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Methane Emissions And Opportunities For Control

Workshop Results Of Intergovernmental Panel On Climate Change

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Coordinated by
Japan Environment Agency
&
United States Environmental Protection Agency

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ABOUT THIS REPORT

This report is based on workshops sponsored by the Japan Environment Agency and the United States Environmental Protection Agency in order to support the Intergovernmental Panel on Climate Change (IPCC). These workshops examined methane emissions and opportunities for control of these emissions as follows:

Workshop of the Agricultural, Forestry and Other Human Activities Subgroup (AFOS)

- o flooded rice fields
- o livestock

Workshop of the Energy and Industry Subgroup (EIS)

- o natural gas systems
- o coal mining
- o waste management systems

The United States Environmental Protection Agency provided the necessary support for assembly of this report. It is a summary of the information presented at the two workshops by experts in the particular subject areas. The material is presented for informational purposes and does not represent the policies of the Japan Environment Agency or the United States Environmental Protection Agency or any of the other government agencies of these countries. The list of workshop attendees is provided in Appendix E.

Acknowledgements

Several organizations have contributed to the workshops upon which this report is based. These include the Japan Environment Agency, the United States Department of Agriculture, the United States Agency for International Development and the United States Environmental Protection Agency. The following individuals from these organizations deserve special acknowledgement for their contributions: Katsuya Sato (Japan Environment Agency), Shuzo Nishioka (Japan Environment Agency), Dennis Tirpak (US EPA), Gary Evans (USDA), Ken Feldman (US AID), and David Mobley (US EPA).

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The organizational and management efforts of Lauretta Burke (US EPA), Kathy Ackley (ICF Incorporated), Shirley Toth (US AID), Leslie Gallo (Science and Policy Associates), David Debusk (US EPA), and Alex Greenwood (ICF Incorporated) were greatly appreciated. Finally, Michael Gibbs of ICF Incorporated deserves special thanks for developing a first draft of this report.

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FINDINGS

Two international workshops held in support of the Intergovernmental Panel on Climate Change (IPCC) provided information on current methane emissions and opportunities for reducing these emissions. The first workshop, held on December 12-14, 1989, by the U.S. Environmental Protection Agency and the U.S. Department of Agriculture, examined greenhouse gas emissions from agriculture in support of the Agriculture, Forestry, and Other Human Activities Subgroup (AFOS) of the Response Strategies Working Group.

The second workshop was held on April 9-13, 1990. Funded jointly by the Environment Agency of Japan, the U.S. Environmental Protection Agency and the U.S. Agency for International Development, this workshop examined methane emissions from natural gas systems, coal mining activities, and waste management in support of the Energy and Industry Subgroup (EIS) of the Response Strategies Working Group.

The information presented at these two workshops provided the information compiled in this summary report. Based on the synthesis of the information presented at the workshops, the following findings are identified.

1. **Atmospheric levels of methane are increasing and will affect tropospheric air quality and global climate change.**

    1.1 Methane is an important greenhouse gas that, based on model calculations, accounts for about 15 percent of the current increase in commitment to global warming.[1]

    1.2 The global average methane concentration is currently increasing by about 1 percent per year. This rate of increase is well characterized for the recent past. In addition, ice core data show that methane concentrations have more than doubled in the last two centuries and that they are now substantially higher than they have been in the past 160,000 years.

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[1] This statement is adopted from the IPCC Workgroup 1 Science Assessment Report. The group discussion at the AFOS workshop attributed about 20 percent of the recent increase in radiative forcing to methane based on the work of Hansen et al. (1988).

1.3 Increasing emissions of methane are the primary cause of increasing methane concentrations. Reduction in the rate of methane destruction in the atmosphere is also a factor.

1.4 Continued increases in methane concentrations will lead to changes in the distribution and concentration of tropospheric ozone, which will also contribute to increases in the greenhouse effect. Furthermore, there is concern that increasing methane concentrations could enhance the formation of stratospheric polar clouds, thus contributing to polar stratospheric ozone depletion.

2. Methane's strong ability to absorb infrared radiation combined with its relatively short atmospheric lifetime makes methane control an important opportunity for addressing global climate change.

2.1 On a kilogram for kilogram basis, methane is a more potent greenhouse gas than carbon dioxide (63 times greater after 20 years, 21 times greater after 100 years, and 9 times greater after 500 years).[2]

2.2 Methane's short atmospheric lifetime enables the control of methane emissions to quickly produce benefits in terms of changes in atmospheric concentration and radiative forcing.

2.3 As a consequence of its stronger short-term impact and the short atmospheric lifetime, methane emissions reductions made in the near term would be substantially more effective than similar carbon dioxide emissions reductions in slowing global warming.

2.4 Given the many methane emissions sources globally, emissions reductions from any single country or source will be small compared to total methane emissions, and small compared to total emissions of all greenhouse gases. Consequently, programs to reduce methane

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[2] These are the values presented are adopted from the IPCC Working Group 1 Science Assessment Report. The values presented at the EIS workshop valued the impact of indirect effects somewhat differently. These include the effect that methane emissions have on levels of tropospheric ozone and the effect that methane concentrations have on the lifetime of methane itself. The values reported at the EIS workshop were 120 times in the first year, 55 times greater over 60 years and 10 times greater over 1000 years.

emissions from many sources would be required in many countries.

2.5 Although emissions-reduction programs would be required in many countries to achieve significant emissions reductions, individual countries can make valuable contributions by developing, demonstrating, and implementing emissions-reduction technologies.

3. **Stabilizing methane concentrations at or below approximately current levels may be achievable with identified emissions control options that are profitable or low cost, but additional analyses are necessary.**

3.1 The recent comprehensive observational record indicates that a reduction in methane emissions of about 30 to 45 Tg[3] per year will stabilize atmospheric methane concentrations assuming that the rate of methane destruction in the atmosphere remains unchanged. This level of emissions reduction is about 10 percent of current anthropogenic emissions.

3.2 Analyses using models indicate that following a reduction in emissions of 30 to 45 Tg per year, stabilization could be maintained if the long-term growth in methane emissions was restrained to about 2 to 3 percent per decade.

3.3 Using the emissions reduction techniques identified at the IPCC Workshops it appears technically feasible to reduce methane emissions by about 67 to 170 Tg per year. While feasible, it is unlikely that this level of emissions reduction can be achieved fully in the next 10 years. Further detailed evaluation of these potentials is needed.

3.4 Based on information presented at the workshop it is possible that profitable and low cost options can be implemented to reduce emissions by about 25 to 50 Tg in the next 10 years. These emissions reductions will be adequate to stabilize atmospheric methane concentrations at approximately current levels. Additional analysis is required to improve the estimate of emissions reductions that can be achieved in the next 10 years.

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[3] 1 Tg = 1 teragram = 10^{12} grams = 10^{9} kilograms = 1 million metric tons.

3.5 Significant research, analysis, and demonstration will be necessary to achieve reductions in methane emissions sufficient to stabilize methane concentrations.

4. A variety of frameworks may be used to structure international action for controlling methane emissions. Economic incentives, market mechanisms, and technology-based approaches are among the options that should be considered as alternatives to regulatory "command-and-control" approaches that require emission rollbacks.

4.1 Methane sources are numerous, diverse, and geographically dispersed. Additionally, methane is generally emitted by complex and highly variable biological and industrial systems whose inputs and outputs cannot be translated easily into emissions. Therefore, precise measurement of emissions from individual locations is difficult.

4.2 Incentive-based control strategies under which best practices are encouraged may be the preferred approach for reducing methane emissions. This approach may encompass the wide range of options available for reducing emissions and may facilitate adaptation among the diverse and decentralized sources.

1. INTRODUCTION

This report compiles the work that has been performed on emissions of methane (CH_4) from anthropogenic sources and options for reducing these emissions by two subgroups of the Intergovernmental Panel on Climate Change (IPCC) Response Strategies Working Group:

- Agriculture, Forestry, and Other Human Activities Subgroup (AFOS) and

- Energy and Industry Subgroup (EIS).

Two international workshops held in support of the IPCC process provided the information for this report. The first workshop, held on December 12-14, 1989, by the U.S. Environmental Protection Agency and the U.S. Department of Agriculture examined greenhouse gas emissions from agriculture in support of AFOS. This workshop examined emissions of methane from livestock systems and rice cultivation, among other agricultural sources of emissions. The second workshop was held on April 9-13, 1990. Funded jointly by the Environment Agency of Japan, the U.S. Environmental Protection Agency and the U.S. Agency for International Development, this workshop examined methane emissions from natural gas systems, coal mining activities, and waste management.

This report summarizes and synthesizes the analyses presented at these workshops in the following manner. Chapter 1 provides an overview of the report. Chapter 2 discusses methane's contribution to global warming. This chapter also summarizes the data that show that atmospheric methane concentrations are increasing and the contribution that these increases are making to global climate change. This chapter estimates the emissions reductions that are needed to stabilize atmospheric methane concentrations. Finally, the unique near-term benefits of controlling methane emissions are discussed.

Chapter 3 summarizes the information presented at the workshops on the manner in which methane emissions can be reduced from its primary anthropogenic sources. The information presented in this section indicates that the emissions reduction techniques discussed at the workshops are adequate to stabilize atmospheric methane concentrations at approximately current levels.

Next, Chapter 4 discusses issues involved in designing a framework for controlling methane emissions internationally. The importance of international cooperation and the key research steps needed to control methane emissions are identified.

Finally, the main body of the report concludes with the findings from the IPCC workshops held on methane. These findings were adopted by those attending the workshops.

Attached to the main body of the report are several appendices. Appendix A presents an overview of methane emissions. Appendices B, C, and D describe the emissions and emissions reduction opportunities for:

- Appendix B: Energy-Related Methane Emissions: Oil and Gas Systems; Coal Mines; and Combustion.
- Appendix C: Waste Management: Landfills; Incineration; and Sewage Treatment.
- Appendix D: Agricultural Sources: Rice Cultivation; Managed Livestock; Animal Wastes; and Biomass Burning.

2. OVERVIEW OF METHANE'S CONTRIBUTION TO GLOBAL WARMING

Methane is an important greenhouse gas, accounting for about 15 percent of the "radiative forcing" added to the atmosphere in the 1980s (see Exhibit 1). The radiative forcing is a measure of the manner in which the radiative properties of the atmosphere are changing in response to emissions of greenhouse gases.

Methane levels are increasing substantially as demonstrated by comprehensive global measurements of atmospheric methane concentrations. These measurements show that over the past 300 years atmospheric methane concentrations have more than doubled, and that its concentration continues to increase by about 1 percent (10 to 16 ppbv[4]) per year (WMO, 1990). Exhibit 2 displays recent measurements of global atmospheric methane concentrations.

These measured increases in methane concentrations are highly correlated with increases in global population and human-related activities that release methane to the atmosphere. The major human-related sources of methane emissions include:

- rice cultivation;
- livestock and other animals (including animal wastes);
- biomass burning;
- coal mining;
- oil and gas systems; and
- landfills.

The approximate levels of emissions from each of these sources are summarized in Exhibit 3 and described more fully in Appendix A. These human-related methane sources account for about 70 percent of total methane emissions from all sources.

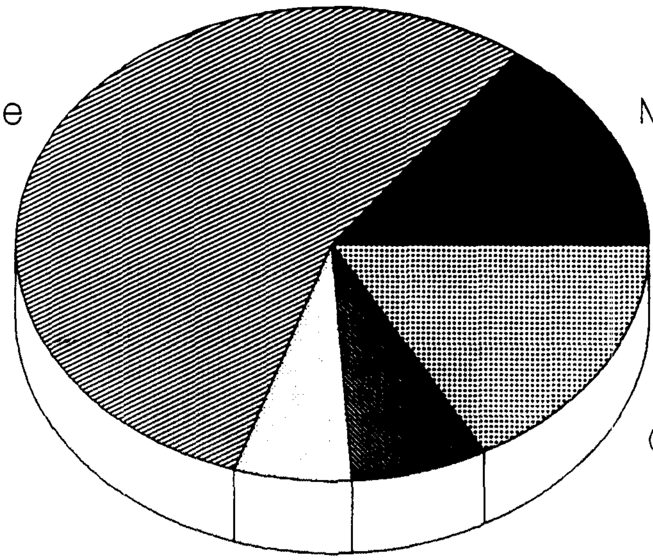
As shown in the exhibit, the total global emissions of methane from all sources are estimated at about 540 Tg per year.[5] Despite uncertainties in each of the major sources of emissions, the total global emissions are well constrained by observational

[4] Parts per billion by volume.

[5] 1 Tg = 1 teragram = 10^{12} grams = 10^{9} kilograms = 1 million metric tons.

EXHIBIT 1

RADIATIVE FORCING ADDED IN THE 1980s



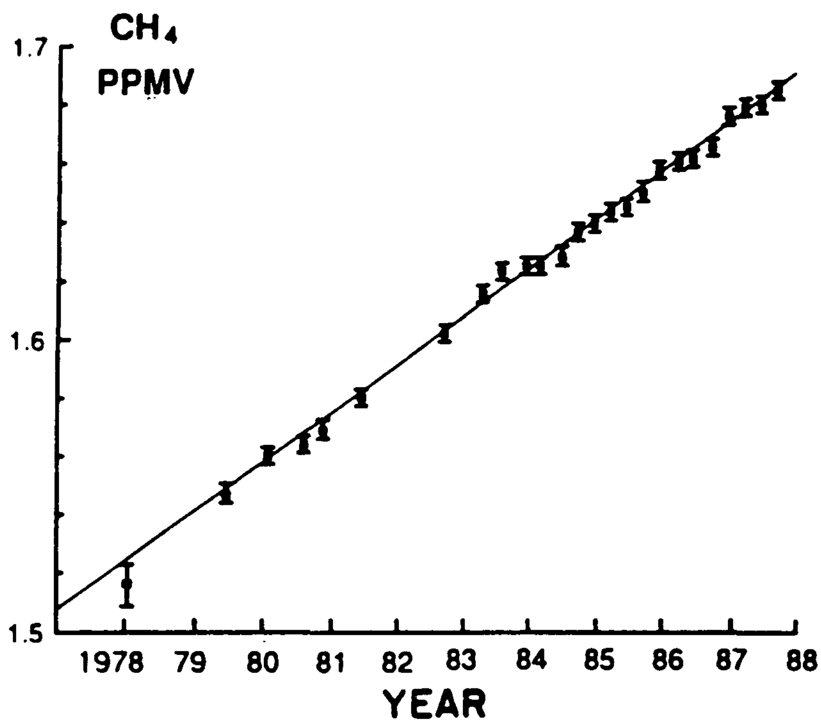
The observed increases in the atmospheric concentrations of key greenhouse gases were used to estimate an increase in the "radiative forcing" of the atmosphere. The radiative forcing refers to the extent to which the constituents in the atmosphere are able to capture infrared radiation (IR) given off by the Earth. By increasing the radiative forcing of the atmosphere, the greenhouse gases are expected to cause global warming.

The analysis indicates that methane contributed about 15 percent of the increase in radiative forcing observed in the 1980s.

Source: IPCC Working Group 1 Science Assessment Report

EXHIBIT 2

OBSERVED INCREASES IN METHANE CONCENTRATIONS



Source: Blake, D.R. and F.S. Rowland, "Continuing Worldwide Increase in Tropospheric Methane, 1978 to 1987," Science, March 4, 1988.

EXHIBIT 3

SOURCES OF METHANE EMISSIONS
10^{12} Grams per Year

	Annual Emissions	Range	Comments	Source
Animals	80	65 - 100	Livestock in developed and developing countries.	Cicerone and Oremland
Animal Wastes	35	NR[a]	Anaerobic decomposition of organic wastes.	IPCC
Wastewater	NR	20 - 25	Anaerobic decomposition of organic matter in the waste water stream	IPCC
Rice Paddies	110	60 - 170	Principally in developing countries.	Cicerone and Oremland
Coal Mining	NR	30 - 50	Surface and (mostly) sub-surface mining.	IPCC
Oil/Gas Systems	45	25 - 50	Production, transmission and distribution.	Cicerone and Oremland
Landfills	NR	25 - 40	Decay of organic wastes.	IPCC
Biomass Burning	55	50 - 100	Forest clearing and waste burning.	Cicerone and Oremland
Natural Wetlands	115	100 - 200	Tundra, bogs, swamps, alluvial formations.	Cicerone and Oremland
Termites	40	10 - 100	Bacteria within termites produce CH_4 as part of the termite's digestive process.	Cicerone and Oremland
Oceans and Freshwaters	15	6 - 45		Cicerone and Oremland
Hydrates	5?	0 - 100	Potentially important future source.	Cicerone and Oremland
Total Emissions[b]	540	440 - 640	Well constrained.	Cicerone and Oremland

Sources: Cicerone and Oremland (1988), "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, December 1988. IPCC, December 1989 and April 1990 IPCC workshops on methane emissions.

[a] NR = not reported at the IPCC workshop

[b] Total annual emissions of 540 Tg per year ±100 Tg is well constrained based on observational data. The point estimates of the individual source estimates presented here do not sum to 540 Tg.

evidence to fall between 440 and 640 Tg per year. The factors that constrain this range are described in Cicerone and Oremland (1988).

Emissions from these activities are expected to increase over the next decade, and to lead to increasing atmospheric concentrations of methane. Business-as-Usual Scenarios for methane emissions and concentrations are shown in Exhibit 4 and Exhibit 5. By 2100, methane concentrations are about 4000 ppbv, or more than doubled from current levels.

Methane's increasing concentration in the atmosphere is important from the perspective of global climate change because methane is very effective at absorbing infrared (IR) radiation. A gram of methane added to today's atmosphere will initially absorb about 70 times as much IR radiation as would a gram of carbon dioxide (CO_2). Unlike carbon dioxide, however, methane has a relatively short atmospheric lifetime, on the order of 10 years, and consequently, the impact of a given amount of methane emissions is relatively short-lived.

Methane's strong IR radiation absorbing characteristic, combined with its relatively short atmospheric lifetime, make it very different from the other major radiatively-important trace gases. In addition, the characteristics of the sources that emit methane are very different from the sources that emit other greenhouse gases such as carbon dioxide and CFCs (chlorofluorocarbons). These differences indicate that methane control may be a good opportunity for achieving near-term benefits in terms of slowing the rate of global warming. The opportunity that methane presents is explored further below, after additional documentation is presented on rising methane concentrations and on the extent of reductions required for stabilization of methane concentrations in the atmosphere.

2.1 Methane Concentrations Are Increasing

It is well documented that global average methane atmospheric concentrations are increasing. Measurements have been performed at six primary sites between 1979 and the present, including frequent and regular measurements at Cape Meares, Oregon. Methane measurements have also been performed by the NOAA/GMCC global distributed monitoring network since 1983. Methane concentrations have increased at every site analyzed consistent with the measurements at Cape Meares (WMO, 1986).[6]

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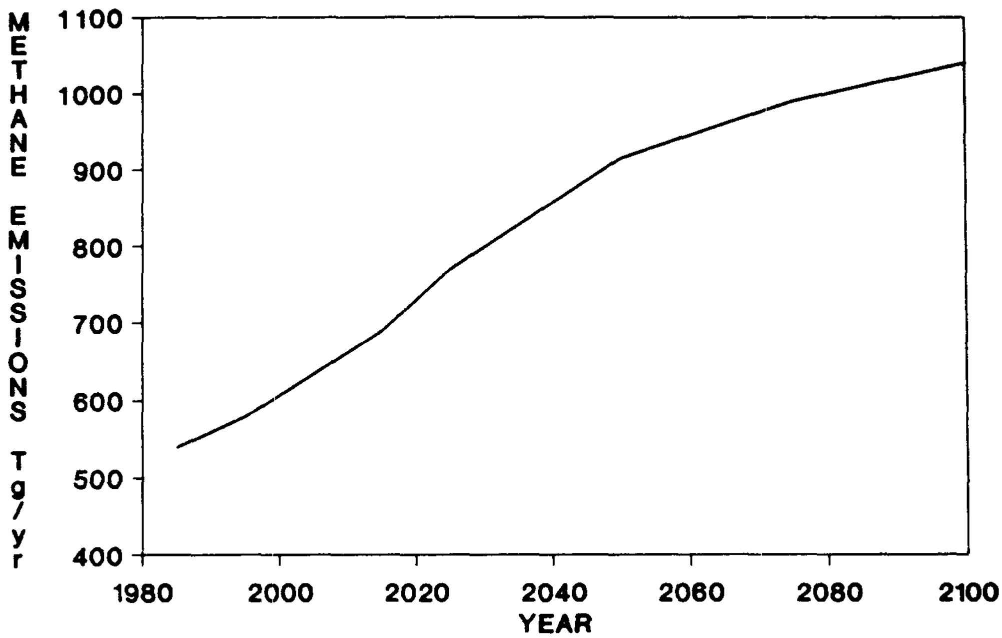
[6] Published estimates of the recent increases in atmospheric methane levels include: Blake and Rowland (1986); Blake and Rowland (1988); Steele et al. (1987); Ehhalt et al.

(continued...)

EXHIBIT 4

BUSINESS AS USUAL SCENARIO FOR METHANE EMISSIONS



Source: IPCC Working Group 1 Science Assessment Report

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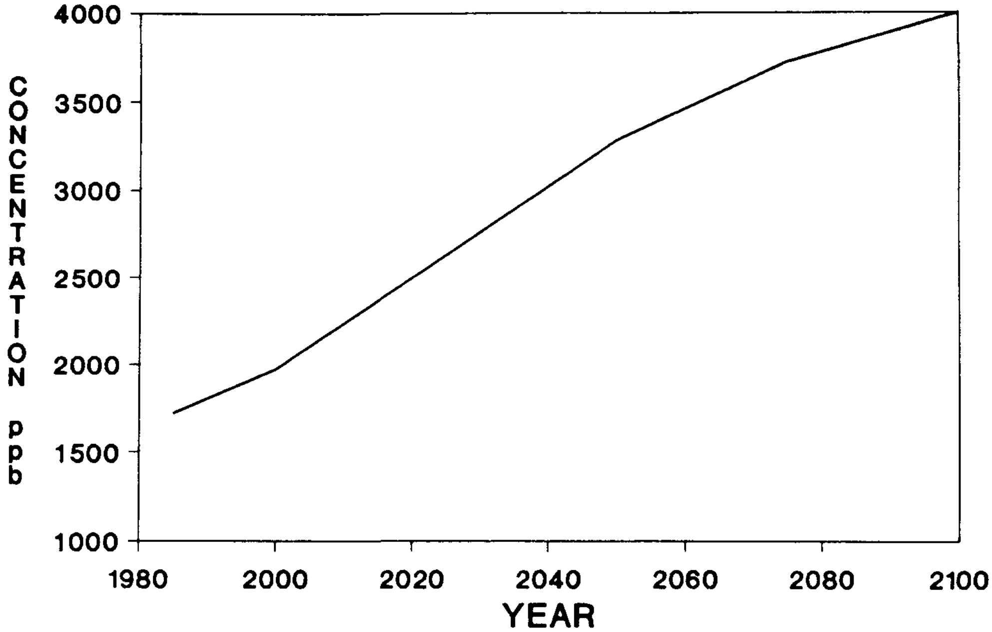
[6](...continued)
(1983); Fraser et al. (1981); Khalil and Rasmussen (1982), and Khalil and Rasmussen (1990), as well as various updates and extensions of these estimates.

EXHIBIT 5

BUSINESS AS USUAL SCENARIO FOR METHANE CONCENTRATIONS



Source: IPCC Working Group 1 Science Assessment Report

As shown in Exhibit 2, Blake and Rowland estimate that the global average methane level in the atmosphere is increasing at an annual rate of about 1 percent (16 ppbv). This estimate is based on measurements of methane levels in "clean air" areas. Consequently, the estimates are not influenced by potential trends in local methane sources, and are representative of trends in the overall global methane abundance.[7]

Steele et al. (1987) report the results of two years of weekly sampling at 23 locations around the globe. These data provide the most detailed picture of the distribution of atmospheric methane across all latitudes, and its seasonal changes. The results of this detailed two-year assessment included that methane levels were found to be increasing wherever sufficiently long records were available. Steele et al. reported an annual average global increase of 0.8 to 1 percent for the period 1983 to 1985. They also reported evidence that the rate of increase may have slowed in the Antarctic region, while no evidence of a slowing was reported at other southern or northern hemispheric locations.

In addition to the recent detailed analyses of atmospheric methane that show recent and ongoing increases in abundance, a series of ice core studies indicate that methane levels have been increasing for about 200 to 300 years, and that levels were fairly constant for the previous 700 to 2,700 years.[8] Additionally, analyses of solar spectra provide estimates of rates of methane increases since 1961 that are consistent with the ice core and recent observational data (Rinsland et al, 1985). Based on these analyses, it is well established that the concentration of methane has more than doubled in the last 300 years and continues to increase today.

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[7] For example, if ambient measurements were taken over time near an area where methane emissions were increasing (e.g., near a coal mine that was being developed for the first time), then increasing concentrations shown in the measurements could be associated with the new source that is near where the air samples were taken. In such a hypothetical case, the air samples would be affected by a local source. The analyses that indicate that global methane levels are increasing were performed in remote locations to ensure that local sources do not influence the measurements. Additionally, diverse locations measured around the world all indicate an increase in methane levels; further supporting the claim that methane levels are increasing globally.

[8] Careful analyses of methane in ice cores indicates that the increase in the last 200 to 300 years is not an artifact of the analysis methods or the reaction of methane in the ice. Ongoing studies are developing more precise relationships between levels of methane in the atmosphere and in the ice.

2.2 Methane Stabilization

Although until recently the role of methane and the possibility of reducing the rate of increase of methane in the atmosphere have not been the subject of widespread discussion, recent analyses presented at two IPCC workshops indicate that methane control is possible and may be achieved at a low cost, if not a profit. As a consequence of these emission control opportunities, methane control may be a very cost-effective way of limiting actual global warming in the next 30 to 60 years.

One reason why this is possible is that relatively small reductions in methane emissions will lead to a halt in the increase in methane concentrations relatively quickly. For example, the observed rate of increase in atmospheric methane concentrations discussed above indicates that methane in the atmosphere is increasing at a rate of about 30 to 45 Tg per year.[9] This result indicates that if the annual methane emissions were reduced by about this amount and held constant, methane concentrations would no longer increase, assuming that the rate of methane destruction in the atmosphere also stayed constant.

This estimate of the emissions reduction needed to stabilize methane concentrations at approximately current levels is on the order of about 10 to 15 percent of the total human-related methane emissions. As a contrast, much larger emissions reductions are required to halt the increasing concentrations of the other trace gases, as follows:

Trace Gas	Emissions Reduction Needed to Halt Increase
Methane	10 - 15 percent
Carbon Dioxide	50 - 80 percent
Nitrous Oxide	80 - 85 percent
Chlorofluorocarbons	100 percent

To test the validity of this estimate of the emissions reduction needed to stabilize methane concentrations, EPA's Atmospheric Stabilization Framework (ASF) was used to estimate the methane emissions reductions needed to stabilize atmospheric concentrations. The ASF is a series of emissions and atmospheric

[9] Each 1 ppbv of increase in global atmospheric methane equals about 2.77 Tg of methane in the atmosphere. Therefore, because the global methane concentration is increasing at a rate of about 10 to 16 ppbv per year, the global atmospheric abundance of methane is increasing at a rate of about 28 to 45 Tg per year.

models that have been used in analyses of global climate change performed for EPA and as part of the IPCC process.[10] The model was used for the analysis presented here because it estimates the composition of the atmosphere (including methane concentrations) based on the interactions among the full set of greenhouse gases.

This analysis relied on two scenarios of future emissions that bracket the Business-as-Usual Scenario developed by the IPCC:

- Rapidly Changing World scenario (RCW) includes rapid economic growth and increases in greenhouse gas emissions from fossil fuel use and land use changes (deforestation); and

- Slowly Changing World scenario (SCW) includes slower economic growth and smaller increases in greenhouse gas emissions.

These two scenarios describe a wide range of potential future emissions and useful for providing sensitivity analyses. These scenarios are described in detail in EPA (1989).

These two scenarios were used to estimate the level of methane emissions that must be achieved in order to stabilize methane concentrations at approximately current levels. The levels of emissions of all the other greenhouse gases were not changed from the values specified in the RCW and SCW scenarios.

Exhibit 6 presents the estimates of methane emissions in the cases examined. As shown in the exhibit, the uncontrolled methane emissions in the RCW and SCW scenarios are estimated at about 505 Tg per year in 1985. This level of emission is slightly lower than the middle estimate provided in Cicerone and Oremland (1988), but is toward the middle of the accepted range of global annual emissions. Regardless, the precise magnitude of the initial emissions does not affect the result of this analysis.

