

BENCHMARKING OF REFINERY EMISSIONS PERFORMANCE

Prepared for:

Canadian Council of Ministers of the Environment

National Framework for Petroleum Refinery
Emission Reductions Steering Committee
Benchmarking Sub-Group

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PREFACE

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- the Canadian Petroleum Products Institute
- staff of Environment Canada and Canadian Council of Ministers of the Environment
- representatives of provincial environment and/or energy departments
- Marbek Resource Consultants Ltd. and AMEC E&C Services Ltd.

EXECUTIVE SUMMARY

In 2001, the Canadian Petroleum Products Institute (CPPI) approached provincial and federal environment and energy departments with a proposal for a new way to regulate air emissions from Canadian petroleum refineries. The proposal involved the establishment of a cooperative process between federal and provincial governments, industry and stakeholders, to develop a national regulatory framework for performance-based facility level caps. These caps, once in place, would achieve significant reductions of refinery emissions, comparable to the environmental performance of refineries in the United States, while maintaining or even strengthening the competitiveness of the Canadian refining sector. CPPI saw such an approach as being complementary to the Federal Agenda on Vehicles, Engines and Fuels, which lays out a regulatory plan for petroleum fuels.

In February 2002, the Canadian Council of Ministers of the Environment (CCME), Environmental Planning and Protection Committee, directed the National Air Issues Coordinating Committee (NAICC) to consider undertaking and funding the development of a multi-pollutant emissions reduction strategy for the petroleum refining sector. Under NAICC-A, the National Framework for Petroleum Refinery Emission Reductions (NFPRER) Steering Committee was formed, and is tasked with providing the principles and methods with which jurisdictions may establish facility emissions caps for criteria air contaminants (CACs) and air toxics from refineries. The basis of the caps is that they will achieve emission levels at least on par with current and anticipated performance of comparable U.S. refineries.

A number of sub-groups have been formed to facilitate the development of the NFPRER, including Health Prioritization, Consultations and Communication, Methodology / Framework Development, Monitoring and Reporting, and Benchmarking.

This report was prepared to facilitate the work of the Benchmarking sub-group. The objectives of this study were to:

- collect emissions performance data for Canadian and comparable U.S. refineries.
- examine parameters that affect refinery air emissions performance and develop methods or correlations to normalize emissions performance
- apply the correlations and compare the performance of Canadian refineries to comparable U.S. refineries

A study on benchmarking of regulatory regimes for refineries was carried out in parallel with the emission performance benchmarking study.

EMISSION PERFORMANCE DATA

The U.S. EPA compiles a comprehensive National Emission Inventory (NEI) covering both criteria air contaminants (CACs – CO, NO_x, SO₂, VOC, direct PM₁₀ and PM_{2.5} and ammonia) and hazardous air pollutants (HAPs). Data on 138 refineries was extracted from the NEI database and used in this study. Although HAPs data are being integrated into the NEI, they were still in draft form while this study was being conducted. As a result, the U.S. Toxics Release Inventory (TRI) was used as the source of emissions data for non-criteria contaminants, including benzene. The most currently available dataset was for the year 1999. NEI emissions data for the U.S. refineries is summarized in Table S-1. It should be noted that the emission correlations developed for this study typically use a subset of the data shown, as not all 138 refineries are used for each correlation.

Table S-1: Summary of U.S. Refinery Emissions by Petroleum Administration Defense District (PADD)

Region	Number of Refineries	Emissions* (tonnes per year)							
		CO	VOC	NOx	SO ₂ *	PM ₁₀	PM _{2.5}	NH ₃	benzene
PADD I	14	37,891	10,220	20,049	48,765	4,514	3,897	1,286	50
PADD II	28	28,220	29,550	63,992	142,489	8,903	7,450	3,917	169
PADD III	54	83,838	63,980	97,746	115,008	18,537	16,864	723	355
PADD IV	15	3,880	8,011	6,721	18,786	2,099	1,735	1,328	32
PADD V	27	10,362	15,396	26,523	30,245	4,655	3,749	5,850	48
ALL	138	164,192	127,157	215,031	355,293	38,708	33,696	13,104	654

Region	Number of Refineries	Emissions* (short tons per year)							
		CO	VOC	NOx	SO ₂ *	PM ₁₀	PM _{2.5}	NH ₃	benzene
PADD I	14	41,775	11,268	22,105	53,764	4,976	4,297	1,418	56
PADD II	28	31,112	32,579	70,551	157,094	9,815	8,213	4,318	187
PADD III	54	92,432	70,538	107,765	126,797	20,437	18,593	797	391
PADD IV	15	4,278	8,832	7,410	20,712	2,314	1,913	1,464	35
PADD V	27	11,424	16,974	29,241	33,345	5,133	4,133	6,450	52
ALL	138	181,021	140,190	237,072	391,711	42,676	37,149	14,447	721

* Emissions data are for 1999, with the exception of 1996 data for SO₂ used for four refineries in Ohio which reported zero SO₂ emissions in the 1999 NEI database

For Canadian refineries, twenty facilities were identified for inclusion in the benchmarking analysis, including national and regional companies. For refineries which are operated by member companies of the Canadian Petroleum Products Institute (CPPI), emissions data for CACs for the year 2001 were generally provided directly from the respective companies. One CPPI facility did not provide data. Emissions performance data for the three non-CPPI member refineries was not available directly from the facilities. In situations where data were not provided, the best available data obtained from regulatory agencies, federal or provincial government inventories or other sources, were used. Data on non-criteria contaminants were extracted from the National Pollutant Release Inventory (NPRI) for 2001. Canadian refinery emission data are summarized in Table S-2.

