of Biomass

Just as biofuels have supplied human energy needs for tens of thousands of years (Smil, 1983), they continue to supply the energy needs of over two billion people even today. Biofuels--wood, charcoal, agricultural residues, dung, and biogas--are primarily used for cooking (50%); space heating (30%) is the second most common use. Industrial uses in boilers, bakeries, brick kilns, foundries, and steel making are common in many countries and account for the remainder. Biomass-processing industries often use biomass residues (bark, chips, sawdust, rice husk, bagasse, etc.) for their internal energy needs, and in areas with abundant biomass resources, electricity also may be produced. Tobacco and coffee curing, tea drying, beer brewing, fish smoking, pottery, and ceramics are other uses. In Malawi, 23% of fuelwood consumption goes to cure tobacco, where 17 kg of fuelwood are required to produce 1 kg of tobacco (Kaale, 1990).

Globally, biomass provides one-seventh of the energy supply (Hall, 1991). In developing countries, it accounts for over a third, and in the rural areas of developing

countries, even more. There is some use even in developed countries: 14% in Sweden, and about 4% in the United States, where biomass-based electric power plant capacity is 9,000 megawatts (Hall, 1991). Because biofuels generally are not traded commercially, published production statistics underestimate their use. Global estimates based on surveys of average per-capita biofuel consumption (~1-5 kg/cap/day--Rosillo-Calle and Hall, 1992) range between 1.3 and 2.7 Pg dm/yr (Crutzen and Andreae, 1990). Generally, the consumption in rural areas is more than that in urban areas, and within rural areas, consumption is greater where biomass resources are plentiful. The scarcity of higher-quality fuels forces people to burn lower-quality fuels; in Asia and Africa, some 400 million tonnes of dung are estimated to be burned annually as fuel (Armitage and Schramm, 1989).

The uncertainty in CH_4 emissions from biofuel burning under confined conditions comes from the uncertainty in per-capita consumption figures and in emission factors for different biofuel-device combinations. Average consumption varies enormously, depending upon local scarcity of biofuel and the adaptation of fire-tending practices by cooks to this scarcity. The fuels vary as well as the devices in which they are burned. In principle, because of the differences in fuel geometry (thickness, etc.) and the conditions under which burning takes place, each device-biofuel combination would be associated with a unique emission factor for CH_4 and other products of incomplete combustion. But measurements exist for only a few instances upon which we must rely for preparing inventories. Surely as the data on both amounts burned and emission factors improve, emission estimates will improve.

Incineration of Municipal Solid Wastes: With the shortage of landfill space close to major urban centers, many communities have been considering and installing incinerators to dispose of municipal solid wastes. Often these incinerators are equipped with energy-recovery units to help defray the costs of operating these facilities. While information on amounts incinerated may be collected and known, there is no information available on emission factors from these sources. As a start, default values may be assumed, such as from wood-fired utility or industrial boilers. As the data base on emission factors improves, this source can be added to national inventories.

Burning of Processed Biomass

Biomass is not only burned directly, frequently, it is upgraded before being burned, which results usually in an enhancement of calorific value or of combustion properties, or both. Figure 4-3 shows that the upgraded biomass fuels can be solid (charcoal, briquettes) or liquid (methanol, ethanol) or gaseous (producer gas, synthesis gas, or biogas). A systematic accounting of emissions must estimate CH_4 emissions not only during the burning of these upgraded fuels but also during their conversion processes. Information, albeit scanty, currently exists on only two of these routes--those of charcoal manufacture and conversion of biomass to biogas in anaerobic digestors. Estimation of emissions from the charcoal cycle is discussed in the methodology in the following section. Recent measurements from one type of biogas digestor in China led Khalil et al. (1990) to conclude that biogas digestors were an insignificant source of CH_4 globally (5-30 Gg/yr). Even if other types of biogas domes are leakier (Gunnerson and Stuckey, 1986; and Kishore et al., 1987), their numbers and total CH_4 production make their contribution to global emissions small. Contributions from other cycles can be added to the national accounts as more information becomes available and if emissions are appreciable.

Charcoal Manufacture and Use: Making charcoal out of wood is a way of increasing its calorific value (which makes its long-distance transport more economic) and of improving combustion properties at the point of use. Charcoal burning is not a significant source of CH_4 globally because the emission factor is small (Delmas et al., 1991; and Smith et al., 1993). Charcoal manufacturing, however, carried out in somewhat inefficient kilns in developing countries has emission factors that are 70 times greater (Delmas et al., 1991) than those from charcoal burning. With the amount of fuelwood that is converted to charcoal being roughly 0.1 Pg/yr, this source yields significant amounts of CH_4 that should be accounted for in national inventories.

4.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

The basic procedure for estimating emissions from biomass burning is similar to the two-part procedures already discussed in previous chapters for estimating emissions from rice cultivation or livestock. In each case, one starts with an estimate of amount of the "activity" (rice acreage, number of animals, or amount of biomass) and multiplies this by an emission "factor" (emissions per unit acreage, animal, or amount of biomass). To estimate the total emissions from each of these sectors, one sums over all the cases for which the emission factors are known to differ--for example, by type of irrigation in rice, by species of animal for livestock, and by the type of burning activity for biomass. Thus,

$$Emissions = \sum_i A_i \times EF_i \qquad (3.2)$$

where A is the amount of biomass burned, EF is the emission factor, and i denotes the different categories for which emissions need to be summed. The units used for emission factors can vary. Besides, on a g/kg basis, there are at least three other common ways of expressing emission factors: as a ratio of the trace gas to CO_2 emitted (see Figure 4-1), as a relative enhancement of the trace gas in the plume over the ambient atmosphere, and on a g/MJ basis, which relates emissions to the energy content of the biomass that is burned. Although this two-part procedure summarizes the basic methodology, several steps and different routes are involved in estimating each part. As Figure 4-4 shows, there are different preferred ways of estimating the amounts of biomass burned for different types of burning.

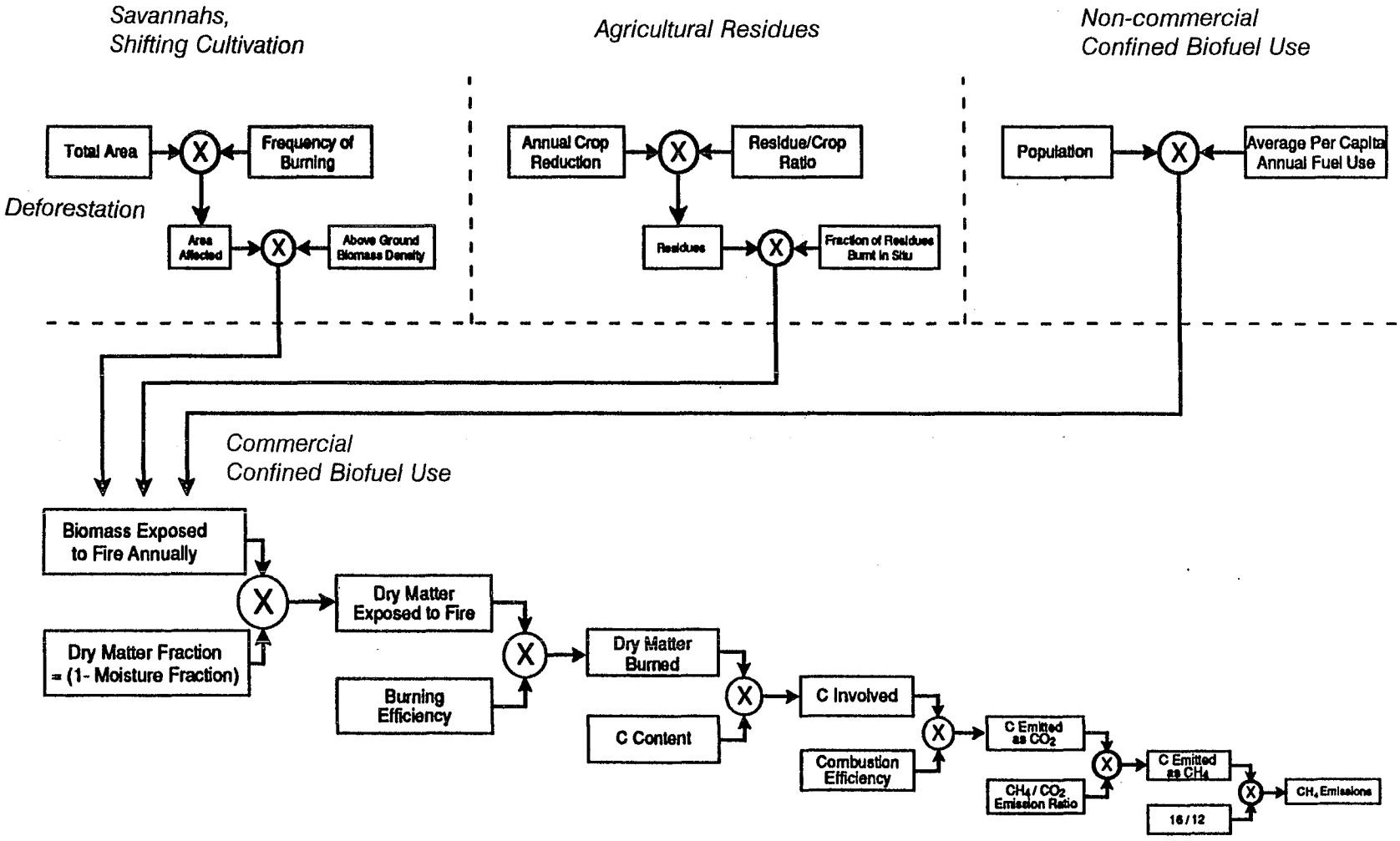
4.3.1 Review of IPCC-OECD Methodology

The most comprehensive methodology for estimating CH_4 emissions from biomass burning is the draft IPCC-OECD methodology (OECD, 1991). While the methodology is simple and straightforward, the following provides a brief review. There are at least four criteria by which any methodology can be judged: completeness, consistency, and correctness and transparency of its assumptions.

As it now stands, the sections on biomass burning are strewn in many different places in the OECD document. Thus, we find biofuels in the energy chapter, dung burning under animal wastes, and savanna and agriculture residues treated in a separate section in the chapter on land-use change. This is explained partly by the primary focus of the IPCC-OECD methodology being on estimating CO_2 emissions, and partly by the existence of many legitimate alternate ways of organizing and aggregating emissions from different subsectors. But the unintended consequences of this method of organization are that it is easy to miss

FIGURE 4-4

ESTIMATING METHANE EMISSIONS FROM BIOMASS BURNING



Note: Italics shows boxes where one starts for different types of biomass

some emissions and to double count others, and it is in general difficult to maintain consistency across different estimating procedures.

Thus, for example, the burning of municipal solid wastes in incinerators or their smoldering in open dumps in developing countries is accounted for in the chapters on stationary sources. Excluded are emissions during all intermediate processing of biofuels to other forms, such as during charcoal manufacture or anaerobic digestion into biogas. Also, sometimes there is a possibility of double counting, such as fuelwood use for energy purposes being counted under deforestation in the land-use section, and agricultural residues being counted once under field burning and again for energy extraction.

The current IPCC-OECD methodology does not account explicitly for all the different routes by which carbon is transformed during biomass burning. There is incomplete accounting of carbon in ash, in aerosol particulates, or in the nonmethane volatile organic compounds (see Figure 4-1). Similarly, as discussed in OECD (1991), there is a possible double counting of carbon as CO and CH_4 as carbon in CO_2.

Because the methodology is scattered, amounts left as charcoal are accounted for in some types of burning (e.g., agricultural residues), acknowledged in some types but ignored in others (e.g., savanna burning, p. 6-32). Moisture content, too, is recognized explicitly as a factor for some types of burning (e.g., agricultural residues), and is unacknowledged but possibly embedded in others (e.g., biofuels, p. 2-47). Some assumptions are implicit in the methods but are not stated explicitly.

Finally, values recommended for certain default assumptions, to be used in the absence of country-specific data, are dated. Values for the percent of agricultural residues burned in developed countries are overestimates, and so are those for combustion efficiencies. The method also makes no distinction between burning fraction and combustion efficiencies, between open and confined burning, or between open burning of different types and uses of the same range of emission factors for all types of burning. It relies on fuelwood production data for estimating biofuel consumption, whereas at least for the noncommercial consumption (which constitutes the largest fraction), surveys of per-capita consumption will yield more reliable estimates (Scurlock and Hall, 1989; and Crutzen and Andreae, 1990).

Some of these problems are recognized and acknowledged in the report but are relegated to footnotes in the interest of keeping the methodology simple. These problems are easy to fix (more types of burning can be added, default assumptions can be changed), and none will make a large difference in estimates compared with the large uncertainties that currently exist in the amounts burned and in the emission rates. Making default assumptions explicit, no matter how conjectural, is preferable, however, to ignoring or submerging them. By forcing research into areas where gaps exist, estimates can be improved over time. The methodology recommended here (see Figure 4-4) is similar to the one proposed by IPCC-OECD (OECD, 1991). All types of biomass burning are presented together to force consistency across methods, so that the same factors are accounted for in all.

4.3.2 Methodology Used in this Chapter

Figure 4-4 summarizes the methodology for estimating CH_4 emissions from different types of biomass burning when the emission factor of CH_4 for that particular type of burning is known as a ratio (to CO_2 emitted). The methodology is shown as a series of (multiplication)

products, and the essential difference between the various types of biomass burning is the way in which the amount of biomass exposed to fire is estimated.

Statistics for amounts of biomass used for large-scale electricity generation are published and available (middle left, Figure 4-4). For all other types of biomass burning, the amounts that are exposed to the fire must be estimated. Different ways have been devised to make reasonable estimates. Thus, the areas burned annually in savannas and in shifting cultivation (top left, Figure 4-4) are estimated from a knowledge of the total areas (ha) involved and the average frequency of burning (#/yr; often <1). For forest areas being burned permanently for agricultural or pastoral use, repeated burnings, as described by Fearnside (1992), can be treated in a similar fashion to savanna burning. Areas affected annually multiplied by the total *above-ground* biomass density (Mg/ha) yield the amount of biomass exposed annually to fires.

The estimate of crop residues produced annually in a country is the product of annual crop production and the average residue to crop ratio (top middle, Figure 4-4). To estimate what fraction of this is burned in-situ in the fields, amounts used in each of the different nonburn routes (fodder, fuel, fiber, construction material, raw material for handicrafts, residues ploughed in or left to decay in the fields, etc.) must be subtracted from the amounts produced. This calculation is needed for each crop grown in the country.

Estimates of amounts of biofuels--fuelwood, charcoal, crop residues, and dung directly burned--that do not enter commercial market channels (as in rural areas of developing countries) are made best by a knowledge of the average consumption per person (top right, Figure 4-4). This, coupled with a knowledge of the population with that consumption, enables an estimate to be made of the amounts burned annually. This method is often useful for estimating consumption in urban areas as well, where although biofuels may be traded, records are not kept, as most of this trade is in the informal sector of the economy.

The next series of steps after the calculation of biomass exposed to fires aims at the accounting of carbon that is present in the biomass. The biomass that is exposed to (open) fires is generally a mixture of living biomass (which can be up to 50% water) and dead biomass in varying degrees of desiccation (moisture content as low as 10%). The next step estimates the amount of dry matter that is exposed to the fire (Figure 4-4). Not all biomass exposed to fire burns. The fraction burned (often termed as burning efficiency) accounts for the portion of dry biomass exposed to the fire that actually burns. Carbon content is expressed generally as a fraction (or a percent) of dried biomass. Multiplying this by the amount of dry matter gives us the amount of carbon that is involved in the fire. While burning efficiency is defined as the portion of biomass that was exposed that burns, combustion efficiency accounts for the fraction of carbon in the fire that is oxidized completely to CO_2. The product of this multiplication yields CO_2 emitted in g-C, multiplying it by the emissions ratio gives us an estimate of CH_4 emitted in g-C. The final multiplication by the ratio of molecular weight of CH_4 to the atomic weight of carbon gives the estimate of the amount of CH_4 emissions expressed as g-CH_4.

As mentioned earlier, emission factors instead of being expressed as ratios are also sometimes expressed in g CH_4/kg dm or g CH_4/MJ. It is a simple matter to convert an emission factor from g CH_4/MJ to g CH_4/kg dm, with a knowledge of the calorific value of the biomass that is involved in burning. Multiplying amounts of dry matter burned by emission factors on a mass basis will yield directly estimates of CH_4 emissions. Table 4-2 summarizes information on emission ratios, arranged in an increasing order by type of burning, that were

TABLE 4-2

BIOMASS-BURNING METHANE EMISSION FACTORS

TYPE	ESTIMATES OF EMISSION FACTORS (LOW-HIGH)			
	$R=\Delta CH_4 / \Delta CO_2$ (%)	g CH_4/kg dm	CH_4 / CO_2 (%)	g CH_4-C/g-C (%)
Wood boilers	-	-	0.02	0.04
Wood stoves	-	-	0.05	0.13
Charcoal burning	0.14-0.85	-	-	0.14
Savannas	0.28-0.66	0.6-2.2	0.12	0.33-0.40
Agricultural residues	0.5-0.8	2.7	-	0.3?
Fuelwood--noncommercial	1.40-1.79	4.8-13.9	0.57	1.56
Dung burning	-	-	-	1.7
Shifting cultivation	-	-	-	1.2-1.8
Deforestation	1.10-1.23	5.2-10.8	0.73	1.99
Charcoal manufacture	6.3-12.06	13.0-21.0	3.28?	6.2-9.0
Emission Factor Definitions	Emission ratio R is the ratio of relative enhancement of CH_4 concentration in the plume of the fire over the background before the fire as compared to the enhancement of CO_2.	Emission factor is defined as the emissions of grams of CH_4 per kilogram of dry matter of biomass burned.	Emission factor is also sometimes expressed as the ratio (or percent) of the mass of CH_4 emitted in a fire to that of CO_2 emitted.	This is same as in the previous column except that the mass of gases emitted is expressed in grams of carbon instead of the full molecular weight basis.

TABLE 4-3

DEFAULT VALUES OF PARAMETERS FOR USE IN CALCULATING METHANE EMISSIONS FROM BIOMASS BURNING
(See Table 4-2 for definition of emission factors.)

Type	Basic data unit	Burning Interval (Years)	Biomass Density (T dm/ha)	Moisture Content (%)	Fraction Burned (%)	Carbon Content (%)	Combustion Efficiency (%)	Range of Emission Factors	
								R=ΔCH4/ΔCO2 (%)	g CH_4 /kg dm
Savanna	Areas			Do not need, as biomass densities are reported in dry-matter units					
Australia	Cheng	2-3	5.0		80-85	40-46	83-85	0.4 (0.2-0.6)	2.2 (1.1-3.2)
Africa	Delmas	1-3	6.6?						
Tropical America	Hao	1-2	6.6						
Asia	Hao	2	4.9						
Shifting Cultivation	Areas								
India	4.9	4-5	23-33	x	40-50	45	80?	-	-
Rest (Open fallow)	Hao	Annual	38						
(Closed fallow)	Hao	Annual	126						
Deforestation	Areas								
F-7	F-7 project	x	114-354	x	30-40	45	80?	1.2 (0.9-1.5)	6.5 (4.9-9.3)
Rest	FAO-1988								
Agricultural Residues	**Crop Production**	**Res/ Crop Ratio**	Burned in-situ (%)						
Developing Countries	FAO	0.7-4	25	~10	90-95	40-48	85-90	0.5 (0.3-0.7)	2.7 (1.6-3.8)
Developed Countries	FAO	0.7-4	2.5?	~10	90-95		85-90		
Confined Burns	Population	p.cap. use							
Fuelwood (noncom.)	Country or region-specific data		x	10-20	100	45-50	87	1.2 (0.9-1.5)	6.5 (4.9-13.9)
Agr. Resid. (noncom.)				~10		40-48	88	-	-
Dung (noncom.)				~10		36-42	85	-	-
Charcoal				?		85	88	(0.14-0.85)	-
Commercial Biomass	**Amount**								
Commercial Fuelwood	FAO	x		~10		45-50	87	Same as above for fuelwood	
Large-Scale Biomass	FAO			~10		45-50	90	Technology-dependent	
Charcoal Manufacture	FAO			-	-	-	-	6.3 (4.0-9.0)	13.0 (10.0-20.0)

used in this chapter to estimate emissions from individual countries. In the absence of actual data, default values for other variables may be picked from the ranges given in Table 4-3 and used to estimate CH_4 emissions from biomass burning. Where direct measurements of emissions have not been made--e.g., open field burning of agricultural residues--values must be interpolated from those measured in other settings--e.g., savanna burning.

4.4 RESULTS

Table 4-1 presents recent published estimates of the ranges of the amounts of biomass burned globally each year. Some categories, such as municipal solid wastes, have not been estimated, but their inclusion is unlikely to broaden significantly the current range of 5-13 Pg dm/yr. The table also indicates that anthropogenically caused fires account for approximately 95% of the biomass burned. Similarly, open fires dominate over confined burns, which account for 35-40% of the biomass burned. If average values in the ranges are assumed to be true, then confined biofuels use is the single largest category, accounting for 38% of *all* biomass burned. Natural, prescribed, and other anthropogenic burning of forests account for about 35%, savanna burning accounts for 21%, and open field burning of agricultural residues the remainder.

If the same emission factor were to be used for all types of burning, CH_4 emissions would be roughly proportional to the amount of dry biomass consumed in the fires. However, emission factors between different types of burning vary by a factor of 15 (Table 4-2). Therefore, the relative contribution to CH_4 emissions from various types of biomass burning is appreciably different from the relative contribution of amounts burned. Although emission factor data are not good enough to permit differentiation among countries for any one type of burning, they are sufficiently reasonable for differentiating among different types of burning. Table 4-4 shows CH_4 emissions from major countries and continents by type of burning. This table is based on anthropogenic sources only, but excludes emissions from prescribed forest burning for reasons already mentioned.

Methane emissions from anthropogenic biomass burning are roughly 49 Tg/yr. Traditional biofuel combustion accounts for 43% of anthropogenic CH_4 emissions from biomass burning. Shifting cultivation in primary and secondary forests accounts for 21%, deforestation 17%, and savanna burning only 12%. This result is significantly different from some earlier studies, which held savanna burning responsible for a majority of trace-gas emissions.

The same table also shows the breakdown by countries. Most of the anthropogenic burning is on three continents: Asia (~40%), Africa (~30%), and Latin America (~25%). China and Brazil are by far the largest emitters. Together with Indonesia, they account for over one-third of CH_4 emissions from biomass burning. Seven countries--including India, Zaire, Nigeria, and Mexico--account for about half the emissions. Approximately two-thirds of the emissions are from 16 countries, each of which emits at least 0.7 Tg/yr, as shown in Table 4-4. Ivory Coast, Mozambique, Tanzania, Zambia, Malaysia, and Venezuela are the remaining other countries with emissions in excess of 0.5 Tg/yr.

TABLE 4-4

ESTIMATES OF METHANE EMISSIONS FROM ANTHROPOGENIC BIOMASS BURNING (Gg CH_4/year)

Country/ Region	Open Burning						
	Savanna Burning	Shifting Cultivation	Permanent Deforestation	Agricultural Residues	Confined Bio-fuels	Charcoal Manu-facture	Total Tg/Yr
Zaire	569.0	395.0	471.0	3.3	193.5	87.3	1.7
Nigeria	94.6	316.1	282.1	22.2	717.5	143.7	1.6
Sudan	400.3	168.5	124.3	5.8	179.3	240.0	1.1
Ethiopia	226.4	145.3	11.7	5.7	478.6	23.1	0.9
Angola	401.0	256.6	98.0	0.5	58.4	17.2	0.8
Other Africa	2447.7	2282.7	914.3	68.6	2322.9	550.9	8.6
China	58.8	0.0	537.5	**226.7**	**6437.0**	0.0	**7.3**
Indonesia	23.6	486.5	1290.0	32.3	1064.9	12.3	2.9
India	20.7	112.0	219.0	189.9	1822.6	188.4	2.6
Myanmar	23.2	576.4	101.0	7.1	247.8	0.0	1.0
Thailand	0.0	25.8	216.6	21.4	343.0	272.7	0.9
Viet Nam	4.6	346.3	66.4	10.4	403.6	0.0	0.8
Bangladesh	0.0	10.1	5.7	14.3	720.8	0.0	0.8
Pakistan	1.0	0.0	5.9	20.2	702.7	0.0	0.7
Other Asia	45.9	482.0	590.0	43.6	1710.0	75.8	2.9
Brazil	**971.8**	**2230.5**	**1425.6**	101.9	684.3	**616.4**	6.0
Mexico	9.7	837.6	255.4	35.8	391.9	12.7	1.5
Colombia	26.2	279.2	607.6	10.7	151.5	51.3	1.1
Other L. A.	218.7	1102.3	1132.3	76.1	813.4	124.2	3.5
U. S..	0.0	0.0	0.0	81.2	401.1	48.0	0.5
Other N. A.	0.0	0.0	0.0	10.7	32.0	0.0	0.0
Australia	321.0	0.0	0.0	8.4	22.7	3.1	0.3
Other Ocn.	14.5	47.2	0.0	4.0	31.7	3.3	0.1
E. Europe	0.0	0.0	0.0	72.5	437.0	16.5	0.5
W. Europe	0.0	0.0	0.0	46.5	206.7	20.2	0.2
Total (Tg)	5.9	10.1	8.4	1.1	20.6	2.5	48.5

Note: The numbers in bold indicate the country with the maximum emissions for that burning category.

4.5 TRENDS

Biomass burning from both natural and anthropogenic sources evidently has affected the global atmosphere from well before the industrial era. Kammen and Marino (1993) have estimated that the global source term from biomass burning rose steadily from 4 Tg CH_4 /yr in 800 A.D. to 15 Tg CH_4/yr in 1800. Since they did not account for all the types of biomass burning (e.g., burning to drive game from hiding) their numbers could be underestimates.

For more recent times, Bolle et al. (1986) have estimated that CH_4 emissions from biomass burning increased from 49 Tg CH_4 /yr in 1940 to 79 Tg CH_4 /yr in 1980. Figure 4-2 and more recent evidence from isotopic studies suggest that while gauging the trend, these numbers might overestimate the true emissions. The IPCC (1992) estimates that CH_4 emissions from biomass burning are currently 40 Tg CH_4.

Nonetheless, the increase in biomass burning in the last few decades has contributed significantly to the increase in the burden of atmospheric CH_4. Though one paper suggests that CH_4 emissions from biomass burning from the Southern Hemisphere alone are still increasing at an annual rate of 3.5 Tg CH_4 (Stevens, 1993), the recent decline in the rate of increase of CH_4 concentrations (Steele et al., 1992) makes it unlikely that today global biomass-burning emissions are increasing significantly (unless some other biogenic source is decreasing even more). Following is a discussion of the current changes in each major biomass burning subsector.

Savannas

The frequency of savanna burning may be increasing because of growing population pressure and more intensive use of rangeland (Crutzen and Andreae, 1990). A legitimate question to ask is, If humans stopped burning savannas, would nature burn as much from accumulated biomass? It is difficult to give an unambiguous answer now because over the long term a transition may occur from this inherently fire-prone ecosystem to a different ecosystem that may have different fire-resistance properties and size distribution.

Shifting Cultivation

Traditionally, the fallow period ranged from 10 to 50 years, but this period has been declining of late because of population pressures. For example, half a century ago, the average fallow period between cycles in India was 20-40 years; now the range is 4± 2 years (Kaul, 1991). The area under shifting cultivation is not expected to increase much beyond its present extent because virgin or secondary forests that could be brought under this practice are becoming scarce (Andreae, 1991). In India, the Forest Act of 1980 forbids any further conversions of existing forest lands, even to shifting cultivation. Instead, the trend is to convert existing shifting cultivation lands to permanent agriculture (Andreae, 1991). Entrenched tribal customs, poor soil conditions, and difficulties of proper soil management in remote and difficult terrains all make this conversion a slow process.

Deforestation

There has been much concern about the rate of destruction of the world's remaining forests. Although the rates in such countries as Brazil and India seem to have peaked recently (Makundi and Sathaye, 1992) due to economic recession and government policies, the global rates are still higher than what they were in the early 1970s and before.

Agricultural Residues

OECD countries discourage their farmers from burning crop stubble because of the air pollution that results. In Australia, this practice is becoming less frequent as low-tillage farming practices become more common and as residue retention replaces pre-harvest burning as a management practice (Howden et al., 1992b). Thus, while earlier estimates using data from the 1960s (OECD, 1991) put the fraction of agricultural residues disposed of by burning in developed countries at 50% (Seiler and Crutzen, 1980), more recent estimates put this figure at 10% (Andreae, 1993).

In some parts of developing countries, agricultural residues used to be common property, available to anyone who had a use for them. With the increase in population and the reduced availability of alternate energy sources, however, residues are becoming more privatized (Barnard, 1990). According to one estimate 800 million people, mostly in Asia, rely on agricultural residues as their *principal* fuel (Barnard, 1990). So while open field burning of residues might decrease in developing countries as well, their use as a fuel is likely to increase. People normally shift down to residues and dung as fuelwood, and other more desirable fuels become scarcer or less affordable. An early estimate of the fraction of (all) residues burned was 0.8 (Seiler and Crutzen, 1980); the more recent estimates of 0.6-0.9 encompass this value (Crutzen and Andreae, 1990).

Biofuel Use: On the one hand, economic development in this century has been accompanied by a movement away from biofuels to higher-quality fuels: from fuelwood, to charcoal, to kerosene, to natural gas (or LPG), and finally to electricity. But the increases in oil prices in the 1970s and balance of payment constraints in the 1980s made remote the hope of a transition to these fuels for a substantial portion of the world's population. In fact, in many areas, increasing population pressure and decreasing fuelwood supplies have hastened a regression to even poorer-quality fuels, like agricultural residues, twigs, cattle dung, roots, and leaves (Smith, 1987). On the other hand, in all the options considered for stabilization of atmospheric concentrations of greenhouse gases, processed and upgraded biofuels are seen to play the major role (Lashof and Tirpak, 1990).

Other Changes

The frequency and the intensity of naturally or accidentally caused wildfires in the next 20-30 years could increase significantly. The amount of combustible material is affected synergistically by a combination of anthropogenic and climatic factors, which include succession of severe drought years, disease, and pest infestations. Human management practices include aggressive fire suppression and closely packed plantation densities. Of course, it is possible that the frequency of droughts could increase with climate change caused by anthropogenic emissions of greenhouse gases, as well as with changes in rainfall regimes caused by deforestation. Both the frequency and the intensity of wildfires have been increasing in California, Canada, and Russia. (In Russia the increase has been due to a transition from aggressive (fire) suppression to laissez faire policies (GECR, 1992).)

4.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

Most studies of trace-gas emissions from biomass combustion rely on measurements of gas concentrations in the exhaust plume of the fire and compare these concentrations to

the background concentrations at that place before the fire. Thus, the relative enhancement R, often used as an emission ratio for CH_4, is defined by:

$$R = \Delta CH_4 / \Delta CO_2 \quad (3.3)$$

where ΔCH_4 is the increase in concentration of CH_4 in the plume over the background, and ΔCO_2 is the same for carbon dioxide. This method has been used for forest fires, and in one instance to estimate trace-gas emissions from cook stoves in Manila (Smith et al., 1993) (see Table 4-3). The basic uncertainty in this procedure stems not from the measurements of gases, which are standard procedures, but from knowing (or accounting for) the differential dilution of the gases in the plume by the background gases. Also embedded is an assumption, perhaps a reasonable one, that the plume gases participate in the combustion process only once. Different sampling protocols also would make measurements done by different teams incomparable. These comments do not apply to the chamber method of measuring emission factors (e.g., Lobert et al., 1991), but it is difficult to simulate in the chamber method the conditions that obtain in open burning in the wild. Clearly, additional work is required to sort out these matters.

In spite of the formidable difficulties, estimating CH_4 emissions from forest burning is slightly easier than estimating net carbon emissions, because only prompt emissions are of concern, and because the latter involves the additional uncertain step of estimating CO_2 uptake by vegetation and soils. However, there are a few second-order effects that fires might set in motion that are highly uncertain. It is known that methanotrophic bacteria in soils act as a CH_4 sink. One would expect burning to modify this sink, but neither the magnitude nor the direction is known. Besides releasing greenhouse gases, open biomass combustion may perturb soils sufficiently to release additional N_2O (Anderson et al., 1988), but it is not clear if this exceeds the background emissions of N_2O from the forests (Goreau and de Mello, 1988). Also, according to Fearnside (1992), relative to the uncut forest, termite attacks on the biomass left to decay on the ground increase following the first burn, converting between 0.2 and 0.8% of the carbon to CH_4 and the rest to CO_2. Not enough is known yet about the long-term changes in these fluxes to warrant their inclusion in national inventories at this stage (Moore, 1992).

Two types of methods have been used by scientists thus far to estimate global emissions from biomass burning. Based on measurements of $\delta^{13}C$, an isotope of carbon, pyrogenic emissions of CH_4 have been estimated to be ~11% of the global source, or about 59 Tg CH_4 /yr (Quay et al., 1988). The other type of studies is based on estimates of amounts of biomass burned in different settings multiplied by emission factors measured in actual, experimental, and laboratory fires. Estimates from these types of studies fall into two clusters: one close to the estimate obtained from isotopic studies (e.g., 51 Tg CH_4/yr, or ~10% of the global source (Andreae, 1991)) and others significantly lower than this (e.g., 30 ± 15 Tg-CH_4 /yr in Crutzen (1991), quoting Crutzen and Andreae (1990)).

Reconciliation among these three sets of numbers will be possible when more detailed studies are undertaken at the national level. There must be differences in burning practices in different ecosystems that only detailed local investigations will uncover. With one exception (Delmas et al., 1991), the studies that estimate CH_4 emissions from biomass burning tend to

use the same emission factor for all types of burning.[5] When emissions from charcoal manufacture are included, however, emission factors can vary by two orders of magnitude. As Menaut et al. (1991) conclude:

> *A substantial improvement will be made only when estimations are performed, for a given year, at a regional scale and then summed up at a larger one. It seems unrealistic to found such estimates on studies done at a scale larger than the basic bioclimatic and phytogeographic units of a region.*

Beginnings in this direction are being made. Several localized studies have appeared in the last two years (e.g., Joshi, 1991; Kaul, 1991; Fearnside, 1992; and Menaut et al., 1991). While more accurate national inventories would help in making accurate estimates of the global emission source, the task of independently verifying national inventories with the current technology is very daunting. The propagation of uncertainty in a chain of multiplications might yield estimates so broad so as to be of little use in national comparisons (Robinson, 1989). Satellite measurements have been proposed to measure areas burned, but these have their uncertainties (Robinson, 1991). Since emission factors from confined biomass burning could be verified in laboratories around the world, they are likely to prove less contentious than those from rice cultivation. Standing biomass densities may be another matter.

Chapter 11 of this report discusses technology-based verification schemes. Until such schemes yield unequivocal results, peer-reviewed and consensus-based default values that countries feel comfortable with should be used, rather than unenforceable and disputable mechanisms. More research is required on the extent of the various types of burnings in different countries, especially in the few largest emitters, and on the ensemble of emissions from them.

4.7 CONCLUSIONS

Methane emissions from biomass burning are estimated at roughly 49 Tg CH_4 /yr. Even though prescribed forest fires are also anthropogenic, they are excluded from this estimate for reasons explained in that section. Also excluded for reasons of data unavailability are emissions from several other categories, such as burning of urban park wastes, municipal solid wastes, and processed biofuels, except charcoal. Naturally caused wild forest fires are excluded as well. If these sources were included, the estimate of CH_4 from biomass burning would become close to those obtained from isotopic studies--i.e., 55-60 Tg/yr. While no formal uncertainty analyses were performed, other studies indicate that the variation around this central estimate would be wide, perhaps ± 40%.

Confined burning of biofuels is the largest single category of emissions, amounting to ~20 Tg/yr. It is likely that emissions from this category are overestimated because of reliance on a uniform default value of per-capita biofuel consumption for all but a few countries. Use of country-specific consumption based on household surveys (many carried out in the late 1970s and early 1980s) would help reduce this uncertainty. For this category, technology-specific emission factors for large-scale biomass combustors also have not been considered.

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[5] This deficiency has been corrected in the more recent studies that have appeared. See, for example, Levine et al., 1993; Andreae and Warneck, 1993; Hao and Ward, 1993.

Similarly, emissions from charcoal manufacture may have been underestimated, since they are sensitive to the assumptions made about the efficiency of the charcoal manufacture process.

Forty percent of the anthropogenic burning is in Asia. Africa (~30%) and Latin America (~25%) are also significant emitters. Methane emissions from biomass burning in Asia are caused largely by biofuel use; in Africa, by savanna burning; and in Latin America, by deforestation. China and Brazil are the two largest emitting countries. With Indonesia, they account for over one-third of CH_4 emissions from biomass burning. Seven countries, including India, Zaire, Nigeria, and Mexico, account for about half the emissions.

Forecasting trends in CH_4 emissions from biomass burning is a difficult exercise. Each type of biomass burning is influenced by different factors--among them, population pressure, the need for agricultural land, economic development, and the availability of alternatives. The share of biomass in the mix of global energy sources in response to the threat of global warming also will affect emissions in the future. Though biomass use (mostly of upgraded fuels) and burning are likely to increase, it should be possible to hold down CH_4 emissions as newer uses become more efficient.

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CHAPTER 5

METHANE EMISSIONS FROM OIL AND NATURAL GAS SYSTEMS

5.1 SUMMARY

Oil and gas systems are an important source of methane emissions, accounting for about 33 to 68 teragrams (Tg)[1] of methane in 1990, or almost 15% of total anthropogenic methane. Methane is emitted during oil and gas production, processing, transportation, and consumption. Sources of emissions within oil and gas systems include: emissions during normal operation, such as chronic leaks or discharges from process vents; emissions during routine maintenance, such as pipeline repair; emissions during system upsets and accidents; emissions associated with venting and flaring gas during oil and gas production; and emissions from incomplete combustion during the use of the oil and gas.

The basis for estimating emissions is weak for most regions at this time. Only a few detailed studies of emission rates have been performed. Better emission data that take into account region- and country-specific factors are needed. Currently available information indicates that gas production and transportation in the former Soviet Union and Eastern Europe are by far the most important sources, accounting for about 50% of emissions. This is a region for which relatively little data are available, however, so these emission estimates must be viewed with caution. The data also indicate that emissions from oil and gas combustion and crude oil transportation and refining are small, accounting for about 5% of total emissions from this source. Overall, additional primary data are needed to improve the estimates of emissions from oil and natural gas systems.

Future trends of emissions from oil and gas systems are ambiguous. Oil and gas production and consumption are expected to increase, which could lead to increased emissions. However, emissions from venting and flaring activities (particularly among the OPEC countries) and emissions from the oil and gas system in the former Soviet Union are expected to decline. Given the uncertainty in the current emission estimates, the trend in future emissions also remains uncertain at this time.

5.2 BACKGROUND

5.2.1 Overview of Oil and Natural Gas Systems

Oil and gas systems can be divided into four main parts: oil and gas production; crude oil transportation, storage, and refining; natural gas processing, transportation, and distribution; and fuel combustion (Figure 5-1).

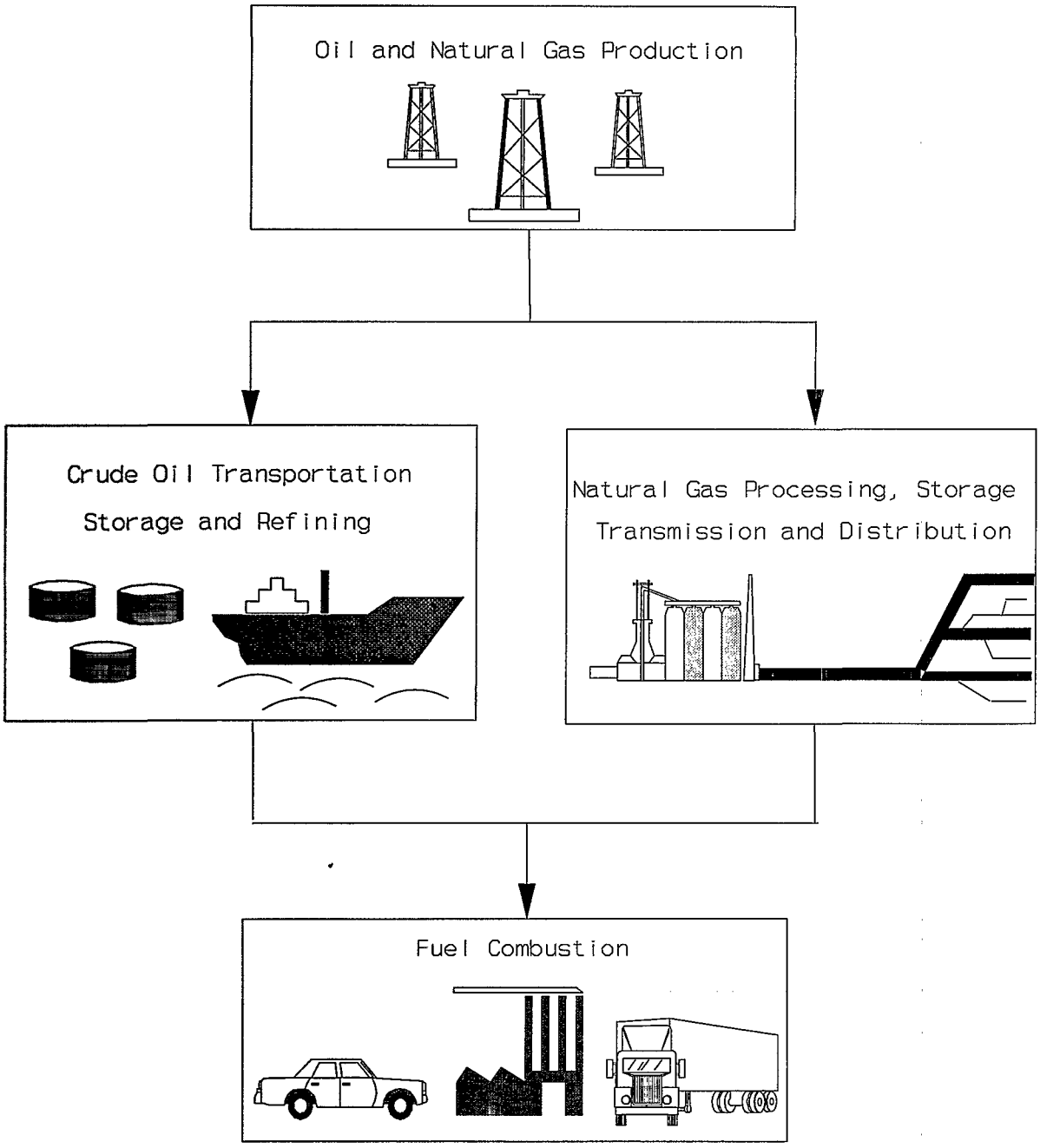
Oil and Gas Production

Oil and gas are withdrawn from underground formations using on-shore and off-shore wells. Oil and gas are frequently withdrawn simultaneously from the same geologic formation, and then separated. Gathering lines are generally used to bring the crude oil and

[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

FIGURE 5-1

STAGES IN THE OIL & NATURAL GAS SYSTEM



raw gas streams to one or more collection points within a production field. Because natural gas is about 90% methane (CH_4), leaks or venting from these systems result in CH_4 emissions. Oil and/or gas are produced in approximately 186 countries worldwide. In 1990, about 133,000 petajoules (PJ), or 20.2 billion barrels, of oil were produced, and 73,000 PJ, or 71.2 trillion cubic feet (Tcf) of gas were produced globally.[2] Most of the world's oil and gas production is concentrated in several countries (Table 5-1). The top 10 countries account for 69% of oil production and 85% of gas production. These top 10 countries consume 53% of the global oil production and 72% of the global gas production.

TABLE 5-1

MAJOR OIL- AND GAS-PRODUCING AND OIL-REFINING COUNTRIES

Oil Production: 1990		Gas Production: 1990		Oil-Refining Capacity as of Jan. 1, 1990	
Country	Production (PJ)	Country	Production (PJ)	Country	Capacity (PJ) [a]
Former Soviet Union	23,722	Former Soviet Union	29,071	United States	39,131
United States	17,758	United States	17,542	Former Soviet Union	29,631
Saudi Arabia	14,191	Canada	3,992	Japan	10,114
Iran	6,672	Netherlands	2,541	Italy	6,754
Mexico	6,191	Algeria	1,975	China	5,300
China	5,782	United Kingdom	1,904	Canada	4,461
Venezuela	4,840	Indonesia	1,579	United Kingdom	4,411
U.A.E.	4,495	Norway	1,131	France	4,382
Iraq	4,277	Saudi Arabia	1,101	Mexico	3,647
United Kingdom	3,848	Mexico	1,011	Germany	3,631
Other Countries	41,610	Other Countries	11,188	Other Countries	66,930
Global Total	*133,386*	*Global Total*	*73,035*	*Global Total*	*178,392*

a. Estimated by converting from barrels per day to petajoules per year.

Sources: Oil and gas production data from UN (1992). Oil-refining capacity from OGJ (1989).

[2] 1 PJ (10^{15} joules) is the energy equivalent of 975 million cubic feet (28 million cubic meters) of natural gas, or 0.019 Tg of natural gas. 1 PJ is the energy equivalent of 151,515 barrels of oil (6 million gallons), or 0.023 Tg of oil.

Crude Oil Transportation, Storage, and Refining

Crude oil is transported by pipelines and tankers to refineries. Often, the crude oil is stored in tanks for a period of time. Methane is usually found in the crude oil stream, and leaks or venting of vapors from these facilities result in methane emissions.

Refineries process crude oil into a variety of hydrocarbon products, such as gasoline and kerosine. During the refining process, methane is separated from the other hydrocarbons and may be leaked or vented. Refinery outputs, referred to as "refined products," generally contain negligible amounts of methane. Consequently, methane emissions are not estimated for transporting and distributing refined products. Refineries are operated in 102 countries of the world, with the top 10 countries accounting for 62% of global capacity (Table 5-1).

Natural Gas Processing, Storage, Transportation, and Distribution

Natural gas is processed to recover liquid hydrocarbons, such as butane and propane, and to prepare the dried gas for transporting to consumers. Most gas is transported through transmission and distribution pipelines. During periods of low gas demand, the excess natural gas is injected into underground storage reservoirs before being distributed for consumption. A small amount of gas is shipped by tanker as liquefied natural gas (LNG). Because only a small portion of gas is transported as LNG, emissions from LNG facilities are not estimated.

The following are the main processing, transportation, and distribution activities for natural gas:

- Gas-processing plants. Natural gas is usually processed in gas plants to produce products with specific characteristics. Depending on the composition of the unprocessed gas, it is dried, and a variety of processes may be used to remove hydrogen sulfide and most of the heavier hydrocarbons, or condensate, from the gas. The processed gas is then injected into the natural gas transmission system, and the heavier hydrocarbons are marketed separately.

- Storage and injection/withdrawal facilities. During periods of low gas demand, natural gas is injected into underground reservoirs for storage. During periods of high demand, the gas is withdrawn from the reservoir, processed if needed, and sent into the distribution network. The storage and injection/withdrawal facilities include a variety of processes and equipment, including compressors, injection/withdrawal wells, and separators and dehydrators.