In the RCW scenario emissions are estimated to grow to about 1,000 Tg per year by 2100. To stabilize concentrations at about 1.7 ppmv (1,700 ppbv), the ASF indicates that methane emissions must be reduced to about 475 Tg in the near term. This is a reduction of about 30 Tg from current levels of emissions. This

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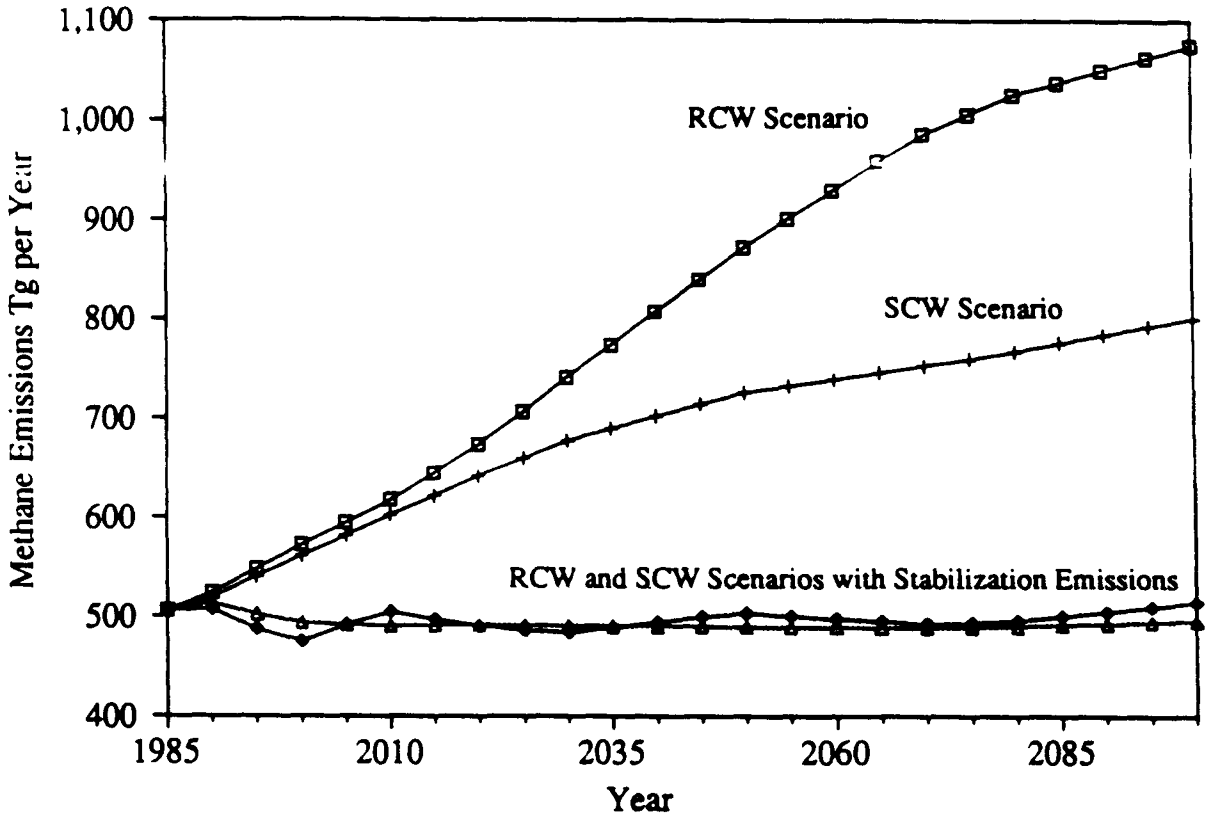
[10] See EPA (1989) for a description of the ASF. The ASF was used in analses for the May 31st, 1990 Intergovernmental Panel on Climate Change Energy and Industry Subgroup Report.

EXHIBIT 6

METHANE EMISSIONS SCENARIOS AND METHANE STABILIZATION



Two base scenarios of methane emissions were analyzed: Rapidly Changing World (RCW) and Slowly Changing World (SCW) from EPA (1989). These scenarios represent a wide range of potential future emissions for greenhouse gases.

The methane emissions needed to stabilize concentrations are labeled as the "Stabilization Emissions" for each scenario. As shown, emissions must be reduced by about 30 Tg by the year 2000 in order to stabilize concentrations. Subsequent growth in emissions must also be restrained over the long-term.

emissions reduction is consistent with the estimates derived above based on the known rate of increase of methane in the atmosphere.

Similar results are seen in Exhibit 6 for the SCW scenario. In this scenario emissions must again be reduced by about 30 Tg to achieve stabilization in the near term. Exhibit 7 displays the estimates of methane concentrations using these emissions. The uncontrolled RCW and SCW scenarios show increasing methane concentrations over time with concentrations increasing by 2100 to about 4,200 ppbv and 3,200 ppbv, respectively. The concentrations are stabilized at about 1,700 ppbv by reducing emissions in the near term, and then restraining growth in the longer term.

This analysis with the ASF indicates that methane stabilization can be achieved and maintained with fairly modest reductions in emissions in the near term and restraints on emissions growth in the long-term. Over the next 30 years this requires that methane emissions be reduced by about 30 Tg by the year 2000, and that subsequent growth in emissions be restrained to under 3 percent per decade in the following 25 years. Furthermore, by limiting emissions growth over the long-term to about 2 to 3 percent per decade, stabilization may be maintained for longer periods of time. This range for the estimates of reductions necessary to stabilize concentrations is fairly robust across the wide range of potential future emissions of other greenhouse gases that is examined.

Despite the various uncertainties in the overall estimate of global methane emissions, it is clear that relatively small reductions in emissions can be expected to halt the increase in methane concentrations. The comprehensive observational record on atmospheric methane concentrations provides confidence in the level of emissions reduction that needs to be achieved, and methane's relatively short lifetime helps to ensure that the effects of emissions reductions will be observed quickly. These elements indicate that stabilization of atmospheric methane concentrations is feasible in the near-term.[11]

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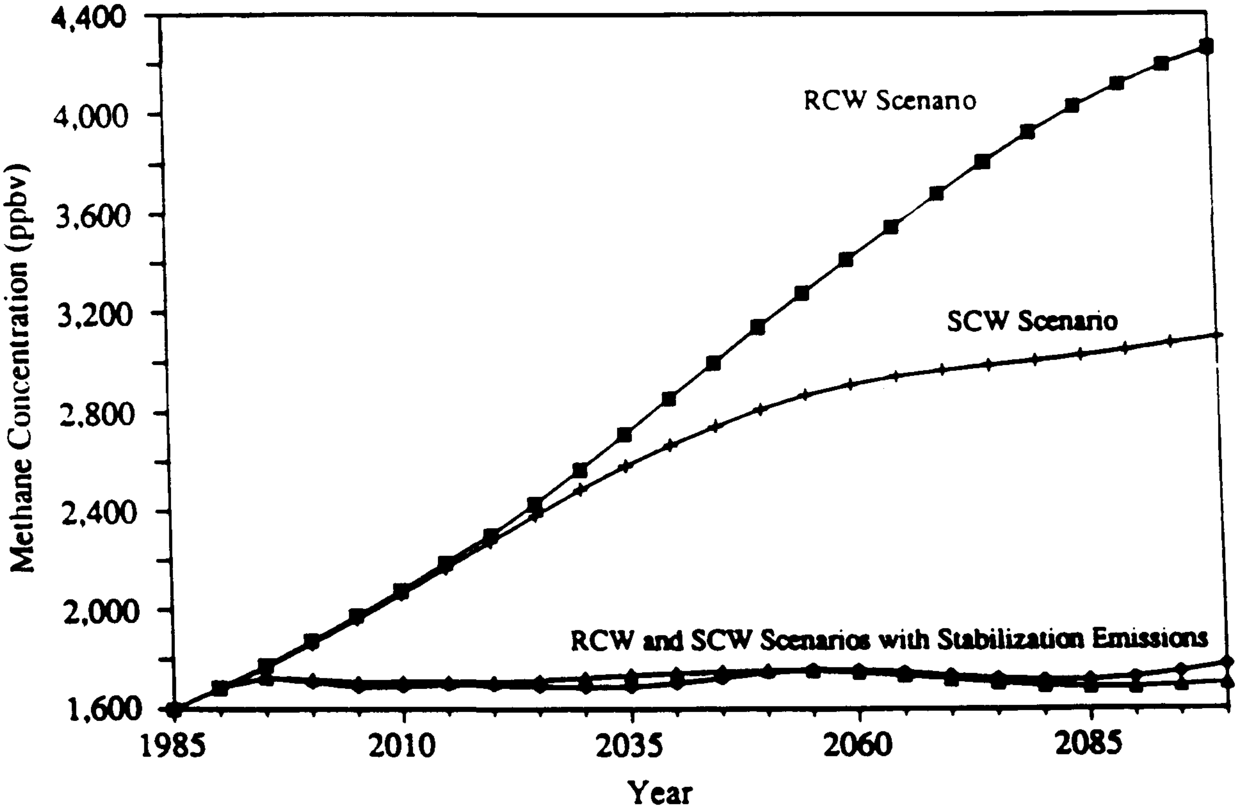
[11] The ability to stabilize methane concentrations could be undermined by other changes in emissions and atmospheric composition, for example associated with increases in methane emissions from natural sources or changes in the atmospheric lifetime of methane. Although the ability to achieve stabilization of atmospheric methane may be jeopardized in these circumstances, the value of methane emissions reductions would actually increase as a result of these changes.

EXHIBIT 7

METHANE CONCENTRATIONS AND METHANE STABILIZATION



Two base scenarios of methane concentrations were estimated: Rapidly Changing World (RCW) and Slowly Changing World (SCW) from EPA (1989). These scenarios represent a wide range of potential future emissions for greenhouse gases.

The methane concentrations estimated using the emissions needed to stabilize concentrations are shown as the "Stabilization Emissions" scenarios. As shown, these scenarios produce methane concentrations on the order of 1,700 ppbv.

2.3 Controlling Methane has Large Near-Term Benefits

Large benefits can be derived by controlling methane emissions and stabilizing atmospheric methane concentrations. The ASF stabilization analysis presented in the previous section also indicates that stabilizing methane concentrations will reduce the radiative forcing added between 1990 and 2020 by about 20 percent. This reduction delays the equivalent buildup of all greenhouse gases by about 10 years by this time.

Methane control represents an opportunity to slow the rate of warming over the next 30 to 100 years. These types of opportunities warrant attention because they could help to "buy time" during which additional cost-effective techniques for reducing carbon dioxide emissions and emissions of other greenhouse gases can be identified, evaluated, and implemented.

The benefits of reducing emissions of a greenhouse gas, such as methane, depend upon the global warming averted by that reduction and upon the speed at which the warming is averted. The amount of warming averted by the reduction in emissions of a unit of the greenhouse gas depends in turn on the potency of the gas which may be characterized through the following factors:

- radiative absorbance;
- atmospheric lifetime;
- indirect effects on the concentrations of other radiatively active gases; and
- past, present, and future emissions of other greenhouse gases and their resulting concentrations.

The concept of the Global Warming Potential (GWP) attempts to capture most of these considerations. A GWP is the ratio of the warming caused by the emissions of a unit of a trace gas to that caused by the emission of carbon dioxide at current concentration levels. The definition of a GWP incorporates an additional consideration over those listed above -- the ratio is calculated over different time periods, comparing the warming of the trace gas to that caused by carbon dioxide for a fixed number of years following the emission.

The GWPs for methane which are calculated to reflect different time horizons are all based on the following information:

- Molecule for molecule, the instantaneous relative radiative forcing of methane is 25 times that of carbon dioxide or 70 times more gram for gram.

- The lifetime of methane is approximately 10 years and that of carbon dioxide effectively 230 years (Lashof and Ahuja, 1990).

- In the atmosphere methane participates in chemical reactions that lead to the formation of tropospheric ozone, itself a greenhouse gas. This tropospheric ozone formation amplifies the methane's IR radiation absorption direct effects by about 70 percent (Lashof, 1989).

Thus, gram for gram methane in the atmosphere is about 120 more times more potent than a gram of carbon dioxide in the atmosphere in terms of its immediate ability to absorb IR radiation. In addition, the GWP must account for the natural conversion of methane into water and carbon dioxide by hydroxyl ions which occurs over time. Since this scavenging is limited by the concentration of hydroxyl ions, an increase in methane emissions tends to reduce the rate of the destruction of methane with a 10 percent increase in methane emissions increasing the concentration of methane by an additional 15 percent (Thompson and Cicerone, 1986).

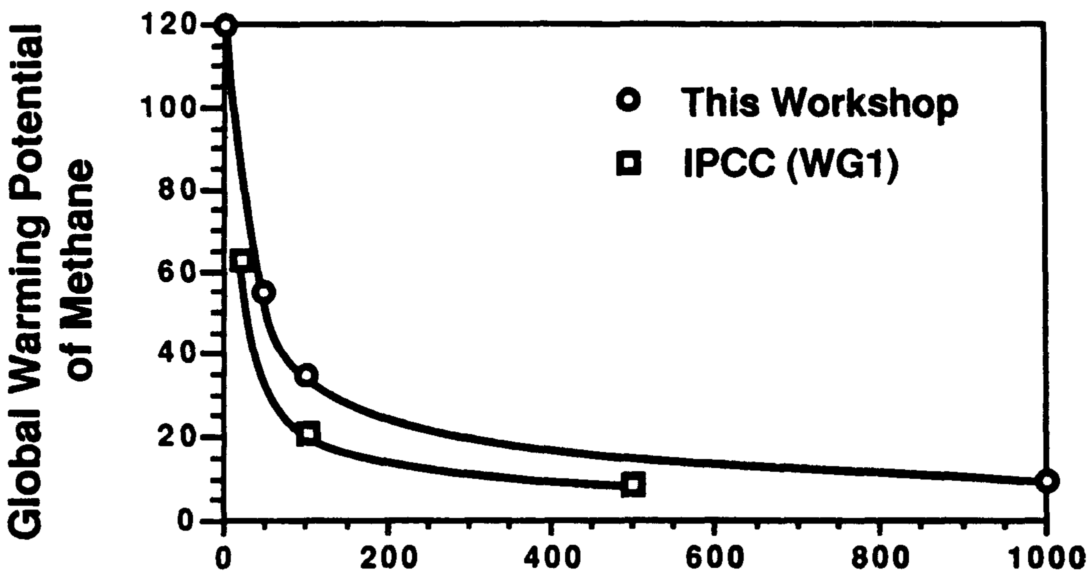
Exhibit 8 shows the GWPs for methane as a function of the time horizon over which the warming is compared. Since methane is a relatively short-lived gas, the large ratio of 120 to 1 is reduced over longer time periods as methane is destroyed and carbon dioxide stays in the atmosphere. The warming from methane is realized in the first few decades after the emission while the warming from carbon dioxide is realized gradually over centuries. Consequently, the GWP of methane decreases with longer time horizons.

Working Group 1 of the IPCC has also estimated GWPs of trace gases. With a somewhat different method for assessing the indirect effects of methane, their estimates of GWPs are somewhat different, although not much smaller than those presented at the EIS workshop. These GWPs are also shown in Exhibit 8.

In terms of the radiative forcing prevented over the next 50 years, a reduction in methane emissions of 40 Tg is equivalent to preventing about 1,400 Tg of carbon dioxide emissions, which is about 6 percent of the total global carbon dioxide emissions from human activities.

One implication of this analysis is that near-term methane emissions reductions will be more effective than similar carbon dioxide emissions reduction in slowing actual warming experienced in the next 30 to 100 years. Because of their differing relative impacts, actions to reduce methane and carbon dioxide emissions actually serve two different, important and complementary goals

Exhibit 8: Global Warming Potential of Methane as a Function of Time Over Which Warming is Compared.



Duration (years) over which warming caused is compared to that caused by carbon dioxide.

-- that of slowing warming and that of ultimately limiting warming. Actions to stabilize global climate change should pursue simultaneous strategies that limit the emissions of different trace gases with these widely differing impacts.

3. OPPORTUNITIES FOR EMISSION REDUCTION

Control of methane may be more feasible than once perceived. Because scientists are unable to quantify emissions from each source precisely, and because there is uncertainty regarding the relative importance of past increases in emissions and increases in methane's atmospheric lifetime in causing the observed increase in concentrations, it has been frequently thought that methane concentrations could not be controlled. However, this logic fails to recognize that to stabilize methane concentrations we do not need to know precisely the emissions from each source nor the relative importance of past changes in emissions and atmospheric lifetimes. To stabilize concentrations we only need to know the amount by which emissions exceed destruction in the atmosphere and how to reduce emissions.[12]

As described earlier, the extent to which methane emissions exceed methane destruction in the atmosphere can be estimated from the observational record. These data indicate that reducing anthropogenic emissions by about 10 percent will stabilize atmospheric concentrations of methane. It is not necessary to characterize all the anthropogenic sources of emissions precisely nor to estimate all their growth rates. It is only important that an adequate level of emissions reductions are achieved from some combination of sources. It will be most cost effective to undertake the least costly opportunities for reducing emissions, as opposed to reducing emissions from all sources of from the fastest growing source. As discussed at the IPCC workshops, many options for reducing methane emissions have low costs, or may even be profitable because methane is actually lost energy, and systems may be redesigned to capture and use this energy in many cases.

Opportunities for reducing methane emissions from its major anthropogenic sources will need to be identified as no one source can provide the reductions required to stabilize atmospheric concentrations. The IPCC workshops identified a set of promising approaches for reducing emissions. These emissions reduction opportunities include:

- <u>Landfills</u>: Methane recovery systems can reduce emissions by 30 to 60 percent in existing landfills and

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[12] Programs may also be necessary to limit emissions of pollutants such as carbon monoxide which compete with methane for the hydroxyl ion in the atmosphere. While these pollutants may hinder the stabilization of methane concentrations, the reductions in methane concentrations that are achieved will still have benefits in terms of limiting warming.

by 90 percent in new landfills, and existing commercial operations show that these systems are profitable in may cases.

- Coal mining: Pre-mining degasification using vertical wells can profitably reduce emissions from underground mines by up to 50 percent in some mines, as shown by existing enterprises. It was also suggested that emissions can be reduced further by using mine ventilation air that contains less than one percent methane as combustion air in gas fired turbines.

- Oil and natural gas systems: Improved handling of casing gas during oil production will reduce venting and flaring emissions. It was suggested that emissions from gas transmission in the USSR could be reduced by improving the USSR gas transmission facilities. Other options for unusually leaky systems may also be possible.

- Livestock: Strategic diet supplementation with locally-produced resources and other animal management practices can profitably reduce emissions by 25 to 75 percent per unit of product.

- Animal wastes and wastewater treatment: Methane recovery systems can profitably capture 50 to 90 percent of the methane emitted by anaerobic waste management lagoons, as demonstrated by current systems. Such lagoons account for one-third of total emissions from animal wastes, and may account for the majority of emissions from wastewater treatment.

- Rice cultivation: Over the long term emissions can likely be reduced by 10 to 30 percent by an integrated management approach to irrigation, fertilizer application, and cultivar selection.

- Biomass burning: Methane emission reductions can be achieved through fire management programs and encouraging the use of alternative agricultural practices.

Depending on the extent to which each of the emissions reduction opportunities is undertaken, the emissions reduction realized may be adequate for stabilizing and possibly even reducing methane concentrations below current levels.

Exhibit 9 presents an estimate of the potential magnitude of emissions reductions that can be achieved. Based on the information presented at the IPCC Workshops, it appears to be technically feasible to reduce methane emissions on the order of

EXHIBIT 9

OPPORTUNITIES TO REDUCE METHANE EMISSIONS

Emissions Source/ Reduction Option	Technically Feasible Reductions (Tg/yr)	Reductions Needed for Stabilization by 2000 (Tg/yr)	Comments
Landfills: Recover methane as an energy source.	30 to 60 percent: 7 to 24 Tg.	Half the technically feasible amount: 4 to 12 Tg.	Emissions are concentrated in developed countries. A small number of large landfills account for the majority of emissions. These emissions can be controlled profitably or at low cost.
Coal Mining: Pre-mining drainage from underground mines using vertical or horizontal wells. Recovery and use of gob gas from longwall mines. Use of ventilation air for combustion air in a turbine.	50 percent of emissions from gassy underground mines: 12 to 20 Tg.	One-third of the technically feasible amount: 4 to 7 Tg.	80 percent of emissions are found in six countries. Emissions are dominated by a small number of gassy mines. In some countries emissions can be recovered profitably. The Peoples Republic of China is the largest coal producer and may have the largest emissions.
Oil and natural gas systems: Control venting and flaring at oil production facilities and improve the transmission system in the USSR.	50 percent of venting/flaring emissions: 7 Tg. 60 to 80 percent of USSR transmission losses: 7 to 19 Tg.	75 percent of the technically feasible venting/flaring emissions reduction: 5 Tg. 50 percent of the transmission emissions reduction: 4 to 9 Tg.	These emissions estimates are particularly uncertain. Proven technologies are currently in use that limit emissions at oil production facilities. USSR transmission emissions may be larger than the 3 to 6 percent assumed here, although precise data are lacking. Funding mechanisms for improving the USSR transmission system are needed.
Livestock: Improve animal productivity through strategic supplementation and productivity enhancing agents.	25 to 75 percent reduction in emissions per unit of product: 15 to 25 Tg at current production levels.	20 to 35 percent of the technically feasible amount: 3 to 9 Tg.	Bovine somatotropin (bST) and fertility-enhancing technologies will improve productivity in developed countries. Diet changes may yield additional reductions. Strategic supplementation of cattle feeding on poor quality forages will improve productivity and reduce emissions. These programs are cost effective in their own right.

Continued

EXHIBIT 9 (Continued)

OPPORTUNITIES TO REDUCE METHANE EMISSIONS

Emissions Source/ Reduction Option	Technically Feasible Reductions (Tg/yr)	Reductions Needed for Stabilization by 2000 (Tg/yr)	Comments
Animal Wastes and Wastewater Treatment: Recover methane from uncontrolled anaerobic treatment lagoons.	50 to 90 percent of lagoon emissions: 5 to 9 Tg from animal wastes and 5 to 9 Tg from wastewater treatment.	50 percent of the feasible reductions from animal wastes and 25 percent of the feasible reductions from wastewater: 4 to 7 Tg.	Animal waste lagoons are primarily used in situations with large concentrations of animals. The recovered methane is a useful energy source. The estimates for anaerobic treatment of wastewater are particularly uncertain, and may be primarily at food processing facilities in developing countries.
Rice Cultivation: Improved irrigation, fertilizer use and cultivar selection.	10 to 30 percent of emissions per product: 6 to 50 Tg at current levels of rice production.	None. Long-term reductions only.	
Total Emissions Reduction	64 - 163 Tg	24 - 49 Tg	

100 Tg/yr (67 to 170 Tg/yr). This level of emissions reduction is clearly sufficient to stabilize methane emissions.

Over the next 10 years about one-third of these technically-feasible reductions need to be achieved in order to stabilize atmospheric methane concentrations. The extent to which emissions will actually be reduced from each source will depend on the level of resources committed to undertaking the steps necessary to reduce emissions. At this time, the estimate of actual emissions reductions that can be achieved in the near term is quite subjective, and more research is needed.

Exhibit 9 shows one set of estimates of how adequate emissions reductions could be achieved across the various emissions sources in order to stabilize concentrations. Although the precise estimates of achievable reductions are uncertain, it is expected that the near-term emissions reductions identified in the exhibit can likely be achieved because they depend on existing technologies that in many cases are cost effective in their own right or provide other important benefits.

For example, the U.S. is in the process of proposing rules to reduce emissions of toxic air contaminants from landfills. As a consequence, methane emissions from landfills will be reduced by about 40 to 50 percent in the following 10 years. Much of this methane can additionally be recovered and used to displace carbon intensive fuels. Similarly, techniques for pre-mining coalbed methane drainage and gob gas recovery and utilization have now been demonstrated. With some effort, these techniques may become economic in their own right in many locations. Coalbed methane resources may become an important source of gas supplies in some parts of the world.

Similarly, programs to increase animal productivity via strategic supplementation have been initiated in some areas of the world; reducing methane emissions is a side benefit (Leng, 1990). Such programs could be encouraged more broadly. Additionally, proven technologies, such as the administration of bovine somatotropin (bST) to increase milk production, can also reduce methane emissions over the next 10 years.

While significant research and analysis remain to be done, the results of the IPCC Workshops indicate that practical techniques exist to reduce methane emissions by an amount that can lead to the stabilization of methane concentrations. Additionally, implementing the available opportunities for reducing methane will help restrain growth in methane emissions in the long-term. For example, methane emissions from landfills and coal mines will not increase as much as currently anticipated in the RCW and SCW scenarios if methane recovery and utilization become standard practice at most of these facilities. Consequently, restraining the long-term growth in methane emissions to ensure stabilization of methane concentrations can also likely be achieved.

In order to realize the emissions reductions that have been identified, the emissions reduction techniques need to be evaluated fully, and the barriers that may inhibit their implementation need to be identified. For example, while it may be profitable to recover and utilize methane that would have been emitted from coal mines, institutional questions of ownership and constraints on receiving fair prices for gas or electricity may block implementation. Similarly, strategic supplementation of livestock may be economically profitable, but lack of capital and infrastructure may block implementation. Efforts to realize technologically possible and economically rational reductions must recognize and overcome barriers and constraints to implementation. In this context international approaches for promoting the steps need to reduce emissions are discussed next.

4. FRAMEWORK FOR CONTROL

4.1 Approaches

A variety of approaches have been used to control pollution emissions for purposes of achieving environmental protection goals. In terms of international controls, the Montreal Protocol on Substances that Deplete the Ozone Layer is currently the only example in which the international community has limited air emissions of a class of substances, in this case CFCs and halons.

The Montreal Protocol was signed in 1987 and has been ratified by all the major CFC producing and consuming countries of the world. Under the Protocol, each nation agrees to limit its production and consumption of two separate groups of compounds, CFCs and halons, to specific levels. The participating nations are each free to achieve their production and consumption limits in any manner that they prefer. Included in this flexibility is the opportunity to trade off among the CFCs or among the halon compounds at agreed on rates. For example, 1 kilogram of CFC-11 may be traded off for 1 kilogram of CFC-12 or 1.25 kilograms of CFC-113. However, trade offs between CFCs and halons are not permitted.

In the U.S. and elsewhere, approaches for protecting the environment have also included technology requirements, ambient standards, and performance standards. Under these approaches specific equipment or practices are identified as the preferred method for preventing discharges of pollutants into the environment, and steps must be undertaken to install the identified equipment and implement the practices. Flexibility is often provided that allows alternative equipment and practices to be implemented that achieve the same performance in terms of emissions reductions achieved.

The recently completed Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal is an example of an international agreement that relies on technology requirements to protect the environment. The purpose of the Basel Convention, which was completed in 1989, is to control the transboundary movement of hazardous wastes. To achieve this objective, the convention establishes a system for defining and tracking international movements of hazardous wastes.

Additionally, the convention sets out a process whereby the parties to the agreement will define the waste disposal technologies and practices that are considered "environmentally sound." These approved technologies and practices will be a technology-based standard, and the parties to the agreement will be responsible for ensuring that these technologies and practices are used when hazardous waste is handled and disposed.

To date much of the discussion surrounding approaches for controlling greenhouse gas emissions has been patterned after the Montreal Protocol experience. This approach would establish national limits on the aggregate emissions of the key greenhouse gases, such as carbon dioxide, methane and nitrous oxide. Each nation would then have the flexibility of achieving its limit by reducing its emissions in the most cost effective manner, including trading among the various gases. This approach has tremendous appeal due to the maximum amount of flexibility that it provides and its likely economic advantages.

However, discussion at the April 1990 IPCC Methane Workshop indicated that the best way to reduce methane emissions may be to provide incentives to implement encouraging technologies. Regulatory approaches that command methane reductions could have major difficulties. These difficulties result from the fact that methane emission sources have a different character than carbon dioxide sources and the CFC sources covered by the Montreal Protocol. Carbon dioxide and CFCs are primarily emitted from industrial activities with well-defined inputs and emissions rates. Consequently, without actually analyzing air samples in the laboratory for carbon dioxide and CFCs, it is relatively easy to document national emissions as well as emissions from individual facilities or processes.

Methane, alternatively, is generally emitted by complex and highly variable biological systems (e.g., rice paddies, livestock, landfills, biomass burning) and industrial systems whose inputs and outputs cannot be translated easily into emissions (coal mines and oil/gas systems). Consequently, for any given activity, the base level of methane emissions is more difficult to document than the base levels of emissions of carbon dioxide and CFCs. Currently, methane emissions rates can only be documented at individual facilities and locations by performing detailed and costly atmospheric measurements. These measurements will generally be valid for a given period of time during which practices and conditions remain stable. An unexpected geologic formation, a shift in available feed inputs, or a change in refuse characteristics can radically alter emissions from coal mines, cattle and landfills.