Table S-2: Summary of Canadian Refinery Emissions by Region

Region	Number of Refineries	Emissions (tonnes per year)								
		CO	VOC	NOx	SOx	PM	PM ₁₀	PM _{2.5}	NH ₃	benzene
Western Canada	7	3,606	4,000	5,089	16,843	1,230	916	649	9	39
Ontario	7	6,295	6,782	10,455	59,090	3,128	2,493	1,660	4	121
Québec	3	1,456	3,326	4,598	14,220	805	633	424	3	30
Atlantic Canada	3	2,172	7,629	9,393	28,440	1,686	1,172	598	10	23
Total	20	13,529	21,736	29,535	118,593	6,849	5,215	3,331	26	213

Region	Number of Refineries	Emissions (short tons per year)								
		CO	VOC	NOx	SOx	PM	PM ₁₀	PM _{2.5}	NH ₃	benzene
Western Canada	7	3,975	4,409	5,610	18,567	1,356	1,010	715	10	43
Ontario	7	6,940	7,476	11,524	65,136	3,448	2,748	1,830	5	133
Québec	3	1,605	3,666	5,069	15,675	887	698	467	3	33
Atlantic Canada	3	2,394	8,410	10,354	31,350	1,859	1,292	659	11	26
Total	20	14,913	23,960	32,557	130,727	7,550	5,749	3,671	28	235

Notes: Data does not include CO and particulate for Parkland Bowden
 Data are for 2001, or most current year where 2001 data is not available

NORMALIZING AND OPERATING PARAMETERS USED FOR BENCHMARKING

Benchmarking can be defined in different ways, depending on the intended use of the analysis. Within the context of this project, ‘environmental benchmarking’, or ‘benchmarking of environmental performance’, was considered to involve determining the levels of emission performance that are being achieved for generic groups of facilities. Moreover, with the intended use of environmental benchmarking understood as an improvement tool, its goal is to lead to improved environmental performance.

For this study, the emission performance of U.S. refineries has been used to develop benchmarks against which the performance of Canadian refineries can be compared. In making these comparisons, normalizing of emissions data may be needed to limit the bias due to differences in scale of operation, feedstock, product specifications, emission control or regulatory differences and other inherent process conditions that may impact on environmental performance.

With the U.S. refinery emission performance data in place, the next step in the benchmarking analysis was to assemble a data base of appropriate process and operating information needed to investigate approaches for normalizing emissions data. Light sweet, light sour and heavy sour crude runs for each refinery were estimated using publicly available information from the U.S. Department of Energy, Energy Information Administration and the Oil and Gas Journal publication. Data was also compiled for each refinery on configuration, capacity and production. Where available, information was also gathered on site-specific parameters which could affect emissions, such as emission control technology, fuel type and the presence of certain processing units.

Initially, each refinery operating in the U.S. in 1999 was categorized according to six different index configurations:

- light sweet crude feed in a fluid catalytic cracking (FCC) operating mode,
- light sour crude feed in a FCC operating mode,
- light sweet crude feed in a coking operating mode,
- light sour crude feed in a coking operating mode,
- heavy sour feed in a cracking operating mode, and
- heavy sour feed in a coking operating mode.

For Canadian refineries, capacities were determined from the Oil & Gas Journal for 2001. Crude slates by Canadian refinery were estimated using published pipeline statistics, Statistics Canada reports, and company annual reports. Canadian refineries were then categorized according to the six index configurations listed above. It should be noted that several Canadian refineries have unique configurations that are difficult to represent using the six index refineries. These include Shell Scotford, Parkland Refining, Nova Chemicals and Petro-Canada's lube plant in Mississauga.

The assembled data on potential normalizing parameters, including operating data and index configurations, was combined with emissions performance data to develop emission correlations for U.S. refineries, as described below.

U.S. REFINERY EMISSIONS CORRELATIONS

For each of the air contaminants of interest, a number of different normalizing options, as well as iterations within those options, were used in order to develop recommended benchmark correlations. The adequacy of the correlations was characterized by the statistical R-squared (R^2) value¹.

A total of 74 U.S. refinery emission correlations were developed over the course of this study. The number of refineries included in each correlation varies, depending on the crude type, configuration and other parameters. Some correlations underwent multiple iterations or trials to examine different refinery crude capacity ranges, or examine the impact of certain processing units or equipment (e.g. VGO hydrotreating, CO boilers, lube plants, aromatics extraction). As noted above, emissions data for 1999 was compiled for 138 U.S. refineries. For a given correlation, only a subset of this data was used, depending on the crude type, configuration, etc. For most correlations, all available U.S. refinery emission data has been included. Situations such as on-going non-compliance with operating permit conditions, and regulatory or emission control differences, were not considered valid reasons for exclusion. Rather, these were considered to be factors which contribute to the overall scatter in emissions performance.

The 74 emission correlations for U.S. refineries developed for this study were reviewed by the NFPRER Benchmarking Sub-Group over a series of draft reports, monthly teleconferences, meetings and correspondence.