- Transmission pipelines. Transmission facilities include high-pressure lines that transport gas from production fields, processing plants, storage facilities, and other sources of supply over long distances to distribution centers or large-volume customers. Although transmission lines are usually buried, a variety of above-ground facilities supports the overall system. These facilities include metering stations, maintenance facilities, and compressor stations located along the pipeline routes. Compressor stations, which maintain the pressure in the pipeline, generally include upstream scrubbers, where the incoming gas is cleaned of particles and liquids before entering the compressors. Reciprocating engines and turbines are used to drive the compressors. Compressor stations normally use pipeline gas to fuel the compressors. They also use the gas to fuel electric power generators to meet the station's electricity requirements.

Distribution systems. Distribution pipelines are extensive networks of generally small-diameter, low-pressure pipelines. Gas enters distribution networks from transmission systems at "gate stations," where the pressure is reduced for distribution within cities or towns.

Fuel Combustion

Natural gas and refined oil products are used in internal and external combustion engines and turbines. During the combustion of refined products, methane is produced and emitted. Because natural gas is primarily composed of methane, incomplete combustion also results in some methane emissions. The rate of methane emissions from fuel combustion varies significantly with engine type, operating conditions, and emission control technologies used.

5.2.2 Sources of Methane Emissions in Oil and Natural Gas Systems

Emissions from oil and gas systems can be divided into five main types: (1) venting and flaring, (2) normal operations, (3) routine maintenance, (4) system upsets, and (5) combustion emissions.

Venting and Flaring

Venting and flaring refers to the disposition of gas that cannot be contained or otherwise handled.[3] Venting and flaring activities release methane because the vented gas typically has a high methane content and because flares do not always destroy 100% of the methane in the gas. Usually, these activities are associated with oil- and gas-production activities. For example, an oil well may produce an amount of gas that is too small to collect and market. This gas may be re-injected into the underground formation or may be flared if re-injection is not feasible or economical. If flaring is not feasible, this gas may be vented, although venting is prohibited in most areas of the world and is undesirable for safety reasons. Gas-production facilities are generally unlikely to vent or flare gas, although in some cases flaring or venting may be necessary during periods of equipment maintenance or as the result of other factors, such as equipment failure.

The combined quantity of gas vented and flared is reported by countries that produce oil and gas (Barns and Edmonds, 1990). The reliability of the data is questionable in many cases because vented and flared amounts are not metered and are often an "accounting balance," whereby total gas use (sales, re-injection, on-site use) is set equal to the total gas withdrawn, by putting any differences between gas withdrawn and gas used in the category of vented and flared.

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[3] Recently, Radian (1992) expanded the definition of "venting and flaring" to include gas releases from any equipment that is designed to release gas, such as a pneumatically operated device that is powered by a pressurized gas stream. Similarly, gas released during turbine engine start-up would also be considered a venting emission. For purposes of this study, planned incidental releases associated with the operation of equipment in the production, processing, and distribution of natural gas are not considered part of venting and flaring. Using the traditional concept of venting and flaring, this study considers emissions from venting and flaring associated with the production of oil and natural gas separately from the emissions from routine equipment venting.

Normal Operations

Normal operations are the day-to-day operations of a facility absent the occurrence of abnormal conditions. Facilities emit methane during normal operations due to a wide variety of operating practices and factors, including:

- Emissions from pneumatic devices. Pneumatic devices are commonly used to regulate and control gas pressures and flows throughout the natural gas system. These devices rely on pressurized gas as an energy source for their operation. In most cases, the natural gas stream itself is a suitable supply of pressurized gas. Most pneumatic devices are designed to release the pressurized gas they use. These emissions depend on the size, type, and age of the devices, the frequency of their operation, and the quality of their maintenance.

- "Fugitive" emissions from system components. These emissions are unintentional and usually continuous releases associated with leaks from the failure of a seal or the development of a flaw, crack, or hole in a component designed to contain or convey oil or gas. Connections, valves, flanges, instruments, and compressor shafts can develop leaks from flawed or worn seals, while pipelines and storage tanks can develop leaks from cracks or from corrosion.

- Emissions from starting and stopping reciprocating engines and turbines at compressor stations.

- Emissions from process vents, such as still vents on glycol dehydrators[4] and vents on crude oil tankers and storage tanks. Vapors, including methane, are emitted from the vents as part of the normal operation of the facilities.

Routine Maintenance

Routine maintenance includes regular and periodic activities performed in the operation of the facility. These activities may be conducted frequently, such as launching and receiving scrapers (pigs)[5] in a pipeline, or infrequently, such as evacuation of pipes ("blowdown") for periodic testing or repair. In each case, the required procedures release gas from the affected equipment. Releases also occur during maintenance of wells ("well workovers") and during replacement or maintenance of fittings.

System Upsets

System upsets are unplanned events in the system, the most common of which is a sudden pressure surge resulting from the failure of a pressure regulator. The potential for unplanned pressure surges is considered during facility design, and facilities are provided with pressure-relief systems to protect the equipment from damage due to the increased pressure.

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[4] Glycol dehydrators are used to remove water from natural gas through continuous glycol absorption.

[5] Scrapers, or "pigs," are devices used for the routine maintenance of pipe, including cleaning, dewaxing, and monitoring the condition of the pipeline.

Relief systems vary in design. In some cases, gases released through relief valves may be collected and transported to a flare for combustion or re-compressed and re-injected into the system. In these cases, methane emissions associated with pressure-relief events will be relatively small. In older facilities, relief systems may vent gases directly into the atmosphere or may send gases to flare systems where complete combustion may not be achieved.

The frequency of system upsets varies with the facility design and operating practices. In particular, facilities operating well below capacity are less likely to experience system upsets and related emissions.

Emissions associated with accidents are also included under the category of upsets. Occasionally, gas transmission and distribution pipelines are accidentally ruptured by construction equipment or other activities. These ruptures not only result in methane emissions; they can be extremely hazardous as well.

Combustion Emissions

Methane emissions related to combustion of oil and gas result, for the most part, from the incomplete combustion of fuel. In the case of natural gas, methane is a major component of the uncombusted fuel and is thus emitted to the atmosphere. In the cases in which methane is not a component of the fuel, methane may be created in the combustion process. In general, the methane emissions resulting from fuel combustion are much less than those associated with the production, processing, or transportation of the fuels.

The amount of methane produced per unit of energy delivered from gaseous and liquid fuels is very sensitive to the combustion technology employed, including the use of emission control equipment (OECD, 1991). For purposes of this analysis, fuel consumption has been divided into two source groups:

- Stationary Sources. These sources include gas-fired boilers; oil- and gas-fired electric utility turbines; gas-, gasoline-, and diesel-powered industrial equipment; large-bore diesel and dual-fuel engines; and gas- and oil-fired residential heating sources.

- Mobile Sources. These sources contribute less methane than stationary sources. They include highway and off-highway vehicles, aircraft, railway transportation, and agricultural, industrial, and construction machinery. Nearly all of this energy use is in liquid fuels, with gaseous fuels playing a very minor role.

Table 5-2 lists those emission types that are the most important sources within each segment of the oil and gas industry. Based on available information, the sources listed as

TABLE 5-2

EMISSIONS FROM OIL AND NATURAL GAS SYSTEMS

Segment	Major Emission Sources	Other Potential Emission Sources
Oil and Gas Production Oil and Gas Wells Gathering Lines Treatment Facilities	Venting and Flaring Normal Operations: fugitive emissions; deliberate releases from pneumatic devices and process vents	Routine Maintenance System Upsets and Accidents
Crude Oil Transportation, Storage, and Refining Pipelines Tankers Storage Tanks Refineries	Normal Operations: fugitive emissions; deliberate releases from process vents at refineries, during loading and unloading of tankers and storage tanks	Routine Maintenance System Upsets and Accidents
Natural Gas Processing, Transportation, and Distribution Gas Plants Underground Storage Reservoirs Transmission Pipelines Distribution Pipelines	Normal Operations: fugitive emissions; deliberate releases from pneumatic devices and process vents	Routine Maintenance System Upsets and Accidents
Fuel Combustion Stationary Sources Oil: Utility, Industrial, Residential Boilers; Engines Gas: Utility, Industrial, Residential Boilers; Engines Mobile Sources: Liquid Fuels[a] Light-Duty Passenger Vehicles, Trucks, Buses, Railways, Ships, Aviation	 Combustion Exhaust Emissions Combustion Exhaust Emissions Exhaust Emissions	

a. A small amount of gaseous fuel is also used in mobile sources.

"major" account for the majority of emissions from each segment. Because data are limited and there is considerable diversity among oil and gas systems throughout the world, other potential sources are also listed, some of which may be important contributors to emissions.

5.2.3 Emission Data

Only very limited data are available that describe methane emissions from natural gas and oil systems. Estimating the emission types defined earlier is complicated by the fact that emission rates from similar systems vary among regions and countries due to differences in supporting infrastructure, operating and maintenance practices, and level of technology used. Because natural gas and oil systems are composed of a complex set of facilities, simple relationships between emissions and gross descriptors of the systems are not easily ascertained.

The available published data reviewed to identify emission estimates include: a detailed consideration of the physical attributes of oil and gas systems; the operation and maintenance characteristics of key facilities; and country- or region-specific factors that may influence emission rates. Three major types of data were identified: (1) survey data, (2) estimates based on reported, unaccounted-for gas, and (3) data from engineering studies and measurements.

Surveys

Several surveys of system operators have estimated emissions as a portion of production or throughput. These studies include Alphatania (1989), AGA (1989), and INGAA (1989). While these surveys provide a basis for identifying the portions of the systems that operators believe are likely to be major sources of emissions, they are not based on detailed assessments of emission rates. Consequently, these surveys do not provide an adequate quantitative basis for estimating methane emissions from oil and natural gas systems.

Estimates Based on Reported Unaccounted-For Gas

Several studies, such as Hitchcock and Wechsler (1972), Abrahamson (1989), and Cicerone and Oremland (1988), assumed that emissions can be approximated by reported amounts of "unaccounted-for" gas. Unaccounted-for gas is defined as the difference between gas production and gas consumption on an annual basis. Like estimates of venting and flaring, unaccounted-for gas often is used as an accounting convenience to balance company or national production and consumption records.

The applicability of unaccounted-for gas estimates is very limited because factors other than emissions account for the majority of the gas listed as unaccounted for, including: meter inaccuracies, use of gas within the system itself, theft of gas (PG&E, 1990), variations in temperature and pressure, and differences in billing cycles and accounting procedures between companies receiving and delivering the gas (INGAA, 1989). Furthermore, because known releases of gas are not reflected in unaccounted-for gas estimates, such as emissions from compressor exhaust, the unaccounted-for gas estimates cannot unambiguously be considered an upper or lower bound on emissions.

Engineering Studies and Measurements

A few studies are based on detailed engineering and/or field measurement analyses. Several engineering analyses have considered how actual or model facilities are built and operated, and extrapolate facility emissions to a system-wide basis. Several measurement studies have measured emissions from operating facilities or have identified actual leaks and have extrapolated these measurements to estimate system-wide emissions.

For purposes of this analysis, data from engineering studies and measurements are the preferred basis for making estimates. Unfortunately, only a few of these types of studies have been performed, which limits the ability to estimate emissions regionally and globally from oil and gas systems. Table 5-3 lists the studies identified and the information they contain. The emission estimates from the studies in the table have been converted to common units of kilograms of methane emissions per petajoule of energy (kg/PJ). Seven studies are listed, with emission estimates for portions of the United States. (U.S. EPA, 1993), Eastern Europe (Rabchuk et al., 1991), and Western Europe (Schneider-Fresenius et al., 1989; and Norwegian SPCA, 1992). Additionally, Barns and Edmonds (1990) present estimates based on a global assessment. Representative uncontrolled emission factors for fuel combustion from OECD (1991) were adopted for developing the fuel-combustion emissions for non-U.S. regions for which region-specific emission factors were not easily available. API (1987) estimates for emissions from marine-vessel loading and ballasting operations were used to estimate global crude oil transportation emissions. Additional studies of this type are needed to improve the basis for making emission estimates. At this time, these data are used as the best available for estimating emissions.

5.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

Emissions were estimated as follows:

1. The global oil and gas systems were divided into five regions. Within each region, the characteristics of the oil and gas system were relatively homogeneous.

2. For each region, representative emission factors for each emission type within each segment were selected, with the objective of taking into account the various system designs and operating practices found in each region.

3. Region-specific activity levels were estimated for use in conjunction with the emission factors to estimate emissions from each segment in each region.

Total emissions were estimated as the sum of the region-specific estimates. This method follows the approach discussed in OECD (1991). As recommended, the oil and gas systems are divided into their major segments, and emissions are estimated for each of the main emission types. Although OECD recommends that emissions from oil and gas combustion be estimated separately, these emissions are combined here. Each step of the method used is discussed in turn.

TABLE 5-3

SUMMARY OF EMISSION FACTORS

Data Source	Study Methodology	Emission Factors and Applicability	
U.S. EPA (1993)	Compilation of estimates from detailed engineering analyses and field measurement studies	**Oil and Gas Production:**	
		300 - 5,000 kg/PJ of oil produced	Emissions from nongas-producing oil wells, including fugitive emissions and routine maintenance emissions in the United States.
		45,900 - 84,200 kg/PJ of gas produced	Emissions from gas production, including fugitive emissions, dehydrator venting, bleeding from pneumatic devices, routine maintenance, and system upsets in the United States.
		3,000 - 13,900 kg/PJ of total oil and gas produced	Venting and flaring emissions from oil and gas production and fugitive emissions from gas-producing oil wells in the United States.
		Crude Oil Transportation and Refining:	
		105 - 1,650 kg/PJ of oil refined	Emissions from oil refining and related oil storage tanks in the United States.
		Natural Gas Processing, Transmission, and Distribution:	
		56,600 - 117,700 kg/PJ of gas consumed	Emissions from gas processing, transmission, and distribution, including fugitive emissions, dehydrator venting, bleeding from pneumatic devices, routine maintenance, and system upsets in the United States.
		Fuel Combustion in Stationary and Mobile Sources	
		70 - 130 kg/PJ of fuel oil used for stationary combustion	Emissions from oil-fired equipment used in the utility, industrial, residential, commercial, agricultural, and military sectors in the United States.
		900 - 3,500 kg/PJ of gas used for stationary combustion	Emissions from gas-fired equipment used in the utility, industrial, residential, commercial, agricultural, and military sectors in the United States.
		17,400 - 31,500 kg/PJ of gas used for stationary combustion	Emissions from compressor engine exhaust used in gas production in the United States.
		5,600 - 16,900 kg/PJ of oil used for mobile combustion	Emissions from highway vehicles and other mobile sources in the United States.

(continued)

TABLE 5-3

SUMMARY OF EMISSION FACTORS (Continued)

Data Source	Study Methodology	Emission Factors and Applicability	
Rabchuk et al. (1991)	Compilation of estimates from previous measurement studies and from official data for 1989	**Oil and Gas Production:**	
		139,700 - 314,200 kg/PJ of gas produced	Emissions from leakages at gas wells, including routine equipment venting in the former Soviet Union
		Natural Gas Processing, Transmission, and Distribution:	
		288,100 - 628,500 kg/PJ of gas produced	Emissions from leakages at collection networks, underground storage facilities, compressor stations, linear part of main pipelines, and distribution networks in the former Soviet Union
		174,600 - 384,100 kg/PJ of nonresidential gas consumption	Emissions from leakages at industrial plants and power stations
		87,300 - 192,000 kg/PJ of residential gas consumption	Emissions from leakages at residential and commercial sectors
Schneider-Fresenius et al. (1989)	Compilation of results from the Battelle study's 1988 literature survey	**Oil and Gas Production:**	
		14,800 - 27,500 kg/PJ of gas produced	Emissions from gas production and treatment facilities in Germany
		Natural Gas Processing, Transmission, and Distribution:	
		71,700 - 133,100 kg/PJ of gas consumed	Emissions from transportation, distribution, and storage of gas in Germany
Norwegian SPCA (1992)	Summary emission estimates for 1989, based on information and measurements collected from oil companies and industry associations	**Oil and Gas Production:**	
		1,100 - 3,400 kg/PJ of oil produced	Emissions from cold venting and flaring from oil activity in Norway

(continued)

TABLE 5-3

SUMMARY OF EMISSION FACTORS (Continued)

Data Source	Study Methodology	Emission Factors and Applicability	
Barns and Edmonds (1990)	Compilation of official reports and projections on international emissions	**Oil and Gas Production:**	
		96,000 kg/PJ of natural gas production	Emissions from gas production and separation facilities in the world
		Eastern Europe and Former Soviet Union 6,300 - 29,700 kg/PJ of gas produced	Emissions from venting and flaring activity
		Other Oil-Exporting Countries 757,600 - 1,046,400 kg/PJ of gas produced	Emissions from venting and flaring activity
		Rest of the World 174,600 - 209,500 kg/PJ of gas produced	Emissions from venting and flaring activity
OECD (1991)	Compilation of representative uncontrolled emission factors drawn from other sources	**Fuel Combustion:**	
		Mobile Sources: 31,400 kg/PJ of oil consumed 560,000 kg/PJ of gas consumed	Emissions from transport fuel combustion
		Stationary Sources: *Eastern Europe and Former Soviet Union* 10,200 kg/PJ of oil consumed 850 kg/PJ of gas consumed *Western Europe* 4,000 kg/PJ of oil consumed 1,100 kg/PJ of gas consumed *Other Oil-Exporting Countries* 5,000 kg/PJ of oil consumed 1,100 kg/PJ of gas consumed *Rest of the World* 5,200 kg/PJ of oil consumed 700 kg/PJ of gas consumed	Emissions from stationary fuel combustion--electric utility, industry, residential/commercial, and other (agriculture and military)
API (1987)	Estimates of hydrocarbon emissions and evaporative cargo losses, based on recent ship and barge emission tests performed during typical operations	**Crude Oil Transportation, Storage, and Refining**	
		745 kg/Pj of oil tankered	Emissions from loading and unloading of oil tankers globally.

5.3.1 Definition of Regions

Regions must be defined considering the limitations in data on emission factors and activity levels, but also recognizing the key differences in oil and gas systems that are found globally. The following five regions were adopted:

- United States. The United States is a large producer and importer of oil and is a large producer of gas. Detailed emission estimates are available for the United States.

- Eastern Europe and Former Soviet Union. Emission rates for this region are probably much higher than those for other regions, in particular for the gas system. This region includes the former Soviet Union (which is by far the largest oil and gas producer in the region), Albania, Bulgaria, the former Czechoslovakia, Hungary, Poland, Romania, and the former Yugoslavia.

- Western Europe. This region is a net importer of oil and gas, and mainly produces oil and gas offshore. This region includes Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom.

- Other Oil-Exporting Countries. This region includes the world's other major oil-producing countries: the 13 OPEC members (Algeria, Gabon, Libya, Nigeria, Ecuador, Venezuela, Indonesia, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, and the United Arab Emirates) and Mexico. Generally, these countries produce large quantities of oil and have limited markets for gas.

- Rest of the World. This region includes the remaining countries of Asia, Africa, the Middle East, Oceania, Latin America, and Canada.

For purposes of defining these regions, countries were aggregated with relatively similar oil and gas systems. Additional investigation would most likely improve the definition of the regions.

5.3.2 Emission Factors

As discussed above, the basis for selecting emission factors is weak because very few detailed studies of emissions have been performed. Using the information summarized in Table 5-3, emission factors were selected by industry segment and emission type for each of the regions. In some cases, data from the United States were used when region-specific information was not available.

Tables 5-4 through 5-8 list the emission factors selected. Emission factors from U.S. EPA (1993) were used for the United States (Table 5-4). Key emission factors for Eastern Europe and the former Soviet Union were taken from Rabchuk et al. (1991) (Table 5-5). Barns and Edmonds' (1990) estimates were used for emission factors for venting and flaring for the several regions, including Eastern Europe.

Studies by Schneider-Fresenius et al. (1989) and Norwegian SPCA (1992) were adopted as representative of emission factors for Western European gas production and

TABLE 5-4

U.S. EMISSION FACTORS

Emission Types	Emission Factor (kg/petajoule)	Source
Oil and Gas Production		
Oil	300 - 5,000 of Oil Produced	U.S. EPA (1993)
Gas	45,900 - 84,200 of Gas Produced	U.S. EPA (1993)
Oil & Gas	3,000 - 13,900 of Oil & Gas Prod.	U.S. EPA (1993)
Crude Oil Transportation, Storage, and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	U.S. EPA (1993)
Storage Tanks	20 - 250 of Oil Refined	U.S. EPA (1993)
Natural Gas Processing, Transport, and Distribution	56,600 - 117,700 of Gas Consumed	U.S. EPA (1993)
Fuel Combustion		
Stationary Sources		
Oil	70 - 130 of Oil Consumed	U.S. EPA (1993)
Gas: Compressor Exhaust	17,400 - 31,500 of Gas Consumed	U.S. EPA (1993)
Gas: Other stationary sources	900 - 3,500 of Gas Consumed	
Mobile Sources		
Oil	5,600 - 16,900 of Oil Consumed	U.S. EPA (1993)
Gas	Not Estimated	U.S. EPA (1993)

TABLE 5-5

EASTERN EUROPE AND THE FORMER SOVIET UNION - EMISSION FACTORS

Emission Types	Emission Factor (kg/Petajoule)	Source
Oil and Gas Production		
Oil	300 - 5,000 of Oil Produced	U.S. EPA (1993)
Gas	139,700 - 314,200 of Gas Produced	Rabchuk et al. (1991)
Oil & Gas	6,300 - 29,700 of Gas Produced	Barns and Edmonds (1990)
Crude Oil Transportation, Storage, and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	U.S. EPA (1993)
Storage Tanks	15 - 250 of Oil Refined	U.S. EPA (1993)
Natural Gas Processing, Transport, and Distribution		
Process., Transport, and Dist.	288,000 - 628,500 of Gas Produced	Rabchuk et al. (1991)
Nonresidential Consumption	174,600 - 384,100 of Gas Consumed	Rabchuk et al. (1991)
Residential Consumption	87,300 - 192,000 of Gas Consumed	Rabchuk et al. (1991)
Fuel Combustion		
Stationary Sources		
Oil	10,200 of Oil Consumed	OECD (1991)
Gas	850 of Gas Consumed	OECD (1991)
Mobile Sources		
Oil	31,400 of Oil Consumed	OECD (1991)
Gas	560,000 of Gas Consumed	OECD (1991)

TABLE 5-6

WESTERN EUROPE - EMISSION FACTORS

Emission Types	Emission Factor (kg/petajoule)	Source
Oil and Gas Production		
Oil	300 - 5,000 of Oil Produced	U.S. EPA (1993)
Gas	14,800 - 27,500 of Gas Produced	Schneider-Fresenius et al. (1989)
Oil & Gas	1,100 - 3,400 of Oil Produced	Norwegian SPCA (1992)
Crude Oil Transportation, Storage, and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	U.S. EPA (1993)
Storage Tanks	15 - 250 of Oil Refined	U.S. EPA (1993)
Natural Gas Processing, Transport, and Distribution	71,700 - 133,100 of Gas Consumption	Schneider-Fresenius et al. (1989)
Fuel Combustion		
Stationary Sources		
Oil	4,000 of Oil Consumed	OECD (1991)
Gas	1,100 of Gas Consumed	OECD (1991)
Mobile Sources		
Oil	31,400 of Oil Consumed	OECD (1991)
Gas	560,000 of Gas Consumed	OECD (1991)

TABLE 5-7

OTHER OIL-EXPORTING COUNTRIES - EMISSION FACTORS

Emission Types	Emission Factor (kg/petajoule)	Source
Oil and Gas Production		
Oil	300 - 5,000 of Oil Produced	U.S. EPA (1993)
Gas	45,900 - 96,000 of Gas Produced	U.S. EPA (1993) and Barns and Edmonds (1990)
Oil & Gas	757,600 - 1,046,400 of Gas Produced	Barns and Edmonds (1990)
Crude Oil Transportation, Storage, and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	U.S. EPA (1993)
Storage Tanks	15 - 250 of Oil Refined	U.S. EPA (1993)
Natural Gas Processing, Transport, and Distribution		
Process., Transport, and Dist.	117,700 of Gas Consumed - 288,100 of Gas Produced	U.S. EPA (1993) and Rabchuk et al. (1991)
Nonresidential Consumption	174,600 of Gas Consumed[a]	Rabchuk et al. (1991)
Residential Consumption	87,300 of Gas Consumed[a]	Rabchuk et al. (1991)
Fuel Combustion		
Stationary Sources		
Oil	5,000 of Oil Consumed	OECD (1991)
Gas	1,100 of Gas Consumed	OECD (1991)
Mobile Sources		
Oil	31,400 of Oil Consumed	OECD (1991)
Gas	Not Estimated	

a. Used for the high estimate of Natural Gas Processing, Transport, and Distribution emissions.

TABLE 5-8

REST OF THE WORLD - EMISSION FACTORS

Emission Types	Emission Factor (kg/petajoule)	Source
Oil and Gas Production		
Oil	300 - 5,000 of Oil Produced	U.S. EPA (1993)
Gas	45,900 - 96,000 of Gas Produced	U.S. EPA (1993) and Barns and Edmonds (1990)
Oil & Gas	174,600 - 209,500 of Gas Produced	Barns and Edmonds (1990)
Crude Oil Transportation, Storage, and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	U.S. EPA (1993)
Storage Tanks	15 - 250 of Oil Refined	U.S. EPA (1993)
Natural Gas Processing, Transport, and Distribution		
Process., Transport, and Dist.	117,700 of Gas Consumed - 288,100 of Gas Produced	U.S. EPA (1993) and Rabchuk et al. (1991)
Nonresidential Consumption	174,600 of Gas Consumed[a]	Rabchuk et al. (1991)
Residential Consumption	87,300 of Gas Consumed[a]	Rabchuk et al. (1991)
Fuel Combustion		
Stationary Sources		
Oil	5,200 of Oil Consumed	OECD (1991)
Gas	700 of Gas Consumed	OECD (1991)
Mobile Sources		
Oil	31,400 of Oil Consumed	OECD (1991)
Gas	560,000 of Gas Consumed	OECD (1991)

a. Used for the high estimate of Natural Gas Processing, Transport, and Distribution emissions.

venting and flaring (Table 5-6). In particular, the venting and flaring estimate is relatively low for the North Sea production facilities examined. No region-specific data were available for the Other Oil Exporting Countries (Table 5-7) and the Rest of the World (Table 5-8). Emission factors in these regions are expected to fall between the relatively low rates found in the United States and Western Europe (Tables 5-4 and 5-6), where emission controls are the highest, and the relatively high rates found in Eastern Europe and the former Soviet Union (Table 5-5), where emission controls are the least stringent. Consequently, a range of emission factors is applied to these regions.

Emission factors for stationary and mobile combustion for the United States, shown in Table 5-4, were taken from U.S. EPA (1993). The non-U.S. emission factors for stationary and mobile combustion shown in Tables 5-5 through 5-8 were developed using data from OECD (1991) and OECD-IEA (1991). The derivation of these emission factors is presented in Appendix A.

5.3.3 Activity Levels

Data on the quantity of oil and gas produced, refined, and consumed were collected for each region for 1990 (Table 5-9). Most of the data were obtained from UN (1992). Data

TABLE 5-9

ACTIVITY LEVELS FOR OIL AND NATURAL GAS SYSTEMS IN 1990 (petajoules/yr)

Factor Type	United States	E. Europe & Former Soviet Union	Western Europe	Other Oil-Exporting Countries[a]	Rest of the World	World Total
Oil Production[b]	17,758	24,454	8,319	57,410	25,445	133,386
Gas Production[b]	17,542	29,071	7,188	9,240	9,994	73,035
Oil Consumption						
Stationary[c]	9,283	11,640	9,927	6,156	19,835	56,841
Mobile[c]	21,460	6,795	12,477	4,198	13,846	58,776
Total[b]	*30,743*	*18,435*	*22,404*	*10,354*	*33,681*	*115,617*
Gas Consumption						
Stationary[c]	18,466	26,574	10,317	6,665	9,796	71,818
Mobile[c]	0	262	11	0	7	280
Non-Residential[d]	11,601	21,803	5,397	6,109	8,415	53,325
Residential[d]	6,865	5,033	4,931	556	1,389	18,774
Total[b]	*18,466*	*26,836*	*10,328*	*6,665*	*9,803*	*72,098*
Oil Refined (Throughput)[e]	30,064	24,591	24,525	14,511	38,486	132,176

a. Includes all the OPEC countries and Mexico.

b. Source: UN, 1992.

c. Total UN (1992) energy estimates divided between stationary and mobile sources, based on sectoral distribution of OECD-IEA (1991).

d. Total UN (1992) energy estimates divided between Nonresidential and Residential, based on sectoral distribution of OECD-IEA (1991).

e. Using McCaslin (1992) estimates of throughput of oil refined in 1990 adjusted, to be consistent with the UN (1992) oil production data for 1990.

on oil-refining capacity were used to approximate oil refined in that year. Data on oil tankered were not available by region. Total oil exported in 1990 was about 31 million barrels per day (BP Statistical Review, 1992). Since some oil is loaded and unloaded more than once before reaching its final destination, and given the occurrence of intrastate tankering, this estimate of total oil exported was adopted as the lower bound for crude oil tankering globally. An upper bound of total oil production (55.4 million barrels per day, based on the UN (1992) estimate for 1990) was used to reflect the fact that some oil is loaded and unloaded many times before it is refined. A regional breakout of this emission factor was not attempted.

5.4 RESULTS

Table 5-10 summarizes the emission estimates by region and industry segment. These emission estimates are the product of the emission factors and activity levels presented earlier. The total global emissions shown in Table 5-10 range from about 33 to 68 Tg for 1990. This range is comparable to the IPCC (1992) estimate of 30 to 70 Tg of methane emissions from oil and gas systems, which represents almost 15% of total methane emissions from anthropogenic sources. Appendix B presents a more detailed estimation of these emissions for each of the different regions.

The largest major category of emissions is Natural Gas Processing, Transportation, and Distribution (16 to 39 Tg). Eastern Europe and the former Soviet Union contribute most to these emissions -- about 13 to 28 Tg. The next largest source of emissions is estimated to be Oil and Gas Production (15 to 27 Tg). The Other Oil Exporting Countries and Eastern Europe and the former Soviet Union, which have similar emission estimates, are the major contributors to emissions (7 to 11 Tg and 4 to 10 Tg, respectively). The Other Oil Exporting Countries are estimated to contribute most to the Venting and Flaring emissions in this category (7 to 10 Tg of the 9 to 13 Tg total).

Very little information was available for estimating emission factors for Crude Oil Transportation, Storage, and Refining and for Fuel Combustion. The estimates of emissions from these sources indicate that they are very minor contributors to the total emission estimates.

Table 5-11 summarizes the emissions for the key countries estimated to have the largest emissions. Emissions by country were estimated using the region-specific emission factors with the individual country's set of activity levels. The top 10 countries shown in Table 5-11 are estimated to account for about 83% of the total global emissions.

The former Soviet Union, the world's largest producer of oil and natural gas, is estimated to have the highest emissions, ranging from 16 to 36 Tg in 1990, accounting for about 50% of the total global emissions. Emissions from the United States are estimated to be the second highest and account for about 8% of the global emissions. Emission estimates for each of the remaining eight countries are all less than 3 Tg.

5.5 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

Because relatively few detailed emission studies have been conducted, the emission estimates must be considered very uncertain. The overall magnitude of the emissions is driven by two key studies:

> Rabchuk et al. (1991) report that emissions from gas production and transportation in the former Soviet Union are high, about 2-4% of total gas production. Their estimates are based partly on previous measurement studies and partly on official data on gas losses. Recent visits to this region indicate that system construction, maintenance, and operations may be consistent with high emission rates (Craig, 1992). However, a better quantitative evaluation is needed to validate the current emission estimates.

TABLE 5-10

GLOBAL EMISSIONS BY REGION AND INDUSTRY SEGMENT (Tg of CH_4 in 1990)

Industry Segment	United States	Former Soviet Union and Eastern Europe	Western Europe	Other Oil-Exporting Countries [a]	Rest of the World	World Total
Oil and Gas Production	0.9 - 2.1	4.3 - 10.1	0.1 - 0.3	7.4 - 10.8	2.2 - 3.2	14.9 - 26.5
Crude Oil Transportation, Storage, and Refining	<0.05	<0.05	<0.05	<0.03	<0.1	<0.5
Natural Gas Processing, Transport, and Distribution	1.0 - 2.2	12.6 - 27.6	0.7 - 1.4	0.8 - 3.8	1.2 - 4.5	16.3 - 39.4
Fuel Combustion	0.5 - 1.0	0.5	0.4	0.2	0.5	1.8 - 2.1
Total	2.4 - 5.3	17.4 - 38.3	1.3 - 2.1	8.4 - 14.8	3.9 - 8.3	33.2 - 68.3

TABLE 5-11

GLOBAL EMISSIONS BY KEY COUNTRIES (Tg of CH_4 in 1990)

Country	Region	Emissions
Former Soviet Union	Former Soviet Union and Eastern Europe	16.3 - 36.0
United States	United States	2.4 - 5.3
Algeria	Other Oil-Exporting Countries	1.7 - 3.0
Canada	Rest of the World	1.2 - 2.8
Indonesia	Other Oil-Exporting Countries	1.3 - 2.4
Saudi Arabia	Other Oil-Exporting Countries	1.0 - 1.8
Mexico	Other Oil-Exporting Countries	1.0 - 1.7
Iran	Other Oil-Exporting Countries	0.9 - 1.5
Romania	Former Soviet Union and Eastern Europe	0.6 - 1.4
Venezuela	Other Oil-Exporting Countries	0.7 - 1.3
All Other Countries		5.9 - 11.1
Total Global Emissions		33.2 - 68.3

Barns and Edmonds (1990) report emissions from venting and flaring by region based on official reports and projections. The emission estimates for the OPEC countries are relatively high and account for most of the emissions from this category. The safety concerns associated with venting, and the value of re-injecting gas into oil reservoirs to maintain reservoir pressures, would tend to question the high emission estimates. Improved data are needed to resolve this question.

The adoption of emission factor estimates from U.S. EPA (1993) for various non-U.S. regions also adds uncertainty to the overall estimates. U.S. oil- and gas-production facilities and refineries are subject to emission control requirements. The use of U.S. emission factors, particularly for refining, may underestimate emissions in other regions. Nevertheless, if the emission factors for oil production and oil refining were increased by a factor of 10 for the entire world, the estimate of total global emissions would only increase by about 1-9 Tg for 1990.

Emissions from both stationary and mobile fuel combustion are also very uncertain because the implications of emission control technologies were not considered. The estimates, which are based on emission factors from uncontrolled sources, indicate that this source is unlikely to contribute significantly to total emissions.

5.6 TRENDS

Overall, future emissions could follow expected trends in oil and gas production and consumption. Pepper et al. (1992) indicate that under current policies, oil and gas production and consumption are expected to increase by about 0.7-1.7% per year globally over the next 10 to 20 years. If production practices remain unchanged during this period, emissions would be expected to increase at a similar rate.

Emission factors will most likely decline in the future, however, for several reasons. First, Barns and Edmonds (1990) report that venting and flaring is declining globally, and in particular has been declining in the OPEC countries, which are the major source of these emissions. By marketing or re-injecting associated gas, methane emissions from this source may decline substantially in the future. Additionally, steps are underway to modernize the oil and gas infrastructure in the former Soviet Union. By improving the efficiency of this system, emissions will decline substantially.

Given the potential for emissions to be reduced from two of the major sources, there is the possibility that emissions will decline over the next 10 to 20 years, even as oil and gas production and consumption increase. Given the paucity of data on current emissions, the trend in future emissions must also remain uncertain at this time.

5.7 CONCLUSIONS

The methane emitted from oil and gas systems in different parts of the world depends on the industry's size, supporting infrastructure, operating and maintenance practices, and level of technology. The method used to estimate the global emissions of 33-68 Tg in this study is consistent with the recommendations in OECD (1991) and is based on developing emission factors for each of the major segments of the oil and gas systems for distinct regions

of the world and using published statistics on the activity levels associated with each of these segments. Lack of sufficient measurement studies makes the emission factors very uncertain. In particular, improved data are needed for venting and flaring emission factors and emission rates for the former Soviet Union.

5.8 REFERENCES

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APPENDIX A

DERIVATION OF NON-U.S. EMISSION FACTORS FOR FUEL COMBUSTION

The non-U.S. emission factors for stationary and mobile combustion were developed using data from OECD (1991) and OECD-IEA (1991). OECD (1991) presents emission factors by type of combustion process, while OECD-IEA (1991) reports estimates of energy combustion by five sectors: electric utility, industry, residential/commercial, transport, and other (agriculture and military).

Emission factors for stationary combustion of oil and gas were developed for each region using an average of the OECD emission factors that corresponded to the electric utility, industry, residential/commercial, and other (agriculture and military sectors). This average was weighted in terms of the amount of fuel combusted by the different stationary sectors reported by OECD-IEA. Tables A-1 and A-2 list the data used to estimate the stationary-source-combustion emission factors. For each region, emissions from the individual stationary sectors are estimated as the product of the OECD emission factors, with the corresponding OECD-IEA estimates of fuel combustion. The average stationary emission factor for a region is estimated by dividing the total emissions from all stationary sectors by the total stationary fuel combustion within the region.

The OECD emission factors for transport were used as the emission factors for mobile sources: 560,000 kg of CH_4 per PJ of gas consumed and 31,400 kg of CH_4 per PJ of oil consumed in the transport sector.

These emission factors are based on the assumption that emission sources remain uncontrolled. The combustion emission factors should consider that emissions are influenced by the level of emission control technology employed. Detailed data on emission controls, however, were not available. This assumption leads to an overestimation of emissions in those countries that have implemented emission control requirements.

TABLE A-1

DERIVATION OF STATIONARY-SOURCE, GAS-COMBUSTION EMISSION FACTORS

Region	Utilities	Industry	Residential/ Commercial	Other (Agriculture & Military)	Total
Eastern Europe & Former Soviet Union					
Consumption (PJ)[a]	10,563	11,240	4,000	771	26,574
Emission Factor (kg/PJ)[b]	100	1,400	1,200	1,300	--
Emissions (1000 kg)	1,056	15,737	4,800	1,002	22,595
Average Emission Factor (kg/PJ)					**850**
Western Europe					
Consumption (PJ)[a]	1,581	3,816	4,337	583	10,317
Emission Factor (kg/PJ)[b]	100	1,400	1,200	1,300	--
Emissions (1000 kg)	158	5,342	5,204	758	11,462
Average Emission Factor (kg/PJ)					**1,100**
Other Oil-Exporting Countries					
Consumption (PJ)[a]	1,522	4,587	515	41	6,665
Emission Factor (kg/PJ)[b]	100	1,400	1,200	1,300	--
Emissions (1000 kg)	152	6,422	618	54	7,246
Average Emission Factor (kg/PJ)					**1,100**
Rest of the World					
Consumption (PJ)[a]	5,054	3,361	1,366	16	9,797
Emission Factor (kg/PJ)[b]	100	1,400	1,200	1,300	--
Emissions (1000 kg)	505	4,706	1,639	21	6,871
Average Emission Factor (kg/PJ)					**700**

a. OECD-IEA (1991) figures scaled down to UN (1992) consumption estimates.

b. Source: OECD, 1991.

TABLE A-2

DERIVATION OF STATIONARY-SOURCE, OIL-COMBUSTION EMISSION FACTORS

Region	Utilities	Industry	Residential/ Commercial	Other (Agriculture & Military)	Total
Eastern Europe & Former Soviet Union					
Consumption (PJ)[a]	3,493	4,248	618	3,280	11,639
Emission Factor (kg/PJ)[b]	700	2,900	1,600	31,400	--
Emissions (1000 kg)	2,445	12,321	989	102,989	118,744
Average Emission Factor (kg/PJ)					**10,200**
Western Europe					
Consumption (PJ)[a]	1,787	3,664	3,791	685	9,927
Emission Factor (kg/PJ)[b]	700	2,900	1,600	31,400	--
Emissions (1000 kg)	1,251	10,626	6,066	21,510	39,453
Average Emission Factor (kg/PJ)					**4,000**
Other Oil-Exporting Countries					
Consumption (PJ)[a]	1,559	2,681	1,284	631	6,155
Emission Factor (kg/PJ)[b]	700	2,900	1,600	31,400	--
Emissions (1000 kg)	1,092	7,775	2,055	19,825	30,747
Average Emission Factor (kg/PJ)					**5,000**
Rest of the World					
Consumption (PJ)[a]	4,708	9,132	3,863	2,132	19,835
Emission Factor (kg/PJ)[b]	700	2,900	1,600	31,400	--
Emissions (1000 kg)	3,296	26,483	6,180	66,947	102,906
Average Emission Factor (kg/PJ)					**5,200**

a. OECD-IEA (1991) figures scaled down to UN (1992) consumption estimates.

b. Source: OECD, 1991.

APPENDIX B

EMISSION ESTIMATES BY REGION

The emission estimates for each of the regions were estimated as the product of the emission factors and activity levels presented in Tables 5-4 to 5-9. The emission estimates for each individual region by emission type are shown in Tables B-1 to B-5. The global estimate is shown in Table B-6.

TABLE B-1

U.S EMISSIONS

Emission Type	Emissions (million kg)	Description
Oil and Gas Production		
Oil	6 - 89	Emissions from nongas-producing oil wells, including fugitive emissions and routine maintenance emissions.
Gas	805 - 1,477	Emissions from gas production, including fugitive emissions, dehydrator venting, bleeding from pneumatic devices, routine maintenance, and system upsets.
Oil & Gas	108 - 490	Venting and flaring emissions from oil and gas production and fugitive emissions from gas-producing oil wells.
Total	918 - 2,056	
Crude Oil Transportation, Storage, and Refining		
Transportation	---	Estimated collectively for the world; see text.
Refining	3 - 42	
Storage Tanks	0 - 8	
Total	3 - 49	
Natural Gas Processing, Transport, and Distribution	1,046 - 2,174	Emissions from gas processing, transmission, and distribution, including fugitive emissions, dehydrator venting, bleeding from pneumatic devices, routine maintenance, and system upsets.
Fuel Combustion		
Stationary Sources		
Oil	0.6 - 1.2	Emissions from all stationary oil combustion.
Gas		
Compressor Exhaust	321 - 582	Emissions from compressor engine exhaust.
Other Stationary Sources	16 - 65	Emissions from all other stationary sources.
Mobile Sources		
Oil	121 - 362	Emissions from all mobile oil combustion.
Gas	0	Emissions from all mobile oil combustion.
Total	459 - 5,290	
Total	2,426-5,290	

TABLE B-2

EMISSIONS FROM EASTERN EUROPE AND FORMER SOVIET UNION
(INCLUDES FORMER SOVIET UNION, ALBANIA, BULGARIA, FORMER CZECHOSLOVAKIA, HUNGARY, POLAND, ROMANIA, AND FORMER YUGOSLAVIA)

Emission Type	Emissions (million kg)	Description
Oil and Gas Production		
Oil	8 - 123	Emissions from nongas-producing oil wells, including fugitive emissions and routine maintenance emissions.
Gas	4,060 - 9,135	Emissions from leakages at gas wells, including routine equipment venting.
Oil & Gas	183 - 863	Emissions from venting and flaring.
Total	4,251 - 10,121	
Crude Oil Transportation, Storage, and Refining		
Transportation	---	Estimated collectively for the world; see text.
Refining	2 - 34	
Storage Tanks	0 - 6	
Total	3 - 40	
Natural Gas Processing, Transport, and Distribution		
Processing, Transportation, and Distribution	8,374 - 18,271	Emissions from leakages at underground storage facilities, compressor stations, linear part of main pipelines, and distribution networks.
Nonresidential Consumption	3,806 - 8374	Emissions from leakages at industrial plants and power stations.
Residential Consumption	439 - 966	Emissions from leakages at residential and commercial sectors.
Total	12,620 - 27,611	
Fuel Combustion		
Stationary Sources		
Oil	119	Emissions from all stationary oil combustion.
Gas	23	Emissions from all stationary gas combustion.
Mobile Sources		
Oil	213	Emissions from all mobile oil combustion, assuming no controls.
Gas	147	Emissions from all mobile gas combustion, assuming no controls.
Total	501	
Total	**17,374 - 38,274**	

TABLE B-3

EMISSIONS FROM WESTERN EUROPE

(INCLUDES AUSTRIA, BELGIUM, DENMARK, FAROE ISLANDS, FINLAND, FRANCE, GERMANY, GIBRALTAR, GREECE, ICELAND, IRELAND, ITALY, LUXEMBOURG, MALTA, NETHERLANDS, NORWAY, PORTUGAL, SPAIN, SWEDEN, SWITZERLAND, AND UNITED KINGDOM)

Emission Type	Emissions (million kg)	Description
Oil and Gas Production		
Oil	3 - 42	Emissions from nongas-producing oil wells, including fugitive emissions and routine maintenance emissions.
Gas	107 - 198	Emissions from gas production and treatment facilities.
Oil & Gas	10 - 29	Emissions from venting and flaring.
Total	119 - 268	
Crude Oil Transportation, Storage, and Refining		
Transportation	---	Estimated collectively for the world; see text.
Refining	2 - 34	
Storage Tanks	0 - 6	
Total	3 - 40	
Natural Gas Processing, Transport, and *Distribution*	740 - 1,374	Emissions from transportation, distribution, and storage of gas.
Fuel Combustion		
Stationary Sources		
Oil	39	Emissions from all stationary oil combustion.
Gas	11	Emissions from all stationary gas combustion.
Mobile Sources		
Oil	392	Emissions from all mobile oil combustion, assuming no controls.
Gas	6	Emissions from all mobile gas combustion, assuming no controls.
Total	449	
Total	1,310 - 2,132	

TABLE B-4

EMISSIONS FROM OTHER OIL EXPORTING COUNTRIES
(INCLUDES ALL OPEC COUNTRIES AND MEXICO)

Emission Type	Emissions (million kg)	Description
Oil and Gas Production		
Oil	18 - 289	Emissions from nongas-producing oil wells, including fugitive emissions and routine maintenance emissions.
Gas	424 - 887	Emissions from gas production and treatment facilities.
Oil & Gas	7,001 - 9,669	Emissions from venting and flaring.
Total	7,443 - 10,845	
Crude Oil Transportation, Storage, and Refining		
Transportation	---	Estimated collectively for the world; see text.
Refining	1 - 20	
Storage Tanks	0 - 4	
Total	1 - 24	
Natural Gas Processing, Transport, and Distribution		
Processing, Transportation, and Distribution	785 - 2,662	Emissions from processing, transportation, distribution, and storage of gas.
Nonresidential Consumption	0 - 1,066	Emissions from leakages at industrial plants and power stations.
Residential Consumption	0 - 49	Emissions from leakages at residential and commercial sectors.
Total	785 - 3,777	
Fuel Combustion		
Stationary Sources		
Oil	31	Emissions from all stationary oil combustion.
Gas	7	Emissions from all stationary gas combustion.
Mobile Sources		
Oil	132	Emissions from all mobile oil combustion, assuming no controls.
Gas	0	Emissions from all mobile gas combustion, assuming no controls.
Total	170	
Total	**8,399 - 14,815**	

TABLE B-5

EMISSIONS FROM THE REST OF THE WORLD
(INCLUDES ALL OTHER COUNTRIES OF ASIA, AFRICA, MIDDLE EAST, OCEANIA, AND LATIN AMERICA)

Emission Type	Emissions (million kg)	Description
Oil and Gas Production		
Oil	8 - 128	Emissions from nongas-producing oil wells, including fugitive emissions and routine maintenance emissions.
Gas	459 - 956	Emissions from gas production and treatment facilities.
Oil & Gas	1,745 - 2,094	Emissions from venting and flaring.
Total	2,211 - 3,181	
Crude Oil Transportation, Storage, and Refining		
Transportation	---	Estimated collectively for the world; see text.
Refining	3 - 53	
Storage Tanks	1 - 10	
Total	4 - 63	
Natural Gas Processing, Transport, and Distribution	1,154 - 2,879	Emissions from processing, transportation, distribution, and storage of gas.
Processing, Transportation, and Distribution	0 - 1,469	Emissions from leakages at industrial plants and power stations.
Nonresidential Consumption	0 - 121	Emissions from leakages at residential and commercial sectors.
Residential Consumption	1,154 - 4,469	
Total		
Fuel Combustion		
Stationary Sources		
Oil	103	Emissions from all stationary oil combustion.
Gas	7	Emissions from all stationary gas combustion.
Mobile Sources		
Oil	435	Emissions from all mobile oil combustion, assuming no controls.
Gas	4	Emissions from all mobile gas combustion, assuming no controls.
Total	548	
Total	**3,918 - 8,262**	

TABLE B-6

WORLD EMISSIONS

Emission Type	Emissions (million kg)	Description
Oil and Gas Production		
Oil	42 - 671	Emissions from nongas-producing oil wells, including fugitive emissions and routine maintenance emissions.
Gas	5,854 - 12,657	Emissions from gas production and treatment facilities.
Oil & Gas	9,045 - 13,144	Emissions from venting and flaring.
Total	14,941 - 26,472	
Crude Oil Transportation, Storage, and Refining		
Transportation	56 - 99	
Refining	11 - 183	
Storage Tanks	2 - 33	
Total	70 - 316	
Natural Gas Processing, Transport, and Distribution	16,345 - 39,405	Emissions from processing, transportation, distribution, and storage of gas.
Fuel Combustion		
Stationary Sources		
Oil	292 - 293	Emissions from all stationary oil combustion.
Gas	65 - 114	Emissions from all stationary gas combustion.
Mobile Sources		
Oil	1,293 - 1,534	Emissions from all mobile oil combustion, assuming no controls (except for the United States).
Gas	157	Emissions from all mobile gas combustion, assuming no controls (except for the United States).
Total	1,806 - 2,097	
Total	33,162 - 68,290	

CHAPTER 6

METHANE EMISSIONS FROM THE COAL FUEL CYCLE

6.1 SUMMARY

In 1990, the coal fuel cycle emitted an estimated 24-40 teragrams (Tg)[1] of methane to the atmosphere globally, which represented approximately 10% of total anthropogenic methane emissions.[2] An additional 1.3 Tg of methane, or approximately 3-5% of total emissions, was recovered by coal mining operations and used as fuel instead of being vented to the atmosphere.