This difficulty in accurately estimating levels of methane emissions from individual sources presents a particular problem for controlling emissions with national limits. Of primary concern is that it will be difficult to document baseline emissions and emissions reductions that are achieved.

An incentive-based approach that promotes encouraging technologies or practices was identified as one alternative method for addressing methane emissions. Under this approach the parties to the agreement could identify those technologies and practices that are preferred for controlling emissions. National and international bodies (e.g., under a UNEP program) could participate in the process of identifying the technologies and practices. Once identified and adopted, the parties to the agreement would be responsible for promoting the implementation of the applicable practices and technologies in their countries. The preferred technologies and practices would vary, depending on the local resources and circumstances.

A major advantage of the incentives for technology approach is that compliance with the control requirements can be more easily monitored. Parties that are complying will have installed equipment or will have instituted practices that can be observed. Consequently, detailed measurements of methane emissions from individual locations would not be required.

Based on the discussion at the April Workshop, the potential use of a technology approach for controlling methane emissions could complement a comprehensive approach and should be explored. Efforts to structure an approach for controlling methane emissions must also recognize the importance of international cooperation. No single country will provide the necessary reductions in methane emissions to stabilize atmospheric concentrations, just as no single source will. Strategies need to be developed which include all countries and which will achieve the necessary reductions while promoting economic growth and agricultural productivity. To achieve a high level of international participation in methane reducing activities, technology transfer programs and joint funding mechanisms will need to be explored and developed.

4.2 Research Needs

Significant research, analysis, demonstration and proof of concepts is required in order to achieve the real reductions in methane emissions in the next 10 years that are needed to stabilize methane concentrations. In particular, the promising opportunities for reducing emissions must be documented and in some cases demonstrated in the field. These efforts should be initiated as soon as practical so that an internationally-recognized set of data that describe opportunities to reduce methane emissions can be developed.

Examples of the research needed include:

- Documentation of the techniques that can be used to recover methane from coalbeds in advance of mining and from gob areas. The parameters that define the circumstances under which this methane can be produced for use must be defined. Demonstration of techniques to use ventilation air in turbines is also a high priority. Techniques for safely collecting and flaring gas that cannot be recovered for use must also be described.

- Standard methods for evaluating and estimating methane emissions from individual landfills is needed. Such methods would enable the potential methane emissions from individual landfills to be evaluated and controlled or recovered as appropriate.

- The transmissions losses from the USSR gas transmissions system need to be quantified and evaluated. The opportunities to reduce these emissions need to be identified.

- The resources available locally to provide strategic supplementation to cattle that are feeding on poor quality forages must be identified. The system for formulating and producing these feeds must be described.

- Techniques for recovering and utilizing methane emissions from anaerobic waste lagoons need to be described. The experience with existing systems should be summarized. The number and size of potential target lagoons needs to be described.

By undertaking these and similar research efforts, the preferred approaches for reducing methane emissions can be defined and described in detail.

5. FINDINGS FOR OIL AND GAS SYSTEMS

1. Emissions Estimates

1.1 Previously published estimates of global methane emissions from oil and gas systems have relied on estimates of 2-4% leakage (by assuming all "unaccounted for" gas is emitted to the atmosphere), resulting in global emissions estimates on the order of 25-45 million metric tons per year.[13]

1.2 Recent preliminary studies based on extrapolating data from selected gas systems indicate that methane emissions from the U.S., Canada, Japan, and Western Europe may be much smaller than previous estimates, and are likely under 1% of throughput (with the possible exception of some countries which rely heavily on old gas systems). These studies are based on accounting and engineering analyses that vary in detail and methodology.

1.3 While projections of primary energy provided by natural gas show significant increases, methane emissions from gas systems are not expected to increase correspondingly since newer, tighter piping and production equipment will be used and older system components will continue to be replaced.

2. Steps to Improve Emission Estimates

2.1 Many uncertainties remain regarding total methane emissions estimates from natural gas systems and regarding emissions in particular regions of the world. The key uncertainties which need to be addressed are:

- emissions from abandoned and old wells;
- post-meter emissions;
- emissions from systems in Eastern Europe, USSR, and developing countries; and

[13] 1 million metric tons = 10^9 kilograms = 10^{12} grams = 1 teragram = 1 Tg

- how representative the systems are upon which preliminary estimates are based.

2.2 Additional data are required to improve existing estimates. These future estimates of methane emissions must differentiate among the sources of emissions, separating out:

- oil production;
- gas production;
- gas transmission;
- gas distribution; and
- gas consumption.

These estimates must also differentiate emissions on the basis of age:

- new systems versus old systems.

2.3 A combination of actual atmospheric measurements and accounting and engineering studies are needed to validate the improved estimates. These studies need to be scientifically credible, independently performed or independently verified, and subject to public examination.

3. Leak Detection and Mitigation: Potential for Emission Reduction

3.1 Gas transmission and distribution companies employ a variety of leak detection and mitigation technologies. These technologies are employed primarily to maintain the safety of natural gas use and to meet required regulations. The precision and cost of techniques varies.

3.2 With the aid of state-of-the-art equipment and rigorous surveillance programs, it is technically possible to detect and reduce methane emissions from transmission and distribution systems, from unintentional and intentional leakage. There may be opportunities for more widespread use of the techniques with the greatest precision and accuracy. For example, pneumatically-driven devices could be replaced by electrical (non-pneumatic) devices. Similarly, leaks that do not pose a safety risk could be repaired based on the environmental benefit.

3.3 While many of these opportunities to reduce emissions are not justified on the basis of current cost accounting and recovery procedures, they may be justified on an environmental basis. The environmental benefits of reducing these leakages must be examined further.

3.4 Additional efforts are necessary to achieve further reductions in methane emissions from natural gas systems. This includes the following:

- Mechanisms for transferring leak control technologies to new users must be developed. Targets of this technology transfer might be systems which have been poorly maintained because of size and/or financial constraints -- the countries of Eastern Europe or smaller systems within the U.S. are possible examples.

- Additional work on designing programs to encourage comprehensive leak detection and mitigation needs to be undertaken. The design of programs to encourage economic replacement and/or upgrade of old system components also needs to be investigated.

- As venting of methane is an unknown and potentially large source of methane emissions from both oil and gas productions, flaring practices and the potential to reduce these emissions must be examined further.

- Fugitive methane from the well system itself (prior to production measurement points) has not been sufficiently investigated in light of new technologies and may be significant. This is especially true in basins of poorly consolidated rock, and in old abandoned wells (gas and oil).

4. Natural Gas as a Transition Fuel

4.1 Fuel switching has the potential for significantly reducing CO2 emissions in the near and longer term and could be used as one component of an integrated strategy to reduce emissions of greenhouse gases. The strategy would also include efforts to increase energy efficiency and to decrease reliance on fossil fuels.

4.2 Fuel switching to natural gas leads to environmental benefits in the form of lower emissions of SO_2, NO_x, and particulates.

4.3 Where possible, substituting the direct use of natural gas for electricity generated by fossil fuels leads to considerable CO_2 emission reduction. The scope for this should be evaluated further.

4.4 Before a fuel switching strategy can be adopted, it must be clear that methane emissions from natural gas operations will not counteract the CO_2 reductions. This would require estimates of both methane and CO_2 emissions and a CO_2 equivalence for methane to be used to calculate the actual reduction that is achieved from fuel switching.

4.5 In determining the CO_2 credit for fuel switching it will be necessary for policy makers to assign the appropriate global warming potential (GWP) to methane in accordance with specific policy goals. It will also be necessary to estimate methane emissions from the fuel switching and the methane emissions from oil and coal.

4.6 If methane emissions from natural gas systems are as low as preliminary data imply, policies which will encourage use of natural gas in appropriate cases need to be developed. These policies need to address gas use in all sectors -- electricity generation, transportation, industry, and commercial and residential appliances.

4.7 Information assessing world-wide resources of natural gas should be improved -- large areas of the world remain unexplored. If methane emissions from natural gas systems are as low as preliminary data imply, further exploration and identification of reserves should be promoted. Natural gas potential from coal seams should be assessed globally. Policies which will encourage continued investment in natural gas infrastructure may need to be developed.

6. FINDINGS FOR COAL MINES

1. Emissions Estimates

1.1 Recent global studies of methane emissions from coal mining provide "order of magnitude" estimates and identify those countries with the largest potential opportunities for methane recovery. There are currently many uncertainties about the absolute levels of emissions from this source, however, and about the contributions of various countries to this total.

1.2 Coal mining activities are an important source of methane emissions on a global scale. Current estimates generally suggest that coal mining activities emit about 30-50 million metric tons, although some estimates are as low as 20 million metric tons and others are as high as 60 million metric tons. These emissions are roughly 7 percent of global methane emissions and approximately 10 percent of global anthropogenic methane emissions. However, since both the current estimates and the methodologies which support them include many uncertainties, more research is necessary to refine these estimates.

1.3 To meet the energy requirements associated with increased population and additional development, coal production will likely increase from its current level of about 5 billion[14] tons. If coal production grows at the rate forecast by the International Energy Agency, production levels could exceed 6 billion tons by 2000. In many countries, this increase in production will likely be accompanied by an increase in the proportion of coal mined in underground mines and the depth of these mines. This implies that methane emissions from coal mining could increase by more than 25 percent over the next decade in many countries.

2. Steps to Improve Emission Estimates

2.1 More research is necessary to refine estimates of methane emissions from coal mining activities.

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[14] 1 billion equals 1000 million.

- One of the most important goals of future research will be to improve the methane emission factors that relate the methane content of the mined coal to the amount of methane emitted from the mine. Among the variables that should be investigated are: depth and rank of coal, geologic and erosional conditions, mine type (underground or surface), mining method (room and pillar or longwall), and age of mine.

- Different models should be developed to approximate emissions in different mining environments and in different coal basins and/or countries.

2.2 These estimates should be further refined by pursuing other research areas, including: (1) improving the instrumentation and techniques used in measuring methane emissions and in-situ gas content; (2) improving data quality (i.e., by collecting better data on methane emissions through ventilation air and degasification systems; (3) improving models for predicting emissions; (4) assessing the relationship between mining practices and emissions; (5) refining estimates of methane emissions from surface mining activities; and (6) investigating emission levels from abandoned mines.

2.3 The methodology used in future studies of methane emissions from coal mining should be clearly documented so that it can be verified by independent analysis. Further, attempts should be made to standardize methane emission measurement methods and estimation techniques to ensure that studies conducted by different researchers are comparable. To this end, consideration should be given to establishing a collaborative international data base on coal and mining characteristics and methane emissions to facilitate the development of global emission estimates.

2.4 To the extent financial resources are limited, future work should focus on those countries where opportunities for recovering methane from coal mining are likely to be large. These countries can be identified based on the "order of magnitude" emission estimates in preliminary studies and based on industry information about the relative gassiness of various coal mines.

2.5 Methane emissions during coal utilization should also be assessed and opportunities for reducing these emissions explored as appropriate. While methane emissions from large utility and industrial coal-fired boilers are low (perhaps less than 10 ppm), it appears that emissions from domestic coal combustion processes could be significant (perhaps on the order of 10-100 ppm).

3. Technical Potential for Reducing Emissions

3.1 Degasification technologies are used successfully in many countries to maintain mine safety and enhance productivity in mines with high methane emission levels. The benefits of using these technologies include increased safety, reduced downtime, and reduced ventilation costs and capacity requirements.

3.2 Current recovery operations at some mines in the United States and other countries have reduced methane emissions to the atmosphere associated with mining operations by 30-40 percent. The effectiveness of degasification operations at these and other mines must be assessed on a site-specific basis and will depend on many factors, including the methane content of the coal and surrounding strata, the magnitude of the methane emissions, the type and age of the mine, the time available for degasification, and geologic conditions at the site. At some mines with high methane emissions, degasification systems might be able to recover higher levels of methane, while at other mines the recovery potential will not exist at all.

3.3 Most current degasification programs are not being undertaken because of the methane recovery potential, but instead are essential to maintain mine safety. Thus, the current experience with methane recovery might represent economically attractive recovery levels, as opposed to the recovery levels that could be technically achieved.

3.4 Additional benefits result from utilization of the recovered methane. These benefits can include revenue or fuel cost savings from production of the gas and reduced methane emissions to the atmosphere.

3.5 Strategies for using recovered methane should seek to minimize methane emissions to the atmosphere. Many technologies are available to use methane recovered during coal mining. Choices among these technologies depends on methane production rates, gas quality, local energy markets and other factors.

3.6 In developing opportunities for using recovered methane, the safety of mining operations cannot be compromised.

3.7 Many of the opportunities to make additional reductions are not justified on the basis of current mining needs, gas market conditions and investment considerations. Additional reductions may be justified on an environmental basis, however, and the environmental benefits of additional recovery should be examined further. If the value of reducing methane is incorporated into economic assessments (i.e., through the provision of subsidies or low-interest loans) the amount of economically attractive degasification would significantly increase.

3.8 Additional research and government funding is necessary to fully develop the potential for using recovered methane. Work in the following areas is required:

- Technologies that use medium-quality gas and small amounts of gas (from small mines) should be given high priority in future research.
- The recovery and use of methane from ventilation air can potentially be an important source of methane reductions in the future, as appropriate technologies are developed and demonstrated.
- Research is necessary on the optimal integration of utilization technologies and mining operations in a manner that ensures mine safety and maximizes gas recovery and use.
- The interrelationship between coal mining, degasification, and methane utilization should be explored.
- Innovative ways of coupling mining operations with methane utilization options should be developed and implemented.
- Future efforts should emphasize assessing recovery potential, identifying candidate sites and developing demonstration projects.

4. Policy Options for Reducing Emissions

4.1 Barriers to methane recovery and use -- such as gas ownership, reasonable terms of gas or electricity purchase, and competing environmental goals--should be identified in various countries. Industry, government and environmental groups should work together to remove barriers and to encourage the economic recovery and use of methane from coal mining.

4.2 Government or other financial incentives that recognize the environmental value of limiting methane emissions could greatly increase the level of methane recovered and utilized by mining and other companies.

4.3 Financing will be needed to implement methane recovery systems in developing and Eastern European nations, even for profitable projects.

4.4 International financing organizations should examine energy and environmental policies and should consider the economic costs and benefits of mine degasification and methane utilization, the environmental benefits of using gas instead of venting it, and the opportunities for technology transfer, feasibility studies, and demonstration projects.

7. FINDINGS FOR WASTE MANAGEMENT SYSTEMS

1. Emissions Estimates

1.1 There are currently large uncertainties in estimates of methane emissions from waste management systems, including landfills, animal waste management systems, and wastewater treatment lagoons.

1.2 Despite these uncertainties, waste management systems appear to be significant anthropogenic sources of methane emissions.

- Landfills emit an estimated 25 to 40 million metric tons of methane globally each year. This methane is produced by the anaerobic decomposition of wastes in the landfills. Although landfill gas monitoring and other detailed landfill analyses have been performed in various countries, global methane emissions from landfills are uncertain because the factors driving the level of methane emissions are highly site specific, including: the waste composition; the extent and rate of waste decomposition; the pathways of methane transport out of the landfill; and the extent of methane oxidation prior to release from the landfill.

- Preliminary analysis and limited monitoring indicate that anaerobic wastewater treatment lagoons that treat wastewater with high BOD (biochemical oxygen demand) loading can produce large amounts of methane emissions. Global emissions from wastewater treatment lagoons may be on the order of 20 to 25 million metric tons each year. This estimate of global methane emissions is very uncertain due to a lack of data on the amount and type of wastewater treated in anaerobic lagoons.

- Preliminary analysis and limited monitoring indicate that animal wastes emit about 30 to 40 million metric tons of methane each year. Wastes managed under anaerobic conditions as part of confined animal management systems are the major source of these emissions. This estimate of global methane emissions is uncertain due to a lack of data on the amount of wastes managed under anaerobic conditions and the extent to which these wastes are decomposed to methane.

Estimates of methane emissions from these systems have been developed for a number of different countries or regions of the world as shown in the following table.

Methane Emissions from Waste Management Systems (million metric tons)

Region/Country	Landfills	Animal Wastes	Wastewater Treatment
Canada	1.8	.3 -.6	?
Japan	0.17	-	0.02
Oceania	1.25	1-2	?
USA	8-18	2-5	?
Western Europe	?	3-8	?
USSR and Eastern Europe	5-8	5-12	?
Developing Countries	4-7	10-19	?
Global Total	25-40	20-40	20-25

1.3 Methane emissions from waste management systems could likely double by 2025 with continued population and economic growth, assuming the continuation in ongoing trends in waste management practices.

2. Steps to Improve Emissions Estimates

2.1 Landfills. Substantial uncertainty remains in methane emissions from landfills. To improve the understanding of these emissions, research is required to:

- Understand how the rate of methane emissions is influenced by key landfill characteristics, such as landfill design and operation; waste characteristics (e.g., composition; degradability; and moisture content); landfill size; and local conditions (e.g., climate and ground cover).

- Characterize current and expected future landfills in terms of those characteristics that influence methane emissions.

- Obtain field measurements of methane emissions from landfills in different regions using different management practices and receiving different types of wastes. Measurement techniques must be developed to collect these data.

- Examine how methane oxidation influences methane emissions.

- Develop a carbon balance for landfills that describes the fate of the carbon added to landfills over time. This carbon balance should describe: carbon storage; methane and carbon dioxide generation; methane oxidation; and methane and carbon dioxide emissions. This balance should be sensitive to various landfill characteristics such as: waste composition (e.g., lignin/cellulose ratios); moisture content; and landfill design.

- Develop methods for scaling up limited measurements and data to develop national and global emissions estimates that reflect differences in cultures, waste generation, and waste management practices.

2.2 Wastewater Treatment Systems. The management of wastewater effluent from domestic, commercial, and industrial facilities has the potential to produce globally significant amounts of methane emissions. While in many cases wastewater is managed in a manner that is presumed to produce negligible methane emissions, emissions data from individual facilities in developed and developing countries indicate that emissions are large in certain circumstances. To better understand methane emissions from wastewater treatment systems, research is required to:

- Collect available data on wastewater management practices throughout the world.
- Identify those areas and facility types that are potentially important sources of methane emissions. Candidate facility types include food processing facilities such as: fruit and vegetable processing; meat packing; sugar production; creameries; and distilleries.
- Characterize and measure the emissions at the important facilities.

2.3 Animal Wastes. While animal wastes are potentially a globally significant source of methane emissions, a lack of field data leaves uncertainties as to the quantity of emissions. To improve the understanding of these emissions research is required to:

- improve current enumerations of animal numbers and waste quantities managed with various practices;
- develop methane emissions measurement techniques;
- measure methane emissions from those situations that appear to be most important from an overall emissions perspective; and
- assess changes in methane emissions over time as management practices change.

The measurements of methane emissions from animal wastes must consider local and seasonal factors that affect emissions.

3. Technical Potential for Reducing Emissions

3.1 Landfills. Technologies and practices exist to reduce methane emissions from landfills by collecting and flaring or utilizing the methane generated in the landfill. In many circumstances these technologies and practices appear to be cost effective. Use of these technologies and practices is believed to reduce methane emissions by 40 to 70 percent at existing landfills. In new landfills, it is believed that methane emissions can be reduced by 70 to 95 percent using currently available technologies and practices. Steps taken to reduce methane emissions from landfills provide other significant environmental and safety benefits. Additionally, when utilized as an energy source, the methane recovered from landfills to reduce emissions may displace more carbon intensive fuels, thereby also reducing carbon dioxide emissions. To promote the reduction of methane emissions from landfills, analyses of existing technologies and practices would be useful, including:

- Defining the best control/recovery/utilization technologies and practices that are appropriate for various landfill situations, including new versus existing landfills.
- Examining the effect of alternative waste management and treatment programs on emissions of methane and other greenhouse gases, including: waste stream separation and recycling; and incineration with energy recovery.

To improve the currently available technologies and practices, research is necessary to:

- Develop techniques for enhancing methane generation in cases where the methane can be captured and utilized.
- Develop cost beneficial uses of recovered methane from landfills (particularly small landfills), such as lower cost electricity generation technologies.

3.2 Wastewater Treatment Systems. Technologies and practices exist to manage wastewater without producing methane emissions, including aerobic treatment and anaerobic treatment with methane recovery and utilization. Therefore, methane emissions from wastewater treatment systems can technically be almost entirely eliminated. In many circumstances, anaerobic treatment with methane recovery and utilization appears to be cost effective due to the value of the energy produced. To promote the reduction of methane emissions from wastewater treatment systems, the best wastewater management practices should be defined based on the demonstrated technical and economic feasibility and the other environmental benefits of the various existing approaches for managing wastewater. The approach of collecting and utilizing the methane produced by anaerobic wastewater treatment should be examined as part of the process of defining best practices. In some areas, existing wastewater management technologies may need to be demonstrated.

3.3 Animal Wastes. Technologies and practices exist that can reduce methane emissions by 50 to 80 percent from animal waste management systems that are used for large numbers of confined animals. These approaches primarily involve anaerobic treatment (e.g., in a lagoon) with methane recovery and utilization. These approaches appear to be cost effective in many circumstances, due to the value of the energy produced. To promote the reduction of methane emissions from animal wastes, the following are required:

- The best waste management practices for reducing methane emissions that are consistent with other environmental objectives, including groundwater protection, water management, and nutrient management, need to be defined.
- Approaches for reducing methane emissions need to be demonstrated under a wider range of conditions than has been demonstrated to date.
- To improve the existing approaches, further work is needed to identify and demonstrate gas utilization opportunities in the agricultural setting.

4. Policy Options for Reducing Methane Emissions from Waste Management Systems

4.1 Market and institutional barriers exist that limit the implementation of cost-effective technologies and practices that will reduce methane emissions from waste management facilities. These barriers should be identified and evaluated. Approaches, including financial incentives, should be identified to overcome these barriers.

- A lack of financing and the unavailability of some technologies are important barriers that must be overcome in some areas.
- In the design of incentives to overcome identified barriers, the incentives should reflect the environmental benefits that will accrue from the implementation of the technologies and practices.

4.2 Analyses of policies that will promote the reduction of methane emissions from waste management systems are necessary, including analyses of policies that:

- promote capacity expansion in the recycling and recovery industries;

- encourage methane recovery and utilization, for example by:

  -- setting fair-market sales prices for recovered methane or electricity produced from recovered methane;

  -- eliminating institutional barriers that limit competition in electricity production, transportation, and sales;

  -- increasing the costs of producing commercial energy from fossil sources, e.g., by imposing carbon dioxide emissions fees;

  -- providing financial incentives for recovering methane, e.g., by providing tax incentives; and

  -- creating a market for energy produced from recovered methane, e.g., by setting goals for non-fossil fuel energy production.

8. FINDINGS FOR RICE CULTIVATION

1. Atmospheric levels of methane are increasing and will affect tropospheric air quality and global climate change.

   1.1 Methane is an important greenhouse gas that, based on model calculations, accounts for about 20% of the current increase in commitment to global warming.

   1.2 The methane concentration in the troposphere is about 1.75 parts per million (ppm) at present and is currently increasing by 0.8%-1.0% (10 to 16 ppbv) per year. This rate of increase is well characterized for the recent past. In addition, ice core data show that methane concentrations have more than doubled in the last two centuries and that they are now substantially higher than they have been in the past 160,000 years.

   1.3 Increasing emissions of methane are the primary cause of increasing methane concentrations. Reduction in the rate of methane destruction in the atmosphere (possibly due to changes in OH number density associated with increasing emissions of carbon monoxide) is also a factor.

   1.4 Continued increases in methane concentrations will lead to changes in the distribution and concentration of tropospheric ozone, which is a key substance in tropospheric chemistry, and could possibly threaten human health and the environment. Furthermore, there is concern that increasing methane concentrations will enhance the formation of stratospheric polar clouds, thus contributing to the polar stratospheric ozone depletion.

   1.5 Although uncertainty exists as to the exact contribution of each source to the annual global emissions of 400 to 600 teragrams (Tg) of methane, it is clear that the major anthropogenic sources include: rice fields; ruminant animals; landfills; biomass burning (e.g., shifting agriculture); venting and incomplete flaring of gas during oil exploration and extraction; leakage of natural gas during natural gas extraction and distribution; and coal mining. Current estimates indicate that anthropogenic sources account for about 60%-70% of current methane emissions. The remaining emissions are from natural sources which are associated with swamps, marshes, lakes, and oceans.

1.6 The most important anthropogenic methane sources are related to agricultural activities, which account for about 50% of the total methane emissions or 70% of the anthropogenic methane released.

2. Rice fields are an important source of methane emissions on a global scale.

2.1 Flooded rice fields emit significant quantities of methane produced by microbial, anaerobic decay of organic matter. Current estimates, based on limited measurements, suggest that rice fields account for up to 20% of global methane emissions and 30% of the total anthropogenic emissions from agricultural activities.

2.2 To meet the rice requirements of increased population, rice production has to increase from the current level of 450 million tons to 550 million tons by the year 2000 and to 750 million tons by the year 2020. Since the projected increase can only be achieved by increasing the yield and harvest area of flooded rice, methane emissions may increase by 20% in the next decade.

3. Reductions in methane emissions are needed to stabilize atmospheric concentrations of methane and/or return them to lower concentrations.

3.1 Based on the current imbalance between methane emissions and destruction in the atmosphere, a 10-20% reduction in anthropogenic methane emissions is required to stabilize atmospheric concentrations at their current levels. Additional reductions would be necessary to reduce atmospheric concentrations.

3.2 Due to the variety of methane emissions sources, reducing emissions from one or two sources will not be sufficient for stabilizing atmospheric concentrations. Reductions in each of the major sources is likely to be necessary.

3.3 A 10% reduction in methane emissions from rice fields will contribute about 15-20% of the emissions reductions required to stabilize atmospheric concentrations of methane. A 20% reduction in methane concentrations will contribute about 30-50% of the needed reductions.

3.4 These reductions should be obtained while maintaining the productivity of the rice fields in all instances.

4. A comprehensive approach including management of water regimes, development of cultivars, efficient use of fertilizers, and other management practices can be postulated to achieve the proposed reduction in methane emissions. However, current understanding of the complex interaction between methane production and oxidation, as well as on the exchange of methane between the atmosphere and rice fields, is insufficient. This understanding is a prerequisite for determining potential options on reduction of methane emission rates. In the long-term a 10-30% reduction may be possible if a comprehensive research approach is developing the required technologies.

4.1 Better understanding of processes contributing to the methane emissions from rice fields can only be achieved by integrated, interdisciplinary projects which will focus on studies of process related factors and which will allow valid extrapolations.

Research is needed on:

- Biogeochemistry of methanogenesis in flooded rice fields
  - methane production
  - methane oxidation
  - factors regulating methanogenesis
- Methane fluxes from flooded rice fields
  - effect of climatic factors
  - effect of soil and water factors
  - effect of cultivars
  - effect of organic and chemical fertilizer
  - effect of cultural practices
  - site, seasonal and diurnal variation
  - relationship with other greenhouse gases (e.g., nitrous oxide)

Research is necessary to develop field level measurement techniques to assess spatial variability. Simulation models are needed to synthesize the process and field level data and to assess regional and global impacts.

4.2 Since preliminary studies show that methods which reduce emissions of methane could increase emissions of nitrous oxide, these interactions should be investigated. In particular, measurements of nitrous oxide emissions in alternately wet and dry soils (rain-fed rice ecosystems) are needed.

4.3 Technologies and practices for reducing emissions from flooded rice fields need to be developed, demonstrated, and assessed. In addition, the costs and benefits need to be evaluated.

4.4 Technologies such as new cultivars and improved water management may have little impact on farm costs, while increased use of fertilizer may add to the costs. Future assessments should attempt to identify the full costs and benefits of new technologies.

5. In order for the benefits of future research on technologies and practices to achieve their potential, governments should examine existing agricultural policies. Analyses of many alternative policies are needed, including: economic policies such as subsidies, taxes, and pricing and trade barriers; cultural practices; technology transfer measures; education programs; and international financial assistance measures.

9. FINDINGS FOR LIVESTOCK

The following are the findings that were adopted by consensus by those attending the workshop. These findings indicate that there are promising opportunities for reducing methane emissions from livestock management systems. Such opportunities remain to be assessed and demonstrated in the field. Undertaking such assessments and demonstrations is a recognized priority.

1. GENERAL

1.1 Given the fact that methane (CH_4) concentrations are increasing globally and will affect global climate and tropospheric air quality, it is recognized that opportunities for reducing CH_4 emissions must be identified, evaluated, and applied in order to reduce global warming and increases in tropospheric ozone.

1.2 Given the diverse set of CH_4 emissions sources globally, emissions reductions from any single country or source will be small compared to total CH_4 emissions, and small compared to total emissions of all greenhouse gases. Consequently, programs to reduce CH_4 emissions from many sources will be required in many countries.