¹ The R^2 value is the square of the Pearson product moment correlation coefficient, and can be interpreted as the proportion of variance in y values attributable to the variance in x values. The R^2 value can range from 0 to 1, with a value of 1 indicating the highest degree of linear relationship between x and y values.

In the sections that follow, a discussion is provided of the benchmark correlations which are recommended for use by the consultant team, as well as the application of those correlations to compare Canadian to U.S. refinery performance.

SO_x

Refinery SO_x emissions are primarily impacted by crude slate sulphur content and FCC throughput. FCCs are the predominant source through catalyst regeneration, while fluid cokers can be a significant source as a portion of the high sulphur coke generated is combusted as an energy source. Fuel combustion can also be a significant source of SO_x emissions, particularly in the case of refineries which use heavy fuel oil rather than still gas or natural gas, and those which burn fuel grade coke. As crude slate sulphur increases, so does the FCC sulphur content. However, many heavy sour crude refineries have FCC feed hydrotreating, which reduces the sulphur content of the FCC feed and hence the SO_x emissions. The efficiency of sulphur recovery units also impact on refinery SO_x emissions; for example a facility with a high recovery efficiency through tail gas clean-up will have lower SO_x emissions compared to a facility with no tail gas clean-up.

SO_x emissions were initially normalized to FCC and fluid coker capacity for all U.S. cracking and coking refineries. SO_x emissions were then normalized to total crude throughput for all U.S. refineries, which resulted in a stronger correlation than was obtained based on FCC and fluid coker capacity. As a result, in an effort to further reduce uncertainty, correlations were developed (on the basis of crude throughput) for increasingly rigorous refinery categories, as follows:

- all refineries
- all refineries with VGO (vacuum gas oil) hydrotreaters
- all refineries without VGO hydrotreaters
- cracking refineries regardless of crude type
- cracking refineries with VGO hydrotreating
- cracking refineries without VGO hydrotreating
- coking refineries regardless of crude type
- coking refineries with VGO hydrotreating
- coking refineries without VGO hydrotreating
- six index refinery configurations

In addition, a number of the SO_x correlations were run for all refineries (of all capacity) and for refineries in the 50 to 250 thousand barrels per day capacity range.

NO_x

NO_x emissions from refineries originate mainly from combustion of fuels in furnaces and boilers. The type of fuel has a significant impact on NO_x emissions. Significant NO_x emissions are also produced through the regeneration of FCC catalyst and the combustion of fluid coke. It is expected that NO_x emissions should correlate with refinery throughput, and be influenced by the refinery's energy intensity – the more conversion capacity installed in a refinery, the higher the energy intensity per unit of crude processed. NO_x emissions were correlated to refinery crude throughput for all refineries, and then for: cracking refineries regardless of crude type; coking refineries regardless of crude type; and six index refineries.

Carbon Monoxide

The primary sources of carbon monoxide at refineries are FCC catalyst regeneration and fluid coke burning, as well as incomplete combustion of fuel in boilers and furnaces. Some refineries have CO boilers to recover heat from CO generated at the FCC or fluid coker. CO emissions

were normalized to both crude throughput, and to combined FCC and fluid coker capacity. Two additional correlations were developed on the basis of FCC and fluid coker capacity for refineries with and without CO boilers.

Particulate

The FCC is the primary source of particulate matter emissions at refineries, from FCC catalyst regeneration and in the regenerator flue gas. Fired heaters and fluid coke burning can also be significant sources. Emissions of the PM₁₀ and PM_{2.5} fractions of particulate matter were correlated separately, and both on the basis of crude throughput. Further correlations were developed on the basis of FCC and fluid coker capacity for all cracking/fluid coking refineries.

Volatile Organic Compounds

VOC emissions arise from a variety of sources at refineries, including process, fugitive, storage and transfer, and wastewater releases. Three correlations were developed, normalizing VOC emissions to crude throughput for all U.S. refineries, and to crude throughput for refineries with and without lubes manufacturing plants.

Ammonia

Ammonia is a byproduct of reactions that occur in hydrotreating processes, with a prominent source being facilities that handle sour water from hydrotreating. Ammonia may also be present as a reagent used in flue gas scrubbers for SO_x control or selective catalytic on non-catalytic reduction systems for NO_x control. It was expected that ammonia emissions would trend with hydrotreating capacity, and an NH₃ correlation was developed on that basis. A second NH₃ correlation was developed, normalizing emissions to crude throughput.

Benzene

Small quantities of benzene exist naturally in crude oil. It is also manufactured at refineries in catalytic naphtha reformers. Many refineries have fractionation facilities to remove benzene from reformate to meet gasoline benzene specifications, while others have aromatics extraction units to remove benzene, toluene and xylene. The extracted components are used in petrochemical manufacturing. Four benzene correlations were developed, two based on crude capacity (with and without aromatics extraction), one based on reformer capacity and the fourth on combined reformer and aromatics extraction unit capacity.

