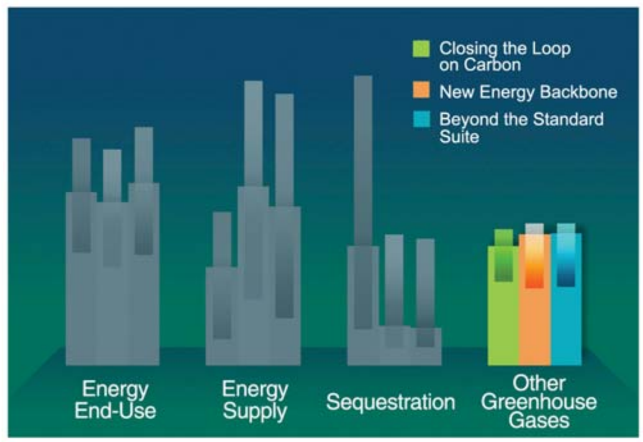
Reducing Emissions of Non-CO_2 Greenhouse Gases

Several gases other than carbon dioxide (CO_2) are known to have greenhouse gas (GHG) warming effects. When concentrated in the Earth's atmosphere, these "non-CO_2" GHGs can contribute to climate change. The more significant of these are methane (CH_4), which can arise from natural gas production, transportation and distribution systems, bio-degradation of waste in landfills, coal mining, and agricultural production; nitrous oxide (N_2O) from industrial and agricultural activities; and certain fluorine-containing substances, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) from industrial sources (Box 7-1).

The Intergovernmental Panel on Climate Change's (IPCC) *Third Assessment Report* (IPCC 2001) states that "well-mixed" non-CO_2 gases, including methane, nitrous oxide, chlorofluorocarbons, and other gases with high global warming potentials (GWPs) may be responsible for as much as 40 percent of the estimated increase in radiative climate forcing between the years 1750 and 2000.[1] In addition, emissions of black carbon (soot), organic carbon and other aerosols, as well as tropospheric ozone and ozone precursors, have important effects on the Earth's overall energy balance.

Developing technologies for commercial readiness that can reduce emissions of these non-CO_2 GHGs



Other Greenhouse Gases Potential Contributions to Emissions Reduction

Potential contributions of Other Greenhouse Gases to cumulative GHG emissions reductions to 2100, across a range of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

BOX 7-1

WHAT ARE THE "OTHER" GHGs?

The term "non-CO_2 GHGs" covers a broad category of gases and aerosols, but usually refers to methane, nitrous oxide, and the high global warming potential (GWP) gases hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Tropospheric ozone, tropospheric ozone precursors, and black carbon (soot) also have important climatic effects. Of these, only ozone is a GHG. Chlorofluorocarbons (CFCs) and other related chemicals contribute to both global warming and stratospheric ozone depletion. Because these chemicals are already being phased out under the Montreal Protocol, they are not addressed in this plan. To streamline terminology for purposes of readability, and unless otherwise noted, the terms "non-CO_2 GHGs" and "other GHGs", include methane, nitrous oxide, high-GWP gases, tropospheric ozone, tropospheric ozone precursors, and black and organic carbon aerosols.

[1] The radiative forcing due to increases in the well-mixed GHGs between the years 1750 and 2000 is estimated to be 2.43 Wm-2: 1.46 Wm-2 from CO_2; 0.48 Wm-2 from CH_4; 0.34 Wm-2 from the halocarbons (CFC and HCFC); and 0.15 Wm-2 from N_2O.

is an important component of a comprehensive strategy to address concerns about climate change. A recent modeling study (Placet et al. 2004) showed that there is a considerable amount of uncertainty about future rate of growth of non-CO_2 emissions, but most models project that emissions will increase over time in the absence of constraints (see Chapter 3). One set of scenarios that included a wide range of advanced technologies[2] for reducing emissions of non-CO_2 gases showed that emissions could potentially be reduced by a range of between 125 and 160 gigatons (Gt) of carbon-equivalent emissions (cumulatively) over a 100-year planning horizon, as shown in Figure 3-19 and highlighted on the figure above. Although bracketed by a range of uncertainties, this figure suggests both the potential role for advanced technology and a long-term goal for contributions from other GHGs in the future global economy.

In the context of global warming, emissions of the non-CO_2 GHGs are usually converted to a common and roughly comparable measure of the "equivalent CO_2 emissions." This conversion is performed based on physical emissions, weighted by each gas' global warming potential (GWP). The GWP is the relative ability of a gas to trap heat in the atmosphere over a given timeframe, compared to the CO_2 reference gas (per unit weight). GWP values allow for a comparison of the impacts of emissions and reductions of different gases, although they typically have an uncertainty of ±35 percent (EPA 2005). The choice of timeframe is significant and can change relative GWPs by orders of magnitude. All non-CO_2 gases are compared to CO_2, which has a GWP of one. The GWPs of other GHGs, using a 100-year time horizon, range from 23 for methane to 22,200 for SF_6, as shown in Box 7-2.

BOX 7-2

GLOBAL WARMING POTENTIALS OF SELECTED GHGs (100-Year Time Horizon)

GAS	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296
Hydrofluorocarbons:	
HFC-23	12000
HFC-125	3400
HFC-134a	1300
HFC-143a	4300
HFC-152a	120
HFC-227ea	3500
HFC-236fa	9400
HFC-43-10mee	1500
Fully Fluorinated Species:	
CF_4	5700
C_2F_6	11900
C_4F_{10}	8600
C_6F_{14}	9000
SF_6	22200

(Source: IPCC 2001)

Non-CO_2 gases have different GWPs due to differences in atmospheric lifetimes and effectiveness in trapping heat. Methane and some HFCs have relatively short atmospheric lifetimes as compared to other non-CO_2 gases. Thus, emissions reductions among these gases manifest themselves as lower atmospheric concentrations in a matter of a few decades. PFCs and SF_6, in contrast, can remain in the atmosphere for thousands of years. Emissions of these GHGs essentially become permanent additions to the Earth's atmosphere, with concomitant increases in the atmosphere's ability to capture and retain radiant heat. Finally, tropospheric ozone and black carbon aerosols (soot) are very short-lived in the atmosphere (i.e., remaining airborne for a period of days to weeks) and therefore do not become well-mixed in the atmosphere. Primarily for this reason, GWP metrics have not been assigned to these gases and aerosols, but they are nonetheless recognized as significant contributors to climate change.

There is a strong record of successful collaboration between industry and government to reduce emissions of non-CO_2 gases, and these partnerships provide a solid foundation from which to pursue additional technological developments and more substantial future emission reductions. Some highlights of the current activities include:

- Industry and the U.S. Environmental Protection Agency (EPA) have developed nine successful public/private partnerships to reduce emissions of methane and high-GWP gases.[3] These programs have led to substantial emission reductions; with U.S. methane emissions in 2003 10 percent below

2 The technologies discussed in this chapter were included in this set of scenarios.

3 The Landfill Methane Outreach Program, Natural Gas STAR Program, AgSTAR Program, Coalbed Methane Outreach Program, SF_6 Emission Reduction Partnership for Electric Power Systems, Voluntary Aluminum Industrial Partnership, SF_6 Emission Reduction Partnership for the Magnesium Industry, PFC Reduction/Climate Partnership with the Semiconductor Industry, and HCFC-22 Partnership Program.

BOX 7-3

The United States is collaborating with 17 countries (Argentina, Australia, Brazil, Canada, China, Colombia, Ecuador, Germany, India, Italy, Japan, Mexico, Nigeria, Russia, South Korea, Ukraine, and the United Kingdom) and over 220 organizations from the private sector, financial community, and other governmental and non-governmental institutions to undertake activities to capture and use methane at landfills, coal mines, oil and gas systems, and agricultural operations.

The United States is committing up to $53 million over the next five years to facilitate the development and implementation of methane projects in developing countries and countries with economies in transition. EPA plays a lead role in the partnership and coordinates efforts with several other departments, including the Departments of State and Energy, the U.S. Trade and Development Agency and the U.S. Agency for International Development. See http://www.methanetomarkets.org.

1990 levels and emissions of many sources of high-GWP gases also declining (EPA 2005). They also provide excellent forums for transferring technical information in an efficient and cost-effective manner. The partnership programs host or participate in annual technical conferences with the respective industries. Public-private partnerships help facilitate effective use of the technologies that are or will soon become available.

- The Federal Government is currently addressing agricultural sources of methane and nitrous oxide through a combination of voluntary partnerships and research, development, and demonstration (RD&D) efforts. Cooperative efforts between Government and the agriculture industry are needed to evaluate and develop technologies for lowering N_2O emissions from soils and methane emissions from livestock enteric fermentation.

- The U.S. Department of Energy (DOE) and EPA have teamed to co-fund the development of the first ventilation air methane (VAM) project in the United States utilizing a thermal flow reversal reactor to oxidize mine ventilation air, which contains low concentrations of methane. The process generates thermal energy that can have many uses. EPA is also working cooperatively with Natural Resources Canada (NRCan) to deploy a similar technology developed by NRCan's CANMET Energy Technology Centre (CETC).

- An international network of those involved in research on non-CO_2 GHGs has been formed by the International Energy Agency (IEA) Greenhouse Gas R&D Programme, EPA, and the European Commission Directorate General Environment. The experts involved in this network cover emissions, abatement options, and systems modeling for policy advice. The network provides an international forum for identification of needed research, as well as creating opportunities for international deployment of non-CO_2 emission reduction technologies.

- An international analytical effort has been undertaken by the Stanford Energy Modeling Forum (EMF) to better characterize the role of non-CO_2 mitigation in addressing climate change.[4] This multi-year effort has led to the development of data on the cost and performance of currently available and near-to-market technologies to reduce non-CO_2 emissions. In addition, the 19 international modeling teams participating in the project have incorporated data on non-CO_2 gases into their economic and integrated assessment models and are improving the capabilities needed to analyze comprehensive climate strategies focusing on both CO_2 and non-CO_2 options.

- Established in November 2004, the Methane to Markets Partnership (Box 7-3) is a new global initiative to advance international cooperation on the recovery and use of methane as a valuable clean energy source. The partnership will increase energy security, enhance economic growth, improve air quality, improve industrial safety, and reduce GHG emissions throughout the world. Methane to Markets has the potential to reduce net methane emissions by up to 50 million metric

4 Results from this study, EMF 21, are to be published in a special issue of the Energy Journal in 2005. See http://www.stanford.edu/group/EMF/research/index.htm.

tons of carbon equivalent annually by 2015 and continue at that level or higher in the future.