1.3 Although emissions-reduction programs will be required in many countries to achieve significant emissions reductions, individual countries can make valuable contributions by developing, demonstrating, and implementing emissions-reduction technologies.

2. THE ROLE OF MANAGED LIVESTOCK IN THE GLOBAL METHANE BUDGET

2.1 Livestock, and in particular ruminants, are comparatively an important source of CH_4 emissions on a global scale.

2.2 Animals produce significant quantities of CH_4 as part of their digestive processes. CH_4 emissions from the digestive processes of all animals have been estimated to be between 60 and 100 Tg/year,[15] accounting for about 15 percent of total global CH_4 emissions from all sources.

2.3 Previous estimates of global CH_4 emissions from ruminant digestive processes have several notable deficiencies, including the following:

-- Previous estimates failed to reflect important differences in CH_4 emissions associated with various stages of animal growth and management. For example, in the U.S. about 25 percent of beef cattle are in fact calves with CH_4 emissions rates significantly lower than emissions associated with adult beef cows.

-- For cattle on poor quality forages, previous CH4 emissions estimates appear to underestimate feed intakes and overestimate CH_4 yield per amount of feed intake. The net effect of these two factors is that overall emissions associated with these populations of animals appear to be underestimated, possibly by large amounts.

-- Previous estimates have neglected potential emissions from animal wastes.

-- Previous estimates failed to consider differences in animal sizes and differences in the feed base of the animals.

-- Estimates of global animal populations need to be refined.

2.4 While previous estimates of CH_4 emissions from ruminant digestive processes are deficient in various respects, the overall magnitude of the estimates is reasonable. Key analyses should be undertaken to improve the emissions estimates, especially for areas in which interventions are most likely to be cost effective. The major animal management systems should be enumerated, and the analyses should focus on the key systems that contribute most to global emissions, and that have the potential to be controlled.

2.5 Animal wastes (including the wastes from non-ruminants such as poultry and swine) are a potentially large source of methane emissions. Under anaerobic waste management systems, uncontrolled CH_4 emissions from

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[15] 1 Tg = 10^{12} grams = 10^9 kilograms = 10^6 metric tons.

cattle wastes are likely to be of the same magnitude as the CH_4 emissions from the cattle digestive processes. Animal wastes under aerobic conditions do not produce CH_4 emissions. Additional analyses should be performed over the next year to quantify the magnitude of CH_4 emissions from animal wastes. Preliminary analyses indicate that emissions from this source may be on the order of 15 Tg/year globally, or about 20 percent of the CH_4 emissions from the digestive processes of animals.

2.6 Reductions in CH_4 emissions from animals will assist in reducing the rate of CH_4 increases, and may be one important component in attempts to stabilize atmospheric CH_4 concentrations.

3. EMISSIONS REDUCTION OPPORTUNITIES

3.1 While many uncertainties exist, it appears that there are a number of technologies that can likely reduce CH_4 emissions from livestock systems by <u>25 to 75 percent per unit of product</u>.

3.2 Total reductions achievable depend on how effectively available interventions are deployed, and whether interventions lead to increases in consumption of livestock products.

3.3 Emerging and available technologies for reducing CH_4 emissions from livestock systems should be widely tested under applicable field conditions as soon as is practical. With adequate resources these tests would identify the best technologies and practices that could be implemented where appropriate.

3.4 Promising avenues of investigation have been identified that could result in additional opportunities for reducing CH_4 emissions from livestock systems.

3.5 Better estimates of CH_4 emissions will allow targeting of cost effective interventions to reduce emissions. The emissions reductions achievable with the best technologies will vary within and among countries with variations in animal, management, and feeding characteristics.

3.6 Animal production research that aims at increasing efficiency of animal production will have considerable impact on CH_4 emissions. This research must be stimulated in all countries with large livestock populations.

4. KEY RESEARCH NEEDED ON SPECIFIC EMISSIONS-REDUCTION OPPORTUNITIES

4.1 Strategic supplementation of extensively managed cattle. Large populations of cattle are consuming forages of variable quality (particularly seasonally) under grazing conditions. The relative productivity of these animals (e.g., in terms of reproductive efficiency) is low in some cases. By providing strategic supplementation of nutrients to these animals, CH_4 emissions could be reduced by: (1) providing a better balance in the rumen, which would reduce CH_4 emissions per amount of feed consumed; and (2) increasing efficiency and productivity such that given levels of production could be achieved with smaller animal numbers.

- -- The size of the animal population that could benefit from this supplementation must be estimated. It is expected that in some areas, the applicable population may be a significant portion of the total animal population.
- -- The types of supplementation appropriate for each area must be defined.
- -- Techniques for delivering the technology efficiently must be identified. Avenues to explore include: range improvement; nutrient feed blocks; bolus.
- -- The monetary and energy costs of producing and distributing the technology must be estimated and balanced against improvements in animal performance.
- -- The reductions in CH_4 emissions and improvements in animal performance (that lead to overall system-wide CH_4 emissions reductions) must be documented and validated under field conditions.

4.2 Diet modifications for intensively managed animals. A significant literature of experimental data from whole animal calorimetry experiments demonstrates that CH_4 emissions vary under different diets. Both increasing the intake of the animals and modifying the composition of the diet can reduce CH_4 emissions per unit of product. Other feed inputs also appear to have promising impacts on CH_4 emissions levels (e.g., whole cotton seeds or polyunsaturated fats). Modifying feeding practices toward low-CH_4 rations could potentially reduce CH_4 emissions by large amounts in certain circumstances.

-- The size and location of the animal populations for which feed modifications are a promising alternative must be identified.

-- Promising strategies for lowering CH_4 should be identified for these populations of animals, taking into account the costs and availability of the candidate feeds. Opportunities for reducing costs and increasing the availability of the candidate feeds should be explored.

-- The potential CH_4 emissions reduction from these approaches should be quantified (e.g., using rumen digestion and animal production models) and verified with experimental data.

4.3 Use of bST or other agents to increase production per cow. The use of bST (or similar technologies) can reduce CH_4 emissions per amount of product produced by: (1) further diluting the maintenance requirements of individual lactating cows (a reduction of about 3 to 5%); and (2) reducing (by about 15%) the size of the herd necessary to support the lactating cows (i.e., dry cows and growing heifers). Economic evaluations have indicated that the use of bST is economic in its own right in some circumstances.

-- The potential system-wide reduction in CH_4 emissions associated with the use of bST should be estimated so that its importance in this regard can be assessed. This assessment should be performed with a range of accepted values for the anticipated performance response from the administration of bST.

-- The CH_4 emissions implications of using other growth regulating agents should also be evaluated.

4.4 Defaunation of the rumen. Based on experimental data, under certain feeding systems, the elimination of protozoa in the rumen results in lower CH_4 emissions and may enhance animal performance.

-- The population of animals whose performance could be increased and whose CH_4 emissions could be decreased through defaunation should be estimated.

-- Techniques for achieving defaunation should be defined and demonstrated under field conditions. The costs of administering these techniques should be estimated and balanced against the benefits of improved animal performance. Initial assessments are that the costs of the defaunation may be economically justified solely by improvements in performance.

-- The overall system-wide CH_4 emissions reduction anticipated must be estimated.

4.5 Strategic supplementation of ruminants fed crop residues and by-products to correct nutrient deficiencies. Research and practice in India and other developing countries indicate that improved rumen performance can be achieved through the use of locally-produced supplements. This improved rumen performance allows for significantly improved animal productivity and increased digestion efficiency, both of which can contribute to significant CH_4 emissions reductions per unit of animal product. Based on experience in India, strategic supplementation systems can be self-sustaining and economic investments.

-- While it has been estimated that strategic supplementation can reduce CH_4 emissions significantly in individual segments of animal populations (e.g., by over 60%), evaluations of overall system-wide performance must be performed that reflect the diverse products produced by cattle and buffalo. In particular, the economic responses to changes in costs of production and demand must be examined. Also, social impacts must be evaluated. Preferred strategies that reduce CH_4 emissions through the use of supplementation should be identified, as well as the obstacles to their implementation.

-- Key areas where strategic supplementation should be investigated include those countries with large cattle and buffalo populations. Examples include: additional expansion in India; Pakistan; Bangladesh; Sub-Saharan Africa; and China. Assessments of these areas should be performed that include infrastructure and marketing needs as well as potential local sources of supplementation inputs.

4.6 Improve reproductive efficiency to reduce brood herd requirements. Improvements in reproductive efficiency will reduce CH_4 emissions by reducing the size of the brood herd needed to sustain a given level of production. Opportunities to accelerate promising developments in this area should be explored.

4.7 Microbiological Approaches.

-- Improve microbial growth efficiency to optimize fiber digestion in the rumen and microbial synthesis. CH_4 emissions may be reduced by balancing the rumen processes so that maximum efficiency is achieved. Microbiological approaches for promoting and achieving this balance should be explored. Analyses of feeds, feed combinations, feed treatments, bio-engineering opportunities and other techniques should be explored.

-- Reduce CH_4 production by manipulating VFA proportions and/or modifying the activities of the methanogens. Techniques for promoting propionate production (a hydrogen sink) should be explored. Additionally, inhibiting methanogens may provide an opportunity for altering the fate of H_2 in the rumen such that less CH_4 is produced.

4.8 Modifications to animal waste management practices. It is anticipated that anaerobic animal waste management practices produce significant CH_4 emissions. Reductions in these emissions are possible.

-- Opportunities for modifying waste management practices in a manner that is consistent with other environmental objectives (such as protecting groundwater quality) should be identified.

-- Opportunities for recovering CH_4 from animal wastes should be explored on various levels, including: (1) integrated resource recovery systems that produce a variety of useful products; (2) anaerobic digesters that produce gas that can be used as a commercial energy source or flared; and (3) small scale projects applicable for small farmers.

-- The costs of the alternative waste management systems must be estimated and balanced against the value of products produced. Indications are that under certain conditions, the systems are economic to implement in their own right.

5. OTHER KEY RESEARCH NEEDS

5.1 Estimates of global CH_4 emissions from livestock should be improved by enumerating the major livestock managements systems (including animal waste management systems) and performing more realistic assessments of the major systems that drive global emissions. These assessments should reflect the stages in animal growth and production and prevailing levels of feed intake.

5.2 Techniques for taking field measurements of CH_4 emissions from animal systems should be developed and applied. Such techniques will be useful for verifying estimates of emissions and validating the effectiveness of emissions reduction techniques in the field. Approaches that should be pursued include:

-- Exploring direct and indirect methods of assessing CH_4 emissions for field applications.

6. INSTITUTIONAL ISSUES

6.1 Reducing emissions from livestock is a particularly attractive option because it usually is accompanied or accomplished by improved animal productivity.

6.2 In designing interventions to reduce CH_4 emissions from livestock, consideration should be given to the impacts of these interventions on other greenhouse gases and other environmental and social areas of interest.

6.3 The implementation of technologies to reduce CH_4 emissions will, in general, succeed only if induced by: incentives, technology transfer, and/or the provision of adequate financing. A mandatory emissions limitation is unlikely to be successful in reducing emissions.

6.4 It is essential that countries maintain or build up the scientific infrastructure required to greatly increase levels of research to find solutions for limiting CH_4 emissions from livestock.

6.5 Current funding specifically to investigate, develop, test, and implement CH_4 reduction technologies and programs does not exist.

6.6 Key national and international authoritative bodies should cooperate in identifying and evaluating the best techniques for reducing CH_4 emissions from livestock systems.

6.7 Potential CH_4 emissions reductions associated with modifications to eating habits of humans are beyond the scope of the meeting, and is primarily a question of social choice and human nutrition and health needs.

REFERENCES

Blake, D.R. and F.S. Rowland, "Continuing Worldwide Increase in Tropospheric Methane, 1978 to 1987," Science, March 4, 1988.

Blake, D.R. and F.S Rowland (1986), "World-wide Increase in Tropospheric Methane, 1978 - 1983," Journal of Atmospheric Chemistry, Vol. 4, p. 43-62.

Casada, M.E. and L.M. Safley, Jr. (1990), "Global Methane Emissions from Livestock and Poultry Manure," presented at the International Workshop on Methane Emissions, April 9-13, 1990, Washington, D.C., sponsored by the Environment Agency of Japan and the U.S. Environmental Protection Agency.

Cicerone, R.J. and R.S. Oremland, "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, Vol. 2, No. 4, 299-327, December 1988.

Ehhalt, D.H., R.J. Zander, and R. A. Lamontagne (1983), "On the Temporal Increase of Tropospheric CH_4," Journal of Geophysical Research, Vol. 88, pp. 8442-8446.

EPA, Policy Options for Stabilizing Global Climate, Draft Report to Congress, D. Tirpak and D. Lashof eds., U.S. Environmental Protection Agency, Washington, D.C., February 1989.

Fraser, P.J., M.A.K. Khalil, R.A. Rasmussen, and A.J. Crawford (1981), "Trends of Atmospheric Methane in the Southern Hemisphere," Geophysical Research Letters, Vol. 8, pp. 1063-1066.

Hansen, J. et al., "Global climate changes as forecast by Goddard Institute of Space Studies Three-dimensional Model," Journal of Geophysical Research, Vol. 93, pp. 9341 - 9362, 1988.

Khalil, M.A.K. and R.A. Rasmussen (1982), "Secular Trends of Atmospheric Methane," Chemosphere, Vol. 11, pp. 877-883.

Khalil, M.A.K. and R.A. Rasmussen (1990), "Atmospheric Methane: Recent Global Trends," Environmental Science and Technology, Vol. 24, pp. 549-553.

Lashof, D.A. (1989), "The Dynamic Greenhouse: Feedback Processes That May Influence Future Concentrations of Atmosperic Trace Gases and Climatic Change," Climatic Change, Vol 14, pp. 213-242.

Lashof, D.A. and D.R. Ahuja, "Relative Contributions of Greenhouse Gas Emissions to Global Warming," Nature, Vol 344 (6626), pp. 529-531, april 5, 1990.

Leng, R.A. (1990), Improving Ruminant Production and Reducing Methane Emissions from Ruminants by Strategic Supplementation, Draft report submitted to the U.S. EPA, Washington D.C.

Marland, G., and R.M. Rotty (1984), "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982," Tellus, vol. 36B, p. 232-261.

Rinsland, C.P., J.S. Levine and T. Miles (1985), "Concentration of Methane in the Troposphere Deduced from 1951 Infrared Solar Spectra," Nature, vol. 318, p.245-249.

Steele, L.P., P.J. Fraser, R.A. Rasmussen, M.A.K. Khalil, T.J. Conway, A.J. Crawford, R.H. Gammon, K.A. Masarie, and K.W. Thoning (1987), "The Global Distribution of Methane in the Troposphere," Journal of Atmospheric Chemistry, Vol. 5, p. 125-171.

Thompson, A.M. and R.J. Cicerone (1986), "Possible Perturbations to Atmospheric CO, CH4, and OH," Journal of Geophysical Research, vol. 91. no. D10, p. 10853-10864.

WMO (1990), Scientific Assessment of Stratospheric Ozone: 1989, World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 20, Geneva, Switzerland.

APPENDICES

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APPENDIX A

OVERVIEW OF METHANE EMISSIONS

A.1 Introduction

The observation that methane (CH_4) is increasing in the atmosphere has sparked considerable interest in assessing the sources and sinks of CH_4 emissions and the factors that are contributing to the observed increase. Several comprehensive reviews of the atmospheric balance of CH_4 have been published, including: Cicerone and Oremland (1988), Bingemar and Crutzen (1987), Bolle, Seiler, and Bolin (1986), WMO (1986), Blake (1984), and Ehhalt (1974). These studies, in turn, draw on a wide range of analyses of specific emissions sources and analyses of CH_4 destruction processes.

As described by Cicerone and Oremland, estimates of total annual global CH_4 emissions are constrained by available pieces of data to fall within a fairly narrow range. Based on direct measurements, the total atmospheric burden of CH_4 can reliably be estimated at 4,800 Tg.[1] Similarly, during the early 1980s the annual increase of atmospheric CH_4 can be estimated, based on direct measurement, to be about 40 to 46 Tg per year.[2] Finally, based on independent analyses of methyl chloroform (CH_3CCl_3), the atmospheric lifetime of CH_4 is estimated at 9.6 years, with a range of 8.1 to 11.8 years.[3]

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[1] Steele (1987); 1 Tg = 1 teragram = 10^{12} grams = 10^9 kilograms = 1 million metric tons.

[2] WMO (1990) summarizes more recent estimates of the rate of increase of atmospheric methane as ranging from 10 to 16 ppbv (parts per billion by volume) per year. This range is about 30 to 45 Tg per year, which is a larger than the range reported by Cicerone and Oremland (1988).

[3] Based on analyses of emissions and atmospheric levels of CH_3CCl_3 over time, the rate of removal of CH_3CCl_3 from the atmosphere by the hydroxyl radical (OH) has been estimated (see Prinn et al. (1987)). Because the major mechanism by which CH_4 is destroyed in the atmosphere is also by reaction with OH, the atmospheric lifetime for CH_4 can be estimated from the atmospheric lifetime for CH_3CCl_3 and the relative reactivity of the two compounds with OH. "Atmospheric lifetime" refers to the (continued...)

Using these estimates, Cicerone and Oremland report annual CH_4 emissions to be in the range of about 450 to 640 Tg per year, with a central estimate of about 540 Tg per year.[4] The uncertainty in Cicerone and Oremland's estimate of total annual emissions is driven primarily by uncertainty regarding the destruction (or loss) rate of CH_4 in the atmosphere. For example, if the lifetime of CH_4 in the atmosphere is as short as 8.1 years (i.e., the destruction rate is faster), then total steady-state emissions would have to be 4,800 Tg ÷ 8.1 years = 593 Tg per year. When added to the observed rate of CH_4 increase, the total emissions are about 640 Tg. Similarly, a lifetime of 11.8 years implies total annual emissions (including the observed increase) of about 450 Tg per year.

As this example indicates, the uncertainty in total annual CH_4 emissions (540 Tg ± approximately 100 Tg) is primarily associated with the estimated destruction rate for CH_4 in the atmosphere. The contribution to the overall uncertainty from the uncertainty in the rate of change in the atmospheric CH_4 abundance is small by comparison.

A.2 Emissions Sources

Although total annual global CH_4 emissions are reasonably constrained by measurements, no such constraints can be applied to most of the known sources of CH_4 emissions. Consequently, the individual contribution of the identified sources is uncertain.

The major sources of CH_4 emissions (summarized in Exhibit A-1) include:

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[3](...continued)
average residence time of the compound in the atmosphere. For example, a lifetime of 10 years implies that approximately 1/10 or 10 percent of the atmospheric abundance of the compound is destroyed each year through various processes (e.g., chemical reactions).

[4] Cicerone and Oremland report a range of 400 to 640 Tg (p. 315 and Table 4). However, they also report a range of 405 to 595 Tg for the emissions necessary to maintain the currently observed concentration of CH_4 at near steady state (p. 312). When combined with the emissions necessary to produce the observed increase in concentrations (40 to 46 Tg per year), annual emissions must be in the range of 450 to 640 Tg per year. The source of the discrepancy is not evident at this time.

- Ruminant animals. CH_4 is produced as part of the normal digestive processes that take place in the rumen of ruminant animals (e.g., cattle, buffalo, sheep, goats, camels). Crutzen et al. (1986) have performed the most detailed assessment of ruminant animals as a source of CH_4 emissions and estimate that in 1983 total CH_4 emissions from managed ruminants (i.e., those kept by humans) and other domesticated farm animals (pigs, mules, and horses) were on the order of 73 Tg, with cattle producing the majority of the emissions (54 Tg). Emissions from domesticated animals are increasing as the population of animals increases and as the diets of those animals increase. Wild ruminants, wild large herbivores (e.g., elephants), and humans were found to produce far less CH_4 (approximately 2 to 6 Tg).

  Crutzen et al. indicate that their estimates have an uncertainty of ±15 percent. The uncertainty may be greater because several components of the calculations are not known precisely, including: the sizes of the populations of animals (particularly in developing countries, which have the largest populations); the amount and type of feed consumed by the animals (which influence the CH_4 emissions rates; see for example, Blaxter and Clapperton (1965)); and the rate at which CH_4 is produced in the rumen. A rigorous evaluation of these uncertainties has not yet been performed.

- Animal wastes. The estimates of emissions from animals do not include potential CH_4 emissions associated with the decomposition of animal wastes. It is well established that in anaerobic environments methanogenic bacteria will help to break down animal wastes and produce CH_4 (e.g., in a waste lagoon). Such emissions have been measured (e.g., see Safley and Westerman (1988)), and may be substantial in locations where large numbers of animals are managed in confined locations (e.g., in dairies and feedlots).

  Casada and Safley (1990) report an initial estimate that CH_4 emissions from animal wastes may be on the order of 35 Tg per year globally. A substantial fraction of these emissions are generated by wastes managed in lagoons from large concentrations of animals. These emissions are expected to

EXHIBIT A-1

SOURCES OF METHANE EMISSIONS
10^{12} Grams per Year

	Annual Emissions	Range	Comments	Source
Animals	80	65 - 100	Livestock in developed and developing countries.	Cicerone and Oremland
Animal Wastes	35	NR[a]	Anaerobic decomposition of organic wastes.	IPCC
Wastewater	NR	20 - 25	Anaerobic decomposition of organic matter in the waste water stream	IPCC
Rice Paddies	110	60 - 170	Principally in developing countries.	Cicerone and Oremland
Coal Mining	NR	30 - 50	Surface and (mostly) sub-surface mining.	IPCC
Oil/Gas Systems	45	25 - 50	Production, transmission and distribution.	Cicerone and Oremland
Landfills	NR	25 - 40	Decay of organic wastes.	IPCC
Biomass Burning	55	50 - 100	Forest clearing and waste burning.	Cicerone and Oremland
Natural Wetlands	115	100 - 200	Tundra, bogs, swamps, alluvial formations.	Cicerone and Oremland
Termites	40	10 - 100	Bacteria within termites produce CH_4 as part of the termite's digestive process.	Cicerone and Oremland
Oceans and Freshwaters	15	6 - 45		Cicerone and Oremland
Hydrates	5?	0 - 100	Potentially important future source.	Cicerone and Oremland
Total Emissions[b]	540	440 - 640	Well constrained.	Cicerone and Oremland

Sources: Cicerone and Oremland (1988), "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, December 1988. IPCC, December 1989 and April 1990 IPCC workshops on methane emissions.

[a] NR = not reported at the IPCC workshop

[b] Total annual emissions of 540 Tg per year ±100 Tg is well constrained based on observational data. The point estimates of the individual source estimates presented here do not sum to 540 Tg.

increase in the future as the practice of managing large concentrations of animals increases. Additional analysis and measurements are required to improve the estimate of these emissions.

- Rice paddies. CH_4 emissions from submerged rice paddy soils have been measured in the field at several locations (e.g.: Cicerone and Shetter (1981); Cicerone, Shetter, and Delwiche (1983); Seiler et al. (1984); Holzapfel-Pschorn and Seiler (1986), Kahlil et. al. (1989), Seiler (1989), Minami (1989), and Washida(1989)). Methanogenic bacteria in the soils produce CH_4 that is transported out of the soils by the rice plant as well as by diffusion.

  Bolle, Seiler, and Bolin (1986) estimate that CH_4 emissions from rice paddies are about 70 to 170 Tg per year. Cicerone and Oremland report a similar range with a central estimate of 110 Tg per year. Most recently, Seiler (1989) estimates a range of 70 to 110 Tg, using measurements from work performed in China and accounting for varying lengths of growing periods and varying seasonal affects.

  Methane emissions from rice paddies will likely increase over the next decade because the harvested paddy area is expected to increase by 25 percent by the end of this century.

- Natural wetlands (tundra, bogs, swamps). Natural wetlands are believed to be a large source of CH_4 emissions. As in submerged paddy soils, methanogenic bacteria produce CH_4. Based on analyses of various assessments of the extent of various wetlands around the world and rates of CH_4 emissions from various types of wetlands (e.g., Sebacher et al. (1986) and Harriss et al. (1985)), Matthews and Fung (1987) estimate these emissions to be about 115 Tg per year. Cicerone and Oremland report a subjective range of 100 to 200 Tg per year around this estimate, indicating that the total emissions from this source are quite uncertain.

- Coal Mining. CH_4 is found to occur naturally in coal seams, having been formed while the coal itself was formed. When coal is mined from underground seams, CH_4 is released. The amounts released vary by the type of coal and the depth of the coal seam. CH_4 may also be released when shallow deposits are mined (i.e., surface-mined coal), although these quantities may be relatively low.

A recent study performed for EPA (ICF Resources (1990)) indicates that CH_4 emissions from coal mining is on the order of 50 Tg per year. The majority of these emissions are estimated to be in five countries: the United States; the People's Republic of China; the Soviet Union; Poland; and South Africa. This study also indicates that CH_4 emissions from coal mining can increase substantially in the next 20 years as: (1) increasing amounts of underground coal is mined; and (2) the coal mined underground is withdrawn from deeper and gassier coal seams.

Discussion at the IPCC Workshop included a wider range of emissions estimates. The workshop participants agreed that CH_4 emissions may be on the order of 30 to 50 Tg per year, with some estimates as low as 20 Tg per year and some as high as 60 Tg per year.

- Natural gas production and distribution and oil production. Natural gas resources (which are mostly CH_4) are exploited around the world. During the production, transmission, and distribution of this gas, quantities may be released accidentally (e.g., during a pipeline rupture or as the result of a slow leak) or intentionally (e.g., during maintenance and repair of a pipeline). When oil is produced, natural gas is also often found and when gas production facilities are not available, this gas may be vented to the atmosphere or flared.

  Total emissions from these sources are quite uncertain. Recent estimates of emissions from natural gas production and distribution systems have relied heavily on estimates of "unaccounted for" gas, which is defined as the difference between the total gas produced and the total gas sold. The assumption underlying these estimates is that all the unaccounted for amounts are released to the atmosphere. Using this approach, these emissions are on the order of 2 to 4 percent of total gas production annually, or about 25 to 50 Tg.

  Other factors that may account for unaccounted for gas include theft and meter inaccuracies. A recent study by Pacific Gas and Electric Company (PG&E (1989)) indicates that emissions to the atmosphere may be a very small portion of the total amount of gas that is routinely referred to as unaccounted for. If the PG&E analysis is correct, then actual emissions from this source may be much smaller than recent estimates would indicate. Engineering analyses performed for EPA (PSI (1990)) also indicate that these emissions may be smaller than had previously been anticipated.

CH_4 emissions from venting and flaring of gas during oil production are also not well characterized. Marland and Rotty (1984) estimate total amounts of gas that are flared and vented. Cicerone and Oremland estimate total CH_4 emissions from vented and flared gas, plus "other stray and explosive losses" to be about 14 Tg per year.

- Fuel Combustion and Biomass Burning. Many combustion processes emit hydrocarbons, including CH_4. For example, CH_4 is found in automobile exhaust, and has been estimated to be found at quantities on the order of 170 ppmv (Campbell (1986)). Combustion of fossil fuels in mobile and stationary sources is consequently a source of CH_4 emissions, although preliminary estimates indicate that the emissions are small (less than 10 Tg per year).

  In analyses of overall CH_4 emissions, CH_4 emissions from biomass burning (i.e., forest clearing and agricultural waste burning) have been studied. Cicerone and Oremland indicate that such estimates are very uncertain and that additional measurements are required. Based on analyses by Seiler (1984) and Crutzen (1987), Cicerone and Oremland report a range of 50 to 100 Tg per year for this source, with a central estimate of 55 Tg.

- Landfills. The decay of organic wastes in landfills and dumps is known to produce CH_4 gas. In the U.S., such gas (when uncontrolled) has been the source of problems at landfills. Consequently, in many locations, such CH_4 gas is either vented, flared, or recovered as an energy source. Bingemer and Crutzen (1987) estimate total emissions from this source to be 30 to 70 Tg per year.

  The factors that lead to CH_4 production in landfills and the subsequent emission of that CH_4 have been studied extensively. At the IPCC Workshop the range of CH_4 emission estimates presented was 25 to 40 Tg per year. This lower range was developed because landfilled waste does not seem to be decomposing as quickly as the assumptions in the earlier estimates reflect.

- <u>Wastewater Treatment Lagoons</u>. CH_4 emissions from wastewater treatment lagoons have not been published. CH_4 emissions have been measured from individual lagoons and other wastewater treatment facilities. The CH_4 is produced by the anaerobic decomposition of organic matter that is found in the wastewater stream.

  Estimates at the IPCC Workshop indicated that CH_4 emissions from wastewater treatment lagoons may be on the order of 20 to 25 Tg per year. It was suggested that emissions are principally expected at specific facilities with wastewater that has a high organic matter content, such as food processing facilities.