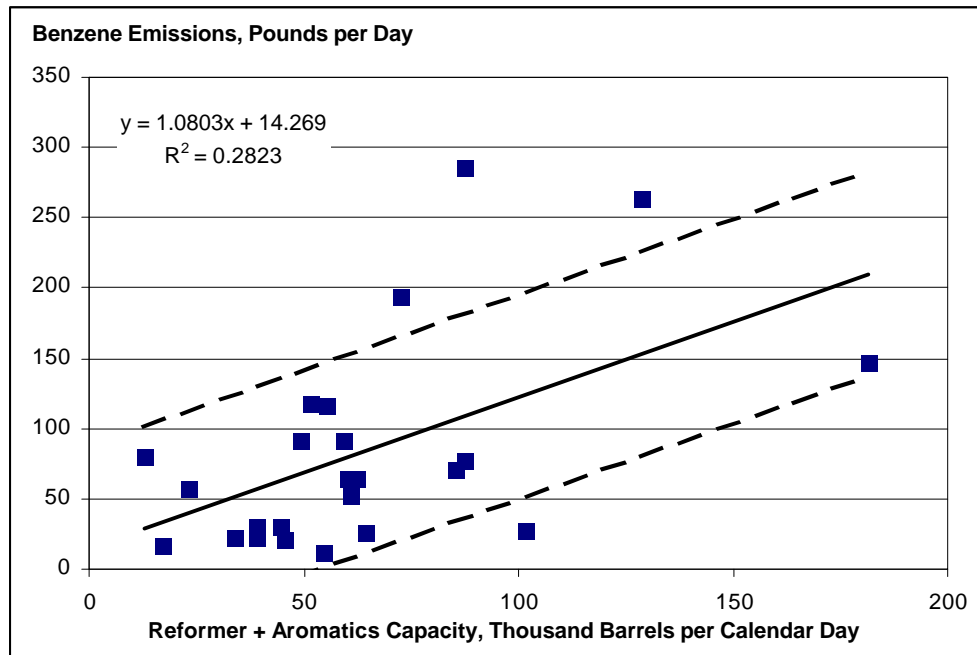
Recommended Correlations

Based on input from the sub-group, the set of correlations summarized in Table S-3 emerged as the most promising correlations to use in the benchmarking analysis. The correlations recommended by the consultant team are discussed and applied in the benchmarking analysis, in the sections that follow. It should be noted that there has been considerable debate within the benchmarking sub-group on the correlations which should be used for benchmarking. While the consultant team's recommended correlations are presented in this report, the other correlations which were developed are documented, should the Benchmarking Sub-Group, NFPRER Steering Committee, or other body wish to consider them or explore them further. In addition, the emissions and operating data used for normalizing have been provided, to facilitate development of new or alternative correlations.

Table S-3 shows correlations which were developed based on all U.S. refineries, and refineries which are in the capacity range of 50 to 250 thousand barrels per day of crude. In general, the correlations using limited capacity range are poorer. For this reason, and to account for large refineries in the U.S. which operate as multiple train facilities (like parallel smaller refineries operating within a single site), the correlations recommended in this study are based on the inclusion of "all data".

All recommended correlations are presented as equations plus or minus a confidence limit. Figure S-1, shown below, illustrates this concept. The actual emission, benzene in this case, is plotted as a function of the selected normalizing variable, unit capacity in this case. A linear correlation is then developed to determine the relationship of the emission to the normalizing variable. The data generally have a fair amount of “scatter” around the correlation. This scatter, is measured as the standard deviation of the actual versus predicted error (difference between actual emissions reported for a given facility, and the emission value predicted by the correlation equation). A 75% confidence limit of the correlation prediction is then determined based on the standard deviation of the actual versus predicted error. The benchmark emission for each Canadian refinery is then determined as the correlation prediction plus or minus the 75% confidence limit of the correlation prediction. As such, the benchmark emissions for the Canadian refineries are not single values, rather a range. Should the actual emission for the Canadian refinery fall within this range, it would be deemed comparable to the U.S. refineries within the 75% confidence limit of the correlation.

Figure S-1: Sample Emission Correlation – U.S. Refineries with Aromatics Extraction – Benzene Emissions



BENCHMARKING ANALYSIS

Benchmark emissions were developed for each refinery in Canada using the emissions correlations developed from U.S. refinery data. A 75% confidence range was determined for each refinery’s benchmark emissions.

All Canadian refineries have been included in the benchmarking analysis. However, four facilities – Shell Scotford, Parkland Refining, Nova Chemicals and Petro-Canada in Mississauga – have been benchmarked using the most appropriate correlations, but it should be noted that they have unique configurations which differ somewhat from the correlations used.

SO_x

Benchmark SO_x emissions were determined for each Canadian refinery on the basis of crude throughput and refinery configuration in 2001. Three refineries, Petro-Canada in Edmonton, Co-op/Newgrade in Regina, and Imperial Oil in Sarnia, are coking refineries. The SO_x benchmark

emissions and 75 percent confidence limits of the benchmark emissions were determined using the all-coking refineries correlation [SOx-7a], while the benchmarks for the remaining refineries were determined using the all-cracking refineries correlation [SOx-4a].