Underground coal mining was the primary source of these emissions, accounting for 70-85% of total emissions (20-28 Tg). Surface mines and post-mining coal transportation and handling operations were estimated to contribute 10-20% (3-8 Tg). Coal combustion was estimated to contribute the remaining 5-10% of emissions (1-4 Tg). Abandoned mines and coal waste piles are also believed to release small quantities of methane, although estimates of these sources are not possible due to the lack of information on their numbers and emission levels.

Almost three-quarters of global methane emissions from the coal fuel cycle was emitted by three countries: the People's Republic of China, the former Soviet Union, and the United States. These countries are also the world's largest coal-producing and -consuming countries. Lesser amounts of methane were emitted by Australia, the former Czechoslovakia, Germany, India, Poland, South Africa, and the United Kingdom. Together, the world's 10 largest coal producers were responsible for 90% of global emissions associated with the coal cycle.

A variety of methods can be used to estimate methane emissions from the coal fuel cycle, depending upon the availability of data. For mining, the simplest (but most uncertain) approach is to estimate emissions by multiplying global average methane emission factors for underground and surface mining and post-mining activities by the relevant coal production levels. For coal combustion, emissions can be estimated using emission factors for various coal end uses and multiplying by coal consumption. The ranges resulting from these methods are large, due to uncertainties about the appropriate emission factors. In those countries where more specific data are available, however, these emission factors have been refined to prepare the U.S. EPA's "Best Estimates" of emissions.

For higher certainty, emissions can be estimated for specific coal basins or coal-consumption sectors using more refined emission factors. If information is available on coal and mining characteristics, it is also possible to develop models to estimate mining emissions by relating various coal characteristics to methane emissions. Such models have been developed based on analysis of coal data from the United States, but cannot be applied with

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[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

[2] Coal is mined for use as an energy source and for metallurgical purposes. Although this chapter is entitled "Methane Emissions from the Coal Fuel Cycle" (to indicate that it encompasses emissions associated with mining, as well as transportation and combustion), emissions due to mining of coal for metallurgical purposes are also included.

any accuracy to other countries. Where such data are available, however, such models could be developed for other countries.

Ultimately, the most detailed and reliable method available for estimating mining emissions is to collect and analyze actual emission data from coal mines. These data are currently only available for underground coal mines, where measurements have been made for safety reasons. In some countries, however, these data may be unavailable or incomplete, and the simpler (but more uncertain) estimation methods will be the most appropriate. Measurement programs are underway in the United States and Australia (and potentially other countries) to quantify emissions from surface mines, and it may be possible to develop additional data of this type in the future for the preparation of more detailed emission estimates.

Significant uncertainties are associated with some of the simpler estimation methodologies because of the absence of measured emission data for many parts of the coal fuel cycle and the lack of internationally available data on coal characteristics and emission levels for key countries. In general, underground mining emissions are the best understood and have the greatest data availability because of the necessity to monitor methane levels in mines for safety reasons. In many countries, however, data on methane emissions from underground mine ventilation and degasification systems may not be collected or published. Methane emissions from surface mines and post-mining activities (i.e., coal transportation, storage, and handling) are currently highly uncertain because of the lack of emission measurements. Detailed emission factors for coal combustion have been developed for the major coal end uses, particularly for developed countries. The applicability of these factors to other countries is uncertain, particularly in the developing world, where combustion efficiencies are much lower. No emission estimates have been prepared for abandoned mines or coal waste piles due to the lack of necessary information. Abandoned mines and coal waste piles, however, are not considered to be a significant source of emissions.

In the future, methane emissions associated with the coal fuel cycle are expected to increase, due to higher levels of coal production and consumption and the use of coal from more gassy mines in many countries. The rate of increase in methane emissions from the coal cycle is uncertain due to questions about future coal-production and -consumption levels and difficulty predicting future coal characteristics, including mine gassiness. In 1990, world coal production was over 4.7 billion tonnes; future coal production could be significantly higher, perhaps reaching 5.3-5.9 billion tonnes in 2000 and 5.9-6.8 billion tonnes in 2010 (U.S. DOE/EIA, 1992b). In addition, the proportion of underground mining could increase as surface-mined coal seams are depleted. At forecasted production levels, emissions could range from 27 to 50 Tg in 2000 and 30 to 58 Tg in 2010, assuming methane emission factors remain constant. If mine gassiness increases as a result of the mining of deeper, gassier coal seams, or if the proportion of underground mining increases relative to surface mining, however, emissions could be even higher than these projections.

Increased methane emissions are particularly likely in countries like China, where coal production is forecast to grow by more than 2% annually between 1988 and 2000, and growth is expected to continue beyond 2000 as well. China may also need to mine deeper and gassier coal seams to maintain coal production, and may thus experience an increase in emissions per tonne of coal mined.

In the future, the use of mine degasification systems may increase to cope with increasing mine gassiness. To the extent that the additional recovered methane is used, the

growth in emissions would be moderated somewhat. In many countries, some of the methane released by underground mines is currently collected by mine degasification systems instead of being diluted in mine ventilation air. This methane typically has a concentration of at least 35% methane in air and can be used as fuel for many purposes. Some countries do not use any of this fuel, while others use most of the methane they recover. In 1990, for example, a reported 1.3 Tg of coalbed methane was used globally from the countries of Australia, China, the former Czechoslovakia, Germany, Poland, the former Soviet Union, the United Kingdom, and the United States. Some methane is also recovered and used in Japan, and perhaps in other countries, but the amounts are unknown. The amount of methane likely to be recovered by mine degasification systems and the extent to which methane utilization could increase in the future are uncertain. There is, however, the potential for significant reductions in emissions from coal mines.

6.2 BACKGROUND

This section briefly describes the processes of methane (CH_4) generation and emission from coal, the key components of the coal fuel cycle, and the results of some previous studies to quantify CH_4 emissions from this source.

6.2.1 Processes of Methane Generation and Emission in Coal

Methane, which is the principal constituent of natural gas, is contained in coal seams and is released to the atmosphere by coal mining and other parts of the coal fuel cycle. Methane is formed during the process of coalification, where organic matter is converted into coal over millions of years. Some CH_4 remains trapped in coal and surrounding strata until a reduction in pressure (caused by mining or natural faulting) enables it to escape into mine workings or to the atmosphere.

The amount of CH_4 contained in a coal seam is heavily dependent on the geological characteristics and depositional history of the coalbed. Such factors as coal rank, depth, and permeability affect the amount and distribution of CH_4 in the coalbed and surrounding strata, which in turn determine the quantity and rate of CH_4 release during mining and at other parts of the coal cycle.[3] In general, higher-ranked coals and coals buried at greater depths tend to contain more CH_4 than shallow or low-ranked coals, up to a point of saturation. The unique features of each coal basin (such as its geological history) can make generalizations difficult, however.

The amount of CH_4 emitted during coal mining is primarily a function of coal characteristics (i.e., rank, gas content, and depth) and mining method. One of the most important features of CH_4 emissions from coal mines is that emissions tend to exceed the amount of CH_4 that would be predicted based solely on the gas content of the mined coal. This is because CH_4 can be emitted not only from the mined coal, but also from coal left behind in the mine, by surrounding coal strata, and, in some cases, by other surrounding gas-bearing strata. Based on research by the U.S. Bureau of Mines, it appears that the emission

[3] Coal rank is a measure of the degree of coalification; as coalification proceeds, coals are transformed from lignite, through the ranks of subbituminous to bituminous and, under certain conditions, to anthracite and graphite. Depth is related to the depth of burial of the coal. Permeability represents the ability of methane to flow through the coal matrix.

factors could be six to nine times the CH_4 content of the underground-mined coal seams (Kissell et al., 1973). Numerous other studies have observed similar relationships in coals mined throughout the world (BCTSRE, 1992; Pilcher et al., 1991; and Bibler et al., 1992). Similarly, preliminary research on surface mines indicates that emissions could exceed the CH_4 content of the mined coal by as much as five times (Kirchgessner et al., 1993).

6.2.2 Key Emission Processes of the Coal Fuel Cycle

Underground mining is the principal source of CH_4 emissions associated with the coal fuel cycle. In addition to underground mining, CH_4 is emitted by surface mines, post-mining activities, and coal combustion. In general, underground mines release more CH_4 than surface mines because the coals tend to be of higher rank and are more deeply buried, which means that more of the CH_4 generated during coalification remains trapped in the coal seam and surrounding strata (Kim, 1977). Post-mining activities include emissions during coal transportation, storage, and handling, covering all activities from the time the coal leaves the mine until combustion. Emissions from coal combustion occur as a result of incomplete or inefficient coal combustion at the point of end use. A variety of other potential CH_4 emission sources are associated with the coal cycle, including abandoned mines and coal waste piles; however, little is known about emissions from these sources.

Underground Mining

In underground mines, CH_4 can be liberated from two sources: (1) ventilation shafts and (2) degasification systems. Ventilation is used in all underground mines to maintain safe mining conditions because CH_4 is explosive in concentrations of 5-15% in air. In most countries, ventilation air must contain CH_4 concentrations of less than 1% in air. Although its concentration is very low, the CH_4 in this air constitutes most of global underground-mining emissions because of the enormous volumes used to ventilate mines.

Degasification systems are typically employed only at those mines where additional CH_4 recovery is needed to supplement ventilation for safety reasons. These systems can be drilled in advance of mining or into fractured gob areas, which are created after mining occurs and the roof collapses. Degasification systems remove CH_4 that would otherwise have to be diluted in the ventilation air, and they produce CH_4 in concentrations that can be used for fuel. Certain degasification systems, for example, can produce CH_4 in concentrations of more than 95%, which can be injected directly into conventional natural gas pipelines. At gassy coal mines, degasification systems can account for a significant fraction of total CH_4 emissions (U.S. EPA, 1993; Pilcher et al., 1991; Bibler et al., 1992; and Marshall et al., 1993).

Surface Mining

In surface mines, exposed coal faces and surfaces, as well as areas of coal rubble created by blasting operations, are believed to be the major sources of CH_4. As in underground mines, however, emissions may come from underlying strata, which may be fractured and distressed due to removal of the overburden, or in some cases from gas-bearing strata in the overburden, which is fragmented during the mining process. Because surface-mined coals are less deeply buried and are often of lower rank, they do not tend to contain as much CH_4 as underground-mined coals. Thus, emissions per tonne of coal mined are generally much lower for surface mines. Due to the large amount of coal produced from surface mines, however, emissions from this source are significant.

Post-Mining Activities

Emissions from post-mining coal storage, transportation, and handling operations result from the natural desorption of CH_4 from the coal after it has left the mine and before combustion. The amount of CH_4 emitted depends upon specific coal characteristics, such as CH_4 content, permeability, and desorption rates. It is believed that underground-mined coals emit more CH_4 during post-mining activities because they tend to have higher gas contents than surface-mined coals. In addition, these coals tend to have lower permeability, which means that CH_4 is emitted from the coal at a slower rate so that a larger proportion remains in the coal and can subsequently be emitted after the coal has left the mine.

Coal Combustion

Some CH_4 is most likely released during coal utilization as a result of incomplete or inefficient combustion. The amount of CH_4 emitted will depend on the combustion unit. In general, well-maintained utility boilers are believed to release small amounts of CH_4, whereas poorly maintained or aging industrial or residential boilers and stoves are believed to have higher emission rates.

Coal Mine Waste Piles

Methane may be emitted from the piles of waste rock and coal that are produced during mining. There are currently no emission measurements for this source. Emissions are believed to be low, however, because much of the CH_4 would most likely be emitted during mining, and the waste rock would have a low gas content compared with the coal being mined.

Abandoned Mines

Emissions from abandoned mines may come from unsealed shafts and from vents installed to prevent the buildup of CH_4 in mines. Except in limited circumstances, CH_4 emissions from abandoned mines are believed to be small. There is very little information on the number of abandoned mines, however, and comprehensive data are currently unavailable on emissions from these mines.

6.2.3 Previous Methane Emission Studies

As shown in Table 6-1, numerous estimates of CH_4 emissions from coal mining have been prepared. Koyama (1964) is credited with the first coal mining emissions study, in which he estimated that 20 Tg of CH_4 were released annually from coal mining. In preparing this estimate, Koyama multiplied an assumed emission factor of 17.7 m^3 per tonne of coal mined by world hard coal production. His estimate used 1960 coal production data; since

TABLE 6-1

EMISSION ESTIMATES FROM SELECTED STUDIES

Study Author	Emission Estimate (Tg)	Year of Estimate	Methodological Issues
Koyama (1963)	20	1960	Hard coal only; no emission estimates for surface mining or post-mining activities. 1960 coal production data.
Hitchcock & Wechsler (1972)	8 - 28	1967	Post-mining not included. Source of emission factors, particularly low end, unspecified. 1967 coal production data.
Seiler (1984)	30	1975	Based on Koyama, with 1975 coal production data.
Crutzen (1987)	34	n/a	Source of emission factors unclear. Hard coal only; no emission estimates for surface mining or post-mining activities.
Okken & Kram (1989)	15 - 45	n/a	Source of emission factors unclear. Hard coal only; no emission estimates for surface mining or post-mining activities.
Zimmermeyer (1991)	24	n/a	Only underground mining considered; no emissions estimates for surface mines or post-mining activities.
Selzer & Zittel (1990)	23	n/a	Adjusted Zimmermeyer by: (1) including surface mines; (2) assuming that 15% of underground mining emissions (3.6 Tg) not emitted to the atmosphere due to CH_4 utilization.
Barns & Edmonds for U.S. DOE (1990)	25	1986	Assumed mathematical relationship between coal rank and depth and that in-situ CH_4 content was equal to the mining emission factor.
Boyer et al. for U.S. EPA (1990)	33 - 64	1988	Statistical approach related CH_4 emissions to in-situ CH_4 content. Correlation based on U.S. data only. Large uncertainty in application of results for global estimates.
Kirchgessner (1993)	47	1988	Statistical approach related coal characteristics to in-situ gas content and in-situ gas content to emissions. Correlation based on U.S. data only. No uncertainty analysis conducted.
CIAB (1992)	24	1990	Country-specific data used where available. Emission factor assumptions tend to be conservative, compared to present study. No uncertainty analysis.
Present study	24 - 40	1990	Country-specific data used where available to prepare best estimates. Global average emission factors used for rest of countries. Only study to include emission estimate for coal combustion.

1960, coal production has increased by more than 75%. In addition, it appears that his study considered only emissions from hard coal production.[4]

Several studies followed Koyama's, and many used similar methodologies with more recent coal production data (Hitchcock and Wechsler, 1972; Seiler, 1984; Crutzen, 1987; Okken and Kram, 1989; Zimmermeyer, 1991; Selzer and Zittel, 1990; and Barns and Edmonds, 1990). These studies resulted in emission estimates ranging from 8 Tg to 45 Tg, depending on the emission factors assumed, the year for which coal production data were obtained, and whether the estimate was prepared for hard coal alone or hard and brown coal. For the most part, the studies estimated emissions from hard coal only and did not include surface mining, post-mining activities, or coal combustion.

Unlike most previous studies, the Boyer et al. (1990) study estimated emissions from underground and surface mines and post-mining activities and provided country-specific emission estimates. The estimates were developed using available data on CH_4 contents and emissions from 59 U.S. underground mines to develop a regression equation. First, CH_4 emissions from underground mining, surface mining, and post-mining activities for the United States were estimated using the available data, which were obtained from a relatively small number of mines. Methane emission factors for underground mining and surface mining were then developed by dividing estimated CH_4 emissions by U.S. coal production. The resulting emission factors -- 27.1 m^3/tonne of coal mined in underground mines and 2.5 m^3/tonne for surface mines -- were multiplied by coal production for other countries to estimate their emissions.

Using this methodology, Boyer et al. estimated global CH_4 emissions to be 47 Tg in 1987. The uncertainty range on this estimate was 33-64 Tg, reflecting the uncertainty of the regression with which the U.S. emissions were estimated and the uncertainty associated with applying U.S. factors internationally.[5]

In 1991, the emission factors developed by Boyer et al. were adopted by the Organization of Economic Cooperation and Development (OECD) for use as a simple estimation method for global CH_4 emissions from coal mining (OECD, 1991). Since publication of the Boyer et al. study, however, a number of country-specific studies have been published, and a great deal of additional data have become available. As a result, the OECD is revising its methodology, which will be published in 1993. The latest recommendations by the OECD regarding methods of estimating CH_4 emissions from coal mining are presented in the next section.

The Boyer et al. approach has also been refined as part of a project undertaken by U.S. EPA's Office of Research and Development (Kirchgessner et al., 1993). Like Boyer et al., Kirchgessner et al. used regression analysis to develop statistical relationships between

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[4] For general emission studies, coal is sometimes classified as one of two types: hard coal or brown coal. Hard coal includes anthracite, bituminous, and some categories of subbituminous coal. It is frequently assumed that hard coal is produced in underground mines, although there are exceptions. Brown coal is generally assumed to be produced in surface mines and includes the lower-ranked subbituminous coals and lignite.

[5] The regression equation developed in Boyer et al. (1990) had an r^2 value of 0.35. The uncertainty associated with applying this equation to estimate U.S. emissions was thus determined to be $\pm$ 23%. An additional factor of $\pm$ 10% was used to reflect the uncertainty associated with applying the U.S. data to estimate global emissions. In the absence of detailed emission data from other countries, this factor was chosen arbitrarily.

selected coal characteristics and CH_4 content and emissions. The Kirchgessner et al. equations, while also developed using U.S. data, are more detailed than Boyer et al.'s and require data on depth, moisture content, heating value, and fuel ratio (fixed carbon to volatile matter). The equations were developed based on U.S. data. Kirchgessner et al. then collected data as available for various countries and used it in the equations to develop a global emission estimate of 46 Tg in 1989. No uncertainty analysis has been conducted, however, and the validity of the data used in estimating emissions for the other countries has not been assessed.

A final recent CH_4 emissions study has been prepared by the Coal Industry Advisory Board (CIAB, 1992), for the Global Climate Committee. This study presents a CH_4 emission estimate of 24 Tg in 1990, and includes estimates from underground and surface mines and post-mining activities. It does not include an estimate of CH_4 emissions from coal combustion. Country-specific emission data were used where available for underground mining, and global emission factors were developed to estimate emissions from surface mines and post-mining activities. In general, the emission factors used in this study, as well as some of the country-specific data used, are considered conservative. Thus, the CIAB estimate is consistent with the lower emissions bound developed in the present study.

6.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

Methane emission estimates should be developed for the four principal sources of CH_4 emissions: underground mines, surface mines, post-mining activities, and coal combustion, as shown in Figure 6-1. Because different types and levels of data are likely to be available in different countries, this study recommends use of a "tiered" approach for estimating emissions.[6] The first tier requires basic and readily available data and can be used to estimate emissions for all coal-producing countries within a relatively large uncertainty band. Higher tiers require additional data and can only be applied if the data are available from the countries in question. The selection among the tiers will depend upon the quality of the data available in the countries for which the estimates are being prepared.

In this study, emission estimates are prepared for most of the world's coal-producing countries using the most basic, "first-tier," approach. In addition, more detailed, higher-tier, estimates have been prepared wherever possible. The coal production and consumption data used in preparing these estimates are shown in Table 6-2.

6.3.1 Underground Mining

Methane emissions from underground mines should include estimated emissions from ventilation systems and degasification systems (if any of a country's mines uses degasification systems to supplement ventilation). This section presents methods of estimating emissions from both of these sources.

Three tiers are available for estimating emissions from underground mining, with the choice among them depending upon the availability of data and the degree to which coal mining is considered a significant source of emissions by particular countries. The first-tier

[6] This approach will also be adopted by the OECD in its revised estimation methodology, due to be published in early 1994.

FIGURE 6-1

FLOW CHART FOR ESTIMATING METHANE EMISSIONS FROM THE COAL CYCLE

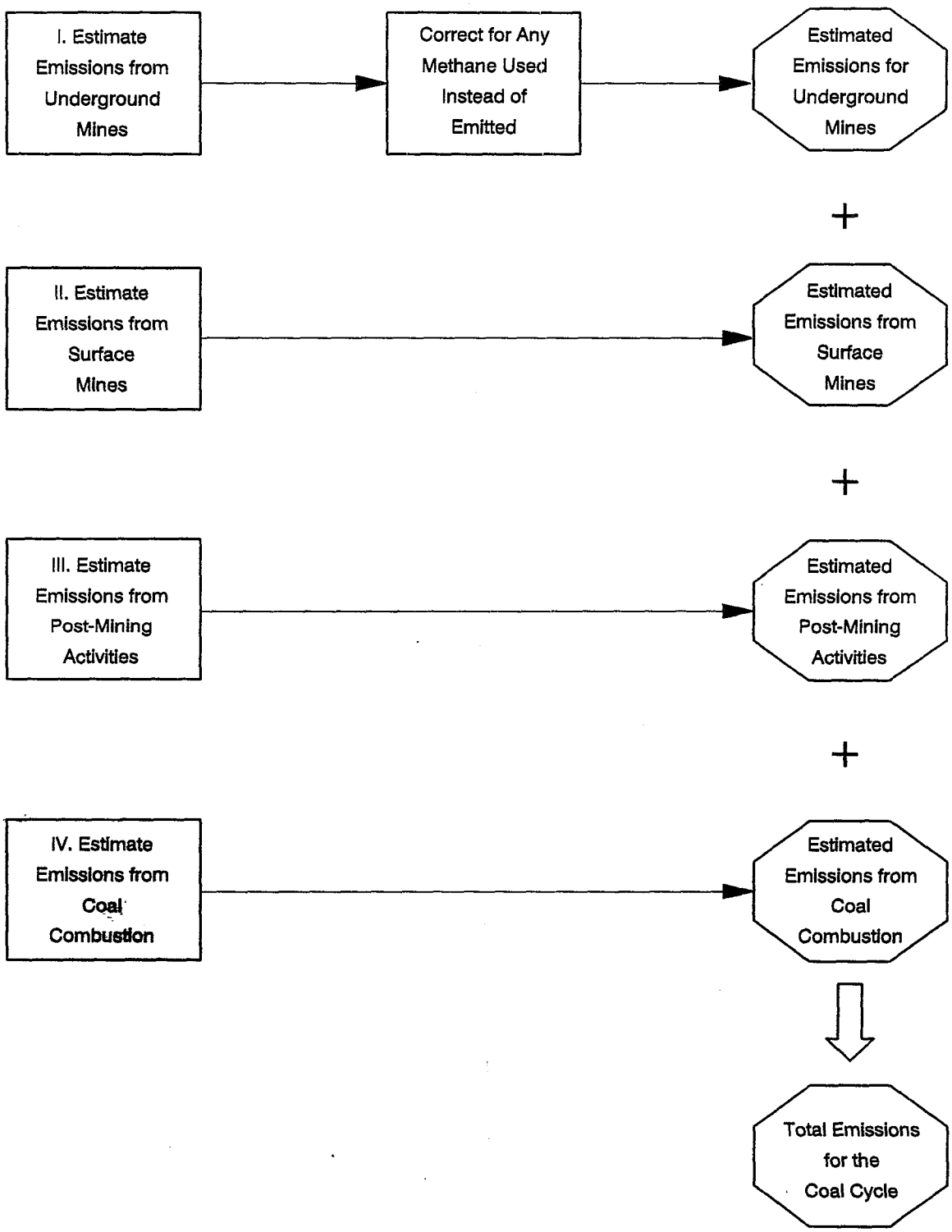

TABLE 6-2

1990 COAL PRODUCTION AND CONSUMPTION DATA (million tonnes)

Country	Coal Production			Coal Consumption			
	Underground	Surface	Total	Utility	Industry	Residential/ Commercial	Total
China	1,023.6	42.7	1,066.3	272.0	575.6	167.0	1,014.6
United States	385.1	548.4	933.6	700.1	104.5	6.1	810.7
Former Soviet Union	392.8	308.6	701.4	364.4	325.1	0	671.5
Germany	76.6	358.9	435.5	146.7	44.7	0.4	191.8
India	109.4	128.6	238.0	122.3	95.8	1.2	219.3
Poland	153.5	58.1	211.6	114.5	72.8	0	187.3
Australia	51.8	153.9	205.7	81.3	3.5	0.2	84.9
South Africa	111.7	62.8	174.5	76.2	56.6	1.8	134.7
Former Czechoslovakia	22.0	84.7	106.7	71.6	33.8	1.4	106.8
United Kingdom	75.3	14.0	89.3	84.4	17.9	5.7	108.0
Canada	3.9	64.4	68.3	42.2	6.8	0.1	49.1
Greece	0	51.9	51.9	50.5	2.3	0	52.9
Turkey	7.5	39.1	46.6	30.4	11.4	10.4	52.2
Spain	15.2	20.6	35.8	39.5	7.0	0.6	47.1
Colombia	0	20.5	20.5	1.4	3.8	0.3	5.5
France	11.4	1.4	12.8	13.2	15.8	1.6	30.7
New Zealand	0.6	2.0	2.6	0.2	1.8	0.2	2.2
Austria	0.6	1.9	2.4	3.5	2.9	0.3	6.7
Belgium/Luxembourg	1.0	0	1.0	4.5	11.7	0.7	16.8
Italy	0	1.0	1.0	11.8	10.5	0.1	22.5
Norway	0.3	0	0.3	0	0.8	0	0.8
Ireland	0	0	0	2.0	0.5	0.8	3.3
Subtotal	*2,442.5*	*1963.5*	*4,406.0*	*2,232.7*	*1,405.6*	*198.9*	*3,837.2*
World Total			4,740.0	2,467.5	1,666.6	222.0	4,356.1

Sources: IEA, 1990, 1992a, and 1992b.

approach --called the "Global-Average Method" -- uses a predetermined range of emission factors (based on experience in a number of countries) to estimate emissions. The most complex, third-tier, approach -- called the "Mine-Specific Method" -- develops emission estimates using detailed emission data for most, if not all, of a country's underground coal mines. In between these two methods is an intermediate, second-tier, approach -- called the "Basin- or Country-Average Method" -- in which more limited information, including either measurements from a subset of mines or statistical or other types of models, can be used to refine the range of possible emission factors presented in the Global Average Method. Each of these approaches is described in more detail below.

Tier 1: Global-Average Method

The simplest method for estimating CH_4 emissions is to multiply underground coal production by a factor or range of factors representing global-average emissions from underground mining, including emissions from both ventilation and degasification systems. This method is useful for those countries where total coal production from underground mines is available but more detailed data on mining emissions, geological conditions, coal characteristics, and the like are not. The emission estimates generated using this method should be presented as a range to reflect the high degree of uncertainty associated with it. The Tier 1 method is presented as equation 6.1.

In the draft IPCC/OECD (OECD, 1991) methodology, a single emission factor of 27.1 m^3 of CH_4 per tonne of coal mined was recommended for all underground mining, based on the Boyer et al. (1990) study. This factor included emissions from both mining and post-mining activities associated with underground coal production.[7] Based on more recent studies and additional country-specific emission data, the OECD is revising this emission factor to reflect some additional issues. First, use of a range of emission factors is suggested to reflect the large variation possible in CH_4 emissions from underground mines in different coal basins and countries. Second, this emission factor should represent only those emissions associated with underground mining (ventilation and degasification systems); post-mining emissions should be handled separately.

In this study, revised global average emission factors of 10-25 m^3/tonne of coal mined are recommended (not including post-mining activities). This range reflects the findings of various country studies, as shown in Table 6-3, and also has been adopted by the OECD for its revised emission methodology (OECD, 1993). As more detailed emission data are published by various countries, the factors can be further revised, if necessary.

[7] Due to a mistake in the draft OECD report, this factor appeared to exclude emissions from mine degasification systems and post-mining activities. However, this emission factor did include these two additional emission sources.

EQUATION 6.1
TIER 1: GLOBAL AVERAGE METHOD -- UNDERGROUND MINES

Low CH_4 Emissions (tonnes) = Low CH_4 Emission Factor (m^3 CH_4/tonne of coal mined) x Underground Coal Production (tonnes) x Conversion Factor

High CH_4 Emissions (tonnes) = High CH_4 Emission Factor (m^3 CH_4/tonne of coal mined) x Underground Coal Production (tonnes) x Conversion Factor

Where:

- Low CH_4 Emission Factor = 10 m^3/tonne.
- High CH_4 Emission Factor = 25 m^3/tonne.
- Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20°C and 1 atm, which is: 0.671 tonnes/$10^3 m^3$.

Tier 2: Country- or Basin-Average Method

The suggested Tier 2 approach -- called the "Country- or Basin-Average Method" -- can be used to refine the range of emission factors used for underground mining by incorporating additional country- or basin-specific information. Basically, this method can be used where limited amounts of additional data are available to develop more appropriate, and most likely narrower, ranges of emission factors for underground mining. For many countries, it is expected that this range will fall within the global average emission factor range of 10-25 m^3/tonne. The range of possible emission factors is not constrained under the Tier 2 approach, however, and in some countries the underground mining emission factors may lie outside the global average emission factor range.

TABLE 6-3

ESTIMATED UNDERGROUND MINING EMISSION FACTORS FOR SELECTED COUNTRIES

Country	Emission Factor (m^3/tonne)	Source
Former Soviet Union	17.8 - 21.7	Marshall et al., 1993; and Airuni, 1992
United States	11.0 - 15.3	U.S. EPA, 1993
Germany (East and West)	22.4	Zimmermeyer, 1991
United Kingdom	15.3	BCTSRE, 1992
Poland	5.9 - 10.5	Pilcher et al., 1991
Former Czechoslovakia	23.9	Bibler et al. 1992
Australia	15.6 - 22.3	Lama, 1991; Saghafi and Williams, 1992
Canada	23.1	Jaques, 1992

The best means of developing country- or basin-specific emission factors is to examine measurement data from a limited number of underground coal mines to approximate what a reasonable narrower range of emission factors might be.[8] These measurement data can be used to develop simple emission models based on physical principles or to select a narrower range based on judgment. Among the key types of data that should be considered in model development are:

- the gas content of the coal, which contributes to the total amount of CH_4 available for emission during mining;
- other potentially relevant coal characteristic data, such as depth, moisture, heating value, and fuel ratio;
- the frequency of coal within the strata above and below the mined coal seam, which also contributes to the total amount of CH_4 available for emission during mining; and
- the method of mining, which determines the amount of ground that is disturbed by mining the coal and the extent to which the CH_4 contained in the mined coal seam and in the coal seams in the surrounding strata is liberated during mining.

This approach was used by Boyer et al. (1990) and, more recently, by Kirchgessner et al. (1993) to estimate CH_4 emissions from coal mining. As mentioned previously, Boyer et al. used data from 59 U.S. mines to relate the gas content of the mined coal to CH_4 emissions from mining. Kirchgessner et al.'s approach used more detailed coal characteristics data to estimate emissions.

[8] If measurement data are available for most or all of a country's underground coal mines, the Tier 3 approach -- called the "Mine-Specific Method" -- should be used to estimate emissions.

Models based on coal characteristics and other data will be most accurate if applied on the coal-basin level. Because coal characteristics, mining methods, and CH_4 emissions can vary significantly within coal basins and particularly within different regions of a country, developing general national models will significantly increase the uncertainty of the emission estimates.

Tier 3: Mine-Specific Method

Because CH_4 is a serious safety hazard in underground mines, many countries have collected data on CH_4 emissions from mine-ventilation systems, and some also collect data on CH_4 emissions from mine-degasification systems. Where such data are available, the Tier 3 approach -- called the "Mine-Specific Method" -- should provide the most accurate estimate of CH_4 emissions from underground mines. Since these data have been collected for safety, not environmental, reasons, however, it is necessary to ensure that they account for total emissions from coal mines. The key issues that should be considered when using mine safety data, as well as the recommendations for resolving them, are summarized as follows:

- *Where and how are ventilation system emissions monitored?*

  When used to develop overall CH_4 emission estimates, ventilation air monitors should be placed at the point where ventilation air exhausts to the atmosphere. If ventilation emissions are not monitored at the point of exhaust, emission data should be corrected based on estimated additional CH_4 emissions between the point of measurement and the point of exhaust to the atmosphere.

  Are ventilation system emissions monitored and/or reported for all mines?

  In some countries, emissions are only reported for "gassy mines." Estimates should be developed for nongassy mines as well. Estimates can be prepared using information about the definitions of gassy and nongassy mines and data on the total number of mines and the coal production at these mines.

- *Are CH_4 emissions from degasification systems reported?*

  Some countries collect and report CH_4 emissions from ventilation and degasification systems, while others only report ventilation system emissions. Both emission sources must be included in emission estimates. If degasification system emissions are not included in reported data, those mines with degasification systems should be identified, and estimates should be prepared on emissions from their degasification systems. Emission estimates can be based on knowledge about the efficiency of the degasification system in use at the mine or the average efficiency of degasification in the country.

6.3.2 Treatment of Methane Utilization

All of the methods described above, with the possible exception of the Mine-Specific Method, assume that all of the CH_4 liberated by mining will be emitted to the atmosphere. In many countries, however, some of the CH_4 recovered by mine degasification systems is used as fuel instead of being emitted. Wherever possible, the emission estimates should be corrected for the amount of CH_4 that is used as fuel by subtracting this amount from total estimated emissions.

In several countries, data on the disposition of CH_4 recovered by degasification systems (i.e., whether it is used or emitted to the atmosphere) have been obtained from the coal industry or energy ministries. Poland, for example, reports that its mine degasification systems recovered 286 million m^3 of CH_4 in 1989, of which 201 million m^3 was used and the remaining 85 million m^3 was emitted to the atmosphere (Polish Central Mining Institute, 1990). Regardless of the method used to develop the emission estimates, the Polish emission estimate should be adjusted to reflect the use of CH_4 by subtracting 201 m^3 from total emissions.

6.3.3 Surface Mining

Two possible approaches for estimating CH_4 emissions from surface mining are recommended, depending on data availability. These approaches are similar to those developed for underground mining, but the results will be much more uncertain due to the absence of emission data. If emission measurements are developed in the future, it should be possible to refine these estimation methodologies.

Tier 1: Global-Average Method

As in the methodology for underground mining, the simplest (Tier 1) approach for surface mines -- called the "Global Average Method" -- is to multiply surface coal production by a range of emission factors representing global average emissions, as shown in equation 6.2.

In the draft IPCC/OECD methodology, an average emission factor of 2.5 m^3/tonne was recommended (OECD, 1991), based on the results of Boyer et al. (1990).[9] Based on more recent analyses and additional studies, a revised emission factor range of 0.3 to 2.0 m^3/tonne has been developed. This revised range has been adopted by the OECD (1993). The low end of the range is consistent with the average in-situ CH_4 content for surface-mined coals reported by various recent studies (Saghafi and Williams, 1992; CIAB, 1992; and Jaques, 1992), and it assumes that no CH_4 is emitted from the strata surrounding the coal. The assumption that surrounding strata do not contribute to emissions from surface mines has been made by some recent studies, including the BCTSRE (1992) study and the CIAB (1992) study. The high end of the range is based on an average in-situ gas content of 0.4 m^3/tonne (which is the U.S. average) and assumes that emissions are increased by a factor of five due to the contribution of surrounding strata. The factor of five is consistent with the results of Kirchgessner et al. (1993) at a U.S. surface mine. Other studies have similarly assumed that surrounding strata contribute to emissions, including Jaques (1992), which assumed a factor of three for Canada.

Given the lack of information and measurements on CH_4 emissions from surface mines, this range must be considered extremely uncertain, and it should be refined in the future as more data become available.

[9] In the draft OECD report, surface mining emission factor appears to exclude emissions from post-mining activities. In fact, the factor of 2.5 m^3/tonne includes both direct emissions from surface mining and those from post-mining activities.

EQUATION 6.2
TIER 1: GLOBAL AVERAGE METHOD -- SURFACE MINES

$$\text{Low } CH_4 \text{ Emissions (tonnes)} = \text{Low } CH_4 \text{ Emission Factor } (m^3\ CH_4/\text{tonne of coal mined}) \times \text{Surface Coal Production (tonnes)} \times \text{Conversion Factor}$$

$$\text{High } CH_4 \text{ Emissions (tonnes)} = \text{High } CH_4 \text{ Emission Factor } (m^3\ CH_4/\text{tonne of coal mined}) \times \text{Surface Coal Production (tonnes)} \times \text{Conversion Factor}$$

Where:

- Low CH_4 Emission Factor = 0.3 m^3/tonne.
- High CH_4 Emission Factor = 2.0 m^3/tonne.
- Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20°C and 1 atm, which is: 0.671 tonnes/$10^3 m^3$.

Tier 2: Country- or Basin-Specific Method

A second-tier estimation of CH_4 emissions -- called the "Country or Basin Specific Method" -- can be used if additional information is available on in-situ CH_4 content and other characteristics of a country's surface-mined coals. Depending on the degree of detail desired, emissions can be estimated for specific coal basins or countries, using equation 6.3.

In equation 6.3, "In-Situ Gas Content" represents the CH_4 actually contained in the coal being mined, as determined by measuring the gas content of coal samples. Average values for a coal mine, coal basin, or country may be available, depending on the country. For surface mines, unlike underground mines, it is frequently assumed that all of the CH_4 contained in the coal is released during mining and that post-mining emissions from surface-mined coals are effectively zero (BCTSRE, 1992; and CIAB, 1992). This assumption could be modified for some countries, however, based on their particular coal characteristics.

EQUATION 6.3
TIER 2: COUNTRY OR BASIN SPECIFIC METHOD -- SURFACE MINES

$$CH_4 \text{ Emissions (tonnes)} = [\text{In-Situ Gas Content } (m^3\ CH_4/\text{tonne}) \times \text{Surface Coal Production (tonnes)} \times \text{Conversion Factor}] + [\text{Assumed Emission Factor for Surrounding Strata } (m^3/\text{tonne}) \times \text{Surface Coal Production (tonnes)} \times \text{Conversion Factor}]$$

Where:

In-Situ Gas Content and Assumed Emission Factor for Surrounding Strata are described in the text.

Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20°C and 1 atm, which is:

0.671 tonnes/$10^3 m^3$.

- "Assumed Emission Factor for Surrounding Strata" represents the possibility that more CH_4 will be emitted during surface mining than is contained in the coal itself because of emissions from the strata below (or in limited cases, above) the coal seam. Some country-specific studies have assumed that there are no emissions from surrounding strata associated with surface-mined coals (BCTSRE, 1992; and CIAB, 1992). If, however, available information indicates that there are gas-bearing strata surrounding the mined coal seam and that these strata are emitting their gas in conjunction with the mining, then these emissions should also be included in the estimates. Other studies, including Jaques (1992) and Kirchgessner et al. (1993), have assumed or observed through measurements that surrounding strata contribute to emissions.

- Emission factors for the surrounding strata can be developed using one of two approaches. Ideally, the assumed emission factor should be based on an evaluation of the gas content of the surrounding strata and verified by measurements. If such data are unavailable, an alternative method of developing an emission factor is to assume that some multiple of the gas content of the mined coal is emitted by the surrounding strata. The Canadian study by Jaques (1992), for example, assumes a factor of three, and Kirchgessner et al. (1993) report that emissions at a U.S. surface mine exceeded the in-situ gas content by a factor of five. It should be noted that the

alternative approach is highly speculative, given the lack of data upon which to base such assumptions.

6.3.4 Post-Mining Activities

Like surface mining emissions, there are currently few measurements of CH_4 emissions from post-mining activities. In fact, many past studies have overlooked this emission source, while others have developed only rudimentary estimation methodologies. Two possible approaches for estimating emissions from post-mining activities are recommended.

Tier 1: Global-Average Method

For the simplest estimates, a global-average emission factor range can be multiplied by coal production for underground mining and surface mining, as shown in equation 6.4. It is important to distinguish between underground- and surface-mined coals because the gas contents and potentially the post-mining emission processes are likely to be very different; hence, emissions could vary significantly.

For underground mining, emission factors of 0.9-4 m^3/tonne are recommended, based on recent studies. The low end of the range was developed by the CIAB (1992) by assuming that underground-mined coal has an average gas content of 1.5 m^3/tonne and that 60% of this gas is emitted after the coal leaves the mine. The high-end emission factor assumes that the underground-mined coal has an average gas content of 10 m^3/tonne. It also assumes that 40% of the CH_4 is emitted after mining.

For surface mining, emission factors of 0-0.2 m^3/tonne are recommended. The low end of the range assumes that there are no post-mining emissions associated with surface mining, based on assumptions made by BCTSRE (1992) and the CIAB (1992). The high end of the range assumes an average gas content of 0.5 m^3/tonne, which is consistent with the average gas content in the United Kingdom (BCTSRE, 1992). It also assumes that 40% of the in-situ CH_4 content is released after mining.

Tier 2: Country- or Basin-Specific Method

Emission estimates can be refined if additional data are available on coal characteristics. This method may be preferable if higher-tier methods have been used to estimate emissions from underground and surface mines. Equation 6.5 summarizes the approach for preparing refined emission estimates.

- "In-Situ Gas Content" represents the CH_4 actually contained in the coal being mined, as determined by measuring gas contents in coal samples. Average values for a coal mine, coal basin, or country can be used, depending upon the availability of data in a particular country.

- The "Fraction of Gas Released During Post-Mining Activities" represents the percentage of the in-situ gas content that is assumed to be emitted during post-mining activities. There are three key issues related to the development of this fraction:

EQUATION 6.4
TIER 1: GLOBAL AVERAGE METHOD -- POST-MINING ACTIVITIES

Low CH_4 Emissions (tonnes) = Low CH_4 Emission Factor (m^3 CH_4/tonne of coal mined)

x Coal Production (Underground and Surface)* (tonnes)

x Conversion Factor

High CH_4 Emissions (tonnes) = High CH_4 Emission Factor (m^3 CH_4/tonne of coal mined)

x Coal Production (Underground and Surface)* (tonnes)

x Conversion Factor

Where:

Underground Low CH_4 Emission Factor = 0.9 m^3/tonne.
Underground High CH_4 Emission Factor = 4.0 m^3/tonne.
Surface Low CH_4 Emission Factor = 0 m^3/tonne.
Surface High CH_4 Emission Factor = 0.2 m^3/tonne.
Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20°C and 1 atm, which is: 0.671 tonnes/10^3 m^3.

*Emissions are calculated individually for underground and surface production using their respective emissions factors before being summed.

(a) *For Surface-Mined Coal*: In most cases, if the Tier 2 approach (equation 6.3) is used to estimate CH_4 emissions from surface mines, post-mining emissions from surface-mined coals are assumed to be zero.[10] If it has been assumed that some of the CH_4 contained in surface-mined coal remains after mining, however, equation 6.5(b) should be used to estimate post-mining emissions, and the value selected for "Fraction of Gas Released During Post-Mining Activities" should be consistent with the assumption used in equation 6.3.

[10] This assumption should be made if the full in-situ gas content is multiplied by surface-mined coal production to estimate emissions. Several studies have made this assumption, including BCTSRE (1992) and CIAB (1992).

EQUATION 6.5
TIER 2: COUNTRY OR BASIN SPECIFIC METHOD
POST-MINING ACTIVITIES

a. Underground CH_4 Emissions (tonnes) = In-Situ Gas Content (m^3 CH_4/tonne)
x Fraction of Gas Released During Post-Mining Activities (percent)
x Underground Coal Production (tonnes)
x Conversion Factor

When Necessary:

b. Surface CH_4 Emissions (tonnes) = In-Situ Gas Content (m^3 CH_4/tonne)
x Fraction of Gas Released During Post-Mining Activities (percent)
x Surface Coal Production (tonnes)
x Conversion Factor

Where:

- In-Situ Gas Content and Fraction of Gas Released During Mining are described in the text.
- Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20°C and 1 atm, which is: 0.671 tonnes/$10^3 m^3$.

(b) *For Underground-Mined Coal*: The assumed fractions for underground mining should be developed based on information about coal permeability, desorption rates, mining methods, and other factors. Recent studies have assumed that 25-60% of the in-situ CH_4 content of underground-mined coal is emitted during post-mining activities (U.S. EPA, 1993; BCTSRE, 1992; and CIAB, 1992).

(c) *Potential Fraction of CH_4 Not Emitted*: It is currently assumed that all of the CH_4 contained in mined coal will be emitted to the atmosphere, although it is possible that a fraction could remain in the coal until the point of combustion and could be burned instead of emitted. At this time, estimates of the extent to which this may be the case have not been developed. If such information becomes available in the future, however, it should be incorporated into equation 6.5.

6.3.5 Coal Combustion

Because data on coal combustion by end-use sector are available from the International Energy Agency (IEA, 1992a and 1992b), one method of estimating emissions from coal combustion is recommended. This method relies on available data on CH_4 emission factors for various types of coal-fired combustion units (Radian, 1990; Selzer and Zittel, 1990; Watt, 1993; Smith and Sloss, 1992; and OECD, 1991). As shown in Table 6-4, the measured emission factors vary substantially, however, and there is substantial uncertainty related to the potential emission levels associated with certain types of coal-fired equipment. Emission levels from utility power plants in Western countries are generally the best understood and are believed to be very low. It is possible, however, that the emissions associated with power plants, industrial boilers, and domestic stoves in non-Western countries could be significantly higher; to date few emission measurements have been reported. The recommended emission factors are shown in the last column of Table 6-4, and the estimation methodology is shown in equation 6.6.