- <u>Other sources of CH_4 emissions</u>. Oceans and freshwater have been estimated to be small sources of CH_4 emissions (Ehhalt (1974)). However, Cicerone and Oremland indicate that the basis for Ehhalt's estimates are dated, and that recent increases in the atmospheric abundance of CH_4 necessitates that these estimates be revisited.

  Zimmerman et al. (1982) identified termites as a potentially large source of CH_4 emissions. As occurs in ruminant animals, bacteria within termites produce CH_4 as part of the termite's digestive process. Given the large number of types of termites, and the uncertainties associated with the sizes of their populations, the emissions from termites is extremely uncertain. Oremland and Cicerone report 40 Tg per year of emissions, with a range of 10 to 100 Tg.

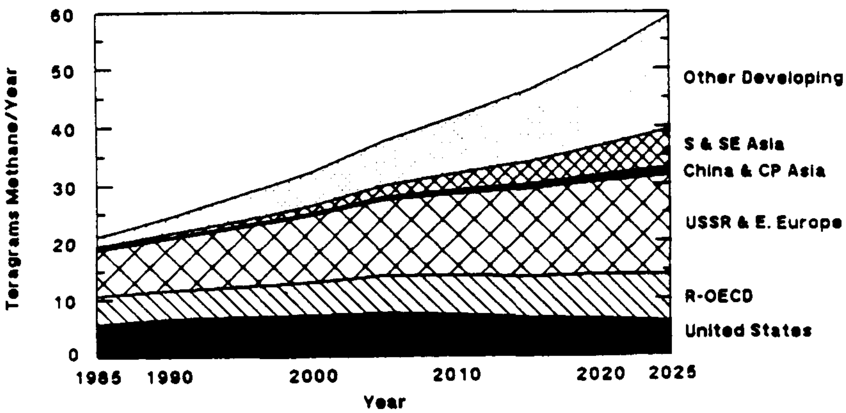
  Methane hydrates (CH_4 molecules trapped in water molecule structures) occur in coastal sediments and permafrost (see for example, Revelle (1983) for a review). It has been hypothesized that global warming could lead to the release of large quantities of CH_4 from these structures. Current emissions from this source are not well quantified, and potential future emissions (associated with a global warming) remain speculative.

Emissions from these sources are expected to continue increasing over the next decades. Projections of methane emissions from the major energy-related and agricultural sources are provided in Exhibit A-2 and Exhibit A-3.

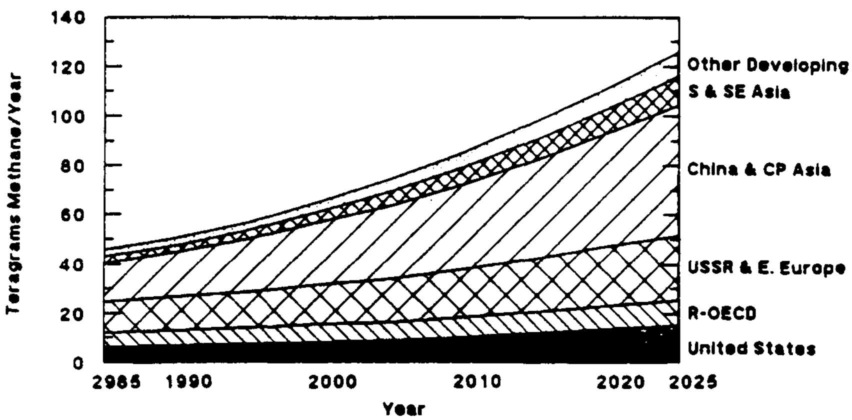
Given this overview of sources of CH_4 emissions, it is clear that increasing emissions from human activities are contributing to the observed increases in CH_4 concentrations. Because of

EXHIBIT A-2

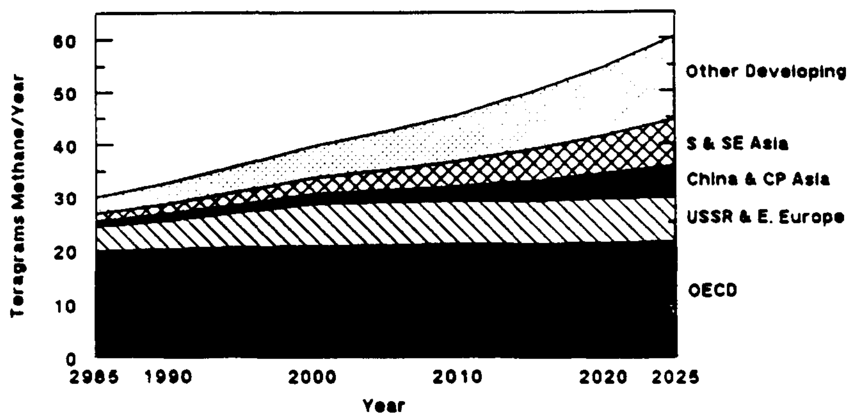
METHANE EMISSIONS FROM ENERGY RELATED SOURCES THROUGH 2025



METHANE EMISSIONS FROM NATURAL GAS PRODUCTION



METHANE EMISSIONS FROM COAL PRODUCTION

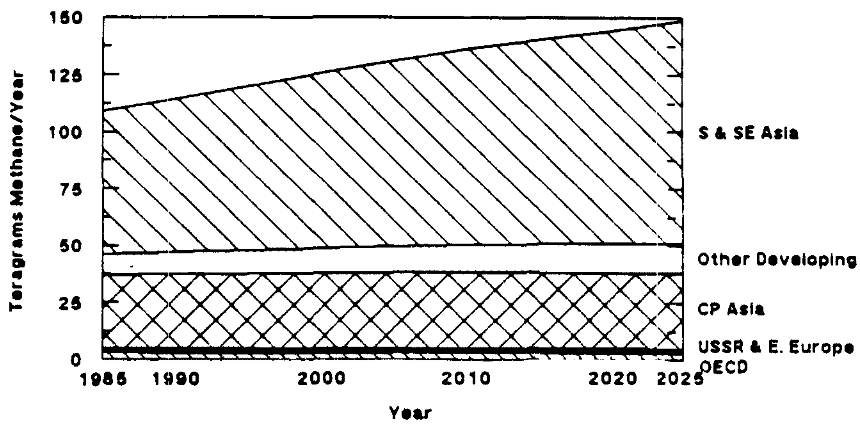


METHANE EMISSIONS FROM LANDFILLS

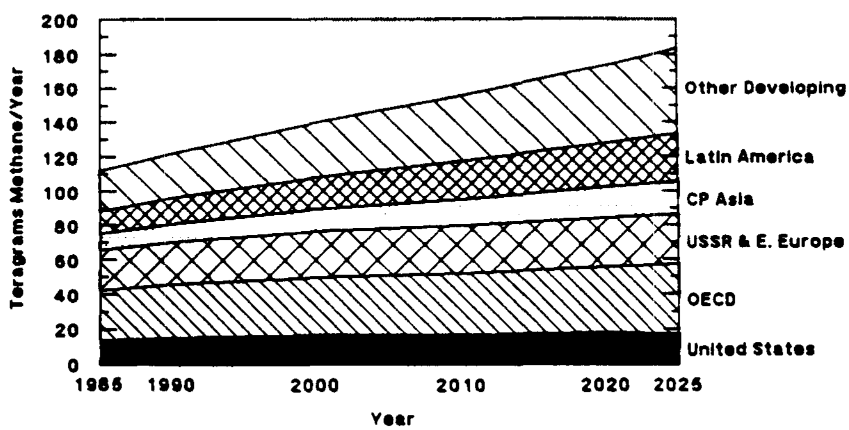
EXHIBIT A-3

METHANE EMISSIONS FROM AGRICULTURAL SOURCES THROUGH 2025

METHANE EMISSIONS FROM RICE



METHANE EMISSIONS FROM ANIMALS: ENTERIC FERMENTATION AND WASTES



their increasing levels of activities, CH_4 emissions have probably increased over the last 200 years from: rice cultivation, animal husbandry, coal mining, waste management, and oil and gas production, distribution, and use. Reductions in the rate at which CH_4 is destroyed in the atmosphere may also be playing a role. However, it is important to understand that regardless of the role played by changes in the rate of destruction of CH_4 in the atmosphere, reductions in emissions will be effective in reducing the rate of increase of CH_4 concentrations and stabilizing or further reducing its concentration.

A.3 Emissions Reduction Opportunities

Initial assessments of these CH_4 sources have identified cost-effective or low cost techniques for reducing emissions. Preliminary results are as follow:

- Coal Mining. CH_4 from coal mining is often pipeline quality and can be recovered as a resource. It is likely that up to 50 percent of CH_4 emissions can be reduced through pre-mining degasification at gaseous mines in the primary coal producing countries.

- Landfills. CH_4 recovery at landfills is becoming recognized as cost effective at many locations and techniques to enhance CH_4 generation and recovery are being continually refined. CH_4 recovery can reduce CH_4 emissions by 30 to 90 percent, the recovery percentage dependent upon site-specific factors. Recovery will occur at U.S. landfills in response to air emission regulations from landfills to be promulgated over the next year or two.

- Livestock. Livestock generate a large portion of annual CH_4 emissions (80 Tg/yr). Through changes in diet and animal management, emissions may be reduced by 25 to 75 percent per unit of product.

- Animal Wastes and Wastewater treatment. Recovery of CH_4 from anaerobic waste treatment lagoons is cost effective at sites with large concentrations of animals (such as feedlots and dairies) and highly concentrated waste streams (such as food processing plants).

- Rice. Recent work shows that CH_4 emissions may be reduced by decreasing use of animal manures as fertilizer. Recently experts agreed that CH_4 emissions could likely be reduced by 10 to 30 percent by an integrated management approach to irrigation, fertilizer application, and cultivar selection. Substantial research, development, and demonstration of practices must precede any real reductions from this source.

- Oil and Gas Systems. Technologies have been proven to reduce CH_4 venting from oil production facilities. It has also been suggested that emissions associated with the USSR gas transmission system could be reduced by improvements in the construction and operation of the system.

- Biomass Burning. Biomass burning can be reduced through fire management programs and widespread use of alternative agricultural practices. Agricultural systems traditionally dependent on the removal of biomass by burning (i.e., long-term shrub-fallow systems and high-yield grain crops) may be modified to incorporate the biomass directly into the soil, thereby improving soil organic matter, in addition to reducing emissions from burning, or removal for use as an alternative fuel source.

In addition to the benefits of reduced CH_4 emissions, it is important to note that steps taken to reduce CH_4 emissions often provide other benefits. For example, recovery of CH_4 from landfills also reduces emissions of toxic air pollutants, reduces odor problems, and produces energy which avoids carbon dioxide emissions associated with other energy sources. In the agricultural area, providing nutritional supplements to livestock which feed on low quality forage and agricultural by-products increases the productivity of the animals and provides a market for locally produced supplements.

The appendices that follow discuss the emissions reduction opportunities from each of the major anthropogenic CH_4 sources in greater detail.

A.4 References

Bingemer, H.G. and P.J. Crutzen (1987), "The Production of Methane from Solid Wastes," Journal of Geophysical Research, Vol. 92, No. D2, pp. 2181-2187, February 20, 1987.

Blake, D.R. (1984), Increasing Concentration of Atmospheric Methane, 1979-1983, PhD Thesis, University of California, Irvine.

Blaxter, K.L. and J.L. Clapperton (1965), "Prediction of the Amount of Methane Produced by Ruminants," British Journal of Nutrition, Vol. 19, pp. 511-522.

Bolle, H.-J., W. Seiler and B. Bolin (1986), "Other Greenhouse Gases and Aerosols: Assessing Their Role for Atmospheric Radiative Transfer." In: Bolin, B., B.R. Doos, B. Warrick and D. Jager (eds.), The Greenhouse Effect Climatic Change and Ecosystems, New York, John Wiley & Sons, pp. 157-203.

Campbell, I.M. (1986), Energy and the Atmosphere, John Wiley & Sons Ltd., New York, New York, 2nd Edition.

Casada, M.E. and L.M. Safley, Jr. (1990), "Global Methane Emissions from Livestock and Poultry Manure," presented at the International Workshop on Methane Emissions, April 9-13, 1990, Washington, D.C., sponsored by the Environment Agency of Japan and the U.S. Environmental Protection Agency.

Cicerone, R.J. and R.S. Oremland (1988), "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, Vol. 2, No. 4, 299-327, December 1988.

Cicerone, R.J., J.D. Shetter, and C.C. Delwiche (1983), "Seasonal Variation of Methane Flux From a California Rice Paddy," Journal of Geophysical Research, Vol. 88, pp. 11022-11024.

Cicerone, Ralph J. and J.D. Shetter (1981), "Sources of Atmospheric Methane: Measurements in Rice Paddies and a Discussion," Journal of Geophysical Research, Vol. 86, pp. 7203-7209.

Crutzen, Paul J., I. Aselmann and W. Seiler (1986), "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," Tellus, 38B, pp. 271-284.

Crutzen, P.J. (1987), "Role of the Tropics in Atmospheric Chemistry." In: Dickinson, R. (ed.), Geophysiology of Amazonia, New York, Wiley & Sons, pp. 107-132.

Ehhalt, D.H. (1974), "The Atmospheric Cycle of Methane," Tellus, Vol. 26, pp. 58-70.

Harriss, R.C., E. Gorham, D.I. Sebacher, K.B. Bartlett, and P.A. Flebbe (1985), "Methane Flux from Northern Peatlands," Nature, Vol. 315, p. 652-654.

Holzapfel-Pschorn, A. and W. Seiler (1986), "Methane Emission During a Cultivation Period From an Italian Rice Paddy," Journal of Geophysical Research, 91, pp. 11803-11814.

ICF Resources (1990), Methane Emissions to the Atmosphere from Coal Mining, draft report prepared for the U.S. Environmental Protection Agency Office of Air and Radiation by ICF Resources Incorporated.

Marland, G. and R.M. Rotty (1984), "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982," Tellus, Vol. 36B, pp. 232-261.

Matthews, E. and I. Fung (1987), "Methane Emissions from Natural Wetlands: Global Distribution, Area, and Environmental Characteristics of Sources," Global Biogeochemical Cycles, Vol. 1, pp. 61-86.

Minami, K. (1989), "Effects of Agricultural Management on Methane Emissions from Rice Paddies," Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

PG&E (Pacific Gas and Electric) (1989), "Unaccounted for Gas Project," Draft Report, November.

Prinn, R. et al. (1987), "Atmospheric trends in methylchloroform and the global average for the hydroxyl radical," Science, Vol. 238, pp. 945-950.

PSI (Pipeline Systems Incorporated) Tilkicioglu, B.H., and D.R. Winters (1990), "Annual Methane Emission Estimate of the Natural Gas and Petroleum Systems in the United States," prepared for the U.S. Environmental Protection Agency Office of Air and Radiation by Pipeline Systems Incorporated.

Safley, M.L. and P.W. Westerman (1988), "Biogas Production from Anaerobic Lagoons," Biological Wastes, Vol. 23, pp. 181-193.

Sebacher, D.I., R.C. Harriss, K.B. Bartlett, S.M. Sebacher, and S.S. Grice (1986), "Atmospheric Methane Sources: Alaskan Tundra Bogs, an Alpine Fen, and a Subarctic Boreal Marsh," Tellus, Vol. 38B, p. 1-10.

Seiler, W. (1984), "Contribution of Biological Processes to the Global Budget of CH_4 in the Atmosphere." In: Klug and C. Reddy (eds.), Current Perspectives in Microbial Ecology, M. American Society for Microbiology, Washington, D.C. pp. 468-477.

Seiler, W. (1989), "Role of Rice Cultivation in Global Emissions of Trace Gases," Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

Washida, N. (1989), "Methane Measurements and Alternative Management Practices: Recent Work in Japan II," Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

WMO (World Meteorological Organization) (1986), Atmospheric Ozone 1985, Global Ozone Research and Monitoring Project Report No. 16, NASA, Earth Science and Applications Division, Washington, D.C.

Zimmerman, P.R., J.P. Greenberg, S.O. Wandiga, and P.J. Crutzen (1982), "Termites: A Potentially Large Source of Atmospheric Methane, Carbon Dioxide, and Molecular Hydrogen," Science, Vol. 218, pp. 563-565.

APPENDIX B

ENERGY-RELATED METHANE EMISSIONS

B.1 Oil and Gas Systems

Emissions

Understanding the rate of methane (CH_4) emissions from oil and natural gas systems[1] is important because these systems have been identified as a moderately important source of global CH_4 emissions, contributing about 25 to 50 Tg/yr or 6 to 13 percent of anthropogenic methane emissions. Improved estimates of CH_4 emissions from these systems will help improve the estimates of global CH_4 emissions and will assist in identifying strategies for limiting future increases in CH_4 concentrations.

In addition, understanding these CH_4 emissions from natural gas systems is important because natural gas produces less CO_2 per amount of energy delivered than other major fossil fuels when burned (see Exhibit B-1), and substituting natural gas for other fuels (e.g., coal and oil) is being considered as a strategy for reducing future CO_2 emissions. For example, displacing an equivalent amount of coal with 5 tcf of natural gas for electric power production would reduce the U.S. emissions of CO_2 from fossil fuel use by about 6 percent (1 tcf = 1 trillion cubic feet = 10^{12} cubic feet). However, because CH_4 is also an effective greenhouse gas, the beneficial impact of this fuel substitution on CO_2 emissions would be significantly diminished (or negated) if CH_4 emissions from natural gas systems are large.

The point at which CH_4 emissions from natural gas systems negate the beneficial impact of switching to natural gas depends on a variety of factors, including: emissions of all the important trace gases during the production, distribution, and use of the various fuels; the energy conversion efficiency with which the fuels can be used; and the relative ability of the various trace gases to contribute to changes in the energy balance of the Earth. While there is uncertainty about each of these factors, it appears that CH_4 emissions on the order of 4 to 10 percent of natural gas throughput would be sufficient to negate the benefits of switching from oil and coal to natural gas in major applications, such as electric power production.

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[1] Methane is the primary component of natural gas.

EXHIBIT B-1

CO_2 EMISSIONS FROM FOSSIL FUEL USE

Fuel Type	Carbon Content (percent)	Energy Content (Btu/kg)	CO2 Emissions (kg/MMBtu)
Natural Gas	72.8%	48,900	54
Crude Oil			
API 31	85.3%	42,950	73
API 14	83.7%	41,350	74
Diesel #2	87.4%	42,500	75
Diesel #3	90.0%	40,250	83
Gasoline	84.6%	45,800	68
Methanol	37.5%	21,500	64
Bituminous Coal			
Low Volatility	59.6%	23,100	98
High Volatility	79.5%	30,900	98

1 Btu = 1 British thermal unit = 1.054×10^3 joules = 2.93×10^{-4} kilowatt-hours

MMBtu = 10^6 Btu

Sources:

Marland, G. and R.M. Rotty (1984), "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982," Tellus, Vol. 36B, pp. 232-261.

Unnasch, S. and C.B. Moyer (1989), "Comparing the Impact of Different Transportation Fuels on the Greenhouse Effect," prepared for the California Energy Commission by Acurex Corporation, March 1989.

Previous assessments of CH_4 emissions have estimated emissions from natural gas systems based on the assumption that 2 to 4 percent of annual throughput is emitted. Some reports have indicated, though, that emissions could exceed these levels in some parts of the world. At these levels of emissions, the benefit of substituting natural gas for other fossil fuels would be substantially diminished. All the emissions estimates have recognized, however, that little data are available upon which to base these estimates. Consequently, it is clear that improved data are needed to assess adequately the potential role that fuel substitution could play in strategies for reducing CO_2 emissions in the U.S. and other countries.

Several estimates of CH_4 emissions from oil and natural gas systems have been made in the course of estimating global CH_4 emissions from all sources:

- **Sheppard, et al. (1982):** venting emissions of 30 Tg/yr and distribution emissions of 20 Tg/yr. Sheppard, et. al. state: "Current flaring and venting of natural gas is [130 Tg/year]; thus because of its high value as a fuel and chemical feedstock we assume that less than 25% of the vented natural gas. . . is released into the atmosphere. . . . An additional leakage source might be from distribution systems which we assume to be as large as 2%. . ."

- **Bolle, Seiler and Bolin (1986):** emissions of 35 Tg/yr. Bolle, Seiler and Bolin's estimates are based on "assuming loss rates of natural gas to be 3-4%."

- **Crutzen (1987):** emissions of 33 Tg/yr. Crutzen uses a 4 percent loss rate.

- **Cicerone and Oremland (1988):** venting emissions of 14 Tg/yr and distribution emissions of 31 Tg/yr. Cicerone and Oremland sum up the derivation of natural gas emission estimates as follows: "Previous estimates . . . appear to have used figures for annual production and assumed loss rates of 2-4%. Loss figures such as these are usually from industrial representatives who mean them to include all unaccounted for gas . . . Unaccounted for gas is typically 2 to 2.5 percent of total production for the United States, but such figures are poorly documented. Other factors that have not been considered previously are emissions from oil exploration and recovery, and from venting and incomplete gas wells and losses due to explosive events."

These estimates of CH_4 emissions are based on rough assumptions about overall leakage rates. Several industry studies have recently provided some new insights into potential emissions.

Pacific Gas & Electric Unaccounted For Gas Study

Pacific Gas & Electric (PG&E) prepared a study on its "unaccounted for" gas (UFG) at the request of the California Public Utility Commission (CPUC). Pipelines and gas distribution companies routinely report figures for UFG. These figures are accounting-oriented, essentially a difference account to make the "volume in" equal the "volume out."

The CPUC was concerned about the unexplained variation in PG&E's UFG account which had been as low as 0.94 percent of PG&E's throughput volumes in one year and as high as 4.65 percent in another while averaging 2.2 percent. This UFG cost ratepayers approximately $54 million in 1985.

The PG&E study found that in 1987 total leakage from the PG&E system was about 1,182 MMcf (million cubic feet), or about 0.14 percent of the total gas receipts in 1987. Of this total, about 223 MMcf was associated with the operation of pneumatic instruments, 307 MMcf was associated with maintenance activities, and 647 MMcf was leaked from the PG&E distribution and transmission system (498 MMcf from leaks in the distribution system). This leakage rate estimate, which includes gas transmission and distribution, but not gas production or processing, is much lower than the 2 to 4 percent estimates used by the atmospheric science community to develop global CH_4 emissions estimates for natural gas systems.

PSI Engineering Analysis

Pipeline Systems Incorporated (PSI) has recently completed an engineering-based estimate of CH_4 emissions from the collective components of the oil and natural gas systems in the U.S., and is considered to be an initial "order-of-magnitude" estimate of emissions (PSI, 1989). Based on available engineering data, and results from the PG&E UFG study, PSI estimated that about 3.1 Tg of CH_4 were emitted from the U.S. natural gas system in 1988. This amounts to about 160 bcf (billion cubic feet or thousand million cubic feet), or on the order of 1.0 percent of total gas usage in the U.S. This emissions estimate is considered to be quite uncertain because data are lacking in many areas needed to estimate emissions precisely. Additionally, emissions rates likely vary across the hundreds of gas facilities in the U.S., making it difficult to define a single representative emissions rate for the entire country.

The emissions estimates developed by PSI are shown in Exhibit B-2 for three main parts of natural gas systems: (1) withdrawal and field separation; (2) gathering, processing, and transmission; and (3) distribution. For each of these three segments, PSI estimated emissions associated with normal operations, routine maintenance, and upsets/mishaps.[2] The largest sources of emissions appear to be the following:

- **Upsets/mishaps during withdrawal and field separation.** The emissions from this segment are comprised primarily of gas that is vented during withdrawal and field separation. The estimates of the amounts of gas that are vented are very uncertain because little data are available for estimating this quantity. PSI indicates that these emissions could be much larger or smaller. Additionally, a significant portion of these emissions may be related to oil production as opposed to natural gas production.

- **Normal operations during gathering, processing, and transmission.** The emissions from this segment are primarily comprised of emissions associated with the operation of pneumatic instruments and from leaks at gas processing plants (i.e., fugitive emissions). The emissions from pneumatic instruments are based on the PG&E UFG study results; the use of such instruments in the U.S. and the emissions per instrument should be examined to improve this component of the estimate. The leaks from gas plants are based on: (1) emissions rates for components such as valves and flanges published by the American Petroleum Institute in 1980; and (2) counts of components in a typical gas plant. This component of the emissions estimate is considered to be reasonably precise.

- **Routine maintenance at transmission facilities.** These emissions are primarily related to pipeline purge and blowdown activities. Consequently, the emissions will vary with operating practices. This estimate, based on the PG&E UFG study results, is considered to be reasonably precise.

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[2] These categories of emissions are defined as: Normal Operations: chronic emissions from the day to day operation of the facility (e.g., leakage around valves); Routine Maintenance: controlled emissions from activities regularly performed on the facility (e.g., blowing and purging); Upset Conditions/Mishaps: episodic emissions due to unplanned events in the proper operation of a facility (e.g., emissions through relief valves) and episodic emissions from abnormal events arising from outside the system (e.g., dig-ins).

EXHIBIT B-2

METHANE EMISSIONS FROM THE NATURAL GAS SYSTEM IN THE U.S.
(10^9 grams)

	Normal Operations	Routine Maintenance	Upsets and Mishaps	Total
Withdrawal and Field Separation	117	<1	1,000	1,117
Gathering, Processing, Transmission	948	551	96	1,595
Distribution	374	5	47	426
Total	1,439	556	1,143	3,138

Source: PSI (1989), "Annual Methane Emission Estimate of the Natural Gas and Petroleum Systems in the United States," prepared for the U.S. EPA by Pipeline Systems Incorporated.

- **Distribution system normal operations.** These emissions are primarily associated with small leaks that develop in distribution piping, e.g., due to corrosion. Very little data are available for estimating these emissions, and emissions could be much larger or smaller.

Not included in these estimates are potential emissions associated with gas appliances and industrial equipment.

Based on the data developed by PG&E and the PSI studies, it appears that CH_4 emissions from natural gas system leakage may be smaller than has been previously believed, at least for the U.S. and potentially for other countries with similar operations.[3]

It must be emphasized, however, that <u>many important uncertainties remain</u>. While these initial studies indicate that leakage from natural gas systems may be on the order of 1.0 percent of annual gas throughput, field data are not yet available to confirm these estimates. Consequently, CH_4 emissions from natural gas systems could be larger or smaller than indicated by these studies.

Emissions Reductions

Many opportunities exist for reducing CH4 emissions from the production, transmission, distribution and use of natural gas. Application of these methods could reduce CH_4 emissions from natural gas systems to 0.1 to 0.5 percent of worldwide throughput.

- **Reducing emissions from the natural gas transmission system in the Soviet Union.** The Soviet Union has the largest reserves of natural gas in the world and exports large quantities of natural gas to Western Europe. It has been suggested that the natural gas transmission system in the Soviet Union may leak significant quantities of CH_4. Reducing these emissions could lower not only current emissions but future emissions as the Soviet Union expands natural gas production.

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[3] See for example, A.D. Little, "Methane Emissions from the Oil and Gas Production Industries," Final report to Ruhrgas A.G., July 1989; Wernstedt, G. and G. Fermback, "Releases of Methane from Natural Gas Activity in Sweden," prepared for Swedegas by Thorell + VBB Energikonsulter AB, August 29, 1989; and The Alphatania Group, "Methane Leakage from Natural Gas Operation," July and August 1989.

- **Replace venting with flaring of natural gas.** Natural gas can be vented or flared during the withdrawal and field separation of oil and gas at production facilities. CH_4 emissions can be reduced by replacing venting systems with flares and by improving the combustion efficiency in flares.

- **Replace cast iron pipes.** Cast iron pipes leak far larger amounts of natural gas than most other types of pipes. Replacing these pipes or repairing the leaks (by sealing the pipe joints) will significantly reduce CH_4 emissions from this source.

- **Increase odorant concentrations.** Mercaptan is added to natural gas to give it a distinctive odor. By increasing the concentration of mercaptan, leaks will be detected sooner. In Japan, the mercaptan concentration is typically ten times greater than the concentration in most U.S. natural gas systems. Natural gas leakage is consequently expected to be much lower in Japan.

- **Install "smart" residential meters.** Smart meters detect unusual natural gas usage patterns (caused by a leak for example) and shut off the supply. These meters are being installed in Japan and are expected to reduce residential leakage of natural gas.

It also was suggested that abandoned oil and gas wells may emit significant quantities of CH_4 to the atmosphere. In addition, the leaky casings in producing oil and natural gas wells may allow significant quantities of CH_4 to be emitted to the atmosphere.

B.2 Coal Mines

Emissions

Coal mining is a significant source of CH_4 emissions. CH_4 is found to occur naturally in coal seams, having been formed while the coal itself was formed. When coal is mined from underground seams, CH_4 is released. The amounts released vary by the type of coal and the depth of the coal seam. CH_4 may also be released when shallow deposits are mined (i.e., surface-mined coal), although these quantities may be relatively low.

