Environmental Protection Series

CO_2

CH_4

N_2O

Canada's Greenhouse Gas Emissions: Estimates for 1990

Report EPS 5/AP/4
December 1992

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Environmental Protection
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Abstract

Estimates of emissions of carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons released to the environment in Canada in 1990 are summarized in this report. It is acknowledged that there are still many uncertainties and gaps surrounding some of the emissions estimates. Further work is necessary to ensure that all potential sources are identified and to verify existing source estimates. All methods used to develop the emissions estimates, and the limitations of these methods, are described. Sources for the estimates include published reports and scientific papers, mass balance, engineering calculations, and engineering judgement. Emissions have been classified by source, sector, province, and fuel type. Although these estimates are considered the best available at this time, they may change when more recent or better data are developed.

Résumé

Le présent rapport renferme des estimations des émissions de dioxyde de carbone, de méthane, d'oxyde de diazote et de chlorofluorocarbures, pour l'année 1990 au Canada. Ceraines de ces estimations présentent de nombreuses incertitudes et lacunes. Il est nécessaire de poursuivre les travaux pour s'assurer de l'identificatin de toutes les sources et pour vérifier les estimations actuelles. Toutes les méthodes utilisées pour déterminer les émissions de même que les limites de ces méthodes sont décrites. Les sources des estimations comprennent des rapports et des articles scientifiques, des bilans matières, des calculs d'ingénierie et des jugements formulés selon les règles de l'art. Les émissions sont classées selon les sources, le secteur d'activité, la province et le type de caburant ou de combustible. Même si ces estimations sont considérées comme les plus dignes de confiance pour le moment, elles ne sont pas immuables et elles peuvent être corrigées à la lumière de données plus récentes et meilleures.

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Acknowledgements

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Summary

This report identifies anthropogenic sources of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) released to the environment as emissions. In addition, emission estimates have been developed for the five major chlorofluorocarbons (CFC-11, -12, -113, -114, -115) and some of their substitutes. Emissions have been defined as gaseous releases to the atmosphere and have been expressed on a full molecular basis.

Estimates of emissions of CO_2, CH_4, N_2O, and CFCs in Canada for 1990 are summarized in Table S.1. Emissions of CO_2 by sector and province are shown in Table S.2. The emission factors used to develop the estimates are summarized in Table S.3. Figures S.1 to S.4 illustrate emissions of each gas by major source.

In 1990, Canadians contributed about 461 Mt of CO_2 to the atmosphere, or about 2% of global emissions. Approximately 94% of these emissions were attributable to the combustion of fossil fuels. Transportation accounted for about 32% of CO_2 emissions, electricity production 20%, industrial sources 17%, and the remainder was attributed to miscellaneous heating and industrial processes. Landfills were the major source of CH_4 and accounted for about 38% of total emissions of about 3.7 Mt. Other major sources of CH_4 were: oil and gas operations 29%, livestock 27%, coal mining 4%, and miscellaneous 1%. Total emissions of N_2O were estimated to be about 92 kt. Fuel consumption accounted for 52% of N_2O emissions, adipic acid production and nitric acid production 34%, fertilizers 12%, and miscellaneous 2%.

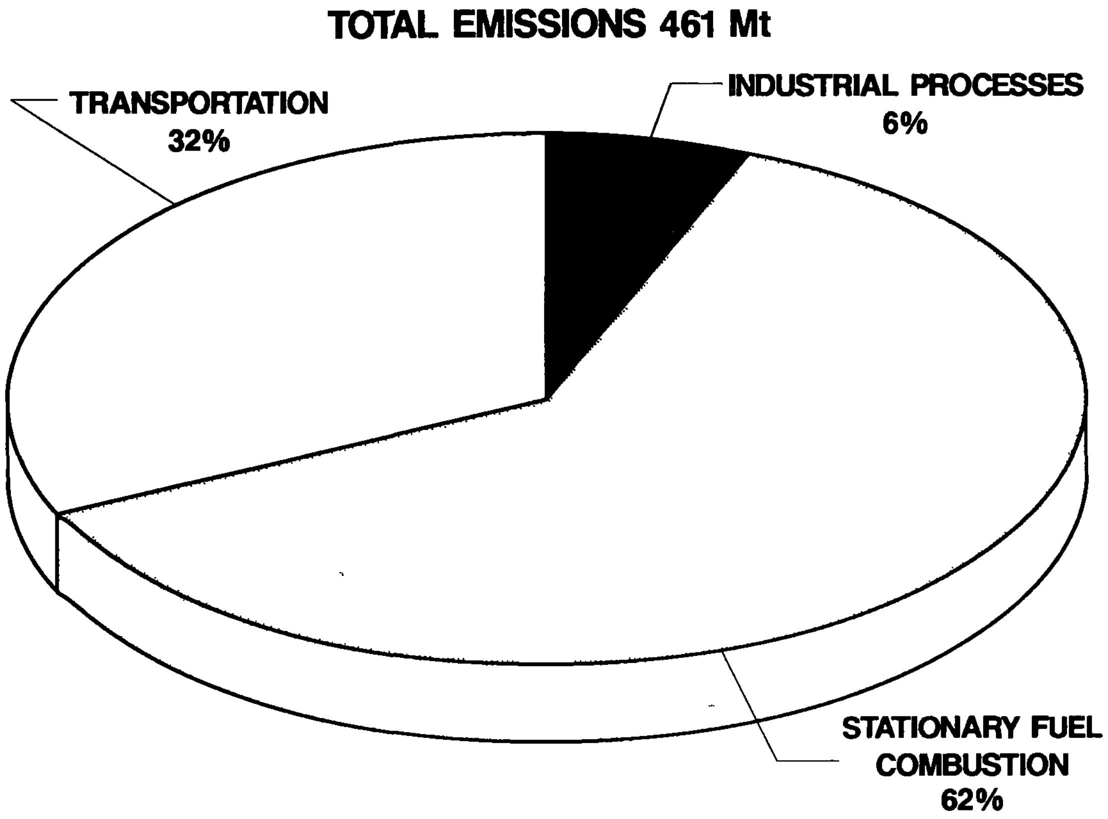
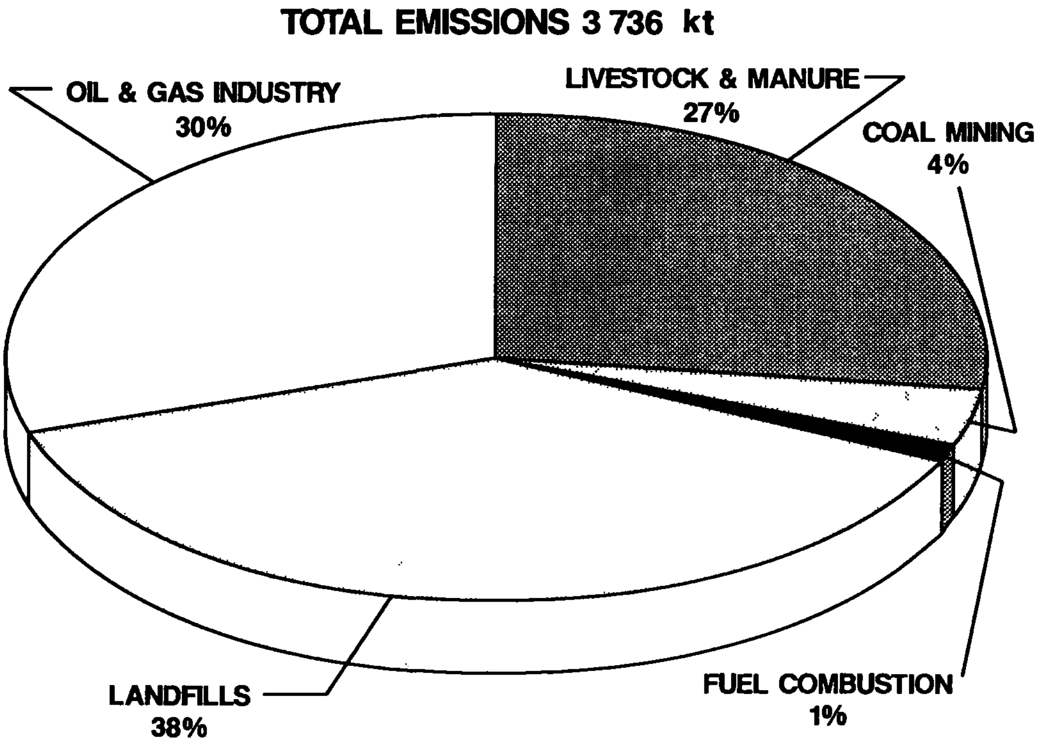


Figure S.1 Carbon Dioxide Emissions by Source (1990)



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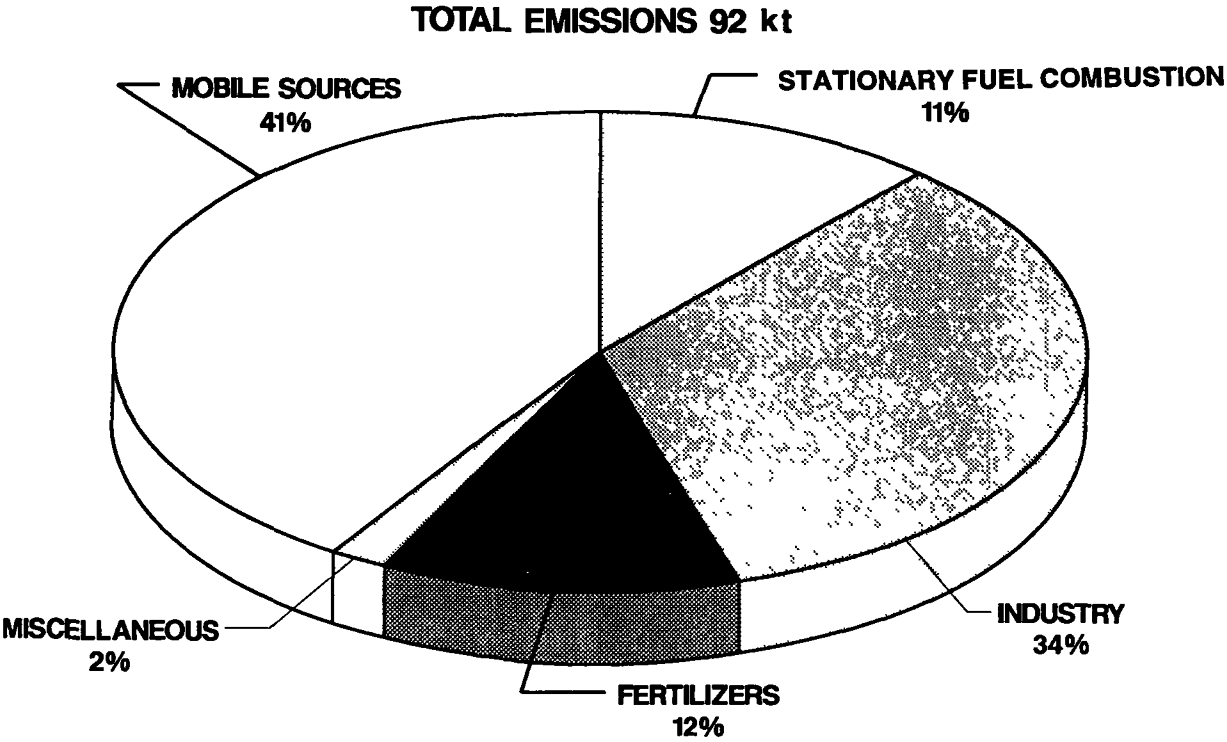

Figure S.3 Nitrous Oxide Emissions by Source (1990)

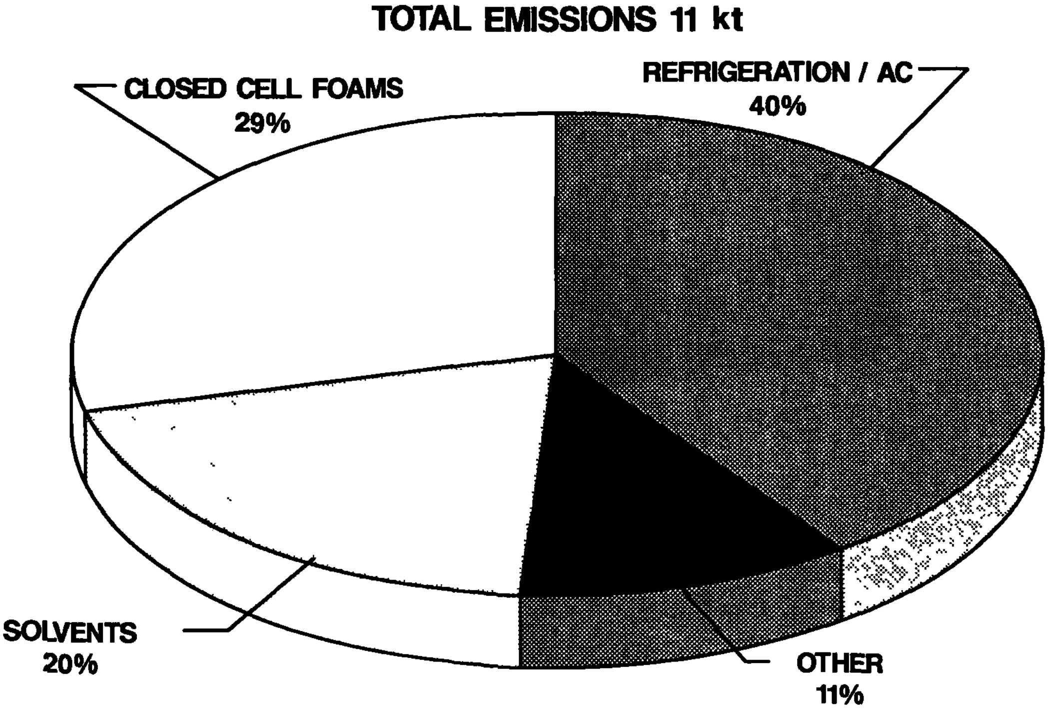

Figure S.4 Chlorofluorocarbon Emissions by Source (1990)

Table S.1 Summary of National Emissions (1990)[a]

Source	CO_2	CH_4	N_2O	CFCs
Industrial Processes				
Upstream Oil and Gas Production	7 567	1 100	-	-
Natural Gas Distribution	?	18	-	-
Cement/Lime Production	7 666	-	-	-
Non-energy Use	13 620	-	-	-
Coal Mining	-	143	-	-
Chemical Production	?	?	31	<1
Subtotal	**28 856**	**1 261**	**31**	**<1**
Fuel Combustion - Stationary				
Power Generation	93 873	1	2	-
Industrial	75 350	3	2	-
Residential	40 733	2	2	-
Commercial	23 984	1	<1	-
Other	52 667	<1	<1	-
Fuel Wood	25 000[b]	1	3	-
Spent Pulping Liquors	28 000[b]	-	-	-
Subtotal	**286 607[c]**	**8**	**9**	**-**
Fuel Combustion - Transportation				
Automobiles	49 019	10	20	-
Light-duty Gasoline Trucks	23 094	5	9	-
Heavy-duty Gasoline Trucks	2 235	<1	<1	-
Motorcycles	149	<1	<1	-
Other	7 292	1	1	-
Light-duty Diesel Trucks	136	<1	<1	-
Heavy-duty Diesel Vehicles	21 410	2	3	-
Other Diesel Engines	14 363	1	2	-
Air	13 137	1	1	-
Rail	6 315	<1	1	-
Marine	7 782	<1	1	-
Subtotal	**144 931[c]**	**23**	**38**	**-**
Incineration				
Wood Waste	7 500[b]	1	?	-
Other	1 370[b]	<1	?	-
Subtotal	**0[c]**	**1**	**-**	**-**
Agriculture				
Livestock/Manure	34 600[b]	1 000	-	-
Fertilizer Use	-	-	11	-
Land Use Change	?	?	-	-
Subtotal	**0[c]**	**1 000**	**11**	**-**
Miscellaneous				
Prescribed Burning	8 600[b]	38	1	-
Landfills	3 870[b]	1 405	-	-
Use of CFCs	-	-	-	11
Anaesthetics	-	-	2	-
Subtotal	**0[c]**	**1 443**	**3**	**11**
National Total	**460 394[c]**	**3 736**	**92**	**11**

---

[a] All figures expressed as kt/year.

[b] Biomass.

[c] Excludes Biomass.

Note: Totals may not add exactly, due to rounding.

Table S.2 Summary of Emissions of Carbon Dioxide (kt) in Canada (1990) Note: Totals may not add exactly, due to rounding.

Sector	Nfld	PEI	NS	NB	Que	Ont	Man	Sask	Alta	BC	Terr.	Can	Percent of Total
INDUSTRIAL PROCESSES													
Cement Production	58	0	173	0	1 443	2 540	115	58	750	635	0	5 772	1.25
Lime Production	0	0	0	95	322	1 089	66	0	133	189	0	1 894	0 41
Stripped Natural Gas	0	0	0	0	0	25	0	379	6 459	705	2	7 569	1 64
Non-energy Use	336	3	100	47	1 894	3 808	54	237	6 545	592	4	13 620	2 96
Subtotal:	**394**	**3**	**273**	**142**	**3 659**	**7 461**	**236**	**674**	**13 886**	**2 122**	**6**	**28 856**	**6.27**
FUEL COMBUSTION													
Stationary Sources:													
Power Generation	1 631	102	6 873	5 895	1 430	25 935	492	10 277	39 704	1 227	307	93 873	20 39
Residential	694	354	1 986	943	6 092	16 452	1 606	2 064	6 411	3 986	144	40 733	8 85
Commercial	247	130	590	563	3 876	8 398	1 398	960	4 850	2 825	146	23 984	5.21
Industrial	1 024	37	717	1 404	13 790	33 204	1 313	2 633	13 804	7 322	103	75 350	16 37
Agriculture	25	20	106	54	301	806	52	298	513	300	3	2 478	0.54
Public Administration	76	39	219	170	379	616	33	85	175	84	187	2 063	0.45
Steam Generation	0	2	0	142	0	181	45	0	10	0	0	379	0.08
Refined Products	0	0	0	0	0	44	0	0	302	0	0	345	0.08
Own Use:													
Natural Gas	0	0	0	0	0	0	0	2 438	21 936	1 865	136	26 376	5.73
RPPs	1 044	1	685	917	2 324	5 274	9	241	2 529	1 078	13	14 116	3.07
Coal	0	0	3	0	0	0	0	1	15	226	0	245	0.05
Pipelines	0	0	0	0	25	2 194	818	1 583	1 228	817	0	6 665	1.45
Subtotal:	**4 742**	**685**	**11 180**	**10 087**	**28 217**	**93 105**	**5 767**	**20 581**	**91 476**	**19 729**	**1 038**	**286 607**	**62.25**
Transportation Sources:													
Gasoline													
Automobiles	864	274	1 649	1 401	10 514	18 018	1 994	2 362	6 647	5 152	143	49 019	10 65
Light-duty Trucks	407	129	777	660	4 953	8 489	940	1 113	3 132	2 427	67	23 094	5 02
Heavy-duty Trucks	39	12	75	64	479	822	91	108	303	235	7	2 235	0 49
Motorcycles	3	1	5	4	32	55	6	7	20	16	0	149	0.03
Total Gasoline:	1 313	416	2 506	2 129	15 978	27 383	3 031	3 590	10 102	7 830	217	74 497	16 18
Diesel													
Light-duty Trucks	2	0	4	5	32	45	5	4	21	16	1	136	0.03
Heavy-duty Trucks	378	74	670	821	5 030	7 064	782	665	3 236	2 581	109	21 410	4.65
Other	350	60	450	343	1 930	2 703	1 022	2 088	3 135	2 005	278	14 363	3.12
Total Diesel:	730	135	1 124	1 170	6 991	9 811	1 810	2 757	6 391	4 602	388	35 909	7.80
Road													
Natural Gas Motor Vehicles	0	0	0	0	9	39	0	0	38	45	0	131	0.03
Propane Motor Vehicles	1	1	6	6	65	647	43	37	439	309	1	1 554	0.34
Total Road:	2 044	552	3 636	3 305	23 043	37 880	4 883	6 384	16 971	12 786	606	112 090	24 35
Off-road													
Rail	0	0	60	118	518	1 622	552	533	1 603	1 308	2	6 315	1.37
Marine	750	84	1 036	439	1 879	1 490	0	0	0	2 104	0	7 782	1.69
Aircraft	921	14	500	91	2 643	3 731	518	254	1 773	2 468	223	13 137	2.85
Off-road Gas	99	31	189	160	1 203	2 061	228	270	760	589	16	5 607	1.22
Total Off-road:	1 770	130	1 784	808	6 243	8 904	1 298	1 058	4 136	6 469	242	32 841	7.13
Subtotal:	**3 814**	**682**	**5 420**	**4 113**	**29 286**	**46 784**	**6 182**	**7 441**	**21 107**	**19 255**	**847**	**144 931**	**31.48**
TOTALS:	8 950	1 370	16 873	14 343	61 162	147 351	12 184	28 696	126 470	41 105	1 891	460 394	100.00

Table S.3 Greenhouse Gas Emissions Factors[a]

	CO_2		CH_4		N_2O	
COMBUSTION SOURCES						
Gaseous Fuels	(t/ML)[b]	(t/TJ)	(kg/ML)	(kg/TJ)	(kg/ML)	(kg/TJ)
Natural Gas	1.88	49.68	(4.8 to 48)	(0.13 to 1.27)	0.02	0.62
Still Gas	2.07	49.68	-	-	0.02	0.62
Coke Oven Gas	1.60	86.00	-	-	-	-
Liquid Fuels	(t/kL)	(t/TJ)	(kg/kL)	(kg/TJ)	(kg/KL)	(kg/TJ)
Motor Gasoline	2.36	67.98	(0.24 to 4.20)	(6.92 to 121.11)	(0.23 to 1.65)	(6.6 to 47.60)
Kerosene	2.55	67.65	0.21	5.53	0.23	6.10
Aviation Gas	2.33	69.37	2.19	60.00	0.23	6.86
LPGs	(1.11 to 1.76)	(59.84 to 61.38)	0.03	1.18	0.23	(9.00 to 12.50)
Diesel Oil	2.73	70.69	(0.06 to 0.25)	(1.32 to 5.7)	(0.13 to 0.40)	(3.36 to 10.34)
Light Oil	2.83	73.11	(0.01 to 0.21)	(0.16 to 5.53)	(0.13 to 0.40)	(3.36 to 10.34)
Heavy Oil	3.09	74.00	(0.03 to 0.12)	(0.72 to 2.88)	(0.13 to 0.40)	(3.11 to 9.59)
Aviation Jet Fuel	2.55	70.84	0.08	2.00	0.23	6.40
Petroleum Coke	4.24	100.10	0.02	0.38	-	-
Solid Fuels	(t/t)	(t/TJ)	(g/kg)	(kg/TJ)	(g/kg)	(kg/TJ)
Anthracite	2.39	86.20	0.02	varies	(0.1 to 2.11)	varies
U.S Bituminous	(2.46 to 2.50)	(81.6 to 85.9)	0.02	varies	(0.1 to 2.11)	varies
Cdn. Bituminous	(1.70 to 2.52)	(94.3 to 83.0)	0.02	varies	(0.1 to 2.11)	varies
Sub-bituminous	1.74	94.30	0.02	varies	(0.1 to 2.11)	varies
Lignite	(1.34 to 1.52)	(93.8 to 95.0)	0.02	varies	(0.1 to 2.11)	varies
Coke	2.48	86.00	-	-	-	-
Fuel Wood	1.47	81.47	(0.15 to 0.5)	(0.01 to 0.03)	0.16	8.89
Slash Burning	1.47	81.47	0.15	0.01		
Incineration						
Municipal Solid Waste	0.91	85.85	0.23	0.02		
Wood Waste	1.50	83.33	0.15	0.01		
PROCESS SOURCES	(t/t)	(t/TJ)	(g/kg)	(t/TJ)	(g/kg)	(kg/TJ)
Cement Production	0.50	-	-	-	-	-
Lime Production	0.79	-	-	-	-	-
Ammonia Production	1.58	-	-	-	-	-
Spent Pulping Liquor	1.43	102.01	-	-		
Adipic Acid Production	-	-	-	-	0.03	-
Nitric Oxide Production	-	-	-	-	(2.0 to 20)	-
Natural Gas Production	0.07	-	2.67	-	-	-
Coal Mining			(1.20 to 16.45)	-	-	-
Non-energy Uses	(t/kL)	(t/TJ)	-	-	-	-
Petrochemical Feedstocks	0.50	14.22	-	-	-	-
Naphthas	0.50	14.22	-	-	-	-
Lubricants	1.41	36.01	-	-	-	-
Other Products	1.45	28.88	-	-	-	-
Coke	2.48	86.00	-	-	-	-
	(t/ML)					
Natural Gas	1.26	33.35	-	-	-	-
Coke Oven Gas	1.6	86.00	-	-	-	-
Agriculture	(kg/head/year)		(kg/head/year)		(g/kg)	(kg/TJ)
Livestock	(36 to 3 960)	-	(0.01 to 120)	-	-	-
Fertilizer Use	-	-	-	-	(1 to 50)	-
Miscellaneous	(kg/t)		(kg/t)		(g/kg)	(kg/TJ)
Landfills	182.00		66.00		-	-

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[a] Note Where ranges are given for emission factors, please consult the report for details.