These partnerships and others that are discussed in this chapter demonstrate the potential for significant near-term emission reductions from currently available technologies. In addition, longer-term analyses have identified the potential for current and future technologies to lead to even more significant emission reductions. Historically, non-CO_2 gases were either not included or were treated in a cursory manner in climate change modeling and scenario studies. This situation is changing, however, and many modelers are incorporating the non-CO_2 gases into their models and are developing the capability to assess the role of the non-CO_2 gases in addressing climate change. Studies published to date indicate that substantial mitigation of future increases in radiative forcing could be achieved by reducing emissions of these other GHGs. It is possible that such reductions could contribute as much as one-half of the abatement levels needed to stay within a total radiative forcing gain that would be consistent with commonly discussed stabilization ranges of CO_2 concentrations.[5]

Achieving significant reductions in the emissions of the non-CO_2 gases is possible, taking into account the current achievements in reducing emissions as well as the results of detailed analyses of the technical and economic potential to reduce emissions from particular sources and sectors. Based on the information presented in this chapter, it is possible to achieve CH_4 emissions reductions of 40 to 60 percent by 2050, and 45 to 70 percent by 2100. Emissions of N_2O can be reduced by 25 to 30 percent by 2050, and 50 percent by 2100 (DeAngelo et al. forthcoming, Delhotal et al. forthcoming). In addition, it is possible to reduce emissions of high-GWP gases by 55 to 75 percent by 2050, and 60 to 80 percent by 2100 (Schaefer 2006).

There are a number of potentially fruitful areas for technologies to mitigate growth in emissions of non-CO_2 GHGs and strong promise that over time emissions could be reduced substantially. The strategy for addressing non-CO_2 GHGs has two key elements. First, it focuses on the key emission sources of these GHGs and identifies specific mitigation options and research needs by gas, sector, and source. Given the diversity of emission sources, a generalized technology approach is not practical. Second, the strategy emphasizes both the expedited development

Target Areas for Reducing Emissions of Non-CO_2 GHGs (2000 Emissions in Tg CO_2 Equivalent)

TARGET AREA	U.S. EMISSIONS	% OF TOTAL U.S. NON-CO_2	GLOBAL EMISSIONS	% OF GLOBAL NON-CO_2
CH_4 Emissions from Energy and Waste	371	34	2836	31
CH_4 and N_2O Emissions from Agriculture	444	41	5428	60
Emissions of High Global Warming Potential (GWP) Gases	139	13	368	4
N_2O Emissions from Combustion and Industrial Sources	98	9	390	4
Emissions of Tropospheric Ozone Precursors and Black Carbon	N/A*			

* Emissions estimates exist but they cannot be converted into CO_2 equivalent units.
Sources: EPA 2005, 2004

Table 7-1. Target Areas for Reducing Emissions of Non- CO_2 GHGs(2000 Emissions in Tg CO_2 Equivalent) [6]

5 U.S. Climate Change Science Program, Prospectus for Synthesis and Assessment Product 2.1. http://www.climatescience.gov/Library/sap/default.htm.

6 For this chapter, the GWP-weighted emissions of methane (estimated at 21) are presented in terms of equivalent emissions of carbon dioxide (CO_2), using units of teragrams of carbon dioxide equivalents (Tg CO_2 equivalent). To convert the emission estimates included in this chapter to giga-tonnes of carbon (GtC), multiply the emissions estimate by .000272. For example, 200 Tg CO_2 equivalent X (.000272) = .054 GtC.

U.S. and Global Methane (CH_4) Emissions from Energy and Waste (2000 Emissions in Tg CO_2 Equivalent)

SOURCE	U.S. EMISSIONS	% OF TOTAL U.S. NON-CO_2 GHG EMISSIONS	GLOBAL EMISSIONS	% OF GLOBAL NON-CO_2 GHG EMISSIONS
Landfills	130.7	12	814	9
Coal Mining	56.2	5	439	5
Natural Gas and Oil Systems	149.7	14	1013	11
Wastewater Treatment	34	3	569	6
Total	**371**	**34**	**2836**	**31**

** Emissions estimates exist but they cannot be converted into CO_2 equivalent units. Sources: EPA 2005, 2004*

Table 7-2. U.S. and Global Methane (CH_4) Emissions from Energy and Waste (2000 Emissions in Tg CO_2 Equivalent)

and deployment of near-term and close-to-market technologies and expanded R&D into longer-term opportunities leading to large-scale emission reductions. By stressing both near- and long-term options, the strategy offers maximum climate protection in the near term and a roadmap to achieve dramatic gains in later years.

The discussion of the key emission sources of other GHGs is organized around five broad categories—or "target areas"—listed in Table 7-1. Following the table, each target area is discussed in subsequent technology sections. Each of these technology sections includes a sub-section describing the current portfolio. The technology descriptions include a link to the CCTP Technology Options for the Near and Long Term (CCTP 2003).

7.1 Methane Emissions from Energy and Waste

In 2000, methane emissions from the energy and waste sectors accounted for 31 percent of global non-CO_2 GHG emissions (Table 7-2), and nearly 50 percent of global methane emissions. The major emission sources in these sectors include coal mining, natural gas and oil systems, landfills, and wastewater treatment. As Table 7-2 shows, among the energy and waste-related methane emission sources, oil and gas systems, and landfills are the largest emission sources, accounting for 9 and 11 percent, respectively, of global non-CO_2 emissions.

The energy and waste sectors present some of the most promising and cost-effective near-term reduction opportunities. Reducing methane emissions, the primary component of natural gas, can be cost-effective in many cases due to the market value of the recovered gas. Efforts in the United States to voluntarily encourage these economically attractive opportunities have already been successful by focusing on the deployment of available, cost-effective technologies. As Table 7-3 shows, emissions from the key sources in the United States have declined in absolute terms by about 16 percent since 1990, equal to about 65 teragrams of carbon dioxide equivalent (Tg CO_2 equivalent).

Despite this success, significant opportunities remain for further emission reductions through the expanded deployment of currently available technologies and the development of promising new technologies. These longer-term technologies could lead to substantial additional methane reductions in the future. The remainder of this section discusses these technical opportunities for the three major emission sources in this category: landfills, oil and gas systems, and coal mines.

Landfills

Methane emissions from landfills result from the decomposition of organic material (yard waste, food waste, etc.) by bacteria in an anaerobic environment. Emission levels are affected by site-specific factors such as waste composition, moisture, and landfill size. Landfills are the second largest anthropogenic methane emission source in the United States, releasing an estimated 131 Tg CO_2 equivalent to the atmosphere in 2003 (EPA 2005). Globally, landfills

Change in U.S. Methane (CH_4) Emissions from Energy and Waste

SOURCE	1990 EMISSIONS	2000 EMISSIONS	% CHANGE
Landfills	172	130.7	- 24
Coal Mining	82	56.2	- 32
Natural Gas & Oil	148	149.7	+1
Total	**402**	**337**	**- 16**

Source: EPA 2005.

Table 7-3. Change in U.S. Methane (CH_4) Emissions from Energy and Waste

are also a significant emission source, accounting for an estimated 814 Tg CO_2 equivalent in 2000 or almost 10 percent of global non-CO_2 emissions (Table 7-2). The majority of emissions currently come from developed countries, where sanitary landfills facilitate the anaerobic decomposition of waste. Emissions from developing countries, however, are expected to increase as solid waste will be increasingly diverted to managed landfills as a means of improving overall waste management. By 2020, three regions are projected to each account for more than 10 percent of global methane emissions from landfills: Africa (16 percent), Latin America (13 percent) and Southeast Asia (12 percent) (EPA 2004).

Potential Role of Technology

The principal approach to reduce methane emissions from landfills involves the collection and combustion (through use for energy or flaring) of landfill gas (LFG). LFG utilization technologies can be divided into two main categories: electricity generation and direct gas use. About 75 percent of the projects in the United States involve electricity generation, using reciprocating engines or combustion turbines. Direct use technologies account for about 25 percent of total projects, but their implementation has grown in recent years. Some of these technologies use LFG directly as a medium-Btu fuel, while others require the gas to be upgraded and delivered to a natural gas pipeline.

Technology Strategy

Additional CH_4 emission reductions at landfills can be achieved through RD&D efforts focused on improvements in LFG collection efficiency, gas utilization technologies, and alternatives to existing solid waste management practices. In the near term, RD&D efforts focused on improving collection efficiency and demonstrating promising emerging gas use technologies can yield significant benefits. These approaches could increase emission reductions from the waste currently contained in landfills, which will emit CH_4 for 30 or more years. Longer-term reductions will result from research on advanced utilization technologies and development of solid waste management alternatives, such as bioreactor landfills.

Current Portfolio

The current Federal portfolio focuses on three areas:

- Research and development of anaerobic and aerobic bioreactor landfills that more quickly stabilize the readily decomposable organic constituents of the waste stream through enhanced microbiological processes. The goal is to have three to five commercial full-scale anaerobic and aerobic bioreactor landfill demonstration units operational by the close of 2006 plus increased market penetration 2007–2012. An additional goal is to further evaluate environmental and public-health impacts, and design and operational issues.[7]
- R&D of emerging technologies that facilitate the conversion of LFG to readily usable forms, such as compressed natural gas/liquefied natural gas, and methanol/ethanol. Near-term goals to convert landfill gas to alternative uses include verifying performance of LNG conversion technology application on landfill gas and converted vehicle

7 See Section 4.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-411.pdf.

performance, development of additional commercially available LNG vehicles (e.g., solid waste collection trucks), and development of distribution/fueling infrastructure. Mid-term goals target research on cost-effective separation technology applications for pipeline quality gas production (Figure 7-1) and to evaluate and demonstrate technologies for producing commercial carbon dioxide.[8]

- R&D on improving LFG collection efficiency and enhancing electricity production from LFG through new and improved electricity generation technologies (fuel cells, microturbines, Organic Rankine Cycle, and Stirling-Cycle engines).[9]

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

Future applied research efforts in the near term could focus efforts to improve LFG collection efficiencies, including research on the design, construction, and operational effectiveness of horizontal wells and other new gas collection systems. Research could also be targeted on the development of additional economical gas utilization technologies and optimizing methane oxidation by cover soils or other advanced cover materials. Development and deployment of near-term technologies to recover LFG from current waste disposal sites could reduce emissions by 50 percent (Delhotal et al. forthcoming).

Over the long term, emissions could theoretically be eliminated through the commercialization and deployment of advanced waste processing and treatment systems such as integrated systems approaches for waste management that could reduce the magnitude of landfill waste and nearly eliminate new landfill waste, such as:

- Source-separation of the solid waste stream into processing categories (recyclables, organics, inerts, etc.) for complete recycling and reuse. This could include (1) designing products to tag and identify waste for recycling; (2) facilitating the decomposition of organics through mechanical biological treatment, followed by rapid and controlled aerobic composting of drier feedstocks, and anaerobic decomposition of wet organics in digesters along with enhanced methane gas recovery; and (3) alternatively, using engineered bacteria that process/break down organic waste without producing methane.

Figure 7-1. Capturing and marketing methane emissions from energy and waste systems can be an economically attractive means for reducing GHG emissions.

Courtesy: EPA

- Centralized or distributed waste management systems that include on-site conversion of waste to hydrogen, other fuels, or electricity. These systems would include pyrolosis, whereby waste is significantly reduced in volume to a glass-like cullet, and gasification, whereby waste is converted to a liquid fuel.