Recent estimates indicate that approximately 50 Tg of CH_4, or about 10 percent of the total CH_4 budget, are released into the atmosphere annually as a result of coal mining and processing

(ICF Resources, 1990). CH_4 emissions from this source are expected to increase in the future, moreover, as shallower coal reserves are depleted and the proportion and depth of underground coal mining increases. It is estimated that by the year 2000, CH_4 emissions from this source could reach 70 to 85 teragrams.

The majority of methane emissions from coal mining are estimated to be in five countries: the United States; the People's Republic of China; the Soviet Union; Poland; and South Africa. The People's Republic of China is estimated to have the largest CH_4 emissions from this source, with about one-third of global emissions. The Soviet Union, the United States, and Poland, in addition to China, are estimated to account for almost three-quarters of world-wide CH_4 emissions from this source.

Previous studies have estimated that CH_4 emissions from coal mining range from 8 to 45 teragrams. The wide range in estimates results from differing methodologies and input data used by these studies, primarily in terms of coal production, coal type and the average CH_4 emissions of the mined coal. None of the previous studies have developed a methodology for relating the coal seam CH_4 content to the CH_4 emissions resulting from mining activities. In addition, some of these previous studies have relied on historic levels of coal production, have estimated CH_4 emissions from hard coal (bituminous and anthracite) production only, and have used undocumented estimates of average CH_4 emissions associated with coal production.

The most accurate approach toward quantifying CH_4 emissions from coal mines would be to measure actual CH_4 emissions at underground and surface coal mines. Given the number of mines involved, however, such an approach is not practical. Instead, recent studies have begun developing relationships between the CH_4 content of the mined coal and the CH_4 emissions measured from the mine. Many geologic and other factors can influence the actual CH_4 emissions from a particular coal mine, however, and thus this approach is very approximate.

Furthermore, data on coal CH_4 contents, CH_4 emissions and even coal production are not readily available for some countries. Thus, recent studies have relied heavily on U.S. data and have extrapolated U.S. CH_4 emission estimates to other countries. The preliminary estimates generated by this approach can be useful to policy makers and researchers in identifying those countries with potentially significant CH_4 emissions from this source and enables them to allocate scarce resource funds more effectively. However, until more data are collected the estimates prepared to date should be considered preliminary and approximate.

Additional work is necessary to improve these estimates. Some possible areas for further research are listed below:

- Data Collection: Additional data are needed for most countries on coal CH_4 contents, CH_4 emissions at a group of mines which represent different coal types, mining depths and mining methods, and coal production. Using these data, country-specific relationships between coal CH_4 content and mining emissions can be developed.

- Surface Mines: Currently, there is limited information on CH_4 emissions from surface mines because these emissions pose lower safety hazards. Research is necessary to measure CH_4 emission rates at surface mines and to develop methods for estimating global CH_4 emissions from surface mines more accurately.

- Geologic Understanding: Additional research is also necessary to improve understanding of the mechanisms by which CH_4 is released during coal mining and the geologic characteristics that influence the amount of CH_4 stored in the coal and its surrounding strata.

In addition to these areas, other important research issues will arise as more information is compiled on CH_4 emissions in various countries.

Emissions Reductions: Methane Control and Recovery

In order to reduce CH_4 emissions from coal mining, it is necessary to employ two types of technology: degasification and utilization technologies. Degasification technologies are required to recover the CH_4 from the coal mine, and utilization technologies are necessary as an alternative to venting the CH_4 into the atmosphere.

Degasification

A number of degasification technologies have been demonstrated, and many mines currently employ them to enhance mine safety and to reduce operating costs at the mine. Based on experience to date, it appears that up to 50 percent of the CH_4 released during coal mining could be recovered by degasification systems used before and during mining activities. Some of these technologies require drilling boreholes from inside the mine works and transporting recovered CH_4 to the surface, while in other cases wells are drilled from the surface to the coal seam and CH_4 is pumped out. To date, these technologies have been used to improve mine safety, and little attention has been paid to the recovery and use of the CH_4 produced. In many cases, the degasification systems are viewed simply as a supplement to the ventilation system. There are four basic degasification techniques available:

Ventilation. The main technique for controlling CH_4 concentration in coal mines is ventilation, and it is used universally in underground coal mines. U.S. regulations require that all coal mines be ventilated by continuously operating mechanical fans which circulate fresh air across the actively mined coal face. As a result of these ventilation requirements, large quantities of CH_4 are vented to the atmosphere in the ventilation air.

Currently, there are limited uses for the CH_4 in ventilation air, which is vented at concentrations of less than 1 percent. It is possible that some of this ventilation air could be used in mine-site powerplant boilers as combustion air. Given the large amounts of air circulated through the mine, however, it is unlikely that on-site generation could use more than a fraction of this air. Another possibility for capturing this CH_4 would be to separate it from the ventilation air. Various techniques for separating the CH_4 and producing a more concentrated product have been considered, but none are economic under current market conditions.

Horizontal and Cross-Measure Boreholes. This degasification measure consists of drilling boreholes from within the mine workings into the unmined areas of the coal seam being mined or the adjacent strata above or below the mined coal seam. These boreholes are typically tens of meters to hundreds of meters in length and several hundred boreholes may be drilled to control emissions in a single mine. Once drilled, these boreholes are often connected to an in-mine vacuum piping system which prevents the release of this CH_4 into the mine workings and transports it to the surface. This piping system reduces CH_4 emissions into the mine workings when the coal is eventually mined. Alternatively, long horizontal boreholes, roughly 1000 ft in length, have been drilled which are connected to an undergroud pipeline which is in turn joined to a vetical borehole that terminates at the surface. Flow from these holes is aided only by the lighter-than-air buoyancy of methane.

Many underground mines, both in the United States and abroad, use horizontal and cross-measure boreholes to supplement their ventilation system. In the United States, horizontal boreholes typically produce pipeline quality gas (with CH_4 concentrations over 95 percent).

Gob Wells. Underground longwall mines (and some room and pillar mines) can release large amounts of CH_4 from the fractured gob area behind the working longwall face. In cases where gas liberation is significant, wells can be drilled from the surface to drain the CH_4 from the gob area and prevent it from entering the mine workings. Generally, these wells are drilled to a point 2 to 15 meters above the mined seam prior to the mining of the longwall panel. As mining advances under the gob well, the CH_4-containing strata around the well will begin to fracture. The CH_4 emitted from this fractured strata flows into the gob well (which often operates on a vacuum) and then to the surface. CH_4 production rates associated with gob wells can be very high (over 1 million cubic feet per day) immediately following the fracturing of the strata, and then decrease to levels around 100,000 cubic feet per day.

The quality of gas produced by gob wells, in terms of its CH_4 concentration, is variable and depends on the strength of the vacuum applied to the gob well and the degree to which mine air is extracted along with the CH_4 in the gob. Maintaining a high quality product requires precise monitoring and adjustment and an ability to integrate gas production and mining operations.

Vertical Wells. The optimum technique for controlling CH_4 emissions from a mine safety standpoint is to employ vertical degasification wells to pre-drain the CH_4 from the coal and surrounding strata before mining operations begin. These wells are similar to conventional oil and gas wells and are drilled into the coal seam before mine development. Many of these wells typically produce large quantities of water and small quantities of gas during their first several months of production. As the water in the coal seam is removed, however, the pressure on the coal seam is lowered and the CH_4 begins to desorb, thereby increasing the CH_4 production rate. Typical production rates for these wells are on the order of 100,000 to 200,000 cubic feet per day over their five to ten year lifetime.

Pre-drainage of CH_4 using vertical wells is a very effective method of reducing the CH_4 content of coal beds and thus the methane emissions associated with the eventual coal mining operation. These wells have not been widely used in the coal mining industry, due largely to their relatively high up-front costs and the difficulties associated with stimulating them and producing gas. Several conventional oil and gas operators are currently producing natural gas from coal seams using these wells in operations that are independent of coal mining activities.

Although these technologies have been demonstrated, additional research is necessary to determine how best to maximize CH_4 production from these systems. The amount of CH_4 actually recovered by these systems will depend on several factors, including:

- Technology Employed: Research is necessary to determine the optimal combination of technologies and the timing of their installation. The issues considered should include the cost of gas recovery, the amount of gas produced, any geologic factors that influence technology selection, and mining needs.

- Well Spacing: Research is necessary to determine the optimal well spacing depending on geologic and other site characteristics. If wells are too far apart, gas recovery will take too long, while if wells are too close together the expense associated with gas recovery may be too high.

- Geologic Characteristics: Research is needed to explore the relationship between a site's geologic characteristics and the need for and use of degasification technologies. The applicability of various degasification technologies, as well as the CH_4 content of the coal and surrounding strata, are highly influenced by geologic conditions.

Utilization

There are many options for using CH_4 recovered from coal mines. In some cases, coal companies are selling high quality gas (95 percent CH_4) to pipeline companies. Recovered CH_4 can also be used to generate power either at the mine site or at nearby powerplants. Turbines and combustion engines have been developed which can use medium or high quality CH_4 (roughly above 30 percent CH_4). Further, recovered CH_4 could be "co-fired" along with coal in coal-fired boilers.

The recovered CH_4 is not widely used, however, and in many cases it is vented to the atmosphere. Additional work in this area should focus on expanding the use of cost-effective utilization. This includes work on

- maximizing CH_4 recovery using degasification technologies;

- encouraging the wider application of utilization technologies;

- integrating the use of mine degasification and CH_4 utilization technologies; and

- assessing the applicability of various utilization options at mines with different gas quality, production rates, and regional needs.

In addition, large quantities of CH_4 are currently removed from mines in concentrations of 1 percent or less and vented to the atmosphere. While wider application of degasification systems and emphasis on maximizing CH_4 recovery may cause the amount of CH_4 vented in this manner to decrease somewhat, coal mines will always require ventilation, and CH_4 will continue to be produced in this manner. Thus a final area for future research could be to explore uses for the low quality CH_4 in ventilation air streams. This CH_4 may be useable as combustion air in nearby powerplants. Further, additional research could be directed at exploring ways to separate low quality CH_4 from the air stream to produce a more concentrated product.

B.3 Combustion: Stationary and Mobile Sources

<u>Emissions</u>

Combustion sources include both stationary (e.g., fossil fuel fired power plants and industrial boilers) and mobile sources (e.g., automobiles, trucks, airplanes, and ships). CH_4 emissions from these combustion sources are, in general, associated with incomplete combustion of fossil fuels. Although CH_4 may not be a component of the fuel, it can be created during the combustion process.

While there is considerable uncertainty in the estimates of CH_4 emissions from these combustion sources, existing data indicate that CH_4 emissions associated with the combustion of fossil fuels are much smaller than CH_4 emitted during fuel production. A range of recent measurements are presented in Exhibit B-3. It is useful to note that if the world's 300 exajoules of current energy demand resulted in CH_4 emissions at a rate of 10 g/GJ[4], that fossil fuel combustion would produce about 3 Tg of CH_4 annually. A more detailed estimate would involve using the emissions factors listed in Exhibit B-3 and estimates of the amount of energy consumed by each combustion source globally. While many uncertainties remain, it appears likely that combustion sources will be a large source of CH_4 emissions.

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[4] 1 GJ = a gigajoule = 10^9 joules.

EXHIBIT B-3

METHANE EMISSIONS FROM COMBUSTION SOURCES

Emission Source	Emissions Factor (grams CH_4 per GJ)	Source
Mobile Sources:		
Gasoline	130	Unnasch and Moyer
Diesel	20	Unnasch and Moyer
Gasoline[1]	36 - 60	Radian
Diesel[1]	2 - 8	Radian
Jet Aircraft	2	Radian
Rail Engines	13	Radian
Ships	20	Radian
Stationary Sources:		
Natural Gas Boiler	0.5	Radian
Coal Boiler	0.3	Radian
Oil Boiler	2	Radian
Wood Stoves	70	Radian

[1] Represents uncontrolled sources (e.g., automobiles without catalytic converters).

Sources:

Radian Corporation (1987), "Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NO_x, CH_4, CO and CO_2," Prepared for the U.S. EPA.

Unnasch, S. and C.B. Moyer (1989), "Comparing the Impact of Different Transportation Fuels on the Greenhouse Effect," prepared for the California Energy Commission by Acurex Corporation, March 1989.

B.4 References

A.D. Little (1989), "Methane Emissions from the Oil and Gas Production Industries," Final report to Ruhrgas A.G., July 1989.

Alphatania Group, The (1989), "Methane Leakage from Natural Gas Operation," July and August 1989.

Bolle, H.-J., W. Seiler and B. Bolin (1986), "Other Greenhouse Gases and Aerosols: Assessing Their Role for Atmospheric Radiative Transfer." In: Bolin, B., B.R. Doos, B. Warrick and D. Jager (eds.), The Greenhouse Effect Climatic Change and Ecosystems, New York, John Wiley & Sons, pp. 157-203.

Cicerone, R.J. and R.S. Oremland (1988), "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, Vol. 2, No. 4, 299-327, December 1988.

Crutzen, P.J., (1987) "Role of the Tropics in Atmospheric Chemistry." In: Dickinson, R. (ed.), Geophysiology of Amazonia, New York, Wiley & Sons, pp. 107-132.

ICF Resources (1990), Methane Emissions to the Atmosphere from Coal Mining, draft report prepared for the U.S. Environmental Protection Agency Office of Air and Radiation by ICF Resources Incorporated.

Marland, G. and R.M. Rotty (1984), "Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982," Tellus, Vol. 36B, 1984, pp. 232-261.

PSI (1989), "Annual Methane Emission Estimate of the Natural Gas and Petroleum Systems in the United States," prepared for the U.S. EPA by Pipeline Systems Incorporated.

Radian Corporation (1987), "Comparing the Impact of Different Transportation Fuels on the Greenhouse Effect," prepared for the California Energy Commission by Acurex Corporation, March 1989.

Sheppard, J.C., H. Westberg, J.F. Hopper, and K. Ganesan (1982), "Inventory of Global Methane Sources and Their Production Rates," Journal of Geophysical Research, Vol. 87, pp. 1305-1312.

Unnasch, S. and C.B. Moyer (1989), "Comparing the Impact of Different Transportation Fuels on the Greenhouse Effect," prepared for the California Energy Commission by Acurex Corporation, March 1989.

Wernstedt, G. and G. Fernback (1989), "Releases of Methane from Natural Gas Activity in Sweden," prepared for Swedegas by Thorell + VBB Energikonsulter AB, August 29, 1989.

APPENDIX C

WASTE MANAGEMENT

C.1 Landfills

Emissions

Solid waste landfills are estimated to account for 30 to 70 Tg[1] of annual global methane (CH_4) emissions, which is roughly 7 percent of all CH_4 emissions and about 14 percent of the anthropogenic emissions (Bingemer and Crutzen, 1987). Exhibit C-1 shows the assumptions used to generate this global estimate. Exhibit C-1 also shows estimates of CH_4 emissions from different parts of the world and from different types of waste.

By far the largest contribution of CH_4 from landfills is from developed countries. CH_4 emissions from landfills can be expected to increase as world population grows, if waste disposal practices do not change. In addition, a major shift in the largest contributors can be expected as waste dumping rates in the developed countries continue to slow down and as population growth and increasing urbanization in the developing countries lead to more waste dumping.

Discussions at the IPCC Workshop included estimates of emissions from individual countries and regions, including:

- Canada: 1 Tg per year;
- Japan: 0.17 Tg per year;
- Oceania: 1.25 Tg;
- United States: 8 to 18 Tg per year;
- USSR and eastern Europe: 5 to 8 Tg per year; and
- Developing Countries: 4 to 7 Tg per year.

The range of global emissions estimates discussed at the workshop was 25 to 40 Tg per year. This range is at the low end of the range estimated by Bingemer and Crutzen (1987).

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[1] 1 Tg = 1 teragram = 10^{12} grams = 10^{9} kilograms = 1 million metric tons.

Exhibit C-1
Methane Generation from Landfills World-wide

	United States, Canada, and Australia	Other OECD	USSR and Eastern Europe	Developing Countries	Total
Municipal Waste Generation (kg C/cap/yr)	148 + 30	56 + 21	38	27 + 17	
Percent Paper Products	72	57	37	41	
Percent Other	28	43	63	59	
Population Considered (millions)	272	471	400	736	
Total Waste Carbon (million tons/yr)	40	26	15	20	101
Fraction landfilled (percent)	91	71	85	80	
Waste C Landfilled (million tons/yr)	37	19	13	16	85
Methane from Landfilled Municipal Waste (Teragrams, based on .5 kg CH4/kg C)	19	10	7	8	31 - 57
Landfilled Industrial Wastes (million tons C/yr)					23 - 44
Methane from Landfilled Industrial Wastes (Teragrams, based on .5 kg CH4/kg C)					12 - 22
Methane from Landfilled Agricultural Wastes					?
Total Methane from Landfills (Teragrams)					30 - 70

Source: Bingemer, H.G. and P.J. Crutzen, "The Production of Methane from Solid Wastes," Journal of Geophysical Research, Vol. 92, No. D2, pp. 2181-2187, February 20, 1987.

Landfill gas, which is composed mainly of CH_4 and carbon dioxide (CO_2), results from the anaerobic decomposition of organic degradable wastes which begins after the waste has been in the landfill for a period of 10 to 50 days (Van Heuit, 1986). While the rate of CH_4 production varies over the first 180 to 500 days (Van Heuit, 1986), eventually an equilibrium is achieved within the landfill and steady state CH_4 generation occurs. Most of the CH_4 generated in a landfill is produced during this steady state phase. Although the majority of CH_4 generation typically takes place within 20 years of landfill completion, it can continue for 100 years or more. At this point transition occurs from anaerobic back to aerobic conditions as the supply of degradable organic material is depleted and air infiltrates the landfill.

Additional work is necessary to obtain better estimates of CH_4 emissions and to better understand the effects of a number of important site-specific factors. These include

- Waste Composition. Probably the most important factor affecting CH_4 generation rates and quantities is the composition of the landfilled waste. The waste represents the "raw material" for CH_4 generation, as it provides degradable organic materials and nutrients for the system. The presence of certain constituents in the refuse could inhibit CH_4 production, such as heavy metals or other toxic substances that retard bacterial growth (Pacey and DeGier, 1986). In addition, different types of wastes are known to decay at different rates, although the actual rates depend on site-specific conditions. Food wastes, for example, are considered readily biodegradable, while paper wastes degrade at a more moderate rate. Textiles and the lignin fraction of wood are considered slowly biodegradable (Wilson et al., 1988; Gunnerson and Stuckey, 1986).

- Moisture Content. The amount of moisture within a landfill is another important factor affecting gas generation rates, as an aqueous environment is required for anaerobic degradation of waste. Not only do methanogenic bacteria perform better as the moisture content increases, but water acts as a transport medium that carries nutrients and bacteria throughout the landfill while moving intermediates away from the bacteria-substrate interface. Several factors affect the moisture content of landfills:

  -- moisture content of the waste at the time of disposal;

-- surface water infiltration;

-- groundwater infiltration;

-- water released during decomposition; and

-- liquid additions to the landfill (e.g., sludge, septic tank pumpings, leachate recirculation).

Refuse is normally 20 to 30 percent water by weight (Pacey and DeGier, 1986; Noble et al., 1988). There is disagreement in the literature as to what moisture content leads to optimal CH_4 generation. For example, Pacey and DeGier (1986) indicate 40 to 45 percent (by weight) as the optimal value. Chian and Dewalle (1979) state that maximum gas production occurs when the moisture content is 75 percent or greater, while Pohland and Harper (1986) suggest that increasing the moisture content above 60 percent results in no change in CH_4 production. Researchers do agree, however, that decomposition is optimized when water is distributed evenly throughout the landfill. The formation of "wet" and "dry" regions within the landfill, a phenomenon that is likely to occur when the refuse is baled prior to disposal, can limit overall CH_4 generation.

- Temperature. Because anaerobic digestion is an exothermic process, landfill temperatures tend to be higher than ambient air temperatures. The extent to which ambient air temperatures influence CH_4 generation rates depends mainly on the depth of the landfill. In shallow landfills, microbial activity may be responsive to ambient air temperatures; CH_4 generation is greatly reduced when temperatures are below 10°C to 15°C (Pacey and DeGier, 1986). In deeper landfills, however, ambient air temperature effects are less significant. A self-regulating average landfill temperature of 35°C within the anaerobic zone can be expected (Gunnerson and Stuckey, 1986).

- pH and Buffer Capacity. Landfill CH_4 generation is greatest when near neutral pH conditions exist within a landfill. A pH range of 6.8 to 7.2 is considered ideal, but CH_4 production takes place in pH environments ranging from 6.5 to 8.0 (Pacey and DeGier, 1986). In acidic environments (i.e., pH below 6.0), the activity of methanogenic bacteria is inhibited. Although landfills are typically acidic when wastes are first buried, the pH usually reaches near-neutral conditions within the first or second year after placement. This is largely due to the buffering effects of liquid within the landfill. Studies have shown that the addition of buffering agents can enhance CH_4 production (Pohland, 1986), although others argue that the results of adding buffers are inconclusive.

- Nutrients. Certain nutrients are necessary for anaerobic digestion to occur. These include carbon, hydrogen, nitrogen, and phosphorus. Potassium, sodium, magnesium, calcium, and sulfur also have a role in the process. In general, municipal solid waste contains the nutrients necessary to support methanogenesis.

- Refuse Density and Particle Size. The particle size and density of the waste also influence CH_4 generation, as these factors affect the transport of nutrients and moisture throughout the landfill (Noble et al., 1988). Although there is some disagreement in the literature on the exact effects of waste density, it is commonly agreed that as density increases, gas generation also increases (Pacey and DeGier, 1986). For example, shredded refuse, which has a high density and a small particle size, retains moisture better and creates a larger surface area for bacterial activity than does non-shredded waste. Shredding may also release microbes from the waste and increase the mass transfer of nutrients. However, increased compaction of the waste may decrease liquid mobility, thereby hindering gas production.

These factors act in combination to define the gas generation capacity and the gas generation rate constant for a landfill. Scientists have used a variety of methods to estimate the gas generation capacity and have produced a range of values as indicated below in a list compiled by Ham and Barlaz (1987):

- 8.2 ft^3 of gas per pound of refuse - theoretical maximum, calculated stoichiometrically based on typical composition of U.S. municipal refuse;

- 1.6 to 4.7 ft^3/lb - theoretical estimate based on degradability of typical waste;

- 3.3 to 4.1 ft^3/lb - laboratory measurement, anaerobic digestion of refuse with sewage sludge; considered the best that could be achieved in a landfill;

- 0.008 to 0.63 ft^3/lb - lysimeters or closed containers; considered to underestimate the amount of CH_4 generated in landfills;

- 0.8 to 6.3 ft^3/lb - full-sized landfills, projected from existing short-term data.

According to Ham and Barlaz (1987), the most likely range is 1.6 to 3.9 ft^3 of gas per pound of refuse. Note that these values are for landfill gas, of which CH_4 constitutes approximately 50 percent; therefore, the most likely value for CH_4 generation capacity lies in the range of 0.8 to 2.0 ft^3 of CH_4 per pound of waste. The value assumed by Bingemer and Crutzen (1987) was 2.6 ft^3 per pound of refuse.

Scientists have also estimated gas generation rates at landfills, which are expressed in terms of volume of CH_4 per unit mass of refuse per unit time. These estimates are typically based on laboratory studies that attempt to simulate landfill conditions. Actual field testing is also done in some cases. As with the gas generation capacity estimates, the estimates of gas generation rates vary considerably. The following values are provided by Ham and Barlaz (1987):

- 1.6×10^{-5} to 0.47 ft^3 of gas per pound of refuse per year - based on lysimeters;
- 0.24 to 0.94 ft^3/lb/yr - pilot-scale or test landfills;
- 0.01 to 0.63 ft^3/lb/yr (typically 0.16 to 0.32 ft^3/lb/yr) - field tests at full-size landfills.

Again, these values are for landfill gas, about half of which is CH_4. According to Ham and Barlaz (1987), these rates would be reached after an initial lag period and continue for 5 to 20 years, followed by a first-order die-off period.

Emission estimates are further complicated because not all of the CH_4 generated in a landfill escapes to the atmosphere. As CH_4 migrates through the landfill towards the surface, if oxygen is present, aerobic bacteria may oxidize the CH_4 into carbon dioxide and water. Researchers disagree over the significance of the impact of CH_4 oxidation on overall emissions. Mancinelli and McKay (1987) suggest that 10 percent of the CH_4 generated is oxidized by aerobic bacteria. Bingemer and Crutzen (1987) cite flux-chamber measurements taken by Jager and Peters (1985) at a soil-covered landfill indicating that only 70 percent of the CH_4 estimated to have been generated was emitted to the atmosphere. On the other hand, landfill gas often escapes through the surface of landfills through fissures and cracks, rather than by diffusion. This results in less opportunity for oxidation, implying that a larger percentage of the CH_4 generated actually escapes to the atmosphere.

The understanding of the contribution of landfills to atmospheric CH_4 emissions would be improved by research efforts in a number of areas. These include efforts to

- Understand how the rate of methane emissions is influenced by key landfill characteristics, such as landfill design and operation; waste characteristics (e.g., composition; degradability; and moisture content); landfill size; and local conditions (e.g., climate and ground cover).

- Characterize current and expected future landfills in terms of those characteristics that influence methane emissions.

- Obtain field measurements of methane emissions from landfills in different regions using different management practices and receiving different types of wastes. Measurement techniques must be developed to collect these data.

- Examine how methane oxidation influences methane emissions.

- Develop a carbon balance for landfills that describes the fate of the carbon added to landfills over time. This carbon balance should describe: carbon storage; methane and carbon dioxide generation; methane oxidation; and methane and carbon dioxide emissions. This balance should be sensitive to various landfill characteristics such as: waste composition (e.g., lignin/cellulose ratios); moisture content; and landfill design.

- Develop methods for scaling up limited measurements and data to develop national and global emissions estimates that reflect differences in cultures, waste generation, and waste management practices.

Emissions Reductions

Technologies and practices exist to reduce methane emissions from landfills by collecting and flaring or utilizing the methane generated in the landfill. In many circumstances these technologies and practices appear to be cost effective. Use of these technologies and practices is believed to reduce methane emissions by 40 to 70 percent at existing landfills. In new landfills, it is believed that methane emissions can be reduced by 70 to 95 percent using currently available technologies and practices.

In more detail, gas recovery systems use pumps to draw gas through a system of vertical or horizontal wells buried in a landfill. The gas is routed to a central facility, where it can be processed in a variety of ways, depending on the end use. CH_4 produced by recovery systems can be used as a medium Btu fuel (about 500 Btu per standard cubic foot, or scf) on-site or sold to a nearby industrial customer, used to generate electricity to sell to an electric utility, or upgraded to high Btu gas (about 950 Btu/scf or greater) and delivered to a natural gas pipeline for blending with pipeline supplies. Revenues from sale of the gas or of electricity generated from the gas can be profitable for landfill owners, or can at least offset the costs of complying with gas control regulations.

Gas recovery systems are not designed to capture all of the gas generated at the landfill, but to focus on gas produced deeper in the landfill, which is richer in CH_4 (Pohland, 1987). According to industry experts (cited in Radian, 1988), from 30 to 65 percent of the generated gas is typically collected in recovery systems. However, as discussed at the IPCC Workshop, gas collection efficiencies of up to 90 percent can be achieved at well-designed landfills equipped with bottom liners and operated with leachate recirculation.

Alternatively, gas control systems have generally aimed at minimizing subsurface lateral migration of gas, which can lead to explosions in structures at considerable distances from the landfill. These systems include (1) trenches or wells that vent gas to the atmosphere passively, or (2) pumps that suction gas from wells installed in the landfill, and either vent the gas to the atmosphere or route it to a flare. Of these gas control systems, only those that flare the collected gas have the potential to reduce CH_4 emissions. In these systems, the amount of generated gas intercepted by the collection system varies, depending on the spacing between wells, the amount of suction applied, the landfill design, and the surrounding soil type and geography.

In addition to the reductions in methane emissions, steps taken to reduce methane emissions from landfills provide other significant environmental and safety benefits. Also, when utilized as an energy source, the methane recovered from landfills to reduce emissions may displace more carbon intensive fuels, thereby also reducing carbon dioxide emissions.

Engineers, scientists, and landfill operators have made major advances during the past two decades in understanding the process of landfill gas generation, control, and recovery. Further efforts in several research areas would help develop effective strategies for controlling CH_4 emissions, including:

- evaluating the feasibility of enhancing CH_4 generation on a practical and widespread scale (currently underway in Europe);

- developing strategies that combine gas enhancement and other landfill practices with increased collection system efficiency;

- identifying techniques to encourage more widespread use of recovery systems;

- developing techniques for enhancing methane generation in cases where the methane can be captured and utilized;

- developing cost beneficial uses of recovered methane from landfills (particularly small landfills), such as lower cost electricity generation technologies.

