



National Round Table on the
Environment and the Economy

Table ronde nationale sur
l'environnement et l'économie

Potential of Including Non-Combustion Sources of GHG Emissions in a Domestic Emissions Trading Program

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Technical Paper Series**

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Potential of Including Non-Combustion Sources of GHG Emissions in a Domestic Emissions Trading Program

Submitted to

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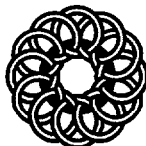


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- actively seeking input from stakeholders with a vested interest in any particular issue and providing a neutral meeting ground where they can work to resolve issues and overcome barriers to sustainable development;
- analyzing environmental and economic facts to identify changes that will enhance sustainability in Canada; and
- using the products of research, analysis and national consultation to come to a conclusion on the state of the debate on the environment and the economy.

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Executive Summary

This issues paper examines the types of emissions trading systems suitable for non-combustion sources of greenhouse gas (GHG) emissions in Canada. It presents background information and analysis of 15 non-combustion sources of GHGs, which accounted for 141 kilotonnes (kt) of carbon dioxide (CO₂) equivalent, or 23% of the total 1995 GHG emissions in Canada. The sources studied include 13 defined by Environment Canada as "non-energy" sources; these accounted for 102 kt of CO₂ equivalent in 1995. In addition, two other non-combustion sources of GHGs from the energy production sector are included, since they also generally involve fugitive emissions of GHGs.

Three primary types of emissions trading systems were considered for each of these non-combustion GHG sources. These systems are emissions rights trading, substance trading and credit trading. Various criteria were used to determine which types of trading programs would be more suitable for each situation. For each source studied, the paper discusses the source and quantity of emissions; the nature of the emissions stream; the measurability of the emissions; some options for emission reductions; and the suitability for emissions trading. The following table summarizes the key data in this study.

Suitability of Trading Systems for Non-Combustion Sources						
Non-Combustion GHG Source	Gas	No. of Sources	Total (kt CO ₂ eq.)	Emissions Rights Trading	Substance Trading	Credit Trading
Upstream oil & gas*	CH ₄ , CO ₂	>100,000	47,350	✓		✓
Landfills	CH ₄ , CO ₂	10,000	18,250	✓		✓
Enteric fermentation	CH ₄	30,000	15,225			✓
Adipic acid production	N ₂ O	1	10,850	✓		✓
Undiff'd petroleum uses	CO ₂	10-50	10,000			
Aluminum smelting	CO ₂ , PFCs	11	9,600	✓		✓
Lime & cement	CO ₂	45	7,630	✓		✓
Livestock manure	CH ₄	35,000	5,700	✓		✓
Fertilizer use	N ₂ O	12	4,030		✓	
Ammonia (less urea)	CO ₂	10	3,800	✓		✓
Agricultural soils	CO ₂	>100,000	2,480			
Magnesium smelting	SF ₆	<10	1,890		✓	
Coal mining*	CH ₄	28	1,700	✓		✓
Nitric acid production	N ₂ O	9	930	✓		✓
Other fluorocarbon uses	SF ₆ , PFCs, HFCs	Millions	500		✓	
Other			1,450			
Total (kt CO ₂ eq.)			141.385			

Note: * Fugitive emissions from energy production operations.

1. Introduction

1.1 Context and Purpose

The National Round Table on the Environment and the Economy (NRTEE) has established a multistakeholder expert group to design and assess different options for a domestic emissions trading program for greenhouse gases (GHGs). Its work will help to inform the public debate on emissions trading and also provide valuable input for assessing ways to implement the Kyoto Protocol when the national multistakeholder post-Kyoto process begins to address domestic emissions trading in detail.

This issues paper is one of a series of papers that discuss possible mechanisms to address key issues that must be considered in the design of a variety of potential emissions trading systems for GHGs. The purpose of this paper is to assess the types of domestic GHG emissions trading programs suitable for various non-combustion sources of GHG emissions. Specifically, the paper assesses each of 15 non-combustion sources of GHG emissions in terms of:

- their emissions;
- the nature of the emitting “sector” (e.g., number of participants);
- the potential to monitor and measure future GHG emission reductions in those “sectors” for the purposes of emissions trading;
- options to reduce emissions from those sectors; and
- their potential to be included in a domestic GHG emissions trading program.

The 15 emission source areas addressed in the paper represent approximately 99% of the GHG emissions

attributed to non-combustion sources in Environment Canada’s 1995 Greenhouse Gas Inventory.¹

1.2 Non-Combustion Sources of GHG Emissions in Canada

In 1995, total GHG emissions in Canada were 619 million tonnes (Mt) of carbon dioxide (CO₂) equivalent, representing approximately 2% of the global total. Carbon dioxide is the primary GHG, representing 81% of total GHG emissions in Canada. The other GHGs defined by the Framework Convention on Climate Change include methane (CH₄), nitrous oxide (N₂O), and three types of fluorocarbons: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆).

The six types of GHGs have different abilities to trap heat in the atmosphere and different atmospheric lifetimes. The concept of global warming potential (GWP) has been developed as the relative measure of the warming effect of a GHG on the atmosphere versus the effect of carbon dioxide.² Each GHG has its own 100-year GWP ratio, which allows comparison between different GHGs. By definition, carbon dioxide has a GWP of 1. Methane has a GWP of 21 and nitrous oxide has a GWP of 310. The fluorocarbons generally have high GWPs, most of which are above 1,000. The most common hydrofluorocarbon is HFC-134a, which has a GWP of 1,300. The most common perfluorocarbon is CF₄, which has a GWP of 6,500. Sulphur hexafluoride has a GWP of 23,900. The high GWPs of the fluorocarbons mean that very small volumes of gases can have significant global warming effects.

1 A. Jaques et al., *Trends in Canada’s Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

2 GWP is defined as the time-integrated change in radiative forcing (warming effect) due to the instantaneous release of 1 kg of a trace gas expressed relative to the radiative forcing from the release of 1 kg of CO₂. While any time period can be chosen for comparison, the 100-year GWP is used as a standard.

The GWP issue is particularly important in the relationship between carbon dioxide and methane. One kilogram (kg) of methane has 21 times the GWP of 1 kg of carbon dioxide. However, when fully combusted (oxidized), 1 kg of methane creates 2.75 kg of carbon dioxide. If methane that is vented to the atmosphere can be captured and oxidized to carbon dioxide, the global warming effect can be reduced by 7.6 times.

This study addresses all non-combustion sources of GHGs in Canada, which produced a total of 141 Mt of CO₂ equivalent in 1995, or roughly 23% of the total GHG emissions in Canada. All emission volumes in this analysis are based on the 1995 Greenhouse Gas Inventory by Environment Canada.³ The sources covered are summarized in the following table. The GHG emissions from non-combustion sources include those from non-energy sources (102 Mt of CO₂ equivalent) and fugitive emissions of GHGs from energy sources such as oil, gas and coal production (39 Mt of CO₂ equivalent). In comparison, combustion sources of GHG emissions (led by transportation, power generation and industrial energy) accounted for about 77% of total GHGs in Canada.

Non-combustion emissions of GHGs are usually calculated using estimated emission factors applied to activity level data. In many cases, the emissions are fugitive in nature, and the emission factors can have high levels of uncertainty. For many of the sources in this report, an error level of $\pm 30\%$ is considered quite good.

A significant portion of non-combustion GHG emissions come from sources emitting GHGs other than carbon dioxide. Methane makes up the largest portion (on a CO₂ equivalent basis) of non-combustion GHG emissions, accounting for about 55% of the 141 Mt total, while carbon dioxide accounted for only 28%.

Fugitive emissions from energy (oil, gas and coal) production accounted for roughly 34% of the total non-combustion emissions. Various industrial sources accounted for another 34% of the total. These include non-ferrous metals (aluminum and magnesium) production, lime kilns (including kilns at cement and kraft pulp and paper mills), and the petrochemicals and chemicals industry (i.e., adipic and nitric acid production). Approximately 17% of non-combustion GHG emissions originate from agricultural sources, namely enteric livestock fermentation, manure decomposition, fertilizer application and soils. Thousands of landfills across Canada contribute approximately 13% to the total. Other non-combustion emissions result from the use of a variety of fluorocarbon gases: HFCs for refrigerants, sulphur hexafluoride in electrical switchgear and PFCs for cleaning.

3 A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

Canada's Non-Combustion Sources of GHG Emissions, 1995

(includes fugitive emissions of CO₂ and CH₄ from energy sources)

Non-Combustion Source	CO ₂	CH ₄	N ₂ O	Others*	Total
	(kt)	(kt)	(kt)	(kt)	(kt CO ₂ eq.)
Upstream oil & gas*	10,600	1,750	0		47,350
Landfills		869	0		18,250
Livestock: enteric fermentation		725	0		15,225
Adipic acid production			35		10,850
Other non-energy petroleum uses	10,000		0		10,000
Aluminum smelting (CO ₂ & PFCs)	3,600		0	1	9,600
Lime, limestone & cement	7,630		0		7,630
Livestock: manure		271	0		5,700
Fertilizer use			13		4,030
Ammonia (less urea)	3,800		0		3,800
Agricultural soils	2,480		0		2,480
Magnesium smelting (SF ₆)			0	<<1	1,890
Coal mining*		82	0		1,700
Nitric acid production			3		930
Other uses of SF ₆ , PFCs and HFCs			0	3	500
Other	490	15	0		1,450
Total (kt actual)				n/a	
Total (kt CO ₂ eq.)	38,600	77,952	15,810	~9,000	141,385

Note: * Fugitive emissions from energy production operations.

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

1.3 Criteria for Evaluating the Potential of GHG Emissions Trading

Cheminfo applied criteria (developed by Dr. Erik Haites of Margaree Consultants⁴) to the various GHG emission sources that were the focus of this study. These criteria were used to determine whether the specific GHG emission sources were amenable to any of the following GHG emissions trading programs:

1. emissions rights trading;
2. substance trading; and
3. credit trading.

1.3.1 Emissions Rights Trading

An emissions rights trading system limits aggregate emissions of a GHG by specified sources at the point of release to the atmosphere. An annual cap on specified GHG emissions by the regulated sources is established, and emission allowances equal to the

⁴ Much of this section was provided by Dr. Erik Haites, Margaree Consultants.

annual cap are allocated to participating sources. Each source is required to monitor its actual emissions and to remit emission allowances equal to its actual emissions to the party that is managing the trading program. Due to the cost of monitoring actual emissions, participation probably would be limited to utilities and large industrial sources. This limitation, however, might result in a significant fraction of the total emissions not being monitored, and the system might have to be complemented by policies to address GHG emissions from smaller sources.

1.3.2 Substance Trading

An allowance trading system can be implemented for substances (such as HFCs, the carbon content of fossil fuels and the nitrogen content of fertilizers) that are ultimately emitted as GHGs. Such a substance trading program is essentially a quota on consumption of the regulated substance. An annual cap on the total quantity of the substance consumed (production + imports - exports) in the country is established. In general, it is important to implement this consumption quota or cap as close as possible to the point at which emissions occur, to provide the widest possible range of mitigation options. All producers, importers and exporters of the substance (or products containing the substance) are required to participate in the program by trading these consumption quotas.

In some cases, the substance whose quotas are being traded might be the same as the GHG emissions being controlled. An example is sulphur hexafluoride, which is a GHG as well as a substance used in various industries leading to those GHG emissions.

The main effect of a substance trading program is to change the prices of products containing the substance. Price increases for fertilizers due to a nitrogen content trading system induce farmers to change their patterns of fertilizer use. Similarly, price increases for fossil fuels due to a carbon content trading system induce customers to switch to less carbon-intensive fuels and to implement energy conservation measures. And price increases for HFCs induce a shift to substitutes.

1.3.3 Credit Trading

In a credit trading system a source can create "credits" by documenting emission reductions achieved. The credits can be sold to other sources to use for regulatory compliance under specified conditions. Credit creation and use are voluntary. Sources may choose to buy credits if they are less costly than alternative compliance options.

A credit trading system supplements voluntary or regulatory policies. A package of voluntary and regulatory policies and measures would be implemented to meet the national GHG emissions limitation commitment. If credit trading is allowed, some sources reduce their emissions below the level required by the applicable voluntary and regulatory policies and measures. Other sources buy credits to achieve compliance with the voluntary or regulatory policies and measures under specified conditions.

Evaluation Criteria to Determine Suitability for Inclusion in GHG Emissions Trading Programs

Emissions Rights Trading	Substance Trading	Credit Trading
<ul style="list-style-type: none"> • actual emissions can be measured or calculated accurately at reasonable cost by the sources 	<ul style="list-style-type: none"> • the substance is a good proxy for actual GHG emissions 	<ul style="list-style-type: none"> • actual emissions can be measured or calculated accurately at reasonable cost by the sources
<ul style="list-style-type: none"> • sources are able to implement measures to change their actual emissions 	<ul style="list-style-type: none"> • the quantity of the substance can be measured or calculated accurately at reasonable cost 	<ul style="list-style-type: none"> • sources are able to implement measures to change their actual emissions
<ul style="list-style-type: none"> • a relatively large share of the total emissions of this gas/source category can be controlled by regulating a reasonable number of sources 	<ul style="list-style-type: none"> • production, sale or use of the substance can be controlled by regulating a reasonable number of entities 	<ul style="list-style-type: none"> • a realistic baseline for emissions in the absence of the emission reduction actions can be defined
	<ul style="list-style-type: none"> • a relatively large share of the total emissions of this gas/source category can be controlled by regulating a reasonable number of entities 	<ul style="list-style-type: none"> • a relatively large share of the total emissions of this gas/source category can be controlled by regulating a reasonable number of sources

Some gases/sources lend themselves to more than one form of GHG emissions trading. In these instances, the gases/sources were compared on the basis of the share of emissions covered (i.e., higher coverage is better) and number of participants (fewer is better). For example, a trading program for the carbon content of fossil fuels will cover a larger share of total energy-related CO₂ emissions with fewer sources than either an emissions rights program or a credit trading program for CO₂ emissions by large industrial, commercial and institutional sources.

1.4 Methodology

To prepare this study, Cheminfo drew upon information gathered in support of a previously completed Cheminfo study entitled *Powering GHG Reductions Through Technology Advancement*, which was completed for Environment Canada in April 1998. That study discussed the respective non-energy emission sources in Canada, the options to reduce their emissions and the research and development necessary to advance these options so that they are

technically and economically feasible. The content of the final report for that study was drawn upon in several instances to assess the emissions trading potential of the various non-energy GHG-emitting sources. In addition, information contained in the reports, journal articles, interview notes, etc. that were gathered/developed in support of the Environment Canada study was also utilized to incorporate specific information pertinent to the assessment of the emissions trading potential of the various non-energy GHG-emitting sources.

Three specific GHG-emitting sources were not covered in Cheminfo's previous study for Environment Canada: (i) soils, (ii) oil and gas operations, and (iii) coal mining. Additional research was conducted to characterize their emissions; to identify and assess options to reduce their GHG emissions; and to describe their industry structure. Emissions from oil and gas production and distribution operations and from coal mining are mostly fugitive (non-combustion) carbon dioxide and methane emissions that Environment Canada includes under energy sources.

Approximately 15 interviews were conducted during the course of this study to gather information that was not available through Cheminfo's previous study for Environment Canada. This information focused on a number of topics, including uncertainty levels for GHG emission estimates attributed to certain emission sources; activity data/industry structure in the respective non-energy "sectors"; and data pertaining to the measurement/monitoring of GHG emissions from those "sectors." In addition, several interviews were conducted to gather information on those GHG emission sources that Cheminfo had not previously assessed.

Cheminfo worked with Dr. Erik Haites of Margaree Consultants to develop the set of criteria for determining which of the various GHG-emitting sources were suitable for inclusion in a domestic emissions trading program and to identify the most appropriate trading scheme. Once the criteria were developed, Cheminfo and Dr. Haites applied these criteria to the 2 energy-related and 13 non-energy GHG-emitting sources that were the focus of this study.

2. Upstream Oil and Gas

2.1 Source and Quantity of GHG Emissions

The Canadian oil and gas sector produces most of the fossil fuel that is the source of the majority of greenhouse gas (GHG) emissions from combustion sources in Canada. However, the oil and gas sector is also a significant source of process or fugitive GHG emissions from non-combustion activities. Methane (CH₄) and carbon dioxide (CO₂) are two naturally occurring GHGs that are emitted from various sources within the oil and gas sector. According to data compiled for Environment Canada's 1995 Greenhouse Gas Inventory, the oil and gas sector emitted an estimated 47,350 kilotonnes (kt) of CO₂ equivalent. This represents about 8% of total Canadian GHG emissions and the largest sectoral contribution to non-combustion GHGs in Canada, accounting for 34% of the total.

Fugitive Emissions from Oil and Gas Operations			
Source	CO₂	CH₄	Total
	(kt)	(kt)	(kt CO₂ eq.)
Oil production	0	500	10,500
Gas production	10,600	600	23,200
Gas transmission	0	500	10,500
Gas distribution	0	150	3,150
Total	10,600	1,750	47,350

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

2.1.1 Emission Sources

The largest source of fugitive GHG emissions from the oil and gas sector is natural gas production. In 1995, a total of 193 billion cubic metres of natural gas were produced in Canada. Both methane and carbon dioxide are emitted from this source. An estimated 600 kt of methane is emitted from the collection and processing of natural gas (equivalent to about 13,000 kt of CO₂). The sources of this methane are the 45,000 natural gas wells and roughly 650 natural gas processing plants operating in Canada in 1996.

Carbon dioxide is present in raw natural gas at levels as high as 26%, and must be removed at the gas processing plant to meet pipeline specifications. The amount of carbon dioxide emitted from natural gas processing is calculated at 10,600 kt, based on an assumed average carbon dioxide content of 7%.

These emissions come from the estimated 650 natural gas processing plants in Canada. Most of these emissions are concentrated in Alberta, which has 550 major installations processing natural gas and accounts for 84% of total Canadian gas production. British Columbia and Saskatchewan are the other two significant provincial sources.

In crude oil production, an estimated 500 kt of methane were emitted from processing activities. These include fugitive leaks, non-combustion equipment exhaust and production upsets. Roughly

70% of calculated methane emissions from crude oil production come from the processing of heavy oil, despite the fact that heavy oil accounts for only 20% of total production. There were an estimated 55,000 oil wells operating in Canada at the end of 1996. Usually, several wells are connected to a crude oil battery, where gases are separated from liquids. Again, crude oil methane emissions are concentrated in Alberta, which has 85% of Canadian oil production. Saskatchewan is the second largest provincial source, having 10% of Canadian oil production.

In long-distance natural gas transmission, an estimated 500 kt of methane were emitted. The principal source of emissions is fugitive leakage and pipeline and compressor station blowdown. The country's network of natural gas pipelines stretches from British Columbia to Quebec, and there are methane emissions from each province. Alberta has the largest volume of natural gas pipelines and accounts for 37% of transmission emissions. Since the major volume of gas flows east from Alberta to Ontario, the provinces of Saskatchewan, Manitoba and Ontario have decreasing shares of transmission pipeline methane emissions.

The natural gas distribution networks supplying end users have relatively low levels of methane losses. An estimated 150 kt of methane was lost from the natural gas distribution network. The largest source of these emissions is Ontario, which has the largest

Regional Distribution of Oil and Gas GHG Emissions				
	Oil Production	Gas Production	Gas Transmission	Gas Distribution
Alberta	85%	84%	37%	17%
Saskatchewan	10%	5%	23%	4%
B.C.	2%	11%	4%	13%
Manitoba	—	—	17%	3%
Ontario	—	—	16%	35%
Quebec	—	—	2%	21%
Atlantic Canada	—	—	—	—

Source: Natural Resources Canada, *Canada's Energy Outlook* (Ottawa, 1997).

volume of natural gas consumption in Canada, due to the large population and industrial base. The Canadian Gas Association, which represents natural gas distribution utilities, reports that total methane losses are 0.13% of marketable production, which in 1995 was 148 billion cubic metres. This volume is lower than the total Canadian production cited above, due to exports.

2.1.2 Industry Structure

There are an estimated 450 exploration and production companies operating in the Canadian oil and gas sector. This sector has a high level of concentration, due to the high degree of capital investment required and its risky nature. The top 8 major companies account for about half of total production and the next 18 senior companies add another 25%. Together, the two groups of 26 companies (6% of the total companies) produce 76% of the oil and gas in Canada.

Natural gas transmission is controlled by approximately five large companies that are regulated by the provincial and federal governments. Two significant pipeline companies are TransCanada Pipelines of Calgary and Westcoast Transmission of Vancouver.

There are fewer than 10 major natural gas distribution utilities in Canada, which supply gas to industrial, commercial and residential end users. Each company operates specific pipeline networks based on distribution rights for specific regions. Some of the major gas utilities include Consumers Gas (south-central Ontario), Union Gas (southwest Ontario), and Gaz Métropolitain (Quebec).

2.2 Nature of the GHG Emissions Stream

In oil and gas production, fugitive methane emissions can occur at various points from the wellhead through the battery to the gathering systems. Most methane gas present in oil is emitted from wellheads, separators, venting and flaring and from other treatment equipment. Some methane emissions come from crude oil storage tanks.

In natural gas production, processing plants are used to remove impurities such as carbon dioxide, hydrogen sulphide and water from the raw gas. Hydrogen sulphide and carbon dioxide are removed from raw gas using amine treatment systems in gas processing plants. The carbon dioxide is separated from the hydrogen sulphide gas and released at a point source. Methane emissions, however, are fugitive and can come from many points between the wellhead and the transmission pipeline.

Concentration in the Canadian Oil and Gas Sector (exploration and production companies)			
Type of Company	Production Range (000s BOE/d)	No. of Companies	Share of Production
Major companies	100-400	8	51%
Seniors	20-100	18	25%
Mediums	5-20	27	8%
Juniors	2-5	47	6%
Others	<2	350*	10%
Total		450*	100%

Notes: * estimate; BOE/d = barrels of oil equivalent per day (an energy-based conversion).

Source: Employment and Immigration Canada, *Human Resources in the Upstream Oil & Gas Industry* (Ottawa, September 1992).

In natural gas transmission, methane emissions come from equipment at compressor stations (blowdown vents, compressor packing, seals and valves) or from leaks along the pipeline. There are no true point source emissions. Fugitive emissions from natural gas distribution come from equipment at gate stations and pipeline leaks.

2.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

In oil production, the methane content of the oil in any well is known from chemical analysis upon well completion. However, since a large portion of methane emissions in the wellhead, collection and processing system are fugitive, it is very difficult to measure emissions on a regular basis. Rough emission factors are used for the entire sector, not for individual sites.

The same is true for methane emissions from natural gas production. Methane emissions occur at various parts of the system and are not present in a measurable point source stream. Calculation of losses tends to be done based on calculations in methane mass balances. Since the amount of methane in and out of a processing system is calculated based on gas flow rates and gas composition measured by gas chromatographs, the measurement error could easily be greater than the magnitude of the methane loss.

Carbon dioxide emissions from natural gas stripping are measurable, however, since carbon dioxide is stripped out of natural gas in a processing plant and is present in a single point source off-gas stream.

Methane emissions from transmission and distribution systems are somewhat easier to calculate from mass balances, because the volumes are larger and more accurate metering systems are used.