- Potential technology options include sort/weight recognition technology; tagging and tracking technology; large and small-scale waste conversion to fuels, power, and products; and genetically engineered bacteria.

Coal Mines

Coal mines are a significant methane emission source in the United States and worldwide, accounting for

8 See Section 4.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-412.pdf.

9 See Section 4.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-413.pdf.

about 10 percent of total anthropogenic methane emissions (EPA 2004). Methane trapped in coal deposits and in the surrounding strata is released during normal mining operations in both underground and surface mines. In addition, handling of the coal after mining (e.g., through storage, processing, and transportation) results in methane emissions. Underground mines are the largest source of coal mine methane (CMM) emissions.

Emissions of CMM in the United States in 2000 were 56 Tg CO_2 equivalent and are projected to increase to 70 Tg CO_2 equivalent by 2010 (EPA 2005). Worldwide emissions of methane from the coal industry are estimated to be 432 Tg CO_2 equivalent and are expected to rise to 495 Tg CO_2 equivalent by the year 2010 as coal production increases (EPA 2004). Globally, almost all CMM emissions come from the major coal producing countries and regions of China; India; the United States; the Confederation of Independent States; Australia; Central, Eastern, and Western Europe; the United Kingdom; and Southern Africa.

Underground mines present the greatest opportunities for reducing emissions; however, emission reductions are also possible at surface mines. Emissions from both underground and surface mines vary, depending on the technology used to mine the coal, the rate of coal production, the technologies employed to remove the methane from the mines, and the local geological conditions.

Potential Role of Technology

Upstream and downstream technologies are integral to reducing methane emissions from coal mines. The most important upstream technological contributions are in the recovery of methane from mine degasification operations and in the oxidation of low-concentration methane in mine ventilation air. Degasification systems are used to remove methane from the coal seams to provide for a safe working environment. These systems generally consist of boreholes drilled into the coal seams and adjacent strata, with in-mine and surface gathering systems used to extract and collect methane. CMM can be recovered in advance of mining or after mining has occurred, and recovery may consist of surface wells, in-mine boreholes, or some combination of the two.

From a technical viewpoint, the most appropriate drainage technology depends on the surface topography, subsurface geology, reservoir characteristics, mine layout, and mine operations. Degasification technologies are used around the world and are commonplace in most of the aforementioned countries. Surface gob wells are used to extract methane after mining has occurred, and in-mine horizontal boreholes are standard at many gassy mines. However, advanced degasification employing long-hole in-mine directional drilling has only been successful in a limited number of countries, including the United States, Australia, China, Japan, United Kingdom, Germany, and Mexico; it is currently being tested in Ukraine. Only the United States and Australia have had success with pre-mine drainage using surface wells. Although gas drainage is practiced primarily at underground mines, drainage is also occurring at surface mines in some countries, including the United States, Australia, and Kazakhstan. Horizontal boreholes can be drilled into the coal seam ahead of mining and the methane extracted.

In a number of countries, commercially applied technologies have led to large reductions in CMM emissions through use of the captured methane. These technologies have included the use of CMM as fuel for power generation (primarily internal combustion engines), injection into the natural gas pipeline system and local gas distribution networks, boiler fuel for use at the mine, local heating needs, thermal drying of coal, vehicle fuel, and as a manufacturing feedstock (e.g., methanol, carbon black, and dimethyl ether production). Technology advances in gas processing over the past decade have also resulted in projects to upgrade the quality of CMM and liquefy the gas, which in turn provide more end-use options and improve access to markets.

Although considerable effort is still directed at improving methane drainage recovery efficiencies and broadening the application of end-use technologies, attention is also focused on the capture and use of coal mine ventilation air methane (VAM). Mine ventilation air generally contains less than 1 percent methane in accordance with regulatory standards. The low concentration greatly limits possible uses of the methane. However, VAM is the largest source of underground methane emissions, and presents a significant opportunity to further mitigate GHG emissions from coal mines if capture and use technologies can be successfully applied. Worldwide VAM emissions in 2000 were 238 Tg CO_2 equivalent and are expected to increase to 282 Tg CO_2 equivalent by 2010 and 308 Tg CO_2 equivalent by 2020. Emissions of VAM in the United States in 2000 were about 37 Tg CO_2 equivalent and are anticipated to rise slightly to 40 Tg CO_2 equivalent by 2010 and remain steady thereafter (EPA 2003a).

Technology Strategy

RD&D efforts aimed at emerging methane reduction technologies for coal mines could target VAM and advanced coalbed methane drilling techniques. The development of technologies to use VAM will enable overall emission reductions at underground mines to reach 90 percent, as compared to the current technical recovery limit of 30 to 50 percent (EPA 1999). The most promising approach for recovering VAM emissions is through commercialization of technologies that convert the low-concentration (typically under 1 percent) methane directly into heat using thermal or catalytic flow reversal reaction processes. The heat can then be employed for power production or other heating. Demonstration projects in Australia, Canada, and the United Kingdom have shown that these technologies can be technically viable. The world's first commercial unit is expected to be operative in Australia in 2006, generating enough thermal energy to supply a 6-MW steam turbine. Future efforts will need to focus on continued testing and commercial deployment of VAM combined with market development support to ensure that it is seen by industry as an energy resource, rather than being vented to the atmosphere.

The other potentially important approach to reduce emissions is the development of advanced drilling technologies. Over the 1990s, advances in steerable motors and stimulation techniques have increased the ability to recover a higher percentage of the total methane in coal seams. This methane, much of which is high quality, may then find a viable market. The most promising technologies include in-mine and surface directional drilling systems, which may enable fewer wells to produce more gas, and advanced stimulation techniques, such as nitrogen injection, that increase the recovery efficiency of surface wells. There is also considerable interest in CO_2 injection; however, this is currently not an option for mine degasification. Injecting the CO_2 into the coal seam renders the coal seams unmineable due to the hazard of releasing too much CO_2 into the mine workings. Although it is difficult to characterize the potential for enhanced gas drainage, these technologies have been shown to obtain drainage efficiencies of 70 to 90 percent (EPA 1999). Future RD&D activities will need to focus on the continued testing and commercial deployment of directional drilling and use of other gases in coalbed methane recovery. In addition, market development support will be needed to ensure that increased drained emissions are put to productive use, rather than vented to the atmosphere.

Figure 7-2. Capturing and using methane from coal mine ventilation air represents an economic opportunity to reduce GHG emissions.

Courtesy: DOE

Current Portfolio

The current Federal portfolio focuses on two areas:

- Research on advances in **coal mine ventilation air systems** is focused on use of VAM in flow reversal reactors; concentrators to increase the methane concentration to levels that will support oxidation; lean fuel turbines; and as combustion air in small-scale reciprocating engines or large-scale mine-mouth power plants, or as co-combustion medium with waste coal (Figure 7-2). The goal of coal mine ventilation air systems' research, development, demonstration, and deployment (RDD&D) program is market penetration by 2005–2010, ultimately leading by the end of the program to the majority of ventilation air methane emissions mitigated.[10]
- Research on advances in **CMM recovery systems** is focused on improving mine drainage system technology through improved directional drilling technologies, in-mine hydraulic fracturing techniques, development of nitrogen and inert gas injection techniques and improved drilling technologies.[11]
- The **Coalbed Methane Outreach Program** (CMOP) is working to demonstrate technologies that can eliminate the remaining emissions from degasification systems, and is addressing methane

[10] See Section 4.1.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-414.pdf.

[11] See Section 4.1.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-415.pdf.

emissions in mine ventilation air. Due to enhanced market opportunities for natural gas and power, further refinement of technical options for the capture and utilization of mine methane, a growing reliance on methane degasification in the Western United States, and CMOP's anticipated success in reducing ventilation air methane over the next few years.

Future Research Directions

- The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. RD&D efforts will be focused on achieving full commercialization and deployment of VAM and advanced coalbed methane drilling techniques. These technologies alone could reduce emissions from underground mining operations by 90 percent (EPA 2003a).
- RD&D efforts will be focused on developing new, fully automated mining systems that will almost eliminate methane emissions. Since underground mining represents about 83 percent of U.S. coal mine methane emissions, this would represent the potential for a 75 percent reduction in overall U.S. methane emissions from this source.

Natural Gas and Petroleum Systems

Methane emissions from the oil and gas industry accounted for approximately 11 percent of global non-CO_2 emissions in 2000 (EPA 2004). Russia and the United States accounted for over 30 percent of global methane emissions from oil and gas systems. Emissions occur throughout the production, processing, transmission, and distribution systems and are generally process related. Normal operations, routine maintenance, and system upsets are the primary contributors. Emissions vary greatly from facility to facility and are largely a function of operation and maintenance procedures and equipment. However, over 90 percent of methane emissions from oil and gas systems are associated with natural gas rather than oil-related operations (EPA 2005, 2004).

As demand for oil and gas increases, global methane emissions are projected to increase by more than 72 percent between 1990 and 2020 (EPA 2004). However, in many developed countries there is increasing concern about the contribution of oil and gas facilities to deteriorating local air quality, particularly emissions of non-methane volatile organic compounds (NMVOCs). Measures designed to mitigate NMVOC emissions, such as efforts to reduce leaks and venting, have the ancillary benefit of reducing methane emissions. In addition, as economies in many Eastern European countries undergo restructuring, efforts are underway to modernize gas and oil facilities. For example, Germany expects to reduce emissions from the former East German system through upgrades and maintenance. Russia also plans to focus on opportunities to reduce emissions from its oil and gas system as part of modernization.

Potential Role of Technology

Reducing methane emissions from the petroleum and natural gas industries necessitates both procedural and technology improvements. Methane emission reduction strategies generally fall into one of three categories: (1) technologies or equipment upgrades that reduce or eliminate equipment venting or fugitive emissions, (2) improvements in management practices and operational procedures, or (3) enhanced management practices that take advantage of improved technology. Each of these technologies and management practices requires a change from business as usual in the schedule and conduct of daily operations. To date, over 90 emission reduction opportunities have been identified by corporate partners in EPA's Natural Gas STAR Program. In many cases, these actions are cost-effective and widely applicable across industry sectors.

Technology Strategy

Despite the current availability of cost-effective methane emission reduction opportunities in the natural gas and petroleum industry, RDD&D efforts could have an important impact on future methane emissions. Both in the near and long terms, RDD&D efforts could focus on increasing market penetration of current emission reduction technologies, improving leak detection and measurement technologies, and developing advanced end-use technologies.

- **Current Emission Reduction Technologies** – Perhaps the greatest environmental benefits would be associated with an enhanced demonstration and deployment effort focused on currently available emission reduction technologies. In 2000, deployment of these technologies in the United States reduced emissions by 15 Tg CO_2

equivalent, approximately 12 percent of total industry emissions (EPA 2005). An enhanced effort would encourage additional technology penetration and emissions reductions.