[b] The SI abbreviations M for mega (× 10^6); G for giga (× 10^9); and T for tera (× 10^{12}) are used throughout this report

Section 1

Introduction

The main purpose of this report is to identify and quantify anthropogenic (human-induced) sources of atmospheric emissions of *greenhouse gases*. Although a number of gases affect the earth's radiation balance, quantifying the indirect effects of some of these gases, particularly of the ozone precursors [nitrogen oxides (NO_x); non-methane hydrocarbons (NMHCs); and carbon monoxide (CO)], is difficult and highly uncertain. In fact, for NO_x, uncertainties are so large it is not possible to give even the sign of the indirect effect (IPCC, 1992). As a result, emissions estimates for NO_x, NMHCs, and CO are not included in this report.

The direct radiative gases that are examined are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This report summarizes the emissions of these gases in Canada for the year 1990 and provides a methodology for estimating emissions. *Preliminary* estimates for some of the major halogenated source gases, i.e., the chlorinated fluorocarbons (CFCs), methyl chloroform (CH_3CCl_3), and carbon tetrachloride (CCl_4), have been made. In addition, a *carbon budget*, albeit incomplete, has been developed for Canada based on currently available source and sink data.

Information used to develop these estimates was obtained from published reports and scientific papers, personal communication, engineering calculations, mass balance, and engineering judgement. The emission estimates are by no means the definitive estimates for 1990. In some cases, especially for CH_4 and N_2O, the estimates fall within wide ranges and there are known sources for which estimates have not been made. Efforts are being made to improve these estimates through ongoing and planned research. Some of these activities include: verification of elevated N_2O levels from aged 3-way catalytic converters; additional measurements of CH_4 emissions from landfills; measurements of CH_4 fluxes from Hudson Bay wetlands; research into nitrogen storage and fluxes from soils; an improvement of the Forestry Canada national carbon budget; research into the role of the oceans relative to CO_2; and the potential generation of CH_4 due to flooding caused by the construction of hydroelectric power dams. Some of these activities are being sponsored by Environment Canada under the Greenhouse Gas Emissions Reporting and Assessment Program (GERAP) (Finlay, 1992).

1.1 Carbon Dioxide

The concentration of CO_2, a trace gas in the earth's atmosphere, varies naturally due to changes in biological activity. Although natural emission and removal processes are more or less in equilibrium, data from atmospheric monitoring reveal increasing concentrations of CO_2 superimposed on the seasonal fluctuations. The contribution of CO_2 caused by burning fossil fuels, harvesting forests, and converting land to agricultural use has been more than sufficient to explain the increases in atmospheric concentrations (Pales and Keeling, 1965; Robinson and Robbins, 1972; IPCC, 1992). The present atmospheric concentration of CO_2 of about 355 ppmv in 1991 (IPCC, 1992) represents an increase of about 27%

over the pre-industrial level of about 280 ppm. The CO_2 concentration is currently increasing at about 1.8 ppmv per year (about 3.8 Gt of carbon) because of the imbalance between emissions from fossil fuel combustion and land use changes and the uptake by oceanic and terrestrial sinks. Although a balanced carbon budget has not been attained, estimates of global emissions are about 6.0 ± 0.5 Gt C from fossil fuel combustion and cement and lime production, and 1.6 ± 1.0 Gt C from land use changes, mostly deforestation (Marland, 1992; IPCC, 1992). The oceans are estimated to be a net sink of about 2.0 ± 0.8 Gt C. The difference between atmospheric accumulation and these fluxes is the missing sink, which is thought to be the terrestrial biosphere (IPCC, 1992).

Carbon dioxide and other gases in the atmosphere trap heat between the surface of the earth and the upper atmosphere. This ability to trap heat, which is commonly referred to as the greenhouse effect, keeps the surface of the planet about 33°C warmer than would be expected given the amount of energy radiated by the earth (Schneider, 1989). Carbon dioxide is one of the most important infrared absorbers in the wavelength ranges 12.5 to 18.2 μm, 11.8 to 9.1 μm, and 4.2 to 4.8 μm (Wuebbles and Edmonds, 1987).

Carbon dioxide and other naturally occurring gases in the atmosphere do not absorb all infrared wavelengths. They are relatively transparent to radiation with wavelengths between 7 and 12 μm. However, other gases such as CH_4, N_2O, and the CFCs are powerful absorbers in this range (EPRI, 1988).

In Canada, carbon dioxide is the most important greenhouse gas because it accounts for about 70%* of the infrared absorption due to all greenhouse gas emissions (Figure 1). This estimate is based on the assumption that the indirect and direct effects of CH_4 are about the same. For all other gases, only the direct 100-year GWPs have been used. Section 2 describes and quantifies the major sources of emissions, and Section 7 outlines the methods used to develop the carbon dioxide emission factors.

Although the general approach used to develop the CO_2 emission factors is based on an earlier report (Jaques, 1990), a number of changes are incorporated in this version. The earlier study included emissions from biomass sources, i.e., the combustion of spent pulping liquors, slash burning, wood waste incineration, and fuel wood combustion. Although these and other processes, such as respiration and fermentation, all produce emissions of CO_2, the source of the carbon is *renewable on human timescales* and, as such, is *fundamentally* different (in terms of timescales) from CO_2 derived from fossil fuels and inorganic carbonates. Because we are interested in only the net flux of carbon from the terrestrial biosphere, these biomass sources of CO_2 are dealt with separately. Section 3 deals with biomass and relies to a large extent on the results of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), (Apps and Kurz, 1991).

The production and use of fossil fuels accounts for almost 97% of Canada's total anthropogenic emissions of CO_2. The remaining 3% can be attributed to industrial processes such as cement and lime production. To provide a perspective on

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* Based on 100-year global warming potentials (GWPs) of 22 for CH_4, 270 for N_2O, and an average of 5 000 for CFCs.

Canada's emissions of CO_2, fossil-fuel emissions were compared with those of the rest of the world. In 1990, Canada's emissions of CO_2 from fossil-fuel combustion and cement and lime production were about 461 Mt or 125 Mt C. This corresponds to about 2% of the global estimate of 6000 Mt C (Marland, 1992). On a per capita basis, however, Canada is currently ranked third in the world, mainly because of its small population and its high per capita use of energy. The industrial world's top ten per capita emitters of CO_2 are shown in Figure 2.

1.2 Methane

Methane (CH_4) is an important greenhouse gas. It plays a major role in controlling the abundance of both tropospheric ozone (O_3), which is an important greenhouse gas near the tropopause, and the hydroxyl (OH) radical, which controls the atmospheric lifetimes of other gases of climatic importance (IPCC, 1992; Dickenson and Cicerone, 1986; Ramanathan *et al.*, 1987). Methane can also be oxidized to form CO_2.

In 1991, the atmospheric concentration of CH_4 was about 1.72 ppmv, which is more than double the pre-industrial level of about 0.8 ppmv (IPCC, 1992). The current annual rate of accumulation is about 13 ppbv or 37 Mt, which is lower than the annual rate of 20 ppbv observed in the late 1970s (IPCC, 1992; Lassey *et al.*, 1991).

As with CO_2, the imbalance between the sources and sinks of CH_4 results in an increase in atmospheric concentration. Several attempts have been made to quantify the CH_4 budget by estimating the magnitude of the major sinks (Vaghjiani and Ravishankara, 1991; Crutzen, 1991; Fung *et al.*, 1991; IPCC, 1992) and sources (Crutzen, 1991; Okken and Kram, 1989; IPCC, 1992). Globally, the major sinks are estimated to total about 460 ± 95 Mt CH_4 per annum, with about 91% attributed to the reaction of CH_4 with the OH radical in the troposphere. A total global annual emission rate of 500 Mt CH_4 has been estimated based on the strength of the sinks and the annual accumulation of CH_4 in the atmosphere. This emission rate includes both anthropogenic (about 360 Mt) and natural (140 Mt) sources (IPCC, 1992).

Landfills are estimated to be the major source of CH_4 emissions in Canada and account for about 38% of total anthropogenic sources. Other major sources include leakage from upstream oil and gas operations (~29%) and domesticated animals (~27%). Clearly, efforts to reduce emissions of CO_2, i.e., improving the efficiency with which fossil fuels are consumed, will not be as effective in reducing emissions of CH_4. Measurements of carbon isotope ratios of CH_4 concentrations in the atmosphere have enabled a number of researchers (Whalen *et al.*, 1989; Manning *et al.*, 1990; Quay *et al.*, 1991; and Lassey *et al.*, 1991), to estimate that about 20% of the total annual global CH_4 emissions (~100 Tg, IPCC, 1992) are produced from *fossil carbon* related sources. Because current CH_4 concentrations, trend, and isotopic mixes are the result of imbalances of sources and sinks weighted exponentially over a period of about 10 years (the average lifetime of a CH_4 molecule), several decades of emission estimates are needed to determine what fraction of these emissions can be considered as *net emissions.* In other words, because CH_4 is not directly sequestered by biomass, it is difficult to quantify the proportion of emissions that should be considered part of a closed cycle. For these reasons, both biomass and fossil fuel related emissions are treated together.

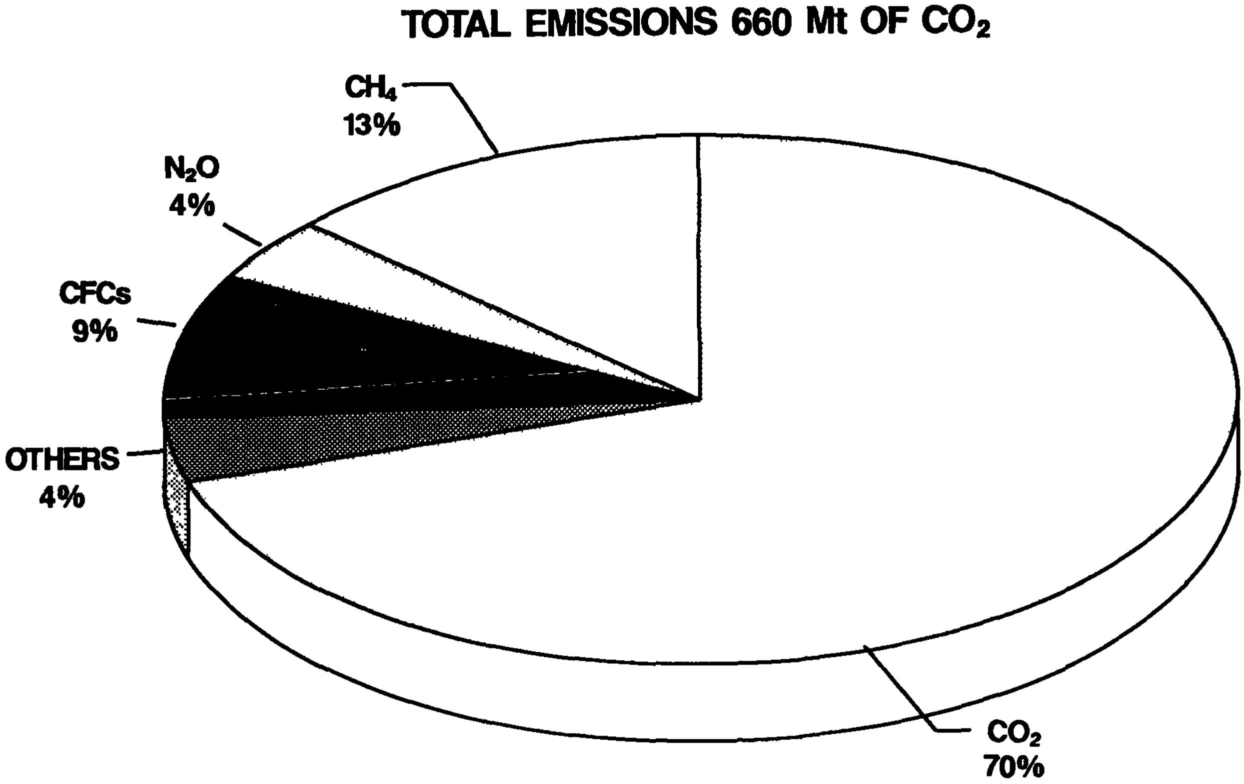

Figure 1 Canada's Greenhouse Gas Emissions

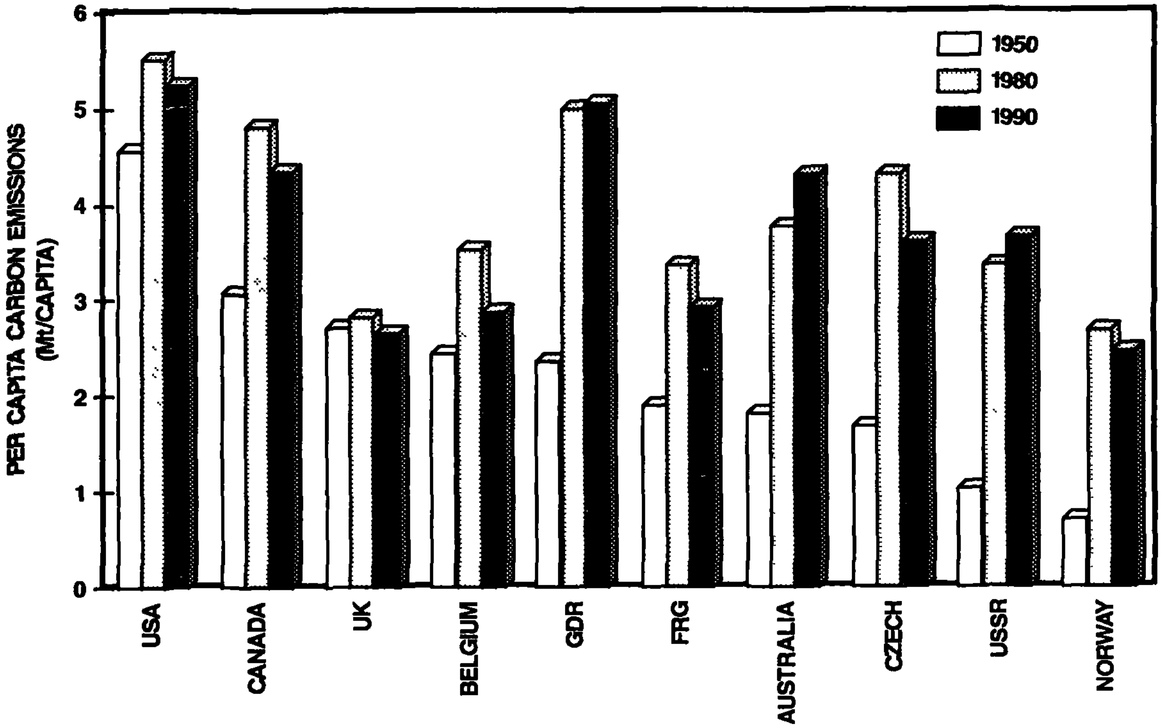

Figure 2 Emissions of Carbon Dioxide by Country

1.3 Nitrous Oxide

Nitrous oxide (N_2O) is another important infrared absorbing trace gas that contributes to the greenhouse effect. On a molecule per molecule basis, N_2O has a radiative forcing of about 200 times that of CO_2.

Based on data from the World Meteorological Organization, (WMO, 1992), the present atmospheric concentration of N_2O is about 310 ppbv, which is about 8% greater than during the pre-industrial era. The current rate of accumulation of N_2O in the atmosphere is about 0.2 to 0.3% per year, which represents about 3 to 4.5 Mt N.

Although the estimates of N_2O emissions are relatively uncertain, it appears that soils dominate (IPCC, 1992). The major sinks identified are stratospheric photo-dissociation and stratospheric photo-oxidation, which are estimated to remove between 7 and 13 Tg N (IPCC, 1992). Removal by soils, thought possibly to be a small sink, has not been quantified. Based on the magnitude of the sinks and the annual atmospheric increase, the total emission rate from all sources should be between 10 and 17.5 Mt N. However, emission estimates based on fuel usage, soil denitrification, and industrial processes are between 5.2 and 16.1 Mt N (IPCC, 1992). It is, therefore, apparent that either the source strengths are underestimated or there are unidentified sources.

The lack of source test data makes current estimates of N_2O emissions highly uncertain. Nevertheless, anthropogenic emissions of N_2O in Canada have been estimated for 1990. Fuel combustion, mainly from aged 3-way catalytic converters, accounts for about 52% of N_2O emissions; industrial processes account for about 36%; and fertilizer use about 12%. Early estimates of emissions from soils (currently considered as natural emissions), are about 10 times larger than emissions from anthropogenic sources.

1.4 Accuracy of the Estimates

This preliminary emission inventory has not addressed error analysis of emission estimates. This will be discussed in detail in future reports, once a systematic approach is taken to evaluating all sources of errors. There is now a wide degree of variation in emission estimates for certain gases and estimates from different sources. Combustion-related emissions of CO_2 are considered relatively accurate. Any small errors are due mainly to three assumptions: (1) the accuracy of the fossil fuel data; (2) the quantity of carbon in the fuel; and (3) the percentage of carbon oxidized to CO_2 during combustion.

Emissions of CH_4 and N_2O, however, depend on many factors. For combustion sources, emissions depend on the type of combustion device, the age of the device, the operating temperatures, fuel types, ambient temperatures, whether or not emission control devices are used, and the condition of the control devices. The rate of CH_4 generation from enteric fermentation depends on the feed, the animal, and its health. For landfills, CH_4 emissions depend on a number of different factors, such as the type and amount of refuse, the climatic conditions, and the age of the landfill. Because of the number of variables involved in developing emission estimates for these gases, the estimates should only be considered accurate to within one order of magnitude. For some sources, the range of estimates can be quite large, especially if only limited measurements exist and are, themselves, highly variable.

1.5 Use of Global Warming Potentials

By definition, a global warming potential (GWP) is the time-integrated change in "radiative forcing" 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 CO_2 (IPCC, 1990). In other words, a GWP is a relative measure of the warming effect that the emission of a radiative gas might have on the surface troposphere. The GWP of a greenhouse gas takes into account both the instantaneous radiative forcing due to an incremental concentration increase and the lifetime of the gas (IPCC, 1990).

Although the concept of GWPs and their use as indices for ranking the relative and cumulative impact of greenhouse gas emissions is useful for policy options, it must be stressed that there are many uncertainties associated with them. The limitations are described elsewhere (IPCC, 1992; Wang *et al.*, 1991; WMO, 1992). However, because the GWP is a measure of the global effect of a given greenhouse gas emission, it is most appropriate for well-mixed gases in the tropopause such as CO_2, CH_4, N_2O, and halocarbons.

There are many additional uncertainties associated with quantifying indirect effects, especially of such gases as ozone (O_3), the production of which depends on the relative concentrations of CH_4, NO_x, CO, and NMHCs. As a result, revised direct GWPs of well-mixed gases have recently been developed (IPCC, 1992) (Table 1). Indirect GWPs for NO_x, NMHCs, CO, hydrochlorofluorocarbons (HCFCs), and HFCs are considered too uncertain to estimate, and earlier indirect GWPs calculated for CH_4 are considered inaccurate and should not be used. However, some of the indirect effects of CH_4 are important and it is likely that the total GWPs for CH_4 (direct plus indirect) will be substantially larger than those shown in Table 1. On the other hand, the indirect effects of some of the other gases, although not as yet quantified, are known to be negative.

Table 1 **Direct Global Warming Potentials of Trace Gases (IPCC, 1992)**

Trace Gas	Lifetime (years)	20 Years	100 Years	Indirect Effect
CO_2	-	1	1	none
CH_4	10.5	34	11	positive
N_2O	132.0	250	270	uncertain
CFC-11	55.0	4 400	3 400	negative
CFC-12	116.0	7 000	7 100	negative
CFC-113	110.0	4 400	4 500	negative
CFC-114	220.0	5 900	7 000	negative
CFC-115	550.0	5 300	7 000	negative
HCFC-22	15.8	4 100	1 600	negative
HCFC-123	1.7	330	90	negative
HCFC-124	6.9	1 500	440	negative
HFC-125	40.5	5 100	3 400	none
HFC-134a	15.6	3 100	1 200	none
HCFC-141b	10.8	1 800	580	negative
HCFC-142b	22.4	3 900	1 800	negative
HFC-143a	64.2	4 600	3 800	none
HFC-152a	1.8	520	150	none
CCl_4	47.0	1 800	1 300	negative
CH_3CCl_3	6.1	360	100	negative
CF_3Br	77	5 600	4 900	negative
$CHCl_3$	0.7	92	25	negative
CH_2Cl_2	0.6	54	15	negative
CO	months	-	-	positive
NMHC	days to months	-	-	positive
NO_x	days	-	-	uncertain

Section 2

Carbon Dioxide Emissions

The methodologies used to estimate emissions of CO_2 in Canada are based on work by Marland and Rotty (1983) and are essentially the same as those used in the previous report on Canadian CO_2 emissions (Jaques, 1990). Emissions were estimated using emission factors developed to reflect the type of fossil fuels consumed in Canada. Some of the emission factors in the 1990 report have been modified to better reflect the regional differences in fuels and a few new sources have been added. A summary of emissions by source is given in Table 2.