2.4 Options to Reduce GHG Emissions

For carbon dioxide stripped from natural gas, there are few options for reducing emissions. The gas must be removed at the processing plants to meet pipeline specifications. Often these plants are decentralized, and the volumes of carbon dioxide are too small to justify long-distance carbon dioxide pipelines for capture, recovery and possible sequestration.

For methane emissions from oil production and from natural gas production, transmission and distribution, losses can be reduced by improving operating practices. Better leak detection and repair programs, capture and recovery of system blowdowns, and better flaring systems can be used. Since methane emissions from natural gas companies represent losses of marketable product, there is already a strong incentive to reduce emissions.

2.5 Suitability for GHG Emissions Trading

A GHG emissions trading program would be difficult to impose on carbon dioxide emissions from natural gas, because carbon dioxide must be removed from the natural gas, and there are currently no economically feasible control options available. However, the carbon dioxide stream is a point source that is measurable with some accuracy.

It would be difficult to establish emissions rights trading or credit trading programs for fugitive methane emissions from oil production and from the production, transmission and distribution of natural gas because of the difficulty of accurate calculations. Moreover, substance trading programs make no sense for these sources, since the methane substance is either a small part of, or the major constituent of, the marketable product.

An emissions rights or credit trading program is more suitable for gas transmission and distribution operations, because the emissions are more easily

calculated on an overall basis and the number of entities is lower. Since throughput can be variable, a rate-based methane credit trading system would likely be preferable, since methane emissions are often expressed as a percentage of throughput or marketable production. This would give transmission and distribution utilities additional incentive to reduce losses.

3. Landfills

3.1 Source and Quantity of GHG Emissions

Methane (CH₄), carbon dioxide (CO₂), minor amounts of oxygen and nitrogen, trace amounts of hydrogen sulphide, hexane, 1-1-1-trichloroethane, methylene chloride, and other volatile substances result from the decomposition of solid waste and are released from waste-containing landfills. This mix of substances is referred to as landfill gas (LFG).

In 1995, landfills accounted for a total of 869 kilotonnes (kt) of methane emissions (18,249 kt of CO₂ equivalent), which represented approximately 13% of total non-combustion greenhouse gas (GHG) emissions in Canada, as well as 3% of total Canadian GHG emissions.

Environment Canada's estimates do not explicitly detail the carbon dioxide directly emitted from landfills, nor the carbon dioxide emitted due to the flaring of some of the methane. It is estimated that these emissions contribute approximately 4 kt of carbon dioxide annually. These emissions are not outlined in the table above. It is believed that Environment Canada accounts for these emissions at other points in the GHG lifecycle, and it is assumed they are included in the department's annual GHG emissions inventory.

3.2 Nature of the GHG Emissions Stream

Methane is generated from landfills by the anaerobic decomposition of waste organic matter by anaerobic bacteria. Under anaerobic conditions, the products of decomposition are methane, carbon dioxide and stabilized organic material.

There are upwards of 10,000 landfill sites in Canada.⁵ While some jurisdictions have information on landfill sites they manage, a comprehensive inventory of landfill sites in Canada has yet to be conducted. Such an inventory would be useful to identify and better characterize GHG emissions, and to establish priorities for action plans in this area. There are several different sizes of landfills, with the GHG emissions profile varying within each of these categories.

While there are thousands of individual landfills located in Canada, methane emissions are concentrated at a handful of sites. For instance, there are approximately 100 to 200 medium and large-sized landfills in Canada, which combined emit approximately 65% of Canada's methane emissions from landfills (this is after some methane is captured by these landfills).

Typically the ratio of methane to carbon dioxide is approximately 50:50 on a volume basis in LFG, but can range substantially from one landfill to another, as well as over the lifespan of a landfill site. A portion of the methane available in LFG is already being captured and oxidized to carbon dioxide. As of December 1995, there were approximately 25 to 30 landfill sites in Canada where LFG extraction systems (see options to reduce GHG emissions below) had been installed or were under construction. The amount of methane reduction has been estimated at 270 kt or 5,700 kt of CO₂ equivalent.⁶ At nearly half of these sites, methane is collected and utilized as an

5 A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

6 Hickling, Emcon Associates, *Options for Managing Emissions from Solid Waste Landfills*, prepared for Solid Waste Management Division and Air Issues Branch, EPS, Environment Canada (Ottawa, 1994).

Trends in CH₄ Emissions from Landfills in Canada		
Year	CH₄ Emissions	CO₂ Equivalent Emissions
	(kt)	(kt)
1990	821	17,241
1991	812	17,052
1992	826	17,346
1993	845	17,745
1994	855	17,955
1995	869	18,249

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

Estimated Emissions and Reduction Potential from Different Landfill Sizes			
Size of Landfill (Mt of waste)	Estimated Number of Landfills in Canada	Range of Annual Methane Production (kt/yr/landfill)	Portion of Total (869 kt/yr) Methane Generated
Small (less than 2)	7,000 to 10,000	0 to 10	35%
Medium (2 to 8)	30 to 100	5 to 75	50%
Large (greater than 8)	10 to 20	10 to 120	15%
Total/overall	~10,000		100%

Note: Estimates are very rough and are meant to indicate the weight of emissions from different-sized landfills.

Source: Cheminfo Services, *Powering GHG Reductions Through Technology Advancement*, prepared for Environment Canada (Ottawa, 1998).

energy source for heating purposes or for generating electricity. At the other sites, the LFG is flared.

Most of the very large sites (landfills with greater than 8 Mt of waste capacity) already have gas collection and treatment facilities. There may be a few very large sites that have yet to install collection and treatment systems. A small percentage of the medium-sized landfills (between 2 Mt and 8 Mt of waste capacity) have installed collection and treatment systems. It is estimated there may be between 30 and 100 sites across Canada in this category. A small portion (less than 5%) of the thousands of small sites (less than 2 Mt of waste capacity) across Canada have installed gas collection systems.

3.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Environment Canada estimated methane emissions from landfills in Canada by utilizing the U.S. Environmental Protection Agency's landfill gas generation model and data on the quantity of refuse deposited in Canadian landfills over each of the past 50 years. This model takes several characteristics, such as mass of refuse and age of the landfills, into account to estimate methane emissions. Based on this methodology, Environment Canada has indicated

that the uncertainty factor for this emission estimate is +/-30%, which is one of the more accurate emission estimates among non-energy GHG sources.

Since the majority of methane emissions are concentrated among a relatively small number of landfills (i.e., 100 to 200), there is potential to assess the progress of methane emissions reduction from landfills by monitoring these landfills and their attempts to reduce methane emissions. These larger landfills account for the majority of GHG emissions.

3.4 Options to Reduce GHG Emissions

Several different technologies are available to reduce methane emissions at landfills. While many of the landfills have already adopted some of these technologies, additional methane emission reductions are possible at several of the individual landfills and among the sector as a whole. Some options to reduce GHG emissions from landfills include flaring the methane; collecting the methane in the LFG and using it as a fuel; and reducing waste generation.

The basic technology infrastructure for addressing emissions and utilizing methane available at large landfill sites already exists and has been applied successfully at sites in Canada, the United States and other countries. However, technology to lower the costs of addressing small sites where the rate of methane emissions is low needs to be researched and developed.

The costs of reducing GHG emissions from landfills relate to the level of emissions reduction desired, as well as the technology options adopted. A low cost option to achieve a 20% to 30% reduction is to capture, collect and flare (i.e., oxidize) the methane generated from the largest sites. This option has no associated direct financial incentive. Some of the landfills generate enough methane to support a larger

investment in gas utilization equipment, such as electrical generating equipment. This option is more capital-intensive but can provide a return to investors through sale of the electricity. The greatest portion of the costs in achieving a higher (additional 10% to 20%) level of GHG reduction is associated with reducing emissions from thousands of small landfills spread across Canada. Even flaring at these sites could cost hundreds of millions of dollars.

3.4.1 Flaring

Landfills (or celled portions of the landfill) are usually capped with an impermeable layer to prevent gas from escaping and to prevent oxygen from infiltrating and affecting the anaerobic methane-generating bacteria. Thick layers of soil, clay and synthetic polymeric geomembranes are used to create capping layers and retaining walls around the site. These precautions maximize the efficiency of the collection system.

Gas collection systems consist of drilled wells or horizontal trenches, interconnecting pipes and a compressor creating negative pressure on the system to ensure gas flows to a central collection point. The efficiency of the system (percentage of methane recovered) will vary depending on the design. While some well-designed systems can achieve close to 100% efficiency, 70% to 80% is more typical. Gas can also be recovered from unsealed landfills with lower efficiency.⁷

Flaring is a simple and low cost option to reduce methane emissions from landfills. This reduction option can achieve a significant reduction in GHG emissions, since the methane is oxidized to carbon dioxide, reducing the overall global warming potential of the emitted gas. The efficiency of the flare system can be as high as 98%. A disadvantage of this system is that the methane is not used as a fuel. Flaring can be used as a stand-alone control option or as a backup with energy recovery systems. Energy

⁷ U.S. Environmental Protection Agency, *Options for Reducing Methane Emissions Internationally, Volume I: Technology Options for Reducing Methane Emissions, Report to Congress* (Washington, D.C., July 1993).

recovery systems that cannot fully utilize the methane fuel may need to flare the stream intermittently.

Flaring can occur in an open or closed flare. Closed flaring systems offer better control of air (oxygen) and gas flow to maximize the efficiency of the combustion process and achieve the greatest GHG reduction. Closed flaring is aesthetically preferable, and can be more easily maintained and tested for operating efficiency and emissions. However, the cost of a closed flaring system can be 5 to 10 times more than that of an open unit.

On a weight basis, the GHG reduction level possible with flaring systems is 87% of the methane oxidized. (Carbon dioxide generated from oxidizing methane lowers the GHG reduction potential.) The reduction efficiency of the process is also affected by the capture efficiency of the LFG. This may lower overall GHG reduction to approximately 30% to 70% for a particular site, and will be influenced by the design of the gas containment and collection systems.

3.4.2 Methane Utilization

Instead of simply being flared, the methane stream collected from landfill gas can be used as an energy source for applications such as:

- electricity generation;
- co-generation of steam and electricity;

- supply into natural gas distribution systems for heating; and
- compressed methane for transportation fuel.

The larger landfill sites in Canada are more likely to have installed electricity generating equipment. Medium-sized facilities tend to utilize the LFG for heating, often selling to a nearby industrial user. In many cases, these landfills have the option of flaring the LFG if customer requirements are less than the generation rate. Smaller facilities, generally with lower rates of production, merely flare the LFG, without any energy recovery. In 1995, approximately 40% of Canadian landfills with collection systems operated flaring systems only.

3.4.3 Reduced Waste Generation and Landfilling

Reducing waste can reduce the amount of methane emitted from landfills. There are several general approaches to achieving lower waste generation and landfilling. One approach is to divert organic waste products that generate methane during anaerobic degradation to municipal composting systems that capture methane. Another approach is to increase the use of alternative disposal methods, such as aerobic composting and waste incineration (which may produce CO₂ but lesser quantities of methane).

Estimated Capital and Operating Costs for Flaring Systems (order-of-magnitude estimates only — will vary substantially site to site)				
Landfill Capacity (Mt)	Capital Costs	Annualized Capital	Annual Operating	Total Annualized Costs
Less than 2	\$100,000	\$20,000	\$3,000	\$23,000
Between 2 and 8	\$150,000	\$23,000	\$4,600	\$27,600
Greater than 8	\$200,000	\$35,000	\$7,000	\$42,000

Note: Excludes collection system.

Source: Based on cost equations developed by the U.S. Environmental Protection Agency, as well as simplifying assumptions on methane flow rate from landfills. See Hickling, Emcon Associates, *Options for Managing Emissions from Solid Waste Landfills*, prepared for Solid Waste Management Division and Air Issues Branch, EPS, Environment Canada (Ottawa, 1994).

3.5 Suitability for GHG Emissions Trading

Credit trading was determined to be the most applicable emissions trading program for GHGs released from landfills. Both large and small landfills could be included in the credit trading program. However, large landfills would verify their credits by installing meters (if not installed already), whereas small landfills would have their credits verified through the application of emission factors and the accepted landfill gas generation model.⁸ Because the amount of waste being shipped to landfills is continually increasing, a credit trading program using an emission rate baseline would be preferred over a baseline of total GHG emissions. This would give landfill operators more flexibility to continue to expand the size of their landfills yet still undertake measures to obtain credits for reduced GHG emissions.

The majority of GHG emissions (i.e., approximately 65%) originate at a relatively small number — estimated at between 100 and 200 — of landfills in Canada. The remaining 35% of emissions are dispersed among thousands of sites. Therefore, a large proportion of the total emissions from this source could be controlled/monitored by addressing a relatively small proportion of the total landfill population.

Many of the larger sources (i.e., large and medium-sized landfills) have installed methane capture systems, making possible relatively accurate estimates of potential and actual emissions. Landfills have one of the more accurate (represented by uncertainty levels) GHG emission estimates attributed to non-energy GHG sources as reported in Canada's latest

GHG inventory. Therefore, a relatively accurate projection of future GHG emissions from this source could be made, assuming the available GHG mitigating options were not installed. This would allow for a process whereby relatively accurate credits for action taken (i.e., GHG mitigated) could be estimated and applied to those landfills that undertake those actions.

An emissions rights trading program would also be suitable for landfills, since the characteristics of landfills in Canada meet the criteria outlining appropriate sources for an emissions rights trading program. Moreover, emission reductions could be relatively easily verified at large and medium-sized landfills. However, while an emissions rights trading program should not be discounted, the credit trading program was deemed more appropriate, because of the potential to accurately estimate credits for action taken to reduce GHG emissions.

The substance trading program was discounted because there is no substance that is an appropriate proxy for the GHG emissions from landfills. The logical candidate would be the quantity of refuse handled over a specific time period. However, GHG emissions vary widely among the different types of refuse sent to landfills. Therefore, using data on the quantity of refuse would not provide accurate estimates of GHG emissions/reductions. Instead data would need to be developed on the quantities of the different types of refuse sent to landfills. This information-gathering process could be quite costly and still would not yield accurate estimates of GHG emissions.

⁸ U.S. Environmental Protection Agency, Scholl Canyon Landfill Gas Generation Model.

4. Enteric Fermentation

4.1 Source and Quantity of GHG Emissions

In Canada, beef cattle produce the majority of methane (CH₄) emissions attributed to enteric fermentation. This large contribution is due to the size of the herd population and the high emission rates per head compared with other livestock such as swine and horses. Poultry contribute negligible amounts of enteric methane emissions. In 1995,

enteric fermentation accounted for a total of 725 kilotonnes (kt) of methane emissions (15,225 kt of carbon dioxide [CO₂] equivalent), which represented approximately 11% of total non-combustion greenhouse gas (GHG) emissions in Canada as well as 2.5% of total Canadian GHG emissions.

Both ruminant (e.g., cattle, sheep) and non-ruminant (e.g., swine, horses) agricultural livestock generate methane emissions. Most of the methane is generated from ruminant animals, in which microbial metabolism of nutrients is the major source of the gas.⁹

Year	CH ₄ Emissions (kt)	CO ₂ Equivalent Emissions (kt)
1990	646	13,566
1991	650	13,650
1992	641	13,461
1993	671	14,091
1994	701	14,721
1995	725	15,225

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

	Population 1995 (million)	CH ₄ Emissions (kt)	CO ₂ Eq. Emissions (kt)
Beef cattle	12.4	563	11,800
Dairy cattle	1.3	133	2,800
Swine	11.9	19	400
Sheep, goats	0.7	5	100
Horses, mules, asses	0.4	5	100
Poultry (all types)	116.1	Neg.	Neg.
Total		725	15,200

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

⁹ A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997), p. 49.

4.2 Nature of the GHG Emissions Stream

There are thousands, if not millions, of sources of GHG emissions attributed to enteric fermentation in Canada. As mentioned, beef cattle are the primary sources of these emissions. There were approximately 12.4 million beef cattle in Canada in 1995. Of these, 3 million to 4 million are on feedlots or are newborns. The remainder are on range feeding (which makes management more difficult and expensive).

Many factors influence annual methane emissions from enteric fermentation, including temperature, diet, animal population, animal size, feed additives and livestock management practices. Emissions are affected by the efficiency with which the animal utilizes feed. This will vary on many factors, such that there is substantial variation between different types of animals or various herds of the same animal.

4.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Environment Canada uses several different emission factors, based on different varieties of cattle, pigs, etc., to develop methane emissions attributed to enteric fermentation. Due to the wide dispersal and types of sources, emission factors are necessary to develop emission estimates.

In order to estimate future reductions in methane emissions from the adoption of technologies or management practices (see below), emission factors would have to be developed that take into account the reduction in methane emissions that can be attributed to those technologies or management practices. For instance, methane emission factors would have to be developed for beef cattle that have not been injected with steroids as well as for beef cattle that have been injected with steroids. Credits could then be obtained by farms that adopted the management practice of injecting steroids. However, verification of this method remains an issue.

4.4 Options to Reduce GHG Emissions

The technologies outlined in this section that can reduce the amount of methane emitted from livestock include greater use of feed additives (e.g., ionophores, antibiotics); steroid implants; improved livestock management and feeding practices; and bioengineering. All of these technologies and practices increase the production of milk or meat in relation to the amount of feed utilized (or time taken for the animal to reach an age where its milk or meat can be utilized) and so achieve methane reductions.

The costs of applying various techniques are difficult to quantify, while the benefits can be significant. In some cases the costs provide immediate financial gain

Examples of Cattle Methane Emission Reduction Options	
	Reductions per Head
Dairy Cattle	
Management practices that improve productivity	10% to 15%
Use of bST hormone to increase production	3% to 7%
Beef Cattle	
Management practices that improve productivity (improve cow-calf sector reproductive performance)	20% to 35%
Use of ionophores to increase efficiency	5% to 15%
Steroid implants on range cattle	<5%

Source: Cheminfo Services, *Powering GHG Reductions Through Technology Advancement*, prepared for Environment Canada (Ottawa, 1998).

for producers (e.g., feed cost reductions). These gains may be offset by increased costs for labour, land and materials.

4.4.1 Management Practices

There are many management practices available to increase the productivity of cow-calf operations. Animal nutrition programs can be applied to some degree by all owners to achieve increases in productivity and reductions in methane emissions.

Nutrition-related problems contribute to low pregnancy rates (and thus low weaning percentages), and difficulty in getting cows to calve at 24 months. In forage-based production programs (found in many Western Canadian operations), producers can improve nutritional management by:¹⁰

- assessing soil conditions (through proper testing) to determine fertilizer requirements for their forage;
- assessing forage quality to determine supplementary nutrients (minerals, proteins, etc.) required; and
- eliminating toxic plants that can influence animal productivity.

It is estimated that these and other management techniques (such as artificial insemination to ensure high pregnancy rates, veterinary care and vaccinations) can theoretically increase productivity by 20% to 35% and achieve similar reductions in GHG emissions.

4.4.2 Ionophores

Ionophores are complex molecules that can modify the movement of ions across biological membranes and therefore affect the metabolism of various microbes. Ionophores are incorporated in ruminant

animal feeds to increase the feed efficiency (production per unit of nutrient), as well as assist in disease control. It is estimated that 30% to 40% of the total Canadian cattle population already use ionophores. Over 90% of the beef cattle that are in feedlots use ionophores. However, beef cattle that are range grazing are not typically using ionophores. Industry suppliers of ionophores estimate 50% of dairy cattle use this feed additive.

Ionophores can reduce methane emissions, although the exact amount per head is difficult to quantify and is dependent on many factors. One Canadian researcher claims reductions of 8% to 10% were observed upon initial ionophore treatment.¹¹ Ionophores reduce methane emissions by increasing the efficiency of feed utilization and therefore overall productivity. Livestock on ionophores can produce more product (i.e., milk, meat) faster and with less feed. This results in a smaller amount of methane emissions per unit of production.

4.4.3 Hormones and Steroids

Bovine somatotropin (bST) is a naturally occurring growth hormone found in cattle. Over the last couple of decades, the ability to synthesize the hormone using recombinant DNA techniques has increased the availability of the product and lowered its price. Studies indicate that bST injections in lactating dairy cows can increase milk production and lower methane emissions by nearly 10%.¹²

Anabolic steroids are effective in increasing the rate of weight gain and improving feed conversion in beef cattle. Small pellets of steroids are often implanted under the skin of the animal's ear. The implants will increase the rate of weight gain by 10% to 15% and improve the feed efficiency by 5% to 10%.¹³ As a result, animals generate less methane over their lifetime. A large portion (as high as 80%) of feedlot

¹⁰ Ibid.

¹¹ Frank D. Sauer, Agriculture Canada, personal communication, January 12, 1998.

¹² U.S. Environmental Protection Agency, *Opportunities to Reduce Methane Emissions in the United States*, Report to Congress, EPA 430-R-93-012 (Washington, D.C., October 1993).

¹³ Ibid.

beef cattle, especially in Western Canada, are already on steroids. The portion of range cattle or cattle on small farms on steroids is not well defined, although it is estimated to be substantially lower.

4.4.4 Bioengineering

Bioengineering involves the application of biotechnology to develop livestock with greater product yield per unit of nutrients consumed. There are various potential biotechnology innovations that increase yield while reducing methane emissions. These include twinning, rumen microbe manipulation and hormone manipulation. These practices have not been broadly adopted in Canada.

4.5 Suitability for GHG Emissions Trading

A credit trading program appears to be the logical choice to apply to methane emissions attributed to enteric fermentation in Canada. This program would operate by developing baseline emission factors that would be applied to each animal contributing to enteric fermentation emissions in Canada. There would be several different emission factors developed representing different livestock (e.g., beef cattle, dairy cattle, swine) as well as different varieties within that livestock category (e.g., bull, steers, calves). It should be noted that these emission factors already exist. Additional emission factors would be developed that reflect the reduction in methane emissions (i.e., enteric fermentation) from specific animals following the application of specified best management practices/technologies (see above). Farmers would obtain credits for applying these best management practices/technologies. Before obtaining credits, farmers would have to demonstrate that they applied these best management practices/technologies. Farmers would receive credits at the point of sale, where the livestock is sold for slaughter or to another farmer.

It is recommended that the baseline for determining future credits be set as a methane emission rate and

not at total methane emissions from the animal. For instance, enteric fermentation from a dairy cow would be set at a baseline emission rate of 105 kilograms (kg) per year of methane. Applying various best management practices/technologies might yield an emission rate of 95 kg per year of methane. Therefore, at the point of sale, a credit of 10 kg per year of methane would be obtained. It should be noted that this is a simplistic example of how the system would operate.

In terms of the criteria for a credit trading program, actual enteric fermentation emissions could be estimated relatively accurately by applying emission factors across the range of livestock that contribute to these emissions. Environment Canada indicates that the uncertainty level for the total of these emissions is +/-20%. In addition, Statistics Canada develops livestock population statistics that could provide a base of data on the number of cows, sheep and other livestock contributing to enteric fermentation emissions.

Farmers have a wide range of best management practices/technologies that can be employed to reduce methane emissions attributed to enteric fermentation. Emission reduction estimates for these practices/technologies have already been developed. However, some form of verification of the application of those practices/technologies would be required to determine whether credits should be received. This might be difficult to carry out, considering the number of farms in Canada. Baseline methane emissions could easily be estimated where these practices are not implemented.