- **Leak Detection and Measurement** – Additional benefits could be realized through improvements in and deployment of leak detection and measurement technologies. Although potential industry-wide emission reductions are difficult to quantify, improved identification and quantification of methane losses and leaks would promote mitigation activities. New technologies will allow for quick, relatively inexpensive detection of leaks that are cost-effective to repair. Some of the emerging leak detection and measurement technologies include the Hi-Flow™ Sampler and hand-held optimal imaging cameras that can visualize methane leaks (e.g., Image Multi-Spectral Sensor [IMSS] camera).
- **Advancing End-Use Technologies** – Research aimed at advancing fuel cell and microturbine technologies could reduce emissions at remote well sites by enabling remote power generation at these locations. For example, power generated from the lower-quality gas can be used to support instrument air systems and eliminate the need for gas-driven pneumatic devices and pumps.

Current Portfolio

The current Federal R&D portfolio primarily focuses on leak detection measurement and monitoring technologies for natural gas systems. Advanced leak detection and measurement technologies enable quick and cost-effective detection and quantification of fugitive methane leaks (Figure 7-3). Natural gas systems' RDD&D goals related to measurement and monitoring technologies are focused on completing of the development and deployment of advanced measurement technologies like the Hi-Flow™ and on advancing the development of imaging technology for methane leak measurement and facilitate demonstration and deployment.[12]

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

Pipelines carrying natural gas as well as facilities where natural gas is liquefied are a source of fugitive emissions of methane. Advances in materials, seals, and valve technology could eliminate or reduce these emissions at the source. Possible research may include:

- Development of more accurate and cost-effective leak detection and measurement equipment, which could be effective in reducing fugitive and vented emissions from gas production, processing, transmission, and distribution operations.
- Long-term research to explore revolutionary equipment designs. This might focus on "smart equipment," such as smart pipes or seals, that could alert operators to leaks or self-repairing pipelines made of material that can regenerate and automatically seal leaks. Development of additional technologies could enable emission reductions of 50 percent by the middle of the century.

Enhanced leak-detection and measurement efforts can yield significant methane emission reductions. Demonstration of improved technologies has indicated that emissions at compressor stations and gas-processing plants can be reduced cost effectively by as much as 80 to 90 percent. More importantly, an enhanced demonstration and deployment effort focused on currently available emission reduction technologies would encourage additional technology

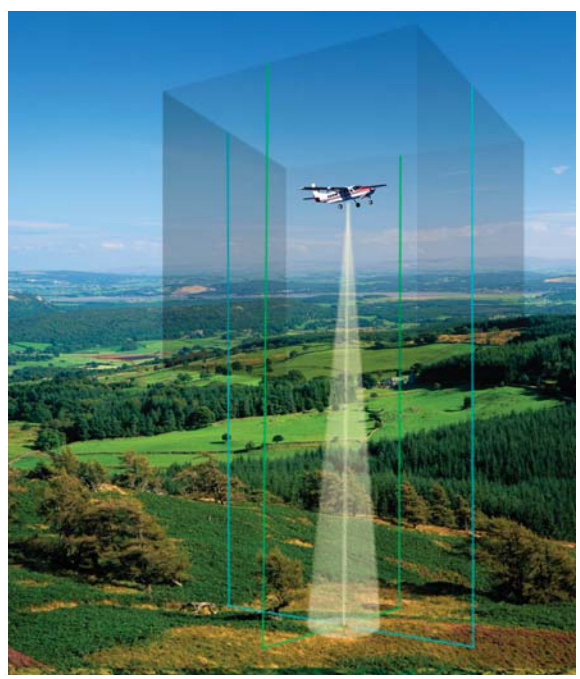


Figure 7-3. Advances in leak detection and measurement systems for natural gas pipelines are enabling significant reductions in methane emissions.

Courtesy: ITT Corporation

12 See Section 4.1.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-416.pdf.

U.S. and Global CH_4 and N_2O Emissions from Agriculture (2000 Emissions in Tg CO_2 Equivalent)

SOURCE	U.S. EMISSIONS	% OF TOTAL U.S. NON-CO_2 GHG EMISSIONS	GLOBAL EMISSIONS	% OF GLOBAL NON-CO_2 GHG EMISSIONS
N_2O Emissions from Agriculture	282	26%	2875	32%
Enteric Methane Emissions	116	11%	1712	19%
Methane Emissions from Manure	38	3%	199	2%
Methane Emissions from Rice Production	8	< 1%	643	7%
Total	**443**	**40%**	**5429**	**60%**

Sources: EPA 2005, 2004.

Table 7-4. U.S. and Global CH_4 and N_2O Emissions from Agriculture (2000 Emissions in Tg CO_2 Equivalent)

penetration. In the United States alone, this effort could reduce emissions by an estimated 37 Tg CO_2 equivalent in 2010.

7.2 Methane and Nitrous Oxide Emissions from Agriculture

Over 40 percent of total U.S. non-CO_2 GHGs come from methane (CH_4) and nitrous oxide (N_2O) emissions from agriculture (EPA 2005). Globally, agricultural sources of methane and nitrous oxide contribute an estimated 5,428 Tg CO_2 equivalent, nearly 60 percent of global non-CO_2 emissions (EPA 2004). These emissions result from natural biological processes inherent to crop and livestock production and cannot be realistically eliminated, although they can be reduced. For example, emissions of oxides of nitrogen (NO_X) can likely be decreased by 15 to 35 percent through programs that improve crop nitrogen use efficiency, through plant fertilizer technology, precision agriculture, and plant genetics (DeAngelo 2006). Table 7-4 shows N_2O and methane emissions from agricultural sources (Tg CO_2 equivalent).

Key research efforts have focused on the largest agriculture GHG emission sources:

- Nitrous oxide emissions from agricultural soil management.
- Methane and nitrous oxide emissions from manure management.
- Methane emissions from livestock enteric fermentation.

Advanced Agricultural Systems for Nitrous Oxide Emissions Reductions

Low efficiency of nitrogen use in agriculture is primarily caused by large nitrogen losses due to leaching and gaseous emissions (ammonia, nitrous oxide, nitric oxide, and nitrogen). In general, N_2O emissions from mineral and organic nitrogen can be decreased by nutrient and water management practices that optimize a crop's natural ability to compete with processes that result in plant-available nitrogen being lost from the soil-plant system.

Potential Role of Technology

Key technologies in the area of nutrient management can be applicable to N_2O mitigation. They focus on the following areas:

- **Precision agriculture** – targeted application of fertilizers, water, and pesticides.
- **Cropping system models** – tools to assist farmer management decisions.
- **Control release fertilizers and pesticides** – delivery of nutrients and chemicals to match crop demand and timing of pest infestation.
- **Soil microbial processes** – use of biological and

chemical methods, such as liming, to manipulate microbial processes to increase efficiency of nutrient uptake, suppress N_2O emissions, and reduce leaching.

- **Agricultural best management practices** – limiting N-gas emissions, soil erosion, and leaching.
- **Soil conservation practices** – utilizing buffers and conservation reserves.
- **Livestock manure utilization** – development of mechanisms to more effectively use livestock manure in crop production.
- **Plant breeding** – to increase nutrient use efficiency and decrease demand for pesticides.

Figure 7-4. Technologies and farming practices, such as precision agriculture and no-till planting, can increase the overall nitrogen efficiency while maintaining crop yields, resulting in reduced nitrous oxide emissions.

Photo: Tim McCabe, USDA Natural Resources Conservation Service

Technology Strategy

Technologies and practices that increase the overall nitrogen efficiency while maintaining crop yields represent viable options to decrease N_2O emissions. Focused RDD&D efforts are needed in a number of areas to develop new technologies and expanded deployment of commercially available technologies and management practices (Figure 7-4).

- Further development of precision agriculture technologies to meet the fertilizer and energy reduction goals could lead to increased adoption of these technologies and improved performance.
- "Smart materials" for prescription release of nutrients and chemicals for major crops currently require modest breakthroughs in materials technology to reach fruition.
- Soil microbial processes could also be manipulated to increase N-use efficiency; however, further development is needed to ensure full efficacy and avoid the introduction of environmental risks.
- First-generation integrated system models, technology, and supporting education and extension infrastructure need to be implemented, and research on using these techniques to improve management expanded.
- Genetically designed major crop plants could utilize fertilizer more efficiently.
- Increased extension efforts are needed to fully utilize best management practices.
- Basic research on process controls and field monitoring programs are needed to ensure that theoretical understanding exists as technology evolves and that changes in management practices to mitigate GHG emissions actually function as theorized.
- Accurate measurement technologies and protocols are needed for assessment and verification.

Current Portfolio

Although many mitigation options for N_2O emissions can be readily identified, their implementation has not been carried out on a large scale. Other than programs to limit nitrogen losses, programs that directly address the issue of N_2O emissions from agricultural soil management are very limited. The current Federal portfolio focuses on N_2O emissions from agricultural soil management; precision agriculture; understanding and manipulation of soil microbial processes; expert system management; and the development of inexpensive, robust measurement and monitoring technologies. Research for reductions in N_2O emissions focus on improved production efficiencies and reduced energy consumption by developing and deploying precision agriculture technologies, sensors/monitors and information-management systems, and smart materials for prescription release utilized in major crops. An additional goal is to improve fertilizer efficiency and reduce nitrogen inputs by developing advanced fertilizers and technologies, methods of manipulating soil microbial processes, and genetically designed major crop plants.[13]

[13] See Section 4.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-421.pdf.

Future Research Directions

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In general, an improved understanding of the interaction and interrelationship among methane, carbon dioxide, and nitrous oxide emissions in agricultural environments is needed. This should involve a systems approach across gases and agricultural systems to synergize related technologies. Other possible further research activities include:

- Precision agriculture in general requires advances in rapid, low-cost, and accurate soil nutrient and physical property characterization; real-time characterization of crop water need; real-time crop yield and quality characterization; real-time insect and pest infestation characterization; autonomous control systems; and integrated physiological model and massive data/information management systems.
- Improved understanding of specific soil microbial processes is required to support development of methods for manipulation of these processes and to identify how manipulation impacts GHG emissions.
- To continue to improve systems management, models that represent an accurate understanding of plant physiology must be coupled with soil process models, including decomposition, nutrient cycling, gaseous diffusion, water flow, and storage on a mass balance basis, to understand how ecosystems respond to environmental and management change.

Other options could include improved utilization of the nitrogen in manure on croplands/pasturelands to offset use of synthetic nitrogen and decrease the quantity of nitrogen excreted from livestock by better matching the intake of nitrogen (e.g., protein) with the actual dietary requirements of the animals. A large portion of the N_2O emissions from soils comes from livestock waste directly deposited on pastures, and this has significant mitigation potential both in the United States and globally.

Wide-scale implementation of these technologies and improved management systems in the United States could lead to reductions in nitrous oxide emissions from agriculture of 15 to 35 percent. In some developing countries, where greater inefficiencies are identified and where potential use of nitrogen is likely to increase greatly in the future as the demand for more crop and pasture production increases, the potential is even greater.