6.3.6 Treatment of Other Coal Fuel Cycle Emissions

Due to lack of data, no emission estimates have been prepared for other fuel cycle emissions, principally from abandoned mines and coal waste piles. Some national experts have speculated that for their countries these sources are negligible (BCTSRE, 1992). However, additional research is warranted before concluding that these emission sources are negligible on a global basis.

Abandoned coal mines are of particular concern because there are many of them, and some could emit significant quantities of CH_4. Most available evidence indicates that CH_4 flow rates decay rapidly once deep-mine coal production ceases (Williams and Mitchell, 1992; and Creedy, 1991). In some abandoned mines, however, CH_4 can continue to be released from surrounding strata for many years. In Belgium, France, and Germany, for example, several abandoned mines are currently being used as sources of CH_4 that can be added to the gas system (Smith and Sloss, 1992; and KfA, 1993). Some U.S. abandoned mines are also producing marketable amounts of gas (Hite, 1992).

TABLE 6-4

SELECTED COAL COMBUSTION EMISSION FACTORS, BY SOURCE
(m^3/tonne of coal consumed)

Source	Watt 1993	Smith & Sloss 1992	OECD 1991	Selzer & Zittel 1990	Radian 1990	Present Study
Utility	0.019-0.022	0.04	0.024-0.028	0.04	0.025-0.026	0.02-0.04
Industry	0.033-0.079	0.04-0.48	--	0.14-0.5	--	0.03-0.5
Boilers	--	--	0.096	--	0.092	--
Kilns/Dryers	--	--	0.04	--	0.012-0.026	--
Residential/Commercial Boilers	0.033	--	0.4	0.93-2.3	0.33	0.33-2.3
Residential Stoves	--	9.2-30	--	12.4-31	--	9.2-30

EQUATION 6.6
TIER 1: COAL COMBUSTION EMISSIONS, BY SECTOR

Coal Combustion Emissions (tonnes) = Sum, over all sectors, of:
Coal Consumption, by sector (tonnes)
x Sectoral Coal Combustion Emission Factor (m^3/tonne)
x Conversion Factor

Where:

- Recommended Coal Combustion Emission Factors are determined for each sector (*power, industry, residential/commercial*), *as shown in Table 6-6.*
- Conversion Factor converts the volume of CH_4 to a weight measure, based on the density of methane at 20°C and 1 atm, which is: 0.671 tonnes/$10^3 m^3$.

U.S. EPA is currently developing a data base of U.S. abandoned and inactive mines in an effort to produce emission estimates. Based on the results of this work, it should be possible to make rough U.S. emission estimates for this class of mines in the future. The number of abandoned mines in other countries is unavailable, but is expected to be large.

6.4 RESULTS

A number of methods of estimating CH_4 emissions have been described in the previous section. One of these methods, the Global-Average Method, can currently be applied in all countries to estimate emissions because it requires only coal-production data. Other methods require more detailed data, and so can be applied only in certain countries. For several countries, however, such data are available and have been used in preparing estimates.

6.4.1 General Findings

Table 6-5 presents emission estimates developed using Global-Average Emission Factors and, where possible, U.S. EPA's Best Estimates, which are based on more information. For comparison, the emission estimates prepared by the CIAB (1992), which also provide recent specific estimates for key countries, are also included. As the table shows, the Global-Average Emission method has been used to develop emission estimates for most of

the world's coal-producing countries.[11] Total emissions in 1990 were estimated to range from 19 to 57 Tg using this method.

For several of the major coal-producing countries, more detailed estimates have been developed. For the most part, these estimates use more detailed emission data on underground mining and more refined assumptions about likely emission levels from surface mines and post-mining activities. In many cases, these estimates have been developed by or in conjunction with in-country personnel well versed in coal mining emission issues. These emission estimates are also shown in Table 6-5, in the column "U.S. EPA Best Estimates," and the methods of preparing these estimates for each country are described in the next section.

When the more detailed data are used, the resulting global emission estimates for coal mining are 24-40 Tg. This estimate is the preferred range of likely emissions from coal mining, because it incorporates the most recent and detailed information from a number of the key CH_4-emitting countries.

Most of the CH_4 emitted by the coal fuel cycle is emitted by mining in the major coal-producing countries (Table 6-6). In fact, China, the United States, and the former Soviet Union are estimated to emit almost three-quarters of the world's emissions from this source. The top-ten emitting countries, which also include Australia, the former Czechoslovakia, Germany, India, Poland, South Africa, and the United Kingdom, together accounted for approximately 90% of both global emissions and global coal production.

[11] For some countries, such as North Korea, data on coal production are not available from international sources. The lack of estimates for these countries is not expected to significantly affect the accuracy of global emissions estimates, however, because coal production data are available for more than 90% of the world's coal production.

TABLE 6-5

ESTIMATED 1990 METHANE EMISSIONS FROM THE COAL FUEL CYCLE (Tg)

Country	Global Average Method		U.S. EPA Best Estimate		CIAB
	Low	High	Low	High	
China	8.4	23.4	9.5	16.6	7.6
United States	2.7	8.1	3.6	5.7	3.3
Former Soviet Union	2.8	8.0	4.8	6.0	4.8
Germany	0.4	1.8	1.0	1.2	1.0
India	0.8	2.4	0.4	0.4	0.5
Poland	1.0	3.0	0.6	1.5	1.2
Australia	0.3	1.2	0.5	0.8	0.5
South Africa	0.8	2.3	0.8	2.3	0.9
Former Czechoslovakia	0.1	0.5	0.3	0.5	0.3
United Kingdom	0.5	1.4	0.6	0.9	0.8
Canada	<0.1	0.2	0.1	0.2	--
Greece	<0.1	0.1	<0.1	0.1	--
Turkey	0.1	0.2	0.1	0.2	--
Spain	0.1	0.3	0.1	0.3	--
Colombia	0	<0.1	0	<0.1	--
France	0.1	0.2	0.1	0.2	--
New Zealand	0	<0.1	0	<0.1	--
Austria	0	<0.1	0	<0.1	--
Belgium/Luxembourg	<0.1	<0.1	<0.1	<0.1	--
Italy	0	0	0	0	--
Norway	0	<0.1	0	<0.1	--
Ireland	0	0	0	0	--
Subtotal	*18.1*	*53.1*	*22.6*	*37.1*	*20.8*
World Total	19.4	57.0	24.4	39.6	25.0

Note: CIAB estimates do not include emissions associated with coal combustion.

TABLE 6-6

1990 ESTIMATED METHANE EMISSIONS FROM THE COAL FUEL CYCLE FOR THE TOP-10 EMITTING COUNTRIES

	Coal Production (million tonnes)			Estimated CH_4 Emissions (Tg)	
Country	Underground	Surface	Total	Low	High
China	1,024	43	1,066	9.5	16.6
United States	385	548	934	3.6	5.7
Former Soviet Union	393	309	701	4.8	6.0
Germany	77	359	436	1.0	1.2
India	109	129	238	0.4	0.4
Poland	154	58	212	0.6	1.5
Australia	52	154	206	0.5	0.8
South Africa	112	63	175	0.8	2.3
Former Czechoslovakia	22	85	107	0.3	0.5
United Kingdom	75	14	89	0.6	0.9
Subtotal -- Top 10	*2,043*	*1,762*	*4,164*	*22.1*	*35.9*
World Total			4,740	24.4	39.6

The estimates also indicate that underground mining is responsible for the bulk of the emissions from the coal cycle, with its share ranging from 70% to 85% (Figure 6-2). Surface mines and post-mining emissions account for another 10-20%. Coal combustion is estimated to emit the remaining 5-10%. About 90% of the coal combustion emissions are estimated to come from China, where large amounts of coal are burned in small, inefficient domestic stoves.

Wherever possible, the estimated CH_4 emissions presented in Table 6-5 have been adjusted to reflect CH_4 utilization in countries with ongoing CH_4-recovery programs. The amounts of CH_4 currently being utilized in those countries for which data are available are shown in Table 6-7, and total about 1.3 Tg (1.9 billion m^3), which represents 3-5% of total emissions. In addition, another 1.5-2.6 Tg (2.2-3.9 billion m^3) are being vented by mine-degasification systems. It is probable that the amounts of CH_4 being recovered, used, and vented by mine-degasification systems are underestimated because no information is available for several countries that may have such systems.

6.4.2 Country-Specific Information

For several of the world's key coal-producing countries, more detailed information has been used to develop the U.S. EPA Best Estimate of CH_4 emissions from coal mining. The information used in developing these estimates is discussed in this section, and the results are compared with those of the Global-Average Method and other recent studies.

FIGURE 6-2

1990 METHANE EMISSIONS FROM THE COAL FUEL CYCLE

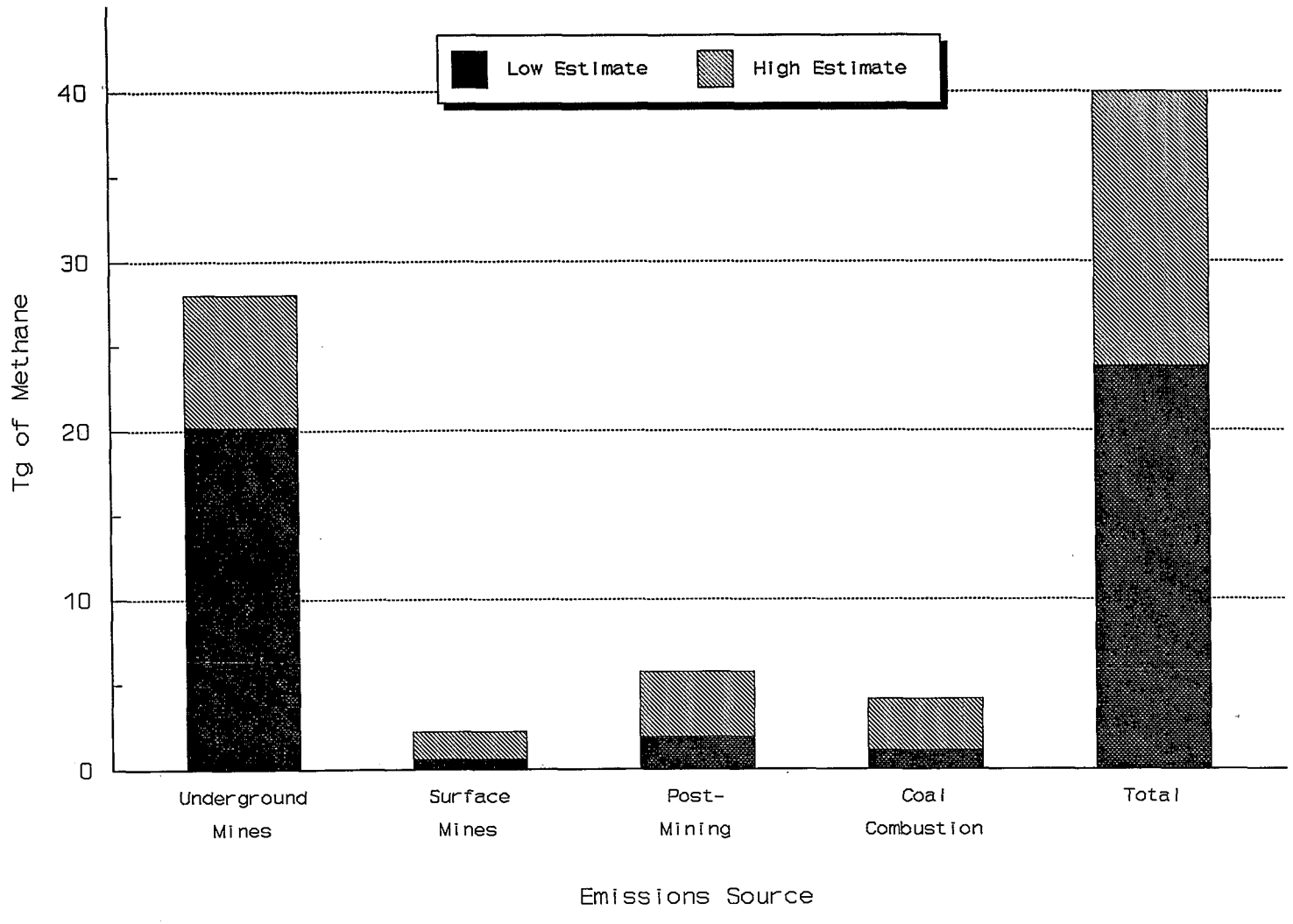

TABLE 6-7

METHANE RECOVERY BY DEGASIFICATION SYSTEMS FOR KEY COUNTRIES (Tg)

Country	Degasification Emissions			Year
	Recovered	Used	Emitted	
Australia	0.10	0.05-0.08	0.02-0.05	1989
China	0.29	0.18	0.11	1990
Former Czechoslovakia	0.09	0.08	0.01	1990
Germany	0.35	0.25	0.10	1990
Poland	0.19	0.14	0.05	1989
Former Soviet Union	0.83	0.19	0.64	1990
United Kingdom	0.20	0.14	0.06	1990
United States	0.7-1.8	0.25	0.45-1.55	1988

Sources: Lama, 1991; Saghafi & Williams, 1992; MOE, 1991; Bibler et al., 1992; Zimmermeyer, 1991; Pilcher et al., 1991; Marshall et al., 1993; Airuni, 1992; Creedy, 1992; and U.S. EPA, 1993.

People's Republic of China

In 1990, the People's Republic of China produced 1,024 million tonnes of coal in underground mines and 46 million tonnes of coal in surface mines (IEA, 1990), making it the world's largest coal producer. Of the underground coal, 44% was produced in large state-owned mines, 20% in large provincial mines, and 36% in small local mines.

Based on data provided by the Chinese Ministry of Energy, it was assumed that underground state mines emitted 10,000 million m^3 of CH_4 in ventilation air in 1990 and an additional 434 million m^3 in degasification systems (MOE, 1991). Thus, the resulting average emission factor for the state-owned underground mines was 23.1 m^3/tonne. Of the total emissions from these mines, moreover, a reported 270 million m^3 of CH_4 were used in 1990 (MOE, 1991). No emission data are currently available for emissions from other underground mines, so a range of possible emissions was estimated based on the state mines. It was assumed that the large nonstate mine would have average emission factors of 25-100% of the state-owned mines (5.8 to 23.1 m^3/tonne), yielding possible emissions of 1,179-4,715 million m^3 (0.79-3.16 Tg). For small local mines, an average emission factor of 1 m^3/tonne was assumed, given the low level of mechanization. This assumption yielded additional emissions of 369 million m^3 (0.25 Tg). The Global-Average Method was used to estimate emissions from surface mines and post-mining activities. Surface mines emitted an estimated 13-86 million m^3 (0.01-0.06 Tg) in 1990, and post-mining activities an additional 922-4,105 million m^3 (0.62-2.76 Tg). China is estimated to have the largest emissions from coal combustion,

constituting 90% of total emissions from this source. This is due to the large amount of coal consumed by industry and in residential stoves. The estimated emissions from 1990 range from 1.05 to 3.56 Tg. These estimates should be considered highly uncertain, however, due to the lack of available data on CH_4 emissions from Chinese combustion sources.

Based on these assumptions, the U.S. EPA Best Estimate for Chinese CH_4 emissions from coal mining in 1990 is 9.5-16.6 Tg. This estimate is within the range developed using the Global-Average Method. The high-end level is significantly lower than that developed using the Global-Average Method, however, due to the likelihood that the nonstate mines will have significantly lower emissions than those represented by the high-global average emission factor. This estimate is higher than the estimate of 7.6 Tg presented in the CIAB (1992) study. There are two main differences between the U.S. EPA and CIAB estimates. First, the CIAB assumed that all coal production in nonstate mines emitted CH_4 at a level of 0.9 m^3/tonne. While emissions are likely to be low for the many small local underground mines, U.S. EPA considers this assumption unduly conservative for the larger nonstate mines, particularly given the reportedly high incidence of CH_4 accidents and explosions in these mines. In addition, the CIAB estimate did not include CH_4 emissions from coal combustion, which are believed to be significant in China.

United States

The United States produced 385 million tonnes of coal from underground mines and 548 million tonnes of coal from surface mines in 1990 (U.S. DOE/EIA, 1992a). U.S. EPA (1993) has prepared a detailed estimate of CH_4 emissions from coal mines in 1988, which totals 3.3-5.2 Tg.[12] Another 0.25 Tg of CH_4 were recovered and used by mine degasification systems. Correcting the 1988 estimate for 1990 coal production (assuming similar emission factors) and including coal combustion, which was not estimated in U.S. EPA (1993), results in a 1990 emission estimate of 3.6-5.7 Tg.

This estimate is within the range of 2.7-7.9 Tg estimated using the Global-Average Method. The CIAB (1992) estimated total emissions of 3.3 Tg in 1990, which is somewhat lower than the U.S. EPA Best Estimate. The key differences between the CIAB study and the U.S. EPA Best Estimate (based on U.S. EPA, 1993) are:

- Treatment of Surface Mines and Post-Mining Activities: The CIAB used conservative emission factors for these sources, and estimated emissions were 462 million m^3 (0.31 Tg). U.S. EPA 1993 developed a wider range of emission levels of 1,043-2,235 million m^3 (0.7-1.5 Tg);

- Amount of Utilization: The CIAB reported utilization of 462 million m^3 (0.31 Tg), while U.S. EPA reported utilization of 373 million m^3 (0.25 Tg) associated with projects at six coal mines;

[12] Estimates were prepared for 1988 because this is the most recent year for which the U.S. Bureau of Mines has published mine-by-mine ventilation emission data.

Level of Degasification System Emissions: The CIAB reported degasification system emissions of 1,471 million m^3, based on personal contacts. U.S. coal companies are not required to report these emissions, and limited data are publicly available on actual emissions. U.S. EPA estimated emissions of 745-2,384 million m^3 (0.5-1.6 Tg), based on an identification of mines reported or believed to have degasification systems in place and on the assumed recovery efficiencies of these systems.

Former Soviet Union

In 1990, the former Soviet Union produced 393 million tonnes of coal in underground mines and 309 million tonnes of coal in surface mines (IEA, 1990), which represents a drop of almost 5% from 1989 (from 740 million tonnes to 709 million tonnes). The Skochinsky Mining Institute reports that CH_4 emissions in 1990 were 7,005 million m^3 (4.7 Tg), of which 280 million m^3 (0.19 Tg) were used (Marshall et al., 1993). This estimate was used to develop the low-end emission estimate, with additional emissions estimated using the Global-Average Method. Surface mining and post-mining activities added an estimated 447 million m^3 (0.3 Tg). Another recent study by Airuni (1992) reports that total CH_4 emissions in the former Soviet Union in 1990 were 8,730 million m^3 (5.86 Tg), not including another 432 million m^3 (0.29 Tg), which was reportedly used. Methane emissions from coal combustion in the former Soviet Union were estimated to be larger than for many countries, because of the amount of coal consumption by industrial and residential customers. These emissions could range from 15 to 179 million m^3 (0.01 to 0.12 Tg) in 1990.

The Skochinsky data were used for developing the low end of the U.S. EPA Best Estimate, and the Airuni estimate for the high end of the range. This yields a Best Estimate of emissions from coal mines in the former Soviet Union in 1990 of 4.82-5.98 Tg. This estimate falls within the range of 2.7-8.1 Tg developed using the Global-Average Method. In addition, the low end of the range is consistent with the estimate developed by the CIAB (1992), which used the Skochinsky data and conservative assumptions of emissions from surface mines and post-mining activities.

Germany

In 1990, Germany produced 77 million tonnes of coal in underground mines and 359 million tonnes of coal in surface mines (IEA, 1990). Reported CH_4 emissions from underground mining, including ventilation and degasification, were 1,724 million m^3 (1.16 Tg) in 1990, of which 371 million m^3 (0.25 Tg) were utilized (Zimmermeyer, 1991). Surface-mining emissions were estimated to be only 5.4 million m^3. An emission factor of 0.015 m^3/tonne was used for this estimate, instead of the global-average emission factor range, because Germany reports that its surface-mined coals are of extremely low rank and low gas contents. Based on the Global-Average Method, post-mining emissions were estimated to be 70-308 million m^3 (0.05-0.26 Tg), with only emissions from underground mining estimated. Methane emissions from coal combustion were estimated to range from negligible to 30 million m^3 (0.02 Tg).

Total CH_4 emissions in 1990 for the U.S. EPA Best Estimate were thus estimated to be 0.96-1.19 Tg for Germany. This estimate is consistent with the range of 0.4-1.8 Tg developed in the Global-Average Method. It is also consistent with the CIAB (1992) study, which used similarly conservative assumptions.

India

India's reported coal production in 1990 was 109 million tonnes in underground mines and 129 million tonnes in surface mines (IEA, 1990). A recent study prepared by the Indian government (Mitra, 1992) was used to prepare the U.S. EPA Best Estimate. This study estimated emissions for the period April 1, 1990, to March 31, 1991; the estimates for this period were assumed to correspond to those for the 1990 calendar year.

Mitra (1992) reported that only a small portion (3.5 million tonnes) of India's underground-mined coal was produced in gassy mines, and that the average emission factor for these mines was 20 m^3/tonne. An additional 27 million tonnes of coal were produced in underground mines, with an average emission factor of 10 m^3/tonne, and the remainder of the underground-mined coal, as well as the surface-mined coal, was assumed to emit 1 m^3/tonne during mining. Post-mining emissions were estimated on the basis of measurements taken to determine the amount of gas remaining in various types of coal after mining. The amount of residual gas ranged from a low of 0.09 m^3/tonne for nongassy underground- and surface-mined coal to a high of 3.7 m^3/tonne for the coal produced in the gassiest mines. Methane emissions from coal combustion are estimated to range from negligible to 60 million m^3 (0.04 Tg).

Using these assumptions results in a Best Estimate of Indian coal mining emissions of 0.4 Tg in 1990. This estimate is significantly lower than that estimated by the Global-Average Method, which ranges from 0.8 to 2.3 Tg. This is because the available data indicate that the underground coal mined in India is much less gassy than that mined in other countries. Over half of India's underground coal production reportedly emits CH_4 at levels comparable to its surface mines, for example, and only 3 percent of the underground coal is mined in gassy mines. The Best Estimate is also slightly lower than the estimate prepared by the CIAB (1992), which estimated an emission level of 0.45 Tg using a statistical model based on available data on coal rank and depth and emission data from other countries.

Poland

In 1990, Poland produced 154 million tonnes of coal in underground mines and 58 million tonnes in surface mines (IEA, 1990). The most recent estimates of Polish CH_4 emissions from underground mines were for 1989, when underground coal production was somewhat higher, at 176 million tonnes. The 1989 emission estimates ranged from 1,045 million m^3 to 1,844 million m^3 (0.70 to 1.24 Tg), with the lower estimate including emissions from only those mines classified as "gassy" according to the Polish system (Pilcher et al., 1991). Emissions from underground mines in 1990 were estimated by calculating the emission factors associated with underground mining in 1989 and assuming that they would be unchanged. Based on this approach, Polish underground-mining emissions in 1990 were estimated to be 909-1,617 million m^3 (0.61-1.09 Tg). In 1989, 201 million m^3 (0.14 Tg) were utilized; and it was assumed that the same amount was used in 1990. Poland has not developed estimates of emissions from surface-mining or post-mining activities. For U.S. EPA's Best Estimate, the Global-Average Method was used to estimate emissions from these sources, with a resulting estimate of 156-744 million m^3 (0.11-0.5 Tg). In the low case, CH_4 emissions from coal combustion were estimated to be negligible, while in the high case they were estimated at 45 million m^3 (0.03 Tg).

Based on these assumptions, U.S. EPA's Best Estimate of 1990 CH_4 emissions from coal mining in Poland is 864-2,150 million m^3 (0.58-1.45 Tg). The U.S. EPA Best Estimates are lower than those estimated using the Global-Average Method, which yields a range of 1.0-3.0 Tg. This is because the average emission factor for underground mines in Poland is at the low end of the global-average emission factor range and, in the case of the estimate for gassy mines only, is below the bottom end of the range. The CIAB (1992) estimated emissions of 1.21 Tg in 1990. It used the high-end 1989 data for underground mines (without adjusting it for lower 1990 coal production) and low-end global average emission factors for surface mines and post-mining activities. A Polish study estimated emissions of 912 million m^3 from underground mining in 1990 (Surowka and Pasierb, 1992), which results in estimates that are consistent with the low end of the U.S. EPA Best Estimate range.

Australia

In 1990, Australia's coal production was reported to be 52 million tonnes from underground mines and 154 million tonnes from surface mines (IEA, 1990). Two recent Australian studies were used to prepare U.S. EPA's Best Estimate of Australia's coal-mining emissions. These studies reported that 1990 CH_4 emissions from underground mining, including both ventilation and degasification systems, ranged from 809 million m^3 (0.54 Tg) in Lama (1991) to 1,162 million m^3 (0.78 Tg) in Saghafi and Williams (1992). Of this, between 70 and 122 million m^3 (0.05 and 0.08 Tg) were reportedly used. Surface-mining emissions were estimated to range from 46 to 124 million m^3 (0.03 to 0.08 Tg), with the lower end of the range associated with an average gas content of 0.3 m^3/tonne and the higher end based on some field measurements at major surface mines (Saghafi and Williams, 1992). No post-mining emissions were assumed to be associated with surface mining, and post-mining emissions from underground mines were estimated to range from 17 to 34 million m^3 (0.01 to 0.02 Tg), assuming an average residual gas content of 0.5-1 m^3/tonne in underground-mined coal (Saghafi and Williams, 1992). Methane emissions from coal combustion are estimated to be negligible.

Total emissions for Australia's coal mines were thus estimated at 750-1,250 million m^3 (0.50-0.84 Tg) in 1990. This estimate is consistent with those developed using other methods. It lies within the range of 0.3-1.2 Tg, developed using the Global-Average Method. The CIAB (1992) estimated emissions of 0.52 Tg, which is consistent with the low end of the range, as would be expected since the CIAB study uses conservative assumptions for surface-mining and post-mining activities and uses the low emission estimate for underground mining, as presented by Lama (1991). The U.S. EPA Best Estimate is also consistent with Lama's study (1991), which presented a best estimate of 0.5-0.6 Tg, and the Saghafi and Williams (1992) study, which estimated emissions from coal mining at 0.76 Tg.

The Former Czechoslovakia

In 1990, the former Czechoslovakia produced 22 million tonnes of coal in underground mines and 85 million tonnes of coal in surface mines (IEA, 1990). Total CH_4 emissions from underground mines in 1990 were reported to be 525 million m^3 (0.35 Tg) (Bibler et al., 1992). Of this, 124 million m^3 (0.08 Tg) were used instead of being emitted. Estimates of CH_4 emissions from surface-mining or post-mining activities are not available. Therefore, the Global-Average Method was used to prepare U.S. EPA's Best Estimate of emissions from these sources. These assumptions resulted in estimated additional emissions of 46-275 million m^3 (0.03-0.19 Tg) of CH_4. Methane emissions from coal combustion are estimated to range from negligible to 30 million m^3 (0.02 Tg).

U.S. EPA's Best Estimate of CH_4 emissions in 1990 is 446-676 million m^3 (0.3-0.47 Tg). This estimate is within the range of 0.1-0.5 Tg, developed using the Global-Average Method for all sources. It tends toward the high end of the range because underground coal mines in the former Czechoslovakia are very gassy and have an average estimated emission factor of more than 25 m^3/tonne. The CIAB (1992) study reported estimated emissions of 0.3 Tg, which is consistent with the low end of U.S. EPA's Best Estimate. The CIAB used the same estimates for underground mining and conservative assumptions to estimate emissions from surface mines and post-mining activities.

United Kingdom

In 1990, the United Kingdom's coal production was reported to be 75 million tonnes from underground mining and 14 million tonnes from surface mining (IEA, 1990). The British Coal Technical Services and Research Executive has done extensive work estimating CH_4 emissions, and it reports that its average CH_4 emission factor from underground mines, including both ventilation and degasification systems, was 15.3 m^3/tonne of coal mined in 1990 (BCTSRE, 1992). At its reported underground coal-production level, this emission factor results in annual CH_4 emissions of 1,148 million m^3 (0.77 Tg). A reported 209 million m^3 (0.14 Tg) of this gas were utilized (Creedy, 1992). British Coal reports that the average gas content of its surface-mined coal is 0.5 $\pm$ 0.3 m^3/tonne. Using this range results in estimated emissions from surface mining of 7-11 million m^3. No post-mining emissions were assumed for surface-mined coal. Underground coal was assumed by British Coal to emit 2 m^3/tonne during post-mining activities, and this assumption results in estimated emissions of 150 million m^3 (0.1 Tg). Methane emissions from coal combustion are estimated to be very low, ranging from negligible to 30 million m^3.

These assumptions result in total estimated emissions of 0.75 Tg in 1990, which is consistent with British Coal's estimate of 0.75 Tg $\pm$ 0.1 Tg, based on its assessment of the uncertainties associated with various assumptions (BCTSRE, 1992). Thus, U.S. EPA's Best Estimate uses a range of 0.65-0.85 Tg. U.S. EPA's Best Estimate is within the range generated using the Global-Average Method and is consistent with the CIAB (1992) study. The Global-Average Method yields an emissions estimate of 0.5-1.4 Tg. The Best Estimate is toward the low end of this range because all of the emission factors reported by British Coal are in the lower end of the global-average emission factor ranges. The CIAB study estimates emissions of 0.76 Tg in 1990, and its estimate, like the U.S. EPA Best Estimate, was based directly on the work of British Coal.

Canada

In 1990, Canada produced 3.9 million tonnes of coal in underground mines and 64 million tonnes in surface mines (IEA, 1990). Environment Canada has prepared a recent estimate of CH_4 emissions from coal mining for 1990 (Jaques, 1992). This study reports that underground coal mining emissions were 90 million m^3 (0.06 Tg), based on the work of Hollingshead (1990) and Stewart (1990). Although some gas utilization is reportedly underway at Canadian underground coal mines, no utilization estimates for these mines are available. Surface-mined coal is estimated by Hollingshead (1990) to contain 46 million m^3 of CH_4, of which only 54% was assumed to desorb during mining based on measured residual gas contents. Thus, emissions from surface-mined coal were estimated to be 25 million m^3 (0.02 Tg). In addition, emissions from the overlying and underlying strata were assumed to be

three times the mined-coal releases, or 75 million m^3 (0.05 Tg). Estimates of post-mining emissions were not provided by Jaques (1992). The Global-Average Method was used to estimate emissions from this source, which represented an additional 4-27 million m^3. Methane emissions from coal combustion are estimated to be negligible in Canada.

Using these assumptions, the U.S. EPA Best Estimate for Canadian CH_4 emissions from coal mining in 1990 is 0.13-0.15 Tg. The U.S. EPA Best Estimate is within the range estimated by the Global-Average Method of 0-0.2 Tg. The CIAB (1992) study did not develop an estimate of CH_4 emissions from Canada.

6.5 TRENDS

This section discusses general and country-specific trends that may influence future CH_4 emissions from the coal cycle. In many countries, overall CH_4 emissions are expected to increase in the future if coal production and mine gassiness grow. It is possible that emissions could fall in some Eastern European countries and the former Soviet Union, however, due to the restructuring of the coal industry, the likely closure of some deep and gassy mines for economic reasons, and possible declines in coal production. This section discusses the key factors that will most likely influence future global trends in emissions and potential developments in key countries.

6.5.1 General Factors Influencing Emissions

Three principal factors will affect future CH_4 emissions from coal mining. Two of these factors -- higher coal production and increased mining in deep, gassy coal mines -- will contribute to higher emissions, while the third factor -- CH_4 utilization -- could moderate the emission increases.

Increasing Coal Production

In 1990, global coal production was 4.7 billion tonnes, of which approximately 55% was mined in underground mines, and the remainder was mined using surface methods. Future coal production is projected to be significantly higher, perhaps reaching 5.3-5.9 billion tonnes in 2000 and 5.9-6.8 billion tonnes in 2010 (U.S. DOE/EIA, 1992b).

Several factors will affect future coal-production levels. Population and economic growth will most likely increase energy demand and, hence, coal production. At the same time, however, it is possible that more stringent environmental regulations of local and global air pollutants, and the relative economics of coal production and use as compared to other fuels, could reduce coal's share of future energy supply. Similarly, improvements in energy efficiency, particularly in some of the most energy-intensive countries, could reduce the need for additional energy supplies and limit the growth in CH_4 emissions associated with increases in coal production. One key uncertainty regarding future coal production involves the potential impacts of carbon taxes or other policy instruments that could be enacted to reduce coal consumption because of concerns about global warming. Several European countries have proposed such policies, although none has enacted them to date.

If forecasted production levels are achieved and CH_4 emission factors remain constant, emissions could increase significantly, ranging from 27 to 50 Tg in 2000 and 30 to 58 Tg in 2010. To the extent that environmental or economic issues or improved energy efficiency reduce coal production, however, emissions could be lower than these projections.

Increased Mining of Deep, Gassy Coal Seams

It is possible that underground coal mines will become gassier over time as shallower coal seams are depleted and mining is initiated in deeper and potentially gassier coal seams. In addition, as the proportion of underground versus surface mining increases, emissions could also increase significantly. Quantifying a possible associated rate of increase in coal mining emission factors is difficult, however, due to an absence of historical data, the difficulty in generalizing about emissions in different coal basins, and the possibility that the most gassy and unsafe mines in some countries may close. If a shift toward gassier coal seams occurs, CH_4 emissions could be higher than the levels projected above.

Increasing Methane Utilization

One moderating factor with respect to increasing CH_4 emissions is the potential for widespread use of the CH_4 recovered by mine-degasification systems. As mines become deeper and gassier, it is likely that they will use additional means of degasification to supplement ventilation systems. As a result, they will recover larger quantities of CH_4 that can be used as fuel. Many countries are becoming increasingly aware of this fuel source, and in the future could develop policies to encourage coal mines to increase their production and use of the CH_4 contained in coal seams.

In 1990, annual CH_4 utilization at coal mines was estimated to be at least 1.3 Tg (1.9 billion m^3). This represented an estimated 3-5% of total emissions from the coal fuel cycle. With increasing recovery efficiencies of degasification systems and additional interest in reducing the waste of a clean-burning fuel, it is likely that utilization rates will increase in the future. If all of the CH_4 that was reportedly recovered by degasification systems had been used in 1990, for example, emissions could have been reduced by an additional 1.5-2.6 Tg (2.2-3.9 billion m^3).

6.5.2 National Trends

In any particular country, trends in CH_4 emissions from the coal fuel cycle will depend on developments in the rest of the energy sector, the particular distribution and accessibility of coal basins, and the markets for recovered CH_4, among other factors. For several of the key CH_4-emitting countries, some of the principal factors that could affect future CH_4 emissions are discussed below.

People's Republic of China

Based on government projections of future coal production and likely mining conditions, the growth in CH_4 emissions from coal mining in China is expected to be substantial. In 1990, China was the world's largest coal producer, with production exceeding 1 billion tonnes (U.S. DOE/EIA, 1992b). Over 97% of this coal was produced in underground mines. Many of China's principal coal basins have very gassy mines, with deeply buried, high-rank coals in complex geologic formations.

In China's 8th Five-Year Plan (1991-95), the State Planning Commission approved plans to increase coal production to 1.2 billion tonnes in 1995 and potentially to 1.4 billion tonnes in 2000. Unless China makes a significant shift toward developing alternative fuels, such as natural gas or renewables, it is likely that this dramatic push to increase coal production will continue.

Given China's current plans, CH_4 emissions from coal mining are expected to increase in the future. It is also likely, however, that China will increase mine degasification and CH_4 utilization. A project is currently underway to demonstrate new CH_4-recovery technologies at mines, and this project should enable China to more effectively produce and use the CH_4 contained in its coal seams.

United States

In 1990, CH_4 emissions from the coal cycle in the United States were estimated to be 3.6-5.7 Tg, associated with the production of almost 1 billion tonnes of coal (U.S. EPA, 1993). Approximately 0.25 Tg of CH_4 was recovered and used instead of being vented. Methane emissions are projected to increase between 1990 and 2010, due to increases in coal production. In 2000, emissions could range from 4.0 to 6.7 Tg, and emissions in 2010 could range from 5.2 to 8.9 Tg (U.S. EPA, 1993). These estimates do not account for the potential increase in coal mine gassiness associated with the mining of deeper and gassier coal seams, however, due to difficulties in quantifying this factor. If deeper and gassier coal seams are mined, therefore, these estimates could be lower than actual emissions.

As the range indicates, there is substantial uncertainty in future emission levels. The principal uncertainties relate to the impact of new environmental regulations, particularly the reduction of acid rain precursors, on future coal production. Two coal-production forecasts were used in preparing these estimates, assuming different levels of coal production and different mixes of underground- and surface-mined coals. To the extent that acid rain legislation encourages additional use of low-sulfur coal, which is generally produced in surface mines in the western United States, the growth in emissions will be moderated.

Emission growth may also be moderated by the potential to increase CH_4 utilization. Currently, CH_4 utilization projects are constrained at many mines due to a variety of legal and institutional barriers. The 1992 Energy Policy Act contains provisions to remove some of these barriers, however, and more favorable state policies may also be enacted over the next several years.

Former Soviet Union

In 1990, coal production in the former Soviet Union was about 700 million tonnes, third in the world after China and the United States (U.S. DOE/EIA, 1992b). By 1991, however, after the dissolution of the Soviet Union, coal production had fallen to only 630 million tonnes. Assuming similar emission factors, this drop in coal production would correspond to emissions of 3.9-5.2 Tg in 1991.

Future CH_4 emissions in the former Soviet Union are difficult to predict because there is substantial uncertainty about future coal production. In the past, many of the gassiest coal mines in the former Soviet Union were subsidized heavily by the government, and they may be unable to survive the transition to a market economy. Thus, it is possible that coal production will not return to its historic levels and that the energy sector instead will

production will not return to its historic levels and that the energy sector instead will concentrate on improving energy efficiency and shifting to cleaner-burning fuels, such as natural gas. These trends would tend to reduce coal production and lower emissions.

Poland

Like the former Soviet Union, Poland's energy sector has suffered significant disruption as a result of the transition to a market economy. In 1988, for example, Poland produced almost 200 million tonnes of hard coal in underground mines and an additional 75 million tonnes of lignite in surface mines. In 1990, hard-coal production was reported to have fallen to only 150 million tonnes, and lignite production to only 60 million tonnes (U.S. DOE/EIA, 1992b).

It is not expected that coal production will continue to decline. The Polish government is reportedly planning to maintain annual hard-coal production at around 140-150 million tonnes and to use additional natural gas to meet its energy needs (FBIS, 1992). The government is also strongly encouraging coalbed CH_4 production, both in coal reserves and in mining areas. Thus, it is likely that emissions in Poland will remain relatively constant or perhaps decline in the future.

The Former Czechoslovakia

Like Poland, the states of the former Czechoslovakia are undergoing a transition to a market economy and are also planning to close several coal mines. In 1980, Czechoslovakia produced almost 30 million tonnes of hard coal and 100 million tonnes of lignite and brown coal. By 1990, however, production had fallen to 22 million tonnes of hard coal and 84 million tonnes of lignite. Production may continue to drop in the future, moreover, due to plans to close at least four hard-coal mines by 1995.

Lower coal production, coupled with an increasing emphasis on coalbed CH_4 utilization, should result in lower CH_4 emissions in the former Czechoslovakia. Currently, this region uses 0.1 Tg of CH_4 recovered from its coal mines (Bibler et al., 1992). By 2000, however, utilization could be much higher due to an aggressive government program to increase coalbed CH_4 production in both nonmining and mining areas.

United Kingdom

In 1990, approximately 75 million tonnes of deep coal and 18 million tonnes of surface-mined coal were produced in the United Kingdom. Over the last 22 years, coal production has fallen significantly; it was 177 million tonnes in 1966. With the reduction in coal production, there has been also a significant decrease in CH_4 emissions associated with the coal cycle, from an estimated 1.4 Tg in 1966 to 0.8 Tg in 1990 (BCTSRE, 1992). The United Kingdom is planning to close several coal mines over the next few years, which is expected to contribute significantly to lower CH_4 emissions.

6.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

The estimates in this report contain two types of uncertainty. First, in many cases, inadequate or missing data result in large uncertainties. Second, there are uncertainties inherent in the methodologies for preparing estimates, which result from generalizing complicated emission processes into global, national, basin-specific, or sectoral emission factors. It is difficult to quantify rigorously the amount of uncertainty, and in this study large ranges have been presented to indicate that the estimates are uncertain. This section discusses some of the specific uncertainties related to particular data types and describes the major sources of uncertainty related to various methodologies.

6.6.1 Data Uncertainties

The methods presented in this report require different types of data upon which to develop emission estimates. All methods use coal-production data, for example, and many require data on coal characteristics and geological information. The availability of such data can greatly influence the selection of an appropriate estimation methodology, and the accuracy of the data determines the reliability of the resulting emission estimates. The key types of data required and some of the major uncertainties related to them are summarized below.

Coal Production

Depending upon the method used, coal production can be required on a national or basin level. In all cases, it is necessary to distinguish between underground- and surface-mined coals, and this will likely be the largest source of uncertainty with respect to available coal-production data. Where coal production is not identified by mining type, it may be necessary to make assumptions about mining methods based on coal types. It is frequently assumed, for example, that hard coal is mined underground and brown coal and lignite are produced in surface mines. While this may be generally true, however, there are some exceptions that can influence emission estimates. The misallocation of coal production among these two categories can have a significant impact on emission estimates because of the large differences in likely emissions from underground and surface mines.

Coal Characteristics

Some estimation methods require data on coal characteristics, including information on coal gas contents, permeability, and other characteristics. The principal source of uncertainty will relate to ensuring that the available data are representative of national- or basin-level conditions. The degree of uncertainty caused by nonrepresentative data will depend on the likely degree of variation in different parameters within the country or basin. Quantifying this uncertainty may require conducting uncertainty analyses on a national or basin-specific level by varying key parameters and observing the resulting changes in emission estimates.

Underground Mine Emission Data

In some countries, data may be available on underground mining emissions from ventilation and, perhaps, degasification systems. Access to such data can enable countries to prepare detailed and relatively reliable emission estimates. The adequacy of these data should be assessed, however, by examining how and where measurements were taken, whether all mines were included, and how emissions from degasification systems were

treated. Where appropriate, estimates of uncertainty in various parameters should be determined in consultation with technical mining experts. The wide ranges used in this chapter for global-average emission factors illustrate the uncertainties associated with these factors (Table 6-8).

6.6.2 Methodological Uncertainties

The methods presented in this chapter are uncertain because they attempt to describe in a simple and consistent manner very complicated emission processes. Methane emissions can vary significantly within different parts of the same coal mine, for example; thus, developing national or global emission factors will inevitably result in oversimplification and inaccuracy. Of all of the components of the coal cycle, however, underground mining emissions are the best understood and have the most available data.

TABLE 6-8

SUMMARY OF GLOBAL AVERAGE EMISSION FACTORS FOR THE COAL FUEL CYCLE

Source	Emission Factor (m^3/tonne)
Underground Mines	10.0 - 25.0
Surface Mines	0.3 - 2.0
Post-Mining Activities	
For Underground-Mined Coal	0.9 - 4.0
For Surface-Mined Coal	0 - 0.02
Coal Combustion	
Power Generation	0.02 - 0.04
Industry	0.03 - 0.5
Residential/Commercial Boilers	0.33 - 2.3
Residential Stoves	9.2 - 30.0

Underground Mining

Three estimation methods have been presented, and the choice among them will depend on data availability and the degree of certainty and detail required in the estimate. In general, those methods that are the easiest to use and rely on the most general information will have the largest associated uncertainties.

- Global Average: The Global-Average Method only requires information on underground coal production for each country, and applies a wide emission factor range to that production. Thus, this method does not take into consideration any country-specific factors that could affect CH_4 emissions, such as mining method or depth, coal characteristics, or geology. The range of suggested emission factors varies by more than a factor of two, which reflects

the uncertainty in this approach. In addition, in some countries, emissions associated with underground mining could lie outside the range if its mines are significantly more or less gassy than coal mines in an "average" basin.

- Country- or Basin-Specific: The Country- or Basin-Specific Method may be somewhat more accurate than the Global-Average Method because it incorporates additional information, potentially including actual CH_4 emission measurements from some mines or data on coal characteristics that might provide insight into the gassiness of the coal. This information will not be comprehensive, however, and there will be uncertainties related to its representativeness and applicability in different parts of a country or coal basin.

- Mine-by-Mine: This method is likely to be the most reliable because it uses emission data from individual mines. Even mine-specific emission data are uncertain, however. The U.S. Mine Health and Safety Administration, for example, estimates that its ventilation air estimates are accurate to ±20%. In addition, in some cases, available data may not accurately reflect total emissions to the atmosphere, because of how the measurements were taken, the lack of information on degasification systems, and other factors.

Surface Mining

Information on CH_4 emissions from surface mines is generally unavailable. Two methods can currently be applied -- the Global-Average and Basin-Specific methods -- and both are highly uncertain. U.S. EPA currently has a program underway to measure emissions from surface mines, which should reduce some of the uncertainties associated with estimating these emissions. Other countries, such as Australia, have also measured CH_4 emissions from surface mines.

- Global Average: The key methodological uncertainty in this approach concerns the use of a global emission factor range. As discussed with respect to underground mining, global emission factors do not account for country-specific factors that could affect CH_4 emissions. To reflect this, the low and high ends of the emission-factor range used vary by more than an order of magnitude. Thus, while this method should provide a reasonable approximation of global emissions, the results could vary substantially from national estimates.

- Basin-Specific: Where the data are available to apply it, this method can reduce the uncertainty by using basin-average gas contents. These gas contents are multiplied by coal production and, if appropriate, then by a factor representing the contribution of surrounding strata to emissions. Key uncertainties are related to the reliability of average gas content values to entire countries or coal basins and the difficulty of determining a reasonable approximation of CH_4 emissions from surrounding strata.

Post-Mining Operations

Like surface mines, CH_4 emissions from post-mining coal transportation, storage, and handling operations are uncertain because there are no available emission data. The Global-Average Method uses highly speculative emission factor ranges for underground and surface mines, and without initiation of a measurement program, the accuracy of these estimates cannot be determined.

Combustion Processes

The principal uncertainty in the method of estimating combustion emissions is related to the emission factors selected. Emission factors can vary significantly, depending on the type of combustion unit and its history (i.e., operating and maintenance practices). Furthermore, the range of measured emission factors is large, and for many coal-consumption sectors, limited data are available. As a result, the emission estimates prepared to date for coal consumption range from insignificant levels of less than 0.1 Tg (Barns and Edmonds, 1990) to levels of more than 10 Tg, which would constitute more than 25% of coal-cycle emissions (Selzer and Zittel, 1990).

6.6.3 Research Needs

As the discussion of uncertainties has indicated, research in several areas could significantly improve estimated CH_4 emissions from the coal cycle. Some of the key areas for future emphasis are:

- Underground Mines: Accurate, mine-specific data, including emissions from both ventilation and degasification systems, are needed. Because underground mining is the largest emission source, efforts to improve the certainty of these emissions will be very important to the development of reliable emission estimates.