The major changes that have taken place are: the inclusion of some refined petroleum products that were not included in the first estimates; the inclusion of CO_2 stripped from natural gas; a modification to the heavy oil emission factor, from 71.54 to 74 t/TJ; an increase in emissions due to forest fires; a decrease in emissions from prescribed burning; the inclusion of non-energy sources such as lubricants, naphthas, and petrochemical feedstocks; and revised coal emission factors that vary provincially.

The basis of the CO_2 emission factor derivations is discussed in Section 7 and is relatively straightforward. The methods used to estimate emissions are based on the carbon contents of the fuels, the fraction of the carbon oxidized, and the quantities of fuels consumed. These methods are consistent with approaches adopted internationally (OECD, 1991). Both the hydrocarbons (HCs) and particulate formed during combustion are accounted for to some extent, but emissions of carbon monoxide (CO) are included in the estimates of CO_2 emissions. Although this creates a problem of double counting when attempting a carbon mass balance, it is minor. Furthermore, CO in the atmosphere undergoes complete oxidation to CO_2 within 5 to 20 weeks of emission (IPCC, 1990).

To facilitate comparison of carbon sources and sinks, and to provide a clearer picture of the major gases emitted, emissions of C, as CO_2, CO, and CH_4 are presented in Table 3. Caution should be exercised when quoting the results given in Table 3 because the emissions for the different gases were estimated using different methods, and, therefore, their accuracy varies. It should also be noted that, to eliminate any double counting, the CO_2 emission estimates were modified to account for that portion of the carbon that initially forms CO and CH_4.

2.1 Industrial Processes

2.1.1 Cement Production

Cement production generates significant quantities of CO_2. Both wet and dry methods are used in Canada to manufacture cement and, regardless of the process, CO_2 is released during the reduction of calcium carbonate. Essentially, CO_2 emissions from cement production are directly proportional to lime content (see Subsection 2.1.2). In 1990, total cement production reported as producer shipments was 11 252 043 t (EMR, 1991a). Based on an emission factor of 0.50 t CO_2/t of cement produced (see Section 7 for derivation) emissions of CO_2 from cement production were estimated to be 5.61 Mt. Provincial emissions were estimated by prorating production capacities in each province by total production.

Table 2 Carbon Dioxide Emissions by Source

	Mt of CO_2	Percent of Total
Natural Gas[a]	140	30.37
Coal	83	18.00
Motor Gasoline	80	17.35
Diesel Oil	47	10.20
Heavy Oil	33	7.16
Light Oil	18	3.90
Aviation Fuel/Gas	13	2.82
Coke and Coke Oven Gas	12	2.60
Still Gas	8	1.74
Kerosene	2	0.43
Liquified Petroleum Gases	7	1.52
Petrochemical Feedstocks	2	0.43
Lubricants	1	0.22
Other Products	1	0.22
Petroleum Coke	6	1.30
Cement/Lime Production	8	1.74
Fuel Wood	25[b]	-
Prescribed Burning	9[b]	-
Incineration	9[b]	-
Spent Pulping Liquors	28[b]	-
Landfills	4[b]	-
Total Emissions	**461**	**100.00**

[a] Includes CO_2 stripped from natural gas.
[b] Biomass sources not included in totals.

Table 3 **Annual Sources and Sinks of Carbon in Canada**[a]

Sources/Sinks	As Emissions (Mt) of			
	C	CO_2	CO	CH_4
Direct Anthropogenic				
(a) Energy Use:				
Fossil Fuels	121.5	431.05	8.57	0.36
Biomass (fuel)	15.0	54.00	0.62	0.00
Subtotal	**136.5**	**485.05**	**9.19**	**0.36**
(b) Non-energy Use:				
Raw CO_2	2.1	7.70	-	-
Incineration	0.4	1.40	0.04	0.00
Cement/Lime Production	2.1	7.56	-	-
Biomass	4.6	14.60	1.29	0.04
Landfills	2.1	3.87	-	1.41
Manure	0.2	-	-	0.33
Domestic Animals	9.9	34.60	-	0.67
Natural Gas Leaks	0.2	-	-	0.29
Coal Mines	0.1	-	-	0.14
Agriculture	?			
Subtotal	**21.7**	**69.73**	**1.33**	**2.88**
Total	**158.2**	**554.78**	**10.52**	**3.24**
Indirect Anthropogenic and Natural				
Wildfires	31.4	98.82	9.88	.33
Wood Products Decay	23.1	84.70	-	-
Insects	0.1	0.37	-	-
Wetlands	18.0	-	-	24.00
Wild Animals	0.1	-	-	0.15
Subtotal	**72.7**	**183.89**	**9.88**	**24.49**
Total All Sources	**230.9**	**738.67**	**20.40**	**27.73**
Sinks				
Oceans	?			
Agriculture	?			
Forest Biomass	92.0			
Soils	17.0			
Peatlands	26.0			
Total All Sinks	**135.0**			

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[a] Net Carbon Budget (Sources - Sinks) = 96 Mt carbon.

2.1.2 Lime Production

Calcined limestone (or quick lime) is formed by heating limestone to remove the carbonates. This is usually done at high temperatures in a rotary kiln and the process releases CO_2. The major use for quick lime is in the steel industry where it is used as a fluxing agent. The pulp and paper industry also uses quick lime in the preparation of digesting liquor and for effluent treatment. In 1990, 2.4 Mt of calcined limestone were produced in Canada (EMR, 1991b). Using an emission factor of 0.79 t CO_2/t of quick lime produced, emissions in Canada were estimated to be 1.9 Mt of CO_2.

2.1.3 Ammonia Production

Most of the ammonia in Canada is produced by the Haber-Bosh process. In this process, a mixture of gas containing nitrogen and hydrogen in a 1-to-3 ratio is reacted catalytically at high temperatures and pressures to produce ammonia. The nitrogen can be derived from the air by means of liquefaction, by the producer gas reaction, or by burning out the oxygen in air using hydrogen. Hydrogen can be obtained from many sources, including water vapour, coke-oven gas, natural gas, fuel oil, catalytic reformer gases, and the electrolysis of water or brine (Industrial Chemicals, 1980). An emission factor was derived for ammonia produced from natural gas by assuming that all the carbon in the gas is eventually converted to CO_2 and released to the atmosphere. However, much of the carbon used to produce ammonia is tied up in the form of urea, which reduces the emissions of CO_2 attributable to ammonia production.

According to the Canadian Fertilizer Institute (CFI, 1992), approximately 3 709 943 t of ammonia and 2 576 670 t of urea were produced in Canada in 1990. Of the 3.7 Mt of ammonia, approximately 0.5 Mt were produced using by-product hydrogen. By using an emission factor of 1.56 t CO_2 /t of ammonia produced from natural gas (see Section 7) and by taking into account the portion of carbon contained in urea (0.73 t CO_2/t urea) emissions of CO_2 from the production of ammonia were estimated to be 3.2 Mt. Emissions of CO_2 from the production of ammonia fall into the general category of non-energy emissions and are included in this category in Table S.2. In Canada, 92% of the ammonia is used in agriculture to sustain soil fertility and grow crops (Environment Canada, 1987). Unlike some of the other non-energy products derived from fossil fuels, the use of ammonia can increase the organic carbon content of soils and thereby act as a sink for CO_2. A 30-year study conducted in Saskatchewan (Campbell *et al.*, 1991) indicated that the carbon content of the surface layer was increased from 36.3 t/ha in a wheat fallow rotation to 41.9 t/ha in a fertilized continuous wheat rotation. Therefore, a proper evaluation of the role of agriculture in climate change, and in particular, its contribution to emissions, requires that both the sources and sinks be quantified. A further discussion of the role of agriculture in sequestering carbon is discussed in Section 3.

2.1.4 Non-energy Uses

A number of petroleum-based products, considered non-energy uses or by-products from combustion, sequester carbon and should not be considered as emission sources of CO_2. These include plastics, rubber, asphalt, bitumen, and formaldehyde (Okken and Kram, 1990). Non-energy sources that release carbon relatively quickly include: ammonia production; naphthas; lubricants; LPGs and natural gas used as feedstocks; coke; and coals. Emissions were estimated for these products using the following assumptions about the percentage of carbon not sequestered in the product: for petrochemical feedstocks, LPGs, and naphthas 20%; for lubricants 50%; and for non-energy uses of natural gas 67% (OECD, 1991). For coals, coke, and coke oven gases used for non-energy purposes, it has been assumed that 100% of the carbon is emitted (See Section 7). Total emissions from non-energy uses of these substances were estimated to be 13.6 Mt in 1990.

2.1.5 Stripped Carbon Dioxide from Natural Gas

Another non-combustion source is CO_2 released during the production of natural gas. Natural gas in its raw state is most often *sour*, i.e., a mixture of several hydrocarbons (primarily CH_4), H_2S, H_2O, and CO_2 that occur in various ratios depending on the production field. During processing, almost all of the gases other than CH_4 are removed to produce the gas that is marketed. Once the higher molecular weight hydrocarbons are removed, the resulting gas is reacted with amine to remove CO_2 and H_2S. Natural gas can contain up to 26% CO_2 (Falls, 1991) at the well-head, although in most cases the CO_2 content is much lower. Based on analyses by the Energy Resources Conservation Board (Alberta Energy, 1990) and Westcoast Energy (Falls, 1991) of the CO_2 content of unprocessed gases and the CO_2 emissions resulting from stripping (on average about 7%), the quantity of CO_2 removed from natural gas during preproduction in 1990 was estimated to be 7.6 Mt.

2.2 Fuel Combustion - Stationary Sources

2.2.1 Power Generation

Total electrical generation in Canada fell to 465 967 GWh in 1990, continuing the downward trend set in 1989 (EMR, 1991b). Fossil-fuel derived electricity amounted to about 22% or 103 983 GWh of the total generation. Of this total, coal-fired stations contributed about 75%, oil-fired 14%, natural gas 9%, and other fuels 2%. Hydro-powered generation accounted for 63% of the total generation and nuclear about 15%. A small amount of tidal power was harnessed and generated 26 MWh (Energy, Mines and Resources, 1991). Nuclear and hydro-powered generation are not considered to be direct emitters of CO_2. However, there is concern that emissions of CH_4 and CO_2 may result from the flooding of land following the construction of hydroelectric dams. Research is being carried out to test this hypothesis (Fisheries and Oceans, 1992). Two basic systems are used to generate thermal power from fossil fuels: steam generation, and internal combustion (gas turbine and reciprocating engines). Steam turbine boilers are fired with coal, heavy fuel oil, crude oil, or natural gas (initial steam may be produced by light fuel oil, natural gas, kerosene, or diesel oil), whereas reciprocating engines use light oil, natural gas, a combination of both, or diesel oil.

Emissions of CO_2 were estimated from the quantities of fossil fuels consumed to produce electricity (by utilities and by industry), and by taking into account the type of fuel, its energy content, carbon content, and the fraction oxidized. These methods are described in detail in Section 7 and the emission factors are given in Table S.3. Based on these emission factors and the quantities of fuels consumed (42 155 kt of coal; 3 459 900 m^3 of heavy oil; 33 300 m^3 of light oil; 2.2×10^9 m^3 of natural gas; and 279 000 m^3 of diesel oil [Statistics Canada, 1991a]), total emissions of CO_2 from fossil-fuel generated electricity were estimated to be 93.9 Mt of CO_2 or about 20% of the total anthropogenic emissions in 1990.

2.2.2 Fuel Combustion

Industrial. The quantities of fuels consumed for industrial purposes in 1990 are reported in Table 4 (Statistics Canada, 1991a). This sector includes mining, pulp and paper, iron and steel, smelting and refining, and chemical manufacturing. Based on the emission factors derived for each fuel type (see Section 7), 1990 emissions were estimated to be 75.4 Mt of CO_2.

Commercial. Consumption of fuels for commercial use is reported in Table 4. Emissions were calculated by fuel type using the factors developed in Section 7, and shown in Table S.2, and were estimated to be 24 Mt in 1990.

Residential. Based on the consumption quantities reported in Table 4, emissions of CO_2 were estimated to be 40.7 Mt. As with the other sectors, the fuels consumed do not include those used for transportation.

Other Fuel. Included in this category are non-transportation fuels reported by Statistics Canada as consumed in agriculture, public administration, pipeline compressors, and in production of primary and secondary energy products. These fuels are shown in Table 4. Emissions for this category were estimated to be 52.7 Mt in 1990. Total emissions from all stationary combustion sources were estimated to be 286.6 Mt.

2.3 Fuel Combustion - Transportation Sources

Emissions of CO_2 from the combustion of fossil fuels used for transportation are discussed in this section. Figure 3 illustrates the relative contributions of CO_2 emissions from each mode of transport.

2.3.1 Gasoline-powered Road Motor Vehicles

This category includes emissions from all gasoline-powered vehicles driven on public roads, including automobiles, trucks, buses, and motorcycles.

The emission factor used to estimate emissions for all motor vehicles that consume gasoline is 67.98 t/TJ (see Subsection 7.2). The derivation of this factor is straightforward and assumes that a percentage of the carbon in the fuel is eventually emitted and forms CO_2. The fraction of carbon in the fuel that is released as CO ideally should be between 0.6% and 1.2% of the carbon released as CO_2 (Environment Canada, 1989). Although in actual use the percentage is higher, it was assumed that the fraction of carbon released as CO eventually forms CO_2. This agrees

Table 4 Fuel Consumption by Stationary Sources (1990)

Sources of Fuel Combustion	Coal (kt)	Natural Gas	Heavy Oil ($\times 10^6$ L)	Kerosene and Stove Oil ($\times 10^6$ L)	Propane ($\times 10^6$ L)	Light Oil ($\times 10^6$ L)
Industrial	1 641	36 655	3 894	50	934	301
Commercial	-	9 763	158	112	833	1 219
Residential	109	13 987	37	437	489	4 328
Other	7	4 707	111	90	279	278

with the methodology adopted by the IPCC (OECD, 1991).

Methane and other organics are released in much smaller quantities than CO_2 and their inclusion or exclusion will affect the estimates much less than any errors inherent in the emission factors. A more detailed discussion of the assumptions made is given in Section 7. The separation of emissions by vehicle type is much more difficult.

MOBILE4.1C is a computer model used to estimate emissions from different classes of vehicles. It is a Canadian version of the U.S. EPA's MOBILE4 model, which incorporates the results of emissions tests performed on more than 10 000 U.S. vehicles over the last 20 years to develop emission rates for different vehicle types and control technologies. By using normal in-use deterioration rates, and assumptions regarding average speeds, ambient temperatures, diurnal temperature ranges, altitude, fuel volatility, and technology penetration rates, emission factors were derived that reflect the current vehicle fleet in Canada. The model develops emission factors for NO_x, HCs, CO, and NMVOCs, but does not calculate estimates of CO_2 or N_2O. Therefore, emission estimates for the greenhouse gases have been developed in a different manner. MOBILE4 defines the various classes of vehicles as follows:

Light-duty passenger cars (automobiles) - any vehicle with a rated gross-vehicle weight of less than 3855 kg that is designed primarily to carry 12 or fewer passengers and does not possess special features such as four-wheel drive for off-road operation.

Light-duty gasoline trucks (LDGT) - vehicles, with a rated gross-vehicle

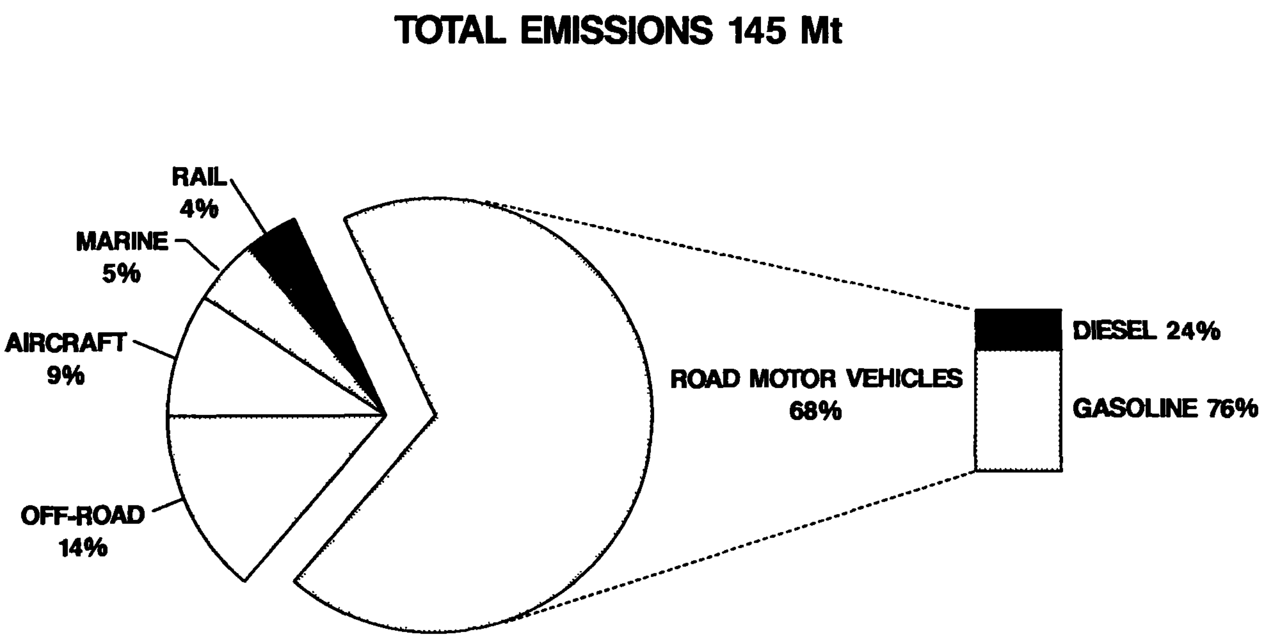

Figure 3 Carbon Dioxide Emissions - Transportation Sources

weight of less than 3855 kg, that are designed primarily for transportation of cargo or less than 12 passengers at a time, or that are equipped with special features for off-road operation. They include most pickup trucks, passenger and cargo vans, four-wheel drive vehicles and derivatives of these.

Heavy-duty gasoline vehicles (HDGV) - any vehicle with a manufacturer's gross-vehicle weight rating exceeding 3855 kg. This group includes large pickups and vans as well as the larger heavy-duty trucks that typically have gross-vehicle weight ratings of 8 t or more.

Based on fuel usage figures available in the Quarterly Report on Energy Supply and Demand (Statistics Canada, 1991a), emissions were broken down into on-road and off-road uses of gasoline. On-road uses accounted for approximately 93% and are assumed to be made up of road transport, retail pump sales, commercial uses, public administration, and a percentage of the gasoline reported to be consumed in agricultural uses. Off-road estimates include snowmobiles, lawnmowers, inboard/outboard marine engines, and forestry, agriculture, and construction equipment. To further segregate emissions within these categories, specifically the on-road group, some assumptions were made regarding vehicle miles driven and types of vehicles. The 1987 national estimates (Jaques, 1990) relied exclusively on Du Pont's Escon computer model to obtain average fuel efficiencies for fleets, and on earlier estimates by Environment Canada of average distances travelled and registration data (Statistics Canada, 1988). In light of more recent data, some of these factors were revised.

From 1979 to 1988, Statistics Canada and Transport Canada conducted a fuel consumption survey that, over the course of 11 years, examined personal-use passenger cars, light trucks, and vans. Unfortunately, certain types of vehicles such as rental cars, taxis, fleet-operated vehicles, driver-training vehicles, and antiques were excluded from the survey. As a result, the target population in 1988, estimated to be 8.2 million (Statistics Canada, 1990; Lawrence, 1991), represents only about 68% of the 11.9 million automobiles registered in Canada in 1988. It was necessary to assume that the fuel consumption figures obtained from these surveys were applicable to the entire automobile fleet. For vehicles not included in the fuel consumption survey, other sources of information were used to estimate fuel consumption.

Vehicle stock figures were estimated from data derived from new vehicle sales and deterioration rates (National Energy Board, 1991a,b). Distances travelled by vehicle type are based on weighted averages of provincial estimates (Terrillon, 1991) and fuel economy figures are based on technology-derived weighted averages of fuel consumption figures (Statistics Canada, 1991a; OECD, 1991; Terrillon, 1991; Lavallee and Terrillon, 1991).

To determine how well these factors represented the actual fleet, an indirect comparison was made by estimating the quantities of fuels consumed in 1990. A summary of the figures used in the calculations is shown in Table 5. Total on-road gasoline consumption was estimated to be 31.49 GL, whereas total gasoline consumption in 1990 was reported as 33.94 GL (Statistics Canada, 1991a). The difference, 2.45 GL, is in excellent agreement with the estimates of off-road gasoline consumption and provides some degree of assurance that the vehicle splits are reasonable.

The gasoline usage splits obtained from the preceding calculations were: automobiles 65.80%; light-duty trucks 31.03%; heavy-duty trucks 2.95%; and motorcycles 0.22%. These percentage splits were applied to the on-road gasoline figures for 1990. Total emissions from on-road, gasoline-powered vehicles in 1990 were estimated to be 75 Mt of CO_2.

To obtain a more refined estimate, this analysis should be done for each province. Total emissions will remain unchanged, but the splits between vehicle types will differ. It is even more important that this be done when calculating emissions of other gases, such as CH_4, N_2O, and the common pollutants, NO_x, VOCs, total particulate matter (TPM), and CO because emissions vary depending on the combustion technology used.

2.3.2 Diesel-powered Road Motor Vehicles

Emissions of CO_2 from all diesel-powered vehicles (automobiles, trucks, and buses) driven on public roads, were estimated using a methodology similar to that used for gasoline-powered road motor vehicles. Based on the splits obtained (Table 5), light-duty diesel vehicles (LDDV) - defined as diesel vehicles with a gross-vehicle weight rating of less than 3855 kg, and heavy-duty diesel vehicles (HDDV) - defined as diesel vehicles with a gross-vehicle weight rating exceeding 3855 kg (most have weight ratings of 10 to 40 t) accounted for 0.63% and 99.37%, respectively, of the total 1990 on-road diesel emissions of 22×10^6 t of CO_2.

2.3.3 Off-road Use of Gasoline

Gasoline consumed in off-road uses includes gasoline consumed by construction equipment, agricultural equipment, forestry equipment, and general utility equipment. Approximately 7% (2.4 GL) of the gasoline sold in Canada in 1990 was consumed by off-road vehicles. Emissions of CO_2 were estimated based on the general emission factor derived for gasoline (67.9 t/TJ) and calculated to be 5.6 Mt of CO_2.

2.3.4 Aircraft

The two main types of aircraft considered in this section are those with reciprocating (piston) and gas-turbine engines. Both types are further divided into subclasses depending on the size of the aircraft and the most commonly used engine for that class. The types of aircraft included in this section are

Table 5 Gasoline/Diesel Oil Consumption by Motor Vehicles (1990)

Vehicle	Population ($\times 10^6$)	Distance Driven (km)	Mileage (km/L)	Consumption (GL)	Percent of Total
Gasoline					
Automobiles	12.00	16 288	9.4	20.72	65.80
LDGT	3.60	16 440	6.1	9.77	31.03
HDGV	0.14	13 244	2.0	0.93	2.95
Motorcycles	0.36	2 860	14.1	0.07	0.22
Diesel					
LDDV	0.02	16 440	5.6	0.05	0.63
HDDV	0.25	82 869	2.5	8.32	99.37

jets, turboprops, piston-engined planes, and helicopters.