The major problem involved in this credit trading system would be the large number of sources where the practices/technologies could be applied and where the credits should be distributed. Including only large farms in the program would not solve this problem, since there are many hundreds or thousands (depending on how they are defined) of large farms.

An alternative system might be to have meat packing plants and dairies hold permits for the total animals or milk purchased. This would reduce the number of entities in the system, but add the complication that foreign trade may not be properly captured. For example, live Canadian-raised cattle might be exported to the United States outside the control of a permit, whereas U.S.-raised cattle might be purchased by a meat packing plant and require an exemption.

Substance trading was not deemed appropriate for enteric fermentation GHG emissions, since there is no substance that is a good proxy for actual GHG emissions. An emissions rights trading program was also discounted, since the number of sources to which emissions rights would have to be allocated would be prohibitive. It was believed that the accounting system for the emissions trading program would be simplified if a credit trading program were implemented.

5. Adipic Acid Production

5.1 Source and Quantity of GHG Emissions

Nitrous oxide (N₂O) is a significant by-product from the production of adipic acid. Adipic acid (COOH[CH₂]₄COOH), a six-carbon dibasic acid, is an important chemical intermediate used in the

manufacture of nylon fibres and resins, plasticizers and other plastics. Adipic acid is manufactured at one industrial chemical plant in Canada.

In 1995, adipic acid production accounted for 35 kilotonnes (kt) of N₂O emissions (10,850 kt of carbon dioxide [CO₂] equivalent), which represented approximately 8% of total non-combustion greenhouse gas (GHG) emissions and 1.8% of total Canadian GHG emissions. In 1995, this was the single largest source of nitrous oxide emissions, representing about 34% of total nitrous oxide emissions in Canada. From 1990 to 1995, the estimated level of nitrous oxide emissions from adipic acid manufacture ranged from 29 kt to 35 kt per year, based directly on production levels of adipic acid. In 1997, control technology was applied to the nitrous oxide emission stream, reducing emissions to a level estimated to be less than 5 kt per year.

There is only one adipic acid plant operating in Canada, the DuPont Canada plant in Maitland, Ontario. This plant has a capacity of about 136 kt per year and is the smallest of three plants that DuPont operates in North America.¹⁴ The Maitland plant represents just less than 15% of the total North American production of 1,000 kt year. North American adipic acid production represents about 45% of worldwide production. There are only a few manufacturers of adipic acid worldwide. Solutia and AlliedSignal operate the only other two adipic acid plants in North America.

Nitrous Oxide Emissions (1990-2000)

	1990	1991	1992	1993	1994	1995	2000
N ₂ O emissions (kt)	34.6	32.3	32.1	29.3	35.4	34.6	5.0
N ₂ O emissions (CO ₂ eq. kt)	10,718	10,000	9,951	9,080	10,968	10,726	1,550
Adipic acid production (kt)	97.4	103.4	107.0	98.0	118.0	111.5	136.4
N ₂ O/adipic acid ratio	0.35	0.31	0.30	0.30	0.30	0.31	0.04

Source: DuPont Canada, *VCR Progress Report*, September 24, 1996.

¹⁴ Others are located in Victoria, Texas (318 kt/yr) and Orange, Texas (181 kt/yr).

5.2 Nature of the GHG Emissions Stream

Adipic acid is produced by a two-step oxidation of the raw material, cyclohexane (C_6H_{12}). Nitrous oxide is generated as a by-product in the second step of this oxidation process. Nitrous oxide gases are stripped from the oxidation products and exhausted through a single point source. The amount of nitrous oxide generated in the nitric acid oxidation reaction is proportional to the production volume of adipic acid at typical levels of about 30%. In 1995, roughly 35 kt per year of nitrous oxide were produced as a by-product from production of about 112 kt per year of adipic acid at Maitland.

Adipic acid manufacturing is the largest industrial source of nitrous oxide emissions, since nitrous oxide is a significant by-product from the oxidation reaction. The other industrial source of nitrous oxide emissions is the production of nitric acid, covered in the next section. In nitric acid production, the nitrous oxide emissions from individual point sources are trace by-products and the volumes are significantly smaller.

5.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

The nitrous oxide emissions from the adipic acid plant are emitted from one point source on the outlet of the catalytic abatement installation. Emissions are calculated based on measurements of nitrous oxide concentrations in the gas stream and the gas flow rate, which can both be easily measured. The reduction of nitrous oxide emissions is measured by the difference between the inlet and outlet concentrations of nitrous oxide at the abatement equipment. The variations within the process or the abatement technology are not known. The

calculations must take into account the time when the abatement technology is shut down or not performing at high efficiency, since emissions are not controlled during these periods.

5.4 Options to Reduce GHG Emissions

There are two possible treatments of nitrous oxide emissions from adipic acid production plants. The first is the conversion of nitrous oxide back to nitric acid (oxidation). The second is its catalytic reduction to inert nitrogen and oxygen gases. The second method was selected by DuPont for all three of its North American adipic acid plants and is described below. No information applicable to adipic acid plants was found for the first treatment method.

In August 1997, DuPont started up a \$15 million catalytic abatement installation (CAI) to treat the emitted nitrous oxide gas stream. The DuPont CAI uses catalytic reduction technology to convert nitrous oxide gases to inert nitrogen gas at specified operating conditions. The catalyst technology is new and specific for nitrous oxide gas. It was developed for DuPont in the early 1990s by Engelhard, a leading catalyst and pollution control technology supplier.

The planned reduction in nitrous oxide emissions is about 80% to 90% in the first year of operation (1997), with higher levels of utilization expected in the second and third years. DuPont reports that the installation is operating well and meeting expectations. The abatement technology is reported to have a reduction efficiency percentage "in the high 90's" when operating steadily. Since the unit has only recently started up, there has been occasional downtime. For example, the abatement unit cannot operate during the occasional start-up and shutdown sequences of the adipic acid plant. Other mechanical problems also require short-term shutdowns for maintenance. With continued learning curve experience, DuPont intends to increase the

operational “up-time” above 90% in future years.¹⁵ DuPont summarizes its success with nitrous oxide reduction as follows:

Over the longer period, we hope to achieve up to 95 per cent abatement, so that by the year 2000 and beyond, we will achieve more than our earlier commitments. It should be noted, however, that business growth will result in higher production levels of adipic acid, so that the 95 per cent abatement will show growing levels of nitrous oxide after 1998-99.¹⁶

5.5 Suitability for GHG Emissions Trading

Since the nitrous oxide emissions are created in the industrial manufacturing process and not as a result of purchased substances, a substance trading program is not applicable in this situation. There is only one point source of nitrous oxide emissions from adipic acid, and emissions are easily measurable and calculated accurately. The emissions have already been significantly reduced from 1990 and 1995 levels, and further incremental reductions are believed to be possible. However, production increases due to business activity may increase the total volume of nitrous oxide emissions over time. The two programs that could be considered are emissions rights trading and credit trading. A trading program for adipic acid would need to be part of a broader emissions trading system given the single adipic acid source in Canada.

An emissions rights trading program would involve an annual allowance for nitrous oxide emissions. If set at current nitrous oxide emissions levels, there might not be much room for further control reductions, and the allowance might have to be adjusted upward to accommodate higher emissions from business activity. The allowance for DuPont might have to be set at a higher level than current emissions to accommodate business growth.

DuPont would likely want to receive credits for its reduction efforts and might favour a credit trading program based on absolute reductions from a baseline set at 1990 levels. This would give the company substantial annual benefits. If the baseline were set at current (post-abatement) levels, DuPont would not receive any credit for its abatement initiatives, and a rate-based credit system would be more appropriate. In this system, a baseline level of X tonnes of nitrous oxide per tonne of adipic acid produced would give DuPont an incentive to minimize the downtime of its high-efficiency abatement equipment, while accommodating growth.

6. Undifferentiated Non-Energy Petroleum Uses

6.1 Source and Quantity of GHG Emissions

This section briefly examines possible industrial sources where carbon dioxide (CO₂) emissions are assumed to be emitted from non-energy uses of petroleum commodity streams. There is no assessment of the suitability of trading programs provided because of the uncertainty of the information in this area.

Petroleum commodities are used as a raw material in the production of several derivative products. Some of these products completely sequester the carbon contained in the petroleum products (e.g., plastic, rubber, resins), while some end uses of petroleum products release carbon dioxide during the production process or later in the product life through combustion.

In 1995, Environment Canada estimated that the undifferentiated non-energy uses of petroleum

¹⁵ Steve Lauridsen, DuPont Canada Ltd., personal communication, February 20, 1998.

¹⁶ DuPont Canada Ltd., VCR Progress Report, September 24, 1996.

products accounted for a total of 10,000 kilotonnes (kt) of carbon dioxide emissions. This estimate represents approximately 7% of total non-combustion greenhouse gas (GHG) emissions in Canada as well as 1.6% of total Canadian GHG emissions. This calculation excludes the net carbon dioxide emissions from ammonia manufacture using methane, which was treated as a separate industrial source. Ammonia manufacture is examined in a later section.

Environment Canada examined non-energy data for several different petroleum commodities from Statistics Canada. The main petroleum commodities for which non-energy data were available included natural gas used as feedstocks, coal and coke, and the liquefied petroleum gases (LPGs) of ethane, propane and butane. Since detailed end use of these products was not clearly known, Environment Canada used various simplifying assumptions about the degree of sequestration of carbon in the ultimate life cycle use. The following percentages represent assumptions about the portion of carbon contained in the non-energy petroleum volumes that was emitted as carbon dioxide: for non-energy uses of natural gas, 67%; for LPGs, 20%; and for coals and coke, 100%.¹⁷

Based on Statistics Canada data provided by Environment Canada, Cheminfo assumes that two areas account for the majority of GHG emissions associated with undifferentiated "non-energy" petroleum uses. These are:

- use of natural gas liquids (NGLs) and crude oil-based liquid feedstocks for the production of ethylene and co-products (i.e., propylene, butadiene, etc.) in large scale facilities; and
- use of natural gas — methane — mostly for the production of methanol and derivatives.

6.2 Nature of the GHG Emissions Stream

It is assumed that 20% of the carbon contained in the NGL feed for ethylene plants is ultimately emitted as carbon dioxide in the production process, while 80% is sequestered in the form of derivatives of ethylene (polyethylene, polystyrene and ethylene glycol, which are used to make polyester fabrics). The two most likely sources of carbon dioxide are (1) the burning of coke off the furnace tubes and (2) the burning of fuel gas, which is a by-product of the ethylene reaction.

The assumption on natural gas is that 67% of the carbon in natural gas is eventually emitted as carbon dioxide from methanol combustion. Some carbon contained in methanol is sequestered in formaldehyde resin, which is a major derivative of methanol used in the panelboard industry.

Canada's petrochemical plants, which currently number approximately 150,¹⁸ are concentrated in three provinces. This total includes primary petrochemicals production as well as many smaller secondary facilities involved in polymers and derivative intermediates production. Ontario is home to approximately half of the total. Most Ontario establishments are located near Sarnia, where there are both petroleum refineries and pipeline terminals for natural gas and its liquid by-products (NGLs). Alberta has a burgeoning petrochemical industry based almost exclusively on natural gas. Quebec has plants in the Montreal area as well as downriver at Bécancour. Their primary raw materials are mainly derived from crude oil-based feedstocks. A methanol plant located in Kitimat, British Columbia, is the largest facility not operating within the aforementioned provinces.

17 A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997), p. 42.

18 Cheminfo Services, *Industry Profile 1996-97 Petrochemicals*, prepared for Statistics Canada (Ottawa, April, 1997).

Primary NGL and Crude Oil-based Petrochemical Producers		
Company	Location	Major Products
Novacor Chemicals	Joffre, AB	Ethylene, polyethylene
Novacor Chemicals	Corunna, ON	Ethylene, polyethylene, propylene, styrene
Imperial Oil Ltd.	Sarnia, ON	Ethylene, polyethylene
Petromont Inc.	Varenes, PQ	Ethylene, polyethylene
Dow Chemical Canada	Fort Saskatchewan, AB	Ethylene, polyethylene, ethylene oxide, glycol, vinyl chloride monomer, dichloroethane

Source: Cheminfo Services.

In Canada, ethylene is produced at five different locations and utilized at nearby plants to make intermediate derivatives that can be transported globally. The industry's major derivative end products are polymers such as polyethylene, polypropylene, polyvinyl chloride and styrenic resins. Synthetic rubber and other polymers used in the manufacture of synthetic fibres, paints and coatings, printing inks and adhesives are also outputs from Canada's petrochemical sector. Ethylene is also used to make ethylene oxide (most of which is converted to ethylene glycol), ethylene dichloride and a variety of other intermediate chemicals.

6.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Environment Canada reports that the uncertainty level associated with its non-energy emission estimates of undifferentiated non-energy uses of petroleum products is +/-30%. The methodology used by Environment Canada to estimate GHG emissions from this source is based on the application of broad emission factors (as described above). Much more detailed emission estimation methodologies may be required for this sector, if emission reductions are going to be credited for emission trading purposes. The emission factors

currently being applied may be too broad to be acceptable as a verifiable accounting of emission reductions. The potential for stack testing at petrochemical facilities is problematic, since there are sometimes hundreds of point sources of emissions at these facilities. Therefore, more research may be required to develop appropriate emission factors specific to the major petrochemical products that are releasing the carbon dioxide.

There is a manageable number of participants in the Canadian petrochemical sector for the purposes of emissions trading. This is especially true when one considers that the major sources of emission credits may be located at only a few firms (e.g., ethylene producers that are not using ethane as a feedstock, and methanol producers).

6.4 Options to Reduce GHG Emissions

Technologies to reduce GHG emissions from the petrochemical sector that are analysed in this report include the following:

- alternative feedstocks for ethylene produced from the NGLs ethane, propane and butane;
- anticoking additives for ethylene production from NGLs; and
- increased production of methanol using available hydrogen and carbon dioxide.

6.4.1 Alternative Ethylene Feedstocks

Ethylene producers typically operate their plants to minimize operating costs and maximize ethylene production. Ethane feedstock provides the best ratio of ethylene produced versus carbon dioxide generated. Of the commercial feedstocks available, ethane requires the least energy consumption per unit of ethylene made. Naphtha and other crude-based liquid feedstocks (e.g., gas oils) are the most energy intensive for petrochemicals production.

Approximately 80% of the ethylene made in Canada is based on cracking ethane. All ethylene produced in

Ratio of Ethylene Produced to CO ₂ Emissions (CO ₂ from combustion of internally produced methane only)	
Petrochemical Feedstock	Ethylene to CO ₂ Ratio*
Ethane	3.45
Propane	0.52
Naphtha	0.88

Notes: * Approximate ratios (will vary depending on actual plant operating conditions); C2 = ethylene. Source: Cheminfo Services.

Alberta uses ethane. Only Eastern Canadian petrochemical facilities rely partially on propane, butane and crude oil liquid-based feedstocks such as gas oils and naphthas to make ethylene. Historically, ethane, most of which has been produced in Western Canada, has not been available to Eastern Canadian petrochemical facilities. Ethylene producers in Ontario (Imperial Oil Ltd. in Sarnia and Novacor Chemicals in Corunna) have been able to access ethane from various sources and have increased the use of this feedstock over time. However, a pipeline to deliver Western ethane has not reached Quebec. Therefore, Petromont's plant in Varennes, Quebec, continues to rely mostly on propane, butane and naphtha feedstocks.

Switching to ethane from propane and crude oil-based gas oils and naphthas can result in a reduction of 30% to 40%, or approximately 500 kt, in carbon dioxide emissions (associated with combustion of internally generated methane only) from ethylene petrochemical plants. A technical factor to consider is the ability of the operational units to accommodate ethane and the unique ratio of co-products produced. Facilities are typically designed to handle a narrow range of feedstocks. Therefore, expensive modifications may be required to major equipment such as furnaces, distillation columns and compressors.

The costs of reducing carbon dioxide emissions by switching to ethane from propane and crude oil-based feedstocks (naphtha and gas oils) can vary substantially for several key reasons. A major factor is the variability of the feedstock prices and the value of co-products (i.e., propylene, butadiene, etc.). The operating cost of reducing carbon dioxide emissions in this area can range from \$100 per tonne of carbon dioxide to a benefit of \$20 per tonne of carbon dioxide, or more. These costs do not take into consideration capital costs for plant modifications or pipeline infrastructure required to deliver ethane to Quebec. These one-time costs can be in the order of \$100 million to \$200 million for furnace modifications and downstream processing changes.

6.4.2 Anticoking Additives

Coke, which is essentially carbon, forms on the inside of furnace tubes as a result of the cracking reactions in the production of ethylene. As coke builds up, the efficiency of the reaction (with respect to energy requirement per unit of production) is reduced. Furnace tubes at ethylene plants need to be decoked. The interval between decoking operations can range from 20 to over 100 days depending on the type of feedstock, furnace design, use of anticoking agents, and operational factors.

Chemical additives that can reduce coke build-up are proprietary blends that minimize the degradation reaction making carbon (C) from the feedstock molecules. They are incorporated in the feedstock in minute quantities, typically in part per million concentrations. By reducing the amount of coke build-up on ethylene furnace tubes, the use of additives typically increases the operating time of the furnaces by 5% to 50%. The carbon dioxide emissions, produced by the periodic burning of this coke build-up on the tubes, are reduced by a comparable amount.

Anticoking additives are already used by most petrochemical producers to extend the service time of furnaces. However, new chemical additive systems are being developed that offer marginal improvements in anticoking capability, and therefore marginal improvements in carbon dioxide emission reductions. It is estimated that the level of carbon dioxide emission reduction from this technology would amount only to 5% to 20% (of CO₂ from decoking activities). This represents less than 1% of total carbon dioxide emissions from petrochemical sources.

6.4.3 Increased Production of Methanol Using Hydrogen, Carbon Dioxide

Methanol is a commodity chemical made by reacting hydrogen with carbon dioxide or monoxide. Increased production of methanol using carbon dioxide does not necessarily translate into reduced carbon dioxide emissions. The problem is that hydrogen is required for the reaction, and the hydrogen is often derived from steam methane reforming, which uses energy and generates carbon dioxide. More work is required to better define the stoichiometric and energy uses (which generate

carbon dioxide) for hydrogen and carbon dioxide around methanol and other petrochemical complexes. Matching available hydrogen (i.e., where hydrogen is used as a fuel) for combination with carbon dioxide sources for the production of methanol can reduce emissions.

Canadian Methanol Capacity		
Company	Location	1995 (kt)
Methanex	Medicine Hat, AB	1,120
Methanex	Kitimat, BC	500
Celanese Canada	Edmonton, AB	780
Celanese Canada	Millhaven, ON	5
Total capacity		2,405

Source: Camford Information Services, *Industry Profile for Methanol* (Toronto, 1996).

6.5 Suitability for GHG Emissions Trading

This report does not discuss the suitability of undifferentiated non-energy petroleum uses for a GHG emissions trading program. Not enough information is available from Environment Canada on the sources of these emissions and the extent to which the emissions actually exist to assess their suitability for various trading programs. This section has been included in order to provide a general description of this portion of the 1995 GHG inventory.

A separate paper is being prepared for the NRTEE on the use of feedstocks and the implications for an emissions trading program. In addition, the energy aspects involved with undifferentiated non-energy uses of petroleum products are addressed in the various papers being prepared for the NRTEE on energy-related GHG emissions.

7. Aluminum Smelting

7.1 Source and Quantity of GHG Emissions

Two different greenhouse gas (GHG) emissions come from the anode in smelting pots in the primary aluminum production industry. In 1995, an estimated 3,600 kilotonnes (kt) of carbon dioxide (CO₂) were emitted from the consumption of carbon anodes and another 6,000 kt of CO₂ equivalent were emitted in the form of about 880 tonnes of perfluorocarbons (PFCs) formed in anode events. Together, these GHGs from aluminum smelting accounted for 9,600 kt of CO₂ equivalent, representing 7% of total non-combustion GHG emissions and about 1.6% of total Canadian GHG emissions.

There has been a 33% increase in emissions from 1990 levels. Increases in aluminum production have driven total anode consumption, while initiatives to reduce anode consumption rates have partially offset the increase in emissions. Efforts to replace older technologies through capital stock replacement will continue to reduce average anode consumption rates over the next 15 years. However, production increases due to economic growth with related increases in

aluminum demand (particularly automobile and aerospace growth) will likely drive total GHG emissions higher.

PFC (CF₄ and C₂F₆) emissions were 0.88 kt in 1995 (a CO₂ equivalent of 6,000 kt per year, on a global warming potential [GWP] basis). Emissions in 1995 were relatively unchanged from 1990, despite peaking in 1993 at a CO₂ equivalent of 7,800 kt. The trend will likely continue downward as smelters continue their installation of process control systems to control alumina levels and minimize anode events.

In 1995, the Canadian primary aluminum industry had a total production capacity of 2.3 million tonnes of aluminum per year from a total of 11 smelters operated by five companies. Since electrical energy is the single most important variable cost for aluminum smelting, all Canadian smelters are located near sources of inexpensive hydroelectric power. With the exception of Alcan's Kitimat, British Columbia, smelter, all smelters are found in Quebec.

Primary aluminum production in Canada in 1995 was 2,172 kt, representing about 95% of capacity. Roughly 40% of this unalloyed primary production is exported. The major domestic end uses are transportation (29%), packaging (23%) and building and construction (19%).

CO ₂ and PFC Emissions from Aluminum Smelting								
	Units	1990	1991	1992	1993	1994	1995	2000
CO ₂ emissions	kt	2,700	3,000	3,000	3,800	3,600	3,600	4,000
PFC emissions	kt CO ₂ eq.	5,700	6,700	6,700	7,800	6,800	6,000	<5,000
Sum of GHGs	kt CO ₂ eq.	8,400	9,700	9,900	11,600	10,400	9,600	<9,000
CF ₄ emissions	kt	0.82	0.97	0.97	1.13	0.98	0.80	
C ₂ F ₆ emissions	kt	0.08	0.10	0.10	0.11	0.10	0.08	
Aluminum production	kt	1,567	1,822	1,972	2,309	2,255	2,172	2,400

Notes: CF₄ emissions trend estimated from total PFC trend using GWP of CF₄ = 6,500; C₂F₆ emissions trend estimated from CF₄ trend using factor of 10%.

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

Primary Aluminum Production Capacity in Canada, 1992			
Company	Location	Origin Year	Capacity (kt/yr)
Alcan Smelters and Chemicals Ltd.	Kitimat, B.C.	1954	272
	Isle-Maligne, Alma, PQ	1950s	73
	Beauharnois, PQ	1950s	48
	Grande Baie, PQ	1983	180
	Arvida, Jonquière, PQ: #1	1950s	84
	Arvida, Jonquière, PQ: #2	1960s	148
	Laterrière, PQ	1987	204
	Shawinigan, PQ	1901	84
	Aluminerie de Bécancour	Bécancour, PQ	1986
Canadian Reynolds Metals Co. Ltd.	Baie-Comeau, PQ	1957	400
Aluminerie Luralco Inc.	Deschambault, PQ	1992	215
Aluminerie Alouette Inc.	Sept-Iles, PQ	1992	215
Total			2,283

Source: Aluminum Association of Canada, *The Aluminum Industry* (n.d.).