- Surface Mines: Expanded measurement programs at surface mines would significantly reduce the uncertainty in emission estimates. To date, only a few countries have undertaken CH_4 measurement programs at surface mines, and information on key issues, such as the degree to which surrounding strata contribute to emissions, is sparse.

- Post-Mining Activities: Expanded measurement programs during post-mining activities could also significantly reduce uncertainty. Key questions to resolve involve the amount of residual CH_4 contained in coals after mining and the degree to which this CH_4 is emitted during post-mining activities, as opposed to being burned during combustion.

- Coal Combustion: Improved measurements of emissions from coal combustion are critical, particularly related to industrial and domestic combustion units, which could be significant sources of CH_4.

- Abandoned Mines and Other Sources: Emissions from other points in the coal cycle currently cannot be estimated due to the lack of information. Measurements should be undertaken at abandoned mines, coal waste piles, and other possible sources to determine whether emissions from these sources are significant.

6.7 CONCLUSIONS

In 1990, CH_4 emissions from the coal fuel cycle were an estimated 24-40 Tg, not including the 1.3 Tg of CH_4 that was recovered and used by coal mines. These emissions represented approximately 10% of total anthropogenic CH_4 emissions. Underground mining was the largest source of CH_4 emissions from the coal fuel cycle, accounting for an estimated 70-85% of the total emissions. Surface mining and post-mining activities (coal transportation, storage, and handling) contributed 10-20% of emissions, and coal combustion contributed the remaining 5-10%.

Methane emissions from the coal fuel cycle could increase in the future if coal production increases. Current projections are for coal production to increase by 10-25% by 2000 and perhaps by 25-50% by 2010. It is likely that this production will be associated with much higher CH_4 emissions from the coal fuel cycle, particularly if the proportion of underground mining increases and if deeper, gassier seams are mined. The future will also present additional opportunities to recover and use CH_4 from coal mining, however, which could serve to moderate the growth in emissions.

The emissions associated with many components of the coal fuel cycle are uncertain, and additional research is necessary to better understand and quantify these sources. Underground mining is the best understood of the sources, but additional measurements, particularly for degasification system emissions, would improve estimates. The data on which surface mining and post-mining emission estimates have been based are very sparse and uncertain. Some measurements have been undertaken in the United States, and other countries may also benefit from undertaking such research efforts. There are several sources, moreover, for which emission estimates cannot currently be prepared due to lack of data, including abandoned mines and coal waste piles. Additional research is warranted to better understand these sources.

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CHAPTER 7

MINOR INDUSTRIAL SOURCES OF METHANE

7.1 SUMMARY

Over the past several years research efforts on the global methane (CH_4) budget have focused on the largest anthropogenic and natural sources and sinks of methane. Recent research indicates there is a large and diverse group of minor industrial sources that also emit methane into the atmosphere (Lacroix, 1993; Piccot et al., 1990b; and Saeger et al., 1989). Individually, these minor sources emit small quantities of methane, but their collective contribution to the global budget may be significant. Global-scale emission estimates have recently been developed for some minor source categories, but additional research will be needed to identify and characterize all source categories which may exist. As a result, there is a high degree of uncertainty associated with current global estimates.

There are hundreds of individual industrial sources that emit some quantity of methane into the atmosphere. In this chapter, emissions are estimated for six minor source categories: peat mining; coke, iron, and steel production processes; miscellaneous industrial processes; paper and printing processes; and chemical manufacturing (excluding ethanol and charcoal production). Peat mining and coke, iron, and steel production processes are the two most significant minor sources discussed in this chapter. Together, these two categories are estimated to account for about 3.3 Teragrams (Tg)[1] per year of methane or approximately 87% of all the emissions from the minor sources examined here. Other potentially significant minor sources include miscellaneous industrial processes, paper and printing processes, and chemical manufacturing. All five source categories discussed in this chapter are estimated to account for about 3.6 Tg/year of methane.

Changes in the technology, economic activity, environmental regulations, and other factors can significantly influence the rate of emissions from many of the industrial sources examined here. Thus, some understanding of country-specific manufacturing, refining, and other processes must be developed before any assessment of how technological and other processes variations may influence current and future emissions from specific source categories. It is clear that research is needed to: (1) identify all significant minor industrial and other sources of methane emissions, (2) develop generic methane emission factors for those sources, (3) develop country-specific methane emission factors for those sources that are representative of the process variations and emissions control differences that exist among countries, and (4) develop representative country- and source-specific production and other activity data needed to represent the activity levels of the individual sources.

7.2 BACKGROUND

Over the past several years researchers have conducted numerous studies to identify and characterize the principal sources and sinks of atmospheric methane (CH_4). Logically, these studies have focused on the largest anthropogenic and natural sources and sinks of

[1]Teragram = 10^6 metric tonnes = 10^{12} grams.

CH_4. Research on anthropogenic sources has concentrated on ruminants, rice paddy fields, natural gas production and distribution, coal mining, biomass burning, and landfills, as described in other chapters of this document. However, there is a large and diverse group of minor industrial sources that also emits CH_4 into the atmosphere. These minor sources have not been included in most global CH_4 budget estimates to date. Individually, they emit small quantities of CH_4, but collectively their contribution to the global budget may be significant. These sources include activities such as coke production and peat mining.

Recently, global-scale emission estimates have been developed for some of the minor source categories (Piccot and Beck, 1993; Berdowski et al., 1993; Lacroix, 1993; Piccot et al., 1990b; Blake, 1984; and Darmstadter et al., 1984). Since very little research has been done to identify and characterize these source categories, this chapter presents preliminary data that are based on limited measurements and may contain large uncertainties. In addition, it is likely that not all minor sources of CH_4 have been identified.

This chapter identifies several minor source categories that have not been included in previous chapters and discusses the research that has been done to estimate emissions from them. Specifically, this chapter includes the following minor source categories: peat mining, coke production and iron and steel production processes, miscellaneous industrial processes, paper and printing processes, and chemical manufacturing. The chapter discusses and recommends emission estimation methodologies and presents global and country-specific emission estimates.

7.2.1 Recent Research

Several researchers have recently performed work to identify, characterize, and estimate emissions from minor sources of CH_4. However, since there has been no targeted effort to identify and characterize all minor sources of CH_4 emissions, it is likely that the sources identified so far represent an incomplete listing. This section provides a brief overview of this body of research and identifies source categories and emissions estimates.

National Acid Precipitation Assessment Program (NAPAP)

During the 1980s, the United States and Canada completed a joint research effort to develop representative emission inventories for the United States and Canada for anthropogenic and natural sources of acid rain precursors as a component of the National Acid Precipitation Assessment Program (NAPAP). Although the primary focus of this effort was on more conventional pollutants, such as sulfur oxides, nitrogen oxides, and volatile organic compounds, preliminary data on CH_4 emissions from specific industrial and other activities were reported as well (Saeger et al., 1989).

The NAPAP emission inventory contains detailed information on hundreds of individual sources that may emit some quantity of CH_4 to the atmosphere. Table 7-1 presents a ranked listing of the most significant CH_4 source categories in the United States (as estimated by NAPAP) and identifies the primary emission sources associated with each category. Although NAPAP clearly ignores the more traditional sources of CH_4, such as ruminants, coal mines, and rice production, it does identify and characterize several nontraditional CH_4 sources. As Table 7-1 shows, CH_4 can be emitted from a wide range of sources, including various residential wood- and waste-combustion activities, mobile sources, fuel production and refining operations, industrial fossil fuel-fired equipment, and various industrial processes, such as

TABLE 7-1

RANKED LISTING OF SIGNIFICANT INDUSTRIAL SOURCES OF METHANE EMISSIONS IN THE UNITED STATES[a]

Source Category	Significant Emission Sources
Residential Fuelwood Combustion	Woodstoves and Fireplaces
Mobile Sources	Light Duty Vehicles
Residential On-Site Waste Burning	Household Trash Burning
Mobile Sources	Medium and Heavy Duty Vehicles
Petroleum Refining	Catalytic Cracker and Process Heater Exhausts Gas Flares and Incinerators Equipment Leaks and Waste Water Fugitives Process Vents Crude Oil and Product Loading and Storage
Oil- and Gas-Production Processes	Compressors Wellheads and General Fugitive Emissions
Internal Industrial and Other Gas Combustion	Stack Gases from Gas-Fired Turbines Stack Gases from Gas-Fired I.C. Engines Stack Gases from Utility, Industrial, and Other Boilers
Industrial Waste Treatment, Storage, and Disposal Facilities	Waste Combustion Facilities Industrial Waste Ponds Miscellaneous Other Waste Treatment/Disposal Sites
Miscellaneous Industrial Manufacturing Processes	Organic Chemical Manufacturing Operations Coke and Commercial Charcoal Manufacturing Operations Industrial Waste Incineration Various Manufacturing Operations
Other External Industrial Combustion	Stack Gases from Wood-Fired Boilers

[a] Ranked by significance based on U.S. data (Saeger et al., 1989).

chemical manufacturing and industrial waste disposal operations. Based on the NAPAP emission inventory, the most significant minor sources of CH_4 in the United States not included in other chapters of this document are the miscellaneous industrial manufacturing processes, such as organic chemical manufacturing operations, coke manufacturing operations, and other various manufacturing operations. The most significant chemical manufacturing operations in the United States appear to be processes involved in the production of carbon black, charcoal, various alcohols (e.g., ethanol and isopropanol), and various feedstock chemicals (e.g., ethylene and ethylene oxide).

Summary of Reported Global Emissions Estimates

Only a few attempts have been made to develop emissions estimates for selected minor industrial sources of CH_4. An early attempt to estimate CH_4 emissions from sources located in urban areas was conducted by Blake (1984). In Blake's analysis, a limited number of ambient air samples collected in several cities were observed to routinely exhibit elevated levels of CH_4. Using these measurements, an emission flux rate for the world's cities was calculated (0.06/m^2/day) and then multiplied by an estimate of the land-surface area covered by the world's cities. Based on these rather crude calculations, Blake estimated that non-automobile-related emissions from the world's urban areas were about 12 Tg/year in the early 1980s. Urban CH_4 sources can include a variety of industrial and other activities examined in this chapter.

In a study by Piccot et al. (1990b), research was conducted to identify and quantify the CH_4 emissions from a wide range of previously uncharacterized sources. Most of the source types examined in this study included industrial processes, such as coke production facilities, petroleum refineries, paper- and metal-coating operations, printing operations, gasoline storage and marketing operations, organic-chemical manufacturing operations, residential wood and waste burning, and fossil fuel combustion. Global emissions for these sources were estimated using source-specific emission factors (i.e., CH_4 emissions per unit of source-specific activity) that were developed from U.S. emission data contained in the NAPAP inventory discussed earlier. For example, country-specific emissions from petroleum refineries were estimated by multiplying an individual country's refinery crude oil throughput by a U.S.-based emission factor that quantifies the CH_4 emission rate per quantity of crude oil throughput at U.S. refineries. Because the CH_4 emission factors were developed based on the emissions from industrial and other operations in the United States, differences in the types of industrial processes, product characteristics, and pollution control equipment used in other countries are not represented in these estimates. The effects of these differences on emission estimates are unknown, but they could be significant for some source categories. In addition, it should be emphasized that data quality ratings for the emission factors used were reported by Piccot et al. to be very low (i.e., highly uncertain), emphasizing the need for additional research on emission factor development.

Global estimates of CH_4 emissions from several minor industrial sources have also been developed by Lacroix (1993). Source-category emissions estimated by Lacroix include petrochemicals (2.0 Tg/year ± 50%) and peat mining (2.0 Tg/year ± 50%). Total emissions from these two sources are 4.0 Tg per year. To generate the global estimate of CH_4 from peat mining, Lacroix multiplied an estimate of world peat production by the CH_4 content of peat, as reported by Glotov et al. (1985). Lacroix's estimate of CH_4 emissions from peat mining includes only the mining process itself. As with coal mining, methane may be emitted from the peat mining process as the peat is disturbed and the methane migrates from the peat into the atmosphere. As identified by Lacroix, the complete cycle of peat production includes dewatering, harvesting, and briquetting, all of which contribute to CH_4 emissions. Specific details of the processes producing emissions from these activities are not yet well-understood and well-quantified. As such, Lacroix suggests that his emission estimate for peat mining is only a crude approximation and may represent a minimum range.

At a conference on global climate issues held in the Netherlands in February 1993, Piccot and Beck (1993) and Berdowski et al. (1993) presented the results of their recent studies on minor sources of CH_4. In their study, Piccot and Beck used 1990 activity data to develop CH_4 emission estimates for a 1990 base year and organized the source categories

into logical groups. Estimates of the global CH_4 emissions from selected minor source categories examined by Piccot and Beck are summarized in Table 7-2, along with the type of activity data used to estimate emissions. Additional categories studied by Piccot and Beck have been discussed in other chapters of this document. The most globally significant minor source categories include peat mining, and coke, iron, and steel production processes. (Emissions estimates for peat mining were based on Lacroix (1993).) Other significant

TABLE 7-2

1990 GLOBAL CH_4 EMISSIONS ESTIMATED FOR SELECTED MINOR SOURCES

Source Description	Source-Specific Activity Parameter Used	Global Emissions (Tg/year)
Peat Mining	Peat production	2.0
Coke Production and Iron and Steel Production Processes	Coke production	0.3
Miscellaneous Industrial Processes	Value added in manufacturing	0.2
Paper and Printing Processes	Kraft paper, newsprint, and other paper production	0.1
Chemical Manufacturing Processes	Ethylene and propylene production	0.1
Total Emissions		2.7

Source: Piccot and Beck, 1993.

source groupings in Table 7-2 include miscellaneous industrial processes, paper and printing processes, and chemical-manufacturing processes (including synthetic organic chemical manufacturing and carbon black operations). In the paper and printing category, kraft-paper manufacturing processes represent approximately 20% of the category's emissions, and printing processes represent approximately 20% of the category's emissions. In the chemical manufacturing category, organic-chemical manufacturing represents over 50% of the category's emissions, and carbon-black production processes represent approximately 25% of the category's emissions. The group of sources found to emit negligible amounts of CH_4 include diesel vehicles, paper-coating operations, solvent use, and asphalt paving. Together, the five source categories included in Table 7-2 were estimated by Piccot and Beck to contribute 2.7 Tg per year to the global budget in 1990.

Berdowski et al. estimated methane emissions from fuel combustion, including non-commercial fuels, and industrial noncombustion sources (the "industrial processes"). Industrial noncombustion sources and processes included production of iron and steel (coke), oil refining, and production of carbon black, ethylene, dichloroethene, styrene, and methanol.

Table 7-3 compares the global emission estimates from Piccot and Beck (1993) and Berdowski et al. (1993) for the minor industrial source categories. Since fossil fuel combustion,

residential on-site incineration, and oil refining are included elsewhere in this document, their emission estimates are not presented in Table 7-3.

TABLE 7-3

SELECTED MINOR SOURCE CATEGORIES AND EMISSIONS ESTIMATES

Piccot and Beck		Berdowski et al.	
Source Category	Emissions (Tg/yr)	Source Category	Emissions (Tg/yr)
Peat Mining	2.0	na	---
Coke, Iron, and Steel Production Processes	0.3	Iron and Steel Production, Including Coke	2
Miscellaneous Industrial Processes	0.2	na	---
Paper and Printing Processes	0.1	na	---
Chemical Manufacturing	0.1	Chemical Manufacturing	0.2
Total Emissions	2.7	Total Emissions	2.2

Sources: Piccot and Beck, 1993; and Berdowski et al., 1993.

7.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

The approach recommended for estimating country-specific emissions from individual source categories is the same as the general method adopted by the Intergovernmental Panel on Climate Change (IPCC) (OECD, 1991). In this method, the first step is to multiply source-specific emission factors by some activity data that represent a surrogate for the level of activity associated with the emission source. However, several important factors must be considered before using this general emission estimation method. First, emission factors for sources can vary significantly among countries as a result of differences in processes, technology vintages, fuel compositions, operational practices, and environmental policies. Therefore, some effort should be made to use emission factors that are representative of the individual countries to which they are applied. This is of particular concern with the types of industrial process and other sources examined here because there is a great potential for variations to exist in the manufacturing process and emission controls associated with these sources. For example, different coke production processes can yield significantly different coke-oven gas compositions. The low-temperature process favored in Europe produces coke-oven gas containing a concentration of CH_4 which is two times higher than that produced by the high-temperature process favored in the United States (Shreve and Brink, 1977). Since coke-oven gas is a principal source of CH_4 emissions at coke production facilities, assumptions made about the types of processes used in a country can significantly affect emission estimates.

Since very little research has been devoted to examining the CH_4 emissions from minor industrial sources, very limited data are available for developing emission estimates, and country-specific estimates have not been reported in the literature. In a recent study conducted for the IPCC, it was concluded that industrial-process-level data for greenhouse gases are so limited that a proposed emission estimation methodology could not be developed for most industrial processes (OECD, 1991). Process-specific CH_4 emission factors for industrial processes either have not been developed or are highly suspect. For example, in recent studies, CH_4 emission factors for a limited number of industrial process and other minor CH_4 emission sources were presented but were characterized as highly uncertain (OECD, 1991; Piccot et al., 1990a).

Preliminary country-specific estimates of CH_4 emissions were developed for selected minor source categories for this chapter using the global emission estimates reported by Piccot and Beck (1993) and Berdowski et al. (1993). These five minor source categories are peat mining, coke-production and iron-and-steel production processes, miscellaneous industrial processes, paper and printing processes, and chemical manufacturing. Country-specific emission estimates were not developed for categories discussed elsewhere in this document. The estimation and allocation procedures used to generate county-specific emissions for each category are discussed in the following paragraphs.

7.3.1 Peat Mining

Total global emission estimates for peat mining developed by Lacroix (1993) were apportioned to individual countries, based on estimates of peat production for each country. Data on peat mining activity were obtained from the U.N. *Energy Statistics Yearbook* (UN, 1992a).

7.3.2 Coke, Iron, and Steel Production Processes

This category includes emissions from all production of metallurgical coke, including coke-oven charging and pushing operations, coke-quenching operations, coke-oven door leaks, coke-oven gas combustion, and other significant sources. Emissions associated with all significant iron-and-steel production processes, such as sintering and blast furnace operations, are also included. Finally, emissions from fluid coking processes at refineries, although very minor in extent, are also included.

An overall emission factor for this category (3.2 tonnes/10^6 tonnes coke produced) was calculated by averaging the emission factor developed using the NAPAP data and the emission factor presented by Berdowski et al. The NAPAP-based emission factor was developed for coke production and iron-and-steel production processes by dividing the total 1985 NAPAP CH_4 emissions from these activities by 1985 coke production in the United States. Darmstadter et al. (1984) estimated emissions from coke-manufacturing processes to be 6 Tg. The corresponding emission factor was not included in the averaging here for several reasons: (1) the age of the data used for the 6 Tg estimate; (2) the estimate represented only coke production and did not include iron-and-steel production processes; and (3) the estimate was extremely high when compared with other emission estimates for this category. Coke production was used as the activity statistic for this category (UN, 1988 and 1992b).

7.3.3 Miscellaneous Industrial Processes

The overall emission factor for this category (0.0676 tonnes/10^9 dollars manufacturing value added) was calculated using the NAPAP data approach described for coke production. Value added in manufacturing for each country was used as the activity statistic for this category (UN, 1988 and 1992b). The NAPAP data do not allow for a specific identification of the industrial processes included under this category. However, the majority of emissions from this category are process-related emissions.

Clearly, there is a significant potential for variations to occur among countries in the emissions from industrial processes. However, because of the wide range of different processes included in this category and the limited country-specific data available on CH_4 emissions from industrial processes, it was concluded that such a refined estimation approach was unjustified.

7.3.4 Paper and Printing Processes

This category primarily includes kraft-paper manufacturing processes and printing and publishing operations. The overall emission factor for this category (0.787 tonnes/10^6 tonnes paper produced) was calculated using the NAPAP data approach described for coke production. The activity statistic for this category was production of kraft paper and paperboard, other machine-made paper, other printing and writing paper, and newsprint.

As with the miscellaneous industrial processes category, there is a significant potential for country-specific variations in the emissions from industrial processes. Because of the range of different processes included in this category and the limited country-specific data available on CH_4 emissions from industrial processes, it was concluded that a more refined estimation approach was unjustified.

7.3.5 Chemical Manufacturing Processes

The dominant sources of CH_4 in the chemical manufacturing processes category are fugitive leaks from manufacturing operations, carbon-black manufacturing, and the production of various alcohols, ethylene oxide, ethylene, ammonia and methanol. The overall emission factor for this category (1.846 tonnes/10^6 tonnes feedstock chemical produced) was calculated using the NAPAP data approach described for coke production. The activity statistic for this category was production of basic feedstock chemicals (i.e., ethylene and propylene). (This category specifically does not include ethanol production or charcoal production.)

As with the miscellaneous industrial processes category, there is a significant potential for country-specific variations in the emissions from industrial processes. Because of the range of different processes included in this category and the limited country-specific data available on CH_4 emissions from industrial processes, it was concluded that a more refined estimation approach was unjustified.

7.4 RESULTS

Country-specific CH_4 emission estimates developed as described in this chapter are presented in Table 7-4 for the five minor source categories. The balance of the global emissions for each source category are reported as the "rest of world" at the bottom of each

TABLE 7-4

METHANE EMISSIONS FROM SELECTED MINOR SOURCES (1,000 tonnes/yr)

Country	Peat Mining	Coke Production	Misc. Industrial Processes	Paper and Printing Processes	Chemical Manuf.	Total Emissions
Former Soviet Union	968.7	257.8	0.0	0.0	8.1	1,234.7
Finland	555.6	1.6	0.9	6.4	0.0	564.5
Ireland	432.5	0.0	0.5	0.0	0.0	433.0
United States	0.0	84.6	63.0	49.5	48.8	246.0
Japan	0.0	153.3	33.7	19.2	18.5	224.7
China (mainland)	0.0	196.6	0.0	3.2	2.6	202.4
Former West Germany	32.3	58.0	16.1	8.0	9.0	123.4
Poland	0.0	54.8	0.0	0.5	0.9	56.2
France	0.0	23.5	10.0	5.0	6.8	45.3
Former Czechoslovakia	8.6	34.0	0.0	0.7	1.7	45.0
United Kingdom	0.0	26.8	7.6	3.3	4.2	41.9
Italy	0.0	20.5	7.5	4.0	4.2	36.2
India	0.0	31.4	2.9	1.4	0.4	36.1
Brazil	0.0	24.6	3.9	3.0	4.3	35.8
Canada	0.0	11.9	4.6	12.6	5.9	35.1
South Korea	0.0	27.1	3.0	0.0	3.1	33.2
Belgium	0.0	17.5	1.2	0.8	0.0	19.5
Spain	0.0	10.3	3.1	1.6	3.0	18.0
Australia	0.0	14.6	2.1	0.9	0.0	17.6
Romania	0.0	14.5	0.0	0.6	0.8	15.8
North Korea	0.0	11.6	0.0	3.1	0.0	14.7
Turkey	0.0	10.4	1.3	0.3	1.2	13.2
Netherlands	0.0	8.8	1.7	2.0	0.0	12.7
Sweden	0.0	3.5	1.5	6.2	0.8	12.0
Mexico	0.0	6.4	1.5	1.7	1.8	11.4
Austria	0.0	5.5	1.5	2.2	0.9	10.1
Former Yugoslavia	0.0	7.3	1.0	0.5	0.7	9.5
South Africa Customs Union	0.0	6.3	0.7	1.4	0.0	8.4

[continued]

TABLE 7-4

METHANE EMISSIONS FROM SELECTED MINOR SOURCES (1,000 tonnes/yr) (Continued)

Country	Peat Mining	Coke Production	Misc. Industrial Processes	Paper and Printing Processes	Chemical Manuf.	Total Emissions
Former East Germany	0.0	3.5	0.0	0.3	1.2	5.0
Argentina	0.0	3.1	1.1	0.6	0.0	4.8
Rest of the World	2.2	29.7	17.3	10.8	9.7	69.8
Total	2,000.0	1,159.5	187.7	150.0	138.6	3,635.8

column. From the data in Table 7-4, it is estimated that total global emissions from these five minor source categories were approximately 3.6 Tg in 1990. Although this estimate should be considered highly uncertain, it is not possible to develop a representative uncertainty range until some additional basic research is conducted.

The most significant minor global sources appear to be peat mining (2.0 Tg) and coke, iron, and steel production processes (approximately 1.2 Tg). Together, these two source categories account for approximately 87% of all the CH_4 emissions from the minor source categories. Emissions from the remaining categories account for about 0.5 Tg.

On a country-specific basis, the former Soviet Union contributes over 1.2 Tg of the total 3.6 Tg of CH_4 from these five source categories. Emissions from the next three highest contributing countries are 0.6 Tg from Finland, 0.4 Tg from Ireland and 0.2 Tg from the United States. Together, these four countries contribute approximately 68% of total global emissions from the five minor source categories. The 30 countries listed in Table 7-4 contribute over 98% of total global emissions from the five minor source categories.

7.5 TRENDS

Without a sound technical understanding of current CH_4 emissions and emission factors for specific processes and countries, it is difficult to examine how future changes in technology, economic activity, environmental regulations, or other factors may affect future emissions from the sources examined here. Therefore, this section presents a qualitative discussion of technological and other factors which could affect future emissions from the major sources examined.

Emissions trends for peat production will likely depend on the energy market. Changing from conventional energy sources to alternative energy sources, such as peat, is unlikely when the price of conventional fuels is low.

Coke production processes were also identified as a significant minor industrial source of CH_4 emissions. For this category, emissions from the coking process and the combustion of coke-oven gas are the most significant contributors to emissions. This is not surprising,

since the major constituents of coke-oven gas are CH_4 (22-32% in the United States) and hydrogen (U.S. EPA, 1987). Coke is manufactured by carbonizing coal (i.e., heating coal in an oxygen depleted atmosphere) and is one of the basic materials used in the conversion of iron ore into iron and steel. In the coking process, emissions of CH_4 and various other organic compounds escape into the atmosphere when the coke ovens are opened and charged with fresh coal and when inadequate seals exist and emissions escape from around leaking coke-oven doors and other openings. Since leaking doors are the most significant emission source of coke-oven gas, the age, design, and operation of the process can have a significant impact on the emissions released (U.S. EPA, 1987).

Future emissions from coke production processes can be significantly altered, depending on the operation and maintenance procedures used, the age and state of repair of the equipment, and new technology developments. The U.S. Environmental Protection Agency (U.S. EPA) conducted a study that estimated that if a comprehensive leak-control program were initiated at U.S. coke facilities, and if coke-oven seals were modified and charging operations were staged, emissions in the United States could be reduced by about 40% (U.S. EPA, 1987). The study also estimated that if existing U.S. coke-oven batteries were rebuilt, emissions would be reduced by 86%. Clearly, there is a potential for existing coke-producing facilities to reduce emissions in the future, but it is likely that the steps just mentioned would only be taken in response to pending environmental regulation. Current regulations for this industry are a result of concern over the carcinogenic effects associated with coke-oven gas emissions. Without some understanding of the current vintages of coke production facilities in specific countries and the environmental regulations which apply to those facilities, it is not possible to estimate accurately how the types of technological and operational influences discussed here could affect future emissions.

Except as noted earlier, it is unlikely that CH_4 emissions associated with the production of coke and the combustion of coke-oven gas will be reduced in the future, unless the actual amount of coke required is reduced and/or if technological changes in the coking process occur. It is possible to adopt a process that reduces coke consumption by using high-grade iron ores and supplemental fuels in the ore reduction process. For example, in the United States, the amount of coke produced per megagram of pig iron produced was reduced by about 40% between 1956 and 1983 as a result of these factors. There is also an innovative process modification that is being developed, whereby coke quenching occurs within the oven rather than outside in a coke-quench car. This modification could reduce the amount of hot-quench gases which escape into the atmosphere during the coke production process.

Miscellaneous industrial processes and various chemical manufacturing processes were also identified as significant minor industrial sources of CH_4 emissions. The substantial number of different processes associated with these two emission categories is too broad to discuss here. However, there is an enormous potential for changes in many of these processes to occur in the future, which could significantly affect CH_4 emissions. For example, two different chemical manufacturing processes could be used to produce the intermediate chemical cumene, which is used in the production of phenol and acetone. One process uses a phosphoric acid catalyst, and CH_4 is emitted from the distillation towers. The emissions of all hydrocarbons from a "typical" plant are 14.5 kg/hour. In another process, an aluminum chloride catalyst is used and the hydrocarbon emissions increase to 50 kg/hour, but the emissions of CH_4 from the distillation towers are eliminated (U.S. EPA, 1980). As was the case with coke manufacturing processes, some understanding of country-specific manufacturing and refinery processes must be developed before any assessment of how technological and processes variations may influence future emissions.

7.6 CONCLUSIONS

In 1990, the total global emissions from the five minor source categories examined in this chapter are estimated to be 3.6 Tg. Although the data used to develop this estimate contain significant uncertainty, they suggest that the combined emissions from these minor sources may account for a portion of the "missing methane" identified in recent global budget studies.

It is clear from the results presented here that basic research is needed to develop an improved understanding of the contribution of minor anthropogenic sources to the global CH_4 budget. The first, and perhaps most important, step in this research should be to develop a complete list of process and other minor sources of CH_4 since this has not yet been done comprehensively. This list should be highly process-specific to facilitate the development of the most specific and appropriate emission factors and activity data possible. The next step should be to develop "generic" emission factors for all sources and to estimate total global emissions using these factors. This preliminary global estimate should only be used to identify the most significant sources upon which future research should be focused. For the most significant sources, research should then be conducted to develop country-specific emission factors that are representative of the individual countries to which they are applied. This is needed because the types of industrial processes and other sources examined here have a great potential to exhibit significantly different emission characteristics as a result of differences in manufacturing processes and emissions controls used in different countries. The preliminary results presented here suggest that research on country-specific emission factors should be focused on coke production processes, various organic-chemical manufacturing operations, and petroleum-refinery operations.

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CHAPTER 8

METHANE EMISSIONS FROM LANDFILLS AND OPEN DUMPS

8.1 SUMMARY

Methane produced by decomposing wastes buried in landfills and open dumps is a significant contributor to global methane emissions, with estimates ranging from 10 to 70 teragrams (Tg)[1] per year (see Table 8-1). Global anthropogenic methane sources emit 360 Tg/yr (IPCC, 1992), which suggests that landfills may account for 3-19% of the total. Methods of managing municipal solid waste (MSW) vary widely, ranging from open dumps and open burning to sanitary landfills with leachate collection systems and landfill gas control. Different management methods affect the rate of methane emissions.

This chapter presents two methods for estimating methane emissions from this source. Application of the IPCC/OECD methodology (OECD, 1991) results in an estimate of 57 Tg/yr. A second, empirical model, developed by the U.S. Environmental Protection Agency's Air & Energy Engineering Research Laboratory (EPA/AEERL), is based on data from landfill gas-recovery projects. EPA/AEERL global methane estimates range from 19 to 39 Tg/yr.

The United States is by far the biggest contributor, with estimates ranging from 8 to 16 Tg/yr. This is a somewhat larger range than reported in EPA's *Report to Congress: Anthropogenic Methane Emissions in the United States: Estimates for 1990* (1993b). This is due to still unresolved variations in the methods used to estimate waste-in-place figures for U.S. landfills. The U.S. domestic report to Congress estimates a range of 8 to 12 Tg per year and is considered the current official figure for U.S. landfill methane emissions.

In the future, some OECD countries plan to place less waste in landfills in favor of recycling and incineration. Also, controls for landfill air emissions are being considered by some OECD countries. The United States plans to issue rules for municipal landfills that will result in a methane emission reduction of about 7 Tg/yr by 2000. With regard to developing countries, no conclusions about the future amount of waste that will be landfilled or dumped can be drawn, due to lack of data. Substantial uncertainty in these estimates results from a lack of data characterizing (1) country-specific waste generation or waste-in-place, (2) waste management practices, (3) methane potential of the waste, and (4) methane oxidation in landfill covers.

8.2 BACKGROUND

8.2.1 Methane Production from the Anaerobic Decomposition of Waste

The anaerobic decomposition of organic matter, as it occurs in a landfill, is a complex process that requires that several groups of microorganisms act synergistically under favorable environmental conditions. Three trophic groups of anaerobic bacteria must be present to produce methane (CH_4) from biological polymers, such as cellulose, hemicellulose,

[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

and protein: (1) the hydrolytic and fermentative microorganisms, (2) obligate proton-reducing acetogens, and (3) methanogens (Wolfe, 1979; and Zehnder et al., 1982).

The hydrolytic and fermentative group is responsible for the hydrolysis of biological polymers. The initial products of polymer hydrolysis are soluble sugars, amino acids, long-chain carboxylic acids, and glycerol. Following polymer hydrolysis, the hydrolytic and fermentative microorganisms ferment the initial products of decomposition into short-chain carboxylic acids, alcohols, carbon dioxide (CO_2), and hydrogen. Acetate, a direct precursor of CH_4, is also formed.

TABLE 8-1

TOTAL GLOBAL AND U.S. ESTIMATES OF METHANE EMISSIONS FROM LANDFILLS AND OPEN DUMPS, ACCORDING TO VARIOUS METHODS

Global (Tg/yr)			United States (Tg/yr)		
Average	Range	Reference	Average	Range	Reference
50	30-70	Bingemer & Crutzen, 1987[a]	na	na	na
62	na	OECD, 1991[b]	23	na	OECD, 1991[b]
na	na	na	6	3-8	Augenstein, 1990[a,c]
15	10-20	Richards, 1989[a]	na	na	na
na	na	na	10	8-12	EPA, 1993[d]
39	25-52	Thorneloe, 1993	12	8-18	Doorn et al., 1994

a. Potential emissions, not corrected for the amount that is flared or utilized.

b. Uses IPCC/OECD methodology (OECD, 1991) with updated country-specific data on MSW generation rates.

c. Uses estimated annual placement rates from 1950 to 1990.

d. U.S. EPA, 1993b.

The second group of bacteria -- the obligate proton-reducing acetogens -- convert the fermentation products of the hydrolytic and fermentative microorganisms to CO_2, hydrogen, and acetic acid. The conversion of fermentation intermediates, such as butyrate, propionate, and ethanol, is thermodynamically favorable only at very low hydrogen concentrations. Thus, these substrates are used only when the obligate proton-reducing acetogenic bacteria can function in syntrophic association with hydrogen scavengers, such as CH_4-producing or sulfate-reducing organisms.

The third group of bacteria necessary for the production of CH_4 are the methanogens. Major substrates used by methanogens for producing CH_4 are acetate, formate, methanol, methylamines, and hydrogen plus CO_2 (Wolin and Miller, 1985).

While CH_4 and CO_2 are the terminal products of anaerobic decomposition, CO_2 and water are the terminal products of aerobic decomposition. Aerobic decomposition occurs in

management facilities where waste is exposed to air, such as when compost is turned for aerating, and in uncontrolled dumps, such as when refuse is spread in thin layers or otherwise exposed to oxygen (e.g., by scavenging). However, when refuse is buried in large piles, whether at an open dump or in a sanitary landfill, the oxygen entrained at burial is consumed rapidly, and substantial quantities of CH_4 may be produced (Bhide et al., 1990).

8.2.2 Factors Affecting CH_4 Potential from Landfilled Waste

Methane formation does not occur immediately after refuse is placed in a landfill or dump. It can take months or years for the proper environmental conditions and the required microbiological populations to become established. Numerous factors control decomposition, including moisture content, nutrient concentrations, presence and distribution of microorganisms, particle size, water flux, pH level, and temperature. Reviews of the effects of each of these factors on CH_4 production are provided in Barlaz et al. (1990), Pohland and Harper (1987), and Halvadakis (1983).

The two factors that appear to have the most impact on CH_4 production are moisture content and pH. The effect of refuse moisture content has been summarized by Halvadakis (1983), although some of the data in the summary relate to manure and not municipal waste. The broadest data sets are those of Emberton (1986) and Jenkins and Pettus (1985). Emberton measured CH_4 production rates in excavated landfill samples under laboratory conditions. Jenkins and Pettus sampled refuse from landfills and tested how CH_4 production was affected by the moisture content of refuse. In both studies, the CH_4 production rate exhibited an upward trend with increasing moisture content, despite differences in refuse density, age, and composition. It is difficult to translate the results of these laboratory studies to actual landfills. A statistically significant correlation between landfill gas recovery and precipitation could not be found, although an inferred correlation was demonstrated by differentiating between landfills in arid and non-arid regions. (Peer et al., 1993; and U.S. EPA, 1993b).

A second key factor influencing the rate and onset of CH_4 production is pH. The optimum pH level for the activity by methanogenic bacteria is between 6.8 and 7.4. CH_4 production rates decrease sharply with pH values below about 6.5 (Zehnder, 1982). When refuse is buried in landfills, there is often a rapid accumulation of carboxylic acids; this results in a temporary pH decrease and a long time lapse between refuse burial and the onset of CH_4 production.

Neutralizing leachate and recycling it back through refuse has been shown to enhance the onset and rate of CH_4 production in laboratory studies (Pohland, 1975; Buivid, 1981; and Barlaz et al., 1987). Given that moisture and pH have been reported as the two most significant factors limiting CH_4 production, the stimulatory effect of leachate neutralization and recycling is logical. Neutralization of leachate provides a means of externally raising the pH of the refuse ecosystem. Recycling neutralized leachate back through a landfill increases and stabilizes both the moisture content and substrate availability of the refuse. It also enhances mixing in what would otherwise be an immobilized batch reactor. Field experience with leachate recycling systems is limited, and more information is needed to fully document its value. In the next few years, new information should become available.

The lapsed time preceding the onset of CH_4 production in landfills is an important aspect when considering the management of individual landfills for biogas recovery or emission mitigation. For evaluating global CH_4 emissions from solid waste management

systems, the age at which landfills and uncontrolled dumps begin to produce CH_4 is less important than the total CH_4 production potential of landfilled refuse.

8.2.3 Determination of the CH_4 Potential of Solid Waste

The CH_4 potential of landfilled refuse can be determined in three basic ways. The theoretical CH_4 potential of the main chemical constituents may be calculated, or laboratory or field tests may be conducted. All three methods have in common the question of whether the data are representative. Even in field tests, waste composition and other parameters that affect CH_4 generation may show unpredictable variety from one location to the next.

Not all CH_4 produced in a landfill would be emitted to the air. Some CH_4 may be converted to CO_2 in the presence of oxygen by aerobic methanotrophic bacteria, as it passes through the cover soil. CH_4 oxidation has been documented in landfill cover soil studied under laboratory conditions (Whalen et al., 1990). However, there are no data on the quantitative significance of CH_4 oxidation above landfills. CH_4 escaping through cracks in a landfill cover most likely will not reside in the cover for a period sufficient to undergo significant oxidation.

Theoretical Approach

Knowledge of the chemical composition and the mass of refuse buried in a landfill makes it possible to estimate the volume or mass of CH_4 that may be produced. The amount of CH_4 that would be produced if all of a given constituent were converted to CH_4, CO_2, and ammonia may be calculated from Equation 8.1 (Parkin and Owen, 1986):

$$C_nH_aO_bN_c + [n-(a/4)-(b/2)+3(c/4)]H_2O \rightarrow$$
$$[(n/2)-(a/8)+(b/4)+3(c/8)]CO_2 + [(n/2)+(a/8)-(b/4)3(c/8)]CH_4 + cNH_3 \quad (8.1)$$

Using the above stoichiometry, the potential of, for instance, cellulose and hemicellulose is 415 and 424 liters (l) CH_4 at standard temperature and pressure per dry kilogram (kg), respectively. (Cellulose ($C_6H_{10}O_5$) and hemicellulose ($C_5H_8O_4$) are major constituents of MSW in the United States (Barlaz, 1988; and Barlaz et al. 1989).) These CH_4 potentials represent maximum CH_4 production if 100% of the cellulose and hemicellulose were converted to CH_4. However, decomposition of these constituents in landfills is well below 100%, mainly because (1) some cellulose and hemicellulose are surrounded by lignin or other recalcitrant materials (such as plastic) and, therefore, are not biologically available; and (2) without active intervention, buried refuse is not evenly exposed to moisture, microorganisms, and nutrients. Instead of relating CH_4 potential to individual constituents, it can also be expressed as a function of the degradable organic carbon (DOC) content of the waste. The higher the DOC percentage, the more CH_4 could be formed, provided the waste degrades under anaerobic conditions.

Laboratory Tests

CH_4 yields of 42-120 liters CH_4/dry kg refuse have been reported in laboratory tests conducted with leachate recycling and neutralization (Barlaz et al., 1987; Barlaz 1988; Kinman et al., 1987; and Buivid, 1981). The laboratory data are not perfectly comparable in that experimental conditions (e.g., moisture, particle size, temperature) are not uniform among studies. Sampling size is limited to volumes that can be reasonably handled and reduced by proven techniques. However, it is possible to obtain multiple samples at presumably representative locations within a landfill to get an estimate of the range and extent of

decomposition. Most laboratory experiments were conducted to explore techniques for enhancing CH_4 production. The enhanced CH_4 production rates could not be expected at field-scale landfills, unless certain enhancement techniques were employed in the field.

A technique for assessing the CH_4 potential of refuse is the biochemical CH_4 potential (BOP) test (Shelton and Tiedje, 1984; and Bogner, 1990). In the BOP test, the anaerobic biodegradability of a small sample of refuse (5-10 grams) is measured in a small batch reactor (100-200 milliliters). While the BOP represents an upper bound of CH_4 potential from refuse, it will be lower than the stoichiometric estimate described in the previous section. BOPs also require representative sampling in landfills.

Field Tests

In field-scale test cells, CH_4 yields were measured as part of the Controlled Landfill Project in Mountain View, California (Pacey, 1989). Yields of 38.6-92.2 liters CH_4 /dry kg of refuse were measured after 1,597 days. However, mass balance data suggested that in certain test cells, significant volumes of CH_4 were not recorded. A number often used by the landfill gas industry as an estimate of CH_4 production in field-scale landfills is 0.1 cubic foot CH_4 per wet pound per year (ft^3/wet lb/yr). Assuming refuse buried at 20% moisture, this converts to 7.8 liters CH_4/dry kg/yr, a number comparable to some of the lower values reported in the literature. Comparison of CH_4 production data between field-scale landfills and laboratory experiments is difficult because there are essentially no data in the open literature on CH_4 production rates in field-scale facilities. Interpretation of data from field-scale landfills or test cells is complicated by questions concerning the mass of refuse responsible for production of a measured volume of gas and the efficiency of gas collection. More scientific CH_4 production data are collected under laboratory conditions than under field conditions (Thorneloe, 1991; and Barlaz, 1991).

8.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

Existing emission methodologies for this source tend to assume that optimal conditions for anaerobic decomposition exist within a landfill. However, this is rarely the case as the information in the previous section and an article by Rathje (1991) indicate. To address this concern, AEERL has used data on landfill gas recovery to develop an empirical model. References used to develop inputs for the estimates are identified in Table 8-2. The methodology developed by AEERL adjusts for gas-recovery efficiency and CH_4 oxidation. Two techniques for estimating emissions from landfills are presented here: the AEERL Regression Model and the draft IPCC/OECD methodology. Because waste-in-place data exist for very few countries, the models use waste-generation rates.

8.3.1 Estimation of Waste-Generation Rates

Municipal solid waste (MSW) consisting primarily of household and commercial refuse is the largest contributor to CH_4 from landfills and dumps. Often MSW is co-disposed with other types of waste, i.e., demolition debris, fly ash, industrial waste, etc. Estimates of waste generation are presented in Table 8-3. Country-specific data were available to determine MSW generation and land-disposal values, especially for developed countries. Information on MSW generation in developing countries is more difficult to obtain and is often anecdotal.

TABLE 8-2

REFERENCES USED

Geographic Region	References*
Africa	1-12
Asia and the Middle East	13-21
Europe	22-36
Latin America	37-38
Australia and Oceania	39
North America	40-43
World	44-51

***Reference Key**

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2. El Halwagi et al., 1986.
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13. Maniatis and Vanhille, 1987.
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16. Pairoj-Boriboon, 1986.
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18. Mei-Chan, 1986.
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20. Cossu, 1990a.
21. Hayakawa, 1990.
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23. Carra and Cossu, 1990.
24. Ettala, 1990.
25. Stegmann, 1990.
26. Lechner, 1990
27. Ernst, 1990.
28. Cossu and Urbini, 1990.
29. Beker, 1990.
30. Gandolla, 1990.
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32. Cossu, 1990b.
33. Frantzis, 1988
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35. Bartone and Haley, 1990.
36. Barres et al., 1990.
37. Kessler, 1990.
38. Yepes and Campbell, 1990.
39. Bateman, 1988.
40. U.S. EPA, 1988.
41. U.S. EPA, 1992b.
42. Thorneloe, 1993.
43. El Rayes and Edwards, 1990.
44. Bartone et al., 1991.
45. Holmes, 1984.
46. Cointreau, 1984.
47. Bingemer and Crutzen, 1987.
48. UN, 1989.
49. Richards, 1989.
50. World Resources Institute, 1990.
51. Diaz and Golueke, 1987.