Emissions of CO_2 were estimated based solely on fuel consumption figures reported by Statistics Canada (1991a) and the emission factors derived in Section 7. The quantities of fuels consumed include only purchases made in Canada and include those made by both Canadian and foreign airlines. Although significant quantities of fuels may be consumed by Canadian airlines outside Canada's air space, and emissions over Canadian airspace are made by aircraft that purchased their fuel outside of Canada, no attempt was made to account for these emissions. Based on emission factors of 69.4 t/TJ and 70.8 t/TJ and fuel quantities of 164 ML and 5000 ML for aviation gasoline and jet fuel respectively, emissions of CO_2 were estimated to be 13.1 Mt in 1990.

2.3.5 *Rail Transport*

Emissions from rail transport are based on the quantities of fuels consumed in the production of energy for locomotion. Based on the quantities of diesel oil reported as consumed by railroads (Statistics Canada, 1991a), and an emission factor of 70.69 t/TJ or 2.79 t/kL, total emissions of CO_2 from rail transport were estimated to be 6.3 Mt or 1.4% of total emissions.

2.3.6 *Marine Transport*

In this section, only ships that use diesel oil and heavy oil are considered. Statistics on gasoline consumption for marine uses were not available from retail sales figures and, therefore, emissions from these sources are included in the off-road gasoline category. Based on emission factors of 70.69 t/TJ and 74.00 t/TJ for diesel oil and heavy oil, respectively, emissions were estimated to be 8 Mt of CO_2 in 1990.

2.3.7 *Other Diesel-powered Vehicles*

Carbon dioxide emissions from diesel-powered engines used in mining, manufacturing, forestry, public administration, construction, and agriculture were estimated by using a diesel-oil emission factor of 70.69 t/TJ and applying it to the quantities of fuels consumed by these industry sectors (Statistics Canada, 1991a). In 1990, total emissions from other diesel engines were approximately 36 Mt of CO_2.

2.3.8 *Other Fuel Uses*

In this category, emissions of CO_2 from the combustion of natural gas and propane were estimated based on figures of energy use for transportation purposes (Statistics Canada, 1991a), and emission factors of 49.68 t/TJ for natural gas and 59.84 t/TJ for propane. Insufficient information was available to split these emissions between different vehicle types. Total emissions from these sources in 1990 were estimated to be 1.7 Mt of CO_2.

2.3.9 *Miscellaneous Sources*

Other sources of CO_2 releases include, but are not limited to, dry ice, compressed CO_2, fire extinguishers, and carbonated drinks. Although these sources have not been quantified individually in this report, they are accounted for in the total emission estimates. In most cases, these sources obtain CO_2 from industry sales, for example CO_2 that is the by-product of the manufacture of ammonia. Therefore, they are accounted for under industrial processes and non-energy use of fuels.

2.4 *Recommendations for Future Work*

In terms of the accuracy of the current national estimates of CO_2, which have been developed based on provincial energy data, very little improvement will be obtained by further disaggregating the emissions. The estimates are based on the consumption of energy and the specific fuels consumed, therefore, improvements in the current CO_2 emissions inventory could be obtained from more detailed breakdowns of the current categories published by Statistics Canada. Statistics Canada (Smith, 1991) has access to statistics that are much more disaggregated and would provide clearer insight into the total emissions of specific industries. The level of detail currently published covers 63 industries and is aggregated over 28 final-demand categories, whereas at its lowest level of aggregation, data on as many as 216 different industries and 132 different final-demand categories are maintained (Smith, 1991).

If Canadian emissions could be examined in more detail, conservation programs could be targeted in the most appropriate and cost-effective manner. Therefore, it is recommended that government and industry continue to work together to ensure that the data are made available to develop full fuel-cycle emissions estimates in conjunction with national and provincial inventories. In addition, for CH_4 and N_2O, there are numerous areas in which the estimates need to be improved. Enlarging the data base of measured emissions is a first step and should be a priority.

Section 3

Biomass - Sources and Sinks

There is little doubt that biomass sources of CO_2 emissions, both anthropogenic (prescribed burning, wood and wood product combustion and decay, landfills, human and animal respiration, and fermentation) and natural (wild fires and decay), add CO_2 to the atmosphere. In fact, biomass contributes about 7% of Canada's energy needs (Boyle, 1992).

However, it is extremely important to note the fundamental difference between biomass and fossil-fuel sources of emissions. Bio-related sources have a sink term, whereas fossil sources do not (at least not on human timescales). The magnitude of this sink term is *directly related to the size of the source term*, assuming that sustainable practices are used. Furthermore, to a large extent, bio-related emissions would occur even in the absence of human intervention; the effect is largely on the timing of emissions (Apps, 1990; Taylor, 1990; Apps and Kurz, 1991). It is misleading to include the absolute biomass-related emission estimates in the totals. What is more appropriate is to treat fossil-fuel sources and bio-related sources and sinks separately and to examine the anthropogenically driven changes in these terms. A first attempt to develop a carbon budget for the forest sector has been made in Canada (Apps and Kurz, 1991) and this report includes the results of that model. Information on the net fluxes of carbon from agricultural practices and other anthropogenically driven fluxes is scarce.

Estimates of carbon losses, mainly as CO_2, from agricultural soils are not available (Benzing-Purdie, 1992). What is known is that converting land to agricultural practices can result in substantial losses of soil carbon, and that most soils currently under cultivation in Canada have lost about 50% of their original carbon content. It is highly probable that most of the carbon loss occurred within the first few years after cultivation and that most of the soils are now in a stable state (Agriculture Canada, 1990). Results of long-term studies at Lethbridge, Alberta, provide evidence for the positive effect of fertilizer application on organic matter reserves (Janzen, 1986; 1992). Soil analysis in 1990 suggested that nitrogen fertilizer application since 1967 had increased the organic carbon content in the surface soil layer by about 3 t/ha in a continuous wheat cropping system. The CO_2 emitted during the manufacture of the nitrogen fertilizer was approximately 0.5 t/ha, which resulted in a net sequestration of carbon in the soil. However, in fallow-wheat cropping systems (where response to nitrogen is much lower), the contribution of fertilizers to organic matter may be minimal, and the use of fertilizers in these unsound practices may result in a net increase in CO_2 emissions (Janzen, 1992). A carbon budget for the agricultural sector has not been developed because of a lack of data. Efforts are now being made to better understand the role played by agriculture (Benzing-Purdie, 1992).

In summary, the use of good management practices can sequester carbon and, in certain cases, offset any emissions caused by the production of fertilizers. Not to use nitrogen, when it is required, would in most cases be environmentally harmful because it would reduce the production of protective biomass.

Other sources of CO_2 released to the atmosphere include human and animal respiration and activities involving fermentation, such as the production of wines. Because the source of carbon is plant matter (foods and other farm crops), the net flux of carbon to the atmosphere from these sources is assumed to balance the carbon being sequestered annually by photosynthesis. Therefore, no estimates of either the sources or the sinks were made in this report.

3.1 Canadian Forest Sector

Global forest ecosystems account for approximately 50% (100 Mt C) of the annual exchange of CO_2 with the atmosphere and are huge carbon pools (about 1500 Mt C for soils and 650 Mt C for standing biomass) (Apps and Kurz, 1991).

To assess the role of Canada's forests, a comprehensive conceptual model of the carbon budget of Canadian forests and forest products was developed (Kurz *et al.*, 1991). The model draws heavily on existing data for forest biomass, soils, and forest-product carbon pools. Five disturbance regimes are simulated: wildfires; insect-induced stand mortality; clearcut logging; clearcut logging with slash burning; and partial cutting. The model includes spatial and temporal dynamics of four major carbon pools: forest biomass; forest soils; peatlands; and forest products. The data for forest biomass were compiled from the National Forest Biomass Inventory (Bonnor, 1985) and Canada's Forest Inventory 1986 (Forestry Canada, 1988). Forest-soil carbon dynamics include detritus and forest-floor carbon. The forest-products sector accounts for all of the wood harvested in the forest-biomass submodel and predicts the rate and form in which the carbon contained in this wood is released to the atmosphere. The model examines the fate of harvested biomass by tracking it through the forest-product sector and accounting for harvesting losses, transportation losses, processing losses in pulp and sawlog operations, and wood-product lifetimes. The fourth carbon pool examined by the model is peatlands. Details on the model are provided by Apps and Kurz, 1991, and Kurz *et al.*, 1991, 1992.

Table 6 contains the results of the carbon budget model of the Canadian forest sector (Kurz *et al.*, 1992), which uses forest-biomass data for 1986, and a 10-year average of forest fire data. A graph of the data is shown in Figure 4.

Table 6 Carbon Budget of Canadian Forest Sector (Mt Carbon)[a]

Carbon Pools	Sink	Source	Transfer	Net Change
Forest Biomass	92	-20	-99	-27
Forest Soils	17	-15	55	57
Forest Products	-	-23	44	21
Peatlands	26	-	-	26

[a] Positive numbers represent increases in carbon pools, negative numbers represent releases to the atmosphere or transfers to other carbon pools.

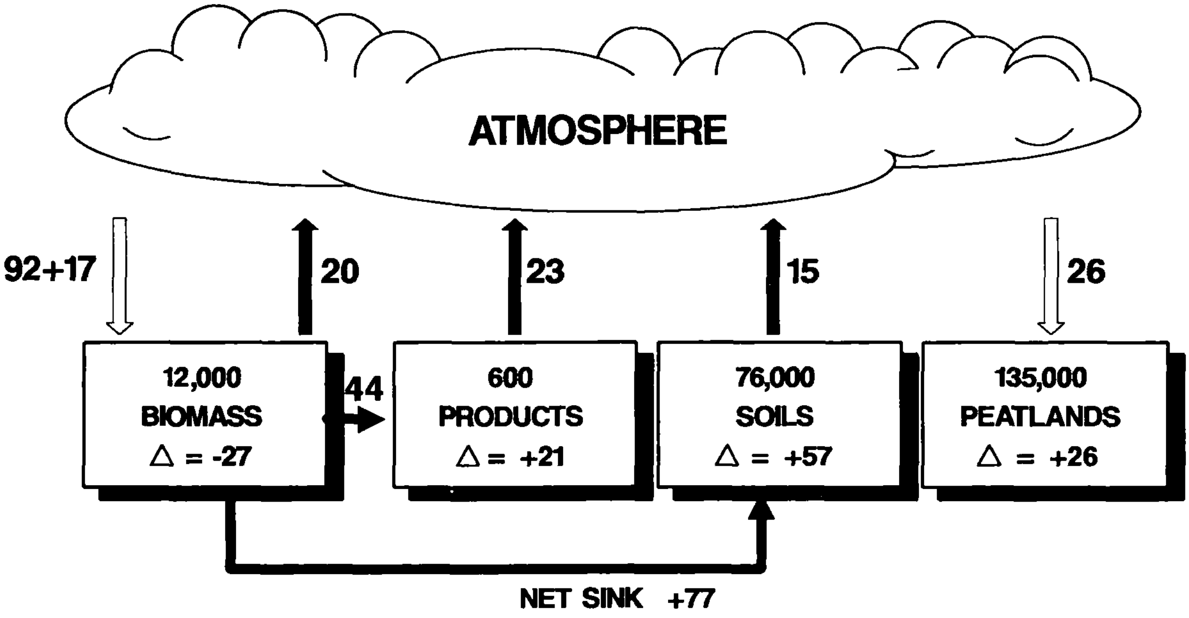

Figure 4 **Carbon Budget of Canadian Forest Sector (All estimates in Mt of Carbon)**

Canada has a total land area of 997 Mha, of which the total forest area is 453 Mha (about 45%). Of the total forested area, approximately 82% is in the boreal forest zone and 18% in the temperate zone (Vineberg and Boyle, 1991).

Statistics for the mid-1970s to the mid-1980s indicate that the change in forested area due to changes in land use is negligible, i.e., the net losses of 4.7 Mha of commercially stocked forested area was offset by an increase in the growing stock of the productive forest lands (Kuhnke, 1989; Vineberg and Boyle, 1991).

During the three-year period 1983-1984 to 1985-1986, approximately 1 965 353 ha of forest were harvested and 1 438 647 ha were regenerated by planting, seeding, and natural processes (Kuhnke, 1989). Annual forest growth rates in Canada vary from 0.2 m^3/ha to 5.7 m^3/ha with an overall average of 1.5 m^3/ha (Power, 1989). The growth rate of trees is a function of site and stand attributes such as species, structure, age, climate, water and nutrient availability, and silviculture practices and, therefore, varies throughout Canada.

3.2 Sources

The following estimates form part of the totals developed by the carbon budget model. Because of the current constraints on the output of the model and the way in which net fluxes, not absolute emissions and sinks, are estimated, some of the emissions have been estimated independently. Continued research is necessary to explore more fully the forest sector and obtain a more detailed carbon budget.

3.2.1 Spent Pulping Liquor and Hog Fuel

Emissions of CO_2 from the pulp and paper industry are mainly caused by the combustion of spent pulping liquors and wood waste (e.g., wood chips and bark). The two major chemical pulping processes are *sulphite*, which operates in a low pH (acid) environment, and *kraft*, which is alkaline. Although the chemical composition of the various possible cooking liquors cover broad ranges (Table 7), the most dominant process is the kraft process. Therefore, an average value between the acid sulphite and kraft processes has been taken as representative of the carbon content of spent pulping liquors. Quantities of spent pulping liquors were reported by Statistics Canada (1991a). Based on an average carbon content of 41% by weight in the spent pulping liquors, 19 423 kt of dry solids in the pulping liquors, and 95% conversion to CO_2, emissions of CO_2 from the pulp and paper industry were estimated to be 27.7 Mt.

Quantities of waste wood consumed for energy purposes in 1990 amounted to approximately 5531 kt (Statistics Canada, 1991a). Based on an emission factor of 1.5 kg CO_2/kg of wood, emissions were estimated to be 8.3 Mt of CO_2.

3.2.2 Prescribed Burning

Prescribed burning to enhance wildlife habitat and range, or to prepare sites following logging, is an important land management practice. Prescribed burning is used after logging (slash burning) primarily to obtain or enhance forest regeneration. Slash is also burned to reduce the hazard of forest fires and to control insects. Although slash burning produces significant amounts of CO_2, much of the carbon in the burned materials would eventually be released as CO_2 during decomposition, and much of the CO_2 is recovered by the new forest. Most prescribed burns consume the finer fuels and litter layers. These small, degradable materials would likely decompose within 1 to 10 years of the harvest. Most of the carbon from this decomposition would eventually be released as CO_2, but some would be incorporated into the soil layers. As a result, prescribed

Table 7 Composition of Pulping Waste Liquors (Rydholm, 1965)

	Acid Sulphite Rayon Pulp	Acid Sulphite Paper Pulp	Bisulphite Paper Pulp	Neutral Sulphite (Semi-chemical)	Kraft
Wood (%)	68	64	74	46	74
Waste Liquor (%)	13 to 17	12 to 16	14 to 18	9 to 11	17 to 22
Ash (% of Total)	10 to 12	12 to 14	18 to 20	35 to 45	35 to 45
Carbon (%)	43	40	35	29	42
Hydrogen (%)	5	5	4	4	5
Oxygen (%)	42	42	42	44	35
Sulphur (%)	6	8	11	8	3
Sodium (%)	4	5	8	15	15
Heat Value (Mcal/t Total Solids)	4 500	4 300	3 500	3 000	3 900

burning will not necessarily result in a net increase in atmospheric CO_2 in the long term (Forestry Canada, 1990a).

The emissions estimated in this report are based on a 10-year average of fires (i.e., 1980 to 1989) and are derived from information supplied by Forestry Canada (Stocks, 1990). Although they are the best data available, they are difficult to measure and vary considerably between regions. The emission factor for CO_2 used is 1500 g/kg of fuel consumed. The quantities of fuels consumed are shown in Table 8.

3.2.3 *Wildfires*

Wildfires (forest fires) are not considered anthropogenic sources of emissions. Nevertheless, they are a major source of CO_2 emissions to the atmosphere. Emissions estimates were developed by Forestry Canada (Stocks, 1990) and are based on the annual average area burned in each ecoclimatic region from 1980 to 1989. The estimates were developed using a CO_2 emission factor of 1500 g/kg and data on the quantities of fuel consumed in each region. Total annual emissions from wildfires in Canada were estimated to be 99 Mt (Table 9).

3.2.4 *Fuel Wood*

Wood burned for residential heating and energy use in industry are considered in this category. Estimates of the quantities consumed are based on the results of a study of the use of firewood for domestic heating and energy data provided by Statistics Canada (Energy, Mines and Resources, 1984; Statistics Canada, 1991a). Emissions were calculated using an emission factor of 1.5 kg/kg of wood consumed. The quantity of wood consumed by households in Canada in 1990 was estimated to be 11.4 Mt, whereas the reported consumption of wood waste was 5.4 Mt. Based on these quantities, total 1990 emissions of CO_2 were estimated at 25 Mt.

3.2.5 *Incineration*

The emissions from waste incineration that are covered in this section include: municipal refuse; industrial refuse; and wood waste. Efforts are continuing to determine the portion of the waste stream from municipal and industrial refuse that is not bio-related and should be included with non-renewable sources.

Municipal Refuse Incineration. Municipal incineration reduces the volume of solid

Table 8 Quantities of Fuel Consumed by Prescribed Burning

Province	Type	Area Burned (ha)	Fuel Consumption (kg/m^2)	CO_2 Emissions (Mt)
British Columbia	Silviculture	53 992	8.0	6.5
	Wildlife Habitat/ Range	44 205	2.0	1.3
Ontario	Site Conversion	3 384	8.1	0.4
	Harvest	4 308	5.9	0.4
Total		105 889		8.6

Table 9 Emissions of Carbon Dioxide from Wildfires

Ecoclimatic Region	Area Burned (ha × 10^3)	Fuel Consumption (kg/m^2)	CO_2 Emissions (Mt)
Boreal	1 760	2.5	66.0
Sub Arctic	560	1.8	15.1
Cordilleran	150	7.4	16.7
Grassland	9	0.3	0.0
Interior Cord	7	3.2	0.3
Cool Temperate	5	2.0	0.2
Sub Arctic Cord	3	2.0	0.1
Pacific Cord	2	14.2	0.4
Total	**2 496**		**98.8**

waste. Some incinerators are best suited to burn wastes with particular characteristics. Typical municipal refuse incinerators consist of either refractory-lined or water-walled combustion chambers with a grate on which refuse is burned.

The emission of CO_2 from the combustion of urban waste depends almost entirely on the carbon content and, therefore, the energy content of the waste. Based on an emission factor of 0.9 kg CO_2/kg of waste, the emissions from the 900 kt of municipal refuse that were incinerated in 1990 were estimated to be 0.8 Mt.

Sewage Sludge Incineration. Sewage sludge is a by-product of sewage treatment processes. In the incineration process, sludge is dried prior to combustion and the temperature is elevated to the ignition point. Air and auxiliary fuel may be required to support and maintain combustion. The residual inorganic ash is disposed of after it cools. Multiple-hearth furnaces were used at three incineration facilities, whereas fluidized-bed incinerators were used at all others. Based on an emission factor of 0.66 kg CO_2/kg of dry waste incinerated, emissions were estimated to be 0.07 Mt.

Industrial Incineration. Industrial and commercial incinerators are usually able to burn from 25 kg to 1800 kg of refuse per hour. The most common design has a multiple chamber in which gases from the primary chamber flow to a smaller secondary mixing chamber where excess air is admitted to promote more complete combustion.

It is assumed that approximately 75% of the waste is incinerated in multiple-chamber incinerators. The remainder is disposed of in controlled-air incinerators that operate by burning refuse in the absence of sufficient air for complete combustion. Emissions were estimated in a similar manner to emissions from municipal refuse, i.e., by using an emission factor of 0.9 kg CO_2/kg of waste. It was estimated that 0.5 Mt of CO_2 were released from the incineration of approximately 500 kt of waste.

Wood Waste Incineration. Wigwam burners are used to dispose of sawdust in the lumber and plywood industries. On the basis of lumber production, the amount of waste wood was estimated to be about 5000 kt, and by using an emission factor of 1.5 kg CO_2/kg of wood, emissions were estimated to be 7.5 Mt of CO_2 in 1990.

3.2.6 *Municipal Landfills*

Landfill gas, which is composed mainly of CH_4 and CO_2, is produced by anaerobic decomposition of organic degradable wastes. This process begins after the waste has been in the landfill for 10 to 50 days. Although the majority of CH_4 and CO_2 is generated within 20 years of landfill completion, emissions can continue for 100 years or more.

A number of important site-specific factors contribute to the generation of gases.

> **Waste Composition** - This is probably the most important factor affecting landfill gas-generation rates and quantities. Different types of wastes are known to decay at different rates, although the actual rates depend on site-specific conditions.
>
> **Moisture Content** - The amount of moisture within a landfill also has an important effect on gas-generation rates because a wet environment is required for anaerobic degradation.
>
> **Temperature** - Because anaerobic digestion is an exothermic process, landfill temperatures tend to be higher than ambient air temperatures. The extent to which ambient air temperatures influence gas-generation rates depends mainly on the depth of the landfill.
>
> **pH and Buffer Capacity** - The generation of CH_4 in landfills is greatest when neutral pH conditions exist. In acidic environments, the activity of methanogenic bacteria is inhibited.
>
> **Nutrients** - Certain nutrients are necessary for anaerobic digestion. These include carbon, hydrogen, nitrogen, and phosphorus. In general, municipal solid waste contains the nutrients necessary to support methanogenesis.
>
> **Refuse Density and Particle Size** - The particle size and density of the waste also influence gas generation because these factors affect the transport of nutrients and moisture throughout the landfill.

These factors act in combination to define the gas-generation capacity and the gas-generation rate constant for a landfill. Some of the landfill gas-generation rates reported in the literature are listed in Table 10. These values are for landfill gas, about half of which is CH_4. To determine the quantity of CO_2 released, it is assumed that 50% of the total gas emitted is CO_2.

The estimate for total CO_2 emissions for landfills in Canada is based on the results of the Scholl Canyon computer model (see Subsection 4.1.6), which was run to determine the quantities of CH_4 emitted from landfills across Canada. It was estimated that 3.9 Mt of CO_2 were released to the environment from decaying refuse in 1990.

3.3 *Sinks*

The major sinks of carbon in Canadian forest ecosystems have been described in the Carbon Budget Model of the Canadian Forest Sector [CBM-CFS] (Apps and Kurz, 1991) and are shown in Table 3. Because of the manner in which the model was designed (to estimate net carbon transfers between carbon pools), absolute sink and source terms are not readily available. Nevertheless, major sinks are the growing bio-stock, soils, oceans, and peatlands. Research is underway to further refine these estimates and to develop estimates for the agricultural sector.