In general, none of the correlations developed for SOx exhibited strong linearity. The all cracking and all coking correlations had R^2 values of 0.22 and only 0.04, respectively. The light sweet crude cracking, light sweet crude coking, light sour crude coking, and heavy crude cracking refinery SOx correlations had better R^2 and narrower confidence limits than the all-cracking or all-coking refineries correlation. However, the light sour and heavy crude coking refinery correlations were very poor with R^2 near zero and wide 75% confidence ranges. Despite these correlations being an improvement to the all-cracking or all-coking refineries correlations for four of the six index refinery configurations, this benchmarking methodology is not recommended. Detailed information on both the U.S. and Canadian refineries crude slates is required to accurately categorize each refinery to establish the benchmark correlations and the benchmark ranges for the Canadian refineries, This information is generally not available in the public domain, and it is not a trivial exercise to estimate each U.S. refinery's crude slate based on publicly available information. A primary goal of this benchmarking exercise was to develop a methodology that was transparent, easy to explain, and relatively simple to update if necessary. Because the six-index refineries methodology does not rely on information readily available in the public domain, it does not readily meet the requirements of being transparent and simple to update. For this reason, the six-index refineries benchmarking methodology is not recommended for SOx.

Figure S-2, shown below, compares the actual emissions for each refinery with the 75 percent confidence range of the benchmark emissions established from the U.S. refinery data. Seventeen refineries fall within the 75% confidence range of the benchmark correlations, and of these, eleven have emissions that are higher than the benchmark mid-point. Three refineries have emissions which exceed the upper limit of the 75% confidence range.

Two special cases are shown for SOx. Sulphur recovery for the Shell and Petro-Canada refineries in Montréal are provided by a third party, Sulconam Inc. The actual emissions for these two refineries are shown with and without the SOx emissions at the Sulconam plant. The Shell Sarnia facility produces steam in excess of its own production needs, for sale to adjacent facilities. The actual emissions for Shell Sarnia have been shown with and without SOx emissions resulting from the production of steam for sale.

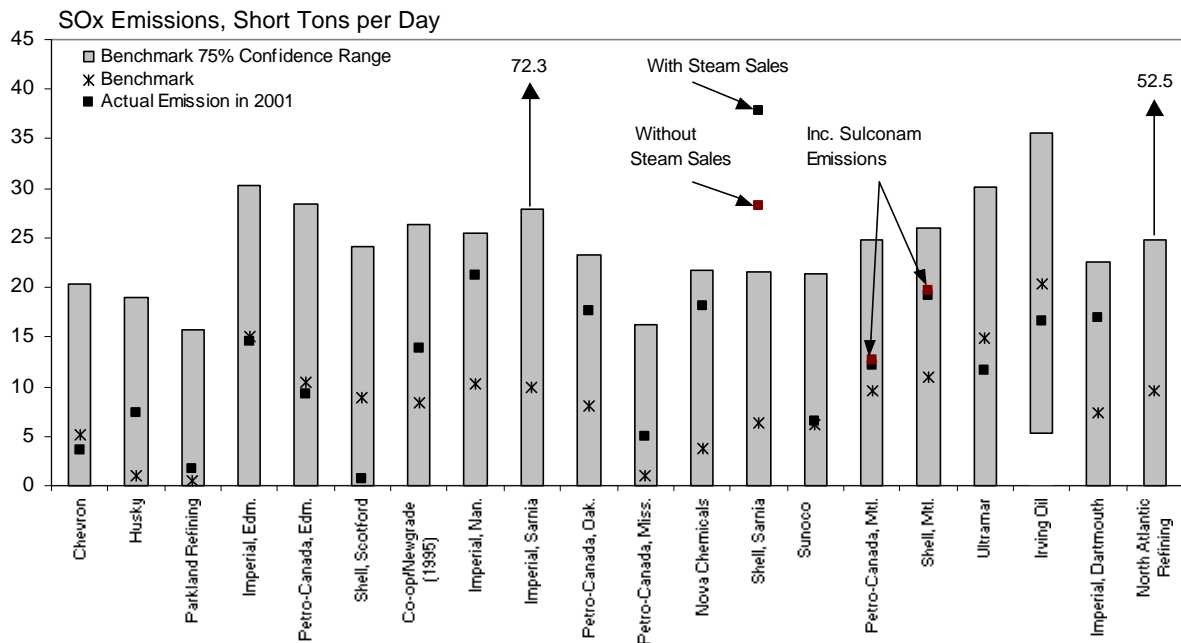
Table S-3: Summary of Emission Correlations for U.S. Refineries