Methane and Nitrous Oxide Emissions from Livestock and Poultry Manure Management

Globally, nitrous oxide and methane emissions from livestock and poultry manure management totaled approximately 400 Tg CO_2 equivalent in 2000 (EPA 2004). Livestock and poultry manure has the potential to produce significant quantities of methane and nitrous oxide, depending on the waste management practices. When manure is stored or treated in systems that promote anaerobic conditions, such as lagoons and tanks, the decomposition of the biodegradable fraction of the waste tends to produce methane. When manure is handled as a solid, such as in stacks or deposits on pastures, the biodegradable fraction tends to decompose aerobically, greatly reducing methane emissions; however, this practice increases emissions of nitrous oxide, which has a greater global warming potential. Practices are needed that minimize both GHGs simultaneously.

Potential Role of Technology

Methane reduction and other environmental benefits can be achieved by utilizing a variety of technologies and processes. Aeration processes, such as aerobic digestion, auto-heated aerobic digestion, and composting, remove and stabilize some pollutant constituents from the waste stream. These technologies facilitate the aerobic decomposition of waste and prevent methane emissions. Anaerobic digestion systems, in contrast, encourage methane generation, and the collection and transfer of manure-generated off-gases to energy-producing combustion devices (such as engine generators, boilers, or odor control flares). Solids separation processes remove some pollutant constituents from the waste stream through gravity, mechanical, or chemical methods. These processes create a second waste stream that must be managed using techniques different from those already in use to manage liquids or slurries. Separation processes offer the opportunity to stabilize solids aerobically (i.e., to control odor and vermin propagation).

Technology Strategy

Methane collection from anaerobic digestion systems plays an important role in reducing emissions from livestock manure management (Figure 7-5). In addition, these systems can provide additional odor-control and energy benefits by collecting and producing electricity from the combustion of methane-using devices, such as engine generators and boilers. Although the use of commercial farm-scale anaerobic digesters has increased over the past five years due to private sector activities, significant opportunity remains. Currently there are only 12 companies that provide proven commercial-scale anaerobic digestion systems and gas utilization options for farm applications in the United States. As of 2003, an estimated 40 anaerobic digester systems, which produce about 1 million kWh/year, were in use at commercial swine and dairy farms in the United States (EPA 2003b).

Expanded technology research and extension efforts could include commercial-scale demonstration projects and evaluation of emerging technologies to determine their effectiveness in reducing emissions, overall environmental benefits, and cost-effectiveness. For example, a number of emerging anaerobic digester systems adopted from the sewage industry are currently under evaluation for farm-scale applications. In addition, it is important to encourage research on odor and nitrogen emission control and ensure that it is coordinated with research on methane production and emission technology development.

Current Portfolio

Methane reduction and other environmental benefits can be achieved by utilizing a variety of technologies and processes, including aeration processes to remove and stabilize some pollutant constituents from the waste stream; anaerobic digestion systems that collect and transfer manure-generated off-gases to energy-producing combustion devises (such as engine generators, boilers, or odor control flares); and solids separation processes to remove some pollutant constituents from the waste stream. The goals of this research activity are to reduce costs and improve biological efficiencies of methane and nitrous oxide emissions by developing new types of digesters; developing separation processes for solid and liquid fractions; and on developing, applying, and evaluating process performance of aeration systems for manure waste streams. The current Federal portfolio focuses these technologies.[14]

Figure 7-5. Methane collection from anaerobic digestion systems plays an important role in reducing emissions from livestock manure management.

Courtesy: EPA

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

- Future research could address technologies to reduce carbon in waste lagoons by solids separation and increase aeration of lagoon waste systems. Additional research could facilitate the shift from anaerobic lagoons to solid waste management systems.
- Future research can lead to improved separation processes that remove solids from liquids for improved waste management and stabilization development of new types of digestors with reduced costs and improved biological efficiencies, development of centralized anaerobic digestion

14 See Section 4.2.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-422.pdf.

systems for multiple farm operations, and development of aeration processes and pollution control methods for manure waste streams.

Expanded extension efforts to the livestock, agricultural, energy, and regulatory communities in a number of key livestock-producing states (for example, by expanding the activities currently conducted through the AgSTAR Program[15]), could lead to additional emissions reductions in the United States. In addition, research that utilizes new technological developments in analytical instrumentation and molecular biology related to a commercial farm's operational ability would be useful. If such activities were undertaken globally, the emission reductions could be substantial.

Methane Emissions from Livestock Enteric Fermentation

Methane emissions from enteric fermentation are the second largest global agricultural GHG source, contributing an estimated 1712 Tg CO_2 of emissions in 2000 (EPA 2004). Methane emissions occur through microbial fermentation in the digestive system of livestock. The amount of methane emitted depends primarily on the animal's digestive system, and the amount and type of feed. Ruminant livestock such as dairy cattle, beef cattle, and buffalo emit the most methane per animal, while non-ruminant livestock such as swine, horses, and mules emit less. Because methane emissions represent an economic loss to the farmer—where feed is converted to methane rather than to product output—viable mitigation options can entail efficiency improvements to reduce methane emissions per unit of beef or milk.

Potential Role of Technology

Reductions in this energy loss can be achieved through increased nutritional efficiency. The goal of much livestock nutrition research has been to enhance production efficiency in order to indirectly reduce methane per unit of product through breed improvements, increased feeding efficiency through diet management, and strategic feed selection. Without reductions in national herds, however, this approach will not result in net decreases of enteric methane. Historic and near-term projected trends show both a decreasing herd size and reduced methane emissions on a per unit product basis.

Technology Strategy

Technologies that would likely reduce methane emissions in addition to enhancing production efficiency include precision nutrition; and improvements in grazing management, feed efficiency, and livestock production efficiency. Research includes but is not limited to investigating between-animal differences to determine if traits for reduced methane production can be inherited, and dietary manipulation of grains, oils, and fats that reduce methane production. Key technologies include the following:

- Precision nutrition can minimize excess nutrients, particularly nitrogen, while meeting the nutritional needs of the ruminal microflora and those of the animal for growth, milk production, and digestion.
- Improved grazing management can increase forage yield and digestibility.
- Using ionophores to improve feed efficiency can inhibit the formation of CH_4 by rumen bacteria.
- Improving livestock production efficiency with natural or synthetic hormone feed additives or implants can increase milk production and growth efficiency and reduce feed requirements.

Current Portfolio

The current Federal research portfolio focuses on improved feed and forage management and treatment practices to increase the digestibility and reduce residence digestion time in the rumen, best-management practices to increase animal reproduction efficiency, and use of growth promotants and other agents to improve animal efficiency. Enteric emissions reduction goals focus on improved production efficiencies for forage and feedstuffs; increased digestibility; means to reach these goals include genetically designed forages; manipulation of ruminal microbial processes to sequester hydrogen, making it unavailable to methanogens; and genetically designed bacteria that can compete with natural microbes.[16]

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology

15 For additional information on the AgSTAR Program, see http://www.epa.gov/agstar/.

16 See Section 4.2.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-423.pdf.

options. The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

In general, an improved understanding of the interaction and interrelationship among methane, carbon dioxide, and nitrous oxide emissions in agricultural environments is needed. This should involve a systems approach across gases and agricultural systems to synergize related technologies. Possible research activities include:

- Further research is needed with precision agriculture technologies such as genetic engineering of plants to enhance digestibility of feeds, reduce fertilizer requirements, and provide appropriate nutrients to enhance beneficial microbial competitiveness; development of livestock with increased productivity and dietary energy use efficiency that can be productive in various environments and use reduced feed resources; and development of models that represent accurate understanding of animal nutrient needs.

- Longer-term research is needed to improve understanding of specific rumen microbial processes to support development of methods for making desirable engineered microbes competitive with natural rumen microbes and development of vaccinations that can reduce methane production in the rumen.

It is estimated that an increase in production efficiency of approximately 25 percent could be realized if maximum implementation were to occur. A large potential exists as well in developing countries, where the livestock population is expected to increase significantly over the next few decades and where production efficiency is currently low (i.e., high methane per unit product).

Methane Emissions from Rice Fields

Another significant source of global anthropogenic methane is rice production. Rice is the dietary staple of a large proportion of the world's population. It is generally grown in flooded paddy fields, where methane is generated by the anaerobic decomposition of organic matter in the soil. Traditional wet cultivation emits an estimated 642 Tg CO_2 equivalent of methane (EPA 2004). Emissions from this source have leveled off in the past two decades.

Although water management, fertilizer selection, cultivar selection, and nutrient management are potential options for limiting methane emissions from rice fields, further research and development is needed to determine their cost-effectiveness and feasibility. Currently, there is no research ongoing in this area.

A number of opportunities for future research exist in this area, some of which include plant genetics, water management, and nutrient management. In general, the greatest challenges for mitigating methane emissions from rice fields arise from uncertainties in effecting changes in cultivation management, which affects rice yields; and developing feasible management practices that reduce methane emissions without increasing nitrogen losses and reducing yields. In addition, reduction of methane emissions

U.S. and Global Emissions of High-GWP Gases (2000 Emissions in Tg CO_2 Equivalent)

SOURCE	U.S. EMISSIONS	% OF TOTAL U.S. NON-CO_2 GHG EMISSIONS	GLOBAL EMISSIONS	% OF GLOBAL NON-CO_2 GHG EMISSIONS
Substitutes for Ozone-Depleting Substances	75	7	126	1
Industrial Use of High-GWP Gases	64	6	242	3
Total	**139**	**13**	**368**	**4**

Sources: EPA 2005, EPA 2004.

Table 7-5. U.S. and Global Emissions of High-GWP Gases (2000 Emissions in Tg CO_2 Equivalent) could be difficult to implement because, in many cases, the necessary actions could involve significant changes in agricultural practices (e.g., shifting to different water management regimes). In principle, application of known techniques could reduce methane emissions by 30 to 40 percent by the year 2020. Achieving these large emission reductions would, however, require finding suitable incentives and delivery mechanisms to induce changes in current practices.

7.3 Emissions of High Global-Warming Potential Gases

In 2000, high-GWP gases represented 13 percent of total U.S. non-CO_2 GHG emissions and 4 percent of global non-CO_2 emissions (Table 7-5). There are two different types of emission sources in this category, and each has different R&D priorities. As discussed below, emissions of high-GWP gases used as substitutes for ozone-depleting substances (ODSs) that are being phased out under the Montreal Protocol are currently increasing. High-GWP gases are also used or emitted by several other industries, and in many cases these emissions can be readily managed or eliminated. Table 7-5 shows emissions of substitutes for ODSs and high-GWP gases (Tg CO_2 equivalent).

Substitutes for Ozone Depleting Substances

High-GWP gases used as substitutes for ODSs are a growing emissions source in the United States and globally. These high-GWP gases are being used as replacements for chemicals (like CFCs) that deplete the stratospheric ozone layer (Box 7-2). ODSs, which are also GHGs, are being phased out under the Montreal Protocol and, thus, are not counted in national inventories. To address ozone depletion, the refrigeration, air conditioning, fire suppression, foam blowing, solvent cleaning, and other industries are in the midst of the ODS phaseout.