These advancements would allow the identification of best control/recovery/utilization technologies and practices that are appropriate for various landfill situations, including new versus existing landfills.

CH_4 emissions from landfills may also be reduced by reducing the amount of municipal solid waste generated and disposed in landfills. For example, roughly 80 percent of the municipal solid waste generated each year in the United States is currently landfilled. Although a majority of municipal waste can be expected to be landfilled in the future, a considerable effort to find alternatives to landfilling is currently taking place because of a variety of environmental concerns such as surface water contamination, leaching of contaminants into ground water, increased regulation, and increased costs of landfilling (the average charge to dispose a ton of waste in the United States increased from $11 in 1982 to $29 in 1988 (Pettit, 1989)). Current efforts are examining the potential for waste reduction, recycling and incineration techniques for management of solid waste.

It is necessary to examine the effect of alternative waste management and treatment programs on emissions of methane and other greenhouse gases, including: waste stream separation and recycling; and incineration with energy recovery. The individual options are as follow:

- Waste Reduction. Reduction of the total waste volume is the first step toward reducing CH_4 emissions from waste management. This could first be accomplished by eliminating wasteful use of resources in living and business activities.

- Recycling. Because it is the organic portion of disposed waste that generates CH_4, sorting waste during collection and diverting the waste to another process may be an effective option for reducing CH_4 emissions. For example, waste paper recovery can greatly reduce the amount of organic waste being landfilled and the collected paper can be used in secondary paper products, biofuel facilities, or composted.

- Incineration. Waste incineration may be a very effective pretreatment method for the reduction of CH_4 from landfills because it can reduce total waste volumes to be landfilled. However, waste incineration is itself a source of greenhouse gas emissions in addition to pollutants such as NO_x. Use of incineration as a CH_4 reduction technology requires careful setup and monitoring of operating parameters such as combustion temperature, air mixture, gas residence time, secondary combustion chamber, and appropriate methods for reducing air pollutants.

C.2 Wastewater Treatment

Wastewater treatment can produce CH_4 emissions if organic constituents in the wastewater are treated anaerobically (i.e., under conditions in which no oxygen is present), and if the CH_4 produced is released to the atmosphere. Wastewater treatment plants in developed countries rely principally on aerobic treatment, or anaerobic treatment in enclosed systems where the CH_4 is recovered and utilized. Consequently, wastewater treatment in most developed countries is not considered a major source of CH_4 emissions.

In developing countries and at individual facilities in developed countries wastewater treatment using anaerobic lagoons is expected to produce large quantities of CH_4 emissions. At facilities with high organic waste loads, a series of anaerobic lagoons is often used to treat the wastewater. The organic waste is converted by anaerobic bacteria to CH_4 and CO_2, which are released into the atmosphere.

Virtually no data are available with which to produce precise estimates of these emissions. A rough estimate was made using the following:

- The organic waste load in wastewater can be described in terms of milligrams of biochemical oxygen demand per liter (mg/l of BOD).

- Food processing facilities generally produce wastewater with very high organic loadings, in the range of 30,000 to 100,000 mg/l of BOD. Food processing facilities include: vegetable and fruit processing plants; meat packing plants and slaughter houses; sugar processing plants; distilleries; and creameries.

- As a general rule, one can expect about 300 liters (0.22 kilograms) of CH_4 per 10^6 mg of BOD.

Based on these assessments, and an inventory of wastewater lagoons in the Kingdom of Thailand, CH_4 emissions from wastewater lagoons in Thailand was estimated at 0.5 Tg per year. Although few data are available, using the Thai estimates as a guide it may be estimated that global emissions are about 20 to 25 Tg per year globally.

An inventory of food processing facilities and their methods of wastewater treatment is required to estimate emissions from this source more precisely. These emissions will also be a good candidate for control because the CH_4 can be captured easily and used as a fuel at the processing plant. Such systems have been demonstrated and it is recommended that they be used more widely.

C.3 Animal Wastes

Emissions

Animal wastes provide a large potential source of CH_4 emissions (Gibbs et al., 1989). Most animal wastes contain organic material. If this material is decomposed under suitable anaerobic conditions, methanogenic bacteria may produce considerable amounts of CH_4.

The potential for animal wastes to produce CH_4 may be expressed in terms of the CH_4 generated per kilogram of volatile solids (VS) of waste material.[2] Exhibit C-2 presents values in the literature for the potential amounts of CH_4 produced per kilogram of VS in different animal wastes. As shown in the exhibit, these values range from .17 to .49 cubic meters (m^3) of CH_4 per kilogram of VS.

[2] Volatile solids are that part of the waste that is combustible.

EXHIBIT C-2

POTENTIAL METHANE EMISSION RATES FROM ANIMAL WASTES
m^3 methane per kilogram volatile solids

	Beef Cattle	Dairy Cattle	Swine	Poultry
Safley, et. al.[a]	0.18	0.26	0.26 - 0.36	0.28
Hashimoto, et. al.[b]	0.17 - 0.33			
Chandler, et. al.[c]		0.27	0.41	0.29
Jewell, et. al.[d]	0.33	0.22	0.38	0.49

[a] Safley, M.L. and P.W. Westerman, "Biogas Production from Anaerobic Lagoons," Biological Wastes, Vol. 23, 1988, pp. 181-193.

[b] Hashimoto, A.G., V.H. Varel and Y.R. Chen, "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age," Agricultural Wastes, Vol. 3, 1981, pp. 241-256.

[c] Chandler, et. al., Second Symp. Biotech. Energy Prod. Conversion, 1979.

[d] Jewell, et. al. Fuel Gas Production from Biomass, D.L. Wise (ed.), CRC Press, Boca Raton, Vol. 1, p. 215.

As an illustrative example, a high producing dairy cow produces about 1000 kilograms of VS of wastes per year. At a rate of 0.25 m^3 of methane per kilogram of VS, the <u>potential</u> methane emissions from this waste is about 175 kilograms. This level of emissions is about twice the methane anticipated to be produced within the rumen of the same cow.

While the <u>potential</u> CH_4 emissions from animal wastes are large, the realized emissions are likely to be much smaller. If aerobic conditions exist (when the manure is in contact with oxygen) then CH_4 production is minimal. If the manure is held under anaerobic conditions (in the absence of oxygen), then the manure can produce CH_4.

Several of the systems used to manage animal wastes include the following:

- <u>Fertilizer</u>. In many parts of the world, manure is used as a fertilizer. If it is spread on dry soils and decomposes aerobically, then little CH_4 production is likely. If the manure is spread on anoxic soils (e.g., flooded rice paddies) then CH_4 production is likely.

- <u>Fuel</u>. Manure is dried and used as a fuel source. Burning dried manure probably creates little CH_4 as the organic material oxidizes directly to carbon dioxide (measurements are required to confirm this expectation) In other cases the manure is collected and used in a biogas (i.e. CH_4) generator where the organic material in the manure is deliberately converted into CH_4, collected and burned as a fuel. CH_4 will only be emitted to the extent that it leaks from the biogas system or was incompletely burned.

- <u>Waste Handling</u>. In locations where large number of animals are held in a confined area (dairies and feedlots, swine and poultry facilities) animal waste required proper handling and disposal. The waste may be piled up until it can be hauled away or washed into ponds for treatment. In either case anaerobic bacteria exist, and some portion of the organic matter in the wastes will be converted to CH_4.

- <u>Pasture and Range</u>. Animals that are grazing on pasture or ranges are not on any true waste handling system. The wastes from these animals dry out and decompose. Minimal amounts of CH_4 are expected from these wastes, although measurements are lacking to quantify the CH_4 releases.

Measurements of CH_4 emissions from waste ponds have been undertaken as part of efforts to capture this CH_4. Safley and Westerman (1988) report the following estimates of biogas production from waste ponds:[3]

- o Poultry digester effluent: 1.38 m^3/kgVS that is 65-85% CH_4;
- o Dairy wastes: 1.50 m^3/kgVS that is 80% CH_4; and
- o Swine wastes: 0.75-0.80 m^3/kgVS that is 85-95% CH_4.

These data indicate that CH_4 emissions may be on the order of 1 m^3 per kilogram of VS added to the ponds during certain periods of the year. These conversion rates are much larger than the conversion rates listed in Exhibit C-2, and it is unlikely that these rates can be sustained throughout the year.

The extent of CH_4 emissions from waste piles has yet to be quantified or measured. Acid formation in the decomposition process may inhibit CH_4 creation in waste piles.

Based on available data, Casada and Safley (1990) estimated CH_4 emissions from animal wastes. Their estimates include the following:

- <u>Animal populations</u>. Data were collected by country on the number, size, and feed types for the following populations of animals: beef and dairy cattle; buffalo; swine; poultry; sheep; goats; and horses/mules/donkeys.
- <u>Waste quantities</u>. The amount of waste produced per animal was estimated for each country or region, taking into account differences in animal size and feed. The amount of VS produced was estimated, and the <u>maximum</u> amount of CH_4 that can be produced from each waste quantity for each animal type was estimated. This maximum is used to estimate the CH_4 emissions <u>potential</u>.
- <u>Waste management</u>. A set of waste management practices was defined. The portion of waste handled using each system was estimated. The systems used were:

  -- pasture/range;
  -- daily spread;

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[3] 1 m^3/kgVS = 1 cubic meter of biogas generated per kilogram of volatile solids added to the pond.

-- solid storage;
-- deep pit stacking;
-- litter;
-- paddock;
-- liquid/slurry storage;
-- anaerobic lagoon;
-- pit storage;
-- anaerobic digester;
-- compost; and
-- burned for fuel.

- Emissions Realized. For each waste treatment system an estimate was made of the portion of the maximum potential CH_4 emissions that is actually achieved. For example, 90 percent of the maximum potential emissions may be achieved if the waste is managed in an anaerobic lagoon. Alternatively, only 5 percent of the maximum may be realized if the waste is spread daily.

Using these estimates, the total global CH_4 emissions from animal wastes was estimated. Using the estimates of the amount of waste handled in each of the waste handling systems, the CH_4 emissions that are actually realized were estimated.

These preliminary estimates put global CH_4 emissions from animal wastes at about 35 Tg per year. This total is comprised of the following:

- Beef and dairy cattle: 19 Tg per year;
- Swine: 9 Tg per year;
- Buffalo: 3 Tg per year; and
- Other: 4 Tg per year.

These estimates divide out regionally as follows:

- North America: 4 Tg per year;
- Western Europe: 7 Tg;
- Eastern Europe: 10 Tg;
- Oceania: 1 Tg;
- Latin America: 3 Tg;
- Africa: 2 Tg;
- Near East and Mediterranean: 1 Tg; and

- Asia and Far East: 8 Tg.

Due to a lack of data and measurements, these emissions estimates are uncertain. In particular, the assumption that 11 percent of the CH_4 potential is realized from the wastes of grazing cattle is very uncertain. Because of the large number of cattle that are grazing, this assumption is an important factor that influences the overall emissions estimate.

Emissions Reductions

The primary technique available for reducing CH_4 emissions discussed to date is to modify the manner in which wastes are managed from large concentrations of animals. Candidates for reducing emissions would be:

- Swine and Poultry Facilities: Swine and poultry are primarily raised in large concentrations in confined structures throughout the world. The CH_4 from these wastes could be recovered and used as fuel without adversely affecting the fertilizer value of the manure. A hog farm in the U.S. has an operating system that recovers CH_4 and produces electricity.

- Dairies and Feedlots: Large dairies and feedlots that treat wastes in lagoons or in drylots present an excellent opportunity for recovering CH_4 emissions. Demonstration projects are required to investigate the preferred method of handling solids that are not broken down anaerobically.

- Digestors: Small low-cost anaerobic digestors are being developed to provide fuel to homes with a small number of livestock. The principal objective is to provide a reliable fuel source because wood is becoming scarce in some locations. This technology could also be promoted as a means of reducing CH_4 emissions from animal wastes.

Opportunities have not yet been identified for reducing CH_4 emissions from the wastes of grazing animals.

C.4 References

Bingemer, H.G. and P.J. Crutzen (1987), "The Production of Methane from Solid Wastes," Journal of Geophysical Research, Vol. 92, No. D2, pp. 2181-2187, February 20, 1987.

Casada, M.E. and L.M. Safley, Jr. (1990), "Global Methane Emissions from Livestock and Poultry Manure," presented at the International Workshop on Methane Emissions, April 9-13, 1990, Washington, D.C., sponsored by the Environment Agency of Japan and the U.S. Environmental Protection Agency.

Chandler, et. al. (1979), Second Symp. Biotech. Energy Prod. Conversion.

Chian, Edward S.K. and Foppe B. DeWalle (1979), "Effect of Moisture Regimes and Temperature on MSW Stabilization," in Municipal Solid Waste: Land Disposal, Proceedings of the Fifth Annual Research Symposium, U.S. Environmental Protection Agency, EPA-600-9-79-023a, August 1979.

Gibbs, Michael J., Lisa Lewis and John S. Hoffman (1989), Reducing Methane Emissions from Livestock: Opportunities and Issues, U.S. Environmental Protection Agency: Washington D.C., EPA 400/1-89/002, August 1989.

Gunnerson, Charles G. and David C. Stuckey (1986), Integrated Resource Recovery: Anaerobic Digestion Principles and Practices for Biogas Systems, World Bank Technical Paper Number 49, Washington, D.C.

Ham, Robert K., and Morton A. Barlaz (1987), "Measurement and Prediction of Landfill Gas Quality and Quantity," Presented at ISWA Symposium "Process, Technology, and Environmental Impact of Sanitary Landfill," Cagliari, Sardinia, Italy, October 20-23, 1987.

Hashimoto, A.G., V.H. Varel and Y.R. Chen (1981), "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age," Agricultural Wastes, Vol. 3, 1981, pp. 241-256.

Jewell, et. al. Fuel Gas Production from Biomass, D.L. Wise (ed.), CRC Press, Boca Raton, Vol. 1, p. 215.

Mancinelli, Rocco L. and Christopher P. McKay (1987), "Methane-Oxidizing Bacteria in Sanitary Landfills," in A.A. Antonopoulos (ed.) Biotechnological Advances in Processing Municipal Wastes for Fuels and Chemicals, Park Ridge, NJ: Noyes Data Corporation, pp. 437-450.

Noble, J.J., T. Nunez-McNally, and B. Tansel (1988), "The Effects of Mass Transfer on Landfill Stabilization Rates," in Proceedings of the International Conference on Landfill Gas and Anaerobic Digestion of Solid Waste, United Kingdom Department of Energy, October 1988.

Pacey, John G. and Joseph P. DeGier (1986), "The Factors Influencing Landfill Gas Production," in Energy From Landfill Gas, proceedings of a conference jointly sponsored by the United Kingdom Department of Energy and the United States Department of Energy, pp. 51-59, October 1986.

Pettit, C.L. (1989), "Tip Fees Up More Than 30% in Annual NSWMA Survey," Waste Age, March 1989, p. 101.

Pohland, F.P. and S.R. Harper (1986), Critical Review and Summary of Leachate and Gas Production from Landfills, EPA/600/2-86/073, U.S. EPA Hazardous Waste Engineering Laboratory, Cincinnati, Ohio, August 1986.

Radian Corporation (1988), Memorandum from Y.C. McGuinn, Radian Corporation, to Susan Thorneloe, U.S. Environmental Protection Agency, "Use of a Landfill Gas Generation Model to Estimate VOC Emissions from Landfills," June 21, 1988.

Safley, M.L. and P.W. Westerman (1988), "Biogas Production from Anaerobic Lagoons," Biological Wastes, Vol. 23, 1988, pp. 181-193.

Van Heuit, R.E., EMCON Associates (1986), "Estimating Landfill Gas Yields," Proceedings of the 9th International Landfill Gas Symposium, GRCDA, pp. 92-103.

Wilson, D.C., B.J.W. Manley, T. Nunez-McNally, S. Shaw, and H.S. Tillotson (1988), "National assessment of Landfill Gas as a Resource," in Proceedings of the International Conference on Landfill Gas and Anaerobic Digestion of Solid Waste, United Kingdom Department of Energy, pp. 369-379, October 1988.

APPENDIX D

AGRICULTURAL SOURCES

D.1 Flooded Rice Cultivation

Recent work on global emissions of methane (CH_4) from flooded rice fields estimates that 60 to 170 Tg of CH_4 are emitted annually. This accounts for about 20 percent of the global CH_4 budget. These estimates incorporate very little available data on CH_4 fluxes from rice fields in Asia, an area from which little data have been available and where over 90 percent of the world's rice is produced. Until more measurements from Asia are available, CH_4 emissions from rice cultivation need to be regarded as highly uncertain.

Other estimates of CH_4 emissions from rice cultivation have been developed over the last twenty years, and it is useful to understand their particular limitations. Some of the earliest reported estimates are based on Koyama's measurements of CH_4 flux from laboratory cultures of rice paddy soil. Extrapolation of this data to other soils yielded a global estimate of 190 Tg per year of CH_4 from rice paddies. Revisions by Ehhalt (1974) and Ehhalt and Schmidt (1978) to account for increases in rice cropping area resulted in global estimates of 220 to 280 Tg/yr. Since methanogenesis is highly sensitive to environmental conditions it seems likely that these estimates which are based on laboratory experiments do not adequately reflect the wide array of situations found in the field.

The first set of emission estimates based on field measurements was provided by Cicerone and Shetter (1981) from work in a California rice paddy. Extrapolation of their results to a global scale yielded a much lower estimate of 59 Tg/yr of CH_4. Comprehensive field measurements in Spanish and California rice paddies by Seiler (1984) resulted in global estimates of 30 to 75 Tg/yr of CH_4. Somewhat higher global emission rates (70 to 170 Tg/yr) were found by Holzapfel-Pschorn and Seiler (1986) when using semi-continuous field measurements of fluxes from Italian rice paddies over a whole vegetation period. It is now believed that the lower rates observed in Spanish paddies may be due to the inflow of Mediterranean water containing sulfate which may suppress CH_4 formation. Recent measurements have also been made by Yagi and Minami (1990), Minami (1989), and Washida (1989) in Japan which may represent the extent of emissions from Japanese soils.

In general, estimates of global CH_4 fluxes from rice paddies have been based on measurements in temperate regions; however, more than 90 percent of the world's rice cropping area lies in the Far East where environmental conditions and agricultural management practices differ significantly. Little data are available on CH_4 emissions from these areas, but recent studies have been conducted in China by Seiler et al. (1989). These measurements yield a global estimate for emissions from paddies of 70-110 Tg of CH_4/year (mean of 90 Tg of CH_4/year). In addition, a 30 day study by Khalil et. al. (1989) at Tuzu in China measured local CH_4 fluxes in the range 2-240 $mg/m^2/hr$, much higher estimates than those observed by previous studies in Europe. In the absence of more comprehensive field studies from Asia, however, even the more recent estimates of global CH_4 emissions from rice must be regarded as uncertain.

Regardless of the current uncertainties, it is likely that global emissions of CH_4 from rice cultivation will increase as the total rice cropping area worldwide increases to meet the growing demand for rice. Based on projections of global population levels, it is estimated that the demand for rice will increase by 50% over the next 30 years, from 440 million tons in 1985 to 680 million tons by 2020. (Exhibit D-1 and Exhibit D-2). As 90 percent of rice production is from wetland rice (including irrigated, rainfed and deepwater rice), wetland rice production is likely to be expanded and intensified in rice growing areas. In addition, since constraints exist on the potential global land area available for cropping, it seems likely that the projected increases in rice production will also be met by shifts in rice production systems, e.g., conversion of rainfed rice lands to irrigated rice lands which are more productive and which may also emit more CH_4.

Part of the uncertainty in global estimates of CH_4 emissions from rice cultivation is due to the sensitivity of CH_4 flux patterns to environmental conditions. CH_4 is produced in flooded rice paddy soil by the anaerobic decomposition of organic matter. The CH_4-generating (methanogenic) bacteria involved are strict anaerobes and require highly reduced conditions for growth. Rice paddy soils, offering conditions of oxygen depletion, moisture, and high organic substrate levels present ideal environments for the proliferation of such methanogens. Recognized substrates metabolized by methanogenic bacteria include hydrogen reduction of CO_2, acetate, formate, methanol, methylated amines and CO (Cicerone and Oremland, 1988). The main pathways of CH_4 production using these substrates are presented in Exhibit D-3.

Field studies indicate that the major portion of the CH_4 released to the atmosphere (over 90 percent) is transported through the rice plants and that the escape of CH_4 by ebullition (bubbling) and diffusion through the water column is less significant. Furthermore, not all the CH_4 produced in paddy soils may be emitted to the atmosphere; for example, the

EXHIBIT D-1

Paddy Rice Requirements at 1985, 2020, 2100
(million tons)

	Scenario	**1985**	**2020**	**2100**
I.	Status Quo			
	a. Top 20 Rice Producers	400	620	790
	b. Rest of World	40	60	80
	c. Total	440	680	870
II.	Hunger Reduction by 15 percent			
	a. Top 20 Rice Producers	450	710	910
	b. Rest of World	50	70	90
		500	780	1,000

Source: IRRI, 1988.

EXHIBIT D-2

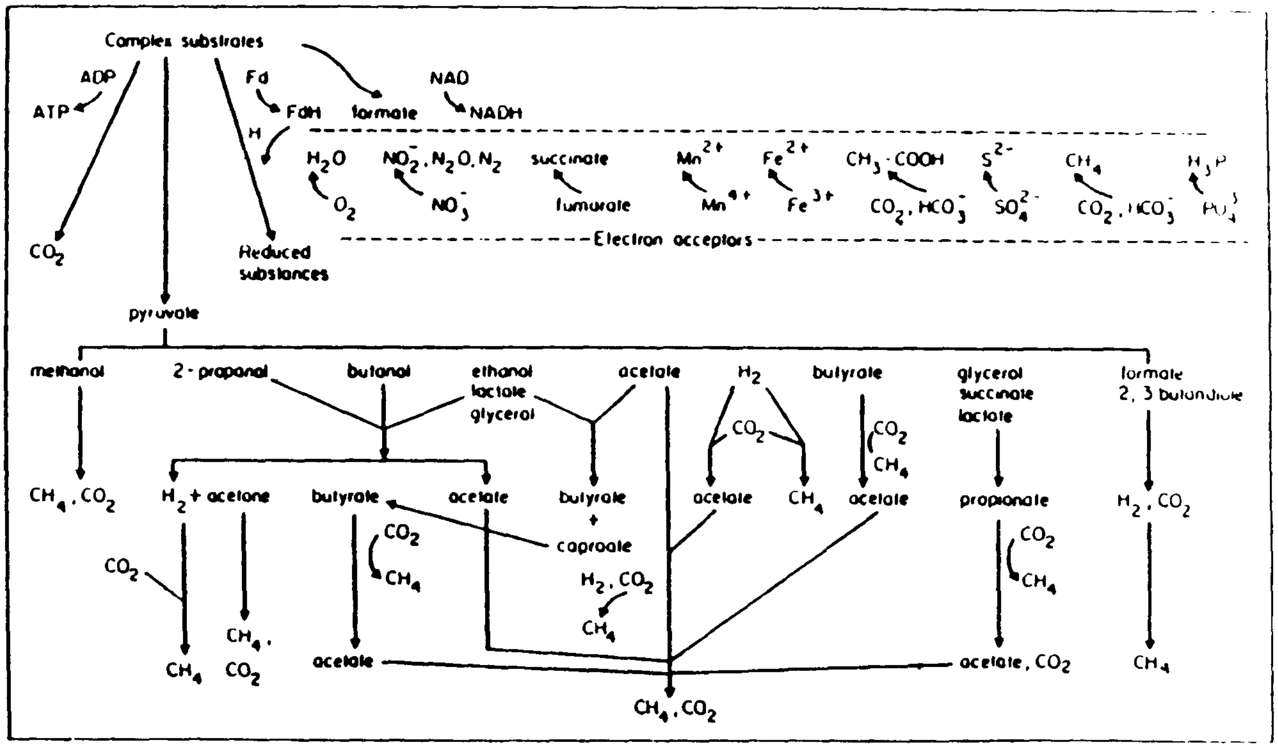
ACTUAL AND PROJECTED HARVESTED RICE AREA AND RICE PRODUCTION BY RICE ENVIRONMENT IN SOUTH AND SOUTH EAST ASIA

Environment	1980				2000			
	Area		Production		Area		Production	
	1000 ha	%	mt	%	1000 ha	%	mt	%
Irrigated	28,867	33	94.2	52	52,741	42	232.1	59
Shallow Rainfed	30,375	35	54.7	30	39,905	32	104.6	27
Medium Deep Rainfed	11,587	13	16.2	9	13,114	11	30.8	8
Tidal Wetland	5,290	6	5.3	3	6,046	5	9.1	2
Upland	11,593	13	11.6	6	12,793	10	18.0	5
Total	87,712	100	182.0	100	124,599	100	394.5	100

Source: IRRI, 1988.

EXHIBIT D-3

PATHWAYS FOR CH_4 PRODUCTION



Source: Neue and Sharpenseel (1984)

consumption of CH_4 by CH_4 oxidizing bacteria that exist in the aerobic zones of the paddy soil environment may significantly limit CH_4 fluxes.

Since methanogenesis is a biological process, any factors influencing the physical, chemical or biological characteristics of the rice paddy environment will influence CH_4 production and emission. Factors affecting CH_4 fluxes from rice paddies include soil temperature, redox (oxidation-reduction) potential, supply of organic matter to the methanogenic bacteria and the introduction of chemicals (e.g., fertilizer) into the soil. Variations in local agricultural management practices (such as the use of organic or mineral fertilizer, incorporation of crop residues, and different water management systems) can result in widely different paddy soil environments and hence significantly affect the CH_4 flux patterns. These factors are outlined in detail below.

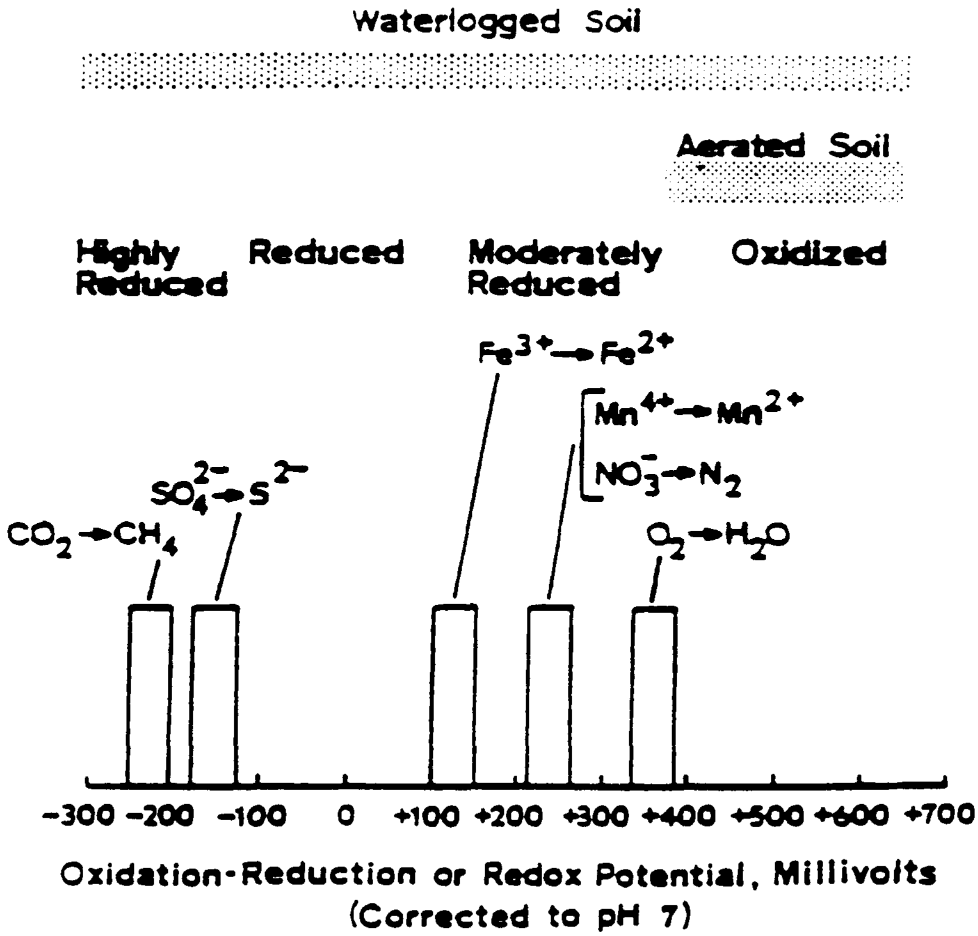
Soil Temperature. Temperature is known to play an important role in the rate of activity of soil microorganisms. Holzapfel-Pschorn and Seiler (1986) report a doubling of CH_4 emissions from rice paddies for a soil temperature increase from 20°C to 25°C. Most methanogenic bacteria display optimum rates of production around 30°C (Neue and Scharpenseel, 1984). Flooding provides a good environment for CH_4 production as it produces high temperatures in the rice paddy soil, typically in the range 25°C to 35°C.