Table 10 Reported Landfill Gas-generation Rates (McGuinn, 1988)

Source	Rate [m^3/(t • yr)]	Comments
1. Ramaswami (1970)	0.28 × 10^4	Lab studies - high percentage of readily biodegradable material
2. Rovers and Farquhar (1973)	0.07 × 10^2	Lab study - little CH_4 product
3. Augenstein *et al.* (1976)	0.05 × 10^4 max (0.17 × 10^2 avg)	Lab study - optimized conditions
4. DeWalle *et al.* (1978)	0.05 × 10^3 max (0.1 × 10^2 to 13 × 10^2 avg)	Lab study - little CH_4 product
5. Buivid (1980)	0.03 × 10^5 max (0.25 × 10^2 to 0.05 × 10^4 avg)	Lab study - optimized conditions
6. Pohland (1980)	0.03 × 10^3 max (2.0 × 10^1 avg)	Lab study - low % COD conversion
7. Emcon (1981)	0.07 × 10^2	Field pumping tests
8. Klink and Ham (1982)	0.26 × 10^3	Lab studies - high moisture % through leachate recycle
9. Jenkins and Pettus (1985)	0.04 × 10^3 (0.13 × 10^3 short-term max)	Incubation of field samples
10. Pacey and Dietz (1986)	0.03 × 10^3	Field control cell, Mountain View Project
11. Emberton (1987)	0.08 × 10^3 0.08 × 10^3	Lab (using field samples) Field
12. Barlaz *et al.* (1987)	0.02 × 10^3	Lab studies using 50% shredded fresh refuse with 50% oil refuse
13. Argonne National Lab (1988, unpublished)	0.2 × 10^2 to 0.14 × 10^3	Biochemical Methane Potential (BMP) assays of leachate from field samples
14. GSF Energy	0.08 × 10^2 (mean) 0.25 × 10^1 (mean min) 0.18 × 10^2 (mean max)	Test well data from 23 municipal landfills

Section 4

Methane Emissions

Emissions of CH_4 were estimated for both anthropogenic and natural sources. Each major source and the method used to estimate the CH_4 emissions is described. Because of the lack of measurement data, emissions were estimated using a top-down approach, i.e., they are national estimates, based on average emission factors, that may or may not be appropriate for certain regions within Canada. In addition, for some sources, such as sewage treatment plants, emissions estimates were not developed. However, efforts are being made to quantify these and any other sources that may have been omitted. Future national inventories will be built from the *bottom up* and will rely to a much greater extent on input from provincial governments and industry. A summary of CH_4 emissions in Canada is provided in Table 11.

4.1 Anthropogenic Sources

4.1.1 Coal Mining Operations

During the formation of coal, CH_4 is also produced. The CH_4 content of coal-beds depends on a number of factors including

Table 11 Summary of Methane Emissions in Canada (1990)

	Annual Emissions (kt of CH_4)	Percent of Total
Anthropogenic		
Municipal Landfills	1 405	37.61
Upstream Oil & Gas Operations	1 100	29.44
Domestic Animals	655	17.53
Manure	345	9.23
Sewage Treatment	-	-
Natural Gas Distribution	18	0.48
Coal Mining	143	3.83
Fuel Combustion	32	0.86
Stationary (9 kt)		
Transportation (23 kt)		
Prescribed Fires	38	1.02
Subtotal	**3 736**	**100.00**
Natural		
Wetlands	24 000	
Wild Fires	980	
Wild Animals	100	
Subtotal	**25 080**	
Total All Sources	**28 816**	

rank, pressure, temperature, degree of fracturing, the distance to outcrop, and the permeability of adjacent strata (Kim, 1978). Although the CH_4 content of undisturbed deposits generally increases with rank and depth, and decreases with temperature, permeability, and fracturing, the CH_4 content may vary significantly from predicted values based on such factors as rank or depth (Kim, 1978; Hollingshead, 1990).

Several estimates of CH_4 emissions from coal mining operations in Canada are available (Environment Canada, 1990; Masszi and Proudlock, 1990; Hollingshead, 1990). The estimate developed in this report is based on the work of Hollingshead (1990) and an analysis of this work by Stewart (1990). Although most of the coal mined in Canada comes from surface mines, which are mostly located in the western provinces, about 50% of the emissions come from deep mines in Cape Breton, which produce about 4% of the coal. The emission estimates given here are in the low end of the range of estimates given by Hollingshead (1990).

Any approach that estimates emissions of CH_4 from the perspective of coal-bed CH_4 as a natural gas supply component should take into account CH_4 desorption over time. In western Canada, coal mines are shallow and located in tectonically and glacially disturbed strata. This has resulted in significant CH_4 desorption over geological time. As a result, the standard curves of CH_4 adsorption versus depth for various coal ranks greatly overestimate the measured CH_4 contents found in western Canadian coal mines (Stewart, 1990).

Surface mines. In western Canadian surface coal mines, much of the CH_4 found in the shallow coal is residual gas that does not desorb. Eight borehole coal samples from the Genessee Mine had residual gas contents averaging 46% of the total CH_4 content. Similar large residual gas percentages have been found in other western Canadian coals. The emission estimates therefore assume that only 54% of the total CH_4 contained in western Canadian surface-mined coal is desorbable. Furthermore, surface coal mines remove overlying strata, which include carbonaceous material, and destress the underlying structure. Methane is released from both the overlying rock and underlying structure and the coal being mined. According to Hollingshead (1990), the total gas contained in surface-mined Canadian coal is 46.2×10^6 m^3. If only a fraction of the total gas is desorbable, for example 54%, the minimum emission estimate would be 25×10^6 m^3/year. Emissions from surface mines are presented in Table 12.

Emission estimates and emission factors were derived on the basis of approximately 64 000 kt of coal mined per year. The amount of CH_4 released from the coal was calculated as:

$0.54 \times 46.2 \times 10^6$ m^3/year $\times 0.72$ kg/m^3 $\times$ 10^{-6} t/kg = 17.96 kt/year.

The amount of CH_4 released from overlying rock and underlying structure was assumed to be approximately three times the mined-coal release: 3×17.96 kt = 53.89 kt. Therefore, the average emission factor is 1.12 kg CH_4/t of coal mined.

Underground Mines. Annual emissions from underground mines have been estimated at between 66×10^6 and 105×10^6 m^3 (Hollingshead, 1990). Stewart (1990) estimated annual releases at 90×10^6 m^3. Based on this information, CH_4 emissions from underground Canadian coal mines were estimated.

If approximately 3940 kt of coal are mined each year, the average emissions would be

Table 12 **Estimated Methane Emissions from Surface Mines (Hollingshead, 1990)**

Coalfield Mine	Estimated Emissions (× 106 m^3/year)		Coalfield Mine	Estimated Emissions (× 10^6 m^3/year)	
	Minimum	Maximum		Minimum	Maximum
British Columbia			Alberta		
Elk Valley Field			Cadomin-Luscar Field		
Fording River	9.3	56	Cardinal River	3.3	19
Westar Greenhills	6.3	38	Gregg River	3.1	18
Line Creek	4.2	25			
			Wabamun Field		
Peace River Field			Highvale	4.1	13
Quintette	3.7	17	Whitewood	1.0	3
Bullmoose	1.4	6	Genesee	0.5	2
Crowsnest Field			Coalspur Field		
Westar Balmer	5.9	28	Coal Valley	1.8	8
Coal Mountain	0.8	4			
			Obed Mountain Field		
Comox Field			Obed Marsh	0.9	4
Quinsam	0.0[a]	0			
			Smoky River Field		
Saskatchewan			Smoky River	0.1	3
Willow Bunch Field			Battle River Field		
Poplar River	0.0	0	Paintearth	0.2	1
			Vesta	0.1	1
Estevan Field					
Boundary Dam	0.0	0	Sheerness Field		
Utility	0.0	0	Montgomery	0.2	1
Costello	0.0	0			
Bienfait	0.0	0	Lethbridge Field		
			Kipp	0.0	0
New Brunswick					
Grand Lake Field					
Minto	0.0	0			
Subtotals	**31.6**	**174**		**15.3**	**73**
Total				**46.9**	**247**

[a] Explanatory notes for mines showing "zero" emissions

1. Comox Field (Quinsam Mine): low inferred CH$_4$ content (0.1 to 0.3 m^3/t); low production (0.35 Mt/year).
2. Lethbridge Field (Kipp Mine): no coal production.
3. Saskatchewan Fields (lignite mines): very low inferred CH$_4$ contents (0.0 to 0.1 m^3/t); maximum emissions are estimated to be in the order of 0.28 × 10^6 m^3/year.
4. Grand Lake Field (Minto Mine): very low inferred CH$_4$ content (0.1 to 0.2 m^3/t); low production (~0.5 Mt/year).

90×10^6 m^3/year or 64.8 kt/year (assuming a density of 0.72 kg CH_4/m^3). Therefore, the average emission factor is 16.45 kg CH_4/t of coal mined.

Based on the source and quantities of coal produced in Canada in 1990 (surface 64.4 kt; underground 4.0 kt) and these emission factors, 1990 emissions of CH_4 from coal mining activities in Canada were estimated to be 143 kt.

A summary of the detailed estimates developed by Hollingshead (1990) are given in Tables 12 and 13. The estimates in this report are based on further analysis of this work. For more information, the original sources should be consulted.

4.1.2 Upstream Oil and Gas Operations

In March 1992, the Canadian Petroleum Association (CPA) released a three volume report entitled "A Detailed Inventory of CH4 and VOC Emissions From Upstream Oil and Gas Operations in Alberta" (Picard *et al.*, 1992). This report provides a thorough assessment of the upstream sector and, although it is limited to Alberta, the results were used to develop estimates for all of Canada. The inventory was developed in three phases: preparation of a preliminary inventory; field validation of the key areas of uncertainty; and updating/finalization of the inventory.

The upstream sector was defined in the CPA report as: "all infrastructure ... used to find, produce, process/treat and transport natural gas, liquified petroleum gas, condensate, crude oil, heavy oil and crude bitumen". Excluded were emissions from heavy oil upgrading, oilsands mining and processing, and fuel consumption due to oilfield construction and transportation. Methane emissions were derived by applying species profiles to the THC estimates (see Table 14). Details on how the calculations were made are provided by Picard *et al.* (1992).

Unfortunately no detailed estimates are available for provinces other than Alberta. Future efforts will develop estimates for the rest of Canada at the level of detail used in the CPA report. Industry practices may be significantly different outside of Alberta and may produce much different levels of emissions. Nevertheless, for the purposes of this study, an estimate for Canada was developed by prorating the Alberta estimates using Canadian production figures (Statistics Canada, 1991a,b). Total Canadian emissions in 1990, including those associated with the production and transmission of natural gas, were estimated at 1100 kt of CH_4.

4.1.3 Natural Gas Distribution

Methane leakage from the natural gas industry is estimated to be between 0.3 and 0.5% of total gas production in Canada.

Emissions of CH_4 were estimated from an analysis of distribution losses reported by member companies of the Canadian Gas Association, (Canadian Gas Association, 1989; Wilson, 1990). The estimated leakage factor (0.3%) is likely low because Canadian facilities and systems are generally newer and of a higher quality than the worldwide average. The estimates from the transmission companies are based on production receipts, unaccounted leaks, and mainline pipeline and compressor station blowdowns. Distribution systems in Canada are continuously monitored using flame ionization techniques and the estimated leakage is 0.03%.

The Canadian Gas Association reports that total losses from production operations are about 0.25% of gross production. Using this leakage rate and gross natural-gas production figures for Canada for 1990, an estimate of 250 kt of CH_4 was derived. A comparison of this figure with the results in the CPA report

Table 13 Methane Emissions from Underground Operations (Hollingshead, 1990)

Coalfield/Mine	Measured Emissions			In-place CH_4 Content (m^3/t)	Total Estimated Emissions	
	Ventilation Per Unit Time (10^6m^3/year)	System "Specific" (m^3/t mined)	Methane Drainage (m^3/t mined)		Min. (10^6m^3/year)	Max. (10^6m^3/year)
Sydney						
Lingan	18 to 30[a]	—	4 to 5	7[b]	32	49
Phalen	20 to 34	—	—	2.5	23	39
Prince	7 to 11	—	—	2.5	10	15
Smoky River						
Smoky River	—	1.7 to 2.7[c]	—	—	1.4	2.3

[a] Values derived from figure quoted by Klanowski (1990). Quoted value (composite) for the three Sydney mines was 2 m^3/s (equivalent to $60 \times 10^6m^3$/year). This composite value was assumed to have an uncertainty of ±25% and was apportioned between the three mines in the ratio 45:40:15 for Phalen:Lingan:Prince mines based on relative levels of production and in-place CH_4.

[b] Percentage of CH_4 content retained by mined coal for release after mining is, for Sydney coals, about 90%, and for Smoky River coals, about 10%.

[c] Values derived from figure quoted by Kapur (1990). Quoted value was 2.24 m^3/t mined. An assumed uncertainty of ±25% yields the range of values in the table.

Table 14 **Methane Emissions from Upstream Oil and Gas Operations in Alberta (Picard *et al.*, 1992)**

Sector	Methane Emissions (kt)	Percent of Total
Drilling	5	0.62
Well Servicing and Testing	4	0.49
Gas Production	297	37.86
Conventional Oil Production	88	11.19
Heavy Oil Production	199	25.35
Crude Bitumen Production	19	2.43
Gas Processing	71	9.09
Product Transmission	38	4.78
Accidents and Equipment Failures	64	8.19
Total	**785**	**100.00**

(which is based on detailed analyses of the types of equipment used in Alberta, typical emissions associated with each piece of equipment, and the various operations used in gas-gathering systems, compressor stations, meter stations, and gas batteries), suggests that CH_4 leakage is underestimated. Unfortunately, the CPA study does not provide sufficient detail to disaggregate the estimates given in Table 14. Because the portion of the emissions attributable solely to leakage is unknown, only the downstream or distribution losses of CH_4 are presented in Table 11. A summary of CH_4 leakages from natural gas distribution is presented in Table 15.

4.1.4 Fuel Combustion

Emissions of CH_4 from mobile and stationary combustion sources are considered. The emission factors used to estimate these emissions have, for the most part, been developed by the U.S. EPA and were taken from several publications (NAPAP, 1987; U.S. EPA, 1985; OECD, 1991).

The vehicle classifications given in MOBILE4 (see Subsection 2.3.1) have been used to develop the emission estimates. The factors quoted in the Ad hoc Committee Report (Energy, Mines and Resources, 1990) were based on early species profiles that estimated CH_4 to be 10% of THCs for motor gasolines and 5% of THCs for diesel fuel. These factors overestimate emissions by as much as a factor of three. The factors used in this report are shown in Table 16. Emission estimates were made in a similar way to the estimates for CO_2 in Section 2.3, and are based on gasoline consumption figures (Statistics Canada, 1991a) and a breakdown of vehicle emission controls by vehicle type (Terrillon, 1991) (Table 17).

Emissions of CH_4 were estimated for Canada on the basis of a weighted average breakdown of vehicle types and emission controls, and the same vehicle efficiencies and fuel consumption patterns used to calculate emissions of CO_2. To improve the estimates, they should be developed by using the different fuel consumption patterns in each province. On-road vehicle emissions were

Table 15 Methane Leakage from Natural Gas Distribution[a]

		CH_4 Emission (kt)
Gross Production	138 890.5 GL[b] (Production Leakage 0.25%)	250
Marketable Production	98 770.8 GL[b] (Transmission Leakage 0.03%)	21
Distribution Leakage	(50% of Marketable Production × 0.05%)	18
Density of CH_4	0.72 kg/m^3	
Total		**289**
Average Emission Factor	2.08 g CH_4/m^3 of natural gas produced	

[a] Source: Canadian Gas Association (1989).
[b] Source: Statistics Canada (1991b).

estimated by converting the gram per mile emission test results to gram per kilogram emission factors and then multiplying by the appropriate national consumption figures. A sample calculation is shown in Table 18.

Other Transportation Sources. Emissions from all other transportation sources (rail, marine, and aircraft) were estimated on the basis of the fuels consumed in each category (Statistics Canada, 1991a) and the appropriate emission factors for each source (Table 19). Total emissions of CH_4 in 1990 from transportation sources were estimated to be 23 kt and their distribution is shown in Figure 5.

Stationary Fuel Combustion Sources. Stationary sources also release small quantities of CH_4 because of incomplete combustion. The sources considered in this category include industrial, commercial, residential, and power generation. Emission factors were taken from U.S. EPA (1985) and are given in Table 20. Total emissions were estimated to be 9 kt, and wood combustion accounted for about 2.5 kt.

Fuel Wood Combustion - For residential wood combustion, fuel usage breakdowns were derived from Roche et Associés (1983), who give percentages of wood consumed in the four main types of fuelwood combustion devices commonly used in Quebec. The emission factors are taken from U.S. EPA (1985) and the quantities of fuel are derived from a study of wood use for domestic heating (Energy, Mines and Resources, 1984) (Table 21).

Waste wood is also consumed by industry for energy (Statistics Canada, 1991a). In 1990, approximately 5500 kt of wood waste were consumed, and based on an emission factor of 0.15 g/kg, CH_4 emissions were estimated to be 0.8 kt.

4.1.5 Incineration

The methods of incineration currently used in Canada are described in Subsection 3.2.5. Emission factors for wood waste and municipal solid waste were taken from U.S. EPA (1985) (see Table 20) and were used to estimate 1990 emissions of CH_4 as 1 kt.

4.1.6 Municipal Landfills

As discussed in Subsection 3.2.6, landfill gas, which is composed mainly of CH_4 and CO_2, is produced by the anaerobic decomposition

Table 16 Methane Emission Factors - Motor Vehicles

Source	Fuel Consumption	Emission Factors		
	(km/L)	(g/km)	(g/kg)	(kg/TJ)
Automobiles				
Advanced 3-way Catalyst	11.9	0.02	0.32	6.92
Early 3-way Catalyst	9.4	0.04	0.50	10.82
Oxidation Catalyst	6.0	0.09	0.72	15.58
Non-catalyst	6.0	0.17	1.38	29.86
Light-duty Trucks				
Advanced 3-way Catalyst	9.4	0.04	0.50	10.80
Early 3-way Catalyst	6.8	0.07	0.64	13.85
Oxidation Catalyst	5.1	0.09	0.61	13.24
Non-catalyst (Gasoline)	5.1	0.17	1.16	25.02
Heavy-duty Vehicles				
3-way Catalyst	2.9	0.10	0.38	8.22
Non-catalyst	2.8	0.17	0.65	14.07
Uncontrolled	2.0	0.37	1.02	21.36
Motorcycles				
Non-catalytic Control	14.9	0.15	2.98	64.46
Uncontrolled	12.8	0.33	5.60	12.41
Light-duty Trucks				
Advanced Control	7.7	0.01	0.09	1.99
Moderate Control (Diesel)	5.1	0.01	0.06	1.32
Uncontrolled	4.3	0.02	0.10	2.22
Heavy-duty Vehicles				
Advanced Control	2.8	0.06	0.19	4.33
Moderate Control	2.8	0.07	0.23	5.24
Uncontrolled	2.2	0.10	0.25	5.70

of organic degradable wastes. A number of site-specific factors combine to determine the quantity of CH_4 that is generated by a given landfill.

Emission Estimates. Methane emissions from landfills in Canada were estimated using the U.S. EPA CH_4-generation (Scholl Canyon) model and data on the quantity of refuse deposited each year in Canadian landfills over the past 50 years (Levelton and Associates, 1991).

In Canada, there are approximately 9987 identified landfill sites. To estimate CH_4 emissions, detailed information on the

Table 17 Distribution of Catalyst-equipped Vehicles in Canada (1990)

Province	Advanced 3-way	3-way Catalyst	Oxidation Catalyst	Non-catalyst
Alberta	0.309	0.034	0.456	0.202
British Columbia	0.266	0.029	0.423	0.281
Manitoba	0.303	0.034	0.457	0.206
New Brunswick	0.424	0.044	0.394	0.138
Newfoundland	0.446	0.049	0.370	0.135
Nova Scotia	0.422	0.047	0.387	0.144
Ontario	0.426	0.047	0.398	0.129
Quebec	0.474	0.053	0.354	0.119
Saskatchewan	0.323	0.036	0.452	0.189
Canada	0.394	0.044	0.401	0.161

Table 18 Sample Calculation of Methane Emissions from Gasoline-powered Automobiles

Gasoline Automobiles	
Gasoline Consumption	20.72 GL
Advanced 3-way	15.54×10^9 kg $\times$ 0.394 $\times$ 0.32 g/kg = 1.96×10^9 g CH_4
3-way Catalyst	15.54×10^9 kg $\times$ 0.044 $\times$ 0.50 g/kg = 0.34×10^9 g CH_4
Oxidation Catalyst	15.54×10^9 kg $\times$ 0.401 $\times$ 0.72 g/kg = 4.49×10^9 g CH_4
Non-catalyst	15.54×10^9 kg $\times$ 0.161 $\times$ 1.38 g/kg = 3.45×10^9 g CH_4
Subtotal	10.24 kt CH_4

Table 19 Emission Factors for Other Transportation Sources[a]

Rail	(Diesel)	5.7 kg/TJ
Off-road	(Gasoline)	4.1 kg/TJ
Marine	(Diesel)	5.7 kg/TJ
Air	(Aviation Gas)	60.0 kg/TJ
Jet Fuel		2.0 kg/TJ

[a] Sources: U.S. EPA (1985); OECD (1991).

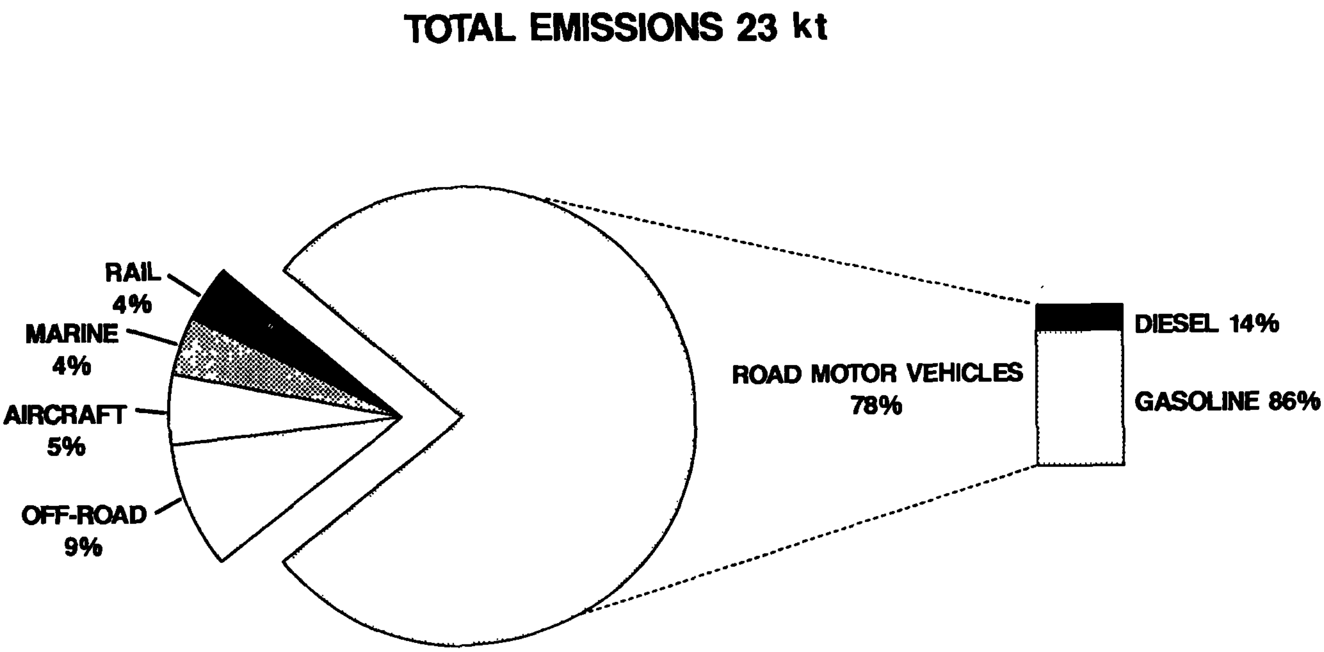

Figure 5 Methane Emissions - Transportation Sources

following items, in both active and inactive sites, is needed: date the landfill was opened; date closed; amount of municipal solid waste (MSW) disposed every year; total amount of MSW on site; and amount of CH_4 collected if the landfill has a gas-recovery system.