Alcan Smelters and Chemicals, based in Montreal, operates 7 of the 11 Canadian smelters and has just under 50% of the total capacity. Alcan has recently announced a new smelter starting up in 2000, which will replace several older smelters that use outdated technology. The four other companies are subsidiaries or joint ventures of U.S. or international aluminum companies. They operate one smelter each.

7.2 Nature of the GHG Emissions Stream

Carbon dioxide emissions are generated by the consumption of carbon anodes in the electrolytic reduction of alumina (Al_2O_3) to elemental aluminum. In a smelter, carbon anodes are made from finely crushed petroleum coke mixed with pitch to form a paste that is formed and baked into a solid anode. Oxygen is removed from the alumina (leaving elemental aluminum) at the carbon anodes and reacts with the carbon to produce carbon dioxide. The carbon dioxide bubbles up from the anode in the

smelting pot and is released into the atmosphere. Carbon anodes are consumed slowly in this process and must be replaced regularly, typically every 20 days of production.

The theoretical minimum rate of carbon anode consumption in aluminum production has been calculated as 350 kilograms (kg) of carbon per tonne of aluminum produced. The older technology smelters have high carbon anode consumption rates ranging from 450 kg to 540 kg of carbon per tonne of aluminum. Most new smelters operate at consumption rates ranging from 410 kg to 450 kg of carbon per tonne of aluminum. With best practices and technologies currently available, the industry has only been able to achieve best rates of 400 kg per tonne. There is a lot of potential for ongoing research to close this gap between theory and practice through better process developments.

PFC emissions are generated from within the smelting pots during irregular "anode effects." Anode effects are described as the overvoltage disturbance of the smelting process that occurs when the

concentration of alumina falls below a certain minimum level in the smelting pot. During these events, the fluorine from the cryolite solution present in the electrolytic bath reacts with the carbon anode to form CF_4 and, to a much smaller extent, C_2F_6 . These disturbances are caused by poor feed control, which allows alumina levels to decline faster than they can be replenished by the feed supply. The PFCs (CF_4 and C_2F_6) are emitted from the pot in bubbles and released to the atmosphere.

7.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Neither of the two GHGs (CO_2 or PFCs) generated from aluminum smelting processes are measured directly. Carbon dioxide emissions from carbon anode consumption are calculated based on the amount of carbon used in the anodes. PFC emissions are calculated through correlations to measured operating parameters such as pot voltage levels and duration time of the anode effect. These correlations were developed by a Canadian research firm that developed a measurement method for PFC emissions.

The accuracy of the indirect carbon dioxide calculations is high, since direct carbon measurement is quite accurate. The accuracy of the PFC calculations, while using indirect correlations, is also thought to be quite accurate and accepted by the industry.

7.4 Options to Reduce GHG Emissions

The primary options to reduce GHG emissions include research to develop inert anodes; replacement of old anode technology with prebake anode technology; and better feed control systems.

7.4.1 Inert Anodes

The generation of carbon dioxide and PFCs from carbon anode consumption could be eliminated by the use of inert anodes, also known as “dimensionally stable” anodes. This subject has been an area of primary research for every major aluminum company over the last 40 years without significant progress. Aluminum companies have yet to find the right alternative material that will (i) not react with the oxygen generated from the alumina, (ii) remain insoluble in the cryolite (Na_3AlF_6) bath, and (iii) be extremely conductive, incurring no economic penalty.

The most promising materials currently being evaluated are ceramic/metal composites consisting primarily of nickel oxide and nickel ferrite with a copper/nickel metal phase. Tin oxide has also been studied.

The carbon dioxide emissions reduction potential with this technology is 100% if it can be commercialized. Few international aluminum companies are researching this area, but Alcan is conducting direct research at present.

7.4.2 Replacement with Prebake Anode Technology

Older smelter technologies have higher rates of carbon anode consumption than modern technologies. The differences are due to the methods of preparing (forming, baking) the carbon anodes and the complexity of the process control systems used for smelting pot operation. By replacing capacity using older technologies with new capacity employing modern technology, the rate of carbon anode consumption can be reduced slightly.

For example, Alcan has stated that it is in the midst of a long-term project to replace all older technologies by higher performance centre-work prebake (CWPB) technology. The project will be complete by the year 2015. This smelter conversion project will gradually decrease the average rate of

carbon consumption to more efficient levels. In 1982, the Alcan average carbon consumption was about 540 kg per tonne of aluminum. This was reduced to about 500 kg per tonne of aluminum by 1995, and is projected to be reduced to 400 kg per tonne levels when current technologies are fully installed in all smelters by 2015.

7.4.3 Improved Feed Process Control

PFC emissions can only be reduced through improved control of the alumina feed to all points in the process to prevent the onset of anode events. There are two main elements of improvement in control. The first is a change in smelting technology that incorporates a redesigned feed system involving a more distributed feed point network. The second is the use of better distributed process control systems to sense and adjust conditions in the electrolytic bath given existing pot technologies.

An example of the feed system improvement is given by the conversion from older Horizontal Slab Söderberg (HSS) process smelters to a point breaker feeder system. In one example of a typical HSS process, the crust on the electrolytic bath is broken on the side every six hours or so, and alumina is injected into the bath. The feed injection frequency is low, and the number of feed points per pot is low. In the modern point breaker system, pistons break the bath crust at several locations to inject a small amount (1.0-1.5 kg per injection per point) of alumina at much shorter intervals. With better cell signal measurements and the use of a neural network, each distributed feed point can be controlled individually, resulting in better control of the alumina concentration throughout the bath. Theoretically, there is no technical limit to PFC reductions with increased neural networks and distributed feed control. Practically, it is assumed that a 20% reduction is easily possible with improved process control systems.

7.5 Suitability for GHG Emissions Trading

In aluminum smelting, the emissions of the two GHGs can be calculated with a reasonable degree of accuracy, based on carbon anode consumption and measurement of acceptable operating parameters. The number of sources in the industry responsible for 100% of the emissions is relatively small (11 smelters operated by five companies), so control can be established at this level.

Aluminum smelting would be suitable for an emissions rights trading program, assuming that PFC emissions could be measured to the required level of accuracy. An absolute industry level could be set, but the companies might be somewhat restricted in the control technologies that are available. Growth in production may increase GHG emissions to a level that exceeds what can potentially be controlled through the application of cost-effective control technologies.

A credit trading program would also be suitable for the industry. With respect to carbon dioxide emissions, the industry uses a rate-based benchmark for carbon anode consumption per tonne of aluminum produced. If a reasonable baseline level could be established among the different producers, then credits could be earned by the continuing efforts to reduce overall carbon anode consumption rates closer to the theoretical minimum. For PFC emissions, a similar baseline could be established based on the rate of PFC emissions per tonne of aluminum or an absolute level of PFC emissions in a base year.

A substance trading program might not be appropriate in this industry, because the GHG emissions do not come directly from measurable substances. In the case of carbon dioxide emissions, it might be possible to measure the volume of carbon in anodes, but these are produced at the smelter sites, from two purchased materials containing varying concentrations of carbon. In the case of PFCs, emissions are generated in the process and there is no correlation with the amount of carbon in the anodes.

8. Lime and Cement Production

8.1 Source and Quantity of GHG Emissions

Carbon dioxide is generated through calcining limestone or other calcareous material. In large lime kilns, the calcining process thermally decomposes the calcium carbonate (CaCO₃) contained in limestone to yield lime (CaO) and carbon dioxide (CO₂).

Carbon dioxide is also generated as a result of natural gas, oil, coal or waste hydrocarbons that serve as fuel sources for the calcining process, or other energy requirements associated with site operations. Total emissions associated with calcination of limestone were estimated at 7,350 kilotonnes (kt) in 1995,¹⁹ representing 5% of non-combustion greenhouse gas (GHG) emissions and approximately 1% of total Canadian emissions.

Lime kilns are found at merchant lime producers as well as at cement plants, kraft pulp mills and some iron and steel facilities that use lime within their operations. Merchant producers of lime also supply these industrial users as well as a broader customer base.

This analysis deals with GHG emissions and the suitability of several emissions trading systems for cement plants and merchant lime production only. Practically all of Canada's 42 kraft pulp mills make lime on-site and may employ renewable fuels (wood fibres) for a large portion of their energy requirements. Within the pulp industry, some of the carbon contained in the carbon dioxide emitted from calcining calcium carbonate originates from the raw wood material used to make pulp. Some energy and carbon dioxide emissions from lime production at kraft pulp mills may also derive from non-renewable

sources. Detailed, possibly mill-specific, investigation is required to differentiate renewable and non-renewable GHG emission sources associated with lime production. This is better undertaken as part of the total energy and GHG emissions analysis at pulp mills, possibly including carbon sequestering/sinks analysis encompassing the forestry sector. Analysis of emissions from lime production at pulp mills is not undertaken here.

Process Emissions from Lime Production		
1995 (kt CO ₂)		
Cement plants	5,360	63%
Merchant lime production*	1,990	27%
Total**		100%

Notes: * Includes production at iron and steel and other producers that use lime in their own processes as well as for the merchant market; ** Excluded from this analysis are GHG emissions associated with lime production at kraft pulp and paper mills.

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

Lime kilns are in operation at approximately 45 facilities in Canada (excluding pulp and paper mills). In Canada, 18 cement plants have kilns to provide lime for internal requirements. There are approximately 17 merchant lime producers in Canada, operating close to 20 facilities. The lime is used in the pulp and paper industry, iron and steel industry, non-ferrous smelters, sugar refineries, waste water treatment, gas scrubbing and various other miscellaneous applications. Some sugar refineries, iron and steel plants, and chemical plants also have their own lime kilns on-site.

¹⁹ This figure excludes 216 kt of CO₂ emissions from a variety of other limestone uses (not individually quantified by industrial sector), as well as 64 kt of emissions from soda ash made from limestone and used in glass production. Estimates from Environment Canada.

Merchant Lime Producers (excludes kraft pulp mills producing for internal consumption)			
Company	Plants	Capacity (kt)	Locations
Beachville Lime Ltd.	2	710	ON (2)
Greybec Calc Inc.	2	582	PQ (2)
Continental Lime*	4	515	MB (2), AB, BC
Steetley Industries	1	345	ON
General Chemicals*	1	292	ON
Algoma Steel*	1	275	ON
Global Stone (Ingersoll) Ltd.	1	225	ON
Koch Minerals	1	200	ON
Havelock Lime, div. of Goldcorp Inc.	1	175	NB
Texada Lime	1	170	BC
Other producers	5	311	
Total	20	3,800	

Note: * Captive uses as well as merchant supply.

Source: Natural Resources Canada, 1996 *Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

8.1.1 Merchant Lime Supply and Consumption

Total Canadian production from merchant lime suppliers was reported at 2,490 kt in 1996, with an associated value of \$212 million. Between 50% and 55% of the production was in Ontario. Lime prices vary depending on grade and transportation costs. High calcium quicklime delivered in bulk quantities is typically in the \$60 to \$80 per tonne price range. High-calcium hydrated lime can sell for \$10 per tonne more. Between the United States and Canada, lime is traded duty-free.

Typically the merchant lime industry operates well below nameplate capacity. In 1996, it is estimated that the capacity utilization rate was less than 70%. In that same year, Canadian imports amounted to only 37 kt (less than 2% of domestic consumption), while exports were 217 kt or approximately 8% of production.²⁰

Merchant Lime Supply and Consumption	
	1996 (kt)
Production	2,490
Imports	37
Total merchant supply	2,527
Domestic consumption	2,310
Exports	217

Source: Natural Resources Canada, 1996 *Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

The largest end use of lime is in the steel industry, where it is used as a fluxing material to remove impurities, adjust the physical properties of steel, protect equipment from aggressive acidic materials and provide an artificial cover of slag on ladles. Lime is also used in paper production as a feedstock for producing precipitated calcium carbonate (PCC), a fine white filler. In construction, lime is often used for soil stabilization and asphalt paving. In water treatment, lime acts to precipitate "hardness" from

²⁰ Natural Resources Canada, 1996 *Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

water and provides a cheap alkali to adjust pH in waste water.

Canadian Merchant Lime Consumption	
Application	% Use
Iron and steel	50
Pulp & paper*	10
Construction	9
Water treatment	9
Sugar refineries	4
All other uses	18

Note: * Includes precipitated calcium carbonate (PCC) production; excludes internal production of lime at pulp mills for causticizing.

Source: Natural Resources Canada, *1996 Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

Merchant production and domestic consumption of lime have remained essentially flat over the last 16 years. Canadian production in 1980, reported at 2,554 kt, is virtually the same as in 1996, reported at 2,490 kt. Similarly, domestic consumption of merchant lime has only increased 5% since 1980, averaging 0.3% annual growth. The long-term outlook for the Canadian lime industry is that it will grow at an average annual rate of 0% to 2%. Most of the growth will come from waste water treatment, flue-gas desulphurization and manufacture of PCC paper fillers. Consumption within the iron and steel industry is expected to decline in the longer term as a result of improved efficiencies, improved ore grades, increase in the use of scrap fed to basic oxygen furnaces (bypassing the need to use lime), and increased use of fluxed iron ore pellets.²¹

Capacities of Major Cement Producers in Canada		
Company	Location	1995 Grinding Capacity (kt/yr)
Lafarge Canada Inc.	Exshaw, AB	1,400
Inland Cement Ltd.	Edmonton, AB	1,512
Lafarge Canada Inc.	Kamloops, BC	300
Lafarge Canada Inc.	Richmond, BC	478
Tilbury Cement Ltd.	Delta, BC	1,000
North Star Cement Ltd.	Corner Brook, NF	245
Lafarge Canada Inc.	Brookfield, NS	600
Blue Circle Canada Inc.	St. Mary's, ON	800
Blue Circle Canada Inc.	Bowmanville, ON	1,300
St. Lawrence Cement Inc.	Mississauga, ON	1,969
Lafarge Canada Inc.	Woodstock, ON	610
Lafarge Canada Inc.	Bath, ON	1,000
ESSROC Italcementi Group	Picton, ON	818
Federal White Cement Ltd.	Woodstock, ON	185
Lafarge Canada Inc.	St. Constant, PQ	1,100
Ciment Quebec Inc.	St-Basile, PQ	940
St. Lawrence Cement	Joliette, PQ	1,200

Note: Ownership and capacity changes have occurred since 1995.

Sources: Portland Cement Association; Natural Resources Canada, *1996 Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

²¹ Ibid.

8.1.2 Cement Suppliers and Consumption

Portland cement is a mixture of inorganic chemicals — mostly calcium oxide (lime), silica, alumina (Al_2O_3), iron and calcium sulphate (gypsum).

Portland cement is made by combining clinker with a small amount of gypsum, which is used to control setting time. Clinker is made by combining lime with silica-containing materials. Most grades of Portland cement contain 60% to 67% lime by weight.

The Canadian cement industry has undergone some rationalization over the last decade. Whereas 10 years ago there were 23 producing plants operating nearly 50 kilns, there are now about 18 plants operating 32 kilns. As the average size of the plants has increased, the total capacity of the industry has remained virtually unchanged in the last 16 years. Capacity utilization typically varies between 50% and 82%.

Cement Supply and Consumption	
	1996 (kt)
Production (includes exported clinker)	12,303
Imports	631
Total supply	12,934
Domestic consumption	7,580
Exports	5,354

Source: Natural Resources Canada, 1996 *Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

The Canadian cement industry exported 44% of its production in 1996, with nearly 97% of exports shipped to the United States. Imports accounted for approximately 8% of domestic consumption. Over 97% of these were from the United States. These figures exclude trade in various value-added articles, such as pipes, stones and building components containing cement. Canada's production and consumption of cement has grown very slowly. Production grew only 0.7% per year between 1980 and 1996.

Cement is typically mixed with aggregates (e.g., stones, sand) and other additives and applied as concrete mixtures in a large number of end uses. End uses include building construction (residential, commercial, industrial, institutional), pipes, roads and sidewalks, marine terminals, shaped products (bricks, blocks, steps, etc.), and many special construction projects (e.g., Hibernia platform, dams, etc.). Canada's cement producers are largely forward-integrated to concrete production.

8.2 Nature of the GHG Emissions Stream

Carbon monoxide (CO), nitrogen (N_2), carbon dioxide (CO_2), sulphur dioxide (SO_2), water (H_2O) and nitrogen oxides (NOx) are all produced in merchant lime kilns and cement plants. Carbon dioxide content can range from 5% to 40% by volume, but is typically 10% to 20%. Kiln gas streams also contain carbon dioxide resulting from combustion of hydrocarbon energy sources (e.g., oil, gas, coal, coke or biomass), nitrogen, oxygen, minor amounts of other gases and a substantial amount of particulate, largely composed of fine calcium carbonate particles. Before gas streams can be processed through carbon dioxide capture and treatment equipment, particulate in the gas stream may need to be removed.

The flow rate of the emissions streams is high. For example, at one 1,000 kt per year plant, the flow rate from a single kiln is 6,000 to 7,000 cubic metres per minute. Smaller plants and smaller kilns have lower gas flow rates.

8.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

In general, emissions of carbon dioxide resulting from production of lime can be easily and relatively inexpensively calculated through carbon mass balance methods involving raw materials or finished products. Measurement of the efficiency of potential emissions control technologies may be somewhat more complicated, depending on the reduction options applied.

Carbon dioxide emissions resulting from calcining limestone to make lime in either cement plants or in merchant lime kilns can be estimated from the mass of limestone used in production. For example, if 1,000 tonnes of limestone (with 100% CaCO₃ content) is calcined, 440 tonnes of carbon dioxide is generated from the reaction. This excludes GHG emissions from energy consumption. However, if impure limestone (e.g., containing dolomitic limestone [CaCO₃×MgCO₃]) is used as a raw material, as may be the case at some lime/cement plants, the emission factor can be different. In the case of dolomitic limestone used for making lime, more carbon dioxide is emitted per unit of raw material used than with pure limestone. For dolomitic limestone, the emission factor (exclusive of energy) is 478 kilograms (kg) of carbon dioxide per 1,000 kg of raw material. Using this simple approach requires chemical analysis of the raw materials to define the carbonate (CO₃) content, which can vary from one "limestone" source to another.

Another approach is to calculate the emissions from the amount of lime (CaO) made or, as in the case of cement production, amount of lime contained in the final cement product. Lime production and sales quantities (expressed in mass units) are well

documented for commercial reasons. In the case of cement, producers closely monitor the composition of the cement content to ensure quality standards and performance requirements (strength, setting time, etc.) are maintained. The lime content of the final cement product is typically within a relatively narrow composition range and well documented, often on a production lot basis. Environment Canada applies an emission factor of 500 kg of carbon dioxide per 1,000 kg of cement produced by the industry.²² The uncertainty in the estimated emissions of 5,360 kt from cement production (excluding energy) is +/-12%. This emission factor is derived based on the assumption that the average lime content of the clinker in Canada is 63.5% by weight. Clinker and minor amounts of gypsum (calcium sulphate) and additives are combined to make the final cement product.

For lime production, Environment Canada applies the emission factor of 790 kg of carbon dioxide per 1,000 kg of lime produced.²³ This emission factor is very close to the theoretical release factor of 786 kg of carbon dioxide per 1,000 kg of lime produced. The uncertainty in Environment Canada's estimate for 1995 emissions from lime production is +/-15%. Part of this uncertainty may result from uncertainty in Canada's total merchant lime production estimates.

It is possible to measure, monitor and calculate carbon dioxide emissions based on lime kiln or cement kiln stack testing of carbon dioxide concentration levels; however, this option is likely to be more expensive than using simplified emission factors applied to production and/or raw material quantities and contents. Some cement plants in Canada are required to carry out continuous emissions monitoring (CEM) of various pollutants. These CEM systems can measure carbon dioxide as well as volumetric gas emissions flow rate. One cement company claims that the capital cost for its

22 A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

23 Ibid.

system was \$0.5 million and required \$0.1 million in annual operating costs (labour, maintenance, verification, etc.). Total annualized capital and operating costs of monitoring for most plants would be between \$0.1 and \$1 per tonne of carbon dioxide emitted. Lower incremental costs might be applicable if a CEM system is already in place.

If the reduction option is to control carbon dioxide emissions from stacks through capture, treatment and sequestration technologies, periodic testing of the efficiency of these systems may be required. Some of the considerations involved in measuring the efficiency of capture and treatment devices for carbon dioxide emissions from lime and cement operations include:

- contribution to total emissions from energy combustion and the calcining process;
- variability in exhaust gas flow rate and concentration; and
- variability in efficiency of potential treatment systems.

The range of variability in process operations may be influenced by changes in the types and quality of fuels; raw materials; production rates; heat zone temperatures; and the mechanisms of potential emissions treatment systems. Other factors may also be involved that are specific to the operations of individual plants. The monitoring system and how regularly measurements are taken will relate to the variation in potential emissions and process variability of the emissions treatment devices. These factors will relate to the accuracy and cost of measurements, monitoring and calculating potential emissions, reduction efficiencies and net emissions.

Periodic or continuous stack gas flow rates and concentrations measurement may not be necessary if the amount of treated (e.g., sequestered) carbon

dioxide can be measured through metering and mass balance methods. For example, if the carbon dioxide was captured and sequestered as an inorganic carbonate (e.g., sodium carbonate), then the weight of the carbonate could be measured to estimate the amount of carbon dioxide it contained. Periodic chemical analyses of the sequestered products may be required. These measurements and calculations could be combined with mass balance calculations involving carbon contained in the limestone as well as in the fossil fuels used as energy sources. This would allow for the separation of energy and non-energy-related emissions and the impacts on each of the emissions reduction options.

8.4 Options to Reduce GHG Emissions

No lime or cement producers have been identified that capture and treat potential emissions of carbon dioxide from their operations. However, technologies are available to indirectly reduce carbon dioxide emissions associated with the production of lime. Many facilities have increased their energy and overall production efficiencies over time. In the cement industry, technology evolution and conservation programs have reduced energy consumption per unit of production by about 24% since 1974.²⁴ Carbon dioxide process emissions associated with the calcination of limestone (excluding energy) can be indirectly reduced by reducing the amount of lime required in cement or other lime application markets (steel making, water treatment, etc.). This would reduce the amount of lime produced and associated emissions.

This brief analysis of technology options to reduce GHG emissions considers different approaches to reducing process emissions from lime production. One relates to technologies that address emissions through reductions in lime consumption in major

²⁴ Natural Resources Canada, *1996 Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

applications such as steel production and cement.²⁵ The second approach is to address carbon dioxide emissions with the installation of capture, treatment and extraction equipment. The extracted carbon dioxide would need to be sequestered or stored to prevent releases to air. Since these systems have yet to be applied, the analysis presented here should be considered theoretical. Some sequestering options are described. Significant chemical alteration of the cement (i.e., substantial replacement of calcium oxide) has not been considered by the industry.

Although technologies are available to remove carbon dioxide from lime kiln gas streams, these technologies are rarely applied, since the gas does not contain commercially useful products. Typically, a low concentration (10% to 20%) of carbon dioxide in the high flow rate gas stream makes capture and extraction of the carbon dioxide uneconomical. The capital and variable operating cost to separate carbon dioxide increases as the ratio of final concentration to starting concentration increases. Merchant carbon dioxide suppliers, who rely on chemical plants, ammonia facilities, crude oil refineries and other sources for higher purity carbon dioxide, have largely ignored lime kilns as a source for their carbon dioxide needs.