TABLE 8-3

WASTE GENERATION RATES AND METHANE EMISSION ESTIMATES USING IPCC/OECD AND AEERL METHODS

Country	Waste Generated (Tg/yr)	IPCC/ OECD Method (Tg/yr)	AEERL's Regression Model		
			Lower Bound (Tg/yr)	Mid-Point (Tg/yr)	Upper Bound (Tg/yr)
Africa					
Congo	0.24	0.01	0.00	0.01	0.01
Egypt	6.99	0.32	0.08	0.13	0.17
Gambia	0.08	0.01	0.00	0.00	0.00
Ghana	2.35	0.05	0.03	0.05	0.06
Kenya	2.28	0.09	0.04	0.06	0.08
Liberia	0.32	0.01	0.01	0.01	0.01
Morocco	3.12	0.12	0.05	0.08	0.11
Nigeria	10.61	0.48	0.18	0.28	0.38
South Africa	11.17	0.43	0.11	0.18	0.24
Sudan	2.79	0.09	0.03	0.05	0.07
Tanzania	2.29	0.09	0.03	0.04	0.06
Uganda	1.47	0.06	0.02	0.03	0.04
Zimbabwe	1.90	0.08	0.02	0.03	0.04
Other Africa	31.46	1.27	0.48	0.75	1.02
Total Africa	*77*	*3.1*	*1.1*	*1.7*	*2.3*
Asia					
Bangladesh	7.99	0.42	0.08	0.13	0.17
China	134.50	3.87	0.64	0.99	1.35
India	66.79	0.80	0.74	1.15	1.56
Iran	10.76	0.31	0.16	0.25	0.34
Iraq	4.21	0.12	0.06	0.10	0.13
Israel	1.20	0.05	0.01	0.02	0.03
Japan	41.00	1.04	0.24	0.38	0.51
Kuwait	0.59	0.14	0.01	0.01	0.02
Malaysia	2.01	0.64	0.03	0.05	0.07
Mongolia	0.18	0.02	0.00	0.00	0.01
Myanmar	3.11	0.08	0.03	0.05	0.07

(continued)

TABLE 8-3

WASTE GENERATION RATES AND METHANE EMISSION ESTIMATES USING IPCC/OECD AND AEERL METHODS (Continued)

Country	Waste Generated (Tg/yr)	IPCC/ OECD Method (Tg/yr)	AEERL's Regression Model		
			Lower Bound (Tg/yr)	Mid-Point (Tg/yr)	Upper Bound (Tg/yr)
Asia (continued)					
North Korea	3.74	0.01	0.06	0.09	0.12
Pakistan	10.34	0.16	0.11	0.17	0.22
Philippines	7.90	0.75	0.08	0.13	0.17
Saudi Arabia	3.54	0.42	0.05	0.08	0.11
South Korea	28.11	0.10	0.04	0.07	0.09
Sri Lanka	2.39	0.10	0.02	0.04	0.05
Thailand	7.04	0.28	0.09	0.15	0.20
Turkey	9.58	0.20	0.18	0.28	0.38
United Arab Emirates	0.41	0.01	0.01	0.01	0.01
Viet Nam	6.29	0.22	0.09	0.14	0.20
Other Asia	34.46	2.04	0.60	0.94	1.29
Total Asia	*400*	*12*	*3.3*	*5.2*	*7.1*
Europe					
Albania	0.37	0.01	0.01	0.01	0.02
Austria	2.60	0.17	0.05	0.08	0.11
Belgium	3.10	0.14	0.04	0.06	0.08
Bulgaria	2.20	0.06	0.02	0.03	0.04
Former Czechoslovakia	2.83	0.15	0.05	0.09	0.12
Denmark	2.35	0.07	0.02	0.03	0.04
Finland	2.50	0.24	0.09	0.13	0.18
France	34.00	0.88	0.41	0.64	0.87
Germany	33.94	1.97	0.48	0.75	1.02
Greece	1.78	0.48	0.05	0.08	0.10
Hungary	3.20	0.24	0.06	0.09	0.12
Ireland	1.10	0.11	0.03	0.05	0.06
Italy	17.30	1.45	0.34	0.53	0.72
Netherlands	8.50	0.44	0.12	0.19	0.26

(continued)

TABLE 8-3

WASTE GENERATION RATES AND METHANE EMISSION ESTIMATES USING IPCC/OECD AND AEERL METHODS (Continued)

Country	Waste Generated (Tg/yr)	IPCC/ OECD Method (Tg/yr)	AEERL's Regression Model		
			Lower Bound (Tg/yr)	Mid-Point (Tg/yr)	Upper Bound (Tg/yr)
Europe (continued)					
Norway	2.00	0.11	0.03	0.05	0.06
Poland	7.90	0.37	0.11	0.17	0.23
Romania	4.50	0.13	0.04	0.06	0.08
Spain	11.00	0.85	0.22	0.35	0.48
Sweden	2.30	0.08	0.03	0.04	0.05
Switzerland/ Liechtenstein	5.80	0.12	0.03	0.05	0.07
Former Soviet Union	40.84	2.49	0.83	1.29	1.76
United Kingdom	32.00	2.85	0.75	1.18	1.60
Former Yugoslavia	3.26	0.17	0.06	0.10	0.13
Other Europe	3.20	0.08	0.06	0.10	0.13
Total Europe	*229*	*14*	*3.9*	*6.2*	*8.3*
North and Latin America and the Caribbean					
Canada	21.00	2.02	0.57	0.89	1.21
United States (1990)	263	20.00	7.50	10.00	16.00
Argentina	5.67	0.28	0.10	0.15	0.20
Brazil	31.00	2.23	0.66	1.03	1.40
Colombia	6.80	0.44	0.15	0.24	0.33
Venezuela	5.23	0.05	0.08	0.12	0.17
Others	38.35	1.48	0.53	0.83	1.13
Total America	*371*	*26.5*	*9.6*	*13*	*21*
Australia and Oceania					
Australia	11.00	1.16	0.23	0.37	0.50
New Zealand	2.10	0.15	0.05	0.08	0.11
Other Oceania	0.54	0.03	0.01	0.01	0.02
Total Oceania	*14*	*1.3*	*0.3*	*0.5*	*0.6*
Total Global	**1097**	**57**	**19**	**27**	**39**

Note: Decimals in country-specific estimates are not meant to indicate precision. Estimates are considered precise to within two significant figures. Totals may not equal sum of individual numbers due to rounding.

Most of the available data for developing countries are provided on a per-capita basis for only the larger cities. This information was combined with population (UN, 1990) and urbanization data (Population Reference Bureau, Inc., 1989) to determine the amount of waste generated in the urban centers of these countries. Two estimates for a rural per-capita refuse generation rate (Kessler, 1990 and United Republic of Tanzania, 1989) were then combined with the rural population value to determine rural waste generation. In cases where no data were available, data from comparable countries were used.

Per-capita MSW generation was in the range of 1.7-1.8 kg/person/day for both the United States and Canada (U.S. EPA, 1992b; and El Rayes and Edwards, 1991). For the United States, these numbers were not used, since estimates of total waste-in-place are available (U.S. EPA, 1988; and Doorn et al., 1994). MSW generation rates in other OECD countries average out to be 1.1 kg/person/day. Information on the amount of MSW generated and landfilled in the European countries that are not OECD members and the former Soviet Union is limited. Average MSW generation for Greece, the former Soviet Union, and Eastern Europe is approximately 0.6 kg/person/day. (References are listed in Table 8-2.)

For most Asian countries, estimates of MSW generation were at best identified for one or two major cities, but not for the entire country. National per-capita MSW generation estimates were found for Indonesia, Sri Lanka, the Philippines, Singapore, Taiwan, and Pakistan. These estimates range from 0.4 kg/person/day for the Philippines to 1.0 kg/person/day for Singapore. The average per-capita MSW generation for these countries is estimated to be 0.6 kg/person/day. (References are listed in Table 8-2.)

Few data are available on MSW production and management in Latin America and the Caribbean Islands. Most of the available information is only for the larger cities. The average per-capita MSW generation rate in Costa Rica, Mexico, Brazil, Colombia, Chile, Paraguay, Peru, and Venezuela is estimated to be 0.8 kg/person/day. (References are listed in Table 8-2.)

Information on MSW generation and disposal for African and Middle Eastern countries is very limited. Some information pertaining to generation rates for African countries was located, but information for only two Middle Eastern countries -- Israel and Yemen -- was obtained. Based on the very limited information for African and Middle Eastern countries, it is estimated that per-capita generation rates range from 0.3 to 1.1 kg/person/day. (References are listed in Table 8-2.)

Not all waste that is generated will actually be landfilled. It may also be incinerated or recycled. For most OECD countries, ample data are available to determine the percentage of landfilled waste. For other countries, a default had to be defined. The default for each country is based on expert judgment and relies on information that is primarily anecdotal. In many countries, much of the garbage is scavenged before it is collected, especially paper, textiles, and metal products. It may also be (1) burned for heating or cooking purposes, (2) fed to domestic animals, (3) dumped in rivers or other bodies of water, or (4) swept out onto the street or buried. In addition, garbage is often burned at the dump to reduce the volume. This practice decreases the amount of material available for anaerobic decomposition. Finally, the open dumps are often scavenged again by humans and animals.

8.3.2. AEERL Regression Model Methodology

The AEERL Regression Model Methodology is detailed in a report entitled "Global Methane Emissions from Landfills and Open Dumps," which AEERL will publish in early 1994. The AEERL model is empirical, based on the assumption that CH_4 flow rates from landfills with landfill gas (LFG) recovery systems can be used as surrogates for CH_4 generation and successively for CH_4 emissions. To investigate the validity of this assumption, AEERL initiated a program to collect data from 30 landfills with LFG recovery systems. The objective of this program was to develop a statistical model of annual landfill CH_4 emissions as a function of climate, refuse mass, age, waste acceptance rate, composition, and compaction, as well as to obtain an emission factor, which could be used to estimate both U.S. and global CH_4 emissions from landfills. Sites were chosen to represent a wide range of climate conditions, as they occur in the United States. The research concluded that the mass of waste-in-place showed a significant correlation with CH_4 flow rates. None of the climate variables -- precipitation, average temperature, and dewpoint -- proved to have significant correlations with CH_4 flow rates. The effect of refuse age on gas production was also analyzed. Gas flow rates correlated most strongly with refuse age for 10- to 20-year-old refuse. Although these results were not conclusive, they suggest that the generation time for gas production is 20-30 years, with an average of 25 years (U.S. EPA, 1991b; and U.S. EPA 1992b). This generation time is within the range of generation times assumed in other landfill gas recovery models (EMCON, 1982; and Augenstein and Pacey, 1990).

To relate CH_4 flow rates from recovery projects to CH_4 generation rates, two assumptions needed to be made. It was assumed that the average recovery efficiency of a gas-collection system is 75% (adapted from Augenstein and Pacey (1990)). Furthermore, it was assumed that 10% of nonrecovered CH_4 is oxidized (adapted from Whalen et al. (1990)). Both assumptions are subject to discussion, as very limited data exist.

The model is detailed in Doorn et al. (1994). As mentioned before, for most countries total waste-in-place data are not available and have to be developed from annual waste generation rates. As the variability of country-specific waste generation rates is unknown, it is assumed that waste generation is steady state. Annual waste generation rates are multiplied by the U.S. generation time (25 years) to obtain a surrogate for waste-in-place, which is in turn multiplied by the U.S. emission factor and two country-specific parameters. (As mentioned in section 8.3.2., CH_4 flow rates are not significantly correlated with climate.) The first parameter accounts for differences in chemical composition, expressed in CH_4 potential. The U.S. average CH_4 potential is corrected for other countries by using country-specific waste composition data. The second factor expresses which fraction of total waste-in-place is decaying under anaerobic conditions.

The U.S. values for generation time and emission factor may be used since country-specific variations in generation times and emissions per waste mass (emission factor) are eliminated in the above described multiplication. For instance, if in a country the generation time would be 12.5 years instead of 25, then the emissions per waste mass (the emission factor) would have to be twice as high, hence the product stays unaltered.

AEERL's global model can be expressed mathematically by:

$$Y = F_M F_D \frac{CH_4POT_M}{CH_4POT_{US}} EGM - Y_R$$

in which:

MSW generated (tg/yr)	=	M	
MSW (%) to landfill or dump	=	F_M	
Degree to which dump or landfill is anaerobic	=	F_D	
Av. CH_4 pot. of landfilled MSW country M (l/kg)	=	CH_4POT_M	
Av. CH_4 potential of landfilled waste US (l/kg)	=	CH_4POT_{US}	= 80
Emission factor (g/g.yr)	=	E	= 0.00187
Time waste produces CH_4 (years)	=	G	= 25
Methane recovered or flared (tg/yr)	=	Y_R	
Methane emissions (tg/yr)	=	Y	

8.3.3 Draft IPCC/OECD Methodology

The draft IPCC/OECD methodology (OECD, 1991) was adapted from a model developed by Bingemer and Crutzen (1987). The IPCC/OECD model uses theoretical calculations based on a mass-balance approach, where an instantaneous release of CH_4 is assumed to enter the atmosphere during the same year that refuse is placed in a landfill. It also assumes that all of the CH_4 that is produced escapes to the atmosphere (i.e., none is oxidized on route to the atmosphere). A third assumption of this method is that all developing nations generate and dispose of municipal solid waste at the same per-capita rate. The model also considers just urban waste, assuming that the large majority of landfilled waste is produced in cities. Of course, country-specific data on MSW generation rates and percentage of waste landfilled are preferred, recognizing that these data, too, have uncertainties.

To calculate the annual CH_4 emissions from MSW, IPCC/OECD used the following equation:

CH_4 Emission = Total MSW Generated (kg/yr) x MSW Landfilled or Dumped(%) x DOC in MSW (%) x Dissimilated DOC (80%) x Concentration of CH_4 in Landfill Gas (0.5 g/g) x Conversion Factor (16 g CH_4/12 g C) - Recovered CH_4 (kg/yr)

where:

DOC	=	degradable organic carbon;
Dissimilated DOC	=	portion of carbon in substrates that is converted to landfill gas assumed to be 80% (Bingemer and Crutzen, 1987); and
Recovered CH_4	=	amount of CH_4 that is recovered through gas-recovery systems and never emitted to the atmosphere.

The method is detailed in OECD (1991). It should be pointed out that two variables in the equation (Total MSW Generated, MSW Landfilled, and the Fraction of MSW Landfilled or Dumped) also are used in the AEERL method. The uncertainties of the IPCC/OECD approach relative to the AEERL method are attributed to assumptions regarding the extent of anaerobic decomposition (i.e., the fraction of dissimilated DOC). Many factors inhibit this

process, and this approach could overstate potential emissions. In addition, the methodology as it is currently used by IPCC/OECD does not adjust for CH_4 oxidation.

8.4 RESULTS

Table 8-3 gives country-specific waste-generated data, as well as CH_4 emission estimates using the IPCC/OECD and the AEERL methodologies. For reasons of comparison, both methods use the same waste-generated data computed by AEERL. Therefore, IPCC/OECD estimates may differ from official IPCC/OECD estimates. As shown in Table 8-3, the global landfill CH_4 emission estimate using the IPCC/OECD methodology is 57 Tg/yr. Both estimates are based on 1990 data for the United States and some European countries. Due to lack of reliable data, no attempt has been made to upgrade other country estimates to 1990 levels. Estimates have been adjusted for the amount of CH_4 released from industrial landfills and the amount of CH_4 that is recovered for energy utilization or flared.

Based on U.S. EPA's regression model methodology, estimates of global landfill CH_4 emissions range from 19 to 39 Tg/yr, with a mid-point of 27 Tg/yr. The estimate for the United States (8-16 Tg/yr) has also been adjusted for the amount of CH_4 that is recovered for energy utilization and for the contribution from industrial landfills. AEERL estimates that 0.6 Tg/yr of CH_4 are emitted from industrial landfills (Doorn et al., 1994). For other countries estimates of CH_4 emissions from industrial and hazardous waste landfills are not available. Emission estimates for countries other than the United States have also been adjusted for the amount of CH_4 that may be recovered for energy utilization. Richards (1989) and Thorneloe (1992b) estimate that worldwide there are 269 sites in 20 countries where landfill gas is recovered, including 114 sites in the United States.

AEERL's estimate for U.S. landfill CH_4 emissions differs from the estimate published in EPA's report to Congress on domestic methane emissions (i.e., 8-12 Tg/yr) because of differences in assumptions made about waste-in-place in U.S. landfills. There are many factors that contribute to the uncertainty of these estimates. Future work to develop more reliable information on waste quantities landfilled and waste composition will help to reduce uncertainties. A midpoint estimate of 10 Tg/yr is used in this report for U.S. landfill methane emissions.

Uncertainties in the AEERL estimate are expressed by giving lower- and upper-bound values. Ranges have not been developed for the IPCC estimate. Due to the impossibility of estimating errors associated with the assumptions made for most -- if not all -- methods, a mathematical approach in which individual errors are propagated is meaningless. Therefore, the following method was adopted. The standard deviation in the emission factor, developed from the landfill-gas-flow data, is 9% (Doorn et al., 1993). Approximate 95% confidence intervals are obtained by adding plus/minus two standard deviations to the estimate. Consequently, it is assumed that errors in all other parameters amount to at least the same error. Therefore, ranges are expressed by adding ±36% to the emission estimate.

8.5 TRENDS

The potential control of CH_4 emissions from municipal solid waste landfills has been targeted by the United States and other countries as part of greenhouse gas reduction programs designed to meet the goals of treaties signed at the United Nations Conference on

Environment and Development (UNCED) held in 1992. For example, the United States has proposed regulations for MSW landfills that will result in a CH_4 emission reduction of about 7 Tg/yr by the year 2000. Since such a reduction would be a significant step toward realizing of the goals established at UNCED, and because this source is amenable to cost-effective control measures, research designed to reduce the uncertainty associated with CH_4 emission estimates has a high priority (Thorneloe, 1993).

In general, the waste generated by developing countries has been projected to increase over the next several decades; in contrast, the waste generated by developed countries is expected to decline. This trend can be attributed to projections of higher population increases in developing countries and not to increased per-capita waste generation. Despite efforts toward source reduction and recycling, per-capita waste generation is expected to increase in the United States (U.S. EPA, 1992a) and in other industrialized countries. The much lower rates of population growth in industrialized countries are expected to result in slower growth in MSW production, as compared to developing countries (U.S. EPA, 1992b). However, this scenario will not be realized if per-capita income decreases in developing countries. Recently, declining economic conditions have resulted in reduced waste generation in Caracas, Venezuela; Mexico City, Mexico; and Buenos Aires, Argentina (Bartone et al., 1991). As methods of MSW disposal change, there will be changes in CH_4 emissions. Trends in global waste management and their impacts on CH_4 release are discussed below.

8.5.1 Europe

In the future, some countries, including the Netherlands, Germany, and Denmark, plan to increase the amount of MSW handled by recycling and incineration and to decrease the amount placed in landfills. Landfills will be large, regional sites that also will be used to dispose of incinerator ash. The decreases in the amount of MSW landfilled, coupled with increases in landfill gas recovery and incineration, are anticipated to lead to reduced CH_4 emissions and increased emissions of CO_2 and other combustion gases.

Sanitary landfills or open dumps are used almost exclusively for MSW management in Greece, Hungary, Portugal, Poland, Romania, Bulgaria, the former Yugoslavia, and the former Soviet Union (Bartone and Haley, 1990; Curi, 1988; and Mnatsaknian, 1991). In the future, Poland plans to prohibit open dumping in favor of sanitary landfilling. The former Soviet Union hopes to establish an effective recycling program. No landfill-gas-recovery sites were identified in these countries. A U.S. company (Natural Power) is negotiating a gas-recovery contract with a landfill in Kiev in the Ukraine. This site has 9 million tonnes of waste. The gas is to be used to generate electricity for the Ukraine capital (Thorneloe, 1992b). If this project proves successful, additional projects may be initiated.

8.5.2 United States and Canada

Landfilling is the predominant MSW management method in both the United States and Canada. Although there is a trend in both countries toward more recycling, more incineration, and less landfilling, absolute MSW generation is projected to continue to grow (U.S. EPA, 1992a; U.S. EPA, 1988; El Rayes and Edwards, 1991; and Alter, 1991). Until the end of the century, it is not expected that the percent DOC in MSW will differ considerably from current levels (U.S. EPA, 1993a). Based on this information and U.S. EPA (1992a) and Willumsen (1990), it can be assumed that the current rate of landfill gas generation will continue for several more decades.

The amounts of CH_4 emitted to the atmosphere will decrease as more is controlled through flaring or utilization (Thorneloe, 1992b; and Bonomo and Higginson, 1988). U.S. landfills are currently recovering about 1.2 Tg of CH_4 and are producing 344 megawatts of power (Thorneloe, 1992a). The new rule for the control of nonmethane landfill gas, proposed under the Clean Air Act Amendments, is expected to have a major impact on reducing landfill CH_4 emissions from both new and existing MSW landfills in the United States and may result in an additional CH_4 emission reduction ranging from 5 to 7 Tg (*Federal Register*, 1991; and U.S. EPA, 1991).

8.5.3 Asia

Some Asian countries are upgrading their collection methods by introducing compactor trucks and covered containers. These changes could serve to decrease the amount of scavenging and increase the amount of MSW that is dumped. Economic constraints, in tandem with a history of slow MSW management development, indicate that the use of sanitary landfills will not increase markedly in the near future for most of Asia. However, increases in population and, thus, total MSW will likely lead to increased CH_4 emissions.

8.5.4 Latin America and the Caribbean Islands

In the future, Brazil hopes to build recycling and composting plants, and sanitary landfills. Mexico also hopes to increase its number of sanitary landfills. Few landfill-gas-recovery sites are currently operating in Brazil, Chile, and Mexico, although there seems to be some interest in increasing the number of such sites in Brazil (Kessler, 1990; and Richards, 1988).

8.5.5 Africa and Middle East

In Africa's foreseeable future, the only MSW management methods reported to hold promise for expanded and successful application are recycling, composting, or possibly biogas recovery if markets and appropriate technologies can be developed to support these systems (Cointreau, 1982; Betts, 1984; Oluwande, 1984; Vogler, 1984; and El-Halwagi et al., 1988). Much of the recyclable material in the MSW stream is currently being recovered, at least when comparing the amount of material recycled in low-income countries with that of middle-income and developed nations. However, because the recycling efficiency is low, recyclable materials are still available in the waste streams, and because wages are low in the developing countries, further recycling may be a viable waste management option (Wright et al., 1988).

8.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

8.6.1 Quantity and Composition of Waste-in-Place

Reliable waste-in-place estimates exist for only few countries. Where these data were not available, waste-generation rates combined with waste management data were used. Local waste-generation data are usually readily available; however, they typically apply to only a certain city or region. Extrapolation of these data to national levels may be a source of considerable uncertainty. Even if a reasonable estimate of rural waste generation can be approximated, it is hard to assess how much of this waste will eventually be landfilled or dumped. In certain rural areas of the world, it may well be that practically all rural MSW is recycled. In the same fashion, waste composition data also usually apply to cities or regions

and have to be extrapolated. Fortunately, the countries that produce the most waste also have the most extensive data on waste generation and composition. In fact, 57% of CH_4 from landfills is produced by six countries only (France, Germany, Italy, United Kingdom, Canada, and the United States). Ongoing research by U.S. EPA will result in the refinement of these estimates to account for waste composition in different geographical regions and the changing waste composition in landfills occurring in countries adopting recycling programs (Barlaz, 1992; and Thorneloe, 1993).

8.6.2 CH_4 Production of Waste in Open Dumps and Industrial Landfills

As discussed in section 8.2.3, assessment of the CH_4 potential and generation from landfilled waste is prone to considerable uncertainty. The uncertainty is enhanced for open dumps. Two issues contribute to the difficulty of estimating CH_4 production from open dumps: both the physical characteristics of open dumps (size, configuration, temperature, moisture, and compaction) and the quantity and composition of open-dumped waste are unknown. Bhide et al. (1990) reported biogas recovery from two uncontrolled landfills in India. Each of these sites was about 8 hectares in surface area and about 3-5 m deep. Neither site contained any cover material, and the oldest of the two landfills accepted waste from 1971 to 1984. Most of the organic matter had decomposed by the time the tests were performed, but biogas was obtained from a well 0.05 m in diameter at a rate of 0.240 cubic meter per hour (m^3/hr) (CH_4 content not presented). Waste had been deposited in the second site "only recently," and the rate of biogas recovery was from 5 to 9 m^3/hr. The CH_4 content of the biogas from the second site was 30-40%. The work of Bhide et al. (1990) suggests that opens dumps are a source of CH_4. Consequently, they have been included in the emission estimates.

The CH_4 production of other types of landfills, such as those containing industrial and hazardous wastes, is not well understood. Definitions of "industrial waste" may vary. Some authors include construction and demolition debris, thus reporting vast amounts of industrial waste, with practically no DOC. Others distinguish between industrial and commercial waste -- commercial waste being waste generated by offices and shops. This waste would typically consist of paper and would, therefore, be a potential source of CH_4. Industrial waste can also consist of waste streams that will decompose under anaerobic conditions. Certain industrial waste streams, such as that of the food industry, have a high organic content and are, therefore, potentially significant sources of CH_4. Landfills containing hazardous waste will have a low CH_4 production because of the low moisture content and the requirement that only solid materials are accepted. In addition, chemicals in the waste stream may be toxic to the microbes. The disposal of industrial and hazardous waste with MSW was common in the United States through 1975 and is still common in most other countries. Waste streams in developing countries are virtually uncontrolled, and mingling of MSW, industrial wastes, and raw sewage in landfills is common (Cointreau, 1982).

8.6.3 Quantity of CH_4 Emitted to the Atmosphere

As mentioned in section 8.2.3, not all CH_4 produced in a landfill would be emitted to the air. CH_4 oxidation has been documented in landfill cover soil studied under laboratory conditions (Whalen et al., 1990). However, there are no data on the quantitative significance of CH_4 oxidation for landfills. CH_4 escaping through cracks in a landfill cover most likely will not reside in the cover for a period sufficient to undergo significant oxidation. Assessment of the amount of CH_4 that may be oxidized on its way out of the landfill (i.e., 10%) is solely a matter of expert judgment.

8.7 CONCLUSIONS

Global and country-specific estimates were developed for CH_4 emissions from landfills and open dumps using the proposed IPCC/OECD and the EPA/AEERL methodologies. The estimates for global and U.S. CH_4 emissions resulting from these two approaches are presented in Table 8-4.

The United States is by far the largest contributor of global landfill CH_4, accounting for up to 50% of the emissions. The other geographic regions that are significant contributors are Europe, accounting for about 20%, and Asia, with about 16%.

Because this source is amenable to cost-effective control through the use of the CH_4, it is under consideration by a number of countries for programs that would result in a reduction in current emissions. The United States, for example, has proposed regulations under the Clean Air Act for new and existing MSW landfills. These regulations are scheduled to be promulgated in the spring of 1994. Approximately 7 Tg in the year 2000 are expected to be reduced. If this CH_4 is recovered for its energy potential, a further reduction of emissions resulting from coal-fired power plants would also be achieved. The United States has also adopted policies that will result in waste-minimization and recycling programs, which should, in turn, reduce CH_4 emissions.

TABLE 8-4

ESTIMATES OF METHANE EMISSIONS FROM LANDFILLS FROM OECD/IPCC AND EPA/AEERL METHODOLOGIES

		EPA/AEERL	
	IPCC/OECD	Range	Mid-Point
Global	57	19-39	29
United States	20	8-16	12

Other countries are considering programs either to regulate or to provide incentives that encourage energy recovery. These countries include Canada, the United Kingdom, Germany, the Netherlands, and Japan. These programs are expected to reduce global emissions of CH_4 from landfills. In addition, many industrialized countries are adopting recycling and waste-minimization programs that decrease the amount of waste in landfills. However, developing countries that are increasing their use of sanitary landfills are expected to generate greater CH_4 emissions in the future. It is important that larger sites are encouraged towards use or control of the CH_4 to continue a decrease in global CH_4 emissions from landfills and open dumps.

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CHAPTER 9

METHANE EMISSIONS FROM LIVESTOCK MANURE

9.1 SUMMARY

Methane is produced during the anaerobic decomposition of the organic material in livestock manure. This report estimates that in 1990 global methane emissions from livestock manure were about 14 teragrams (Tg)[1] with a range of about 10-18 Tg. Three animal groups account for about 80% of total emissions: swine, about 40%; nondairy cattle, about 20%; and dairy cattle, about 20%. Liquid-based systems, such as lagoons and liquid/slurry storage, account for about 60% of total emissions.

Three regions of the world contribute about 85% of total emissions: Europe (Eastern and Western), about 40%; Asia and the Far East, about 30%; and North America, about 15%.

Methane emissions from livestock manure could increase significantly during the coming decades. As the demand for livestock products increases, animal populations and manure production will increase. Also, the use of liquid-based systems for managing livestock manure (which promote methane production) may increase substantially because of growing concerns over the direct land application of livestock manure and the increased adoption of large, confined animal management practices.

This estimate of methane emissions from animal manure is lower than previous estimates of 25 $\pm$ 5 Tg. Recent laboratory analyses indicate that the rate of methane production is lower than previously estimated for several key manure management conditions, including manure deposited on pastures and range. Additional laboratory and field measurements are required to improve the basis for making these emission estimates.

9.2 BACKGROUND

Microbiological decomposition is a process in which microorganisms derive energy and material for cellular growth by metabolizing organic material -- for example, organic material in livestock manure. When decomposition occurs in an oxygen-free environment (anaerobically), methane (CH_4) is produced. Because the quantity of livestock manure produced annually is large, and because the manure is primarily composed of organic material, the potential for CH_4 emissions is great. However, only a portion of this emission potential is realized because when the manure is kept in contact with oxygen (e.g., spread on fields) CH_4 production is minimal.

The principal determinants of CH_4 production from livestock manure are the following:

- Characteristics of the manure. Potential CH_4 production is directly related to the quantity of manure and the fraction of the manure available for decomposition. These factors vary by animal species and their diet.

[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

- Manure management system. The manure management system strongly influences CH_4 production from livestock manure. Manure management systems that promote anaerobic (oxygen-free) decomposition will produce the most CH_4.

- Climate. Temperature and rainfall affect both the rate and the total amount of CH_4 production in livestock manure. A warm and moist environment promotes CH_4 production.

9.2.1 Characteristics of the Manure

The composition of livestock manure, which is primarily a function of the animal species and diet, determines its maximum CH_4-producing capacity. For a given species, the greater the energy content and digestibility of the diet, the greater the CH_4-producing capacity of the manure. For example, cattle fed a high-energy grain diet produce a highly biodegradable manure. Cattle fed a roughage diet will produce a less biodegradable manure containing more complex organics, such as cellulose, hemicellulose, and lignin. Under similar conditions, the manure of cattle fed the high-energy, corn-based diet will produce about twice as much CH_4 per unit of volatile solids[2] (VS) as the manure of the cattle fed a roughage diet.[3]

The CH_4-producing capacity of livestock manure is generally expressed in terms of the quantity of CH_4 that can be produced per kilogram of volatile solids (VS) in the manure. This quantity is commonly referred to as B_o with units of cubic meters of CH_4 per kilogram VS (m^3 CH_4 / kg VS). B_o values for many common feeding conditions have been determined experimentally.

9.2.2 Manure Management System

The characteristics of a manure management system determines how much of the maximum CH_4-producing capacity (B_o) can be realized. These characteristics include:

- Contact with oxygen. Under aerobic conditions where oxygen is in contact with the manure, CH_4 is not produced.

- Moisture content. Liquid-based systems promote an oxygen-free environment and anaerobic decomposition. In addition, water is required for bacterial cell production and metabolism and acts as a buffer to stabilize pH. Moist conditions lead to larger CH_4 emissions than do dry conditions.

- pH. Methane-producing bacteria are sensitive to changes in pH. The optimal pH is near 7.0, but CH_4 will be produced between 6.6 and 7.6. Deviation in pH from 7.0 will decrease the rate of CH_4 production.

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[2] "Volatile solids" (VS) are defined as the organic fraction of the total solids (TS) in waste that will oxidize and be driven off as gas at a temperature of 600°C. Total solids are defined as the material that remains after evaporation of water at a temperature between 103° and 105°C.

[3] The quantity of manure produced is also affected by the digestibility of the diet. At a given level of dry matter intake, a higher-digestibility diet results in less manure excretion than a low-digestibility diet. However, dry-matter intake and digestibility are not independent, so that a simple inverse relationship between digestibility and manure production is not generally observed under realistic production conditions.

- Nutrients. Bacterial growth depends on the availability of nutrients, such as nitrogen, phosphorus, and sulfur. Deficiency in one or more of these nutrients will inhibit bacterial growth and CH_4 formation. Animal diets typically contain sufficient nutrients to sustain bacterial growth, and so nutrient availability is not usually a limiting factor in CH_4 production.

9.2.3 Climate

The climatic conditions in which manure decomposes have a strong influence on CH_4 production. These conditions include:

- Temperature. Methanogenesis in livestock manure has been observed between 4° and 75°C. Temperature is one of the major factors affecting the growth of the bacteria responsible for CH_4 formation (Chawla, 1986). Methane production generally increases with rising temperature within this range and levels off between 60° and 75°C.

- Moisture. For nonliquid-based manure systems, the moisture content of the manure is determined by rainfall and humidity. Because the moisture content of the manure will determine the rate of bacterial growth and manure decomposition, moist climate conditions promote CH_4 production.

9.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

The approach described in OECD (1991) is recommended for estimating CH_4 emissions from livestock manure. Emissions from this source depend on the quantity and type of manure, the characteristics of the manure management system, and the climatic conditions in which the manure decomposes. While limited data are available on which to base emission estimates, a study recently prepared for the U.S. EPA (Safley et al., 1992) and ongoing laboratory studies being conducted at Oregon State University (Hashimoto and Steed, 1993) provide an adequate basis for making initial estimates. Additional research is ongoing to provide the necessary data for refining these estimates.

The steps used to estimate emissions are as follows:

- Estimate the amount of volatile solids produced for each animal type (VS_i), using published statistics on animal populations, animal sizes, and manure generation rates.

- Estimate the maximum CH_4-producing capacity for the manure from each animal type (B_{oi}), based on published literature values and animal diets.

- Define the manure management systems in use, and for each system estimate its CH_4-producing potential (CH_4 conversion factor, or MCF_j).

- For each animal type, estimate the fraction of total manure managed by each manure management system (management system percentage, or $MS\%_{ij}$).

- Estimate CH_4 emissions for each animal type and manure management system (TM_{ij}) by multiplying the amount of volatile solids produced by the animal type (VS_i) by the CH_4-producing capacity of the manure (B_{oi}) by the CH_4-producing potential of the manure management system (MCF_j) by the percentage of the manure handled by the management system ($MS\%_{ij}$).[4]

- Total CH_4 emissions will be the sum over all animal types (*i*) and all manure systems (*j*).

Currently, Hashimoto and Steed (1993) are developing improved estimates of MCFs for key manure management systems, including examining the variability of the MCF values with temperature. The initial results of this investigation have been incorporated into this assessment by assigning each country to one of three climate categories based on mean annual temperature.[5]

Using this approach, total annual CH_4 emissions (TM_i) for animal type *i* in a particular climate region is the sum of annual emissions over all applicable manure systems *j*:

$$TM_i = \sum_j VS_i \cdot B_{oi} \cdot MCF_j \cdot MS\%_{ij} \qquad (9.1)$$

where:

VS_i	=	total volatile solids produced annually (in kilograms) for animal type *i*;
B_{oi}	=	maximum CH_4-producing capacity per kilogram of VS for animal *i*;
MCF_j	=	CH_4 conversion factor for manure system *j* in the climate region; and
$MS\%_{ij}$	=	percentage of the animal type *i*'s manure handled using manure management system *j*.

The amount of volatile solids produced depends on the number of animals and their mass:

$$VS_i = N_i \cdot TAM_i \cdot vs_i \qquad (9.2)$$

where:

N_i	=	number of animals;
TAM_i	=	typical animal mass in kilograms; and
vs_i	=	average annual volatile solids production per unit of animal mass.

In many cases, either the typical animal mass (TAM_i) or volatile solids production per unit of animal mass (vs_i), or both, are not known. In these cases, total annual VS production per head was estimated directly, so that the total annual VS production for the population of animals can be estimated by:

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[4] In Safley et al. (1992), MS% is referred to as WS% for waste system percentage.

[5] The mean annual temperature is an imperfect predictor of the mean annual MCF. Based on Hashimoto and Steed's preliminary analysis, the relationship between temperature and MCF is nonlinear and increasing in the range between 0° and 30°C. This is particularly true for liquid-based systems. For liquid-based systems in many temperate climates, using the mean annual temperature to predict the mean MCF will most likely understate the true mean MCF. The preferred approach would be to use the mean monthly temperature to predict the mean monthly MCF and to average these monthly MCFs for an annual figure. However, accurate monthly temperature data for all the countries of the world were not readily available.

$$VS_i = N_i \cdot \overline{vs_i} \quad (9.3)$$

where:

N_i = number of animals; and

$\overline{vs_i}$ = average annual volatile solids production per head.

Total annual CH_4 emissions from all animals (TM) is estimated as the sum over all *i* animal types:

$$TM = \sum_i TM_i \quad (9.4)$$

The following sections describe the data collected by Safley et al. and Hashimoto and Steed to implement this method.

9.3.1 Volatile Solids (VS) Production

Methane emissions from livestock manure are related to the amount of volatile solids (VS) produced. The data required to estimate total VS production are shown in Equation 9.2: the number of animals (N_i), their average size (TAM_i), and their average VS production per unit of animal size (vs_i). Animal population data are available for all countries. For cattle and buffalo, the animal size data used to estimate CH_4 emissions from enteric fermentation (Chapter 2) are used here also. For the other species in developed countries,[6] data on animal size and VS production per unit of animal size are generally available, and Equation 9.2 can be implemented. For developing countries, however, animal size data are not generally available, and total VS production must be estimated using Equation 9.3.

For each country, the animal populations were divided into the following 11 categories: beef cattle,[7] dairy cattle, swine, sheep, goats, chickens, ducks, turkeys, horses, donkeys, and camels. Population statistics from FAO (1992) were used. For 13 developed countries, data for estimating the typical animal mass (TAM) for each category were available from *Meat and Dairy Products* (1988) and Taiganides and Stroshine (1971).[8] For developed countries without country-specific TAM data, the average of the values for the 13 countries was used.

Total VS production rates per unit of animal mass for the United States were used as the basis for VS production for the developed countries. In some cases, small adjustments were made to several of the rates to reflect differences in diets. Table 9-1 presents average statistics for the TAM, manure production, and VS production estimates for the developed countries.

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[6] For purposes of this analysis, developed countries include: Albania, Australia, Austria, Belgium, Bulgaria, Canada, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, the Netherlands, New Caledonia, New Zealand, Norway, Poland, Portugal, South Africa, Sweden, Switzerland, United Kingdom, the United States, the former Soviet Union, the former Yugoslavia, and the former Czechoslovakia.

[7] The category "beef cattle" includes buffalo.

[8] The 13 countries for which TAM data were obtained are: Australia, Austria, Belgium, Denmark, France, the former West Germany, Ireland, Italy, the Netherlands, South Africa, the United Kingdom, the former Soviet Union, and the former Yugoslavia. TAM data were not required for the United States because VS/head data were available for animal types in the United States.

TABLE 9-1

LIVESTOCK MANURE PRODUCTION DATA FOR DEVELOPED COUNTRIES[a]

Animal Type	Typical Animal Mass (TAM) (kg)	Total Manure Production		Volatile Solids Production	
		Kg/Day/ TAM	Kg/Day/ 1000 Kg Mass	Percent of Total Manure Production	Kg/Day/ 1000 Kg Mass
Beef Cattle[b]	375.0	21.80	58	12.4	7.2
Dairy Cattle	550.0	47.30	86	11.6	10.0
Swine	59.0	5.00	85	10.1	8.6
Sheep	67.0	2.70	40	23.0	9.3
Goats	64.0	2.60	41	26.6	10.8
Chickens	1.1	0.10	91	19.4	17.6
Ducks	1.4	0.15	107	17.3	18.5
Turkeys	6.8	0.30	44	19.4	8.6
Horses[c]	450.0	23.00	51	19.6	10.0
Donkeys	300.0	15.30	51	19.6	10.0
Camels	450.0	23.00	51	16.0	8.2

a. Average values estimated for developed countries. Individual country data are used when available.

b. Includes buffalo.

c. Includes mules.

Sources: Safley et al., 1992. TAM for cattle taken from Chapter 2 of this report.

With the exception of cattle and buffalo, estimates of the typical animal mass (TAM) for each category were not made for the developing countries because of the lack of data. Instead, manure and VS production per head were estimated directly using published literature sources (Jain et al., 1981; Ramen et al., 1989; Singh et al., 1985; Gunaseelan, 1987; Lichtman, 1983; Gorkhali, 1984; and Chen et al., 1988). Table 9-2 summarizes the manure production and VS production estimates by animal type for developing countries.

9.3.2 Maximum Methane-Producing Capacity (B_o)

The maximum amount of CH_4 that can be produced per kilogram of VS (B_o) varies by animal type and diet. Safley et al. found that little data are available describing the B_o values for manures produced in countries other than the United States. Consequently, Safley et al.'s B_o estimates for countries other than the United States were adopted here. In making their estimates, Safley et al. considered the impact of the variation in livestock diets around the world on the CH_4-producing potential by estimating the energy content of the feed consumed by the animals in different regions. Table 9-3 lists the B_o values adopted for developed and developing countries.

TABLE 9-2

LIVESTOCK MANURE PRODUCTION DATA FOR DEVELOPING COUNTRIES

Animal Type	Total Manure Production (kg/head/day)	Volatile Solids Production	
		Percent of Total Manure Production	Kg/Head/Day
Cattle (nondairy)[a]	13.60	12	1.70
Dairy Cattle	27.50	12	3.20
Swine	4.10	10	0.41
Sheep	1.60	23	0.37
Goats	1.80	27	0.49
Chickens	0.12	19	0.02
Ducks	0.12	17	0.02
Turkeys	0.26	19	0.05
Horses and Mules	18.40	20	3.70
Donkeys	12.20	20	2.40
Camels	18.40	16	2.90

a. Includes buffalo.

Sources: Safley et al., 1992. Estimates for cattle based on TAM data in Chapter 2 of this report.

9.3.3 Descriptions of Manure Management Systems

Various manure management practices are in use throughout the world. In many parts of the world, manure is spread on fields as a fertilizer. In other cases, manure is used as an energy source. The following is a brief description of the major systems in use for managing livestock manure.

Pasture/Range — The manure from pasture- and range-grazing animals is allowed to lie as is, and is not handled at all.

Daily Spread — Manure is collected in solid form by some means, such as scraping. The collected manure is applied to fields regularly (usually daily).

Solid Storage — Manure is collected as in the daily spread system, but is stored in bulk for a long period of time (months) before any disposal.

Drylot — In dry climates animals may be kept on unpaved feedlots where the manure is allowed to dry until it is periodically removed. Upon removal, the manure may be spread on fields.

TABLE 9-3

B_0 VALUES FOR DEVELOPED AND DEVELOPING COUNTRIES

Animal Type	United States (m^3 CH_4 / kg VS)	Developed Countries (Non-U.S.) (m^3 CH_4 / kg VS)	Developing Countries (m^3 CH_4 / kg VS)
Cattle (nondairy) and buffalo	0.17/0.33[a]	0.17	0.10
Dairy Cattle	0.24	0.24	0.13
Swine	0.36/0.47[b]	0.45	0.29
Sheep	0.19/0.36[c]	0.19	0.13
Goats	0.17	0.17	0.13
Chickens	0.30/0.34[d]	0.32	0.24
Ducks	0.32	0.32	0.24
Turkeys	0.30	0.30	0.24
Horses and Mules	0.33	0.33	0.26
Donkeys	0.33	0.33	0.26
Camels	0.26	0.26	0.21

a. The lower value is for cattle not in feedlots. The higher value is for feedlot cattle.

b. The lower value is for breeder hogs. The higher value is for market hogs.

c. The lower value is for sheep not in feedlots. The higher value is for feedlot sheep.

d. The lower value is for broilers. The higher value is for layers.

Source: Safley et al., 1992.

Deep-Pit Stacks With caged layers, the manure may be allowed to collect in solid form in deep pits (several feet deep) below the cages. The manure in the pits may only be removed once a year. This manure generally stays dry.

Litter Broilers and young turkeys may be grown on beds of litter, and the manure/litter pack is removed periodically between flocks. This manure will not be as dry as with deep pits, but will still be in solid form.

Paddock Horses are frequently kept in paddocks where they are confined to a limited area, but not entirely confined to their stalls. This system is similar to pasture and drylot manure systems.

Liquid/Slurry These systems are generally characterized by large concrete-lined tanks built into the ground. Manure is stored in the tank for six or more months until it can be applied to fields. To facilitate handling as a liquid, water may be added to the manure.

Anaerobic Lagoon Anaerobic lagoon systems are characterized by flush systems that use water to transport manure to lagoons. The manure resides in the lagoon for periods from 30 days to over 200 days. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields.

Pit Storage Liquid swine manure may be stored in a pit while awaiting final disposal. The length of storage time varies, and for this analysis is divided into two categories: less than one month or greater than one month.

Anaerobic Digester The manure, in liquid or slurry form, is anaerobically digested to produce CH_4 gas for energy. The amount of CH_4 produced depends on the operating characteristics of the digester and the characteristics of the manure. The digester effluent is often used as a fertilizer.

Burned for Fuel Manure is collected and dried in cakes and burned for heating or cooking. This system is common in Asia and the Far East; in India it is estimated that two-thirds of cattle manure is burned for fuel (NCAER, 1965).

Building Material Manure is used as a building material in South Asia. It is applied to walls and floors to seal cracks and may have antiseptic properties.

9.3.4 Methane Conversion Factors (MCFs)

The extent to which the maximum CH_4-producing capacity (B_o) is realized for a given livestock manure management system must be known to determine the amount of CH_4 that is emitted. This fraction is defined as the Methane Conversion Factor (MCF) for the manure system. For example, a manure system that produces no CH_4 emissions would have an MCF of 0. A manure system that achieves the full potential CH_4 emissions would have an MCF of 1.

To assess the MCF values for the wide range of livestock manure management systems defined in the previous section, two broad classifications of livestock manure-handling systems can be defined, based on the total solids content of the manure:

- Solid systems have a total solids content greater than about 20%.
- Liquid/slurry systems have a total solids content less than 20%.

Liquid/slurry systems will typically cause the development of anaerobic conditions, which result in CH_4 production. The solid systems limit the development of anaerobic conditions and, thus, limit the amount of CH_4 that is produced from the manure.

Safley et al. reviewed the literature to investigate the appropriate range of MCF values for manure management systems and found that data on MCF values were not available for some systems. Consequently, they estimated values using the broad classifications of solid versus liquid/slurry management. To improve the MCF estimates, the U.S. EPA is sponsoring research to estimate better the MCFs for several key livestock manure systems (Hashimoto and Steed, 1993). Preliminary findings from this research indicate that:

- The estimated MCF value of dry *in situ* pasture, range, paddock, and solid storage manure is 1-2%. The estimated MCF for drylot manure is 1-5%. These values are lower than the 5-10% values used by Safley et al. However, to date the new analysis has not considered the effect of moisture, for example, from periodic rainfall or humidity. Consequently, these new values are most representative for arid regions.

  These estimates are consistent with the findings of Lodman et al. (1993) and Williams (1993). For range-deposited manure, both studies report MCFs of less than 1%; for feedlot-deposited manure, Lodman et al. (1993) estimate an overall MCF of 5%. Lodman et al.'s results are based on U.S. beef cattle, and Williams's results are based on Australian free-range dairy cows.

- The MCF for liquid/slurry and pit storage varies between 10% at 10°C and 65% at 30°C. Safley et. al. used a value of 20%.

- The MCF for daily spread is less than 1%, whereas the Safley et al. estimate was 5%.

- The MCF for anaerobic lagoons is about 90%. This estimate is based on continuous CH_4 measurements taken over a two and one-half year period at a North Carolina dairy (Safley, 1991) and includes an assessment of surface oxidation of the CH_4. The MCF of 90% for anaerobic lagoons is the same value as was used by Safley et al.

The MCFs for an individual country will depend on the temperature (see footnote 5). For purposes of this analysis, three climate categories were defined, corresponding to the temperature range used by Hashimoto and Steed (1993) to estimate MCFs:

- Warm climates -- having a mean annual temperature near or above 30°C;

- Temperate climates -- having a mean annual temperature near 20°C; and

- Cool climates -- having a mean annual temperature near or below 10°C.

Countries were assigned to each category based on Hammond Incorporated (1981). The MCF values for each system and climate category are listed in Table 9-4.

9.3.5 Livestock Manure Management System Usage (MS%)

Safley et al.'s estimates of the use of the manure management systems was used here. Safley et al. divided the world into eight primary regions, generally along the well-recognized geographic and economic classifications used by the Food and Agriculture Organization of the United Nations (FAO, 1992). Detailed information on the use of manure management systems was collected for selected countries by contacting the Ministry of Agriculture in each country. In addition, individual researchers in many countries provided information. Countries for which manure system information was not obtained were assumed to have manure system usage comparable to countries in their region with similar gross national product (GNP) per capita values and similar climates. Table 9-5 lists the percentages of manure managed by the major systems for each region of the world.