normalizing parameter	All Data				50 to 250 thousand barrels per day capacity				
	correlation no.	regression	R ²	sample size	correlation no.	regression	R ²	sample size	
SO_x									
all US refineries	crude runs	SOx-1a	y = 0.0552x + 2.3546	0.15	130				
all US refineries with VGO hydrotreating	crude runs	SOx-2a	y = 0.0288x + 3.0671	0.17	41	SOx-2b	y = 0.0283x + 2.9761	0.08	49
all US refineries without VGO hydrotreating	crude runs	SOx-3a	y = 0.0843x + 1.3956	0.22	89	SOx-3b	y = 0.077x + 2.6826	0.08	26
US cracking refineries	crude runs	SOx-4a	y = 0.0946x + 0.0883	0.22	52	SOx-4b	y = 0.0295x + 5.0832	0.04	36
US cracking refineries with VGO hydrotreating	crude runs	SOx-5a	y = 0.0461x + 1.2855	0.29	19	SOx-5b	y = 0.0598x - 0.2528	0.33	15
US cracking refineries without VGO hydrotreating	crude runs	SOx-6a	y = 0.1268x - 0.2345	0.29	33	SOx-6b	y = 0.0145x + 7.7291	0.01	21
US coking refineries	crude runs	SOx-7a	y = 0.0286x + 6.9124	0.04	53	SOx-7b	y = 0.0598x + 3.8066	0.04	35
US coking refineries with VGO hydrotreating	crude runs	SOx-8a	y = 0.0242x + 3.9019	0.10	22	SOx-8b	y = -0.0263x + 9.6087	0.09	11
US coking refineries without VGO hydrotreating	crude runs	SOx-9a	y = 0.0469x + 6.9473	0.06	31	SOx-9b	y = 0.0947x + 2.0578	0.07	24
<i>simplified indexing</i>									
US light sweet crude cracking	crude runs	SOx-10a	y = 0.0338x + 2.5928	0.37	25	SOx-10b	y = 0.0364x + 2.6403	0.14	15
US light sweet crude coking	crude runs	SOx-11a	y = 0.0339x + 0.8659	0.25	10	SOx-11b	y = 0.0099x + 3.2739	0.03	9
US light sour crude cracking	crude runs	SOx-12a	y = 0.1452x - 3.4547	0.25	21	SOx-12b	y = 0.023x + 7.1269	0.02	19
US light sour crude coking	crude runs	SOx-13a	y = 0.021x + 6.288	0.09	22	SOx-13b	y = -0.0316x + 12.441	0.16	13
US heavy crude cracking	crude runs	SOx-14a	y = 0.1023x + 2.6842	0.53	4	SOx-14b	y = -0.122x + 13.75	1.00	2
US heavy crude coking	crude runs	SOx-15a	y = 0.07x + 6.4084	0.06	20	SOx-15b	y = 0.1798x - 2.7234	0.16	13
NO_x									
US cracking and coking refineries	crude runs	NOx-1a	y = 0.0439x + 0.2357	0.54	107	NOx-1b	y = 0.0307x + 1.3713	0.25	78
US coking refineries	crude runs	NOx-2a	y = 0.0433x + 0.7941	0.51	53	NOx-2b	y = 0.0349x + 1.7513	0.22	35
US cracking refineries	crude runs	NOx-3a	y = 0.0389x + 0.2644	0.41	54	NOx-3b	y = 0.0241x + 1.5454	0.32	39
CO									
refineries with CO boiler	FCC + fluid coking cap.	CO-1a	y = 0.0439x - 0.1069	0.55	24	CO-1b	y = 0.0153x + 1.0143	0.05	15
refineries without CO boiler	FCC + coker capacity	CO-2a	y = 0.119x - 1.0412	0.15	79	CO-2b	y = -1E-05x + 4.4156	<0.01	54
all US refineries	crude runs	CO-3a	y = 0.0387x - 0.5486	0.14	135				
PM₁₀									
US cracking/fluid coking refineries	FCC + fluid coking cap.	PM ₁₀ -1a	y = 0.0161x + 0.2542	0.35	99	PM ₁₀ -1b	y = 0.007x + 0.6686	0.06	67
all US refineries	crude runs	PM ₁₀ -2a	y = 0.0079x + 0.0511	0.46	131	PM ₁₀ -2b	y = 0.0041x + 0.4673	0.10	75
PM_{2.5}									
US cracking/fluid coking refineries	FCC + fluid coking cap.	PM _{2.5} -1a	y = 0.0148x + 0.1751	0.36	99	PM _{2.5} -1b	y = 0.0073x + 0.5123	0.08	67
all US refineries	crude runs	PM _{2.5} -2a	y = 0.0072x + 0.0012	0.46	131	PM _{2.5} -2b	y = 0.004x + 0.3535	0.11	75
VOC									
US refineries without lube plants	crude runs	VOC-1a	y = 0.0144x + 1.2611	0.18	113	VOC-1b	y = 0.0039x + 2.611	0.01	69
US refineries with lube plants	crude runs	VOC-2a	y = 0.018x + 0.9076	0.72	21	VOC-2b	y = 0.0252x - 0.1707	0.60	8
NH₃									
all US refineries	crude runs	NH ₃ -1a	y = 3.5296x + 202.42	0.06	135	NH ₃ -1b	y = 0.6146x + 367.71	<0.01	80
benzene									
US refineries without aromatics extraction	crude runs	C ₆ H ₆ -1a	y = 0.0961x + 12.859	0.21	90	C ₆ H ₆ -1b	y = -0.0037x + 26.008	0.00	53
US refineries with aromatics extraction	crude runs	C ₆ H ₆ -2a	y = 0.2749x + 33.606	0.12	24	C ₆ H ₆ -2b	y = 0.0625x + 46.483	0.01	17
US refineries without aromatics extraction	Reformer Cap	C ₆ H ₆ -3a	y = 0.3867x + 14.065	0.22	79				
US refineries with aromatics extraction	Reformer +Aromatics cap	C ₆ H ₆ -4a	y = 1.0803x + 14.269	0.28	24				