Potential Role of Technology

For many industries, the ODS phaseout is accomplished by switching to alternative chemicals. For most industries, the most popular and highest performing alternatives are chemicals like HFCs, which do not deplete the ozone layer but are potent GHGs. At the same time, the phaseout is providing industries with an opportunity to improve processes and practices related to chemical use, management, and disposal in ways that reduce the emissions of HFCs and PFCs, where those chemicals are used as alternatives. As the ODS phaseout continues, opportunities exist to find better life-cycle climate performance alternatives and/or continue reducing emissions.

Technology Strategy

To reduce emissions of GHGs used as ODS substitutes, focus might be given to the following: (1) finding alternative gases with lower or no GWP to perform, safely and efficiently, the same function currently served by the HFCs and PFCs; (2) exploring technologies that can reduce the use of these chemicals and/or the rate at which they are emitted; and (3) supporting responsible handling practices and principles that reduce unintended and unnecessary emissions.

Current Portfolio

The Federal R&D portfolio is focused on the two largest sources of hydrofluorocarbon emissions. These emissions arise from the supermarket refrigeration and motor vehicle air conditioning sectors.

- **Motor Vehicle Air Conditioning: Hydrofluorocarbon Emissions** – The motor vehicle industry phased out the use of CFC-12 (with a GWP of about 10,000) in new car air conditioners between 1992 and 1994, and since then has used exclusively HFC-134a (with a GWP of 1300). R&D is underway to commercialize even lower-GWP refrigerants, mainly CO_2 (GWP=1) and HFC-152a (GWP=120). Due to the high-pressure and toxic effects of CO_2, and the flammability of HFC-152a, additional safety engineering and risk mitigation technologies are being developed. Furthermore, research and testing are needed to maintain or improve the energy efficiency (and hence gas usage and CO_2 emissions) of the new air conditioners. In the United States, direct refrigerant GWP emissions can be reduced by more than 95 percent and indirect fuel use emissions reduced by 30 percent or more, for a total reduction of total vehicle fuel emissions (in vehicles with air conditioning) by up to 2 percent.
- **Supermarket Refrigeration: Hydrofluorocarbon Emissions** – Supermarkets are phasing out the use of ozone-depleting

refrigerants and substituting HFCs, which are potent GHGs. Technologies under development include distributed refrigeration, which reduces the need for excessive refrigerant piping (and hence emissions), and secondary-loop refrigeration, which segregates refrigerant-containing equipment to a separate, centralized location while using a benign fluid to transfer heat from the food display cases. The RDD&D goals for reducing HFC emissions from supermarket refrigeration include improving costs and energy-use performance of these new technologies and educating store designers and builders regarding new technologies and how these technologies can be integrated into new or retrofitted stores at a net savings.[17]

- The Significant New Alternatives Program (SNAP) has continued its progress in phasing down the use of global warming, ODSs like CFCs and hydrochlorofluorocarbons (HCFCs). SNAP has worked closely with industry to research, identify and implement climate and ozone friendly alternatives, supporting a smooth transition to these new technologies. In addition, SNAP has initiated programs with different industry sectors to monitor and minimize emissions of global warming gases like HFCs and perfluorocarbons (PFCs) used as substitutes to ozone-depleting chemicals.

Figure 7-6. Astron Remote Plasma Source (for NF3 CVD chamber cleaning) , an important technology for reducing PFC emissions from semiconductor manufacturing.

Courtesy: EPA

Future Research Directions

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- Continuation of the responsible-use practices developed to control emissions of ODSs has had and will continue to have a substantial effect on HFC and PFC emissions. Research indicates that approximately 80 percent of previous ODS uses have been replaced through conservation methods and use of non-fluorocarbon technologies. Continued emphasis on this success is needed, for example, by using equipment and technologies to reduce emissions during service and maintenance.
- Long-term research could focus on technologies that hold the most potential for reducing or eliminating total GHG emissions, including associated energy production emissions, and are practical for their applications. Key areas for consideration over the long term are the investigation of new technologies and processes to replace current uses of ODSs and avoid or reduce emissions of high-GWP gases. This includes research to find alternative refrigerant/AC working fluids that are not high-GWP gases. Another approach is research on solid state refrigeration and AC systems that not only eliminates the working fluid, but reduces the overall energy use.
- A focused RD&D program to develop and deploy safe, high-performing, cost-effective climate protection technologies could result in U.S. emission reductions of 50 percent or more by 2020. However, due to the long lifetimes of many of the products that use these gases, efforts need to be taken in the near term to realize the stock turnover necessary to achieve these reductions in a cost-effective manner.

[17] See Section 4.3.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-436.pdf.

Industrial Use of High-GWP Gases

High-GWP synthetic gases are generally used in applications where they are critical to highly complex manufacturing processes and provide safety and system reliability, such as in semiconductor manufacturing, electric power transmission and distribution, and magnesium production and casting. High-GWP gases are also emitted as byproducts from the manufacture of refrigerants (HCFC-22) and from the production of primary aluminum.

Potential Role of Technology

Incremental improvements to current technology have been made through the initiation of voluntary public-private industry partnerships. EPA's partnerships with industries, including the U.S. primary aluminum producers, HCFC-22 manufacturing, electric utility industry, magnesium producers, and semiconductor industry, are identifying new technologies and process improvements that not only reduce emissions of high-GWP gases but also improve production efficiency, thereby saving money. With continued support, production technologies are expected to further improve, allowing these industrial sectors to cost effectively reduce and possibly eliminate emissions of high-GWP gases.

Technology Strategy

High-GWP gas-emitting industries are implementing an RDD&D strategy focused on pollution prevention. The industries have established long-term goals of reducing, and in some cases eliminating high-GWP emissions, and are pursuing these goals by investigating and implementing source reduction, alternative process chemicals, high-GWP gas capture and reuse, and abatement.

While the U.S. sources of high-GWP emissions are well defined, they are also very diverse, and thus a customized approach for each industry is required. New and enhanced R&D will accelerate and expand options to stabilize and reduce emissions. Opportunities exist for both near- and long-term RD&D on technologies, including alternative chemicals for plasma etching for semiconductors and magnesium melt protection, as well as continued demonstration of advanced plasma abatement devices for the semiconductor industry.

Current Portfolio

The current Federal portfolio for reducing industrial emissions of high-GWP gases focuses on five areas:

- **Research on the Semiconductor Industry: Abatement Technologies** – Abatement of high-GWP gases from the exhaust gas stream in semiconductor processing facilities may be achieved by two mechanisms: (1) thermal destruction and (2) plasma destruction. The RDD&D goals for the thermal-destruction mechanism target lowering high-GWP emissions from waste streams by more than 99 percent, while minimizing (1) NO_X emissions to levels at or below emissions standards, (2) water use and burdens on industrial wastewater-treatment systems, (3) fabrication floor space, (4) unscheduled outages, and (5) maintenance costs. Plasma-destruction mechanism goals focus on the application of plasma technology (Figure 7-6) to develop a cost-effective POU abatement device that lowers exhaust stream concentrations of high-GWP gases by two to three orders of magnitude from etchers and plasma-enhanced chemical vapor deposition chambers; and transforms those gases into molecules that can be readily removed from air emissions using known scrubbing technologies.[18]
- **Research on the Semiconductor Industry: Substitutes for High-GWP Gases** – One method of reducing high-GWP gas emissions from the semiconductor industry is to use an alternative chemical or production process. Identifying and replacing high-GWP gases with more environmentally friendly substitutes for chemical vapor deposition clean and dielectric etch processes is a preferred option when viewed from the perspective of EPA's pollution prevention framework. The goal of reducing high-GWP gases in the semiconductor industry is to identify the chemical and physical mechanisms that govern chemical vapor deposition chamber cleaning and etching with perfluorocarbons and non-perfluorocarbons as well as govern process performance so that emissions of high-GWP gases may be significantly reduced without either adversely affecting process productivity or increasing health and safety hazards.[19]
- **Semiconductors and Magnesium: Recovery and Recycle** – Three recovery-and-recycle technologies are being investigated and evaluated:

[18] See Section 4.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-431.pdf.

membrane separation, cryogenic capture, and pressure swing absorption. The goal in this area is to develop and demonstrate a cost-effective, universally applicable recovery-and-recycle technology (all fabrication facilities and all high-GWP gases) that can yield "virgin"-grade high-GWP gases for semiconductor fabrication or magnesium plant reuse or sufficiently pure high-GWP gases for further use or purification elsewhere.[20]

- **Aluminum Industry: Perfluorocarbon Emissions** – Current efforts to reduce perfluorocarbon emissions from primary aluminum production focus on using more efficient smelting processes to reduce the frequency and duration of anode effects, which create the PFC. Another concept, now in the research and development phase, involves replacing the carbon anode with an inert anode. Doing so would completely eliminate process-related PFC emissions. The goal to reduce PFC emissions in the aluminum industry is to develop a commercially viable inert anode technology design by 2007, with commercialization expected by 2010–2015. If successful, the nonconsumable, inert anode technology would have clear advantages over conventional carbon anode technology, including energy efficiency increases, operating cost reductions, elimination of PFC emissions, and productivity gains.[21]

- **Research for Electric Power Systems and Magnesium: Substitutes for SF_6** – The challenge is to identify substitutes to SF_6 with low or no global-warming potential that satisfy the magnesium industry's melt protection requirements and meet the electric power industry's high-voltage insulating needs (Figure 7-7).[22]

Figure 7-7. Improvements to production technologies, such as alternative cover gases, can cost-effectively reduce, and possibly eliminate, emissions of high global warming potential gases, in this case sulfur hexafluoride (SF_6).

Credit: 3M™ Performance Materials Division

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

Long-term research might focus on technologies that hold the most potential for reducing or eliminating total GHG emissions, including associated energy production emissions, and that are practical for their applications. Many of these research efforts may prove to be high risk due to unknown commercial viability, and thus are unlikely to be pursued by the industry without significant government funding. Possible research activities include:

- Research to identify environmentally friendly alternative cover gases to replace SF_6 for

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19 See Section 4.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-432.pdf.

20 See Section 4.3.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-433.pdf.

21 See Section 4.3.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-434.pdf.

22 See Section 4.3.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-435.pdf.

magnesium melt protection. Another possible option is to develop and deploy manufacturing processes that eliminate the need for a cover gas such as injection molding of thixotropic metal alloys (i.e., semi-solid metal casting).

- Research focused on improved process controls and computer-based operator-training tools to further reduce PFC emissions from aluminum smelting.
- Research on the potential to use pure fluorine to replace SF_6 and PFCs in chemical vapor deposition (CVD) chamber cleaning and plasma etching processes in numerous electronics manufacturing processes. Although fluorine is not a GHG, it is a toxic and corrosive substance and designing systems to use it would be a challenge.
- Research could focus on finding alternatives to the use of SF_6 in high-voltage electric transformers, switchgear and circuit breakers, and in airborne military radar systems. Alternatives include new electric equipment designs that do not require GHG dielectric gases and solid state technologies and materials that do not require dielectric gases.