In many cases, this information was not available. Therefore, the following approach was taken to obtain a reasonable estimate of emissions.

(1) The population (P) of the provinces and territories for the period 1941 to 1990 was obtained from Statistics Canada.

(2) MSW disposed per capita was obtained from the published literature.

(3) The amount of MSW incinerated over this period was determined from the relevant municipalities.

(4) Major municipal landfills were asked to provide information such as the date the landfill was opened, date closed, MSW disposed each year, the population served, and the amount of gas collected.

(5) The climate at each landfill site, including mean daily temperature and yearly precipitation, was used to estimate a value of the kinetic rate constant (k) for the Scholl Canyon model.

In 1990, the MSW generation rate per capita was estimated to be 1.75 kg/day, whereas the average reported moisture content of the MSW received was 24.4%, which meets the minimum limit for anaerobic biodegradation.

The Scholl Canyon model requires two input parameters, L_0, the potential CH_4 generation capacity of the refuse, and k, the kinetic rate

Table 20 Stationary Source Methane Emission Factors

Source	Gross Energy Content	Emission Factors	
	(TJ/10^{6}m^3)	(kg/10^{6}m^3)	(kg/TJ)
Natural Gas	37.78		
Utility Boiler		4.80	0.13
Industrial Boiler		48.00	1.27
Domestic/Commercial		43.00	1.14
	(TJ/10^{3}m^3)	(kg/10^{3}L)	(kg/TJ)
Residual Oil	41.73		
Utility Boilers		0.03	0.72
Industrial Boilers		0.12	2.88
Commercial Boilers		0.06	1.37
Distillate Oil	38.68		
Utility Boilers		0.006	0.16
Industrial Boilers		0.006	0.16
Commercial Boilers		0.026	0.67
Residential Boilers		0.214	5.53
LPGs	25.53		
Industrial Boilers		0.03	1.18
Domestic Boilers/Heaters		0.03	1.18
	(TJ/kt)	(g/kg)	
Wood	18.00		
Fuel Wood		(0.15 to 0.5)	(0.01 to 0.03)
Wood Waste		0.15	77.00
Municipal Incineration	10.60	0.23	0.02
Coals	(14.31 to 29.12)	0.015	(1.05 to 0.52)

Table 21 Emissions of Methane from Fuelwood Combustion

Combustion Device	Fuel Consumed	CH_4 Emission Factor (g/kg)	Emissions (t)
Conventional Stove	0.243 × 11 400 kt	0.20	555
Slow Combustion	0.118 × 11 400 kt	0.50	672
Fireplace	0.475 × 11 400 kt	0.01	54
Furnace	0.164 × 11 400 kt	0.15	281
Total			**1 562**

constant. The higher the cellulose content of the refuse, the higher the value of L_0. In addition, the calculation of CH_4 emissions requires information on the chemical composition of the MSW, the MSW disposal history, and the efficiency of any gas-collection system.

Values of L_0 range from 60 to 270 m^3 CH_4/Mg refuse (McGuinn, 1988). The default value of L_0 used in this report is 232 m^3 of CH_4/t. The CH_4 kinetic rate constant, k, represents the first order rate at which CH_4 generation decreases from the time of refuse placement. The higher the value of k, the higher the decrease in CH_4 generation rate with time. The value of k is affected by four major factors: refuse moisture content; availability of nutrients for methanogens; pH; and temperature. A wide range of values of the potential methane generation capacity of refuse has been reported (Table 22). Typically, 50 to 60% of the landfill-gas volume is CH_4. For these estimates, it has been assumed that 50% of the landfill gas is CH_4 and 50% CO_2.

Values of k for specific landfill sites were determined by considering average annual precipitation and mean daily temperature.

In 1990, 2106.9 × 10^6 m^3 of CH_4 (1405 kt) were emitted to the atmosphere from landfills. This figure excludes the 205 kt portion of CH_4 generated and captured. This estimate is about 22% lower than one derived using the simple methodology described by Bingemer and Crutzen, (1987). A crude CH_4 emission rate (65.96 kg CH_4/t MSW) can be derived based on the emissions calculated by the Scholl Canyon model and the quantity of MSW generated (21.3 Mt).

Table 23 summarizes Canadian estimates of CH_4 emissions and includes the amounts recovered by gas collection systems (Levelton and Associates, 1991). Because there are insufficient data, no estimates of CH_4 emissions were made for landfilled wood wastes or pulping wastes.

4.1.7 Domestic Animals

The anaerobic microbial fermentation of carbohydrates in the digestive system of animals produces CH_4. The CH_4 produced represents a loss of energy to the animal. The mechanisms of CH_4 production in the rumen have been studied extensively (Baldwin and Allison, 1983); however, there is very little experimental data on CH_4 emissions from farm animals.

Table 22 Quoted Values of Potential Methane Generation Capacity of Refuse (McGuinn, 1988)

Estimation Method[a]	Estimated L_0 (m^3 CH_4/t)	Assumptions Made
1. Balanced Stoichiometric	230 to 270	Chemical composition of composite refuse ($C_{99}H_{149}O_{59}N$), and paper ($C_{203}H_{334}O_{138}N$) and food wastes ($C_{16}H_{27}O_8$)
2. Biodegradability of Materials	6 to 230 47 (average)	Assumes 1.5 kg biodegradable COD/kg volatile solids and 351 L/kg biodegradable COD
3. Biodegradability of Materials	47 (average)	Wet, composite refuse is 70% decomposable organics; 50% of decomposable organics is volatile; 375 L gas/kg volatile matter; 50% of gas is CH_4
4. Biodegradability of Materials	120	Wet, composite refuse is 70% decomposable organics: 70% decomposable organics converted to gas; 690 L gas/kg dry decomposable organics, 25% moisture content; 50% of gas is CH_4
5 Total Organic Content	190 to 270	1 mol organic carbon yields 1 mol gas; CH_4 is 50% of gas produced, 100% of organic carbon is converted to gas
6. Stoichiometric Equation	210	For overall municipal solid waste
7. Stoichiometric Equation	229	For overall municipal solid waste
8. Weighted Biodegradability	170	—
9. Weighted Biodegradability	91	—
10. Weighted Biodegradability	119	—
11. Weighted Biodegradability	59	—

[a] Entries 1 through 5 are based on Mg of wet refuse, whereas entries 6 through 11 are based on Mg of dry refuse. Entries 1 through 5 were not converted to a dry refuse basis because percentage moistures were not known.

Table 23 Provincial Methane Emissions from Landfills (1990)

Province/Territory	Generated	Recovered	Emitted	
	(t)	(t)	(t)	(× $10^6 m^3$)
Newfoundland	27 105	0	27 105	40.6
Nova Scotia	42 186	0	42 186	63.2
Prince Edward Island	5 267	0	5 267	7.9
New Brunswick	34 954	0	34 954	52.4
Quebec	324 957	68 590	256 367	384.3
Ontario	786 465	112 018	674 447	1 010.9
Manitoba	32 726	1 649	31 077	46.6
Saskatchewan	31 368	0	31 368	47.0
Alberta	74 249	1 086	73 163	109.7
British Columbia	250 631	22 005	228 625	342.7
Northwest Territories	655	0	655	1.0
Yukon	331	0	331	0.5
Canada	**1 610 891**	**205 348**	**1 405 543**	**2 106.8**

The range of CH_4 generation rates from animals varies considerably and depends (in dairy cattle) on diet, metabolic live weight, and milk production (Kirchgessner *et al.*, 1991). Because the CH_4 production rate depends on such a large number of variables, including energy intake, enteric ecology, and energy expenditure of the animal, and is also affected by factors, such as quantity and quality of feed, body weight, age, and exercise, the figures for CH_4 emissions from livestock must be considered as preliminary estimates (Table 24).

Emission estimates were based on the quantity and quality of feed available in Canada and the animal populations. The emission rates used in this report are based on the results of several studies (Crutzen *et al.*, 1986; Kirchgessner *et al.*, 1991; Blaxter and Clapperton, 1965) reported by Kinsman (1992). The rates fall within the middle of the CH_4 generation ranges reported in the literature. Crutzen *et al.* (1986) estimate that about 5 to 9% of the gross energy intake of ruminants is lost to CH_4 production. Emission rates were derived by assuming that a certain percentage of the digestible energy (DE), i.e., the difference in gross energy intake and the energy remaining in the feces, is lost as CH_4. In poultry, urine and feces are excreted together. Therefore, energy requirements of poultry are normally expressed as metabolized energy (ME), and CH_4 production as a percentage of their ME. Methane emissions by animal type are shown in Figure 6.

4.1.8 Manure

The methodology used to estimate emissions of CH_4 from animal manures was taken from Casada and Safley, Jr. (1990). To develop their estimates for Canada, they relied on information about existing waste management systems from provincial departments of agriculture .

The potential for CH_4 production is directly related to the amount of volatile solids present

Table 24 Methane Production by Domestic Animals (1990)

Animal		Population (× 10^3)	CH_4 Annual Production (kg/head)	Total Emissions (kt)
Horses		340	18.00	6
Mules		4	10.00	<1
Cattle				
Bulls		237	120.00	28
Dairy Cows		1 379	120.00	165
Beef Cows		3 590	48.00	172
Dairy Heifers		644	72.00	46
Beef Heifers		741	36.00	27
Heifers for Slaughter		627	36.00	23
Steers		1 213	48.00	58
Calves		3 854	24.00	93
Pigs				
Boars		65	5.00	<1
Sows		1 045	5.00	5
Pigs	(<20 kg)	3 238	1.00	3
Pigs	(20 to 60 kg)	3 230	2.00	7
Pigs	(>60 kg)	2 955	3.00	9
Sheep		399	10.00	4
Lambs		360	6.00	2
Goats		64	5.00	<1
Poultry				
Chickens		61 642	0.00	<1
Hens		21 336	0.02	<1
Turkeys		7 372	0.01	<1
Humans		26 000	0.05	1
Total				**655**

in the animal waste. To quantify the CH_4 production rate from the waste, the effect of animal type on CH_4 production must be determined. The live weight, the total manure produced, the total quantity of solids, and the total quantity of volatile solids all affect CH_4 production.

The amount of CH_4 that could potentially be produced from the volatile solids in the waste of each type of animal was determined from published reports. For animals for which no published information was available, estimates were derived by assuming similarities with other animals. Potential CH_4 generation rates were based on the typical diet of each type of animal.

Based on information about livestock and poultry populations in Canada and the types of waste management systems in use, CH_4 emissions in 1988 were estimated as 332 kt (Casada and Safley, Jr., 1990). A summary of the emission factors used for each type of animal and their emissions is given in Table 25.

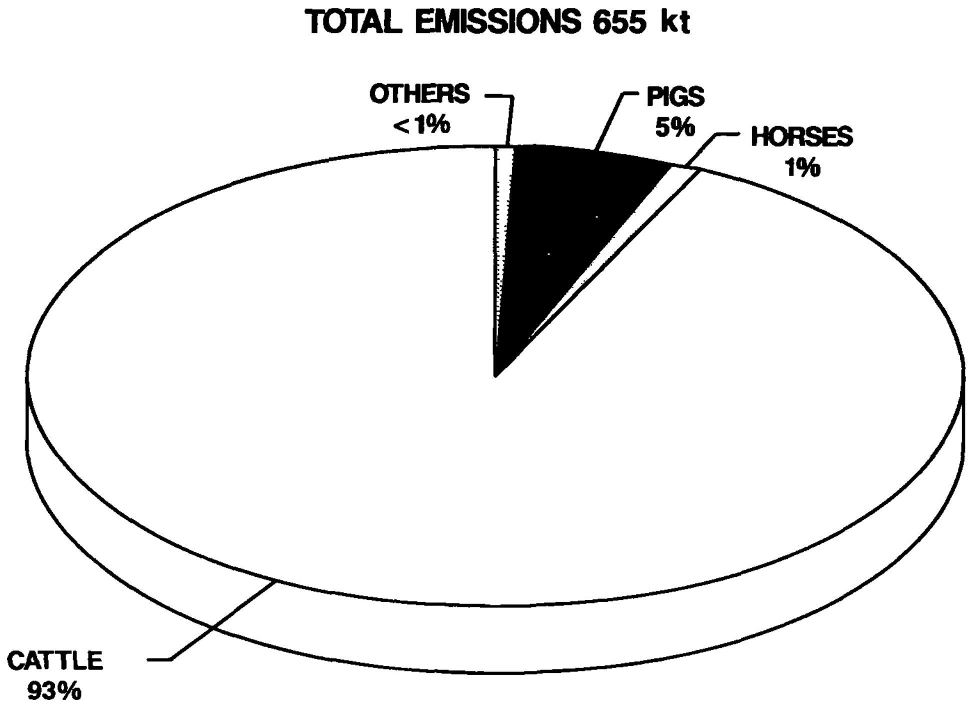

Figure 6 Methane Emissions by Animal Type

Table 25 Emissions of Methane from Manure

Animal Wastes/ Manure	Population in Canada (× 10^3)	Volatile Solids Production (× 10^3t/year)	Methane Conversion Factors[a]	Emissions (kt/year)
Horses	340			0.00
Mules	4			0.00
Cattle - Dairy	2 023	2 260.50	0.019	86.89
Cattle - Beef	10 262	1 103.80	0.011	124.60
Pigs - Breeding	2 000	561.50	0.043	48.29
Pigs - Market	8 533	140.30	0.044	52.68
Sheep and Lambs	759	338.80	0.019	4.89
Goats	64			0.00
Poultry				
Chickens	61 642	5.60	0.024	8.15
Hens	21 336	7.90	0.018	3.03
Turkeys	7 372	22.60	0.019	3.17
Total Manure Emissions				**331.70[b]**

[a] Methane conversion factor (kt CH_4/1 000 population/kt volatile solid).
[b] Estimate for 1990 is 345 kt.

4.1.9 *Prescribed Fires*

Methane emissions from prescribed fires and slash burning are considered in this section. The emissions are based on a 10-year average of fires (i.e., 1980 to 1989) and are derived from information supplied by Forestry Canada (Stocks, 1990; Radke *et al.*, 1991; Taylor, 1992). The CH_4 emission factor of 5 g/kg of fuel consumed that is used in this report is the median of measured values that range from 3.3 g/kg to 6.6 g/kg. The quantities of fuels consumed in prescribed fires are shown in Table 26.

4.2 *Natural Sources*

4.2.1 *Wetlands*

The methodology used to estimate CH_4 emissions from wetlands is based on work done by Matthews and Fung (1987). Methane emissions were calculated using CH_4 fluxes for the major wetland groups and simple assumptions about the duration of the CH_4 production season. Because of the large degree of uncertainty in CH_4 flux rates and wetland information, the flux rates developed by Matthews and Fung were reduced by 25% for Canada (Fung *et al.*, 1991). In addition, in more recent studies of northern wetlands, especially bogs, the CH_4 emission rates are significantly lower than those reported by Mathews and Fung (Moore and Knowles, 1990; Vitt *et al.*, 1990; Naiman *et al.*, 1991; Price, 1991). The national emission estimates given in this report may have to be modified when the rates and classifications proposed by Price (1991) are evaluated.

Methane flux rates were developed for several major wetland ecosystems (Table 27). The growing season was assumed to be 100 days for northern latitudes, i.e., greater than 60°N, and 150 days for latitudes between 30°N and 60°N. Information on wetland areas and type was taken from "Wetlands of Canada" (Canadian Wildlife Service, 1988). Methane emissions from wetlands in 1990 were estimated to be 24 Mt.

4.2.2 *Wildfires*

Emissions of CH_4 from forest fires in Canada were estimated by using the same methodology used to develop estimates for prescribed burning (Stocks, 1990) and an emission factor of 5 g/kg of fuel consumed (Radke *et al.*, 1991). The estimates of the quantities of fuel consumed were based on the areas burned in each ecosystem over the last 10 years and fuel consumption rates for each ecoclimatic region (Table 28).

4.2.3 *Wild Animals*

The energy requirements of wildlife are not as well defined as the energy requirements of domesticated animals. Based on the assumption that the production of CH_4 by wildlife and domestic animals is similar, i.e., 9% of (DE) intake, emission rates were developed (Crutzen *et al.*, 1986; Hicks, 1991). Emissions were estimated for those animals for which population estimates were readily available.

Based on a range of percentage DE intake from 6.7 to 14.3%, the following annual CH_4 generation rates were developed: deer 5 kg/head; sheep 6 kg/head; caribou 9 kg/head; elk 14 kg/head; and moose 17 kg/head (Hicks, 1991). Emissions from wild animals were estimated to be 100 kt.

Table 26 Fuels Consumed in Prescribed Burns

Province	Type	Area Burned (ha)	Fuel Consumption (kg/m^2)	CH_4 Emissions (kt)
British Columbia	Silviculture	53 992	8.0	21
	Wildlife Habitat/ Range	44 205	6.4	14
Ontario	Site Conversion	3 384	8.1	1.4
	Harvest	4 308	5.9	1.2
Total		**105 889**		**37.6**

Table 27 Methane Flux Rates for Wetland Ecosystems

		Ecosystem	Annual Flux Rate (g CH_4/m^2)
Fung *et al.* (1991)	1.	Forested and Non-forested Bogs	22.5
	2.	Forested Swamp	7.5
	3.	Non-forested Swamp	13.5
	4.	Alluvial Formations	3.0
Price (1991)	1.	Beaver Ponds	15.0
	2.	Marsh	20.0
	3.	Fens and Swamps	5.0
	4.	Bogs	0.5

Table 28 Emissions of Methane from Wildfires

Ecological Region	Area Burned (ha)	Fuel Consumption (kg/m^2)	CH_4 Emissions (kt)
Boreal	1 760 000	2.5	220
Sub Arctic	560 000	1.8	50
Cordilleran	150 000	7.4	57
Grassland	9 000	0.3	-
Interior Cord	7 000	3.2	-
Cool Temperate	5 000	2.0	-
Sub Arctic Cord	3 000	2.0	-
Pacific Cord	2 000	14.2	-
Total	**2 496 000**		**327**

Section 5

Nitrous Oxide Emissions

Emissions of N_2O were estimated for both anthropogenic and natural sources. These are summarized in Table 29. Each major source and the method used to estimate the quantity of N_2O emitted is described. All estimates reported as N refer only to the nitrogen component of N_2O. Emission estimates given in the summary tables are shown on a full molecular basis as N_2O.

5.1 Anthropogenic Sources

5.1.1 Combustion Sources

Nitrous oxide is produced directly from the combustion of fossil fuels, although the mechanisms that cause N_2O formation are not completely understood. Recent studies (Muzio and Kramlich, 1988; Linak *et al.*, 1989) indicate that emissions data measured at stationary combustion sources before 1988 are inaccurate and greatly overestimate emissions unless the stored samples are dried, and any SO_2 removed, or N_2O measurements are made immediately. These recent findings bring into doubt the findings of Hao *et al.*, (1987), that suggest a relationship between N_2O and fuel nitrogen or N_2O and NO_x. More recent measurements have shown that stationary source emissions are much lower than previously thought.

Nitrous oxide formation in internal combustion engines is also not well understood. Uncontrolled engine exhaust emissions contain very little N_2O. Prigent and De Soete (1989) show that N_2O represents less than 1% (between 0.4 and 0.75%) of the overall NO_x emissions from either gasoline or diesel engines without catalytic converters. However, N_2O is produced when NO and NH_3 react over the platinum in catalytic converters (Otto *et al.*, 1970). The production of N_2O is highly temperature-dependent. Prigent and De Soete (1989) found that new platinum-rhodium 3-way catalysts (TWCs), which are used to decrease NO_x emissions, could increase the N_2O concentration in the exhaust during catalyst light-off, but produced very little N_2O at medium temperatures (400 to 500°C).

Several studies report emissions of N_2O from cars equipped with and without catalytic converters (Dasch, 1992; Urban and Garbe, 1980; Prigent and De Soete, 1989; De Soete, 1989; Prigent *et al.*, 1991). The results of these studies are comparable for non-catalyst and oxidation catalyst equipped vehicles, but differ for 3-way aged catalysts. The only consistent and systematic studies on the effect of aging on catalysts are De Soete (1989) and Prigent *et al.* (1991). These authors observed a peak of N_2O formation close to the catalyst light-off temperature and found that the amount of N_2O emitted increased 2 to 4.5 times after aging. The increase in N_2O emissions appears to be due to a shift in light-off temperature caused by aging. As a consequence, the catalyst operates in the optimum temperature range for N_2O formation.

In summary, estimates of emissions from fossil-fuel combustion that were made before June 1988 appear to be incorrect for two reasons: (1) emissions from stationary combustion sources were overestimated because of a sampling artifact in stored grab samples containing NO and SO_2; and (2) N_2O emissions from automotive sources were underestimated because the effects of the

Table 29 **Summary of Emissions of Nitrous Oxide in Canada (1990)**

Sources	Emissions	
	kt N_2O	Percent of Total
Anthropogenic		
Stationary Combustion		
Natural Gas	1.55	1.69
Coal	2.46	2.67
Heavy and Light Oil	2.22	2.41
Wood	3.90	4.24
Mobile Sources		
Gasoline	29.40	31.97
Diesel	6.97	7.58
Heavy Oil	0.65	0.71
Aviation Fuels	1.27	1.38
Nitric Acid Production	1.02	1.11
Adipic Acid Production	30.00	32.62
Fertilizer Use	11.00	11.96
Miscellaneous	1.53	1.66
Total Anthropogenic	**91.97**	**100.00**
Natural		
Soils and Land	1 150.29	
Marine	2.2	
Total Natural	**1 152.49**	

aging of catalytic converters were not taken into account.

Emission factors were developed for the combustion of fossil fuels by both stationary and mobile sources based on measurements made in Europe and Canada (De Soete, 1989; Prigent and De Soete, 1989; Prigent *et al.*, 1991; Canadian Electrical Association/ CANMET, 1990; and U.S. EPA, 1989) and are summarized in Tables 30 and 31.

To maintain consistency with other emission estimates, De Soete's values for the volume of flue gas produced (under stoichiometric combustion conditions) for natural gas, heavy oil, and coal were adopted. The densities shown in Table 32 were used to convert from volume to mass.