Table S-4: Correlations Used for Canadian Refineries

facility	location	province	SOx	NOx	benchmark correlation				
					CO	PM ₁₀	PM _{2.5}	VOC	C ₆ H ₆
Chevron	Burnaby	B.C.	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Newgrade / Consumer's Co-op	Regina	Saskatchewan	SOx-7a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Husky	Prince George	B.C.	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Imperial Oil	Strathcona	Alberta	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-2a	C ₆ H ₆ -3a
Imperial Oil	Dartmouth	Nova Scotia	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Imperial Oil	Nanticoke	Ontario	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Imperial Oil	Sarnia	Ontario	SOx-7a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-2a	C ₆ H ₆ -4a
Irving Oil	Saint John	New Brunswick	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
North Atlantic Refining	Come By Chance	Newfoundland	SOx-4a	NOx-1a	CO-3a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Novacor Chemicals	Corunna	Ontario	SOx-4a	NOx-1a	CO-3a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -4a
Parkland Refining	Bowden	Alberta	SOx-4a	NOx-1a	CO-3a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Petro-Canada	Edmonton	Alberta	SOx-7a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Petro-Canada	Oakville / Mississauga	Ontario	SOx-4a	NOx-1a	CO-3a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-2a	C ₆ H ₆ -3a
Petro-Canada	Oakville	Ontario	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a
Petro-Canada	Montréal	Québec	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -4a
Shell	Montréal	Québec	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-2a	C ₆ H ₆ -3a
Shell	Sarnia	Ontario	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -4a
Shell	Scotford	Alberta	SOx-4a	NOx-1a	CO-3a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -4a
Sunoco	Sarnia	Ontario	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -4a
Ultramar	Lévis	Québec	SOx-4a	NOx-1a	CO-1a,2a	PM ₁₀ -2a	PM _{2.5} -2a	VOC-1a	C ₆ H ₆ -3a

FIGURE S-2: SO_x EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES



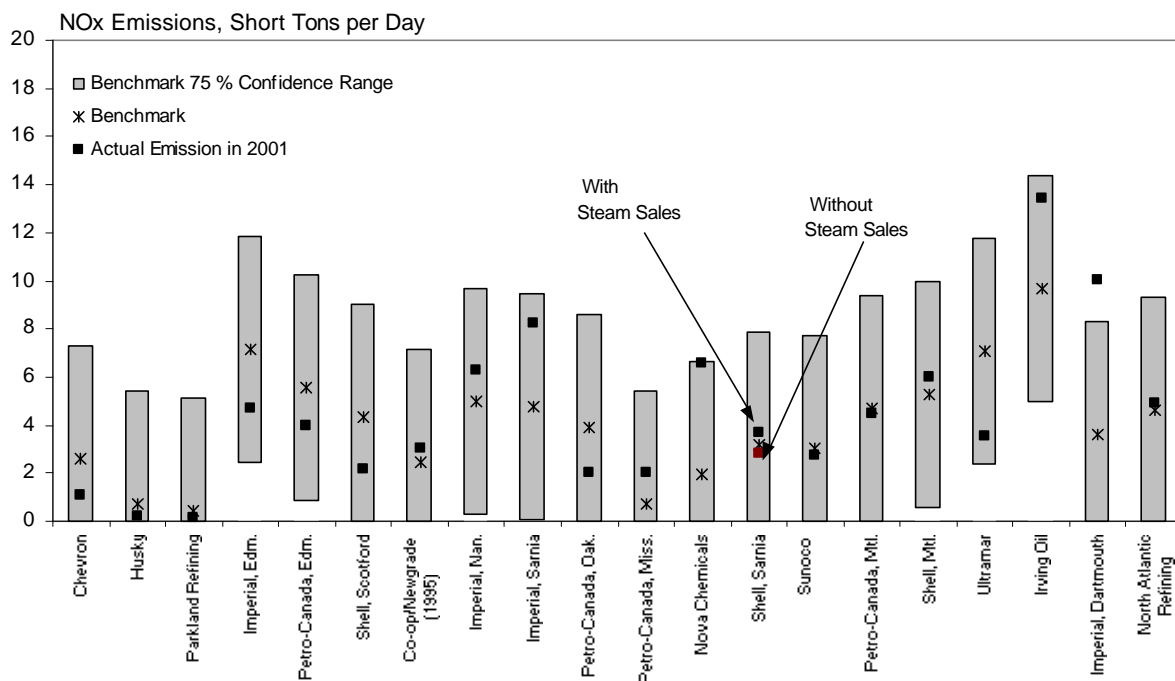
Note: "with steam sales" and "without steam sales" means with and without SO_x emissions resulting from the production of steam for sale

NO_x

Benchmark NO_x emissions were determined for each Canadian refinery using a correlation and 75% confidence limits that incorporate all U.S. cracking and coking refineries as a function of crude throughput. This correlation [NO_x-1a] had the highest R² for NO_x, of all correlations tested, at 0.54. The correlation predicts benchmark NO_x emissions plus or minus 4.7 short tons per day, within a 75% confidence range.

Figure S-3, shown below, compares the actual emissions for each refinery with the 75 percent confidence range of the benchmark emissions established from the U.S. refinery data. Only one refinery is above the 75% confidence range while the remaining 19 are within the range. Of the 19 within the range, 10 have emissions lower than the benchmark range mid-point and 8 are above. As described earlier for SO_x emissions, emissions from the Shell Sarnia refinery have been shown with and without emissions generated from the generation of steam for sale. The exclusion of NO_x emissions from steam sales puts the Shell Sarnia facility slightly below the mid-point of the benchmark range, while inclusion puts it slightly above. The inclusion of emissions from the Sulconam sulphur recovery plant do not result in an appreciable increment in NO_x emissions for the Petro-Canada and Shell refineries in Montréal, so have not been shown here.