Because of the lack of application of emission control systems, the operating experience in handling dilute carbon dioxide streams is not defined. While general carbon dioxide reduction options are available, it has yet to be determined which technology best fits the particular requirements of each facility in the lime and cement industry. Generally, lime producers still have to analyse options for controlling and ultimately disposing of the carbon dioxide that is emitted. Additional research is required to identify optimal

solutions for the lime kilns in controlling their emissions and finding a sink for the output.

8.4.1 Reducing Lime Consumption and Production

Fly ash, metal slags and volcanic ash are being incorporated in cement and concrete formulations in Canada and other countries. These materials are typically waste products generated from industrial processes producing electrical energy (e.g., coal power plants) or making metals. These products can be incorporated in cement formulations without materially affecting the performance for various end uses.

Fly ash is a mixture of inorganic chemicals produced from the combustion of powdered coal or other fuel-containing inorganic matter. In Canada, fly ash is being used in minor amounts in cement and in greater amounts in concrete products. While cement formulations can use up to 8% by weight of fly ash, nearly all Portland cement sold contains less than 2%. In other countries, fly ash is typically incorporated in greater amounts. The fly ash is incorporated into the mixture at the cement plant through various process operations.

Most European countries have allowed the use of slags or fly ash in cements, even though the ingredient produces cements with different properties. There are reports that slag- or fly ash-containing cements last longer and are more tolerant of salt water than pure clinker cements.²⁶ However, increasing the slag or fly ash content to very high levels will compromise the performance of the cement.

A recent study concluded that substituting fly ash for clinker can reduce GHG emissions by 5% to 20%.²⁷ This rate of reduction not only takes into account the

25 An analysis of technical options to reduce lime consumption in steel production is quite complex and considered beyond the scope of this study. It also requires a benchmarking of the consumption of lime versus potential targets for each of the steel producers. Steel producers are already practising some lime reduction strategies (i.e., minimizing the presence of acidic silicon dioxide [SiO₂], which is neutralized with lime).

26 Oak Ridge National Laboratory, et al., *Scenarios of U.S. Carbon Reductions, Potential Impacts of Energy Technologies by 2010 and Beyond*, prepared for the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy (September 1997).

27 G. Sauer, "Cement, Concrete and Greenhouse Gas," paper presented at the CGLI Second Roundtable on North American Energy Policy, April 1997.

lower levels of process carbon dioxide emissions resulting from reduced lime use, but energy-related savings resulting from processing (e.g., grinding) a lesser quantity of clinker. Other benefits of this technology option are that emissions of nitrogen oxides and sulphur dioxide and other pollutants associated with cement production are also reduced.

Fly ash or slags may be available at low cost, free of charge, or incentives may even be available to cement makers to incorporate this waste material in their product. Some producers of fly ash may have a financial interest in shipping fly ash waste to cement plants, rather than disposing of it in landfill sites at higher costs. Concrete producers have an interest in adopting fly ash, since they view the substance as a means to lower material costs. International cement technology suppliers active in Canada have expressed a willingness to develop new specifications for cement containing fly ash.²⁸ They point to their business operations in other countries where fly ash has already been adopted.

Before fly ash can be incorporated in greater amounts in cement, cement and concrete product specifications and standards may need to be changed. This process may represent the largest cost component to this option. Changing cement product standards (or any standards) is usually not easily achieved.

It should be kept in mind that slags, fly ash and other materials are already incorporated into concrete formulations, although the amount of such materials is not well defined. Concrete mixes are largely composed of aggregate materials and minor portions of cement that acts as the binder. The concrete manufacturing industry is composed of many participants. According to cement producers, this industry group is not interested in having cement manufacturers incorporate slags, fly ash and other similar materials in cement, preferring to do it themselves at less cost.

8.4.1.1 Carbon Dioxide Capture and Sequestering Technologies

There are various potential technologies (yet to be proven) that could capture and sequester carbon dioxide from lime production. Several technologies are available for separating gases contained in the gas emission stream, including:

- cryogenic separation;
- pressure swing adsorption; and
- membranes.

Cryogenic separation relies on distillation. Distillation requires gases to be condensed to liquids. Cryogenic systems must liquefy the oxygen, nitrogen and carbon dioxide, which are gases at room temperatures and atmospheric pressures, before separation can occur. This requires low temperatures and high-pressure operating conditions. In pressure swing adsorption (PSA) units, molecular sieves (carbon- or zeolite-based) with pore dimensions similar to the gases being separated are placed in vessels. Hollow polymeric fibre membranes can be designed to selectively allow passage of one molecule while restricting others. Gas separation is achieved by designing systems that take into consideration differences in membrane solubility and diffusion of molecules to be separated.

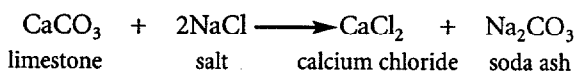
8.4.1.2 Sequestering and Disposition of Carbon Dioxide

Once the carbon dioxide has been captured and extracted, the question arises as to what can be done with it. Existing commercial uses of carbon dioxide for beverages, refrigeration, neutralization and other applications are well serviced by gas suppliers. Typically merchant suppliers have not needed to extract carbon dioxide from dilute sources (such as lime kilns), since the cost of extraction is high relative to sources that offer a high concentration carbon

²⁸ Environment Canada, Environmental Technology Advancement Directorate, *Powering Greenhouse Gas Emission Reductions Through Technology Advancement* (Ottawa, April 1998).

dioxide stream. Gas suppliers have sought opportunistic sources of carbon dioxide from ammonia plants, hydrogen plants (e.g., at crude oil refineries) and chemical plants.

Carbon dioxide can be reacted with salt solutions and various alkali hydroxides to form carbonates. One commercial process uses the carbon dioxide produced from a lime kiln as a reactant with sodium chloride to make calcium chloride and sodium carbonate. The overall reaction is as follows:



Whether this process results in a “permanent” sequestration of the carbon dioxide depends on the application of the soda ash. A large portion of the soda ash commercially produced in this process is used in glass manufacture. In this case, carbon dioxide contained in the carbonate is dissociated and released during heating in the glass-making process. However, in other applications, such as detergents, water treatment and some chemicals manufacturing, the carbonate may remain sequestered.

Carbon dioxide can be dissolved in water to produce weak carbonic acid. This acid has many possible neutralization applications in a variety of end-use markets. Potential markets for carbon dioxide would include a portion of the existing hydrochloric, nitric, sulphuric and phosphoric acid markets. However, the portion of the acid market into which carbon dioxide would fit would be low, since in many applications the type of acid used is specific to the equipment and chemistry of the process. In addition, carbonic acid works best at high pH levels, and large quantities are required to achieve results in the lower pH range.

8.5 Suitability for GHG Emissions Trading

The lime and cement industry is suitable for emissions trading systems. Credit trading might be preferable for the non-energy emissions resulting

from the calcination of limestone. Emissions from calcining (non-energy source) could be incorporated within a total emissions trading program, or treated separately if required, since the two sources of GHGs can be easily distinguished in these operations. GHG emissions from calcining closely correlate with lime or cement production. Options (e.g., reduced production, capture and sequestration) to reduce GHGs from calcining emissions can be substantially different than those addressing energy-related emissions (e.g., energy efficiency improvement projects). The main features of the lime and cement industry that favour credit trading include:

- actual emissions of carbon dioxide from calcining limestone in making lime can be accurately measured and/or calculated at the plant as well as industry level;
- the cost of measuring and monitoring emission rates is reasonably low (in some cases incremental to existing monitoring systems employed for other pollutants);
- although few technology options are available to reduce emissions, a baseline of emissions can be readily established for the industry and individual plants; and
- nearly all facilities are large emitters and can be readily identified. Practically 100% of the emission sources can be covered under a trading program.

This industry is also suitable for an emissions trading allowance program, potentially linked with other industries, which would allow the industry to grow. While the industry’s production has been growing very slowly, increased production can be expected in the long term. Since carbon dioxide emissions from calcining limestone are inherent in the chemical reaction used to make the final products (lime and cement), capping the total industry emissions would cap production of lime or cement. The ability to purchase some emissions rights would allow the industry to expand slowly over time.

Substance trading might be most suitable on the portion of the cement industry that is forward-integrated to concrete production. Trading allowances could potentially be established on cement sales or limestone raw material usage. The ability to reduce lime consumption through the increased substitution of cement alternatives (such as fly ash) would result in reduced emissions in the cement production process. Cement producers not integrated to concrete production might have less interest in applying this emissions reduction option, since they have less influence on the use of cement in their customers' concrete formulations. The merchant lime-producing industry, which is typically not forward-integrated, would not be very suitable for substance product trading.

9. Livestock Manure

9.1 Source and Quantity of GHG Emissions

Methane emissions from livestock manure are predominately attributed to beef cattle, pigs and dairy cattle. Other much smaller sources include sheep and poultry. In 1995, livestock manure accounted for a total of 271 kilotonnes (kt) of methane (CH₄) emissions (5,700 kt of carbon dioxide [CO₂] equivalent), which represented approximately 4% of total non-combustion greenhouse gas (GHG) emissions in Canada as well as 1% of total Canadian GHG emissions.

Livestock waste decomposition occurs either aerobically or anaerobically. Under aerobic conditions, organic material in the waste is decomposed by aerobic and facultative bacteria using oxygen. The end products of aerobic decomposition are carbon dioxide and stabilized organic material. Under anaerobic conditions, organic material in livestock waste is decomposed by anaerobic and

Trends in CH ₄ Emissions from Livestock Manure in Canada		
Year	CH ₄ Emissions	CO ₂ Equivalent Emissions
	(kt)	(kt)
1990	246	5,166
1991	248	5,208
1992	247	5,187
1993	257	5,397
1994	263	5,523
1995	271	5,691

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

facultative bacteria. End products of anaerobic decomposition are methane, carbon dioxide and stabilized organic material. Bacteria responsible for methane production in animal waste are strictly anaerobic.

Three factors influence methane emissions from livestock manure, namely (i) the type of livestock feed utilized (i.e., high energy content and digestibility of feed results in greater CH₄ emissions from the waste); (ii) the characteristics of the animal waste management system utilized; and (iii) climatic conditions.

Manure management systems that utilize anaerobic conditions (e.g., liquid/slurry storage systems, pit storage systems, and anaerobic lagoons) contribute the most methane emissions. A small percentage of livestock manure worldwide is managed with these systems; however, it has been estimated that these types of systems are responsible for about 60% of global livestock manure methane emissions. Manure management systems that involve contact of the manure with air (e.g., uncollected on the range) have low methane production potential.²⁹

With respect to climatic conditions, the factors that influence the level of methane emissions are (i) temperature — methane production generally

²⁹ Ibid.

increases with rising temperature; and (ii) moisture — the moisture content of the livestock waste determines the rate of bacterial growth and waste decomposition. Moist conditions promote methane production.³⁰

9.2 Nature of the GHG Emissions Stream

There are thousands of individual sources of methane emissions from livestock manure in Canada. Due to their large population, beef cattle represent approximately 50% of all manure-related methane emissions. Dairy cattle, because their manure management systems are more likely to promote

anaerobic decomposition, contribute 16% to total methane emissions, even though there is a relatively small population in Canada. Beef cattle are more likely to be ranging animals that promote aerobic decomposition of manure, while dairy cattle are often herded into barns and the manure stored in pits, lagoons, etc., that promote anaerobic decomposition.

It has been suggested that manure management systems that store manure under anaerobic conditions contribute approximately 60% to methane emissions from this source. The larger farms in Canada are where these complex manure management systems have been installed and are therefore where the manure-related methane emissions are concentrated.

1995 Canadian CH ₄ Emissions from Livestock Manure			
	Number of Animals (000s)	Emission Estimates (kt CH ₄)	Emission Factor (kg CH ₄ per animal)
Cattle – beef	12,448	135	10.8
Cattle – dairy	1,271	44	34.4
Goats	22	Nil	0.0
Sheep	717	4	5.1
Pigs	11,939	77	6.4
Horses/mules/asses	356	Nil	0.0
Buffalo	N/A	N/A	N/A
Camels and llamas	N/A	N/A	N/A
Poultry	116,113	12	0.1
Other	N/A	N/A	N/A
Total	142,865	271	1.9

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

30 U.S. Environmental Protection Agency, *Global Methane Emissions from Livestock and Poultry Manure* (Washington, D.C., February 1992), pp. 11-15.

Large Livestock Farms in Canada			
Province	Farms with > 100 Dairy Cows	Farms with > 1,000 Pigs	Farms with > 50 Beef Cattle
Newfoundland	14	1	0
Prince Edward Island	10	31	65
Nova Scotia	34	48	150
New Brunswick	21	30	69
Quebec	214	1,126	1,244
Ontario	311	734	1,821
Manitoba	72	373	3,731
Saskatchewan	48	151	8,104
Alberta	224	460	13,870
British Columbia	214	56	1,340
Canada	1,162	3,010	30,394

Source: Statistics Canada, fax communication, 1998.

9.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Due to the wide dispersal of sources of livestock manure in Canada, the most logical approach to estimating total methane emissions, and the approach currently utilized by Environment Canada, is to apply emission factors to the number of livestock in Canada. The emission factors that were utilized by Environment Canada to estimate livestock emissions were outlined earlier in this section. Currently, Environment Canada indicates that the uncertainties with respect to these emission estimates are +/-50% to 30% (this means that the actual CH₄ emissions from manure may be 50% higher or 30% lower than 271 kt). This relatively high uncertainty can be attributed to the large number of variables that affect methane emissions generated from livestock manure, for instance, the composition of the feed, size of the animal, climatic conditions, and type of manure management system.

Developing data on these variables as they relate to actual conditions on Canadian farms, and then applying individual emission factors that incorporate these specific conditions, will increase the accuracy and reduce the uncertainty attributed to methane emissions from livestock manure. For instance, determining exactly what percentage of dairy and beef cattle reside on farms that have installed manure management systems that promote the anaerobic decomposition of manure, and thus methane emissions, will increase the accuracy of the respective emission estimates. If these data were developed, an emission factor could be applied to the number of livestock located on farms with those manure management systems, while another emission factor (a smaller one) could be applied to the number of livestock on farms without those manure management systems.

Monitoring for reductions in methane emissions from livestock manure in Canada would require data on these variables. Currently, the main variable that alters methane emissions from livestock manure from year to year is changes to the total herd in Canada.

9.4 Options to Reduce GHG Emissions

Technologies exist that can reduce methane emissions from livestock manure on Canadian farms. However, methane emissions from livestock manure in Canada are for the most part uncontrolled. Two main types of technologies are discussed in this section: aerobic composting and anaerobic digesters.

Several types of aerobic composting technologies are currently being developed in Canada. These systems use various different processes to aerobically compost liquid livestock manure to produce fertilizer that can be applied to fields or even sold on the commercial or consumer markets. The two large categories of aerobic composters are continuous and batch. Continuous systems require manure to be fed into the composting system daily, while batch composters may only need liquid manure to be fed into the system approximately six times over a 30-day period. Aerobic composting through the utilization of manure to produce an organic fertilizer reduces methane emissions. It should be noted that there are few, if any, commercial farms (besides pilot projects) in Canada that have installed aerobic composting systems. However, several Canadian companies are quite close to full-scale commercialization of their respective aerobic composting systems for manure.

Most of the research to date to reduce methane emissions from livestock manure has been focused on anaerobic digesters to collect the biogas that results from the microorganism decomposition of manure. Biogas technology is a manure management tool that

recovers and uses methane as an energy source. Collected biogas can then be used as a fuel source to generate electricity for use on the farm; sold to the electrical grid; or used for heating or cooling needs.³¹ The largest potential to reduce methane emissions is at farms where manure is managed anaerobically in liquid or slurry form or stored over time as a solid.

There are three main types of anaerobic digesters: covered lagoons, plug flow digesters, and complete mix digesters. These digesters are suitable for large-scale, intensive farm operations that are common in North America, Europe, and regions of Asia and Australia. It has been shown that when anaerobic digesters are introduced at farms that have been emitting large amounts of methane, emissions have been reduced by up to 70% to 80%.

Covered lagoon digesters contain a floating impermeable cover placed over the surface of a manure treatment/storage lagoon. Biogas from the decomposing manure is collected under the cover. Covered lagoon digesters have been shown to be quite applicable to swine and dairy operations. At these operations, recycled water flushes the manure from the confinement facilities. Water and manure then run into the primary lagoon (through a solids separator at dairy operations), which has a large cover made of durable membrane. Under this cover, microorganisms work to break down the manure and produce biogas, which is about 70% methane and 30% carbon dioxide. The biogas bubbles to the surface and is captured under the cover. The gas is then piped out and used to generate electricity, heat water and even run chillers.³²

31 U.S. Environmental Protection Agency, *A Manual for Developing Biogas Systems at Commercial Farms in the United States*, AgSTAR Handbook (Washington, D.C., July 1997), p. 1.

32 Ibid.

Economics for Actual Anaerobic Digesters in the U.S. (C\$)			
	Covered Lagoon	Plug Flow	Complete Mix
Farm description	1,000 milker, dairy	15,000 total head with 5,000 milkers	1,500 sow, farrow to finish
Total capital costs	\$370,000	\$435,000	\$360,000
Annual electricity benefits	\$81,000	\$180,000-\$230,000	\$72,000
Annual operating costs	\$15,000	\$17,500-\$22,000	\$7,000
Payback period	5.5 years	<3 years	4-5 years

Source: U.S. Environmental Protection Agency, *Methane Recovery from Animal Manures — The 1997 Opportunities Casebook*, 1997.

Plug flow digesters are constant volume, flow-through units that decompose high solids (>11%) dairy manure (plug flow digesters only work with dairy scraped manure and cannot be used with other livestock manure) to produce biogas and a biologically stabilized effluent. The plug flow digester design is a long tank, often built below ground level, with a gas-tight, expandable cover. The tank volume equals the volume of the manure input times the manure retention time, which is typically 15 to 20 days. Plug flow digester systems also include the manure collection system, mixing pit equipment, and an effluent storage system.³³

Complete mix digesters are heated, constant volume, mechanically mixed tanks that decompose swine or dairy manure (3% to 8% total solids) to produce biogas and a biologically stabilized effluent. The basic complete mix digester design is a vertical, poured concrete or steel, circular container, with a gas-tight collection cover. Because complete mix digesters are heated to optimize methane production, they can be economically sized for use in any climate.

9.5 Suitability for GHG Emissions Trading

The discussion of the suitability of emissions trading programs to encompass methane emissions from manure management is similar to the discussion of enteric fermentation (elsewhere in this report). The most appropriate emissions trading program would be a credit trading program based on an emission rate (i.e., emission factor) for baseline emissions, as well as an emission rate once certain best management practices/ technologies are employed. The farmer would receive credit once it was verified that these practices/ technologies were employed. The credits would be received at the point of sale.

With manure management, as opposed to enteric fermentation, significant quantities of methane emissions are concentrated at fewer farms. The farms that employ manure management systems that promote anaerobic decomposition of manure have greater quantities of methane emissions. In contrast, large beef cattle farms, for example, where the cattle are free roaming for the most part, and where the manure is decomposed aerobically, do not contribute significant amounts of manure-related methane emissions, even though there may be a very large number of livestock located on those farms. Despite the differences between enteric fermentation and manure management, the recommended emissions trading program is the same (i.e., a credit trading program).

³³ U.S. Environmental Protection Agency, *Plug Flow Digesters*, AgSTAR Technical Series (Washington, D.C., February 1997), pp. 1-2.

Having made this recommendation, it is important to note that an emissions rights trading program may be more attractive for manure management than for enteric fermentation, because there are not as many “major” sources. Emissions rights could be allocated among the largest farms that promote anaerobic decomposition of manure. There are several technologies/best management practices that could be employed to reduce methane emissions and that could be easily verified. Emissions trading could then take place among those large farms. It is not recommended that the smaller farms, which contribute only minor amounts to overall manure-related methane emissions, be included in any such emissions rights trading program. The inequity of allocating rights to those farms that promote anaerobic decomposition of manure, while not distributing rights to those farms that do not employ those manure management systems, would have to be addressed.

The substance trading program was discounted because there is no one substance that is an appropriate proxy for methane emissions from manure management. The level of methane emissions at farms results from a number of factors including feed used, size and type of animal, weather conditions, manure management systems in place, etc. Due to these wide-ranging factors and lack of an appropriate substance upon which to base a trading program, the substance trading system is not considered appropriate.

10. Fertilizer Use

10.1 Source and Quantity of GHG Emissions

In 1995, fertilizer application accounted for a total of 13 kilotonnes (kt) of nitrous oxide (N₂O) emissions (4,030 kt of carbon dioxide [CO₂] equivalent), which represented approximately 3% of total non-

combustion greenhouse gas (GHG) emissions in Canada as well as 0.6% of total Canadian GHG emissions. A significant increase in nitrous oxide emissions from fertilizer application in Canada has occurred in the first half of the 1990s (i.e., >24%). The reason for this upward trend in nitrous oxide emissions has been the increase in fertilizer application, specifically nitrogen-based fertilizers.

Trends in N ₂ O Emissions from Fertilizer Application in Canada		
Year	N ₂ O Emissions	CO ₂ Eq. Emissions
	(kt)	(kt)
1990	11	3,410
1991	11	3,410
1992	12	3,720
1993	13	4,030
1994	13	4,030
1995	13	4,030

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

When nitrogen-based fertilizers are applied to soil, nitrous oxide emissions generally increase unless the amount of nutrient applied precisely matches the plant uptake and soil capture. Nitrous oxide emissions from fertilizer application occur due to anaerobic and aerobic processes. When either inorganic or organic fertilizers are applied to soil, most of the nitrogen is oxidized to nitrates before it is taken up by the plants. This process is referred to as nitrification. Anaerobic emissions of nitrous oxide occur when soils become waterlogged. In an anaerobic environment, such as that of waterlogged soil, nitrates are reduced by facultative anaerobic bacteria to nitrous oxide and nitrogen (N₂) gas, which are emitted to the atmosphere. This process is referred to as denitrification: the loss of nitrogen in the soil.³⁴

Several factors control the rate of the two microbial processes (nitrification and denitrification) that

³⁴ A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

result in nitrous oxide emissions. Among these variables are soil water content, temperature, nitrate or ammonium concentrations, available organic carbon for identification, and pH.³⁵

10.2 Nature of the GHG Emissions Stream

Emissions of nitrous oxide are dispersed across the country, wherever fertilizer is applied. However, a large portion of these emissions is located in the agricultural belt on the Prairies. No data currently exist in Canada on the consumption of urea, anhydrous ammonia or the other nitrogen-based fertilizers by large farms in Canada. Therefore, it is difficult to estimate just how many farms in Canada would represent, say, 50% of nitrogen-based fertilizer application (and potentially nitrous oxide emissions) in Canada.³⁶

Nitrogen-based fertilizers are used to increase the nitrogen content of soils to a point that maximizes crop yield. Different types of nitrogen-based fertilizers are applied in Canada. Urea and anhydrous ammonia are the two most commonly used fertilizers, together representing approximately 72% of the mineral nitrogen applied as fertilizer annually in Canada.