Significant opportunities exist to reduce emissions. A focused RD&D program to develop safe, high-performing, cost-effective climate protection technologies could result in emission reductions of 40 percent or more over the near term and a dramatic reduction and, in some cases, elimination of emissions by key industries within a few decades.

7.4 Nitrous Oxide Emissions from Combustion and Industrial Sources

Stationary and mobile source combustion and the production of various industrial acids account for about eight percent of non-CO_2 emissions in the United States and four percent globally (EPA 2005, 2004). U.S. emissions of N_2O associated with industrial acid production declined significantly after 1996 due to voluntary industry action and could remain relatively stable. Although generally not accounted for in N_2O emission inventories, significant emissions of NO_X from combustion sources are chemically transformed in the atmosphere and are eventually deposited as nitrogen compounds, which subsequently result in emissions of N_2O in a manner similar to emissions from fertilizer application (Figure 7-8). In 2000, the U.S. N_2O emissions from combustion and industry accounted for nearly 10 percent of total non-CO_2 GHG emissions, with the combustion sources accounting for over 70 percent of these (EPA 2005). Table 7-6 shows N_2O emissions from combustion and industrial sources. R&D priorities differ between N_2O combustion and industrial sources. The priorities for reducing N_2O emissions for each of the sources are discussed below.

U.S. and Global N_2O Emissions from Combustion and Industrial Sources (2000 Emissions in Tg CO_2 Equivalent)

SOURCE	U.S. EMISSIONS	% OF TOTAL U.S. NON-CO_2 GHG EMISSIONS	GLOBAL EMISSIONS	% OF GLOBAL NON-CO_2 GHG EMISSIONS
Combustion	68	6	230	2
Industrial Sources	26	2	160	2
Total	**93**	**9**	**390**	**4**

Sources: EPA 2005, 2004.

Table 7-6. U.S. and Global N_2O Emissions from Combustion and Industrial Sources (2000 Emissions in Tg CO_2 Equivalent)

Combustion

Combustion of fossil fuels by mobile and stationary sources is the largest non-agricultural contributor to N_2O emissions. Nitrous oxide can be formed under certain conditions during the combustion process and during treatment of exhaust or stack gases by catalytic converters. Since N_2O emissions do not contribute significantly to ozone formation or other public health problems, N_2O has not been regulated as an air pollutant and has historically not been a focus of emission control research.

Potential Role of Technology

A better understanding is needed of how and when N_2O forms and how N_2O emissions can best be prevented and reduced. For both stationary and mobile combustion sources, N_2O emissions appear to vary greatly with different technologies and under different operating conditions, and the phenomena involved are poorly understood. For stationary sources, catalytic NO_X reduction technologies can reduce N_2O emissions. Other NO_X control technologies either have no impact or can increase N_2O.

Technology Strategy

A key to identifying the most promising approaches and technologies for reducing N_2O emissions is understanding how N_2O is formed during combustion and under what circumstances catalytic technologies contribute to N_2O emissions. The main research thrust in the near term is to improve scientific understanding of these basic questions.

Current Portfolio

The current Federal research portfolio on N_2O emissions from combustion is focused on better understanding the formation and magnitude of N_2O emissions from fuel combustion and catalytic-converter operation; evaluating the climate-forcing potential of atmospheric nitrogen deposition, especially from combustion; and developing emission models to assess the potential climate benefits from changes in emissions from nitrogen oxide. The goal in this area is to determine linkages of NO_X emissions from transportation combustion and catalytic-converter operation to climate-change impacts due to nitrogen deposition and develop enhanced modeling capabilities.[23]

In addition, Federal research on advanced engine/combustion technologies and alternative fuel vehicles will contribute to a reduction in N_2O emissions. Research in these areas is described in the Transportation section of Chapter 4 (Reducing Emissions from Energy End-Use and Infrastructure).

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

Limited but recent additional collection of nitrous oxide test data have provided statistically reliable emissions estimates for most gasoline-powered passenger cars and light duty trucks. It will be important to develop vehicle- and engine-testing programs to generate nitrous oxide emissions data for a variety of vehicles and engines equipped with a range of current and advanced emission-control technologies and operated over a range of real-world operating conditions, particularly for diesel engines. In addition, future research could determine the effect of catalyst formulation including noble metal loadings and compositions for alternative catalysts that result in less nitrous oxide formation. Also, an intensified research effort is needed to assess the role of airborne nitrogen compounds emitted from combustion and deposited onto the ground, and how they interact with soil-generated nitrous oxide emissions.

The development of new combustion technologies and catalyst formulations that reduce or eliminate nitrous oxide emissions will require new Federal efforts to facilitate joint public-private RD&D activities that can effectively address the reduction of nitrous oxide emissions from combustion and industrial sources. This could include research that would form the basis for identification of new technologies in the future. Some areas for near-term study are outlined below:

23 See Section 4.4.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-442.pdf.

Figure 7-8. Nitrogen oxides from combustion sources are chemically transformed in the troposphere, resulting in the formation of nitrogen compounds that are deposited on the ground. These compounds, in turn, give rise to emissions of nitrous oxide, a GHG.

Courtesy EPA

- Characterizing nitrous oxide from diesel and advanced technology engines through collaborative research between the EPA National Vehicle and Fuels Emission Laboratory (NVFEL), state air agencies and manufacturers of vehicles/engines. This research may include a variety of vehicles and engines equipped with a range of current and advanced emission control technologies and operated over a range of real-world operating conditions.
- Characterizing nitrous oxide from heavy-duty diesel vehicles that meet future (2007/2010) emission standards. Research is now being started in this area. As these vehicles will most likely use catalytic after-treatment, they may be an additional source of nitrous oxide that previously had not existed. Research on how to minimize these emissions is also needed. Emissions of nitrous oxide from combustion sources could be significantly reduced with improved catalyst technologies and other advances.

Industrial Sources

Nitric acid is an inorganic compound used primarily to make synthetic commercial fertilizer. As a raw material, it also is used for the production of adipic acid and explosives, for metal etching, and in the processing of ferrous metals. Facilities making adipic acid used to be high emitters of nitrous oxide, but now that adipic acid plants in the United States have implemented nitrous oxide abatement technologies, nitric acid production is the largest industrial source of nitrous oxide emissions.

Potential Role of Technology

The nitric acid industry currently controls NO_X emissions using both non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. NSCR is very effective at controlling nitrous oxide while SCR can actually increase nitrous oxide emissions. NSCR units, however, are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. A catalyst to reduce nitrous oxide emissions from SCR plant is being developed in the Netherlands, and a manufacturer of nitric acid is testing a catalyst for use in the ammonia burners in nitric acid plants. Both research groups claim to be capable of reducing nitrous oxide emissions by up to 90 percent and their technology can be easily installed on existing plants. These technologies could be available for commercial application by 2010. Another manufacturer has developed an integrated destruction process; however, this process is only considered suitable for use on new plants because of the high capital costs and long operational down times needed to retrofit existing plants.

Technology Strategy

Additional research is needed to develop new catalysts that reduce nitrous oxide with greater efficiency, and to improve NSCR technology to make it a preferable alternative to SCR and other control options.

Current Portfolio

The current Federal portfolio focuses on developing catalysts that reduce nitrous oxide to elemental nitrogen with greater efficiency and promoting the use of NSCR over other NO_X control options such as SCR and extended absorption. The goal in this area is to focus on development of catalysts that reduce nitrous oxide to elemental nitrogen with greater efficiency and to promote the use of NSCR over other NO_X control options such as SCR and extended absorption.[24]

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks

24 See Section 4.4.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-441.pdf.

to consider a full array of promising technology options. The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

The use of a catalyst that can reduce a higher percentage of nitrous oxide emissions might be a promising avenue for future research. Current technology is primarily implemented to reduce NO_X emissions, not to reduce nitrous oxide. In the longer term, in order to achieve further reductions in nitrous oxide emissions from nitric acid production, an advanced NSCR technology that is not energy intensive will likely need to be developed and implemented at most nitric acid production facilities.

7.5 Emissions of Tropospheric Ozone Precursors and Black Carbon

Understanding of the role of black carbon (BC) and tropospheric ozone in climate change is still evolving. Large uncertainties remain with regard to emission levels, atmospheric concentrations, net climatic effects, and mitigation potential. However, research to date indicates that these substances influence the global radiation budget, particularly at regional scales. Complicating our understanding is that BC, which tends to have a warming effect, is co-emitted with organic carbon (OC), which tends to have a cooling effect on climate, much like sulfate aerosols.

Mitigation options for BC and tropospheric ozone can already be identified in various sectors. However, for particular emission sources it is often difficult to precisely quantify the emission implications of different mitigation scenarios for these substances, and even more difficult to quantify the climatic implications of such scenarios. Activities to reduce tropospheric ozone precursors and BC will have large public health and local air quality benefits, in addition to their role in mitigating climate change. In fact, it is expected that even in the absence of climate-change-driven mitigation actions, reductions in tropospheric ozone and BC will be achieved as local and regional air quality concerns are addressed, in the United States and many other countries.

Potential Role of Technology

Ozone and particulate matter (PM), of which BC is a component, have been key targets of air pollution control efforts in the United States for many years. National, State, and local regulations have aimed at reducing the significant human health and environmental impacts from high levels of tropospheric ozone and particulate matter. Emission control programs directed toward reducing ozone have focused on the primary precursors that contribute to formation of 1-hour peak ozone concentrations in and near urban centers, such as i.e., emissions of NO_X and volatile organic compounds (VOC).

Programs aimed at reducing PM have led to significant advances in emission control technologies in the transportation, power generation, and industrial sectors, which have and will continue to reduce emissions of BC in the United States. Power plants and other large combustion sources use control technologies such as high-efficiency electrostatic precipitators, fabric filters, and scrubbers to reduce particulate matter, including BC. Regulatory efforts for other stationary sources have addressed biomass burning and include new source performance standards for residential wood heaters and limits on open and agricultural burning.

Technology Strategy

The approach to address the most significant sources of tropospheric ozone precursors and BC involve the following abatement technology areas:

- **Transportation control technologies:** PM emissions smaller than 2.5 microns (PM 2.5) from on- and off-road diesel vehicles (the largest source of BC emissions in the United States) are being targeted by stricter vehicle emission standards, where per-vehicle PM emissions are expected to be reduced by 90 percent over the next decade. Total national mobile source PM 2.5 emissions are expected, by 2020, to decline by 53 percent compared to 1996 levels and by 24 percent compared to projected 2020 baseline levels.
- **Temperature reduction in cities:** Heat islands form as cities replace natural vegetation with pavement for roads, buildings, and other

structures. There are several measures available to reduce the urban heat island effect that can decrease ambient air temperatures, energy use for cooling purposes, GHG emissions, and the chemical formation of smog (ozone and precursors). (See Urban Heat Island Technologies in the Buildings subsection of Chapter 4.)