Natural Gas Combustion. Emissions from the combustion of fuels at stationary sources were estimated in a similar manner. For

Table 30 Range of Nitrous Oxide Emission Factors

Conventional Stationary Combustion	
Coal	mean values lie between 2 and 10 ppmv
Heavy Oil	mean values lie between 1 and 10 ppmv
Natural Gas	mean values lie between 1 and 3 ppmv
Mobile Combustion Sources	
Gasoline	
No Catalysts	mean values lie between 3 and 40 ppmv
New Catalysts	average values are from 2 to 5 times uncontrolled
Aged Catalysts	average values are about 7 times uncontrolled values
Diesel Fuel	mean values lie between 3 and 40 ppmv

Table 31 Nitrous Oxide Emission Factors - Fossil Fuels

Fuel Type	Emission Factor (kg N_2O/t)	Fuel Consumption (Mt)	Emissions (kt)
Stationary Combustion			
Coal (conventional)	0.05	49.29	2.46
Coal (fluidized bed)	2.11	0.00	0.00
Natural Gas/Still Gas	0.03	58.40	1.75
Light and Heavy Oil	0.14	15.90	2.23
Mobile Sources			
Gasoline			
No Catalyst	0.31	6.16	1.91
Oxidation	0.60	6.13	3.68
3-way Catalyst	0.60	6.63	3.98
Aged 3-way Catalyst	2.20	9.01	19.83
Diesel	0.46	15.15	6.97
Heavy Oil	0.46	1.41	0.65
Aviation Fuels	0.31	4.10	1.27
Total Fossil Fuel Sources			**44.73**

Table 32 Densities Used to Convert from Volume to Mass

Fuel	Stoichiometric Flue Gas Volume (Nm^3/kg)	Density (kg/Nm^3)	ppmv
Natural Gas	10.91	0.78	1 to 1.5
Coal	8.54	—	3.7 to 7.8
Heavy Oil	9.72	930	1 to 12
Gasoline	—	750	depends on control
Diesel	—	870	3 to 40

example, the following calculations were used to determine the emissions from natural gas combustion and to derive an emission factor.

The average concentration of N_2O in the flue gas is 1.25 ppmv. From stoichiometric combustion equations, the volume of flue gas produced from the combustion of 1 kg of natural gas is 10.91 m^3 and at standard pressure and temperature (1 atm and 60°F) the molar volume is 23.7 m^3. This implies that the concentration of N_2O in the flue gas is equivalent to $1.25 \times 10^{-6}(44 \text{ kg}\cdot\text{mol}/23.7 \text{ m}^3)$ or 2.32×10^3 $\mu g/m^3$. As N_2, this is equivalent to $28/44 \times 2.32 \times 10^3$ $\mu g/m^3$ or 1 477 $\mu g/m^3$ of flue gas. If it is assumed that excess air is 10%, the volume of flue gas will be 12 m^3/kg of fuel.

In 1990, the consumption of natural gas and still gas in Canada was approximately 74.86 TL or about 58.4 Mt, which resulted in emissions of approximately: (58.4×10^9 kg x 12 m^3/kg x 1 477 $\mu g/m^3$) or 1.04 kt.

The average emission factor for natural gas would, therefore, be 0.0178 kg N/t or 0.028 kg N_2O/t.

Emission factors were derived for coal, oil, gasoline, and diesel in a similar manner (Table 31).

The vehicle technology splits given in Table 17 and the fuel consumption patterns used to estimate emissions of CO_2 and CH_4, were used to estimate N_2O emissions for both on-road and off-road transportation. The results are shown in Table S.1. A 10-year lifespan was assumed, therefore, 90% of the 3-way catalyst equipped vehicles were assumed to be aged (Table 33).

It is clear that more measurements and information are needed to confirm the effects of catalysts on emissions and to better define vehicle technology penetration rates.

Wood Combustion. Emissions of N_2O were estimated for fuelwood combustion based on an emission factor of 0.16 g N_2O/kg (Rosland and Steen, 1990; Radke *et al.*, 1991).

Approximately 5500 kt of waste wood are consumed annually for industrial purposes, and about 11 400 kt of wood are consumed for residential use. Total emissions were estimated to be 2.7 kt of N_2O from wood combustion for energy purposes. Prescribed burning produced another 1.2 kt of N_2O.

Table 33 Calculation of Nitrous Oxide Emissions from Automobiles

Automobiles (Gasoline)		
Aged 3-way catalysts	2.2 g/kg × 15.54 × 10^6 kg × 0.394 =	13.47 kt
New 3-way catalysts	0.6 g/kg × 15.54 × 10^6 kg × 0.040 =	3.79 kt
Oxidation	0.6 g/kg × 15.54 × 10^6 kg × 0.401 =	1.91 kt
No catalyst	0.3 g/kg × 15.54 × 10^6 kg × 0.161 =	0.77 kt

5.1.2 Nitric Acid Production

Nitric acid (HNO_3) is an intermediate product formed during the manufacture of nitrogen fertilizers. The quantity of HNO_3 formed depends on gas composition, reaction conditions, reactor design, and catalyst type. In addition, the concentration of HNO_3 in the exhaust gases depends on the type of plant and its emissions controls.

Emissions of N_2O were estimated using information provided by industry, which in turn is based on company-specific measurements and calculations (ICI, 1991; Norsk Hydro, 1991). Reported emissions ranged from 2 to 20 kg of N_2O/t of ammonia (NH_3) consumed in the production of HNO_3 (median 8.5 kg N_2O/t of NH_3). A recent analysis of emissions from the production of HNO_3 indicates that emissions from Canadian plants are at the low end of this range (Collis, 1992a).

For 1990, N_2O emissions in Canada from the production of HNO_3 were estimated to be 1 kt. This estimate was based on a value of 3.4 kg N_2O/t of NH_3 and an estimated consumption of 300 kt of NH_3 (Corpus Information Services, 1990a).

5.1.3 Adipic Acid Production

Thiemens and Trogler (1991) have shown that there can be significant releases of N_2O during the production of nylon. Approximately 0.303 kg N_2O/kg of product are released during the production of adipic acid.

In 1990, approximately 100 kt of adipic acid were produced (Corpus Information Services, 1991). Based on this information, the quantity of N_2O emitted during adipic acid formation was estimated to be 30 kt.

5.1.4 Fertilizer Application

Nitrous oxide can be released from the soil under either anaerobic or aerobic conditions. Liberation of N_2O from soils is associated with the oxidation of mineral nitrogen. When either organic or inorganic nitrogen fertilizers are applied, most of the nitrogen is oxidized to nitrates before it is taken up by the plants. This oxidation process is known as nitrification.

If soils become anaerobic, i.e., waterlogged or poorly drained, the nitrates can be reduced by facultative anaerobic bacteria to N_2O, which can be further reduced to N_2 before it is lost to the atmosphere. This process is called denitrification. The amount of N_2O formed depends on a number of soil factors, such as oxygen supply, water content, temperature, structure, organic matter content, and nitrate concentration. Most of the sampling periods used to generate the N_2O emissions from fertilizers in Canada were less than one year; therefore, the estimate of total annual atmospheric emissions might be low. On the other hand, the estimates of emissions of N_2O from the application of anhydrous ammonia are probably high because the application rates in Canada are generally low. More research is necessary to improve the estimates (Canadian Fertilizer Institute, 1992).

Table 34 summarizes the percentage of nitrogen fertilizer evolved as N_2O (Eichner, 1990). Based on these loss rates, the Canadian Fertilizer Institute has derived a range of N_2O emissions (Collis, 1992b). Average loss rates are shown in Table 35.

Estimates of total emissions of N_2O from fertilizer production in Canada range from a low of 3.3 kt to a high of 27.8 kt and average about 10.7 kt.

5.1.5 Miscellaneous Sources

Anaesthetic Usage. An emission factor for N_2O emissions from anaesthetics was estimated on the basis of consumption patterns in the United States. It was assumed that all of the N_2O used for anaesthetics was eventually released to the atmosphere. Based on an emission rate of 57.8 g per capita (Ortech, 1991) and an estimated Canadian population of 26 million, 1990 emissions were estimated to be 1.5 kt.

Propellant Usage. An emission factor was also developed for N_2O used in propellants. Based on consumption patterns in the United States, an emission factor of 3.03 g N_2O per capita was used to estimate that Canadian emissions in 1990 were 0.03 kt.

High Voltage Transmission Lines. Estimates of N_2O formation due to corona loss on high voltage transmission lines have not been made. Data on this phenomenon are scarce and further scrutiny is required before estimates are made.

5.2 Natural Sources

Very little recent work has been undertaken by Environment Canada to evaluate natural sources of N_2O emissions. Estimates in this report are based on a report prepared in 1981 (Environment Canada, 1981).

The flux rates that are estimated should only be interpreted to indicate the order of magnitude. Nitrous oxide is emitted into the atmosphere from several sources, including soils, oceans, fresh waters, fires, lightning, and vegetation. The fluxes from soils and marine waters are the dominant global sources of N_2O. Production from other sources, particularly lightning, is considerably smaller (Environment Canada, 1981).

More information on the methods used to develop the nitrogen flux rates and emissions estimates is available (Environment Canada, 1981).

Based on the flux rates in Table 36 and the appropriate land and water surface areas, emissions of N_2O as N were estimated to be 732 kt from soils and land and 1.4 kt from marine environments (shown in Table 29 as kt of N_2O).

Table 34 Percentage of Nitrogen Fertilizer Evolved as Nitrous Oxide

Fertilizer Type	Percentage of N Fertilizer Evolved as N_2O		
	Low	High	Average
Urea	0.07	0.18	0.11
Ammonium Sulphate, Phosphate	0.02	0.90	0.25
Ammonium Nitrate	0.04	1.71	0.44
Anhydrous Ammonia	0.86	6.84	2.70
Calcium Nitrate	0.001	0.50	0.07

Table 35 Loss of Nitrogen as Tonnes of Nitrous Oxide from Mineral Nitrogen Fertilizer in Provinces of Canada (1989)[a]

Nitrogen Source	Loss (%)[b]	Atlantic (t)	Quebec (t)	Ontario (t)	Manitoba (t)	Saskatchewan (t)	Alberta (t)	B.C. (t)	Canada (t)	(%)
Urea	0.11	5.5	50.7	89.6	75.7	127.1	144.4	20.7	513.7	(4.8)
Ammonium Sulphate/ Phosphate	0.25	20.5	77.0	156.3	107.4	121.7	138.8	15.9	637.5	(6.0)
Ammonium Nitrate	0.44	39.6	52.9	96.4	81.4	38.5	114.1	20.9	443.8	(4.2)
Anhydrous Ammonia	2.70	-	70.8	696.8	2 461.8	1 936.9	3 612.3	277.0	9 055.6	(85.0)
Calcium Nitrate	0.07	-	1.3	-	-	-	-	-	1.3	(0.0)
Total		**65.6**	**253.7**	**1 039.1**	**2 726.3**	**2 224.2**	**4 009.6**	**334.5**	**10 651.9**	**(100.0)**

[a] Source: Canadian Fertilizer Institute, 1992.
[b] From Table 34.

Table 36 Annual Nitrous Oxide Flux Rates in Canada (kg N/km^2)

Terrestrial Biogenic Zones	N_2O
Soils	
Chernozemic	107.4
Solonetzic	44.9
Luvisolic	27.2
Podzolic	225.4
Brunisolic	47.0
Regosolic	6.7
Gleysolic	26.3
Organic	157.9
Rockland	5.0
Forest and Brush Fires	
Tundra	
Boreal Forest - Barrens	
Ontario, Quebec, Atlantic Provinces,	0.27
Prairie Provinces, Territories	0.49
Boreal Forest	
Ontario, Quebec, Atlantic Provinces	1.05
Prairie Provinces, Territories	1.96
Aspen Parkland	0.98
Coastal - Mountain	0.49
Great Lakes - Acadian	
Forests	1.26
Grasslands	0.02
Aquatic Biogenic Zones	
Marine	
Arctic	29.00
Pacific	101.00
Atlantic - South	84.00
Atlantic - North	59.00
Lightning	
Tundra	0.05
Boreal Forest - Barrens	0.19
Boreal Forest	0.39
Aspen Parkland	0.62
Coastal - Mountain Forests	0.27
Great Lakes - Acadian Forests	0.54
Grasslands - Agriculture	0.67

Section 6

Emissions of Halogenated Species

6.1 *Chlorofluorocarbons*

Although chlorofluorocarbons (CFCs) are usually referred to collectively, several different formulations are produced commercially and others have been developed experimentally. They are identified by a numbering system that is based on a system originally devised by Du Pont to distinguish fluorinated hydrocarbons. For example, working from right to left, the first digit on the right of CFC-11 (CCl_3F) refers to the number of fluorine atoms, the second digit refers to the number of hydrogen atoms plus one, and the third digit is the number of carbon atoms minus one (the zero is not written).

Emissions of CFCs in 1990 were estimated using the methodology developed by Gamlen and Steed (Gamlen *et al.*, 1986). Statistics on the consumption of CFC-11, CFC-12, and CFCs-113 to -115, were obtained from the Commercial Chemicals Branch of Environment Canada and are based on confidential data supplied by industry.

To calculate the overall release rate of CFCs, the time delay for release from their varied uses must be estimated. The most efficient way to do this is to group the uses of each CFC into six categories that have similar release patterns. The six categories given by McCarthy *et al.* (1977) and Gamlen *et al.* (1986) are: aerosols; hermetically sealed refrigeration (long lifetime, about 12 years); non-hermetically sealed refrigeration (short lifetime, about 4 years); closed-cell foams; open-cell foams; and other uses.

The reliability of the end-use analysis is thought to be accurate for the major markets, i.e., aerosols, refrigeration, and foam. Of less certain reliability is the subdivision within each category. The subdivision of foam into open-cell and closed-cell types is not as easily verified because of differences in the reporting of company sales data. Because the consumption data were confidential and preliminary, all estimates for 1990 assumed that the end-use markets were similar in proportion to those of 1987 (for which estimates were much more detailed). Total consumption of CFCs in 1987 was about 22 kt. In 1990, consumption had fallen to about 13 kt, and in 1991 to about 9 kt (Environment Canada, 1992b).

6.1.1 Release Scenarios

Fugitive Emissions. The methods used to estimate emissions are outlined by Gamlen *et al.* (1986) and will only be described briefly. During the manufacturing of CFCs, a portion of the product is lost directly to the atmosphere, therefore there is no delay between production and release. Based on surveys within the industry, approximately 3.3% of CFC-12 and 2.0% of CFC-11 are lost as fugitive emissions during production .

The release of fugitive emissions can be described as: $R(F)_t = 0.02\ P_t$ for CFC-11, where P_t is the annual production in year t; and $R(F)_t = 0.033\ P_t$ for CFC-12. In Canada, fugitive emissions were estimated to be 365 t in 1990.

Aerosols. Releases from aerosols were estimated by assuming that half of the aerosols were released in the year of sale and half were released the following year: $R(A)_t = 0.5\ S(A)_t + 0.5\ S(A)_{(t-1)}$, where S(A) represents annual sales. Emissions from the use of aerosols in 1990 were estimated to be 127 t.

Long-lifetime Refrigeration. Analysis by McCarthy *et al.* (1977) found that domestic refrigerators and freezers had an average lifetime of 12 years, and that there was a 2% loss of CFCs to the atmosphere during filling. To develop estimates for Canada, it was assumed that 8% of the total CFC-12 sold for refrigeration was of the long-lifetime variety. This is the same proportion given by Gamlen *et al.* (1986). Analyses of previous consumption patterns revealed that approximately 58% of the CFC-12 sold for long-lifetime uses is released each year. Therefore: $R(LLR) = (0.08 \times TR)\ 0.58$, where TR represents the total Canadian production of CFCs for refrigeration. Emissions in 1990 from the use of long-lifetime refrigerants amounted to 262 t.

Short-lifetime Refrigeration. A four-year life for this category has been proposed. This implies that, on average, the refrigerant is recharged every four years, not that the refrigerator life is four years. Automobile and some household air conditioners fall into this category. Total emissions in 1990 were estimated to be 3965 t.

Open-cell Foam. A two-month release rate has been assumed for this use of CFCs. Therefore: $R(OC)_t = 0.83\ S(OC)_t + 0.17\ S(OC)_{t-1}$, where S(OC) represents the sales of open-cell foams. Total releases in 1990 from this category were estimated to be 607 t.

Closed-cell Foam. Closed-cell foam can be subdivided into rigid polyurethane and isocyanurate foams (CFC-11), and non-urethane foams, polystyrene, and some extruded polyolefins (mainly CFC-12 when the blowing agent is chlorofluorocarbon).

In the past, most CFC-12 in Canada was used for polystyrene foams rather than for polyolefins. Recently, manufacturers have switched to using HCFCs, but the quantities are confidential. Most of the CFC is lost from the product to the atmosphere within two years, with 75% being lost within one year. Therefore, for CFC-12: $R(CC)_t = 0.5\ S(CC)_t + 0.5\ S(CC)_{(t-1)}$.

Most of the CFC-11 is used in rigid polyurethane (mainly in refrigeration equipment and buildings) and three principal factors determine actual release: production loss; diffusion loss during product use; and losses on disposal.

Total emissions of CFCs from closed-cell foams were estimated to be 3121 t.

Other. This category comprises about 17% of the demand for CFCs in Canada. The major uses are: CFC-12 in sterilant gas mixtures; and CFC-113 as a solvent. These uses, like aerosols, are assumed to have a six-month release delay. Emissions in 1990 from this category in Canada were estimated to be 2210 t.

Total 1990 emissions of CFCs are summarized in Table 37. The emissions delayed from previous years must be added to these emission estimates. The preceding calculations may or may not take into account the fact that consumption of CFCs dropped considerably from 1989 to 1990 and that, from 1985 to 1989, consumption was relatively stable. Any discrepancies are due in part to changes from the original patterns of use upon which the emission methodology was based. The consumption of CFCs (kt) for 1985 to 1990 was: 19.2 in 1985; 20.6 in 1986; 21.9 in 1987; 21.7 in 1988; 19.6 in 1989; and 13.6 in 1990.

Table 37 Chlorofluorocarbon[a] Releases[b] in Canada (1990)

Source	Emissions (t)
Fugitive	365
Aerosols	127
Long Lifetime Refrigeration	262
Short Lifetime Refrigeration	3 965
Open-cell Foams	607
Closed-cell Foams	3 121
Other	2 210
Total CFCs	**10 657**

[a] Includes CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115.

[b] Based on methodology developed by the Fluorocarbon Program Panel of the Chemical Manufacturers Association.

The rate of release of stored CFCs depends on the particular CFC and the type of application. For example, domestic refrigerators and freezers (long-lifetime refrigeration) have an average lifetime of 12 years ± 4 years with a 2% loss on filling (Gamlen *et al.*, 1986).

Losses of CFC-11 from closed-cell foam are due to three principal factors: production loss; diffusion loss during product use; and losses on disposal. Current estimates use a production loss of 10%, and a loss of 4.5% per year for 20 years, which represents a combination of product lifetime and diffusional loss.

Although releases of some CFCs will continue after their phaseout in 1996, no accurate estimates are available because of a lack of information on the timing of the phaseout of particular uses and the future use patterns of these substances. In addition, there is a lack of data on the total quantity of *banked* CFCs.

6.2 Hydrochlorofluorocarbons

Because of the confidential nature of the data, and the resulting lack of details on end-uses, no attempt was made to estimate emissions on a detailed basis. In 1990, approximately 8.4 kt of HCFCs were consumed in Canada (Environment Canada, 1992b). Although data are limited, consumption was assumed to equal emissions.

6.3 Carbon Tetrachloride

Carbon tetrachloride (CCl_4) is both produced and imported into Canada. It is primarily used as a feedstock in the production of CFC-11 and CFC-12 (Corpus Information Services, 1990b) and is not directly released to the atmosphere. Data for 1989 indicate that approximately 803 t of CCl_4, or about 3% of the apparent consumption, was for non-feedstock uses (Environment Canada, 1992b). No estimate was made of the percentage of this quantity released to the atmosphere.

6.4 Methyl Chloroform

The major use for 1,1,1-trichloroethane, or methyl chloroform (CH_3CCl_3), is as a cleaning agent for metals. According to Corpus Information Services (1990c), the demand for CH_3CCl_3 in 1989 was about 16 kt. It is assumed that all of it was released to the atmosphere.

6.5 Tetrafluoromethane and Hexafluoroethane

During the production of primary aluminum using the electrolytic process, two carbon fluoride gas compounds are indirectly formed: tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) (PFCs). These gases can absorb infrared radiation; therefore, a substantial accumulation in the troposphere could lead to an increase in the greenhouse effect (Wang *et al.*, 1981; Fabian *et al.*, 1987).

Because PFCs can remain in the troposphere for thousands of years, the aluminum industry is increasing its efforts to reduce these emissions for preventative purposes (Alcan, 1992). Efforts are being made to reduce emissions, and more research is needed to understand more precisely the role of the anode effect (duration, amplitude, and number) and the means to control or reduce this effect. Although all of the factors that give rise to PFC emissions are not fully understood, it seems clear that PFCs form during secondary reactions that occur almost exclusively when the electrolytic bath no longer contains sufficient alumina (anode effect).

Global estimates of PFC emissions have been reported to range from 1 to 2 kg CF_4/t of aluminum and 0.1 to 0.2 kg C_2F_6/t of aluminum. Recent measurements in Norway (Rosland, 1992) indicate that emissions from old Soderberg production plants with an anode effect frequency of 2 to 3 per day range from 1 to 3 kg CF_4/t of aluminum, while emissions from modern pre-baked plants are less than 0.06 kg CF_4/t of aluminum.

Preliminary estimates of emissions in North America, based on recent data, are also estimated to be much lower than the global estimates. Emissions in North America are estimated to range from 0.2 to 0.8 kg CF_4/t of aluminum. The most modern smelters produce the lowest levels of emissions (Alcan, 1992).

In 1990, Canada produced about 1.8 Mt of aluminum. Based on emission factors of 0.8 kg CF_4/t of aluminum and 0.08 kg C_2F_6/t of aluminum, maximum emissions were estimated to be 1.5 kt.

Section 7

Carbon Dioxide Methodology

Carbon dioxide is one of the end products of the combustion of organic materials (coal, petroleum, gas, and wood) and the incineration of waste materials. Inorganic carbonates also decompose thermally to yield CO_2 and oxides.

Because CO_2 is produced when a fuel is burned, the calculation of CO_2 emissions is relatively straightforward. This is illustrated in Equation 1, where ΔH is the heat of reaction and C_xH_y denotes a generalized hydrocarbon fuel:

$$CxHy + (x + 1/4y)\, O_2 \rightarrow xCO_2 + 1/2\, yH_2O + \Delta H \qquad (1)$$

For each type of fuel burned, the annual CO_2 emissions can be expressed as the product of three terms: the amount of fuel consumed; the carbon content of the fuel; and the fraction of the fuel oxidized.

For simplification, emissions from fossil fuels have been estimated for three classes of fuels: gaseous, liquid, and solid. This method is similar to the one used by Marland and Rotty (1983), who estimated global CO_2 emissions from a broad sampling of fuel production data (United Nations, 1978). All emission factors developed in this report were converted to energy units to facilitate comparisons between energy use and emissions of carbon.

7.1 Gaseous Fuels

7.1.1 Natural Gas

All fuel consumption figures for Canada were obtained from Statistics Canada (1991a,b). The quantities of fuel consumed are described in Section 2 of this report.

The carbon content of a fuel is usually determined from its hydrocarbon fraction (in this case CH_4). Keeling (1973) calculated that the average carbon content of natural gas was 524 g of C/m^3. Subsequent work (Marland and Rotty, 1983) produced a more appropriate value.

To develop an emission factor that relates the consumption of natural gas, in terms of its energy content, to a mass unit of carbon, it is necessary to determine an average heating value that is representative of Canadian gas.