Based on current estimates, the application of anhydrous ammonia is the source of most fertilizer-related nitrous oxide emissions in Canada. Compared with anhydrous ammonia, 750,000 more tonnes of urea are applied in Canada (which corresponds to a total of 158,000 more tonnes of nitrogen nutrient applied with urea than anhydrous ammonia). However, urea represents only about 8% of nitrous oxide emissions, while anhydrous ammonia represents 85%. This disparity is due to the fact that

Canadian Fertilizer Use and Related N ₂ O Emissions in 1995				
Fertilizer Material	Quantity (tonnes)	N Content (tonnes)	Average Loss (% N)	N ₂ O (tonnes)
Nitrogen				
Urea	1,304,730	600,176	0.11	1,037
Ammonia sulphate	205,330	43,119	0.12	81
Ammonium nitrate	256,697	87,957	0.26	369
Anhydrous ammonia	553,727	442,581	1.63	11,336
Nitrogen solutions	232,906	66,029	0.11	114
Other nitrogen	3,199	0	0.11	0
Calcium ammonium nitrate	32,849	8,470	0.03	4
Phosphate				
Monoammonium phosphate	937,031	103,073	0.12	194
Diammonium phosphate	180,785	32,541	0.12	61
10-34-0	1,705	238	0.11	0
Other fertilizers	293,804	64,171	0.11	111
Total	4,002,765	1,448,355		13,300

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

35 Intergovernmental Panel on Climate Change, *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change* (1996), p. 761.

36 Interview with Jim Farrell, Canadian Fertilizer Institute, August 5, 1998.

anhydrous ammonia has such a high emission factor (i.e., 1.63%) compared to urea (i.e., 0.11%) and all the other nitrogen-based fertilizers.

10.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

There is currently very high uncertainty regarding the nitrous oxide emissions attributed to fertilizer application in Canada. In fact, Environment Canada does not even allocate an uncertainty factor to estimates of nitrous oxide emissions attributed to fertilizer application in their GHG inventory. Currently, Environment Canada utilizes emission factors (i.e., average loss [% N] in table above) for the various different nitrogen-based fertilizers and applies these factors to fertilizer application quantities.

International work on this subject has indicated that up to 50% of nitrous oxide releases from fertilizer application may not be included in current estimates. Current nitrous oxide emission estimates are based on emission factors developed from on-field emission measurements, while much of the fertilizer applied to fields is released off-site due to runoff and losses of ammonia. Future emission estimates for Canada may reflect these additional sources, since the new GHG inventory procedures document, published by the Intergovernmental Panel on Climate Change, details some new methodologies to estimate emissions from these additional sources.

Emission factors will be the method used to estimate nitrous oxide emissions in the future. To incorporate those technologies and practices (see below) that can reduce nitrous oxide emissions, adjusted emission

factors will have to be developed that reflect their relative contribution to reducing nitrous oxide emissions, and therefore quantify the credit that would be accrued and used for emissions trading purposes.

10.4 Options to Reduce GHG Emissions

A wide variety of farm management practices and technologies have been developed or are in the development stage that can reduce nitrous oxide emissions from fertilizer application.³⁷

Three technologies or management practices are discussed in this section, namely: (i) fertilizer management practices; (ii) nitrification inhibitors; and (iii) irrigation water management.

10.4.1 Fertilizer Management Practices

A better matching of mineral fertilizer to crop requirements would result in a reduced demand for fertilizer and consequently reduced nitrous oxide emissions. This increased efficiency can be achieved by:^{38, 39}

- using nitrogen testing kits to more closely match crop requirements to nutrient inputs;
- regularly calibrating machinery to ensure accurate delivery of fertilizers;
- paying careful attention to the frequency, timing and appropriate placement of fertilizer applications;
- dispensing with the maintenance concept, which fails to recognize the amount of residual nitrogen in the soil and the soil's nitrification potential;

³⁷ Carbon dioxide emissions from soil are not included in this investigation.

³⁸ Organization for Economic Cooperation and Development, *Policies and Measures for Common Action, Working Paper 7 — Agriculture and Forestry, Identification of Options for Net GHG Reduction* (Paris, July 1996), p. 26.

³⁹ Center for Agricultural Science and Technology, *Preparing U.S. Agriculture for Global Climate Change* (Ames, Iowa, June 1992), p. 76.

Expected Reduction of N₂O Emissions Assuming Global Application of Mitigation Practices

Practice Followed	Estimated Decrease in N ₂ O Emissions (Mt N/yr)
Match N supply with crop demand <ul style="list-style-type: none"> • Use soil/plant testing to determine fertilizer N needs • Minimize fallow periods to limit mineral N accumulation • Optimize split application schemes • Match N application to reduced production goals in regions of crop overproduction 	0.24
Tighten N flow cycles <ul style="list-style-type: none"> • Integrate animal & crop production systems — manure reuse in plant production • Maintain plant residue N on the production site 	0.14
Use advanced fertilization techniques <ul style="list-style-type: none"> • Use controlled-release fertilizers • Place fertilizers below the soil surface • Use foliar application of fertilizers • Use nitrification inhibitors • Match fertilizer type to seasonal precipitation 	0.15
Optimize tillage, irrigation and drainage	0.15
Total	0.68

Source: Intergovernmental Panel on Climate Change, *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change* (1996), p. 763.

- adjusting the rate of nitrogen application to a reasonable yield goal for the specific crop and field or soil;
- placing nitrogen deep enough in the soil to lower the nitrous oxide/nitrogen gas (N₂O/N₂) ratio when denitrification does occur; and
- taking into account soil nitrogen mineralization and the nitrogen from legumes, manures, organic wastes, irrigation water and other potential sources.

It has been estimated that increased fertilizer efficiency has the potential to reduce nitrous oxide emissions by 0.3-0.9 million tonnes (Mt) N₂O-N per year globally. In addition, fertilizer production is very energy intensive, so reducing fertilizer use, and therefore production, will also reduce carbon dioxide emissions.

⁴⁰ Ibid. p. 77.

10.4.2 Nitrification Inhibitors

Nitrification inhibitors are chemicals applied with fertilizers to maintain the added nitrogen as ammonium. Nitrification inhibitors stabilize fertilizer applied as ammonia (NH₃) or in the ammonium (NH₄⁺) form by inhibiting the activity of the Nitrosomonas bacteria in the first step of the nitrification process. Nitrogen losses are reduced if applied nitrogen remains in the NH₄⁺ form for several weeks after application, especially when applied in the fall or when there may be heavy rainfall during the spring. An inhibitor, such as nitrapyrin or acetylene, can be effective in many field crop situations.⁴⁰

10.4.3 Irrigation Water Management

Usually emissions of denitrification gases occur immediately following each irrigation. Since nitrous oxide can be further altered to nitrogen during transport to the soil surface, there is greater opportunity to decrease the nitrous oxide/nitrogen ratio of the resulting gases when the mineral nitrogen is placed deeper in the soil. Infrequent irrigation decreases the number of denitrification cycles and also helps move soluble nitrogen deeper into the soil, where supplies of oxygen are more limited. This reduces the amount of nitrous oxide that may form from nitrogen.⁴¹

There has not been a significant level of economic analysis undertaken on the practices to reduce nitrous oxide emissions from fertilizer application. This is because some of the practices may not be used by a large number of farmers and, where they are, they relate to complex farming systems, making it difficult to isolate costs and benefits.⁴² Fertilizer management practices, nitrification inhibitors and irrigation water management technologies are all available and have low reported capital costs.⁴³ These practices are more likely to be economically feasible on crops that have high nitrogen demands (e.g., corn, cotton and wheat).⁴⁴

10.5 Suitability for GHG Emissions Trading

A substance trading program is believed to be the most appropriate emissions trading system to address nitrous oxide emissions from fertilizer application. However, a typical substance trading program would

not be suitable because of the wide variation in nitrous oxide emissions from different nitrogen-containing fertilizers. Under a typical system, where nitrogen were simply allocated and not linked to nitrous oxide emissions, producers could conceivably use all available nitrogen allocated to them to produce the fertilizers with the highest nitrous oxide emission factor. The result would be higher nitrous oxide emissions.

The substance trading program proposed here would be based upon adjusted nitrogen, which is actually the quantity of nitrogen used to produce fertilizer adjusted to take the respective nitrous oxide emission factors of different fertilizers into account. The system would be applied at the fertilizer production level, since there are only a handful of nitrogen-containing fertilizer producers in Canada. Each of the Canadian fertilizer producers would be given a cap on the amount of adjusted nitrogen that could be used to produce fertilizer. The adjustment to the nitrogen would serve to link potential nitrous oxide emissions from the application of fertilizer to Canadian soil to the fertilizer that is produced in Canada. With this adjustment, producers could decide how to allot their adjusted nitrogen among the various nitrogen-based fertilizers that can be produced.

For instance, if a producer chose to manufacture anhydrous ammonia with the allotted adjusted nitrogen, then this producer would use up a large proportion of its allotted adjusted nitrogen on a small quantity of anhydrous ammonia because of the high emission factor. For example, if a producer was allocated 100 tonnes of adjusted nitrogen, the company could use 61 tonnes of nitrogen to produce

41 Symbiotic Environmental Research and Consulting, *Inventory of Technologies to Reduce Greenhouse Gas Emissions from Agriculture* (Ottawa, 1997), pp. 16-17.

42 Organization for Economic Cooperation and Development, *Policies and Measures for Common Action, Working Paper 7 — Agriculture and Forestry, Identification of Options for Net GHG Reduction* (Paris, July 1996), p. 32.

43 Symbiotic Environmental Research and Consulting, *Inventory of Technologies to Reduce Greenhouse Gas Emissions from Agriculture* (Ottawa, 1997), p. 26.

44 Intergovernmental Panel on Climate Change, *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change* (1996), p. 765.

Canadian Nitrogen-based Fertilizer Producers	
Company	Plant Location
Agrium	Redwater, AB
Agrium	Ft Saskatchewan, AB
Saskferco Products	Belle Plaine, SK
Agrium	Carseland, AB
Terra International	Courtright, ON
Agrium	Joffre, AB
Hydro Agri Canada	Maitland, ON
Orica Canada	Carseland, AB
Simplot Canada	Brandon, MB
Western Cooperative Fertilizers	Calgary, AB
Pacific Ammonia	Kitimat, BC

Source: Canadian Fertilizer Institute, fax communication, 1998.

anhydrous ammonia, which has a nitrous oxide emission factor of 1.63 (i.e., 61 tonnes of nitrogen multiplied by 1.63 = 100 tonnes). The manufacturer could also opt to use 909 tonnes of nitrogen to produce urea, which has a nitrous oxide emission factor of 0.11 (i.e., 909 tonnes of nitrogen multiplied by 0.11 = 100 tonnes). Applying the adjustment addresses the disparity in emission factors between the different nitrogen-based fertilizers.

However, the actual emissions trading system might have to take several other factors into consideration. These include the fact that urea production sequesters carbon dioxide; the effect that applying different fertilizers has on crop yields (i.e., different potential sequestering rates); the fact that urea production requires more energy than other nitrogen-based fertilizers; and the fact that urea releases carbon dioxide in the field but anhydrous ammonia does not.

Since emissions take place from farms, a substance trading program administered at the producer level would have to take fertilizer trade into account. Producers and importers of fertilizers may have to hold permits, while producers would be entitled to receive credits for any fertilizer exports if the destination country did not participate in a trading

program. This would match the permits with the domestic consumption of fertilizer and therefore with the nitrous oxide emissions.

There are other potential emissions trading programs that could be applied to address nitrous oxide emissions from fertilizer application. For instance an emissions rights, substance trading and credit trading program could all be applied at the farm level. However, these options are not viewed as favourable due to the much larger number of participants in this system compared with an emissions trading program at the fertilizer producer level. It should be noted that a credit trading program could also be applied at the producer level, with credits being accumulated from a shift in production to fertilizers with a lower nitrogen oxide emission factor.

11. Ammonia Production

11.1 Source and Quantity of GHG Emissions

Ammonia (NH₃) is produced in large industrial plants from nitrogen gas and hydrogen gas, mixed in a 1:3 ratio and reacted over a catalyst. Nitrogen gas is derived from air through liquefaction and separation. Hydrogen gas is usually produced from natural gas in a process known as steam methane reforming. In this process, carbon dioxide is produced as a co-product with hydrogen and must be separated as a fairly pure gas stream. If carbon dioxide (CO₂) from ammonia manufacture cannot be used further, it is emitted to the atmosphere.

Urea is a solid form nitrogen-based fertilizer that is produced from ammonia and carbon dioxide. Urea production is often integrated with ammonia production to use the by-product carbon dioxide produced in the steam methane reforming process. In the form of urea, the carbon can be sequestered in plants or may be released to the atmosphere after application to soils.

Trends in CO₂ Emissions from Ammonia Production						
	1990	1991	1992	1993	1994	1995
Net CO ₂ emissions (kt)	3,200	3,400	3,500	3,600	3,800	3,800
Gross ammonia production (Mt)	3.7	3.7	3.8	4.1	4.2	4.2
Urea production (Mt)	2.6	2.4	2.5	2.9	2.9	2.9

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

Environment Canada estimates that the net amount of carbon dioxide emitted from ammonia production was 3,800 kilotonnes (kt) in 1995. This represents about 3% of non-combustion greenhouse gas (GHG) emissions and about 0.6% of total GHG emissions. The calculation is based on emission factors and the industrial production levels of ammonia and urea. The net emissions of carbon dioxide from ammonia production take into account the carbon dioxide used in the manufacture of urea.

Urea is made by reacting ammonia with carbon dioxide. Approximately 0.6 kilograms (kg) of ammonia and 0.75 kg of carbon dioxide are required for every 1 kg of urea made. A large portion of the carbon dioxide produced from ammonia plants is already used to make urea. Canadian production of urea represents 55% of the total domestic demand for ammonia.

Canadian Ammonia and Urea Capacities, 1995			
Company	Location	Ammonia (kt)	Urea (kt)
Agrium Inc.	Redwater, AB (2)	880	600
Agrium Inc.	Ft Saskatchewan, AB	440	370
Agrium Inc.	Carseland, AB	550	730
Agrium Inc.	Joffre, AB	420	0
Canadian Fertilizers Ltd.	Medicine Hat, AB	1050	680
Pacific Ammonia Inc.	Kitimat, BC	260	0
Saskferco Products Inc.	Belle Plaine, SK	630	930
Sherritt International	Ft Saskatchewan, AB	150	100
Simplot Canada Ltd.	Brandon, MB	190	150
Terra International	Courtright, ON	380	250
Total capacity		4,950	3,810

Source: Canadian Fertilizer Institute, fax communication, 1998.

11.2 Nature of the GHG Emissions Stream

The carbon dioxide emitted from ammonia manufacture is concentrated as a fairly pure stream (greater than 90% purity) in a single point source from the steam methane reforming plant. Carbon dioxide is usually separated from hydrogen gas in a pressure swing absorption (PSA) unit on the tail end of the steam methane reforming unit.

11.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Since the carbon dioxide gas stream is fairly concentrated and emanates from a single point source, emissions can be calculated fairly accurately from gas flow rates and concentration measurements.

11.4 Options to Reduce GHG Emissions

The model for reducing carbon dioxide emissions by sequestering with ammonia in increased amounts of urea involves one of three options:

- increasing production of urea at Canadian facilities to fill existing capacity;
- expansion of existing urea facilities; and
- construction of new urea production facilities.

Urea production is currently dictated by the market demand for urea fertilizers. Urea demand in North America has grown steadily over the last decade at an average annual rate of about 7% per year. Roughly half of all Canadian production of urea is exported, mostly to the U.S. Midwest. The capital cost to construct a new 750 kt per year urea plant in Canada

is roughly estimated at \$200 million to \$300 million.⁴⁵

11.5 Suitability for GHG Emissions Trading

The fact that there are only 10 ammonia plants and eight urea plants operated by seven companies in Canada means that most of the carbon dioxide emissions from ammonia manufacture are covered by a small number of entities in a trading system. The emissions are measurable and verifiable. Producers have the ability to increase the amount of urea production, either through increased production at existing plants or through the addition of new capacity.

An emissions rights trading program or a credit trading program would be suitable for the carbon dioxide emissions from ammonia production. Since carbon dioxide is created in the production process, a substance trading program would not be suitable.

12. Agricultural Soils

12.1 Source and Quantity of GHG Emissions

Agriculture and Agri-Food Canada applies a computer model (i.e., the Century model) to develop an estimate of carbon dioxide emissions that adequately reflects the complexities that affect carbon fluxes in agricultural soils. The Century model requires several different inputs, such as multiple soil organic matter compartments; decomposition rates that vary as a function of soil temperature and precipitation; and carbon and nitrogen flows. In addition, the Century model takes several agricultural management practices into account, including planting, fertilizer application, tillage and grazing.⁴⁶

⁴⁵ Industry sources.

⁴⁶ A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997), p. 52.

Environment Canada estimates that in 1995, there were 2,480 kilotonnes (kt) of carbon dioxide (CO₂) emitted from agricultural soils, which represents approximately 2% of total non-combustion greenhouse gas (GHG) emissions in Canada or about 0.4% of total Canadian GHG emissions.

Trends in CO₂ Emissions from Agricultural Soils in Canada	
Year	CO₂ Emissions (kt)
1990	7,090
1991	5,820
1992	5,000
1993	3,940
1994	3,490
1995	2,480

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

There has been a decrease in carbon dioxide emissions from agricultural soils over the 1990 to 1995 time period. The trend in net emissions is toward an overall state of equilibrium of carbon in Canadian soils, which was predicted to occur in 1997. The Century model has estimated that the rate of decline in carbon dioxide emissions from 1990 to 1996 is approximately five times greater than for the period 1980 to 1990, reflecting changes in agricultural practices.⁴⁷

12.2 Nature of the GHG Emissions Stream

Carbon dioxide emissions from agricultural soils occur from a vast number of farms across Canada. These emissions result from the aerobic decomposition of organic matter in soils. When the carbon in soils is in equilibrium, the amount of

carbon sequestered in organic matter offsets the emissions from organic matter decomposition, and the net carbon stock is stable. Many factors affect the rate of decomposition, including climate conditions and soil management practices.

It should be noted that the carbon dioxide emissions profile for agricultural soils varies across Canada. Regionally, most of the carbon dioxide would be emitted or sequestered on the agricultural belt in the Prairies as well as in Ontario.

Carbon dioxide emissions from agricultural soils can vary widely among farms, even if the same crops are grown on these farms. There are several different agricultural management practices that can either promote carbon dioxide fluxes or the sequestration of carbon dioxide. The mix of these agricultural practices has significant impacts on overall net carbon dioxide fluxes from individual farms. A brief discussion of a number of these agricultural practices is provided below.

12.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Both Environment Canada and the Intergovernmental Panel on Climate Change (IPCC) have recognized that there is a relatively high uncertainty with respect to estimating carbon dioxide fluxes from agricultural soils. Environment Canada has not developed uncertainty levels for carbon dioxide emission estimates from agricultural soils, as it has done for several other non-energy sources of GHG emissions. The IPCC suggests that there is a high degree of uncertainty in their estimates concerning both flux rate and carbon (C) storage capacity, as well as in the level at which various mitigation options could be implemented.⁴⁸

⁴⁷ Ibid.

⁴⁸ Intergovernmental Panel on Climate Change, *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change* (1996), p. 757.

As mentioned, the Century model is currently being used in Canada to estimate carbon dioxide fluxes from agricultural soils. Several data sources are required as inputs to the model. On a Soil Landscape of Canada polygon basis, Statistics Canada agricultural census data were used to obtain crop cover and percentage of conventional and no-tillage figures for census years. Yearly crop coverage from 1990 to 1995 was taken from Statistics Canada core data. Soil data were derived from the Canadian Soil Information System, and recent fertilizer consumption and tillage practices were derived from the Farm Income Policy and Programs Directorate of Agriculture and Agri-Food Canada. Based on these inputs, the Century model was used to estimate annual carbon dioxide fluxes for 1990 to 1995.

The Century model will probably have to be used in the future to estimate the increased sequestration of carbon dioxide due to the implementation of agricultural practices that discourage carbon dioxide fluxes. However, the verifiability of these emission estimates is questionable, since there are several factors that influence carbon dioxide fluxes from agricultural soils. Implementing agricultural practices to sequester more carbon in the soil can have a range of success depending on weather conditions and many other factors. The ability to capture all of these conditions at an individual farm level, for the purposes of a GHG emissions trading program, is questionable.

12.4 Options to Reduce GHG Emissions⁴⁹

Soil organic carbon in permanently cropped fields can be increased through a number of management practices, such as increased return of organic materials to soil; decreased periods of fallow; use of perennial and winter cover crops; recycling of organic wastes; reduced tillage; erosion control; and agroforestry. Several long-term experiments have

demonstrated that for many soils, organic carbon levels are directly proportional to the annual rate of carbon input. Increasing crop production through better nutrient management, reduced fallow periods, and improved cultivars can increase carbon inputs to soil if crop residues are retained.

Summer fallow is used extensively in semi-arid areas of Canada to offset rainfall variability and increase soil waste storage. Eliminating or reducing summer fallow through better water management could significantly increase carbon in semi-arid croplands and decrease soil erosion.

Greater use of perennial forage crops can also significantly increase soil carbon levels, due to high root carbon production, lack of tillage disturbance, and protection from erosion. Where climate permits, winter cover crops decrease erosion and provide additional inputs of carbon, thereby increasing soil organic carbon. Another management practice to sequester more carbon is to apply large quantities of manure to the fields. Reduced or no-tillage often (but not always) increases soil carbon. However, several studies have shown genuine increases in soil organic content as a result of reduced tillage.

The potential carbon sequestration in Canadian agricultural soils over the next 50 years was recently estimated using long-term field data and the Century model. The researchers applied the following assumptions to the Century model: cropland area in Canada would remain within 5% of the current area; there would be a major reduction in summer fallow in the Chernozemic soil zone; and cropping practices would be intensified, with increased fertilizer use, improved residue management with reduced tillage, and better erosion control. Over a 50-year period, the researchers estimated an increased storage of 22 million tonnes (Mt) of carbon from reduced summer fallow and 69 Mt of carbon from increased hay crops in rotations. Proper fertilization and erosion control through zero-tillage and other measures were also

⁴⁹ The majority of this section was taken from Ibid.

projected to further increase carbon storage. Summing all of these management practices resulted in estimates of annual carbon storage equivalent to 3.4% of Canada's present carbon dioxide emissions.

The potential costs associated with promoting carbon storage in agricultural soils include fossil fuel requirements (e.g., fertilizers), lost production (e.g., set-aside programs), and additional labour and financial requirements (e.g., land restoration). These potential costs may constrain the potential for increasing carbon storage.

12.5 Suitability for GHG Emissions Trading

An emissions trading program for agricultural soils can be evaluated with regard to carbon fluxes as well as to the sequestration of carbon. With respect to carbon fluxes, soils are not deemed to be an appropriate source for emissions trading for a number of reasons. For example, agricultural soils are thought to be too small a source of carbon dioxide to warrant inclusion in an emissions trading program. As well, there are thousands of sources of carbon dioxide from agricultural soils distributed throughout Canada, and the actual credits that could be obtained by farmers would for the most part be minimal. Finally, soils are expected to become a net carbon sink in 1997, although future runs of the Century model will have to determine whether this expectation is correct.