TABLE 9-4

METHANE CONVERSION FACTORS (MCFs) FOR LIVESTOCK MANURE SYSTEMS

MCFs Based on Laboratory Measurement	MCF at 30°C	MCF at 20°C	MCF at 10°C
Pasture, Range, Paddock[a]	2%	1.5%	1.0%
Liquid/Slurry[a]	65%	35.0%	10.0%
Pit Storage < 30 days[a]	33%	18.0%	5.0%
Pit Storage > 30 days[a]	65%	35.0%	10.0%
Drylot[b]	5%	1.5%	1.0%
Solid Storage[a]	2%	1.5%	1.0%
Daily Spread[a]	1%	0.5%	0.1%

MCF Measured by Long-Term Field Monitoring	Average Annual MCF
Anaerobic Lagoon[c]	90%

MCFs Estimated by Safley et al.	Average Annual MCF
Litter[d]	10%
Deep-Pit Stacking[d]	5%
Anaerobic Digester (Chinese)[e]	14%
Anaerobic Digester (Indian)[e]	5%
Burned for Fuel[f]	5-10%

a. Hashimoto and Steed, 1993.

b. Based on Hashimoto and Steed, 1993.

c. Safley et al., 1992, and Safley and Westerman, 1992.

d. Safley et al., 1992.

e. MCFs taken from Safley et al. (1992). Yancun et al. (1985) showed that typical Chinese digesters leaked at least 14% of the CH_4 produced. The typical floating-cover digesters used in India do not appear to be as leak-prone as the Chinese digesters (Stuckey, 1984; and Lichtman, 1983), so an MCF of 5% was adopted.

f. Methane emissions associated with combustion are not included in this estimate.

TABLE 9-5

LIVESTOCK MANURE SYSTEM USAGE

Animal Type	Anaerobic Lagoons	Liquid Systems[a]	Daily Spread	Solid Storage & Drylots	Pastures, Ranges, & Paddocks	Used for Fuel[b]	Other Systems[c]
			North America				
Nondairy Cattle[d]	0%	1%	0%	14%	84%	0%	1%
Dairy Cattle	10%	23%	37%	23%	0%	0%	7%
Poultry[e]	5%	4%	0%	0%	1%	0%	90%
Sheep	0%	0%	0%	2%	88%	0%	10%
Swine	25%	50%	0%	18%	0%	0%	6%
Other Animals[f]	0%	0%	0%	0%	92%	0%	8%
			Western Europe				
Nondairy Cattle[d]	0%	55%	0%	2%	33%	0%	9%
Dairy Cattle	0%	46%	24%	21%	8%	0%	1%
Poultry[e]	0%	13%	0%	1%	2%	0%	84%
Sheep	0%	0%	0%	2%	87%	0%	11%
Swine	0%	77%	0%	23%	0%	0%	0%
Other Animals[f]	0%	0%	0%	0%	96%	0%	4%
			Eastern Europe				
Nondairy Cattle[d]	8%	39%	0%	52%	0%	0%	1%
Dairy Cattle	0%	18%	1%	67%	13%	0%	0%
Poultry[e]	0%	28%	0%	0%	1%	0%	71%
Sheep	0%	0%	0%	0%	73%	0%	27%
Swine	0%	29%	0%	0%	27%	0%	45%
Other Animals[f]	0%	0%	0%	0%	92%	0%	8%
			Oceania				
Nondairy Cattle[d]	0%	0%	0%	0%	100%	0%	0%
Dairy Cattle	0%	0%	0%	0%	100%	0%	0%
Poultry[e]	0%	0%	0%	0%	3%	0%	98%
Sheep	0%	0%	0%	0%	100%	0%	0%
Swine	55%	0%	0%	17%	0%	0%	28%
Other Animals[f]	0%	0%	0%	0%	100%	0%	0%
			Latin America				
Nondairy Cattle[d]	0%	0%	0%	0%	99%	0%	1%
Dairy Cattle	0%	1%	62%	1%	36%	0%	0%
Poultry[e]	0%	9%	0%	0%	42%	0%	49%
Sheep	0%	0%	0%	0%	100%	0%	0%
Swine	0%	8%	2%	51%	0%	0%	40%
Other Animals[f]	0%	0%	0%	0%	99%	0%	1%

(continued)

TABLE 9-5

LIVESTOCK MANURE SYSTEM USAGE (Continued)

Animal Type	Anaerobic Lagoons	Liquid Systems[a]	Daily Spread	Solid Storage & Drylots	Pastures, Ranges, & Paddocks	Used for Fuel[b]	Other Systems[c]
			Africa				
Nondairy Cattle[d]	0%	0%	1%	3%	96%	0%	0%
Dairy Cattle	0%	0%	12%	0%	83%	0%	5%
Poultry[e]	0%	0%	0%	0%	81%	0%	19%
Sheep	0%	0%	0%	1%	99%	0%	1%
Swine	0%	7%	0%	93%	0%	0%	0%
Other Animals[f]	0%	0%	0%	0%	99%	0%	1%
			Near East and Mediterranean				
Nondairy Cattle[d]	0%	0%	2%	0%	77%	18%	2%
Dairy Cattle	0%	0%	3%	3%	77%	18%	0%
Poultry[e]	0%	1%	0%	0%	71%	0%	28%
Sheep	0%	0%	0%	0%	100%	0%	0%
Swine	0%	32%	0%	68%	0%	0%	0%
Other Animals[f]	0%	0%	0%	0%	100%	0%	0%
			Asia and Far East				
Nondairy Cattle[d]	0%	0%	16%	14%	29%	40%	0%
Dairy Cattle	6%	4%	21%	0%	24%	46%	0%
Poultry[e]	1%	2%	0%	0%	44%	1%	52%
Sheep	0%	0%	0%	0%	83%	0%	17%
Swine	1%	38%	1%	53%	0%	7%	0%
Other Animals[f]	0%	0%	0%	0%	95%	0%	5%

a. Includes liquid/slurry storage and pit storage.

b. Includes anaerobic digesters and burned for fuel.

c. Includes deep-pit stacks, litter, and other systems.

d. Includes buffalo.

e. Includes chickens, turkeys, and ducks.

f. Includes goats, horses, mules, donkeys, and camels.

Source: Safley et al., 1992.

9.4 RESULTS

This report estimates that 1990 global CH_4 emissions from livestock manure were about 14 Tg. Table 9-6 summarizes the global distribution of emissions by region and animal type. Table 9-7 presents the global distribution of emissions by region and livestock manure management system. The major findings are that:

- Of the 14 Tg, liquid livestock manure management systems (liquid/slurry storage, pit storage, and anaerobic lagoons) account for about 8.6 Tg, or about 60% of total emissions from livestock manure. These systems are used at confined, intensive livestock operations in developed countries and may provide profitable opportunities to recover CH_4 for use as a fuel. Currently, virtually no CH_4 is recovered from these systems for use as fuel.

- Of the 14 Tg, three regions account for 85% of the total: Europe (Eastern and Western), with 5.9 Tg (42%); Asia and the Far East, with 3.9 Tg (28%); and North America, with 2.3 Tg (16%).

- Of the 14 Tg, about 11.4 Tg are from three animal groups: swine, cattle (beef and draft animals), and dairy cows.

Table 9-8 summarizes the emission contributions from the countries in each region with the greatest emissions.

9.5 TRENDS

Future CH_4 emissions from livestock manure will be driven by future levels of animal production and manure management system usage. As discussed in Chapter 2 of this report, increasing human population will lead to increasing production of milk, meat, hides, and other livestock products. This trend is contingent on continued economic growth and is subject to many factors. Parikh et al. (1988) project a 1.6% annual increase in milk and bovine/ovine meat production through the year 2000. U.S. EPA (1989) projects a similar but slightly lower growth rate. Growth rates are expected to be larger among developing countries because of greater population growth and because of the high income elasticities of demand for livestock products among the relatively poorer populations of most developing countries.

Some have questioned whether developing countries can achieve significant increases in animal production because livestock feed availability may impose a constraint on production increases. Parikh et al. (1988) address this issue and expect feed costs to increase as supplies tighten in some regions. However, assuming that economic development continues, the prices for livestock products are also expected to increase, substantially offsetting the increased cost of feed.

TABLE 9-6

METHANE EMISSIONS BY ANIMAL TYPE AND REGION FOR 1990 (Tg CH_4)

Animal Type	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & Med.	Asia & Far East	Total[c]
Dairy Cattle	0.8	1.1	0.5	<0.1	0.1	<0.1	0.1	0.4	2.9
Nondairy Cattle[a]	0.2	0.9	0.9	<0.1	0.3	0.1	0.1	0.8	3.2
Swine	1.1	0.9	0.9	0.1	0.2	<0.1	<0.1	2.0	5.3
Poultry	0.3	0.1	0.2	<0.1	0.2	<0.1	<0.1	0.4	1.3
Other Animals[b]	<0.1	0.1	0.3	0.1	0.2	0.2	0.1	0.3	1.2
Total[c]	2.3	3.1	2.8	0.3	0.9	0.3	0.3	3.9	13.9

a. Includes buffalo.

b. Includes sheep, goats, horses, mules, asses, and camels.

c. Totals may not add due to rounding.

TABLE 9-7

METHANE EMISSIONS BY REGION AND SYSTEM FOR 1990 (Tg CH_4)

Manure Management System	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Near East & Med.	Asia & Far East	Total[a]
Pasture/Range	0.1	0.1	0.1	0.2	0.5	0.3	0.1	0.3	1.7
Liquid/Slurry[b]	0.5	2.7	1.0	0.0	0.2	0.0	0.0	1.8	6.1
Solid Storage	0.1	0.1	0.3	0.0	0.1	0.0	0.0	0.2	0.9
Anaerobic Lagoon	1.4	0.0	0.6	0.1	0.0	0.0	0.0	0.4	2.5
Drylot	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.3
Burned for Fuel	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	0.9
Daily Spread	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Other Systems	0.1	0.1	0.7	0.0	0.1	0.0	0.0	0.2	1.4
Total[a]	2.3	3.1	2.8	0.3	0.9	0.3	0.3	3.9	13.9

a. Totals may not add due to rounding. Values listed as 0.0 are less than 0.05.

b. Includes pit storage.

TABLE 9-8

METHANE EMISSIONS FOR MAJOR COUNTRIES FOR 1990 (Tg CH_4)

Country	Dairy	Cattle[a]	Swine	Sheep & Goats	Poultry[b]	Other[c]	Total
			North America				
Canada	0.02	0.03	0.06	0.00	0.03	0.00	0.15
United States	0.73	0.17	1.05	0.00	0.22	0.02	2.19
Total	*0.76*	*0.20*	*1.11*	*0.00*	*0.25*	*0.02*	*2.34*
			Western Europe				
France	0.58	0.32	0.19	0.01	0.04	0.00	1.15
Germany (West)	0.09	0.09	0.11	0.00	0.01	0.00	0.30
Italy	0.11	0.20	0.18	0.01	0.02	0.00	0.51
Netherlands	0.03	0.03	0.06	0.00	0.01	0.00	0.14
Spain	0.05	0.03	0.20	0.01	0.01	0.00	0.31
United Kingdom	0.06	0.08	0.03	0.02	0.02	0.00	0.21
Other	0.13	0.11	0.15	0.02	0.02	0.01	0.44
Total	*1.05*	*0.85*	*0.92*	*0.07*	*0.14*	*0.02*	*3.05*
			Eastern Europe				
Germany (East)	0.02	0.04	0.16	0.00	0.01	0.00	0.22
Hungary	0.00	0.01	0.39	0.00	0.01	0.00	0.41
Poland	0.03	0.05	0.03	0.01	0.01	0.03	0.16
Former Soviet Union	0.38	0.71	0.15	0.15	0.17	0.02	1.58
Other	0.06	0.10	0.15	0.03	0.04	0.01	0.39
Total	*0.48*	*0.90*	*0.89*	*0.19*	*0.24*	*0.06*	*2.75*
			Oceania				
Australia	0.01	0.03	0.12	0.08	0.01	0.00	0.24
New Zealand	0.01	0.01	0.02	0.03	0.00	0.00	0.07
Other	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Total	*0.02*	*0.04*	*0.14*	*0.10*	*0.01*	*0.00*	*0.31*
			Latin America				
Argentina	0.00	0.04	0.01	0.01	0.01	0.01	0.08
Brazil	0.03	0.13	0.12	0.01	0.08	0.04	0.41
Mexico	0.01	0.02	0.04	0.00	0.03	0.04	0.14
Other	0.04	0.08	0.05	0.01	0.04	0.05	0.27
Total	*0.07*	*0.27*	*0.22*	*0.03*	*0.16*	*0.14*	*0.89*
			Africa				
Ethiopia	0.01	0.02	0.00	0.01	0.00	0.03	0.07
Nigeria	0.00	0.01	0.00	0.00	0.01	0.00	0.03
Somalia	0.00	0.00	0.00	0.01	0.00	0.02	0.03
South Africa	0.00	0.00	0.00	0.01	0.00	0.00	0.03
Tanzania	0.01	0.01	0.00	0.01	0.00	0.00	0.03
Other	0.02	0.04	0.02	0.03	0.01	0.02	0.14
Total	*0.04*	*0.08*	*0.03*	*0.08*	*0.03*	*0.07*	*0.33*

(continued)

TABLE 9-8

METHANE EMISSIONS FROM MAJOR COUNTRIES FOR 1990 (Tg CH_4) (Continued)

Country	Dairy	Cattle[a]	Swine	Sheep & Goats	Poultry[b]	Other[c]	Total
Middle East & Mediterranean							
Egypt	0.01	0.01	0.00	0.00	0.00	0.00	0.03
Sudan	0.01	0.02	0.00	0.01	0.00	0.01	0.05
Turkey	0.02	0.01	0.00	0.01	0.00	0.01	0.06
Other	0.02	0.01	0.00	0.03	0.03	0.03	0.12
Total	*0.06*	*0.06*	*0.00*	*0.05*	*0.04*	*0.05*	*0.25*
Asia & Far East							
China	0.05	0.08	1.49	0.07	0.13	0.08	1.91
India	0.18	0.50	0.01	0.04	0.06	0.01	0.81
Indonesia	0.01	0.02	0.04	0.05	0.03	0.03	0.19
Japan	0.13	0.05	0.18	0.00	0.12	0.00	0.48
Viet Nam	0.00	0.01	0.09	0.00	0.01	0.00	0.12
Other	0.04	0.09	0.17	0.02	0.07	0.02	0.42
Total	*0.41*	*0.77*	*1.99*	*0.19*	*0.42*	*0.15*	*3.93*
World Total	2.89	3.16	5.29	0.71	1.28	0.51	13.85

a. Nondairy cattle and buffalo.

b. Includes chickens, turkeys, and ducks.

c. Includes horses, mules, asses, and camels.

The level of production determines how much manure is produced; the systems used to manage the manure determine how much CH_4 is produced. Unlike livestock production, forecasts of future livestock manure management practices are not available. However, if current trends toward the increasing use of confined and intensive livestock production systems continue, then there will likely be greater use of liquid-based manure-handling systems, such as lagoons and liquid/slurry storage systems. Such systems are often preferred for large-scale livestock production systems because they allow for the efficient collection, storage, and, in some cases, treatment, of livestock manure. Because liquid systems produce significantly more CH_4 than solid systems, a shift toward liquid systems would result in significantly higher emissions in the future. At this time, there are no plans for collection of CH_4 from liquid manure management systems on a large scale.

9.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

The estimates presented above should be regarded with caution. Some of the data on which they are based are uncertain. At this time, insufficient information exists to provide a statistical confidence limit for these emission estimates. The greatest uncertainty results from the MCF assumptions for the manure management systems. While assumptions concerning other factors are also uncertain, their contribution to the overall uncertainty is likely to be less.

To capture the uncertainty in these estimates, this chapter defines "high"- and "low"-case emission estimates as follows:

- High case. The MCFs for dry manure management systems are double that of the base case. This is plausible, given that the dry-system measurements performed by Hashimoto and Steed simulated arid conditions.

- Low case. The MCFs for the liquid systems are half that of the base case. This is plausible if liquid systems are much less anaerobic than indicated by measurements in the United States.

Table 9-9 lists the MCF assumptions used to estimate the low and high cases.

TABLE 9-9

BASE-, HIGH-, AND LOW-CASE EMISSION ESTIMATE ASSUMPTIONS

	Methane Conversion Factors (MCFs) Relative to the Base Case	
Management System	High Case	Low Case
Solid Systems		
Pasture/Range	Double	Unchanged
Drylot	Double	Unchanged
Solid Storage	Double	Unchanged
Liquid Systems		
Liquid/Slurry Storage	Unchanged	Half
Pit Storage, less than 1 month	Unchanged	Half
Pit Storage, greater than 1 month	Unchanged	Half
Anaerobic Lagoon	Unchanged	Half

As shown in Table 9-10, the range of emissions implied by these cases is about 10-18 Tg. The high-estimate assumptions have the greatest influence on the estimates for areas with animals managed on dry systems, such as Latin America and Eastern Europe. The low-case estimates have the largest impact on those areas that use liquid systems, including North America and Western Europe.

The true uncertainty in the estimates may be larger because this range only reflects the uncertainty in several key variables. Limitations of the analysis that must be considered include:

- Little information is available to assess the CH_4 produced by pasture and range manure. Because a large fraction of livestock manure is managed on pastures and range, this creates uncertainty in the overall emission estimate.

- The CH_4-producing potential of liquid/slurry and pit storage manure systems may be much greater than assumed in this report. Because of the widespread use of these systems, total emissions may be underestimated.

TABLE 9-10

EMISSION ESTIMATE RANGES FOR 1990 (Tg CH_4)

Region	Base Case	High Case	Low Case
North America	2.3	2.8	1.4
Western Europe	3.1	3.4	1.7
Eastern Europe	2.8	3.9	2.0
Oceania	0.3	0.5	0.2
Latin America	0.9	1.6	0.8
Africa	0.3	0.6	0.3
Near East & Mediterranean	0.3	0.4	0.3
Asia & Far East	3.9	4.9	2.8
Total	13.9	18.2	9.5

- Limited data exist on the numbers and characteristics of livestock manure systems in use in some parts of the world.

- In some countries, limited information is available on livestock populations and livestock characteristics, including manure production.

The U.S. EPA is sponsoring research to verify the MCFs for several key livestock manure systems, including liquid/slurry storage, drylots, and pasture/range. In addition, research is necessary to measure the CH_4 capacity (B_o) of livestock manure in developing countries and to improve the characterization of livestock manure management systems throughout the world.

9.7 CONCLUSIONS

The amount of CH_4 emitted by animal manure depends on how the manure is managed. Liquid manure management systems, including lagoons and liquid/slurry storage pits, tend to promote CH_4 formation and emission. Dry manure management systems tend to have lower CH_4 emissions. Because liquid management systems are used primarily in large-scale confined livestock management facilities in developed countries, the developed countries are the primary source of CH_4 emissions from livestock manure.

The method used to estimate emissions of 10-18 Tg CH_4 in this study is based on previous methods discussed in OECD (1991) and Safley et al. (1992). This emission estimate is lower than the previous estimates, however, because recent investigations indicate that emission rates from dry systems are lower than estimated previously. Investigations are continuing, however, and additional data are needed to reduce uncertainty in the estimates.

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CHAPTER 10

METHANE EMISSIONS FROM WASTEWATER

10.1 SUMMARY

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. Methane emissions from these sources are estimated to range from 30 to 40 teragrams (Tg)[1] per year. This represents 8-11% of the total global anthropogenic methane emissions, estimated at 360 Tg/yr (IPCC, 1992). Methane from wastewater treatment is potentially amenable to cost-effective control, and research by the Air & Energy Engineering Research Laboratory of the U.S. Environmental Protection Agency (U.S. EPA/AEERL) is designed to reduce the uncertainty associated with emission estimates for this source.

Global and country-specific estimates were developed for methane from domestic wastewater. For industrial wastewater, only global estimates are presented, as adequate country-specific data are not available. Industrial wastewater is estimated to be the major contributor to methane from wastewater emissions, accounting for 26-40 Tg/yr. Domestic wastewater is estimated to emit approximately 2 Tg/yr, with Asia accounting for 65%. Substantial uncertainty in these estimates results from 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, and flaring or utilization practices. Revisions of these initial estimates are planned as field-testing efforts result in more reliable emission factors and as better data become available on global wastewater management.

10.2 BACKGROUND

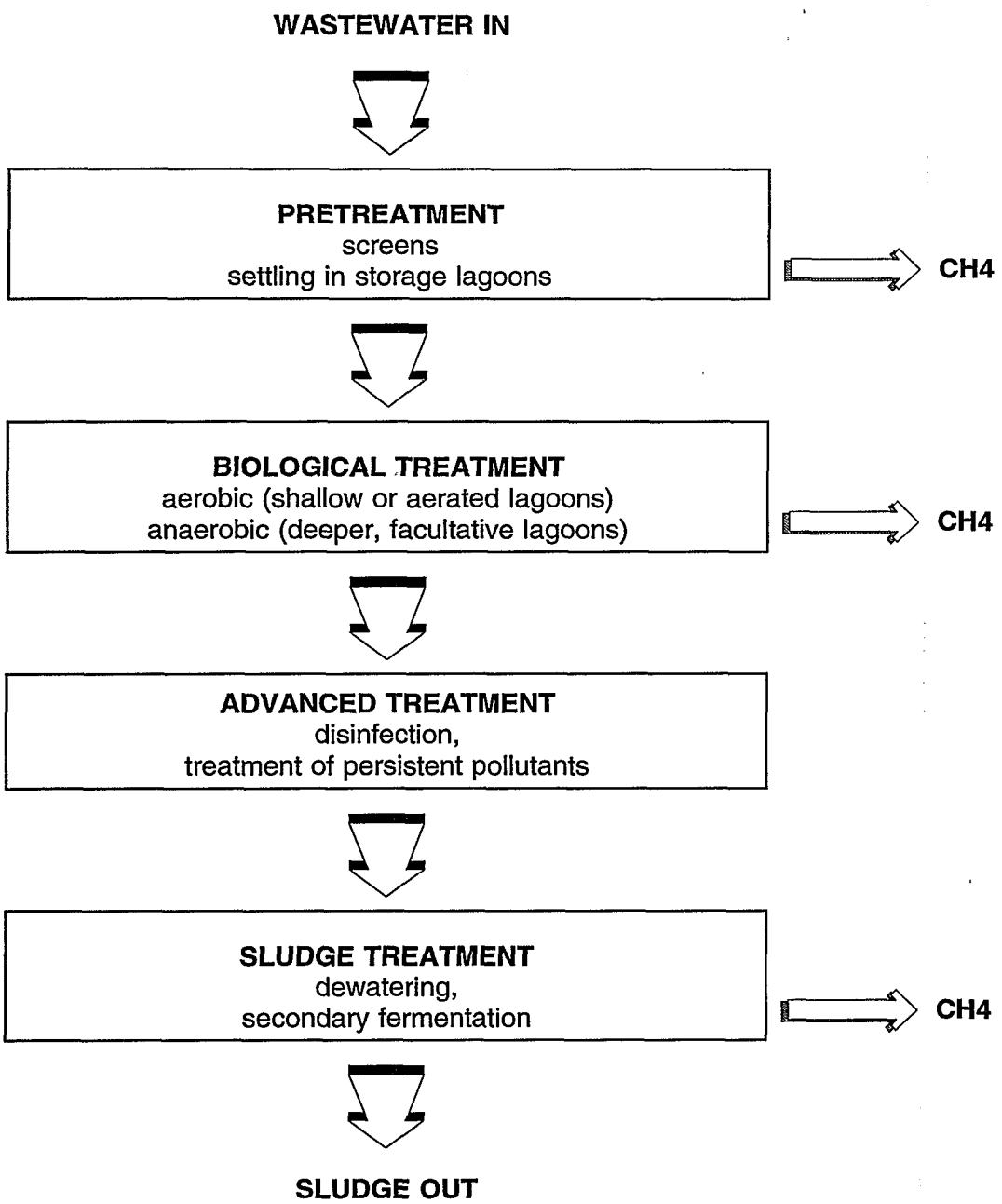
Highly organic waste streams, including domestic or commercial wastewater and wastewater from such industries as food processing and pulp and paper plants, have a high potential for methane (CH_4) emissions. These waste streams quickly deplete available oxygen as their organic matter decomposes. The concentration of organics in wastewater may be expressed in terms of biochemical oxygen demand (BOD) in milligrams per liter (mg/l). A standardized test of BOD is the BOD_5, where the amount of oxygen consumed by the waste under standard conditions is measured over a five-day period. The maximum, or ultimate, BOD is denoted as BOD_U. Typically, the BOD_5 would be 60-70% of the BOD_U. Untreated domestic waste streams would have a BOD_5 ranging from 110 to 400 mg/l. Food-processing facilities, such as fruit-, sugar-, and meat-processing plants; creameries; and breweries can produce untreated wastewater with a BOD as high as 10,000-100,000 mg/l. In the literature, BOD may also be expressed as "BOD loading," in kg/capita/day, where the BOD was multiplied by a wastewater production rate (liters per day per person).

Treatment of wastewater and its residual solids by-product (sludge) under anaerobic conditions results in CH_4 emissions (Figure 10-1). Treatment of wastewater in developed countries typically occurs aerobically, using aerated impoundments. Digesters are often

[1] Teragram = 10^6 metric tonnes = 10^{12} grams.

FIGURE 10-1

WASTEWATER TREATMENT SYSTEMS AND METHANE PRODUCTION



Notes: Treated water can leave the process at various stages. Certain wastewater treatment systems might have more or fewer stages.

used, and the gas is either flared or used. However, facultative (containing both anaerobic and aerobic zones) and anaerobic lagoons may also be used for storage and treatment.

U.S. EPA estimated in 1987 that there are approximately 5,500 municipal waste stabilization lagoons in the United States that treat 5.2 x 10^6 m^3/day of wastewater (OMPC, 1987). The CH_4 potential from these lagoons is not well understood, and little field data are available. Industrial and commercial wastewater processes also use lagoons for treatment and storage.

Methane production varies, depending upon temperature, retention time, BOD loading, and lagoon maintenance. Facultative lagoons, the most common type, treat wastewater by both anaerobic fermentation and aerobic processes. At the bottom of the lagoon, where an anaerobic environment exists, organic matter is digested to CH_4 and CO_2. As these gases bubble to the surface, much of the CO_2 is adsorbed by algae and is used, along with nutrients liberated during digestion, to produce algal biomass. Aerobic conditions, supported by algal growth, are maintained near the surface. Between 20 and 30% of the BOD loading to a facultative pond is anaerobically metabolized. As BOD loading increases and natural surface aeration diminishes, facultative lagoons proceed to a more anaerobic state. This results in higher CH_4 production, providing that the temperature is higher than 15°C. Under these conditions, a facultative lagoon may act more as an anaerobic pond, with possibly 95% of the lagoon volume functioning anaerobically. Fermentation, and thus CH_4 production, is negligible at temperatures below about 15°C, at which point the lagoon serves principally as a sedimentation tank (Gloyna, 1971).

The depth of the lagoon is also an important factor in CH_4 production. Shallow lagoons, one meter or less in depth, are not expected to produce large quantities of CH_4 because the intake of oxygen from the surface, as well as the production of oxygen due to photosynthesis, prevent the formation of a significant anaerobic zone. Facultative lagoons are typically 1.2-2.5 meters deep; lagoons deeper than 2.5 meters are typically referred to as anaerobic lagoons.

10.3 RECOMMENDED METHODOLOGY FOR ESTIMATING EMISSIONS

The methodology used to estimate CH_4 emissions from wastewater is based on BOD loading in the wastewater flow.[2] The BOD of wastewater correlates with CH_4 production (Orlich, 1990; and Metcalf and Eddy, Inc., 1979). Wastewater with greater BOD concentrations will yield more CH_4 than wastewater with comparatively lower BOD concentrations, given equivalent conditions. BOD is a commonly measured parameter, and data are available on BOD loading rates for domestic wastewater and different kinds of industrial wastewater. Consequently, data collection efforts focused on obtaining BOD concentrations in wastewater. It is recognized that other parameters may be important, and field work is under way by U.S. EPA/AEERL that will help determine what other variables need to be considered in future refinements of these initial emission estimates. The field work being conducted will include characterization of wastewater lagoons and septic sewage systems (Thorneloe, 1992).

[2] The draft methodology employed by the IPCC/OECD (IPCC, 1990) does not include CH_4 emissions from wastewater. The revised methodology, due to be released in late 1993, will include this emission source and will recommend an inventory method that follows what is described here.

Applying BOD data required the definition of two additional factors. The first factor expresses the CH_4 yield per unit BOD loading and is estimated to be 0.22 kg CH_4 per kg BOD_5 (Orlich, 1990). The second factor accounts for the fraction of the wastewater in which anaerobic conditions will develop. In absence of country-specific data, values for this factor are assumed. Many limitations were found in the available data, and research is underway to reduce the uncertainties with the initial estimate for CH_4 emissions from wastewater.

Two equations were developed to estimate wastewater CH_4 emissions -- one for domestic wastewater and one for industrial wastewater.

Domestic wastewater:

$$\left(\frac{\text{Country Population}^{a}}{}\right)\left(\frac{\text{kg } BOD_5^{b}}{\text{capita day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{0.22 \text{ kg } CH_4^{c}}{\text{kg } BOD_5}\right)\left(\frac{\text{Fraction Anaerobically Digested}^{d}}{}\right) = \frac{\text{kg } CH_4}{\text{yr}} \quad (10.1)$$

a. Population Reference Bureau, Inc., 1991. (Used 1990 population.)
b. Gloyna, 1971; Mara, 1976; Mullick, 1987; and Viessman and Hammer, 1985.
c. Orlich, 1990; and Metcalf and Eddy, Inc., 1979.
d. Assignment of this fraction is solely a matter of professional judgment in the absence of country-specific treatment data.

Data are available for BOD_5 loadings in domestic wastewater for some countries (Gloyna, 1971; Mara, 1976; Mullick, 1987; and Viessman and Hammer, 1985). These data were used to develop estimates for other countries, and these values were adjusted for population and BOD concentration.

Industrial wastewater:

$$\left(\frac{\text{World Wastewater Outflow } m^3{}^{e}}{\text{yr}}\right)\left(\frac{1{,}000 \; l^{f}}{m^3}\right)\left(\frac{\text{kg } BOD_5^{g}}{l \text{ wastewater}}\right)\left(\frac{0.22 \text{ kg } CH_4^{h}}{\text{kg } BOD_5}\right)\left(\frac{\text{Fraction Anaerobically Digested}^{i}}{}\right) = \frac{\text{kg } CH_4}{\text{yr}} \quad (10.2)$$

e. Carmichael and Strzepek, 1987.
f. Assumed 1 m^3 = 1,000 kg = 1,000 l (conversion factor for volume).
g. From Table 10-1 of this Chapter.
h. Orlich, 1990; and Metcalf and Eddy, Inc., 1979.
i. Assignment of this fraction is solely a matter of professional judgment in the absence of country-specific treatment data.

Since country-specific industrial wastewater volumes are not known at this time, the estimated worldwide wastewater outflow for specific industries had to be used.

10.3.1 Assumptions and Data Used to Estimate Emissions

BOD Loading

The sources of information that were used to obtain BOD values for industrial wastewater are summarized in Table 10-1. Many of the BOD values were reported as "BOD" without clarifying whether these values were BOD_5 or BOD_U. All unspecified BOD values were assumed to be BOD_5. This is considered a fairly safe assumption, since BOD measurements are typically BOD_5.

TABLE 10-1

BIOCHEMICAL OXYGEN DEMAND (BOD) ESTIMATES FOR VARIOUS INDUSTRIAL WASTEWATERS

Industry[a]	BOD (kg/l)	References and Notes
Iron and Steel	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p. 67, Carmichael and Strzepek (1987), since it was the lowest value obtained for industrial sources.
Nonferrous Metals	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p. 67, Carmichael and Strzepek (1987), since it was the lowest value obtained for industrial sources.
Fertilizer	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p. 67, Carmichael and Strzepek (1987), since it was the lowest value obtained for industrial sources.
Food & Beverages	0.035	This value is an average of the following categories of the fruit and beverage industry.
Fruits/Vegetables	0.003	Barnes et al., (1984), p. 213.
Cereals	0.001[c]	U.S. EPA (1974a), pp. 39 & 40.
Meats	0.020[c]	U.S. EPA (1975), pp. 58 & 60; U.S. EPA (1974c), pp. 39 & 41.
Butter	0.003[c]	U.S. EPA (1974b), p. 59; and Barnes et al. (1984), p. 316.
Cheese	0.003[c]	U.S. EPA (1974b), p. 59; and Barnes et al. (1984), p. 316.
Cane Sugar	0.002[b]	Barnes et al. (1984), p. 20.
Beet Sugar	0.010[b]	Barnes et al. (1984), p. 12; and U.S. EPA (1974d).
Wine	0.135[c]	Barnes et al. (1984), p. 73.
Beer	0.085[c]	Barnes et al. (1984), p. 73.
Other Beverages	0.083[c]	Barnes et al. (1984), p. 73.
Pulp and Paper	0.004[b]	Carmichael and Strzepek (1987), p. 49; and Hall et al. (1988), as cited in Torpy (1988), p. 20.
Petroleum Refining (Petrochemical)	0.004[c]	Average of values reported in Carmichael and Strzepek (1987), pp. 33 & 36.
Textiles	0.001[b]	Carmichael and Strzepek (1987), p. 67.
Rubber	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p. 67, Carmichael and Strzepek (1987), since it was the lowest value obtained for industrial sources.
Miscellaneous[d]	0.002	No BOD values were obtained. Used BOD reported for the pharmaceutical industry in Carmichael and Strzepek (1987), p. 85.

a. Industries presented here are taken from Table 47, pp. 116 and 117 in Carmichael and Strzepek (1987).
b. Reported as BOD. This is assumed to be ultimate BOD.
c. Reported as BOD_5.
d. Industries in this group were undefined.

For domestic wastewater, BOD_5 loading can range from 0.023 to 0.091 kg/capita/day. Domestic wastewater BOD_5 loading has been reported from 0.023 to 0.045 kg/day in developing countries and from 0.024 to 0.059 kg/day in developed countries (the lower value was reported for rural France (Mara, 1976)). The BOD increases when substantial amounts of kitchen wastes are discharged to sewers, for instance, as the result of using sink disposals. Viessman and Hammer (1985) suggest a BOD_5 loading for the United States of 0.045-0.078 kg/capita/day, due to increases in BOD_5 from additional loads of organic solids. In fact, domestic wastewater BOD_5 loading can be as high as 0.091 kg/capita/day according to Mullick (1987, citing Gotass (1956) and Laak (1986)). BOD_5 values of the organic load were adapted from Mara (1976) for domestic wastewater for different geographic regions:

Africa	0.037 (kg/capita/day)
Asia, Middle East, Central & South America	0.04 (kg/capita/day)
N. America, Europe, Former USSR, Oceania	0.05 (kg/capita/day)

Country-Specific Fractions of Anaerobically Degrading Wastewater

Both aerobic and anaerobic methods are used to treat wastewater. Waste in untreated wastewater may also degrade under either aerobic or anaerobic conditions. Therefore, only the fraction of the wastewater that is prone to anaerobic conditions needs to be included in the calculations. This fraction is assumed in the absence of country-specific data. The following text describes wastewater treatment activities, or the absence thereof, based on the available information in the literature. The geographic coverage is irregular, and much of the information is anecdotal. Brief summaries are provided of country-specific data, along with conclusions on how the data were used. More information is available for domestic wastewater treatment than for industrial wastewater treatment. It is known that industrial wastewater in developing countries is often discharged with domestic wastewater (UNEP, 1980). Therefore, for developing countries, any information available to assess the portion of domestic wastewater that may undergo anaerobic digestion is also applied to industrial wastewater.

Africa

Where wastewater is treated in Africa, it is most often directed to pit latrines and public sewer systems. Latrines may be considered aerobic. In coastal cities, public sewer systems often serve only to route sewage to a coastal outfall, thus preventing anaerobic conditions from developing.

- Ethiopia. In Addis Ababa, sewerage is provided by a combination of septic tanks and cesspools.

- Kenya. Coffee- and sugar-processing industries produce the bulk of the industrial wastewater in Kenya (UNEP, 1980). Other small Kenyan industries that are expanding include the dairy-, fruit-, and vegetable-processing and meat industries. Wastewater stabilization ponds appear to be the preferred method of treating industrial wastewater.

- Tanzania. In 1973, Dodoma, Tanzania, had no sewerage systems, and residents were using septic system, soak-away pits, and pit latrines. At that time, the city planned to build waste-stabilization ponds (UNEP, 1980). Dar es Salaam, Tanzania, has at least one series of waste-stabilization ponds.

Vacuum trucks are used to extract and haul sewage from central areas of the city to the ponds. The city also has sewage outfall off the Indian Ocean. Pit latrines, pour-flash latrines, and open defecation are common means of human waste disposal in small villages and rural areas throughout the country (Huff, 1992).

- Algeria. The World Bank (1985a) reported that in 1985 about 70% of the urban population of Algeria had access to public sewerage, but only 25% of the rural population had sewerage. Wastewater from the cities was discharged, untreated, directly into the Mediterranean or into rivers.

- Senegal. Public sewerage is provided only in some of the larger cities, but merely serves a small portion of the population. The existing sewerage networks do not function properly, as the lines are often blocked with debris and solid waste. The remainder of the urban population uses pit latrines and septic tanks. (World Bank, 1985b). The World Bank estimates that less than 20% of the rural Senegalese population has any provision for excreta disposal. Where provision exists, it is usually by pit latrine.

Based on this sparse information, it is assumed that 10% of all domestic wastewater and 10% of all industrial wastewater produced in Africa is treated or disposed of in such a way that anaerobic conditions result.

Asia and Oceania

Based on the following information, it is not possible to accurately estimate the volume of domestic and industrial wastewater subjected to anaerobic decomposition in Asia. The disposal systems mentioned -- e.g., pit latrines, vault systems, canals, and even rivers -- can become anaerobic throughout portions or all of their respective volumes, given favorable moisture, pH, and temperature. Further, it is clear that wastewater stabilization lagoons are in use. Due to lack of any definitive data, it could be assumed that the fraction of Asia's domestic and industrial wastewater subject to anaerobic decomposition may be comparable to the African value of 10%. However, the literature does suggest that agriculture and food industries, both of which are producing high BOD wastewater, are more prevalent in Asia than in Africa. The literature also suggests that sanitation through pit latrines and vault systems -- systems that are potentially anaerobic -- is a more common practice in Asia than in Africa. Therefore, the 10% value may be too low, so a fraction of 15% is adopted to represent the portion of Asia's wastewater (domestic, as well as industrial) that decomposes anaerobically. This percentage is also applied to Oceania, as information for that region was unavailable.

General observations have been made for various regions and economic cooperatives within Asia. Schiller and Droste (1982) reported that the vacuum truck and vault systems have been used in East Asia over the past century for municipal wastewater. Wastewater with high BOD from certain agricultural industries is treated in lagoons (Jalal and Aziz, 1986). The volume of wastewater was not reported.

- Middle East. Mullick (1987) indicates that wastewater stabilization lagoons are a favored treatment method in much of the Middle East. The Al-Hassa Oasis, Saudi Arabia uses facultative stabilization ponds for its wastewater treatment (Abderrahman and Shahalam, 1991). These lagoons have a potential to develop anaerobic conditions.

- India. Only 3 percent of India's total population is served by wastewater treatment facilities (UNEP, 1980). Some areas of the country are better equipped than others. In Kerala, a state along the southwest coast, septic tanks serve 40% of the urban population, and latrines serve 52% (World Bank, 1985c). Only 37% of the rural population of Kerala has pit latrines, and the remaining people have no sanitary facilities. Most of the wastewater discharge in India results from domestic sewage even in the larger, more industrialized cities. In Bombay, only 13% of the water pollution comes from industry; in Calcutta, 11%; and in New Delhi, 10%. It is reported that the BOD loading in the industrial effluent is very high (UNEP, 1980).

- Pakistan. The UNEP (1980) reports that only 10% of Pakistan's population has sewerage service. Generally the sewage is not treated and is discharged into rivers or onto land for cultivation. A few existing treatment facilities do not work to capacity because of a lack of skilled operators and inadequate maintenance. Industrial wastewater is also discharged without treatment.

- Thailand. Some of Thailand's wastewater is treated in anaerobic lagoons. Orlich (1990) estimates that wastewater-stabilization ponds in Thailand emit 0.5 Tg CH_4/yr.

- Turkey. The UNEP (1980) reports that few towns in Turkey have completed sewerage systems and, in most cases, sewage is discharged into private septic tanks or directly into rivers and lakes without any treatment. Since 1978, new industries have been required to treat their wastewater before discharge, but industries in operation before that date still discharge their waste without treatment. Izmir, Turkey, reported plans to develop a wastewater lagoon system using a three-stage system of anaerobic ponds followed by facultative and maturation lagoons. The lagoon system is expected to cover 2,000 hectares and will likely be the largest lagoon system in the world. It will have the capacity to treat 1,520 million l/day when operating at full capacity. It is estimated that this single lagoon may emit over 12,000 metric tonnes of CH_4 per year (McNitt and Tekeli, 1988).

- China. The total discharge of industrial wastewater and urban domestic sewage in China is approximately 30 billion metric tonnes/yr, of which 80% is industrial wastewater. Only 15% of the total wastewater flow receives treatment (GEMS, 1989). However, China has a history of using anaerobic digesters since the 1920s. These were originally developed to digest domestic wastes to provide biogas for household energy. China's earliest industrial application of anaerobic digestion may date to 1967, when it was applied to treat distillery waste. China's application of anaerobic digestion to industrial wastewater is still mostly pilot-scale, but successful treatment has occurred with such varied waste streams as alcohol distillates, acetone and butanol dregs, slaughterhouse wastes, paper pulp black liquid and furfuraldehyde, tannery waste, and assorted others (Li, 1986).

- Taiwan. Excreta from nearly half of the population of Taipei is collected by carts and placed in vaults and then is sold as fertilizer, discharged into the rivers, or dumped into local canals and drains. The remaining population and

industry use septic tanks or discharge directly into rivers (Schiller and Droste, 1982).

North Viet Nam. The double-vault compost toilet has gained widespread acceptance in north Viet Nam (Schiller and Droste, 1982).

Latin America

In Latin America the discharge of domestic sewage and industrial effluent is a major source of water pollution. Between these two sources of contamination, domestic sewage is usually the more severe source, particularly in large urban areas (UN, 1990). The entire region generally lacks wastewater treatment plants, and virtually all municipal sewage and industrial effluent is discharged into the nearest water course without treatment. Even in major cities, the wastewater flows are only partly controlled (directed) through interceptor sewers and planned outfalls (UN, 1990).

According to two reports, 41-66% of the total population in Latin America has access to these sewer systems (Bartone, 1990; and PAHO, 1990). Bartone (1990) indicates that 90% of the sewered wastewater is discharged directly into receiving waters without any kind of treatment. Based on Bartone (1990) and assuming that 66% of the total population has sewer service, then 59% of the sewered population's wastewater is discharged without treatment, and only 7% is retained at treatment facilities, which most probably consist of lagoon systems (Bartone, 1990; UNEP, 1980; and Yanez, 1980). The UN (1990) estimates that less than 2% of urban sewerage flows receives treatment. Also, the wastewater treatment plants in Latin America often do not function properly or do not function at all (UN, 1990; and Bartone, 1990). Bartone states that a World Bank survey of 42 mechanical treatment plants showed that 33 of them were out of service at the time of the survey.

Industrial wastewater effluent in the region is dominated by the pulp and paper, chemicals, petrochemicals and petroleum refining, metal production (particularly iron and steel production and nonferrous metal refining), food-processing (especially sugar and coffee), fish-meal, electricity generation, and textiles industries (UN, 1990). The share of Latin America's activity in these industries (1982) was: 17.7% of petroleum refining, 14.7% of chemicals production, 11.4% of the total number of beverage industries, 8.7% of food manufacturing, 7.1% of the iron and steel industries, 6.3% of nonferrous basic industries, and 5.4% of paper products industries (UN, 1990).

It was assumed that approximately 10% of all domestic wastewater in Latin America degrades anaerobically. This is to account for emissions from wastewater treatment plants and communities with sewer services that use septic systems, pit toilets, and cesspools. The same percentage was adopted for industrial wastewater.

North America, Europe, and Australia

Wastewater in developed countries is not expected to be a major source of CH_4. Wastewater in developed countries is typically treated aerobically, using aerated impoundments. However, anaerobic techniques have steadily been gaining favor in wastewater treatment for a variety of industrial processes (Torpy, 1988). Very little is known about the volume of domestic and industrial liquid waste that is anaerobically decomposed in Europe and North America. The treatment methods expected to have the greatest potential for CH_4 production are anaerobic and facultative stabilization lagoons, septic tanks, cesspools,

and anaerobic sludge digesters. Stabilization lagoons have long been used for wastewater from agricultural and food industries in the United States and Canada (Environment Canada, 1979).

The Organization of Economic Cooperation and Development (OECD) (1991) reports that approximately 60% of the population of OECD countries and 73% of the North American population is served by wastewater treatment plants. UNEP (1980) indicates that approximately 25 liters of digester gas per capita per day are produced in mechanical-biological wastewater treatment plants in Western Europe. The fraction chosen to represent the volume of anaerobically degraded wastewater in North America, Europe, and Australia is 15%; this may overestimate the amount of wastewater anaerobically digested within municipal lagoons and septic systems, but it may approach or underestimate the total volume of anaerobically digested wastewater when consideration is given to industrial wastewater treatment.

- United States. In the United States, individual septic systems are the most common treatment and disposal method for an estimated 25% of the population not served by an established sewage authority (Hick, 1992). Depending on temperature, retention time, and system configuration, these septic systems could emit CH_4 to the atmosphere, either through cracks and leaks in the tanks or through vent pipes in the systems, assuming that CH_4 is not completely oxidized in the surrounding soil.

  An estimated 5,500 municipal waste stabilization lagoons in the United States treat 5.2 x 106 m^3/day of wastewater from 8% of the population served by municipal wastewater treatment systems (OMPC, 1987). Mullick (1987) reports that in Texas, alone, 470 wastewater treatment plants use one or more lagoons to treat wastewater.

  Anaerobic digestion is widely used in the United States in municipal wastewater treatment plants to stabilize sludge. An estimated 65.5 x 10 m^3/day of wastewater flows through treatment plants using anaerobic digesters to treat sludge (OMPC, 1992). Table 10-2 summarizes data for the United States.

- Canada. Approximately 1,000 sewerage lagoons represent about half of the existing wastewater treatment systems. Municipal wastewater lagoons are quite prevalent in Canada, providing up to 50% of domestic wastewater treatment (Townshend and Knoll, 1987). Anaerobic processes to treat industrial wastewater are becoming increasingly popular.

- Former West Germany. UNEP (1980) reports that West Germany uses more than a thousand lagoons for wastewater treatment, and aerated lagoons are becoming increasingly popular.

- Australia. This country was among the first to advocate the advantages of pond systems designed specifically to operate as anaerobic units. Municipal and industrial wastewater have been treated in anaerobic lagoons in Australia since the 1950s.

TABLE 10-2

SELECTED WASTEWATER TREATMENT METHODS IN THE UNITED STATES[a]

Wastewater Treatment Methods	Flow (1×10^6 m^3/day)[b]	Population Served (%)
Municipal Wastewater Lagoons[c]	5.2	8
Septic Systems	15.0	25
Anaerobic Sludge Digestion Processes	65.5[d]	Unknown

a. See text for sources of information.

b. Estimated actual flow is given for septic systems and anaerobic sludge digestion processes; estimated design flow is given for lagoons.

c. Includes lagoons receiving domestic and domestic/industrial wastewater, with no pretreatment.

d. Actual flow represents the total flow associated with the treatment plant at which the anaerobic digestion unit is located.