- **Biomass burning:** Important sources of BC aerosols in the United States include combustion of not only fossil fuels but also biomass. Available options to reduce open biomass burning include changing the frequency and conditions of prescribed burning and reducing open waste burning. However, open biomass burning emits greater amounts of OC relative to BC, meaning that, from a strictly climate-carbonaceous aerosol perspective, reducing these emissions could lead to net warming.

Current Portfolio

The current Federal portfolio focuses on the representative technologies listed below. Transportation goals are focused on developing cost-effective NO_X and PM (black carbon) engine and vehicle controls, especially for diesel engines, hybrid-diesel, and gasoline drive trains for medium- and heavy-duty vehicles (Figure 7-9). Goals for temperature reduction in cities are focused on understand and quantifying the impacts that heat island reduction measures have on local meteorology, energy use, GHG emissions, and air quality. Basic research goals are focused on better understanding of the joint role of BC and OC in climate change, including establishing linkages between air pollution and climate change by enhancing modeling capabilities; designing integrated emissions control strategies to benefit climate, regional and local air quality simultaneously.[25]

- Transportation control technologies include advanced tailpipe NO_X controls (including NO_X adsorbers), particulate matter filters (traps) for diesel engines (including catalyzed traps capable of passive regeneration), and hybrid and fuel cell vehicles.
- Representative technologies for temperature reduction in cities include the following:
  - Strategically planted shade trees.
  - Reflective roofs: There are over 200 ENERGY STAR® roof products, including coatings and single-ply materials, tiles, shingles and membranes. Energy savings with reflective roofs range as high as 32 percent during periods of peak electricity demand (and average 15 percent for the summer season).
  - Reflective paving materials: There are several reflective pavement applications being developed, including new pavement and resurfacing applications, asphalt, concrete, and other material types.
- Alternatives to biomass burning include prescribed burning programs (which are directed at minimizing wildfires) and regulation or banning of open burning (such as in land clearing).

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio.

Basic research is needed to both better understand the role of black and organic carbon and tropospheric ozone precursors in climate change, and to achieve emission reductions in the near and long terms. Much of this research is a focus of the Administration's Climate Change Science Program. Some of the areas where basic research is needed include the following:

- The study of the roles of tropospheric ozone and BC and OC in global warming has begun only relatively recently. Although there are strong indications that these pollutants are important actors in climate change, much more research is needed to address the complex optical, chemical, and meteorological factors involved. For BC, this new research would be aimed at establishing more clearly how these pollutants affect solar radiation and cloud formation. For BC and tropospheric ozone, new research could focus on how

25 See Section 4.5.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-451.pdf.

atmospheric concentrations vary with geography, time, and the presence of other compounds in the atmosphere.

- Greater understanding of the use of different definitions of and measurement protocols for BC (and its differentiation from elemental carbon and organic carbon), and the implications of such differences for climate assessments, is also needed. Much of this work is underway.
- Advanced, real-time measurement techniques for fine PM and carbonaceous soot are needed. It is difficult to measure the composition, number, volume, and mass densities of nanometer-size particles at combustion sources and in the atmosphere.
- Quantification of the synergies and potential tradeoffs among GHGs, BC, OC, tropospheric ozone, and other criteria air pollutants for different mitigation options, whether these options are targeted for climate, air quality, or both issues.
- Regarding BC emissions from open biomass burning, potential mitigation options include wildfire suppression and altering prescribed burning practices. However, it remains difficult to quantify emission reduction benefits due to large uncertainties in the time dynamics of wildfires and uncertainties in emissions factors resulting from different kinds of fires. Furthermore, the climate benefits are difficult to quantify because greater amounts of OC relative to BC are emitted from biomass burning. Further research into this area could support practices that reduce both BC and OC emissions for health and regional haze concerns, while at the same time understanding the net climatic effects. This type of effort could also enhance carbon sequestration on forestlands.
- A thorough study of life-cycle GHG and particulate matter emissions is needed to resolve questions of the overall climate impacts of vehicle emissions (including CO_2 and organic carbon particles) of vehicles operating on gasoline as compared to diesel fuel (taking into account the future schedule of diesel vehicle PM standards).
- Jet fuel additives could be found that minimize emission of carbonaceous particles (e.g., black carbon/soot) from aircraft engines during take-off, landing, and cruising.

Figure 7-9. Research is needed to better understand the role of particulate matter (e.g., black carbon) emissions from combustion in climate change mitigation.

Courtesy: EPA

- Computational models of soot formation are needed to enable inexpensive design of combustion devices and their optimum operational conditions.

Research and development of alternative, non-carbon based fuels could lead to significant reductions in emissions of tropospheric ozone precursors and BC in the longer term. Additional longer-term research needs include the following:

- Efforts to develop technologies to reduce NO_X emissions from on-road heavy-duty diesel engines are moving beyond engine-based technologies to exhaust after-treatment technologies.
- For both NO_X and particulate control technologies for diesel engines, designs capable of being retrofitted onto engines in the existing fleet could significantly accelerate the heath and climate benefits of these technologies by reducing the time that is otherwise required for engines to be retired and replaced by new models.

Improved understanding is necessary to translate these measures into quantifiable reductions in ozone precursors, BC, OC, and the associated climate effects.

7.6 Summary

This chapter reviews various forms of advanced technology, their potential for reducing emissions of non-CO_2 GHGs, and the R&D strategies intended to accelerate the development of these technologies. Although uncertainties exist about both the level at which GHG concentrations might need to be stabilized and the nature of the technologies that may come to the fore, the long-term potential of advanced technologies to reduce emissions of non-CO_2 GHGs is estimated to be significant, both in reducing emissions (as shown in the figure at the beginning of this chapter) and in reducing the costs for achieving those reductions, as suggested by Figure 3-21. Further, the advances in technology development needed to realize this potential, as modeled in the associated analyses, animate the R&D goals for each technology area focused on reducing emissions of non-CO_2 GHGs.

As one illustration among many hypothetical cases analyzed,[26] GHG emissions were constrained to a high level over the course of the 21st century in such a way that a stabilized GHG concentration levels could ultimately be attained. The lowest-cost arrays of advanced technology to reduce emissions of non-CO_2 GHGs, when compared to a reference case, resulted in reduced or avoided emissions of about 150 Gt of carbon equivalent over the 100-year planning horizon. This amounted to roughly 25 percent of all GHG emissions reduced, avoided, captured and stored, or otherwise withdrawn and sequestered needed to attain this level. Similarly, the costs for achieving such emissions reductions were reduced by roughly a factor of 3. See Chapter 3 for other cases and other scenarios.

As described in this chapter, CCTP's technology development strategy supports achievements in this range. The overall strategy is summarized schematically in Figure 7-10. Advanced technologies are seen entering the marketplace in the near-, mid-, and long-terms, where the long-term is sustained indefinitely. Such a progression, if successfully realized worldwide, would be consistent with attaining the potential for reducing emissions of non-CO_2 GHGs portrayed at the beginning of this chapter.

The timing and pace of technology adoption are uncertain and must be guided by science and supported by appropriate policies (see Approach 7, Chapters 2 and 10). In the case of the illustration above, the first GtC per year (1GtC/year) of reduced or avoided emissions, as compared to an unconstrained reference case, would need to be in place and operating, roughly, around 2050. For this to happen, a number of new or advanced technologies to reduce emissions of non-CO_2 GHGs would need to penetrate the market at significant scale before this date. Other cases would suggest faster or slower rates of deployment. See Chapter 3 for other cases and other scenarios.

Throughout Chapter 7, the discussions of the current activities in each area support the main components of this approach to technology development. The activities outlined in the current portfolio sections address the highest-priority investment opportunities for this point in time. Beyond these activities, the chapter identifies promising directions for future research, identified in part by the technical working group and assessments and inputs from non-Federal experts. CCTP remains open to a full array of promising technology options as current work is completed and changes in the overall portfolio are considered.

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26 In Chapter 3, various advanced technology scenarios were analyzed for cases where global emissions of GHGs were hypothetically constrained. Over the course of the 21st century, growth in emissions was assumed to slow, then stop, and eventually reverse in order to ultimately stabilize GHG concentrations in the Earth's atmosphere at levels ranging from 450 to 750 ppm. In each case, technologies competed within the emissions-constrained market, and the results were compared in terms of energy (or other metric), emissions, and costs.

Technologies for Goal #4: Reduce Emissions of Other Gases

	NEAR-TERM	MID-TERM	LONG-TERM
Methane from Energy & Waste	• Bioreactor Landfill Technology • Methane to Markets • New Drilling Techniques for Recovery of Coal bed Methane • Leak Detection, Measurement, and Mitigation Technologies for Oil & Natural Gas Systems	• Advanced Landfill Gas Utilization (e.g., Fuel Cells, Microturbines), Cover, and Collection Technologies • Ventilation Air Methane Technology • Advanced End-Use Technologies to Use Methane at Remote Well Sites	• Integrated Waste Management System with Automated Sorting, Processing & Recycle • Automated Coal Mining to Eliminate Methane Emissions • Smart Pipes and Self-Repairing Pipelines
Methane & N_2O from Agriculture	• Anaerobic Digesters that Produce Heat and Electricity • Precision Agriculture • Improved Livestock Production Efficiency	• Better Understand Relationship among CH_4, CO_2, N_2O, N_2 & C in Agriculture • Soil Microbial Processes • Prescription Release of Nutrients and Chemicals for Crops • Genetically Designed Forages and Bacteria to Improve Digestion Efficiency	• Zero-Emission Agriculture
High GWP Gases	• Advanced Refrigeration Technologies (Distributed and Secondary-Loop) • Advanced Abatement, Recovery, and Recycling Technologies • Advanced Aluminum Smelting Processes to Reduce Anode Effect	• Alternative Refrigeration Fluids (Non-GHG) • Substitutes for SF_6 in High-Voltage Applications and Magnesium Production • Inert Anode to Eliminate PFC Emissions in Aluminum Production	• Solid-State Refrigeration/AC Systems • New Equipment and Process Designs that do not Require High-GWP Gases
N_2O from Combustion	• Catalytic Reduction of N_2O in Nitric Oxide Plants • Better Understand N_2O Emissions from Vehicles	• Catalysts That Reduce N_2O to Elemental Nitrogen in Diesel Engines • Understand Role of N Compounds from Combustion with Soils and N_2O	• Advanced Vehicles and Non-Carbon Based Fuels
Ozone Precursors & Black Carbon	• Particulate Matter Control Technologies for Vehicles • Reflective Roofs to Reduce Heat Island Effects • Better Understand Effects of Ozone Precursors & Black Carbon	• Model Linkages Between Air Pollution and Climate Change • Jet Fuel Additives to Minimize Black Carbon and Soot	

Figure 7-10. Technologies for Goal #4: Reduce Emissions of Other Gases
(Note: Technologies shown are representations of larger suites. With some overlap, "near-term" envisions significant technology adoption by 10–20 years from present, "mid-term" in a following period of 20–40 years, and "long-term" in a following period of 40–60 years. See also List of Acronyms and Abbreviations.)

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