The potential of agricultural soils to be included in a trading program as a sequester of carbon would also be problematic for some of the same reasons. For instance, accounting for the sequestration of carbon would be very cumbersome due to the wide range of farms that could potentially be claiming credits (i.e., in the thousands). In addition, the accuracy of the current estimates of the sequestering capabilities of certain agricultural practices might not be acceptable, especially in view of the wide range of factors that can influence the overall sequestering capability of those practices. Furthermore, the verifiability of

sequestering carbon is unclear and might prove to be quite problematic and resource-intensive.

Nevertheless, if a trading program were to be developed for agricultural soils on a sink basis, then it should be noted that sequestration and storage actions are only suitable for credit trading. Emissions rights cannot be allocated and then traded, since agricultural soils are expected to be a net sink in the near future, if not already. In addition, there is no one substance that could be traded that would reflect the sink potential or gross emissions of agricultural soils.

The key to any trading program for agricultural soils would be the ability to estimate and then verify the carbon sequestering capabilities of various agricultural practices on a farm basis, or potentially even on a regional basis.

13. Magnesium Smelting and Die Casting

13.1 Source and Quantity of GHG Emissions

Sulphur hexafluoride (SF_6) is a heavy, inert specialty gas that has a global warming potential (GWP) estimated to be 23,900 times that of carbon dioxide. Small amounts of this gas have a significant impact on greenhouse gas (GHG) totals. This section examines its use and emissions in primary and secondary magnesium production as a component of inert blanket gases used to prevent molten magnesium from igniting explosively in air.

The primary and secondary magnesium industry is the largest industrial source of sulphur hexafluoride emissions in Canada, accounting for an estimated 75 tonnes of SF_6 in 1995, or about 1,900 kilotonnes (kt) per year of carbon dioxide (CO_2) equivalent. This represents just over 1% of total non-combustion GHG emissions and 0.3% of total Canadian GHG emissions.

In Canada, the 75 tonnes per year of sulphur hexafluoride used for magnesium operations is estimated to be about 35% to 40% of the total demand of 200 tonnes per year. Worldwide, the magnesium end use represents only about 10% to 15% of sulphur hexafluoride use, but Canada has a greater fraction because of its large primary magnesium industry.

The other significant end use of sulphur hexafluoride is as an insulating gas (dielectric) for electrical utility equipment, representing roughly 60% of use in Canada. There are numerous miscellaneous uses for high purity sulphur hexafluoride in the electronics, small metal parts and medical products industries, which may account for less than 5% of use. These other end uses are examined in section 16.

Estimated Canadian SF₆ Demand, 1995	
	Volume (t/yr)
Electric equipment	120
Primary magnesium production	50
Secondary magnesium processing	25
Miscellaneous (electronic, medical, analytical)	5
Total (all imported)	200

Sources: Interview with Canadian distributor; Cheminfo Services estimates.

13.1.1 Magnesium Production

There are two primary magnesium production plants operating in Canada. The Norsk Hydro facility in Bécancour, Quebec, is the largest. This market-leading company operates worldwide. It has a capacity of about 43 kt per year, but is increasing capacity to 68 kt per year by the year 2000. There are plans to increase again to 86 kt per year thereafter, due to high demand growth for diecast automotive parts. A second, much smaller facility is operated by Timminco in Haley Station, Ontario. It has a capacity of about 4 kt per year and produces magnesium, calcium and strontium alloys. Magnola Metallurgy is

building a new 58 kt per year magnesium smelter in Asbestos, Quebec, which will start up in June 2000. It represents a potential future source of sulphur hexafluoride emissions.

Primary and Secondary Magnesium Production in Canada	
Company	Location
Primary Producers	
Norsk Hydro	Bécancour, PQ
Timminco	Haley Station, ON
Secondary Processing (Diecasters)	
Trimag	Haley Station, ON
Dynacast	Pointe Claire, PQ
Magnesium Products Ltd.	Strathroy, ON
ITM	Quebec City, PQ
Indalloy	Rexdale, ON

Source: Company interviews.

In secondary magnesium processing, magnesium ingots are die cast into auto and aerospace parts. The die-casting process also requires the use of a sulphur hexafluoride blanket gas on small furnaces, since the magnesium is cast as molten metal. Roughly 30% of the magnesium produced in Canada is used by domestic die casters. The remainder is exported. There are only about five or six die casters who work with magnesium in Canada.

Over the 1990 to 1995 period, emissions have been steadily decreasing due to continuing efforts to decrease utilization rates. While primary production increased marginally, sulphur hexafluoride utilization rates fell to levels of about 0.7 to 0.8 kilograms (kg) of sulphur hexafluoride per tonne of magnesium produced. Norsk Hydro, which accounts for a good portion of sulphur hexafluoride usage, claims it decreased its utilization rate to 0.64 kg per tonne in 1997 and is projecting a rate of 0.53 kg per tonne in 1998. In theory, there is a practical minimum limit in the range of 0.4 to 0.5 kg per tonne.

SF₆ Emissions from Magnesium Manufacturing							
	1990	1991	1992	1993	1994	1995	2000
SF ₆ emissions (t)	120	136	91	84	85	79	100
CO ₂ eq. (kt)	2,870	3,250	2,170	2,010	2,030	1,980	2,390

Sources: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997); personal communications with Environment Canada personnel.

The planned increase in capacity at Norsk Hydro and start up of Magnola Metallurgy will likely add another 25 to 30 tonnes per year of sulphur hexafluoride emissions after 2000. The projected emissions for the year 2000 assume this extra usage.

13.1.2 Supply

All Canadian supply is imported. The total Canadian market demand for sulphur hexafluoride is estimated at roughly 200 tonnes per year. The gas is produced in the United States by only two producers: Air Products (Hometown, PA) and AlliedSignal Specialty Chemicals (Metropolis, IL), which participate in the highly specialized fluorinated compounds industry.

The Canadian market is supplied by specialty gas distributors that ship sulphur hexafluoride in small cylinders in three different grades (by increasing purity): commercial, instrument and very large scale integration (VLSI). The major Canadian distributors are Air Products Canada Ltd., Praxair Canada Ltd. and Canadian Liquid Air.

13.2 Nature of the GHG Emissions Stream

When casting molten magnesium in primary production or secondary processing operations, an inert blanket gas is required to protect the magnesium surface from oxygen, because of the strong tendency of magnesium to oxidize explosively in air. While the inert gas is composed largely of nitrogen or carbon dioxide, sulphur hexafluoride is used as a small component in the mixture to aid the protection of the magnesium surface and control burning. Sulphur hexafluoride concentration levels

are very low and, over the last few years, have been reduced to less than 1% in the inert gas. Sulphur hexafluoride is a very heavy gas (roughly three times heavier than air) and settles quickly to the surface with little turbulence in a contained surface area. When it contacts molten magnesium, a small portion of it chemically reacts with the magnesium to form a thin, impermeable molecular skin that is non-oxidizing. The skin can be separated later from the molten magnesium, leaving the latter in high purity form. This technique is preferred to mixing non-oxidizing fluxes with the magnesium because the purity issue is critical in die-casting operations.

Sulphur hexafluoride is not harmful to humans in the range of concentrations used for magnesium production. The threshold limit value (TLV) issue is not significant. Sulphur and sulphur dioxide have been used for this purpose in the past, but their use was discontinued due to health concerns and odour problems. Concentrations of sulphur dioxide above three parts per million are considered a workplace hazard.

13.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

The sulphur hexafluoride emissions from magnesium processing are not directly measurable, because they are a small portion of the inert gas, which is not emitted as a point source. Emissions are believed to occur mostly through leakage from the magnesium smelting furnaces. To maintain the concentration levels required, a make-up of fresh sulphur

hexafluoride is supplied from purchased cylinders. The purchased sulphur hexafluoride is easily measurable. It is assumed that the portion that reacts with magnesium is small, such that the volume of purchases is roughly equal to the volume of atmospheric emissions.

13.4 Options to Reduce GHG Emissions

There are two basic technologies for reducing sulphur hexafluoride emissions from magnesium production: reducing the utilization rate, and replacement with another blanket gas.

13.4.1 Reducing Consumption

Increased attention to process control has allowed average concentrations of sulphur hexafluoride in the inert blanket gas to be reduced from the 1% level of several years ago to levels as low as 0.1% at times.

The key to these improvements has been the improved ability to measure minute concentrations of sulphur hexafluoride at various points on the molten magnesium surface. A better system of gas injection with improved metering has been used. A control system minimizes variations. Both Norsk Hydro and Timminco report use of these process control techniques. A second approach to reduction is the recycling of sulphur hexafluoride gas.

Timminco reported that some gas is recycled but did not provide details for proprietary reasons. Norsk Hydro, as an industry leader, is likely to practise some form of reuse or recycling. From the Norsk Hydro utilization rate numbers, it appears that further reductions in the sulphur hexafluoride utilization rate will be small, since it is approaching the theoretical minimum. Therefore, there is little potential to reduce sulphur hexafluoride emissions through better process control.

13.4.2 Replacement with Alternative Blanket Gas Component

In theory, any inert gas would be able to replace sulphur hexafluoride if it could completely block out oxygen. The chemical reaction with magnesium involves the sulphur atom. Sulphur and sulphur dioxide have been identified as the most promising alternative (albeit older) technologies. The use of argon (a heavy inert gas) is also being researched, although argon does not involve a chemical reaction with magnesium. The critical technology issue with the sulphur dioxide option is how to control sulphur dioxide emissions to protect health and control odour. The capital requirements would likely include special distributed feed systems, process control systems, containment systems and pollution control systems.

Norsk Hydro is conducting research into the replacement of sulphur hexafluoride gas with sulphur dioxide at its research centre in Oslo, Norway. The cost of the research project is estimated at between \$1 million and \$10 million by a Canadian staff member. Norsk Hydro claims that it will definitely be replacing sulphur hexafluoride gas in the future, but it does not know the timetable. Further work is needed to determine, for example, what type of pollution control technology is needed to protect the health of workers and how to contain the gases. Timminco only conducts process research. It is not known whether a sulphur dioxide system could be adapted for use at smaller die casters.

The reduction potential with this system would be 100%, since a complete replacement is involved. Sulphur dioxide costs significantly less than sulphur hexafluoride (\$440 per tonne for bulk SO₂ versus \$30,000 per tonne for packaged SF₆), but the consumption rate may be higher.

13.5 Suitability for GHG Emissions Trading

Sulphur hexafluoride emissions from primary and secondary magnesium production are not directly measurable, but the use of the purchased substance is measurable. Although Norsk Hydro is researching a replacement system, it is not known whether this technology can be transferred to other companies. The small magnesium die casters might find it prohibitively expensive to develop their own replacement systems.

A substance trading program is likely suited for this industry because of the ease of measuring gas purchases. The use of sulphur hexafluoride in magnesium production is concentrated in only a few firms (2 primary producers and about 5 to 10 die casters). Furthermore, the supply of the gas is concentrated in only a few distributors and could be regulated easily.

Because magnesium production as a source of sulphur hexafluoride is too small to have its own competitive trading program, it would have to be combined with other GHG sources. Since the other emissions of sulphur hexafluoride (see section on other uses of SF₆ contained in this report) are also based on volumes purchased by a limited number of utility companies, the entire sulphur hexafluoride supply should probably be considered for a substance trading program.

14. Coal Mining Emissions

14.1 Source and Quantity of GHG Emissions

This section deals with methane (CH₄) emissions from coal mining and related coal processing activities. Carbon dioxide (CO₂) emissions associated with combustion of coal as an energy source and other uses are not included in this analysis.

Environment Canada's estimated methane emissions from coal in 1995 were 82 kilotonnes (kt), or 1,700 kt of CO₂ equivalent. This represented 1.2 % of non-combustion greenhouse gases (GHGs) or 0.3% of total Canadian GHG emissions.

Methane is contained naturally in coal deposits. The methane concentration relative to the amount of surrounding coal varies depending on such factors as the type of coal, geology of the region, and depth of the coal bed. Methane concentrations can vary from seam to seam and even within different sections of the same seam. For example, the methane concentration at the centre may be different from that at the edge of the seam, where some of the methane may have already migrated to the surrounding soil. Soils or overburden around coal beds also contain methane that has desorbed from the coal and migrated into the soil. At coal fields where the coal is close to the surface, some of this methane may be continually released to air.

Methane is released to the atmosphere when coal is mined (or extracted) and during related post-mining activities. Mining activities result in emissions from the exposed coal surfaces and the coal rubble, as well as release of pressure on the coal. Emissions from post-mining activities occur during preparation, transportation, storage or final crushing before combustion. In 1996, Canada exported approximately 46% of its coal production. Coal mined in British Columbia accounted for about 70% of exports. Nearly all the rest was exported from

Coal Production and Exports by Province			
Province	1996 Coal Production (Mt)	Share of Production	Exports (Mt)
Alberta	36.1	48%	10.1
British Columbia	25.4	33%	25.0
Saskatchewan	10.9	14%	0.0
Nova Scotia	3.1	4%	0.1
New Brunswick	0.3	1%	0.0
Total Canada	75.8	100%	35.2

Source: Natural Resources Canada, *1996 Canadian Minerals Yearbook, Review and Outlook* (Ottawa, 1997).

Provincial GHG Emissions from Coal Mining				
Province	1996 Coal Production (Mt)	Emission Factors⁵⁰ (t CH₄/kt coal)	Total GHG Emissions (CO₂ eq.)	Share of Emissions
Alberta	36.1	0.19 – 0.45	300	17%
British Columbia	25.4	0.58	570	34%
Saskatchewan	10.9	0.06	14	1%
Nova Scotia	3.1	13.79	830	48%
New Brunswick	0.3	0.13	1	<1%
Total Canada	75.8		1,700*	100%

Note: * Rounded.

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

Alberta. A portion of methane emissions may be emitted during post-mining activities for coal exported to offshore markets.

14.2 Nature of the GHG Emissions Stream

The concentration of methane contained in coal differs across Canada. In general, coal in Alberta, which is open-pit or strip-mined, is low in methane, while coal mined underground in Nova Scotia has a much higher methane content and can result in much higher emissions. Underground coal is subject to higher pressure, which favours the adsorption of methane with the coal matrix.

Methane released during underground mining of coal is removed from the mine since it presents a hazard to the working environment. High flow ventilation systems are designed to pump fresh air through the mine and move methane from the mine for release to the surface. The concentration of methane in the vented air is low, typically 0.2% to 1.0% by volume. One industry source provided an example of one underground mine where the air flow rate was 12,000 cubic metres/minute.⁵¹ This makes treatment (e.g., combusting the methane — or essentially air) of these streams economically and potentially environmentally unfeasible (e.g., it may be that the CO₂ emissions produced from combustion of the air would exceed the reduction in CH₄/CO₂

50 A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

51 B. King, Neill & Gunter, Halifax, Nova Scotia, personal communication, August 1998.

equivalent released, although this needs to be confirmed through analysis).

In open-pit or strip-mining operations, there are no contained methane streams. Methane is released to air from the surface of all coal exposed to air during the mining process. Similarly, there are no contained methane streams from post-mining activities. Not all of the methane in the coal will be released during post-mining activities (prior to combustion). The amount released will depend on such factors as the time between mining and use (e.g., combustion, steel making), the surface area of the coal particles, ambient temperatures and other factors.

14.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

In general, estimates of Canada's GHG emissions associated with coal mining and post-mining activities are not highly accurate. Environment Canada reports the uncertainty in its estimates of total emissions of 1,700 kt for Canada in 1995 as +/- 50% to 20% (i.e., the upper range of emissions could be 2,550 kt and the lower level could be 1,360 kt). One expert claims that individual coal fields within a province, or even mined seams within a field, can have methane concentrations that vary substantially. More research would be required to better define uncertainty levels between one portion of a defined coal bed boundary and another (e.g., between the centre of the seam and the edge).⁵² There are different issues with respect to measuring, monitoring and calculating emissions from underground mining, surface mining and post-mining activities.

The best measurement of emissions occurs at underground mines. Only direct monitoring techniques have been applied to methane emissions from underground mines. The methane content of vented air can be relatively easily and inexpensively monitored, and is often undertaken due to operational safety considerations.⁵³ Therefore only incremental costs are likely to be required to calculate total mine emissions. There were only a few underground producing mines in Canada in 1995 (assumption based on data for 1996), accounting for less than 5% of 1995 Canadian coal production, but nearly 48% of estimated GHG emissions. It is not clear in these estimates what portion of GHG emissions were attributable to actual underground mining activity versus post-underground mining activities. This split may be useful in that emissions reduction activities (i.e., reducing the time between mining and use) could be implemented on that portion of emissions.

The accuracy of continuous emissions monitoring equipment in monitoring methane emissions from underground mines is relatively high and can be readily applied to estimating emissions for the mine, given the measured flow rate of vented air.⁵⁴

Most of Canada's coal is produced in Western Canada from strip and open mining operations. Although the amount of coal produced is carefully measured and monitored (due to its commercial value), the amount of methane emissions from surface mining is not typically measured or monitored. To provide a rough estimate of these emissions, samples of coal to be mined were analysed for methane concentrations and to estimate the amount of emissions that might result. Methane concentration estimates for some coal fields in Alberta, Saskatchewan and British Columbia ranged from 0.15 to 2.0 cubic metres per

52 Ibid.

53 J. Fiedler and F. Sussman, *Methane Emissions Trading: Determining the Suitability of Methane Sources for Trading, and of Integrating Methane and Carbon Dioxide Sources in a Single Trading System — Draft*, prepared for the Center for Clean Air Policy's GHG Trading Braintrust (June 24, 1998).

54 B. King, Neill & Gunter, Halifax, Nova Scotia, personal communication, August 1998.

Mining Types for Members of The Coal Association of Canada			
Mining Type	1996 Coal Production (Mt)	Share of Production	Producing Mines
Strip	34.7	47%	12
Open pit	33.4	45%	11
Underground	2.6	4%	2
Surface and underground	3.0	4%	1
Total Coal Association members	73.7	100%	26
Total Canada	75.8		28

Source: The Coal Association of Canada, *1997 Directory* (Calgary, 1997).

tonne of coal.⁵⁵ Environment Canada assumed that 60% of contained methane is emitted. It is not clear whether current estimates include methane emissions released from overburden at surface mining operations. Overburden can contain methane.⁵⁶

Methane emissions from post-mining coal activities are not easily measured, monitored or calculated. While the general emission factor of 60% on contained methane is applied to estimate total coal emissions, it is unclear what portion of these emissions is emitted during post-mining activities. With a large amount of coal exported, some of these emissions may be occurring outside Canada.

In general, emissions from post-mining activity have yet to be well defined. Specific emission factors have not been identified (at least in this study) for each of the post-mining activities (transportation, processing, grinding, etc.). These emission factors may be useful, since they would relate to estimating the impact of applying potential GHG emission technologies or practices.

14.4 Options to Reduce GHG Emissions

In Canada, methane emissions from underground coal mines are not treated, although methane from these underground operations is being captured and routed for venting. The main problem is that the vent stream contains too low a concentration of methane (mixed with air — oxygen and nitrogen) and too high a volume. Attempting to heat the methane/air stream in order to oxidize/combust the contained methane may be possible, but it is economically unattractive and potentially technically and environmentally unfeasible.⁵⁷ For example, the amount of carbon dioxide emitted as a result of the energy used to heat the gas stream could be greater than GHG emissions reduced as a result of destroying the methane. In addition, treating these dilute streams may even result in emissions of other pollutants (nitrogen oxide, carbon monoxide, etc.). The dilute streams do not offer significant heating value due to the contained methane.

55 A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

56 B. King, Neill & Gunter, Halifax, Nova Scotia, personal communication, August 1998.

57 Oxidizing methane to produce water and carbon dioxide reduces GHG emissions because the methane molecule has 21 times more GWP than carbon dioxide (on a mass basis). However, carbon dioxide has a high molecular weight, so the theoretical reduction potential is only 87% when methane is oxidized.

In Canada, the use of mine vent streams to provide the air/oxygen requirements of boiler systems (even those as close as two to four kilometres distant) has not proved to be economically feasible. In some cases, these systems can cost tens of millions of dollars with little incentive.⁵⁸ However, this control option may be more feasible in the United States, where large mines may have nearby energy users that could utilize these methane-containing streams.

No known methane emission control options are employed at surface mining operations in Canada. With emissions resulting from all exposed areas of surface coal, there is no practical way to collect and treat the methane.

Methane gas can theoretically be collected from the coal prior to mining. This is referred to as degasification. This option may be more suitable for underground mines, which have a higher methane content in the coal. Degasification involves drilling wells or boreholes into the coal and sucking the methane out under pressure (using energy). The concentration of methane in this air stream can be as high as 60% by volume. At this high concentration, the gas has heating value.⁵⁹ According to one report, 21 U.S. underground coal mines operate degasification systems, with 15 of these using the gas. Up to 60% of the gas could be captured using these systems.⁶⁰ There are no known cases of surface mines employing degasification techniques. Surface mines have lower methane concentrations, and the option may not be technically, economically or environmentally feasible.

Although no practices have been documented that reduce methane emissions from post-mining activities, it is possible to contemplate some that may

work at low cost. One practice could be to consume the coal as soon after it is mined as possible. This would result in more methane contained in the coal being oxidized during combustion (either as a fuel or in steel production). After about one month, the amount of methane contained in mined coal is likely to be low or practically gone.⁶¹ Another option may be to increase the particle size of the coal. This would extend the time the methane is contained in the coal. These are only suggestions of possible options for reducing methane emissions from post-mining sources.

14.5 Suitability for GHG Emissions Trading

An emissions rights (i.e. allowance trading) trading system would be most applicable to the few underground mines operating in Canada. These mines, all of which are in Atlantic Canada, represent nearly 50% of estimated emissions from all mining activities. Techniques are readily available to measure emissions from these sources in support of an emissions rights trading system. However, proven and cost-effective options (i.e., degasification) have not been applied in Canada for reducing emissions from these sources. An emissions trading program applied to underground mines might have to be linked with other industrial sources, since there are only a few underground mines in Canada. This would not provide for a robust market.

For surface mining, allowances could be based on emission factors. However, some improvements in testing might be required, as well as a better understanding of how emissions relate to coal extracted from different seams at different levels.

58 B. King, Neill & Gunter, Halifax, Nova Scotia, personal communication, August 1998.

59 Ibid.

60 J. Fiedler and F. Sussman, *Methane Emissions Trading: Determining the Suitability of Methane Sources for Trading, and of Integrating Methane and Carbon Dioxide Sources in a Single Trading System — Draft*, prepared for the Center for Clean Air Policy's GHG Trading Braintrust (June 24, 1998).

61 B. King, Neill & Gunter, Halifax, Nova Scotia, personal communication, August 1998.

Similarly, emission factors could be developed to address emissions and corresponding allowances from post-mining activities. It might be important to incorporate this information into the trading program, since post-mining reduction practices may achieve better emissions reduction results than reduction practices carried out during mining.

With relatively few mines in Canada (about 29), the trading system would have a high level of coverage from this source area. All mine operators could be involved and the administration of the trading system would remain manageable.