10.4 RESULTS

Approximately 10-15% of the world's domestic wastewater will undergo anaerobic digestion, and BOD loading data for various geographical regions lie between 0.037 and 0.05 kg/capita/day. Applying these values, combined with country populations, to Equation 10.1 results in a CH_4 emission estimate for global domestic wastewater of approximately 2 Tg/yr. Country-specific CH_4 emission estimates for domestic wastewater are given in Table 10-3.

Since country-specific industrial wastewater volumes are not known at this time, the estimated worldwide volumes for specific industries were used. Information from Carmichael and Strzepek (1987) was used to estimate the 1990 global industrial wastewater outflows for specific industries. In their table, Carmichael and Strzepek presented a global estimate of wastewater outflow in the year 2000. Table 10-4 presents the industrial wastewater outflows, BODs, and CH_4 emission estimates for both developing and developed countries. Based on an assumed fraction of industrial wastewater that will undergo anaerobic digestion of 10% and 15% and the BOD loadings from Table 10-1, the resulting estimate of global CH_4 emissions from industrial wastewater ranges from 26 to 40 Tg/yr.

These numbers are comparable to Orlich's (1990) estimate. On the basis of the Thai data, Orlich approximated that global CH_4 emissions from wastewater lagoons would be roughly 20-25 Tg/yr. Orlich's estimate was limited to lagoons, whereas the EPA/AEERL estimates also include untreated wastewater.

10.5 TRENDS

In developing countries where sufficient land is available, lagoon systems using a series of anaerobic, facultative, and aerobic treatment ponds will continue to be recommended for wastewater treatment (Bartone, 1990; and UNEP, 1980). They are relatively inexpensive

TABLE 10-3

ESTIMATES OF GLOBAL AND COUNTRY-SPECIFIC METHANE EMISSIONS FROM DOMESTIC WASTEWATER, 1990 (Tg/yr)

Country	Emissions
Africa[a]	
Egypt	0.02
Kenya	0.01
Morocco	0.01
Nigeria	0.04
South Africa	0.01
Sudan	0.01
Tanzania	0.01
Uganda	0.01
Other Africa	0.09
Total Africa	*0.21*
Asia[b]	
China	0.54
North Korea	0.01
Viet Nam	0.03
Other Asia	0.92
Total Asia	*1.50*
South and Central America[a]	
Argentina	0.01
Brazil	0.05
Colombia	0.05
Mexico	0.03
Venezuela	0.01
Other	0.02
Total South and Central America	*0.13*
North America	
Canada	0.02
United States	0.15
Other North America	0.04
Total North America	*0.21*
Europe	
France	0.01
Former German Democratic Republic	0.01
Italy	0.01
United Kingdom	0.01
Total Europe	*0.04*
Former Soviet Union	0.18
Oceania	
Australia	0.01
Total Oceania	*0.01*
World Total	2.30

a. 10% of BOD is assumed to be anaerobically degraded.

b. 15% of BOD_5 is assumed to be anaerobically degraded.

TABLE 10-4

ESTIMATE OF GLOBAL METHANE EMISSIONS FROM INDUSTRIAL WASTEWATER 1990 (Tg/yr)

	Developed Countries				Developing Countries				Worldwide			
			Percent of BOD_5 Anaerobically Degraded				Percent of BOD_5 Anaerobically Degraded				Percent of BOD_5 Anaerobically Degraded	
Industry	Industrial Wastewater[b] Outflow (mil m^3/yr)	BOD_5 [c] (kg/l)	10%	15%	Industrial Wastewater Outflow (mil m^3/yr)	BOD_5 [c] (kg/l)	10%	15%	Industrial Wastewater Outflow (mil m^3/yr)	BOD_5 [c] (kg/l)	10%	15%
			Emissions				Emissions				Emissions	
Iron & Steel[a]	168,000	0.001	4	6	56,000	0.001	1	2	224,300	0.001	5	7
Nonferrous Metals[a]	26,600	0.001	1	1	8,850	0.001	0	0	35,000	0.001	1	1
Fertilizer[a]	14,300	0.001	0	1	4,500	0.001	0	0	19,000	0.001	0	1
Food & Beverages	7,700	0.035	6	9	2,600	0.035	2	3	10,300	0.035	8	12
Pulp & Paper	33,300	0.004	3	4	11,100	0.004	1	2	44,400	0.004	4	6
Petroleum Refining	54,700	0.004	5	7	18,200	0.004	2	2	73,200	0.004	6	10
Textile	34,600	0.001	1	1	11,450	0.001	0	1	46,100	0.001	1	2
Rubber[a]	6,800	0.001	0	0	2,300	0.001	0	0	9,100	0.001	0	0
Miscellaneous	9,500	0.002	0	1	3,200	0.002	0	0	12,700	0.002	1	1
Total	355,500		20	30	118,200		6	10	474,100		26	40

a. This group was identified in Carmichael and Strzepek (1987).

b. Carmichael and Strzepek (1987).

c. Sources of BOD values are given in Table 10-1.

to build and operate and provide excellent effluent quality when properly operated. Should the number of wastewater lagoons increase, the potential for future CH_4 emissions from wastewater treatment will also increase, assuming emissions are uncontrolled.

As mentioned before, state-of-the-art treatment of wastewater typically occurs aerobically using aerated impoundments. Also, in other steps of the process, digester tanks are often used, and the collected gas is either flared or used, therefore reducing CH_4 emissions. Many "developed" countries practice limited wastewater treatment. Only in Northern Europe and North America are wastewater disposal and treatment highly regulated and, consequently, relatively advanced. As countries in other regions are required to develop more stringent regulations and implement advanced wastewater treatment technologies (for instance under European Community regulations), CH_4 emissions per capita may decrease. This reduction would not necessarily be nullified by economic growth or population increases. With increasing population and industrial activity, water could become more scarce, thus creating an economic incentive to reduce its usage. Also, improvements in production techniques are nowadays aimed at waste minimization, which may lead to reduction of BOD loadings in waste streams and, consequently, CH_4 emissions.

10.6 MEASUREMENT, UNCERTAINTY, AND VERIFICATION ISSUES

The estimates developed using Equations 10.1 and 10.2 are considered initial estimates to help identify the major sources of uncertainty and to target potentially cost-effective control measures (Thorneloe, 1992). There are major uncertainties with these estimates which are identified in this section. Research is underway to reduce these uncertainties so that more reliable estimates can be made.

10.6.1 Activity Data: Quantities of Wastewater Flows

When using industrial wastewater data, researchers should give special care to the definition of "wastewater," especially when data are pulled from different references. Sources may or may not include cooling water and storm water when representing quantitative wastewater data, whereas BOD or other qualitative data would typically not represent these types of wastewater. For example, in 1980, about half of all wastewater generated by U.S. manufacturing plants resulted from cooling operations (U.S. EPA, 1980). If the wastewater flows from Table 10-4 include cooling water or other nonpolluted water, CH_4 emission estimates in this chapter will be overstated.

Specific volumes of domestic and industrial wastewater outflow for each country are not available, as are the volumes that are biologically treated under anaerobic conditions. Major data limitations exist for quantifying the fraction of wastewater subject to anaerobic decomposition. Data are needed for specific volumes of wastewater undergoing anaerobic decomposition. Data regarding the effect of recycling industrial wastewater outflow are also limited.

A large volume of the world's wastewater is emitted to lakes, rivers, and oceans without any kind of treatment. In many regions of the world, sewage and possibly also industrial wastewater may be discharged into smaller lakes or into dry riverbeds (UNEP, 1980; and WHO, 1987). No data are available regarding the extent to which anaerobic conditions could develop under these circumstances (UNEP, 1980 and 1988).

Emissions from unsewered wastewater treated in septic systems, pit toilets, or cesspools might be considerable. No data are available on CH_4 emissions from these systems. Depending on temperature, retention time, and system configuration, these septic systems could emit CH_4 to the atmosphere, either through vent pipes in the systems or through cracks and leaks in the tanks, assuming that CH_4 is not completely oxidized in surrounding soil.

10.6.2 Methane Yield per Unit BOD Loading

The value of 0.22 kg CH_4 per kg BOD_5 used in section 10.3 is one of two estimates that were found. Orlich (1990) used data from an inventory of lagoons in Thailand, which presumably contained wastewater from agricultural industries (food and beverage industries). Orlich's assumption is supported by an estimated yield of 0.25 kg CH_4/kg BOD_U (corresponding to 0.18 kg CH_4/kg BOD_5) for the anaerobic decomposition of glucose (Metcalf and Eddy, Inc., 1979). As no other data exist, Orlich's estimate was adopted for all wastewater. Differences in the physical and chemical conditions in lagoons have not been accounted for. For example, this factor may be lower in moderate or cold climates. To reduce the level of uncertainty in CH_4 yields and other parameters, EPA/AEERL is conducting a field testing program at lagoons, other wastewater treatment facilities, and septic sewerage systems (Thorneloe, 1992). This will result in improved emission factors that will be used to develop more reliable emission estimates.

10.6.3 Efficiency and Output of Wastewater Treatment Facilities

Wastewater that is accepted by treatment plants and supposedly treated aerobically may still be subject to anaerobic conditions, due to poor functioning of the facilities. Adjustment has not been made for (1) the amount of CH_4 that is controlled through use or flaring and (2) the amount of CH_4 that is oxidized prior to atmospheric release. Both fractions are potentially significant, particularly in such countries as the United States, where control is required for reducing hydrogen sulfide (H_2S) emissions. Data are being collected to account for this in future estimates for this emission source.

10.6.4 BOD Values and Other Physical and Chemical Data

Data on physicochemical wastewater characteristics are limited, especially for country-specific wastewater volumes. For industrial wastewater, BOD values reported for source categories are averages of BOD values given for several process wastewater streams. For iron & steel, fertilizer, and nonferrous metals, no BOD values were assumed because published values were not available.

The estimate presented in this chapter could be improved if data were obtained on the chemical characteristics of process wastewater streams. For instance, a distinction can be made between carbonaceous and nitrogenous oxygen demand. Wastewater with a high nitrogenous oxygen demand or other noncarbon reductive ions is not a potential source of CH_4. The emission methodology does not account for such factors as temperature, pH, and retention time, all of which influence the rate and extent of anaerobic decomposition and, consequently, the CH_4 emissions.

10.7 CONCLUSIONS

Global and country-specific estimates were developed for CH_4 from domestic wastewater. Domestic wastewater is estimated to emit approximately 2 Tg/yr, with Asia accounting for 65%. For industrial wastewater only global estimates are presented, as adequate country-specific data are not available. Industrial wastewater is estimated to be the major contributor to CH_4 emissions from wastewater, accounting for 26-40 Tg/yr. These numbers are comparable to an estimate by Orlich (1990). On the basis of the Thai data, Orlich reported that global CH_4 emissions from wastewater lagoons would be roughly 20-25 Tg/yr. Orlich's estimate was limited to lagoons, whereas the EPA estimates attempt to include untreated wastewater and septic sewage systems.

Substantial uncertainty in these estimates results from a lack of data characterizing wastewater management practices, the quantities of wastewater that are subject to anaerobic conditions, the extent to which CH_4 is emitted, and flaring or utilization practices. EPA is conducting a field-testing program to develop more reliable emission factors that will result in reducing the uncertainty in these estimates. Country-specific activity data are also being collected, along with information on current trends. This information will be used to revise these initial estimates and to project future emissions.

It is expected that CH_4 emissions from wastewater treatment in developed countries may decrease because aerobic techniques, as well as CH_4 utilization, are becoming increasingly popular. Also, some countries require the control of H_2S emissions, which results in controlling CH_4 emissions. The trend in developing countries is toward using facultative lagoons for treatment. This may lead to an increase in CH_4 emissions in developing countries.

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CHAPTER 11

VERIFICATION OF METHANE EMISSIONS

11.1 INTRODUCTION

At the United Nations Conference on Environment and Development, held in Rio de Janeiro in June 1992, 154 heads of state signed an international agreement to promote and cooperate in activities that would mitigate future climate change and its potential impacts. The ultimate objective of this agreement, The United Nations Framework Convention on Climate Change (FCCC), is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN, 1992). The FCCC, however, does not define numerically the level at which greenhouse gas concentrations should be stabilized or the time period over which this stabilization should occur. Except for a general goal of reducing emissions to 1990 levels by Annex I countries[1], no commitments for specific emission reductions by a certain date, either nationally or globally, are contained in the FCCC.

Although specific emission reduction timetables are not contained within the FCCC, all Parties to the Convention are required to develop and submit national inventories of annual greenhouse gas emissions and sinks. These inventories are to be based on comparable methodologies agreed upon by the Conference of the Parties (COP), and are to be updated periodically. In fact, Parties to the Convention have begun to compile emission inventories in order to comply with commitments and reporting requirements under Articles 4.1(a) and 12.1(a), and the process of developing an internationally agreed-upon emission inventory methodology is underway through the Intergovernmental Panel on Climate Change (IPCC), with technical assistance from the Organization for Economic Cooperation and Development (IPCC, 1991 and 1993; OECD, 1991; and van Amstel, 1993).

The FCCC currently contains no measures for verification of national inventories submitted to the COP, but an international system to review and verify national inventories of methane (CH_4) and other greenhouse gas emissions and sinks may prove useful for several reasons. As discussed in previous chapters of this report, CH_4 emission estimates for individual sources are poorly constrained since they are based on flux measurements that are either scarce or vary by up to several orders of magnitude. Moreover, CH_4 emissions are controlled by a wide variety of biogeochemical and socioeconomic factors that, in many cases, are neither well understood nor well quantified. In addition, the activity data that are used to extrapolate from individual flux measurements to national emission totals are often uncertain. A verification system, through systematic exchange, review, and comparison of data, most likely would improve scientific understanding of greenhouse gas sources and sinks. As a result of the verification process, flux measurements, activity data, and relevant biogeochemical and socioeconomic information, that perhaps had not been widely disseminated previously, would become available to both the scientific and the policy communities. Therefore, the verification process would promote greater sharing and exchange of data, as well as increased dialogue among scientists and policymakers.

[1] Annex I countries are the developed countries, including countries with economies in transition.

An international verification system also would contribute toward the ultimate objective of the FCCC. By improving the quality of information about greenhouse gas sources and sinks, a verification system would help policymakers set appropriate priorities for emission reduction policies among different gases and among different countries. A verification system would also be useful for monitoring progress toward the goal of reducing emissions to 1990 levels, at both the global and the national levels.

From a compliance standpoint, a verification system would be useful for three reasons (e.g., Lewis, 1992): (1) to deter incorrect reporting, (2) to detect cases of incorrect reporting and provide mechanisms for revising inventories, and (3) to increase confidence in the FCCC and foster greater trust and collaboration among parties, thereby encouraging more nations to sign and ratify the Convention. A system of verification would allow the Parties to address potential problems promptly and in a coordinated and collaborative fashion. Also, such a system would help determine how technical and financial assistance can be used to support countries in improving their inventories.

An emission inventory verification system would be most effective if implemented through a two-part structure (e.g., Fischer, 1992; and di Primio, 1992): (1) an internal, national monitoring and assessment process and (2) an international verification process. Through the national monitoring and assessment process, a country would compile, review, and process information on greenhouse gas emissions and sinks with the ultimate purpose of producing their implementation report -- i.e., their greenhouse gas inventory. The national process would increase national capability for producing inventories, as well as help nations determine what additional data should be acquired to improve national emission and sink estimates.

The international component of a verification system would examine national reports for reliability and completeness. Auxiliary data, not provided in the national implementation reports, could also be employed by the international system in order to verify the reported inventories. Substantial learning about greenhouse gas emissions and sinks would be acquired through the review and exchange of national data and inventory estimation methods. This process would most likely further the development of more accurate inventories as well as improved inventory methods.

If the Parties to the Convention agree that an inventory verification system is useful, they must decide what should be reviewed, how it will be verified, and the degree (or intrusiveness) of review and verification required. These decisions will involve financial, political, scientific, and technical considerations. For example, verification methods must be robust in order to ensure confidence in the system, but costly data collection that does not contribute significantly to the knowledge base must be avoided. The intrusiveness of the verification system must not be so great as to be interpreted as encroachment on proprietary political or commercial information and thereby create mistrust among the Parties to the Convention. Although systematic review and monitoring of emission inventories are likely to increase confidence in the FCCC, these activities may also undermine the process if Parties to the Convention perceive them as too intrusive. Also, the ability to assess and verify emissions from numerous sources is constrained by technological and scientific limitations. For example, limited technological capabilities for measuring the area of savannas burned annually preclude accurate estimations of trace gas emissions from biomass burning, while limited scientific understanding of the factors that control CH_4 production during anaerobic decomposition precludes accurate assessments of CH_4 emissions from waste management practices.

Despite these difficulties, it is worthwhile at this point to discuss the scientific and technological mechanisms available for verification of emission and sink estimates, to assist nations in the interim as they develop their inventories as required by the FCCC. If countries understand the methods for verifying their inventories, they will be better able to monitor and verify their own calculations, as well as develop more accurate and complete inventories. And if effective monitoring systems are in place nationally that include mechanisms for independent verification, compliance with eventual emission reduction obligations is more likely. Moreover, the establishment of accurate national verification systems will minimize the need for an extensive and highly intrusive international monitoring and verification system.

The remainder of this chapter discusses scientific and technological mechanisms available for verification of CH_4 emission estimates. Since the many financial, political, and institutional issues associated with emission verification could not be covered in this report, the reader is referred to the small but growing body of literature on this subject for additional information (e.g., Fischer et al., 1990; Feldman, 1992; Ausubel and Victor, 1992; and U.S. GAO, 1992a and 1992b).

11.2 VERIFICATION METHODOLOGIES

As documented in this report, CH_4 is released as a by-product of a wide variety of activities in the agricultural, energy, waste management, and industrial sectors. Because of the great number and variety of emission sources, absolute verification of CH_4 emission estimates through comprehensive, direct measurement is essentially impossible. Some sources are stationary point sources, and emissions from them can be measured fairly accurately. Their emission rates, however, may vary significantly from region to region, so a complete assessment would require an extremely detailed network of measurements (e.g., emissions associated with venting and leaking from oil and natural gas systems). Other sources, either stationary or mobile, are too numerous and intermittent for continuous measurement to be feasible (e.g., emissions from wood stoves, automobiles, and livestock). Many CH_4 sources, such as rice cultivation and savanna burning, are areal rather than point sources, making comprehensive emission measurement physically and logistically impossible.

Mass-balance equations have been used successfully as a verification technique in nuclear arms control agreements. This procedure balances an initial inventory against a final inventory by accounting for all mass flows into and out of the system, and for all transformations in the system within a given period. Emissions of greenhouse gases, however, occur in an open system. Emissions from each source are released to the atmosphere where they become mixed with those from other sources. It is not possible to verify precisely the mass flows out of an individual greenhouse gas emission "system" after the emissions have been released. As discussed in section 11.2.2, various atmospheric measurements can be used to constrain estimates of emissions from various sources or groups of sources (e.g., fossil sources), but at present, these measurements have limited usefulness in determining either individual source strengths (e.g., CH_4 from landfills) or total emissions from small countries or regions. Because of these difficulties associated with verification of emission inventories, due to both the varied nature and openness of emission sources, greenhouse gas emission inventories have been described by Fischer et al. (1990) as having "poor verification suitability."

Due to the technical, logistic, and financial difficulties of measuring CH_4 emissions from every source in a nation or region, national and regional emission estimates for each source

category are calculated by multiplying (1) a representative emission factor, which is derived from theory, experiment, and/or expert judgment, by (2) an activity level, which is based on national or regional statistics and expert judgment. The emission factors quantify the amount of CH_4 released per unit of activity -- e.g., per animal, per tonne of municipal waste landfilled, per kilogram of fuelwood burned. The activity levels are used to extrapolate from unit emission factors to national or regional emission estimates for each source. For example, the average annual CH_4 emissions per head of a particular type of livestock (the "emission factor") would be multiplied by the national population of that type of livestock (the "activity level") to obtain the annual, national emissions of CH_4 from that type of livestock.

Although it is impossible to verify a national emission inventory through direct measurement or mass-balance calculations, an inventory can be verified through an assessment of the plausibility, accuracy, and completeness of the calculations used to estimate emissions. This direct, or "bottom-up," method of verification would include an evaluation of the plausibility and completeness of the inventory results, the accuracy and appropriateness of the methodologies used, the accuracy of the calculations, and the accuracy and appropriateness of the numbers used in the calculations, especially the emission factors and activity levels.

Additional information with which to verify national CH_4 emission estimates can be obtained through monitoring the atmospheric signatures of the emissions themselves. This "top-down" monitoring approach works because the atmosphere does not mix trace gas concentrations uniformly. Regions of strong emissions are clearly revealed by elevated concentrations in the lower atmosphere. Also, the isotopic contents of atmospheric CH_4 can place bounds on individual source strengths, since isotopic contents vary among different sources. Because winds spread the concentrations some distance from the source(s), however, this approach is limited. National emission estimates for individual sources cannot be verified accurately with this technique, especially if the country is small. This technique can, however, provide cross-checks on total CH_4 emissions from a broad region or a large country located upwind from the measurement site. This is particularly true of regions with relatively large CH_4 emissions, such as Southeast Asia. Also, the use of isotope measurements in this technique can provide constraints on estimates of national and regional CH_4 emissions from certain individual source categories (e.g., biomass burning, coal mining, oil and gas systems). This technique can also be used to put bounds, albeit wide, on global estimates of individual source strengths based on consistency with the atmospheric variations (e.g., Fung et al., 1991). This top-down monitoring approach, therefore, is most useful as a cross-checking device in verification of national CH_4 emission inventories.

11.2.1 Direct Verification

"Bottom-up" verification of national inventories of CH_4 emissions would entail a series of steps through which the plausibility, accuracy, and completeness of the inventories would be evaluated. These steps are as follows:

- Evaluate the plausibility of the results.
- Evaluate the inventory methods used.
- Evaluate the accuracy of the calculations.
- Evaluate the accuracy and appropriateness of the emission factors used.

- Evaluate the accuracy and appropriateness of the activity levels used.

For this type of verification system to be successful, the documentation of the emission estimates must be complete and transparent. Not only must emission estimates by source category be provided, but also the methodologies used to estimate emissions must be clearly defined. The data provided must be detailed enough so that the emission estimates can be reconstructed. Scientific and technical references used to determine emission factors, as well as data sources for activity data, must be cited and must be available to other scientists. If those references are not published and internationally available, the original data that were used in the calculations would need to be provided as well.

Evaluate the Plausibility of the Results

The plausibility, or reasonableness, of the emission inventory should be evaluated first. All or some subset of the anthropogenic CH_4 source categories will be included in the inventory, depending upon the types of agricultural, energy, waste management, and industrial activities that occur in the nation. Evaluation of whether all of the source categories that should be included have been included will require some knowledge of national practices in each of the relevant sectors. For example, a high emission estimate for domestic livestock does not imply that the emission estimate for animal wastes necessarily should be high too. Even if a nation has a large livestock population, if all of the animal wastes are managed aerobically (e.g., spread on fields) then emissions from this source would be negligible. Presumably, once methodologies are agreed upon internationally, there will be some minimum cut-off for individual source estimates, so that if a country's emission estimate for a particular source is less than, for example, 0.01 teragrams (Tg)[2] CH_4/yr, that country would not be required to estimate emissions from that source.

Comparison of the emission inventory with those compiled by other groups provides an independent, but somewhat risky, method of verification. Care must be taken to ensure that the emission estimates for the same source and region are compared, or the comparison will be meaningless. The year of inventory should also be the same, but this variable is not as important if the temporal variation in the activity level is not likely to be significant. Some sources (e.g., biomass burning and rice cultivation) may, however, vary significantly from year to year due to climatic, political, or social factors. Comparison of emission estimates from different years for such sources could result in misleading results.

Significant differences between the subject inventory and other inventories for the same source, region, and year could be the result of one or more of the following: (1) a different methodology, (2) different emission factor(s), and/or (3) different activity level(s). Determining which factor(s) is(are) responsible could indicate that more or less detailed investigation is needed in the next steps in the verification process. For example, estimates of CH_4 emissions from cattle may differ between two countries in which livestock management practices and production levels are similar because the population sizes (i.e., activity levels) differ. Evaluation of this is simple. If both activity levels and emission factors vary, the reasons for differing emission factors, which could be complex, will need to be reviewed and evaluated as well.

[2] Teragram = 10^6 metric tonnes = 10^{12} grams.

If inventories for previous years are available, the inventory under examination can be compared to the previous submissions. Any significant decline or increase in emissions should be explained by the supporting information provided in the national report. Possible reasons for a significant change in emissions include a change in the accepted emission methodologies, new scientific research that results in altered emission factors, demographic or economic changes that alter activity levels, and new or strengthened controls on emissions.

Last, national emission inventories for each individual source category should be summed to obtain global emission estimates for each source. The global estimates should not lie significantly outside the accepted range for each source.[3] This could result, however, from many countries submitting small, but consistent, over- or underestimates. Determining which countries are responsible for the discrepancy would be difficult, unless the differences are due to obvious errors or differences in assumptions. Also, the accepted ranges for most individual sources are quite broad, so this step will have limited usefulness. And if some countries overestimate their emissions, and some underestimate their emissions, the differences may cancel out. Atmospheric measurements of the concentration and isotopic composition of CH_4 provide information about the geographic distribution of emissions, and may help resolve this issue (see section 11.2.2, entitled "Indirect Verification").

Evaluate the Inventory Methods Used

The methodology used should be compared with what has been agreed upon by the COP. If it differs, an explanation of the reasons for the differences can justify a more appropriate method and perhaps subsequently be used to improve the internationally accepted methods. Substantial improvements to the methods should be expected as scientific understanding of the biogeochemical and socioeconomic factors that control CH_4 emissions increases. Evaluation of inventory methods through a formal verification process would, therefore, promote development of improved methods.

Although Parties to the Convention are required to use inventory methodologies that are agreed upon by the COP, there may be more than one methodology to choose from for an individual source category. For example, in chapter 6 of this report, a tiered approach to estimating CH_4 emissions from coal mining is recommended. A country would select a particular tier, or methodology, depending upon the quantity and quality of available data with which to implement the method.

Countries may also choose to revise agreed-upon methodologies, because of particular socioeconomic or climatic conditions, or because new research results indicate that such a change is necessary. For example, if an inventory methodology is based purely on experiments in temperate countries, a tropical country may choose to alter the methodology based on expert judgment.

For these reasons, the methodologies employed should be reviewed and evaluated for their appropriateness, given the context of a particular country whose inventory is under review.

[3] The results of this step will not be meaningful unless all countries ratify the FCCC and submit an inventory, or if, as part of the verification process, inventories are derived for those countries that do not submit them.

Evaluate the Accuracy of the Calculations

Evaluating the accuracy of the calculations is quite straightforward, assuming that the implementation report is complete and sufficiently detailed. All the calculations must be checked to ensure that the math is correct.

Evaluate the Accuracy and Appropriateness of the Emission Factors Used

Relatively few measurements have been made of CH_4 emissions. Moreover, since variables affecting emissions are numerous, varied, and sometimes poorly understood, emission factors are highly uncertain. Development of emission factors is an ongoing "science," and factors are revised and updated constantly in the scientific literature as new information is published. As a first step, the emission factors used in the national inventories should be evaluated against existing "default" factors in the inventory methods agreed upon by the COP. Revisions to the internationally accepted methodologies, however, will lag behind new scientific research results that indicate that factors should be revised. Therefore, these "default" factors may, in some cases, be out of date -- i.e., they may not be consistent with current scientific understanding. Emission factors used in a national inventory may vary significantly from the "default" factors because a country has developed new emission factors based on scientific research and/or expert judgment, and has used them in the inventory rather than the "default" factors. By essentially accelerating the dissemination of new research results, the international review, evaluation, and sharing of emission factors in this step in the verification process are likely to improve the accuracy of the factors used in the methodology, as well as refine them to account for significant differences in technologies, climate, management systems, and other variables.

Emission factors for a single activity vary among and within individual countries. Therefore, choosing the correct emission factor for a specific activity requires an understanding of not only the biogeochemical processes by which CH_4 is produced and emitted from that activity, but also the various management practices that affect emissions. For example, production of CH_4 in livestock varies not only among animal species, but also among types within species -- e.g., mature dairy cows, mature draft bullocks, and pre-weaned calves. At the same time, CH_4 production is affected by the physical and chemical characteristics of the feed, the feeding level and schedule, the use of feed additives to promote production efficiency, and the activity and health of the animal.

Evaluation of emission factors, therefore, should also include an evaluation of both the biogeochemical and the socioeconomic or management variables used to derive the factors. Information contained in scientific studies on the subject, as well as in other emission inventories, should be used in this evaluation. Emission factors for certain sources are likely to be similar to those in other countries with similar management practices, climatic conditions, etc. For example, very few experimental measurements of CH_4 flux from flooded rice fields have been performed in Asia. Many Asian countries, therefore, will have to rely on estimates derived in other, similar regions for this factor. Additional reports and data sources, such as international and national agricultural production statistics, may be useful in comparing variables. Outside sources of information, however, should be used with caution. International data bases (e.g., the UN Food and Agriculture Organization (FAO) Agricultural Production Statistics) sometimes do not agree with national or regional data bases. The reasons for this are often not clear, since international data bases are usually based on data provided by individual countries. National sources may be preferable, since they are usually based on primary, rather than secondary, sources.

Evaluate the Accuracy and Appropriateness of the Activity Levels Used

Levels of activities that result in the emissions of CH_4 are well quantified for some sources because accurate national and international data bases exist, particularly in the agriculture and energy sectors (e.g., livestock, rice cultivation, and fossil fuel production, transport, and consumption). This is not true for all CH_4 sources, in particular, biomass burning, landfills, and liquid wastes. When specific data bases are not available, ancillary data and expert judgment will have to be used. Therefore, the process of compiling inventories will indicate which data sets are inadequate for accurate assessments and which are inconsistent. This process will point out what new data need to be collected within each country, and may also instigate improved coordination of data collection and dissemination among countries. This could be particularly useful for the collection and dissemination of large, geographically broad, and expensive data sets, such as those compiled through remote sensing.

Activity levels are based primarily on national compilations and statistics, which are typically reported to a central repository. The reliability of the data and the plausibility of the results should be evaluated. The data can be compared to international data bases, such as the FAO Agricultural Production Statistics and the UN Energy Statistics, although as discussed above, the results from such comparisons should only be used as general guides. Nevertheless, interannual or regional variability in reported activity levels may indicate that further data collection is recommended. Outside reports, such as fuelwood surveys by the World Bank and nongovernmental organizations, national reports on rice cultivation or livestock management, and regional studies of energy supply and demand, also can be useful for cross-checks. Again, care must be taken to ensure that activity levels for the same activity and year are being compared, since data bases are not always clearly defined. For example, estimates of rice area harvested annually may or may not include upland rice areas. Upland areas should not be counted, or should be assigned an emission factor of zero, when estimating emissions because they are not flooded and, therefore, are not believed to produce CH_4.

11.2.2 Indirect Verification

The atmospheric distribution of CH_4 reflects the geography of its sources and sinks. Broad regions of elevated CH_4 concentrations exist over strong source regions (e.g., Thom et al., 1993) because the distribution is not completely smoothed out by atmospheric circulation (Fraser et al., 1986; and Steele et al., 1987). Mathematical models of tracer transport in the atmosphere have been used to deduce objectively, from spatial and temporal distributions of atmospheric concentrations, not only the total annual emissions and destruction of CH_4, but even rough seasonal and geographic distributions for these sources and sinks (Taylor et al., 1991; Fung et al., 1991; Tie et al., 1991; Quay et al., 1991; and Brown, 1993). Thus, precise measurements of atmospheric CH_4 at a judiciously selected global network of sites can provide valuable information for overall verification of total CH_4 emissions from a particular region.

While spatial variations of atmospheric CH_4 are related to regional source strengths, there is a limit to the information about the distribution of CH_4 sources that can be extracted from these variations. Atmospheric transport models, by themselves, yield CH_4 source/sink information that has been integrated over a few weeks and a few thousand kilometers. Individual sources and sinks cannot be differentiated. For example, once CH_4 emitted in Europe from livestock, landfills, coal mining, and natural gas distribution systems mixes during

transport to a monitoring site in the North Atlantic Ocean, concentration measurements at the monitoring site only will provide information about the sum of emissions from these sources. Therefore, the attribution of an observed concentration profile to a particular distribution of sources must make use of constraining data other than atmospheric CH_4 concentrations (e.g., Fung et al., 1991).

One type of information that can be used to constrain direct estimates of emissions is the isotopic content of CH_4 in the atmosphere (Cicerone and Oremland, 1988; Tyler, 1986; Wahlen et al., 1989; and Quay et al., 1991). Different CH_4 sources have different isotopic compositions, so the isotopic composition of atmospheric CH_4 reflects the proportions of CH_4 released by the different sources. Analysis of CH_4's radiocarbon content (i.e., carbon-14 content, or ^{14}C) provides a means of estimating fossil versus modern CH_4 source strengths, while its stable isotopic composition (i.e., the ratio of carbon-13 to carbon-12, or $^{13}C/^{12}C$) provides a means of distinguishing between biogenic and nonbiogenic sources.

Carbon-14 is a radioactive isotope, with a half-life of ~5,700 years. As long as an organism is alive, it exchanges carbon with its surroundings, and its ^{14}C content equals that of atmospheric carbon dioxide. Once an organism dies, absorption of ^{14}C ceases, and the residual ^{14}C continues to decay. The longer an organism has been dead, the lower its ^{14}C content. The formation of fossil fuels occurs on geologic time scales, so that CH_4 associated with these sources (oil, gas, and coal) contains zero ^{14}C. The ^{14}C content of atmospheric CH_4 will thus reflect the fraction released from fossil carbon, and will decrease with increasing CH_4 release from fossil fuels relative to release from nonfossil sources. Therefore, the ^{14}C content of atmospheric CH_4 can place bounds on the emissions associated with the oil, natural gas, and coal fuel cycles (Manning et al., 1990; Wahlen et al., 1989; and Quay et al., 1991).[4]

Similarly, measurement of the $^{13}C/^{12}C$ isotope ratio of atmospheric CH_4 can place bounds on biogenic and nonbiogenic source strengths (Cantrell et al., 1990; Stevens and Engelkemeir, 1988; Tyler et al., 1988; and Quay et al., 1988). Sources of biogenic CH_4 (i.e., CH_4 produced by bacteria during anaerobic fermentation) include wetlands, rice cultivation, livestock, solid and liquid wastes, and oceans and fresh waters. Nonbiogenic CH_4 is derived from thermal alteration of buried organic matter (i.e., fossil sources: oil, natural gas, and coal)[5] and from incomplete combustion during biomass burning. Methane from biogenic sources has the lowest, or most negative, $^{13}C/^{12}C$ values, while CH_4 from thermogenic sources has mean values, and CH_4 from biomass burning has the highest values (Quay et al., 1991). Therefore, the $^{13}C/^{12}C$ ratio of atmospheric CH_4 reflects the proportion of CH_4 input from biogenic versus nonbiogenic sources.[6]

Together, radiocarbon and stable isotope measurements of atmospheric CH_4 can narrow uncertainties about source strengths. For example, if a CH_4 sample has a relatively low $^{13}C/^{12}C$ ratio, but contains significant ^{14}C, it is almost certainly of biogenic origin. Methane from biomass burning would also have a significant ^{14}C content, but would have a relatively

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[4] Methane from a few nonfossil sources (wetlands, bogs, rice fields, and tundra), is slightly depleted in ^{14}C (e.g., Wahlen et al., 1989). Therefore, it contributes a small uncertainty to these calculations.

[5] A small portion of natural gas deposits (~20%) contains biogenic CH_4 (Rice and Claypool, 1981) -- i.e., a small portion is biogenic rather than nonbiogenic.

[6] The $^{13}C/^{12}C$ isotope ratio of atmospheric CH_4 is also a function of sink strengths because oxidation rates vary between $^{13}CH_4$ and $^{12}CH_4$.

high $^{13}C/^{12}C$ ratio. If, however, a CH_4 sample contains no ^{14}C, it is of fossil origin. Data on CH_4 isotopes are thus a critical supplement to CH_4 concentration measurements for identifying and verifying the location and magnitudes of individual CH_4 sources or groups of sources.

Available Measurements and Techniques

Measurements of atmospheric CH_4 concentrations are obtained by analysis of air samples collected at regular intervals from locations or sites established for long-term monitoring, and occasionally during transects by aircraft or ships. Samples are usually transported to a laboratory, where they are analyzed for CH_4 content. Gas chromatography with flame ionization detection is a widely accepted method of determining CH_4 concentrations in air samples, and yields a precision of 0.5% or better (Rasmussen and Khalil, 1981; and Steele et al., 1987). Infrared absorption methods can also be used, although they are less precise and more expensive than gas chromatography. The advantage of infrared absorption methods is that high-frequency measurements can be made, which makes this technique particularly useful for measuring CH_4 concentrations from aircraft.

The existing network of long-term monitoring sites established by the Climate Monitoring and Diagnostics Laboratory of the National Oceanic and Atmospheric Administration (~30 sites) was designed to represent "clean" air (i.e., well-mixed, background concentrations, rather than concentrations that are spatially or temporally distinct due to their proximity to anthropogenic sources) (Steele et al., 1987). The strategy was formulated over 15 years ago (Komhyr et al., 1985). The purpose then was to capture the broad-scale hemispheric and latitudinal gradients in atmospheric trace gas concentrations. The choice of remote marine sites was dictated by sampling economy: spatial variability of trace gases near urban or "polluted" sites is translated, via the winds, into temporal variability at a site. Recent efforts in the last several years have focused on the addition of sites to narrow the estimates of contributions from the various sources and of removals by sinks. For example, data from around the Pacific rim, sampled by aircraft flown for dedicated research missions, or sampled via collaborative programs with ships of opportunity, will not quantify individual sources, such as CH_4 from rice cultivation in China, but will put integrative constraints on the upwind source -- i.e., constraints on the total regional strength of all sources from the Asian continent (Dlugokencky et al., 1993).

Additional monitoring sites would improve understanding of regional source strengths. Some strong regional sources, such as biomass burning in the Southern Hemisphere, currently have no monitoring sites near enough to capture much of their seasonal signal. However, as monitoring sites move closer to source regions, the CH_4 signal becomes more variable. Many years of data are required to obtain an average seasonal cycle, which can then be used to constrain source strength estimates in atmospheric models of tracer transport.

Satellite capabilities for monitoring and mapping CH_4 concentrations near the surface do not exist at present. An instrument named MOPITT (Measurements of Pollution in the Troposphere) (Drummond, 1992) proposed for the Earth Observing System (proposed launch date of 1998) is purportedly able to measure CH_4 concentrations near the ground. With a target accuracy of 1% for CH_4 concentration, MOPITT will, at a minimum, provide repeated global coverage, reveal CH_4 "hot spots," and identify the scattered source regions. This information can be used to test the plausibility of national emission inventories, as well as cross-check tracer model inferences of regional sources/sinks.

Maintenance and Calibration of Standards

Current analytical techniques for measuring CH_4 concentrations, such as gas chromatography with flame ionization detection, require measurement of CH_4 concentrations in air samples relative to a "standard" of known CH_4 content (Steele et al., 1987). Infrared absorption methods, although absolute rather than relative, frequently use a reference gas to improve the accuracy of the measurements. For CH_4 measurements, working standards are usually prepared in individual laboratories from natural air and are then intensively calibrated against a primary set of standards that is maintained in the laboratory. The working standards are used up over time, since they are destroyed in the measurement process. As a "batch" of working standards is used up, a new batch is prepared and, again, intensively calibrated against the laboratory's primary set of standards. Currently, laboratories around the world either create their own primary standards or obtain them from one of several different sources. There are no formal mechanisms for intercalibration of these standards among laboratories, although some comparisons among different laboratories occur informally.

For ambient atmospheric CH_4 measurements to be useful for verification of national emission estimates, it is important that: (1) measurements made at different laboratories within one country or in different countries must be capable of being compared quantitatively, and (2) changes in the measurements made at different times at a single laboratory must be capable of being interpreted as changes in sources or sinks. To achieve these goals, an international standard scale -- i.e., a stringent set of "international primary" standards with known CH_4 concentrations covering the range expected near ambient levels -- must be established and maintained (WMO, 1981; and U.S. DOE, 1986).

These international primary standards would be propagated to "secondary" standards that would then be used throughout the international measurement community. Individual laboratories would use these secondary standards to calibrate their working standards. In this way, CH_4 measurements at different laboratories would all be made relative to working standards derived from the same set of standards. Nonetheless, frequent intercalibrations (i.e., about every two years) between laboratories would be necessary to ensure that secondary standards are accurately propagated to working standards, especially since laboratories have to switch from one "batch" of working standards to the next as they are used up. The precision of the secondary standards should be ± 0.5 ppbv. A protocol for establishment of the primary standard and intercalibration of secondary standards (rather than the current informal comparisons among different laboratories) needs to be investigated. Also, the financial feasibility of propagating the international primary standards to secondary standards would have to be studied in greater detail..

The internal consistency of the international standard scale would ensure, in part, the quality of the measurements. Maintenance of the secondary standards at each laboratory ensures that year-to-year changes in the CH_4 concentration data record can be interpreted correctly as changes in source (and/or sink) strengths and locations, rather than being interpreted incorrectly due to the use of improperly calibrated standards. Moreover, the establishment of an international CH_4 standard scale for atmospheric measurements will allow for quantitative comparison of measurements from one laboratory with those from other laboratories around the world. Maintenance and calibration of standards, and intercomparison of methods and results, are thus critical if useful atmospheric data for verification purposes are to be obtained.

Standards should exist not only for CH_4 concentration measurements, but also for the determination of radiocarbon and stable isotopic contents. The radiocarbon content is given by the decay activity of ^{14}C, which is reported using the percent modern (pM) scale:

$$pM = (^{14}C_{sample}/^{14}C_{standard}) \times 100$$

The standard represents 95% of the ^{14}C activity of an oxalic acid standard maintained by the U.S. National Institute of Standards and Technology (NIST, formerly the U.S. National Bureau of Standards). The NIST oxalic acid standard is used internationally as the standard for ^{14}C measurements.

The situation is more difficult for $^{13}CH_4$. When determining isotopic contents of CH_4 in air samples, the CH_4 in a sample is converted to CO_2 and H_2O, which are then measured for isotopic content. Hence, among the standards that may be required for this determination are a set of pure CO_2 standards (gas or solid standard, such as barium carbonate) covering the range of atmospheric $^{13}CH_4$, and CH_4 in whole air standards to compare sample preparation methods. At present, there are no international isotopic standards for $^{13}CH_4$.

Development of techniques for measuring CH_4 concentrations that give better precision than is currently available with gas chromatography with flame ionization detection (0.5% or better) should be encouraged, particularly for application to propagating an international standard scale to secondary standards. While methods for absolute calibration of CH_4 standards are feasible (e.g., techniques used in isotope work to extract CH_4 from whole air samples (Lowe et al., 1991)), it is doubtful they can reach the precision of a relative method, such as a gas chromatograph commonly used for atmospheric measurements. Nevertheless, absolute calibration should be explored. If efforts to this end are successful, measurements made with respect to a different scale could then be converted to the absolute scale. Investigations of measurement techniques other than gas chromatography should be encouraged to obtain higher precision and to propagate the international primary standard scale to secondary standards.

Sampling and Reporting Strategy

There are several ways to obtain measurements of atmospheric CH_4 and its isotopic content for verification. Long-term monitoring sites provide information on seasonal, year-to-year changes, and secular trends in the sources in a region. Regular or occasional transects by aircraft or shipboard, or other intensive measurement campaigns, serve as spot checks that can detect and quantify spatially mixed, in-situ emissions.

For the atmospheric data to be useful for verifying annual CH_4 emissions from a region, the measurements must be made with adequate temporal and spatial coverage. In particular, measurement or sampling frequency must be great enough, and measurement duration must be long enough, that the measurements define a full seasonal cycle. The concentration data thus far have shown that the seasonal cycle is different in different places. For example, at Cape Grim, Tasmania, the seasonal cycle consists of a winter maximum and summer minimum. At Pt. Barrow, Alaska, however, there are double peaks in concentration, one in February and the other in October. These seasonal cycles provide valuable information about strengths of some of the sources and sinks and are an important constraint in atmospheric tracer models. A full year of atmospheric concentration data is necessary to determine the annual mean at each station. The annual means at all the stations are combined to define the latitudinal distribution of the atmospheric concentration, an important

constraint on source/sink locations in tracer models. For most locations, weekly samples are sufficient to accomplish this. The samples should be collected from a well-defined wind sector, such that samples are representative of well-mixed, large volumes of air, rather than a local pollution source. At sites where the concentrations are highly variable, in-situ, high-frequency measurements may be required. Since all sites have some interannual variability, multiple years of measurements are required to derive accurate averages. Concurrent measurements, such as meteorological data and other chemical species (such as CO_2, CFCs, aerosols) should be obtained to aid in the interpretation of the in-situ measurements.

Methane data can be collected and catalogued either by the World Meteorological Organization's archive in Japan or by the Carbon Dioxide Information Analysis Center in Oak Ridge, Tennessee. Ideally, the data should be reported based on the yet-to-be established international CH_4 standard, in one-year segments, and in a timely manner (i.e., within the next calendar year). The data should also be scrutinized, and suspect data should be flagged appropriately by the laboratory that made the measurements. For example, those samples collected when the wind was out of sector or measured during a time of less than optimal analytical performance should be indicated as such.

11.3 CONCLUSIONS

An international system to review and verify national inventories of CH_4 emissions (and emissions and sinks other greenhouse gases) should prove useful for several reasons. A verification system, through the exchange, review, and comparison of data, would promote dialogue and sharing of data among scientists and policymakers. This process is likely to improve scientific understanding of the CH_4 budget and refine national emission estimates, thereby increasing confidence in the FCCC and the emission inventory process. Verification of national emission inventories would also be useful in monitoring progress toward national and global emission reduction goals.

Because of the great variety and number of CH_4 emission sources, and because emissions from different sources become mixed in the atmosphere, it is not possible to verify national CH_4 emission inventories precisely through direct measurement or mass balance equations. An inventory can, however, be verified in terms of its plausibility, accuracy, and completeness. This direct, or "bottom-up," method would include the following steps:

- Evaluate the plausibility of the results.
- Evaluate the inventory methods used.
- Evaluate the accuracy of the calculations.
- Evaluate the accuracy and appropriateness of the emission factors used.
- Evaluate the accuracy and appropriateness of the activity levels used.

The results of this process would be used to improve national emission estimates, and presumably would also be used to update and refine the internationally accepted inventory methodologies.

Additional information with which to verify national CH_4 emission estimates can be obtained from a "top-down" monitoring approach, in which the atmospheric signatures of the emissions, in conjunction with a transport model, are used to test the plausibility of emission estimates. Measurements of atmospheric CH_4 concentrations and radioactive and stable isotope contents can thus be used to provide cross-checks on total CH_4 emissions from broad regions or large countries and on national and regional CH_4 emission estimates from certain sources. This technique can also be used to constrain estimates of global CH_4 emissions from individual sources or groups of sources. Atmospheric transport models that synthesize the concentration and isotope data have proven useful in narrowing uncertainties about individual CH_4 source strengths.

The effectiveness and accuracy of this "top-down" monitoring technique in verification of national, regional, and global emission estimates could be increased through a number of research activities, including: (1) spatial expansion of the network of concentration measuring sites; (2) greater temporal frequency of measurements at sites with seasonally varying source strengths; (3) greater spatial coverage, and accuracy, of isotope measurements; (4) establishment of international standards, and improved maintenance and calibration of standards, both at individual laboratories and internationally; and (5) standardized collection and cataloguing of CH_4 data at international centers.

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