Depending on the source of a gas, its composition can vary greatly. Considine (1977) reported that the composition of high-BTU natural gas was approximately 95% methane, 4% nitrogen, and 1% heavier gases. This differs somewhat from other reports (U.S. Bureau of Mines, 1976). When natural gas liquids are removed, there is a reduction in the heating value of the natural gas. Based on the U.S. reference gas shown in Table 38, and assuming that 20% of the ethane, 72% of the propane, all of the heavier hydrocarbons, and all of the H_2S, CO_2, and H_2O were removed, Marland and Rotty (1983) calculated that the resulting gas had a heating value of 9103 kcal/m^3. This dry gas contained 0.550 kg C/m^3 at 0°C, and with the separated CO_2 included, it would produce 0.555 kg C/m^3 when completely oxidized. At standard temperature (60°F) the carbon content would be 525.4 g C/m^3.

Marland and Rotty (1983) found that the carbon content per unit energy could be closely represented by a linear relationship with heating value:

$$Cg = 57.357 + 1.459 \times 10^{-3} (\Delta H_H - 8898) \qquad (2)$$

where C_g is the amount of carbon (in g C/1000 kcal) and ΔH_H is the higher heating value* of the gas (in g C/1000 kcal/m^3 at 15.6°C).

Because of differences in gas composition, many different calorific contents for natural gas have been reported in the literature. The United Nations (1978) and Hirschler (1981) reported a value of 38.90 MJ/m^3. Using their regression equation and an upper-end mean world value of 37.24 MJ/m^3, Marland and Rotty (1983) derived a mean world value of 13.70 t C/TJ for the carbon content of dry natural gas (Tables 38, 39).

Although the National Energy Board (1986, 1988) publishes gross energy conversion factors (Table 40), the values are not indicative of any year and there is no way to determine what quantities are applicable to individual factors. Because Statistics Canada (1991a) provides conversion factors that are revised yearly and that take into account regional differences, their average heating value of 37.78 MJ/m^3 was used to represent natural gas consumed in Canada in 1990.

Substituting this value (37.78 MJ/m^3 or 9040 kcal/m^3) in equation (1) yields 57.57 g C/1000 kcal or 13.76 t C/TJ. This is similar to the value derived by Marland and Rotty (1983), and to the value derived by taking an average of the National Energy Board figures (Table 40).

The portion of the fuel that does not undergo oxidization must be subtracted from this factor. For natural gas, a fraction of annual consumption remains unoxidized each year because of incomplete combustion. Some of the carbon in the gas remains as soot, either around the burner, or in the stack, or is released into the environment. Although the exact amount of unoxidized carbon is difficult to quantify, a conservative estimate is about 1.5% (see Subsection 7.2). Therefore, the factor used to estimate emissions of CO_2 from the combustion of natural gas was 13.55 t C/TJ or 49.68 t CO_2/TJ.

This factor was also applied to natural gas flaring. Although the carbon content, and therefore the energy content, per gram of fuel is lower for unprocessed gas, any error in applying the same factor is estimated to be less than the error caused by the uncertainties associated with the oxidation assumptions. A summary of the emission factors developed for natural gas and still gas is presented in Table 41.

7.2 Liquid Fuels

Petroleum-derived liquids have been divided into eight different fuels, and emission factors have been developed separately for each fuel. As with natural gas, all liquid fuel consumption figures are from Statistics Canada (1991a,b). Expressed in physical units, the consumption figures can be found in Section 2 of this report.

Brame and King (1967) reported that the range of carbon in liquid petroleum products was 79 to 87%. Keeling (1973) used an average of these values (84%), whereas Marland and Rotty (1983) used 85%. According to Zimen *et al.* (1977), the carbon

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* Higher heating value is the gross calorific value of a fuel that includes the latent heat of the water vapour in the products of combustion.

Table 38 Composition of Natural Gas (Percentage by Volume)

1976 U.S. Dry Gas	Weighted World	1976 Adjusted	Reference Gas
Methane	88.32	89.24	92.88
Ethane	4.65	4.52	3.91
Propane	2.12	1.95	0.62
Other Hydrocarbons	1.53	1.54	—
CO_2	0.92	0.78	—
Other	2.46	2.42	2.59
Higher Heating Value (kcal/m^3)	9 685.60	9 680.26	9 102.62

Table 39 Mean Heating Value of Dry Natural Gas

	U.S. (kcal/m^3)	World (kcal/m^3)
1980	—	8 825
1979	9 068	8 839

Table 40 Gross Energy Content Factors[a] for Natural Gas (MJ/m^3) (National Energy Board 1986, 1988)

British Columbia	
Domestic	39.10
Huntingdon	39.10
Kingsgate	37.65
Grassy Point	38.20
Alberta	
Domestic	38.80
Cardston	37.65
Aden	36.06
Eastern Canada	37.65
Canadian Average	38.03

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[a] Value of 37.78 MJ/m^3 used to represent Canadian natural gas consumed in 1990 (see text for details).

content of crude oil and natural gas liquids is approximately 95% by mass. With the exclusion of propane, the highest value reported by Keeling (87% carbon by mass) has been used in all calculations in this report.

Table 42 shows the energy contents and densities used to convert the emission factors for the liquid fuels. The energy content factors were taken from Statistics Canada (1991a,b) and the National Energy Board (1986, 1988, 1991a); whereas, the specific gravities were obtained from the Institute of Petroleum (1973) and Perry and Chilton (1973). The assumed density of heavy oil was based on an emission factor derived for Alberta (Energy, Mines and Resources, 1990).

To determine the fraction of the liquid fuels that undergoes oxidation, the portion that is not fully oxidized during combustion must be estimated. An approximation was made by comparing the 1985 emission estimates of volatile organic compounds (VOCs) and total suspended particulates (TSPs) attributable to the combustion of liquid fuels, with the mass of liquid fuels combusted. In 1985, 54 650 kt of liquid fuels were consumed in Canada (Statistics Canada, 1986). The emissions of VOCs and TSPs from the combustion of

Table 41 Carbon Dioxide Emission Factors for Gaseous Fuels

	Energy Content (TJ/GL)	Carbon (g/m^3)	CO_2 (t/ML)	CO_2 (t/TJ)
Natural Gas	37.78	512.46	1.88	49.68
Still Gas	41.73	565.42	2.07	49.68
Coke Oven Gas	18.61	436.36	1.60	86.00

Table 42 Densities and Heat Contents of Selected Fuels

Fuel	Specific Gravity Ranges	Density (kg/L)	Energy Content (TJ/ML)
Motor Gasolines	0.71 to 0.79	0.75	34.66
Aviation Gasolines	0.70 to 0.78	0.74	33.52
Kerosenes	0.78 to 0.84	0.81	37.68
Diesel Oils	0.82 to 0.92	0.87	38.68
Light Oils	0.85 to 0.95	0.90	38.68
Heavy Oils	0.92 to 0.99	0.98	41.73
Aviation Turbo (Jet Fuel)	0.78 to 0.84	0.81	35.93
Propane	0.508	0.51	25.53
Butane	0.579	0.58	28.62
Ethane	0.377	0.38	18.36

liquid fuels in 1985 were estimated to be 1027 kt and 108 kt, respectively (Environment Canada, 1989) (Table 43). Carbon monoxide, an incompletely oxidized material that is formed during combustion and discharged to the atmosphere, is assumed to undergo complete oxidation fairly rapidly (0.1 to 0.4 years) in the environment (Bach, 1988). Methane, another product of inefficient combustion, undergoes complete oxidation in some finite time (7 to 10 years) (Bach, 1988; Marland and Rotty, 1983). Therefore, for this class of compounds, any difference between the total amount of carbon being oxidized in a given year, and the amount of carbon that would be released by full oxidation of the year's discharge, would result either from a change in annual fuel consumption or from methane formation. Because the amount of methane and other hydrocarbons formed is small, the assumption that an equivalent fraction of material is oxidized each year should not introduce significant error.

Consequently, 1.14 Mt or 2.1% of the total mass of fuels (total VOC and TSP emissions), represents the incompletely oxidized material from the combustion of liquid fuels. However, some of this material undergoes oxidation over time. Many of the hydrocarbons emitted, especially from engine exhausts, are highly reactive (National Research Council, 1979). Data on urban aerosols show that their composition is about 20% carbon (National Research Council, 1979; Marland and Rotty, 1983). For these reasons, the fraction of liquid fuel that undergoes combustion each year but remains unoxidized in the environment was estimated to be 1.5%.

For each liquid fuel, emissions of CO_2, expressed as tonnes of carbon, were estimated by converting the energy contents of the fuels (Table 42) to mass per energy unit. This was done by multiplying the densities in Table 43 by the appropriate carbon content and by one minus the percentage of the fuel unoxidized (0.985). These emission factors are presented in Table 44.

7.3 *Solid Fuels*

7.3.1 Coals

As with gaseous and liquid fuels, emissions of CO_2 from the combustion of solid fuels are directly related to the quantity of fuel consumed, the carbon content of the fuel, and the fraction oxidized. The quantities of fuels consumed were taken from Statistics Canada (1991a,b). Emission factors were developed for lignite, sub-bituminous, Canadian bituminous, U.S. bituminous, and anthracite coals. The carbon contents of coals vary significantly among regions in Canada (Lauer, 1990; Energy, Mines and Resources, 1990) and the emission factors reflect this. The emission factors used in this report are based on an analysis of the different coals consumed in Canada (Lauer, 1990) (Table 45). These emission factors, which are similar to the factors derived in the previous national CO_2 inventory, were based on information obtained from several publications (Environment Canada, 1982; Canadian Electrical Association, 1985; Marks, 1978; Campbell, 1986). For the five coal types used in Canada, the percentage carbon contents (average values) and energy contents (National Energy Board, 1986; Statistics Canada, 1988) used in this report are given in Table 46.

To determine the fraction of carbon in coal that remains unoxidized, a method similar to that used by Marland and Rotty (1983) and the Carbon Dioxide Information and Analysis Center (1988) was adopted. In Canada, over 80% of the coal is consumed by power utility boilers. Consequently, data on the products of combustion from these units should represent most of the coal consumed. An

Table 43 Consumption of Liquid Fuels in Canada (1985)

Fuel	Volume ($\times 10^3$ m^3)	Density (t/m^3)	Mass (kt)
Motor Gasoline	32 732	0.75	24 549
Kerosene	860	0.81	697
Diesel Oil	15 007	0.87	13 056
Light Oil	7 344	0.90	6 609
Heavy Oil	4 523	0.98	4 433
Aviation Gasoline	177	0.74	131
Aviation Turbo	4 300	0.81	3 483
Propane	3 319	0.51	1 692
Total			**54 650**

Table 44 Carbon Dioxide Emission Factors

Liquid Fuels	Energy Content (TJ/ML)	C (g/L)	CO_2 (t/kL)	CO_2 (t/TJ)
Motor Gasoline	34.66	642.60	2.36	67.68
Kerosene	37.68	695.20	2.55	67.65
Aviation Gas	33.52	634.20	2.33	69.37
Propane	25.53	416.65	1.53	59.84
Butane	28.62	479.18	1.76	61.38
Ethane	18.36	301.63	1.11	60.24
Diesel Oil	38.68	745.75	2.73	70.69
Light Oil	38.68	771.28	2.83	73.11
Heavy Oil	41.73	842.18	3.09	74.00
Aviation Turbo	35.93	694.17	2.55	70.84
Petroleum Coke	42.38	787.20	2.89	100.10

analysis of the bottom ash at the Battle River Generating Station (Canadian Electrical Association, 1985) showed that its average carbon content was 5.5%, and that the bottom ash averaged 12.25% of the total coal input. Based on these results and an average carbon content of 50% in the coal, the total amount of carbon that remains uncombusted in the ash is approximately 1.35%. An examination of data from the Tennessee Valley Authority Bull Run Steam Plant (Marland and Rotty, 1983) showed that between 0.14 and 2.7% of the combustible fraction of the coal remained unburned. Therefore, it was assumed that 1.0% of the carbon in the coal currently consumed in furnaces is discharged unburned.

Table 45 Coal Emission Factors

Province	Coal Type[a]	Carbon (t/t)	CO_2 (t/t)	CO_2 (t/TJ)
New Brunswick	H.V. Bit	0.609	2.333	83.0
Nova Scotia	H.V. Bit	0.626	2.295	84.5
Quebec	M.V. Bit	0.682	2.501	85.9
	Anthracite	0.651	2.387	86.2
Ontario	Lignite	0.407	1.492	93.8
	L.V. Bit	0.688	2.523	91.6
	Power M.V. Bit (U.S.)	0.682	2.501	85.9
	Steel M.V. Bit (U.S.)	0.670	2.457	81.6
Manitoba	Lignite	0.415	1.522	95.0
	L.V. Bit	0.688	2.523	91.6
Saskatchewan	Lignite	0.366	1.342	93.8
Alberta	Sub-Bit	0.474	1.738	94.3
	L.V. Bit	0.464	1.702	94.3
British Columbia	L.V. Bit	0.464	1.702	94.3
Coke		0.676	2.479	86.0

[a] Bit = Bituminous; H.V. = High Volatile; M.V. = Medium Volatile; L.V. = Low Volatile.

An estimate of the fraction of coal that does not undergo oxidation must also be made for coal used for non-fuel purposes. Based on information supplied by the U.S. Department of Energy (1982) and Marland and Rotty (1983), approximately 5.91% of the coal going to coke plants ends up as light oil and crude tar (Table 47). These coke by-products are used mainly in the chemical industry and, therefore, they do not undergo oxidation within the period for which the emission estimates in this report are being made. The Canadian coke by-products industry is similar to the industry in the United States. Emissions can be calculated by adjusting downward by 6% the amount of coal reported to have been consumed to produce coke. This, however, does not account for coke consumed in provinces that do not produce coke. Therefore, emissions were calculated by applying a general emission factor of 86 t/TJ for both coke and coke-oven gas (Energy, Mines and Resources, 1990).

7.3.2 Wood and Refuse

The combustion of other solid fuels, such as fuelwood, refuse, and slash, also produce CO_2 emissions. An emission factor for wood

Table 46 Characteristics of Coals Consumed in Canada

Province	Coal Type[a]	Heat Content (TJ/kt)	Carbon Content (%)
New Brunswick	H.V. Bit	26.90	61.5
Nova Scotia	H.V. Bit	27.15	63.2
Quebec	M.V. Bit	29.12	68.9
	Anthracite	27.70	65.8
Ontario	Lignite	15.90	41.1
	L.V. Bit	27.53	69.5
	Power M.V. Bit (U.S.)	29.12	68.9
	Steel M.V. Bit (U.S.)	30.10	71.2
Manitoba	Lignite	16.01	41.9
	L.V. Bit	27.53	69.5
Saskatchewan	Lignite	14.31	37.0
Alberta	Sub-Bit	18.44	47.9
	L.V. Bit	18.04	46.9
British Columbia	L.V. Bit	18.04	46.9
Coke		28.83	68.3

[a] Bit = Bituminous; H.V. = High Volatile; M.V. = Medium Volatile; L.V. = Low Volatile.

combustion and slash burning is easily calculated (Hirschler, 1981). If it is assumed that the chemical composition of wood is similar to that of cellulose, i.e., $C_6H_{12}O_6$, and that 100% combustion takes place, an emission factor of 1.47 t CO_2/t of wood combusted or 0.40 t C/t of wood can be calculated. The average thermal value of urban waste is between 8.4 MJ/kg and 12.7 MJ/kg (Burns and Seaman, 1973). An intermediate calorific value of 10.6 MJ/kg corresponds to 37% of that of hard coal (Hirschler, 1981). The conversion of organic matter to CO_2 is responsible for virtually all the heat released by incinerated waste. Therefore, the emission of CO_2 per tonne of refuse incinerated was estimated to be approximately 35% of the emissions from each tonne of hard coal, or 0.246 t carbon/t of refuse incinerated.

7.4 Industrial Processes

7.4.1 Cement and Lime Production

Two industrial processes (cement and lime production) emit CO_2 either without or

Table 47 **Light Oil and Tar Produced from Coal in Coke Plants**[a]

Year	Crude Light Oil and Crude Tar (Mt)	Coal to Coke Plants (Mt)	Coal Converted to Light Oil and Tar (%)
1980	3.63	60.51	6.00
1979	4.01	69.94	5.74
1978	3.68	64.77	5.68
1977	4.03	70.49	5.72
1976	4.36	76.84	5.68
1975	4.40	75.84	5.80
1974	4.68	81.83	5.71
1973	5.01	85.37	5.87
1972	5.04	79.56	6.33
1971	4.61	75.48	6.11
1970	5.25	87.54	6.00
1969	5.36	84.73	6.33

[a] Values are Mt of coal equivalent by heating value.

through indirect combustion. Cement is usually produced in a cement kiln in which calcium carbonate ($CaCO_3$) from a calcium-rich material (limestone, chalk, or marl) is broken down into CO_2 and calcium oxide (CaO). The CaO ultimately combines with the silicates in clay or shale to form dicalcium and tricalcium silicates (Helmuth *et al.*, 1979). Calcium aluminates are also formed in Portland cement clinkers. The world average value for lime content in cement is between 60 and 67% (Orchard, 1973). Emissions were estimated by using 63.5% as the amount of CaO in the cement. A factor of 0.136 t carbon/t of cement produced was obtained by dividing the molar mass of CO_2 by the molar mass of CaO and multiplying this by the fraction of CaO contained in the cement.

Therefore, for cement:

(12.01 g/mole C)/(56.08 g/mole CaO) x 0.635 = 0.136 t C or 0.5 t CO_2

and for lime:

(12.01 g/mole C)/(56.08 g/mole CaO) x 1 = 0.214 t C or 0.79 t CO_2

For cement, this is the same value used by Hirschler (1981), Acres International Limited (1987), and CDIAC (1988).

Most of the ammonia (NH_3) produced in Canada is made by the Haber-Bosh Process (Geadah, 1985). Nitrogen and hydrogen are reacted in a 1-to-3 ratio at high temperatures and pressures to produce NH_3. The hydrogen is obtained from natural gas. The material and energy requirements for the production of 1 t of NH_3 are illustrated in Table 48 (Industrial Chemicals, 1980).

Based on this material balance, and an assumption that all the carbon in the natural gas is ultimately released to the environment, an emission factor relating CO_2 emissions to NH_3 production was developed. By assuming

Table 48 Material and Energy Requirements for Production of One Tonne of Liquified Ammonia

Natural gas (92% CH_4)	812	m^3
Catalyst for Shift Reaction	0.15	kg
Synthesis Catalyst	0.25	kg
Caustic Soda (100%)	4.00	kg
Monoethanolamine	0.15	kg
Fuel Gas (for Driving Compressors)	7 108	kWh
Electricity	119	kWh
Water	25	m^3

that the carbon content was 525 g/t of natural gas and that 812 m^3 of natural gas are required for every tonne of NH_3 produced, an emission factor of 0.426 t of carbon/t of NH_3 produced was calculated.

The pulp and paper industry is a major consumer of wood for the production of pulp and paper products and for the production of energy. The major sources of CO_2 from this industry are combustion of spent pulping liquor (SPL) and wood waste. The average energy content of SPL is about 14 TJ/t (Statistics Canada, 1991a). A CO_2 emission factor was estimated by assuming that the average carbon content of the SPL was 41% (Rydholm, 1965; McCubbin, 1983) and that 95% of the carbon contained in the fuel was released during combustion. Not all the carbon in the black liquor is released from the recovery boiler stack - a portion is formed into Na_2CO_3. The carbon in the Na_2CO_3 makes its way through the various stages of the recovery cycle and is released as CO_2 from the lime-kiln stack (Wellisch, 1992). These small losses of carbon are replaced with makeup $CaCO_3$, which produces CaO and CO_2 in the lime kiln, or with makeup CaO, which does not emit additional CO_2 at the mill site. A very conservative value of 5% has been assumed for the makeup limestone (Wellisch, 1992). Expressed in energy terms, the emission factor derived for SPL is 102.01 t CO_2/TJ. Table 7 contains an analysis of the composition of waste liquors from different processes. Table 49 summarizes the emission factors for individual sources of CO_2.

7.4.2 Non-energy Uses of Coal, Coke, and Petroleum Coke

The use of fossil fuels for purposes other than energy are considered in this section. The non-energy products listed in Table 49 do not sequester all of their carbon.

For coal, coke, and petroleum coke, non-energy emissions of CO_2 have been assumed to equal 100% of the stored carbon.

The major industries that report the non-fuel use of coal, coke, and petroleum coke are: the iron ore industry; the steel industry; the aluminum industry; and the electrical product industry.

The *iron ore* industry mixes coke breeze with iron ore concentrate in the formation of iron ore pellets. Although the use is categorized as non-fuel, the coke breeze is oxidized in the process of indurating the pellets.

The *steel industry* consumes bituminous coal and coke to manufacture the carbon electrodes used to melt ferrous scrap in the

Table 49 Industrial Sources of Carbon Dioxide Emissions

	Emission Factors		
	C	CO_2	CO_2
SOLID FUELS	(g/kg)	(g/kg)	(t/TJ)
Fuel Wood			
Residential	400.00	1 466	81.47
Industrial	400.00	1 466	81.47
Slash Burning	400.00	1 500	81.47
Incineration	250.00	916	—
PROCESSES	(g/kg)	(kg/kg)	(t/TJ)
Cement Production	140.00	0.513	—
Limestone Production	215.00	0.788	—
Ammonia Production	430.00	1.577	—
Spent Pulping Liquor	410.00	1.503	107.38
NON-ENERGY PRODUCTS			(t/TJ)
Petrochemical Feedstocks	$0.68\ t\ C/m^3 \times 0.2$	-	14.22
Naphthas	$0.68\ t\ C/m^3 \times 0.2$	-	14.22
Lubricants	$0.77\ t\ C/m^3 \times 0.5$	-	36.01
Other Products	$0.79\ t\ C/m^3 \times 0.5$	-	28.88
Natural Gas	0.67 × Fuel Emission Factor		33.35
LPGs	0.20 × Fuel Emission Factor		12.00
Coke Oven Gases	1.0 × Fuel Emission Factor		86.00
Coke	1.0 × Fuel Emission Factor		86.00
Coals	1.0 × Fuel Emission Factor		(81.6-86.0)

production of steel at electric furnace steel mills. Mini-mills produce about 30% of Canadian steel.

In the *aluminum industry*, petroleum coke and coal tar pitch are mixed together to form a paste that is baked into carbon anode blocks. The blocks are used as electrodes during the electrolytic process used to produce pure aluminum. On average, modern aluminum smelters using pre-bake technology consume about 0.45 kg to 0.48 kg of electrode for every 1 kg of aluminum produced.

The *electrical product industries* use coke and petroleum coke to manufacture synthetic graphite electrodes. In the process, petroleum coke (70% by weight) is blended with pitch (25% by weight) and some additives (5% by weight). This is followed by extrusion, baking, and graphitization. Electricity is used to graphitize petroleum coke and coke in a furnace. Graphite electrodes are used by the steel industry in electric arc furnaces. Carbon electrodes are used in ferroalloy and phosphorous industries and to make blocks for aluminum smelters.

Most of the coal, coke, and petroleum coke consumption classified as non-fuel use leads to the oxidation of any inherent carbon (Coombs and Lomas, 1992).

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