Redox Potential. It has been shown that methanogenic bacteria can only function at redox potential levels below -200 mV and that a correlation exists between CH_4 emissions and soil redox potential. When rice paddy soil is flooded, the following processes ensue; depletion of O_2, reduction of nitrate, reduction of Mn^{4+} and Fe^{3+}, and finally reduction of sulfate and methanogenesis. If sufficient organic matter is available, the low redox potentials necessary for methanogenesis may be achieved. Waterlogged paddy soils often display the redox range (<-200 mV) required for CH_4 production (Exhibit D-4).

Soil pH. Methanogenesis is favored by a neutral (pH=7) or slightly above neutral pH with the exact optimum pH influenced by the type of soil (Minami 1989). Flooding acts to stabilize the soil pH value around neutrality (i.e., increase it for acid soils and decrease it for alkaline soils).

Substrate and Nutrient Availability. The availability of oxidizable substrate may have an effect on the pattern of CH_4 emissions. Seiler et al. (1984) report seasonal peaks in CH_4 fluxes from paddy soils that may correspond to increases in soil organic matter content; i.e., peak emissions were observed following the incorporation of crop residues prior to flooding,

EXHIBIT D-4



The critical redox potential at which oxidized inorganic redox systems begin to undergo reduction in flooded soils.

Source: W. Patrick (1989)

and following the release of organic matter, in the form of root exudates and root litter, at the heading and flowering stages of the rice plants.

CH_4 Oxidation. The action of CH_4 oxidizing bacteria (methanotrophs) is important in limiting the flux of CH_4 to the atmosphere. CH_4 can be oxidized by both aerobic and anaerobic bacteria; the processes involved in aerobic oxidization are better understood, and these bacteria can be found in rice paddies at the narrow oxidized floodwater-soil interface. Seiler and Conrad (1981) estimate a global CH_4 consumption rate by methanotrophs of 31 ± 16 Tg/year, and Holzapfel-Pschorn et al. (1986) report that 67 percent of the CH_4 produced during a rice growing season was oxidized and only 23 percent escaped to the atmosphere.

Plants and CH_4 Transport. The rice plants themselves are the major conduits for CH_4 transport to the atmosphere. Holzpfel-Pschorn et al. (1986) report that emissions via the plant constitute more than 90 percent of the total emissions (the remaining emissions escaping by ebullition and diffusion through the water column), and note that the flux rate is controlled by the rate of CH_4 production in the soil and is not curtailed by limitations of the diffusion processes from the soil into the root system or through the aerenchyma of the plant. The emissions from fields without rice plants are reported to be about 50 percent of those with plants and the emissions are almost exclusively due to ebullition (Schutz et al. 1989).

Water Depth. The depth of the paddy soil water may also affect the CH_4 flux; Sebacher et al. (1986) report that increases in floodwater depths up to 10 cm cause increased CH_4 emissions but further increases decrease the emissions.

Rice Production System. Flooded rice paddies produce CH_4; dry upland rice does not. About 87 percent of the rice cropping area worldwide consists of various forms of wetland rice (e.g., irrigated, rainfed, deep-water), (Dalyrymple 1986). The floodwater depth and the length of the flooding period are both believed to affect CH_4 emissions (Sebacher et al. 1986).

Application of Organic Matter. The nature, volume and mode of application of organic matter to rice paddy soil is known to affect CH_4 production; studies indicate that organic matter application enhances emissions (Delwiche 1988, Minami 1989, and Washida 1989). In addition, more information is needed on emissions patterns in Asia where organic fertilizer (as opposed to mineral fertilizer) is predominantly used in rice cultivation; information is also needed on the effect of such practices as the incorporation of crop residues (e.g., rice-straw) into the paddy soil.

Application of Mineral Fertilizer. Due to the nature of the reduction sequence in flooded soils, the addition of chemicals such as nitrate or sulfate may suppress CH_4 production. Since the reduction of these chemicals takes place at potential levels above that required for methanogenesis, the methanogenic bacteria cannot function until nitrate and sulfate reductions are complete and the redox potential has fallen below -200mV. In addition, the presence of sulfate may inhibit CH_4 production due to competition for substrates between the sulfate reducing bacteria and methanogens, and due to the possibility that CH_4 is oxidized to CO_2 by the sulfate reducing bacteria (see Yagi and Minami 1989 and Bouwman 1989).

Early studies indicated an increase in CH_4 emissions following the application of mineral fertilizer (Cicerone and Shetter 1981). However, Yagi and Minami (1989) found a short but profound decline in methane emissions following mineral amendments. Other recent work indicates that the relationship between CH_4 flux and mineral fertilizer is a complex one depending on rate and mode of application (e.g., incorporation vs. surface application), (Schutz et al. 1989). In particular, the effects of nitrate and sulfate in raising the soil redox potential and possibly suppressing methanogenesis need to be further investigated. It should also be noted that the processes of nitrification and denitrification in soils fertilized with nitrogen fertilizer lead to the evolution of the greenhouse gas, nitrous oxide.

High Yield Plant Varieties. The Green Revolution of the 1960's resulted in high yield varieties with shorter growing seasons that have helped to reduce the volume of CH_4 produced per unit of rice. The shorter growing season, however, allows multiple plantings, thus increased adoption of such varieties may cause an increase in total CH_4 emissions.

Options for Reducing Emissions

Due to the importance of rice as a food staple, it is necessary to develop emission reductions options that also maintain the productivity of the rice paddies. It is believed that this can be accomplished through a comprehensive approach including better water management, efficient use of fertilizers, selection of cultivars, and other management practices, and that emissions can by reduced by 10 to 30 percent.

A great deal of additional information is needed on CH_4 emissions from rice paddies in order to develop reliable options for stabilizing or reducing atmospheric CH_4 concentrations. Improved understanding of the processes contributing to CH_4 emissions from flooded rice fields can only be achieved by integrated, interdisciplinary projects which focus on process related factors and which will allow for valid extrapolation. Research is needed on the following aspects:

- biogeochemistry of methanogenesis in flooded rice fields including CH_4 production, CH_4 oxidation, and methanogenesis regulating factors;
- factors affecting CH_4 fluxes from flooded rice fields such as climate, soil and water, cultivars, fertilizer application, and cultural practices;
- variations in CH_4 fluxes between sites, seasonally, and diurnally;
- effects of techniques to reduce CH_4 emissions on emissions of nitrous oxide; and
- field level measurement techniques to assess spatial variability and simulation models to synthesize the process and field level data.

Technologies and practices for reducing emissions from flooded rice fields need to be developed, demonstrated and assessed, including an evaluation of the costs and benefits. To realize the full potential of the research, existing and possible agricultural policies regarding rice production need to be examined. This includes alternative economic policies such as subsidies, taxes, pricing and trade barriers; cultural practices; technology transfer measures; education and information programs; and international financial assistance measures.

D.2 Managed Livestock

<u>Emissions</u>

Among livestock, ruminant animals produce significant quantities of CH_4 as part of their normal digestive processes. The rumen, a large fore-stomach, provides the opportunity for CH_4 to be created within the animal. Within the rumen over 200 species and types of microorganisms have been identified, although a smaller number (10 to 20 species) are thought to play an important role in rumen digestive processes (Baldwin and Allison, 1983). Rumen methanogenic bacteria are the source of CH_4 produced within ruminant animals.

Rumen methanogenic bacteria are generally a very small fraction of the total population of microorganisms in the rumen. Although they can convert acetate (a fermentation product produced in the rumen) to CH_4 and carbon dioxide (CO_2), this pathway for CH_4 production in the rumen is believed to be of minor importance in animals fed adequate and balanced diets (Baldwin and Allison, 1983). Instead, the conversion of hydrogen (H_2) or formate and CO_2 (produced by fermentative bacteria) is believed to be the primary mechanism by which methanogenic bacteria produce CH_4 in ruminants.

The creation of CH_4 in the rumen represents energy which is subsequently not available to the host animal for maintenance or growth. Methods of reducing CH_4 creation in ruminants have been investigated as part of an overall attempt to improve the efficiency of rumen metabolism. CH_4 creating bacteria, however, play an important role in the complex ecology of the rumen so that simply eliminating or suppressing them will not "free up" energy that can be used by the animal.

Because the creation of CH_4 within the rumen is part of the partitioning of energy within the animal, CH_4 emissions from ruminant animals have been estimated for purposes of understanding the utilization of energy by ruminant animals. Various authors have summarized these measurements of CH_4 emissions from individual ruminant animals.[4] The rate of CH_4 creation can be described in terms of a "CH_4 yield," which is the energy content of the CH_4 produced as a percentage of the food energy intake of the animal.

A system for describing the food energy intake of ruminant animals has been developed and is summarized in Exhibit D-5. As shown in Exhibit D-5, on a "whole-animal basis," the manner in which the energy intake of an animal is utilized can be defined as follows:

- <u>gross energy</u> is the total energy intake by the animal where the energy content of the feed is defined as the total energy it releases when it is burned;
- <u>digestible energy</u> is the gross energy intake minus the energy eliminated in feces;
- <u>metabolizable energy</u> is the digestible energy minus the energy eliminated in urine and CH_4; and
- <u>net energy</u> is the metabolizable energy minus the heat produced by the animal. Net energy is the energy available to the animal for maintenance and growth.

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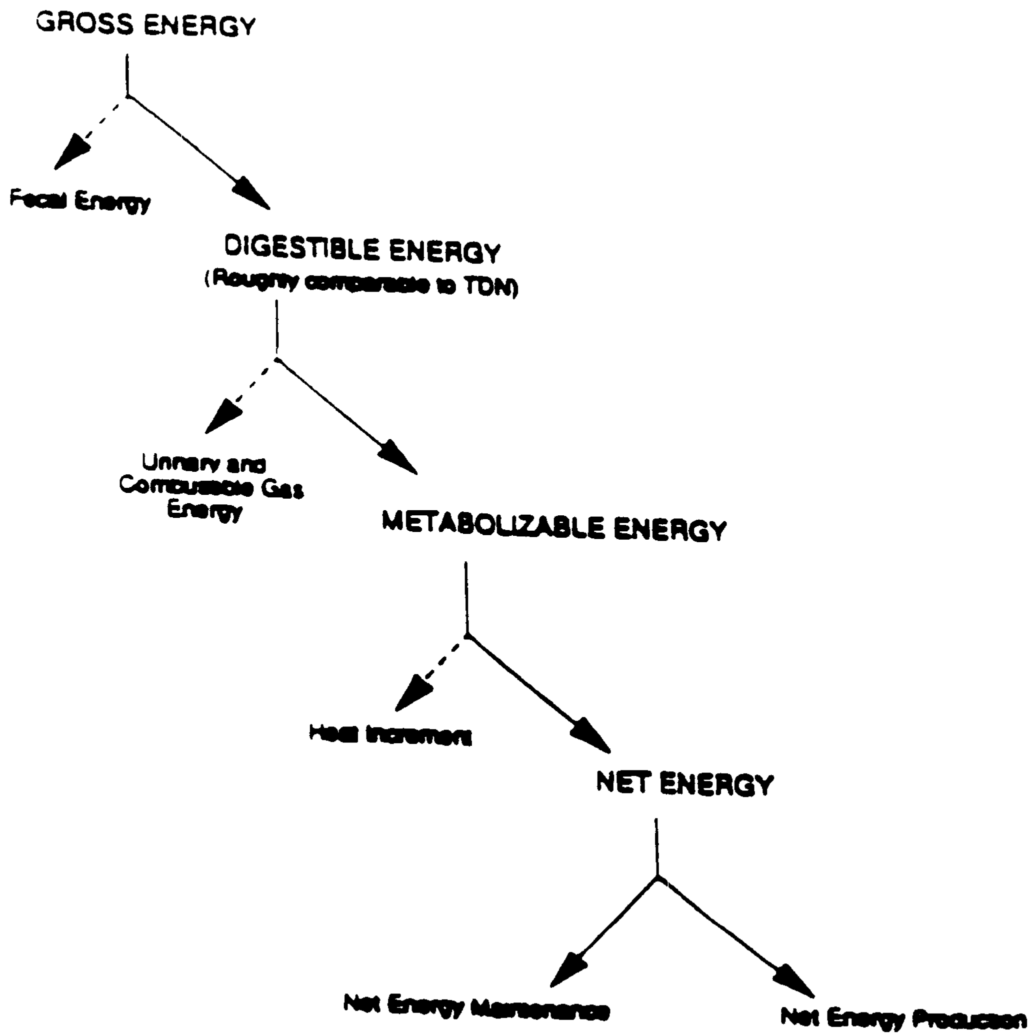
[4] See, for example, Blaxter and Clapperton (1965) and Moe and Tyrrell (1979).

EXHIBIT D-5

ENERGY UTILIZATION IN RUMINANT ANIMALS



Source: Ensminger, M.E., The Stockman's Handbook, The Interstate Printers & Publishers, Inc.: Danville, Illinois, 1983, p. 245.

CH_4 yield can be expressed as the CH_4 created as a percentage of any of these energy quantities. Some previous estimates express the CH_4 yield as a percentage of the gross energy consumed, although there are indications that expressing the CH_4 yield as a percentage of the digestible energy consumed may be preferred. Most published CH_4 yield estimates for ruminants fall in the range of 4 to 9 percent of gross energy intake.

Using an estimate of the CH_4 yield for an animal, its total annual CH_4 emissions can be estimated by multiplying its relevant annual energy intake by the appropriate percentage (e.g. 6 percent) and then converting the energy value (e.g. in megajoules or MJ) to a mass basis (e.g. kilograms). For example, if a cow consumes 60,000 MJ per year in gross energy and has a CH_4 yield of 6 percent of gross energy, then total CH_4 emissions would be equal to 3,600 MJ, or about 65 kilograms.[5]

Crutzen et al. (1986) have performed the most comprehensive assessment of CH_4 emissions from ruminant animals to date and estimate CH_4 emissions of 71 Tg/yr from ruminant animals. Exhibit D-6 lists their estimates. Various deficiencies in these estimates have been identified, particularly relating to the emissions estimates from animals grazing on poor quality forages and fed poor quality crop residues. Actual emissions from animals in these situations may be much lower or higher. Additionally, some have pointed out that the estimates by Crutzen et al. do not reflect variations associated with different stages of animal growth and development.

Analyses that would be useful for improving the estimates of CH_4 emissions from livestock include:

- Characterize the animal population. The manner in which an animal population is managed and the type of feed they consume influences the overall level of CH_4 emissions. Data are required that describe the management of animals along dimensions that influence CH_4 emissions. These analyses should focus on those populations of animals that are good candidates for emissions reduction.

- CH_4 yields associated with poor quality forages and crop residues. Little data are available to describe the CH_4 yields associated with animals consuming poor

[5] Of note is that the methane yield varies with the quantity and quality of food energy consumed. Because feed consumption by ruminant animals often varies throughout the year, it will likely be preferred to estimate feed intakes and methane emissions at least seasonally.

EXHIBIT D-6

GLOBAL METHANE EMISSIONS FROM RUMINANT ANIMALS

Animal	Methane Emission per animal (kg/yr)	Total annual emissions (Tg)*
Cattle in developed countries	55	31.5
Cattle in developing countries	35	22.8
Sheep in developed countries	8	3.2
Sheep in developing countries	5	3.7
Buffalo	50	6.2
Goats	5	2.4
Camels	58	1.0
TOTAL		71.0

* 1 Tg = 10^{12} grams

Source: Crutzen, P.J., I. Aselmann, and W. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," Tellus, 38B, 1986, pp. 271-284.

quality feeds. The number of animals in this situation (at least part of the year) is large, including many of the world's grazing animals (e.g., in parts of North America, Africa, and Australia) and many animals fed crop residues in Asia. Measurements of CH_4 emissions from these animals under realistic field conditions are needed.

The data developed under these analyses could then be used in a model of animal and waste management practices to improve the estimates of CH_4 emissions.

To develop these data needed to improve estimates of CH_4 emissions, techniques for taking field measurements of CH_4 emissions from livestock need to be developed and implemented. These measurements will not only provide better estimates of current emissions but will also validate the effectiveness of emissions reductions techniques.

Indirect calorimetry is the laboratory technique currently used to measure CH_4 emissions from animals. The method involves placing an animal in confinement for a period of several days, and measuring the amount of inputs (feed, oxygen, carbon dioxide, water) and outputs (feces, CH_4, heat) from the chamber. Field techniques are required as companions to calorimetry that can be implemented under field conditions and for grazing animals.

Emissions Reductions

While many uncertainties exist, it appears that there are a number of technologies that can potentially reduce methane emissions from livestock systems by 25 to 75 percent per unit of product. The reductions that are achieved depend upon how effectively interventions are deployed and how interventions affect the supply and demand for livestock products.[6]

Potential options for reducing CH_4 emissions should be evaluated in terms of:

- **Time frame:** the period when the option may become viable (near term vs long term).
- Applicability: the categories of animals for which the option may be used to reduce emissions (e.g. dairy cows in India).

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[6] Interventions could potentially lead to an increase in methane emissions by increasing the consumption of livestock products.

- Emissions reduction: the extent to which emissions are reduced.

- Impact on animal productivity: the manner in which implementing the option would affect production of animal products.

- Costs: the cost of implementing the option.

- Implementation: methods of implementing the option, including any special challenges posed, such as social constraints.

Some of the promising options for reducing emissions include:

Strategic supplementation of extensively managed cattle. Large numbers of cattle consume forages of variable quality, particularly seasonally, under grazing conditions. These diets may be deficient in certain vital nutrients (e.g. nitrogen) that hinder animal productivity and reproductive efficiency. Supplementing the diets of these animals (through range enhancement or bolus) can reduce the amount of CH_4 produced by providing a better balance in the rumen and by increasing the efficiency and productivity of the animal (thereby reducing the size of the animal population necessary to produce a given level of products).

Diet modifications for intensively managed animals. Experimental data from whole animal calorimetry experiments demonstrate that CH_4 emissions vary under different diets. Both increasing the intake of the animals and modifying the composition of the diet can reduce CH_4 emissions per unit of product produced (e.g., per kilogram of meat produced). Other feed inputs also appear to have promising impacts on CH_4 emissions levels (e.g., whole cotton seeds or polyunsaturated fats). Modifying feeding practices toward low-methane rations could potentially reduce CH_4 emissions by large amounts in certain circumstances.

Use of bST of other agents to increase production per cow. The use of bST or productivity enhancement agents reduces CH_4 emissions per unit of product produced by increasing the productivity of the animal. For example, bST would reduce CH_4 emissions per amount of milk produced by:

- further diluting the maintenance requirements of individual lactating cows (resulting in a 3 to 5 percent reduction in CH_4 emissions per amount of milk produced); and

- reducing (by about 15 percent) the size of the herd necessary to support the lactating cows (i.e., dry cows and growing heifers).

Economic evaluations indicate that the use of bST can be economic in its own right. Similar analyses of other productivity enhancing agents should also be performed.

Strategic supplementation of ruminants fed crop residues and byproducts to correct nutrient deficiencies. Large numbers of cattle and buffalo are fed crop residues and byproducts. In many areas, these feeds may be lacking in certain vital nutrients (e.g. nitrogen), inhibiting digestive efficiency and productivity. Research and practice in India has shown that supplementing the diets of these animals with locally produced supplements dramatically improves rumen performance and animal productivity. These supplements reduce CH_4 emissions per amount of product produced by:

- balancing the fermentation patterns in the rumen so that the CH_4 yield (the amount of CH_4 produced per amount of feed consumed) is reduced;
- increasing the reproductive efficiency of the animals so that the maintenance requirements of the breeding herd are diluted significantly;
- increasing the milk yields per cow so that the maintenance requirements of the individual lactating cows are diluted significantly; and
- reducing the time required to reach maturity for individual animals (particularly cows) so that they spend a larger portion of their lives in a productive mode.

Large reductions in CH_4 emissions per amount of product produced appear to be achievable with the supplementation strategies currently being adopted in India. The feasibility and benefits of implementing these strategies in additional locations should be assessed.

Improve reproductive efficiency to reduce brood herd requirements. Increasing the reproductive efficiency of animals will reduce CH_4 emissions by reducing the size of the brood herd needed to sustain a given population of animals.

Alter microbial conditions in the rumen. CH_4 emissions may be reduced by balancing the microbiological processes in the rumen so that maximum efficiency is achieved. Techniques for achieving this balance included better feeds, feed combinations, feed treatments and bio-engineering. Options for promoting propionate production in the rumen and/or defaunating the rumen should also be explored.

These various opportunities for reducing CH_4 emissions from animals must be evaluated under field conditions to document the impact that they will have on CH_4 emissions.

D.3 Biomass Burning

Emissions

CH_4 is produced by incomplete combustion during biomass burning. The amount of CH_4 produced depends on the material burned and the degree of combustion. Estimates range from 50 to 100 Tg of CH_4 annually (Cicerone and Oremland, 1988). This represents 10 to 20 percent of total annual CH_4 emissions. While a few studies have attempted to understand and measure CH_4 emissions from biomass burning (Crutzen et al., 1979, 1985), extrapolation to a global estimate is difficult because of the lack of global data on area burned, fire frequency, and characteristics of fires.

Biomass is burned to convert forest and savannah ecosystems into agricultural or pasture land, to return nutrients to the soil, to reduce shrubs on rotational fallow lands, or to remove crop residues. In all instances associated with biomass burning, emissions of greenhouse gases are not well estimated and no consistent measurement techniques are now in use. Furthermore, no estimates have separated temperate from tropical sources. Currently, agricultural burning, due to shifting agriculture and burning of agricultural wastes, is estimated to account for over 50 percent of the biomass burned annually. The feasibility of monitoring fires from space will improve these estimates significantly.

Emissions Reductions

Biomass burning can be reduced through fire management programs and widespread use of alternative agricultural practices. Agricultural systems traditionally dependent on the removal of biomass by burning (i.e., long-term shrub-fallow systems and high-yield grain crops) may be modified to incorporate the biomass directly into the soil, thereby improving soil organic matter, in addition to reducing emissions from burning, or removal for use as an alternative fuel source.

Conversion of forest land to agricultural land may be reduced by adopting sustainable agricultural practices which optimize yields, or adopting intensive practices on suitable agricultural soils. Emissions from burning crop residues and the routine burning of savannahs may be reduced though stable agriculture, including use of chemical and organic amendments, and improved forage species and management systems.

Policy options developed to reduce methane emissions from biomass burning must have value to the farmer beyond the greenhouse gas-reducing benefits. Policies must not hamper national food security goals and should have value to the nation in reducing net costs of competition on the world market. The pressure to convert forest land to crop and pasture land needs to be reduced, in turn reducing emissions from burning, soil exposure and erosion. Increasing the productivity of croplands on suitable soils using appropriate, intensive systems will have that effect. Reclaiming and restoring degraded agricultural lands should also be explored, in addition to enhancing the indigenous uses of native forests and establishing forest cropping systems to reduce the demand for further deforestation.

Education programs which teach improved organic-residue management, and provide an understanding about the consequences of soil degradation, need to be developed and proliferated.

Collaborative research among scientists in developed and developing countries is needed to assure consideration of regional and local physical and cultural factors, with special focus on carbon and nitrogen cycling, burning practices and soils. In addition, research is required in the following areas:

- Remote-sensing and monitoring methodology development is needed to evaluate the effects of policies to reduce these practices.

- Better estimates are needed on amounts of biomass burned annually, instantaneous emissions from the fire front and longer-term biogenic emissions from a burn.

- Improved efficiency of technologies and devices for broadcast burning, charcoaling and use of fuel wood for heating and cooking. These devices and technologies need to be practical and affordable to indigenous populations.

- Appropriate tree species for agro-forestry by sites and regions, and the effects of these trees on soils and cropping systems.

- Potential sinks for greenhouse gases in agricultural systems of the tropics and the interactions between sources and sinks. Long-term studies are needed to quantify the effects of different agricultural management systems on these sinks and especially on soil properties.

D.4 References

Baldwin, R.L. and M.J. Allison (1983), "Rumen Metabolism," Journal of Animal Science, Vol. 57, pp. 461-477.

Blaxter, K.L. and J.L. Clapperton (1965), "Prediction of the Amount of Methane Produced by Ruminants," British Journal of Nutrition, Vol. 19, pp. 511-522.

Bouwman, L. (1989), Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

Cicerone, R.J. and R.S. Oremland (1988), "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, Vol. 2, No. 4, 299-327, December.

Cicerone, Ralph J. and J.D. Shetter (1981), "Sources of Atmospheric Methane: Measurements in Rice Paddies and a Discussion," Journal of Geophysical Research, Vol. 86, pp. 7203-7209.

Crutzen, P.J., L.E. Heidt, J.P. Krasnec, W.H. Pollock, and W. Seiler (1979), "Biomass Burning as a Source of Atmospheric Gases CO,H2, N20, NO, Ch3Cl, and COS,: Nature, Vol. 282, pp.253-256.

Crutzen, P.J., I. Aselmann and W. Seiler (1986), "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," Tellus, 38B, pp. 271-284.

Dalrymple, D. (1986), "Development and Spread of High-yielding Rice Varieties in Developing Countries," Bureau for Science and Technology, Agency for International Development, Washington, D.C.

Delwiche, C. (1988), "Methane Emission Rates," Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, D.C., February 29-March 1.

Ehhalt, D.H. (1974), "The Atmospheric Cycle of Methane," Tellus, Vol. 26, pp. 58-70.

Ehhalt, D.H. and U. Schmidt (1978), "Sources and Sinks of Atmospheric Methane," Pageoph., vol. 116, p. 452-464.

Ensminger, M.E. (1983), The Stockman's Handbook, The Interstate Printers & Publishers, Inc.: Danville, Illinois.

Holzapfel-Pschorn, A. and W. Seiler (1986), "Methane Emission During a Cultivation Period From an Italian Rice Paddy," Journal of Geophysical Research, 91, pp. 11803-11814.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler (1986), "Effects of Vegetation on the Emission of Methane from Submerged Rice Paddy Soil," Plant and Soil, Vol. 92, pp. 223-233.

IRRI (1988), World Rice Statistics, 1987, The International Rice Research Institute, Los Banos, Philippines.

Khalil, M.A.K., R.A. Rasmussen, and M.X. Wang (1989), as presented by M.R. Riches, "Flux of Methane from Rice Paddies in China," Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

Minami, K. (1989), "Effects of Agricultural Management on Methane Emissions from Rice Paddies," Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

Neue, H.U. and W.W. Scharpenseel (1984), Gaseous products of decomposition of organic matter in submerged soils, In: Organic Matter and Rice, International Rice Research Institute, Los Banos, Philippines, pp. 311-328.

Moe, P.W. and H.F. Tyrrell (1979), "Methane Production in Dairy Cows," Journal of Dairy Science, Vol 62, pp. 1583-1586.

Schutz, H., A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg, and W. Seiler (1989), "A Three Year Continuous Record on the Influence of Daytime, Season and Fertilizer Treatment on Methane Emissin Rates from an Italian Rice Paddy Field," Journal of Geophysical Research.

Sebacher, D.I., R.C. Harriss, K.B. Bartlett, S.M. Sebacher, and S.S. Grice (1986), "Atmospheric Methane Sources: Alaskan Tundra Bogs, an Alpine Fen, and a Subarctic Boreal Marsh," Tellus, Vol. 38B, p. 1-10.

Seiler, W. (1984), "Contribution of Biological Processes to the Global Budget of CH_4 in the Atmosphere." In: Klug and C. Reddy (eds.), Current Perspectives in Microbial Ecology, M. American Society for Microbiology, Washington, D.C. pp. 468-477.

Seiler W., A. Holzapfel-Pschorn, R. Conrad, and D. Scharffe (1984), "Methane Emissions from Rice Paddies," Journal of Atmospheric Chemistry, Vol. 1, pp. 241-268.

Seiler W. and R. Conrad (1981), "Contribution of Tropical Ecosystems to the Global Budgets of Trace Gases, Especially CH_4, H_2, CO and N_2O," In: R.E. Dickinson (Ed.), Geophysiology of Amazonia, Vegetation and Climate Interactions, Wiley and Sons, New York, pp. 133-160.

Seiler, W. (1989), "Role of Rice Cultivation in Global Emissions of Trace Gases," Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

Washida, N. (1989), "Methane Measurements and Alternative Management Practices: Recent Work in Japan II," Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems of the IPCC Response Strategies Working Group, December 12-14.

Yagi, K. and K. Minami (1990), "Effects of Organic Matter Applications on CH_4 Emissions from Japanese Paddy Fields," Soils and the Greenhouse Effect, A.F. Bouwman (ed.), John Wiley & Sons, New York, pp. 467-473.

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