An issue with the trading system would be measurement and verification, especially at surface mining operations and post-mining operations in general. The variation in methane concentration in different regions, areas of the coal field, mine or seam may make it difficult to establish acceptable emission factors on which to base allowances. In addition, the ability to validate these emission factors as reasonably representative of actual emissions may also pose problems that could reduce the credibility of the system.

An alternative to the allowance trading system would be to allow coal mines to generate credits for emissions reductions associated with recovery. This system would be most suitable for underground mines, which can accurately measure their emissions. The system might be less suitable for surface mining operations, where emissions are much more difficult to measure or monitor. In this system, the difficulty of assigning emission allowances and verifying compliance with their allowed emissions would not arise, since there would be no initial allowance. The key disadvantage is that a credit system only reduces and redistributes the overall cost of control, but does not provide additional controls on emissions. Other

issues are that early credits, profitable recovery, baseline determination, and other factors become more important than under an allowance system. In addition, unlike an allowance system, a credit system provides no incentive to reduce coal production, which is also an effective way to reduce emissions.⁶²

15. Nitric Acid Production

15.1 Source and Quantity of GHG Emissions

Nitrous oxide (N_2O) is emitted in trace amounts as a combustion by-product in the nitric acid production process. The emissions of nitrous oxide from nitric acid production have been estimated at about 3 kilotonnes (kt) per year over the last five years.⁶³ This level is equivalent to about 1,000 kt of carbon dioxide (CO_2) emissions, and represents only about 1% of total non-combustion greenhouse gas (GHG) emissions or less than 0.2% of total Canadian GHG emissions.

The emission estimates were originally based on the use of an average emission factor for all Canadian industry multiplied by the total Canadian production of nitric acid. The average emission factor employed in the inventory was 8.5 kilograms (kg) of nitrous oxide per tonne of ammonia used, which corresponds roughly to 3 kg of nitrous oxide per tonne of nitric acid produced.⁶⁴

Nitrous oxide emissions have remained stable at this level over the last five years because nitric acid production has been relatively stable, ranging from 910 kt to 991 kt. Emissions are forecast to increase slightly as nitric acid production increases to fill new capacity.

62 J. Fiedler and F. Sussman, *Methane Emissions Trading: Determining the Suitability of Methane Sources for Trading, and of Integrating Methane and Carbon Dioxide Sources in a Single Trading System — Draft*, prepared for the Center for Clean Air Policy's GHG Trading Braintrust (June 24, 1998).

63 A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

64 The average was calculated from various emission factors ranging from 2 kg to 20 kg N_2O per tonne of ammonia used, as provided by European industry in 1990 and 1991.

N₂O Emissions from Nitric Acid Production							
	1990	1991	1992	1993	1994	1995	2000
N ₂ O emissions (kt)	3.0	2.7	2.9	2.8	2.7	3.0	3.5
N ₂ O emissions (kt CO ₂ eq.)	930	840	900	870	840	930	1,090
Nitric acid production (kt)	990	912	960	917	910	991	1,150

Note: Average emission factor used = 3 kg N₂O/tonne HNO₃.

Source: Camford Information Services, *Nitric Acid Profile* (Toronto, 1996).

Nitric acid (HNO₃) is an important inorganic chemical, manufactured from ammonia. Over 80% of nitric acid is used as an intermediate in the production of ammonium nitrate (NH₄NO₃), an inorganic solid used as a nitrogen fertilizer and for explosives. Nitric acid is also used in adipic acid manufacturing, uranium extraction and the preparation of specialty explosives.

In 1995, five companies operated a total of nine nitric acid plants at six sites in Canada. Two companies are expanding their facilities by adding one new plant

each. These plants will come on-stream in 1998, which will bring the total to 11 plants by the end of 1998. In 1995, the total nitric acid production capacity was 1,150 kt per year, and total domestic production was 991 kt.

Revised information collected in a recent study suggests that the majority of nitrous oxide emissions are concentrated at one plant site in Canada as shown in the table. The next section explains this situation.

Canadian Nitric Acid Plants					
Company	Location	Process	Capacity	Control	Est'd N₂O
Existing (1995)			(kt/yr)		(kt/yr)
Agrium Inc.	Ft. Sask., AB	HP	175	NSCR	0.15
Orica (once ICI)	Beloil, PQ	DP	90	NSCR	0.08
Orica (once ICI)	Carseland, AB	DP	290	None	2.24
Hydro-Agri (#1)	Maitland, ON	HP	65	NSCR	0.06
Hydro-Agri (#2)	Maitland, ON	HP	85	NSCR	0.07
Hydro-Agri (#3)	Maitland, ON	HP	160	NSCR	0.14
Simplot Canada (#1)	Brandon, MB	HP	100	NSCR	0.09
Simplot Canada (#2)	Brandon, MB	HP	65	NSCR	0.06
Terra International	Courtright, ON	HP	120	NSCR	0.10
Existing Total			1150		3.00
New in 1998					
Orica (#2)	Carseland, AB	HP	90	SCR	0.70
Simplot Canada (#3)	Brandon, MB	HP	100	NSCR	0.09

Notes: HP = high pressure; DP = dual pressure.

Sources: Cheminfo Services interviews; Camford Information Services, *Nitric Acid Profile* (Toronto, 1996).

15.2 Nature of the GHG Emissions Stream

Nitrous oxide is formed in trace amounts in the first stage of the two-stage manufacturing process, the catalytic oxidation of ammonia to nitrogen dioxide. The reaction products pass through an absorber tower, where nitrogen dioxide is converted to nitric acid (the second stage of the process). Depending on the configuration, the tail gases that pass from the absorber tower to the atmosphere consist mostly of nitrogen, a small concentration of oxygen, and trace quantities of nitrous oxide, nitric oxide (NO), nitrogen dioxide (NO₂) and other nitrogen oxides (NO_x). Nitrogen oxide levels (NO and NO₂) in the absorber tail gas usually range from 2,000 to 6,000 parts per million (ppm). The nitrous oxide concentration is usually less than half of the NO_x concentration in this stream, typically ranging from 1,000 to 2,000 ppm. NO_x levels must be controlled to a low limit (150 ppm) under permit to meet provincial ambient air objectives.

The nitrous oxide emissions are not shared equally among the nine existing plants. The Orica (former ICI Canada) plant at Carseland, Alberta, is believed to account for about 2.24 kt per year of nitrous oxide or over 75% of total emissions, while all eight others are believed to contribute the remaining 0.7 kt. This is due to the types of controls that are installed in the nine plants.

There are two basic types of nitric acid production technologies: high pressure and dual pressure. Eight of the nine existing Canadian nitric acid plants are high-pressure process designs, which have non-selective catalytic reduction (NSCR) abatement technology installed to control NO_x emissions to outlet levels of about 150 ppm for provincial NO_x objectives. This abatement technology also reduces nitrous oxide emissions to less than 150 ppm. The total nitrous oxide emissions from eight of the nine plants that use nitrous oxide controls are estimated to be only about 700 tonnes, or roughly one-quarter of the industry total.

The other Canadian nitric acid plant (Orica in Carseland, Alberta) is a dual pressure process design, which does not use any abatement technology to control NO_x emissions. In the dual pressure design, the more efficient absorption in the tower reduces NO_x emissions to acceptable levels, and no NO_x abatement is necessary. Although the control of NO_x emissions has been designed into the process, the extended absorption process has no significant effect on the reduction of nitrous oxide emissions. Orica reports that they have no actual tail gas data, but that an emission factor of 9 kilograms (kg) per tonne of nitric acid has been assumed for their Carseland plant. This is an upper bound estimate based on Orica's knowledge of other dual pressure design plants. Using this emission factor, the Carseland plant emissions (maximum 2.3 kt per year) may represent up to about three-quarters of the total nitrous oxide emissions (3.0 kt per year) calculated in the inventory.

The two new nitric acid plants starting up in 1998 are also high pressure designs. The new Simplot plant #3 in Brandon, Manitoba, will use an NSCR abatement technology (which will control N₂O emissions), but the new Orica plant in Carseland, Alberta, will use a selective catalytic reduction (SCR) abatement unit that does not address nitrous oxide emissions.

15.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Nitrous oxide emissions from nitric acid production are all from single point sources within industrial plants. Emissions are easily calculated, based on measurements of nitrous oxide concentrations in the gas stream and the gas flow rate. The reduction of nitrous oxide emissions is measured by the difference between the inlet and outlet concentrations of nitrous oxide at the abatement equipment. The variations within the process or the abatement technology are not known. The calculations must

take into account the time when the abatement technology is shut down or not performing at high efficiency, since emissions are not controlled during these periods.

15.4 Options to Reduce GHG Emissions

The control of nitrous oxide emissions is a new issue for nitric acid plants. To date, plants have installed technology to control NO_x emissions only. NO_x control technologies include catalytic reduction (non-selective and selective) and thermal reduction (non-selective and selective).

The only technology known to effectively reduce nitrous oxide emissions from a tail gas stream is non-selective catalytic reduction (NSCR). NSCR abatement uses a reducing gas (such as natural gas or hydrogen purge gas) in the presence of a reduction catalyst (often platinum on a honeycomb ceramic base). In the NSCR process, natural gas (chiefly methane, CH₄) first consumes the excess oxygen in the tail gas stream and then, once starved of free oxygen, uses the various nitrogen oxides as an oxygen source, thereby reducing them to nitrogen. Water and carbon dioxide are also present in the exhaust gases. The operating temperatures are high, usually about 1,200°F. This process can only be used on tail gas streams having excess oxygen concentrations less than 2.5%, since the reactions would generate too much heat for the catalyst to remain viable at oxygen concentrations beyond this level. The high-pressure design plants commonly use NSCR abatement technology. The conversion of nitrous oxide is reported to be at least as high as the conversion of NO_x using NSCR.

Selective catalytic reduction (SCR) is an alternative NO_x abatement process, but it does not reduce nitrous oxide emissions. SCR abatement uses ammonia as a reducing gas in the presence of a catalyst. It operates at lower temperatures (550-1,100°F) than the NSCR process. As with the NSCR

process, the ammonia first consumes the excess oxygen and then reduces nitrogen oxides to nitrogen and water. NO_x emissions (NO and NO₂) are reduced by up to 95%, but nitrous oxide is not reduced because of the lower temperatures. No Canadian plant currently uses SCR abatement, but the new Orica plant (#2) at Carseland has an SCR unit in the design.

Thermal reduction technologies have been identified for NO_x control, but it is not known whether they are effective for nitrous oxide control. Two types of thermal reduction technologies identified are non-selective, non-catalytic reduction (NSNCR) and selective non-catalytic reduction (SNCR). Like NSCR, NSNCR uses hydrocarbon gases, such as natural gas, in a low oxygen environment, but without a catalyst. The fuel reduces the nitrogen oxides. This process, known as "burnout," operates above 1,500°F. The SNCR process can be used in higher oxygen environments, but uses urea to reduce nitrogen oxides. The temperatures range from 1,700-2,100°F. This process is patented by Nalco FuelTech. The higher temperatures drive up the costs for these processes, due to increased heat exchange requirements and fuel usage.

There have been some developments in catalyst technology that have been shown to have a minor effect in reducing the amount of nitrous oxide generated in the first stage ammonia oxidation reaction. Catalysts containing low palladium levels or none at all have been found to create marginally lower concentrations of nitrous oxide by-product. The effect is called a "secondary effect," since it only deals with reductions of a few percent. For example, with a palladium-free catalyst, the emission factor for nitrous oxide might be reduced from 3.0 kg to 2.9 kg per tonne of nitric acid. Moreover, this catalyst has roughly the same cost as the typical platinum, palladium, rhodium catalysts and poses no known significant cost barrier.

15.5 Suitability for GHG Emissions Trading

Like the adipic acid production source, nitrous oxide emissions from nitric acid are from point sources within a limited number of industrial plants. Nitrous oxide is created within the process, and levels depend on reaction conditions such as residence time, catalyst life, temperature and pressure. Therefore, this source is not considered suitable for a substance trading program. The two programs that could be considered are emissions rights trading and emission credit trading.

Emissions are easily calculated based on measurements of gas concentration and flow rates. These measurements are already being done to show compliance with NO_x emission limits.

It appears that most companies in this industry have already achieved significant nitrous oxide reductions using the best available control technology. One company appears to require the installation of similar control technology to achieve the same level as the others. Since there are only five companies and about 11 point sources, the number of sources is relatively small and would need to be integrated into a larger GHG trading market.

An emissions rights trading system could be established in this industry that gave allowances to each company. Regulatory authorities would have to decide whether to give the one higher emitting plant an allowance based on current levels or on maximum achievable reduction levels.

A credit trading system for this industry could be rate-based, measuring tonnes of nitrous oxide emitted per tonne of nitric acid produced.

16. Other Uses of SF₆, PFCs and HFCs

16.1 Source and Quantity of GHG Emissions

Three types of greenhouse gases (GHGs), sulphur hexafluoride (SF₆), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs), are considered as having global warming potential (GWP) beyond that of the main three naturally occurring greenhouse gases of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). This secondary group has several factors in common. All gases are synthesized compounds containing fluorine, which forms very strong bonds with carbon and sulphur. Most of these gases have very high 100-year GWPs. With the exception of PFCs generated in aluminum smelting, these gases are all purchased, used in closed systems and emitted in small volumes (from leakage or maintenance activities) from many multiple sources.

The major source of PFC emissions is aluminum smelting. A major source of sulphur hexafluoride emissions is primary magnesium manufacturing. These two emission sources are covered separately in Environment Canada's Greenhouse Gas Emissions Inventory and have separate sections in this report. This section deals with the other uses of sulphur hexafluoride, PFCs and HFCs.

The 1995 Greenhouse Gas Emissions Inventory only accounted for 3 kilotonnes (kt) of HFC emissions from refrigeration systems or 500 kt of CO₂ equivalent. The other uses of sulphur hexafluoride and PFCs were not identified in that study. This estimate represents only 0.3% of non-combustion GHG emissions or less than 0.1% of total Canadian GHG emissions.

Additional research has determined that the total estimated emissions from these three gases in other uses are closer to 1,200 kt of CO₂ equivalent.

Summary of SF₆, PFC and HFC Use and Emissions, 1995
(excludes SF₆ use in magnesium manufacturing & PFCs from aluminum smelting)

GHG	GWP	1995 Use (tonnes)	Emission Factor	1995 Emissions (kt CO ₂ eq.)
SF ₆ Electrical equip.	23,900	120	0.05	140*
SF ₆ Electronics, misc.	23,900	5	1.0	120*
PFCs	6,500-9,200	50	1.0	400*
HFCs	140-11,700	3,198	Various	500
Total				1,200

Note: * Cheminfo Services estimates (see sections for details).

Source: A. Jaques et al., *Trends in Canada's Greenhouse Gas Emissions (1990 to 1995)* (Ottawa: Environment Canada, April 1997).

Less than half of the estimated emissions (500 kt of CO₂ equivalent) are accounted for by HFCs used in air conditioning and refrigeration applications. Of the three types of gases sold in commercial markets, HFCs had the highest consumption in Canada in 1995, with about 3,200 tonnes consumed. The total consumption of sulphur hexafluoride in Canada is estimated at about 200 tonnes, about 75 tonnes of which is used in inert cover gases in primary and secondary magnesium production. The use of PFCs in Canada is estimated at about 50 tonnes.

None of the three types of gases are produced commercially in Canada, all being imported from the United States. The following table lists the major suppliers of these gases.

Company	SF ₆	PFC	HFC
Air Products and Chemicals	✓	✓	
AlliedSignal Specialty Chemicals	✓	✓	✓
DuPont		✓	✓
3M Specialty Chemicals		✓	
Elf Atochem			✓

Source: Cheminfo Services.

Canadian sales are distributed through the Canadian subsidiaries of these companies, a limited number of chemical distributors and refrigeration wholesalers.

16.2 Nature of the GHG Emissions Stream

16.2.1 SF₆ — Electrical Switchgear and Miscellaneous Uses

The largest end use for sulphur hexafluoride is as an insulating gas (a dielectric) in high-voltage electrical circuit interrupters or circuit breakers, generally known as gas-insulated switchgear or GIS. Sulphur hexafluoride gas is sealed under pressure inside large, grounded, aluminum-cased cylinders called switchgear arrays. The majority of sulphur hexafluoride-insulated switchgear is used in urban substations handling the junction points of high-voltage transmission lines. The use of sulphur hexafluoride has allowed the dense concentration of transmission lines in urban substations that have a limited ground area.

Most of the sulphur hexafluoride used in electrical equipment is for maintenance replenishment of existing switchgear. The remainder is used to fill original equipment. Major utility companies in charge of high-voltage systems purchase sulphur

hexafluoride for both purposes. The gas insulation is designed to be at a certain pressure and is periodically checked under leak detection and repair programs. Switchgear manufacturers quote standard leak rates of 1% of charge per year, which is low enough to have no significance to electrical protection. Ontario Hydro says that it is achieving better leak performance than this. A study of sulphur hexafluoride use in this area has not been done publicly. Sulphur hexafluoride emissions are estimated based on a total stock estimate of 600 tonnes and average leak rate of 1% (6 t per year to 140 kt per year CO₂ eq.).

There are also a variety of very small volume miscellaneous uses in the electronics, analytical and medical industries. For example, sulphur hexafluoride can be used as an etchant in integrated circuit board production. One Canadian distributor reports sales of one to three cylinders per year to hundreds of small companies and laboratories, which account for less than 2% of total sales volume. The market use is estimated at 5 tonnes per year and all use is assumed to be emitted, representing about 120 kt per year of CO₂ equivalent.

16.2.2 PFCs

A small quantity of PFCs are purchased and used in commercial markets in Canada. The main PFC compounds are CF₄ (R-14), C₂F₆ (R-116), C₃F₈ (R-218) and C₄F₁₀ (R-410). The lighter compounds have low boiling points and require very low temperatures for separation. The total Canadian market is assumed to be about 50 tonnes per year, all of which is assumed to be emitted. At an average GWP of 8,000, this represents about 400 kt per year of CO₂ equivalent.

Most commercial uses for PFCs are in low-volume niche markets. PFCs are used as replacements for ozone-depleting substances in specialty ultra-low temperature refrigerant blends, aerospace, electronics (plasma etching, chemical vapour deposition [CVD] and CVD chamber cleaning in semiconductor

manufacturing), computer, telecommunications, medical, metal working, specialty cosmetics and other applications where high purity and cleanliness is required. PFCs have been successfully applied in advanced vapour degreasing processes, and are the preferred solvents for use with Teflon and other amorphous copolymers containing trifluoroethylene. Higher molecular weight PFCs such as perfluorobutane and perfluorohexane have been used to replace halons in fire extinguishing applications.

16.2.3 HFCs

HFCs are used as refrigerant fluids in various types of refrigeration systems. In 1995, the volume of HFCs consumed in Canada was 3.2 kt. About 90% of this volume is HFC-134a, a replacement for CFC-12. The remainder of the HFC volume is accounted for by HFC-125 and HFC-143a, two gases closely related to HFC-134a. The dominant use of HFCs is in mobile air conditioning, where HFC-134a was unanimously selected by automobile manufacturers to replace CFC-12. All new vehicles are now charged with HFC-134a. Existing vehicles with CFC-12 systems, when maintenance is required, are being retrofitted with HFC-134a. HFC-134a has also been selected as the primary replacement for CFC-12 in domestic refrigeration in North America. HFC-134a is used in some commercial and industrial refrigeration systems for medium temperature applications, but it is generally not as efficient as hydrochlorofluorocarbons (HCFCs) (particularly HCFC-22 and R-502 blends), which are used more often. Only small quantities of HFCs are used as propellants in air and auxiliary blowing agents. HCFCs dominate the use in these areas.

The volume of HFC use was less than 1 kt in 1993 and may reach as much as 22 kt in 25 years with the phase-out of CFCs and HCFCs under the Montreal Protocol.

Estimated CFC, HCFC and HFC Use in Canada, 1990-2020					
(assumes complete HFC replacement for all HCFCs)					
Type of Fluorocarbon	1990	1993	1996	2015	2020
			(kt)		
CFCs	13	8	0	0	0
HCFCs	<1	4	11	4	0
HFCs	<<1	<1	3	14	22
Total fluorocarbons	14	12	14	18	22

Sources: Environment Canada, Commercial Chemicals Evaluation Branch, *1996 Use Pattern Forecast for HFC and HCFCs* (Ottawa, 1994); Cheminfo Services estimates.

According to Environment Canada, the majority of HFC emissions (60% of the 500 kt of CO₂ equivalent) come from air conditioning applications, including mobile and stationary sources, where HFC-134a is used. The other significant source of emissions, accounting for 29% of the total, is refrigeration, including domestic, commercial and industrial types. In each of these applications, emissions are assumed to come from leaks during original equipment manufacturer charging and during the life cycle, as estimated by replenishment service volumes.

16.3 Potential for Measuring, Monitoring and Calculating the GHG Emissions Stream

Virtually none of the emissions from these three gases are directly measurable. Most emissions are due to unmeasurable fugitive leaks and can occur over a long time period. Emissions from maintenance work occur all at once, but the total emissions volume still cannot be measured directly. There are too many small emission sources for an accurate accounting of emissions.

The only method currently used to estimate total emissions is to measure use and apply certain emission factors. This method accounts for any

recycling volumes that may be achieved. For the use of gases in original equipment, an emission factor based on the estimated charge loss is used. For the use of gases in maintenance or service of existing closed systems, the emission factor is assumed to be 1.0 (i.e. the replacement gas is equal to the volume that has been lost over time). For use of gases in non-closed systems, an emission factor of 1.0 must be used.

16.4 Options to Reduce GHG Emissions

For most applications of these gases, there are few commercial alternatives. The focus among the users of these GHGs has been on reducing emissions through improved capture and control. Some of the options for reduction of GHG emissions are briefly outlined below. For more details about each of these options, see Environment Canada's study, *Powering Greenhouse Gas Emission Reductions Through Technology Advancement*.⁶⁵

Options for reducing sulphur hexafluoride emissions include:

- better switchgear equipment design (high-quality impermeable seals);
- stringent leak detection and repair programs (use of gas handling and recycling carts);

65 Environment Canada, Environmental Technology Advancement Directorate, *Powering Greenhouse Gas Emission Reductions Through Technology Advancement* (Ottawa, April 1998).

- air-insulated or vacuum switchgear (less effective); and
- fluid-filled (oil/paper) switchgear (older technology).

Options for reducing PFC emissions include:

- use of hydrofluoroethers (HFEs), a family of CFC substitutes for cleaning purposes; and
- capture and recycling systems.

Options for reducing HFC emissions include:

- lower GWP HFCs (these tend to be more flammable);
- use of propane/butane (flammable, but currently used in European domestic refrigeration);
- ammonia (toxic, but used in large commercial refrigerated warehouses and ice arenas);
- carbon dioxide (requires very high compression pressures); and
- capture and recycling systems (legislated for all auto air conditioning and refrigeration service).

16.5 Suitability for GHG Emissions Trading

The emissions of all the high GWP GHGs are difficult to measure directly at the emission source. This rules out emissions rights and credit trading programs. Since emissions are calculated based on substance use, a substance trading program would be the most suitable for these gases. Since there are too many small volume end uses, such a program would be more easily administered at the supplier or distributor level, which involves only a few participating companies. This system would be similar to those currently in place for some of the ozone-depleting substances.