FIGURE S-3: NO_x EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES



Note: “ with steam sales” and “without steam sales” means with and without NO_x emissions resulting from the production of steam for sale

CO

Benchmark CO emissions were determined for the Shell Scotford Refinery, the North Atlantic Refinery, Parkland, Nova Chemicals, and Petro-Canada’s Mississauga lube plant using the all-U.S. refineries correlation that normalizes CO emissions to crude throughput ([CO-3a], with R² = 0.14). These refineries were benchmarked on this basis since none have FCC units. The remaining refineries were benchmarked using FCC + Fluid Coker capacity as the normalizing variable for both refineries with and without waste heat boilers ([CO-1a] and [CO-2a], R² = 0.55 and 0.15, respectively).

Figures S-4(a) and S-4(b), shown below, contain comparisons of the Canadian refinery CO emissions to the relevant benchmarks. Canadian refinery performance was compared to U.S. refineries with CO boilers, resulting in all refineries falling within the 75% confidence range, and without CO boilers where three refineries fall above the benchmark range.

Particulate Matter

Benchmark PM₁₀ and PM_{2.5} emissions were determined on the basis of total crude throughput for each refinery in Canada, using correlations [PM₁₀-2a] and [PM_{2.5}-2a], which both have R² values of 0.46. Figures S-5a and S-5b, shown below, compare the actual particulate emissions for the Canadian refineries to the benchmark range. For PM₁₀, all refineries fall within the benchmark range (if emissions from steam sales are excluded for Shell Sarnia), and for PM_{2.5}, two refineries are slightly below the 75% confidence range.

FIGURE S-4a: CO EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES
(Based on U.S. Refineries Without CO Boilers)

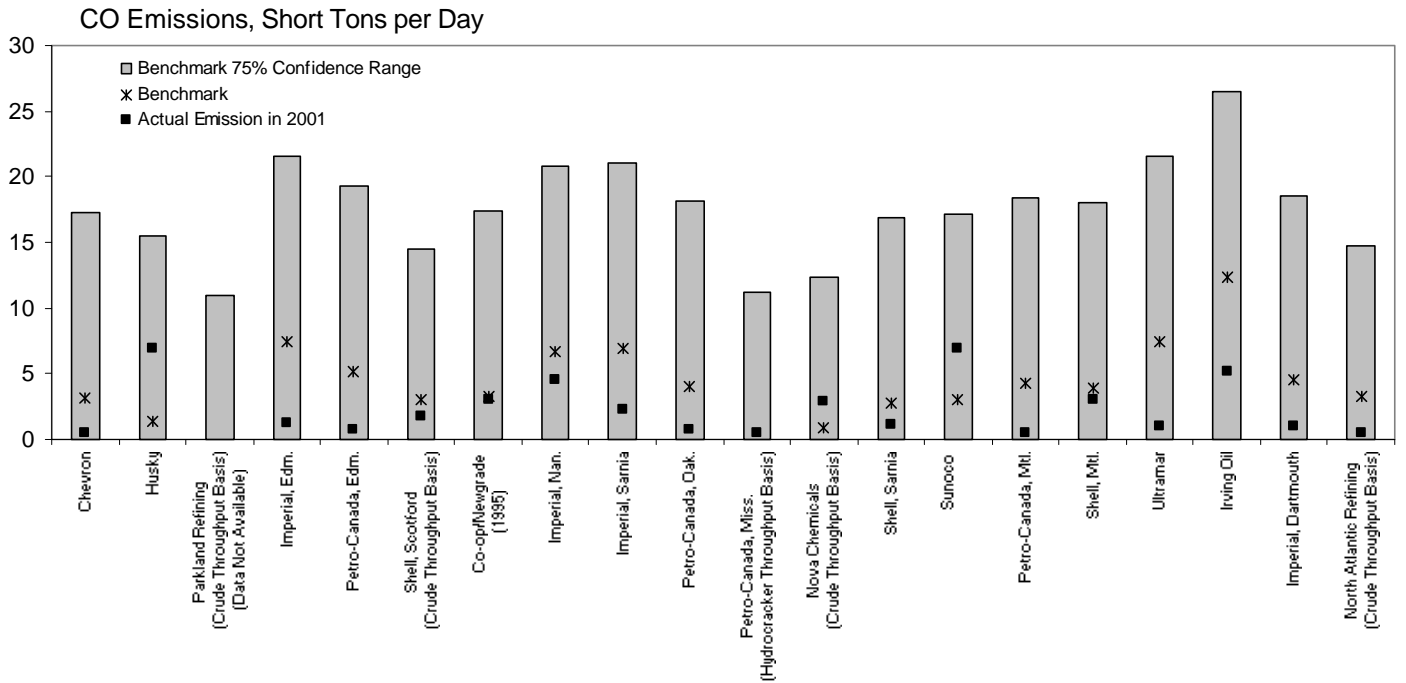


FIGURE S-4b - CO EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES
(Based on U.S. Refineries With CO Boilers)

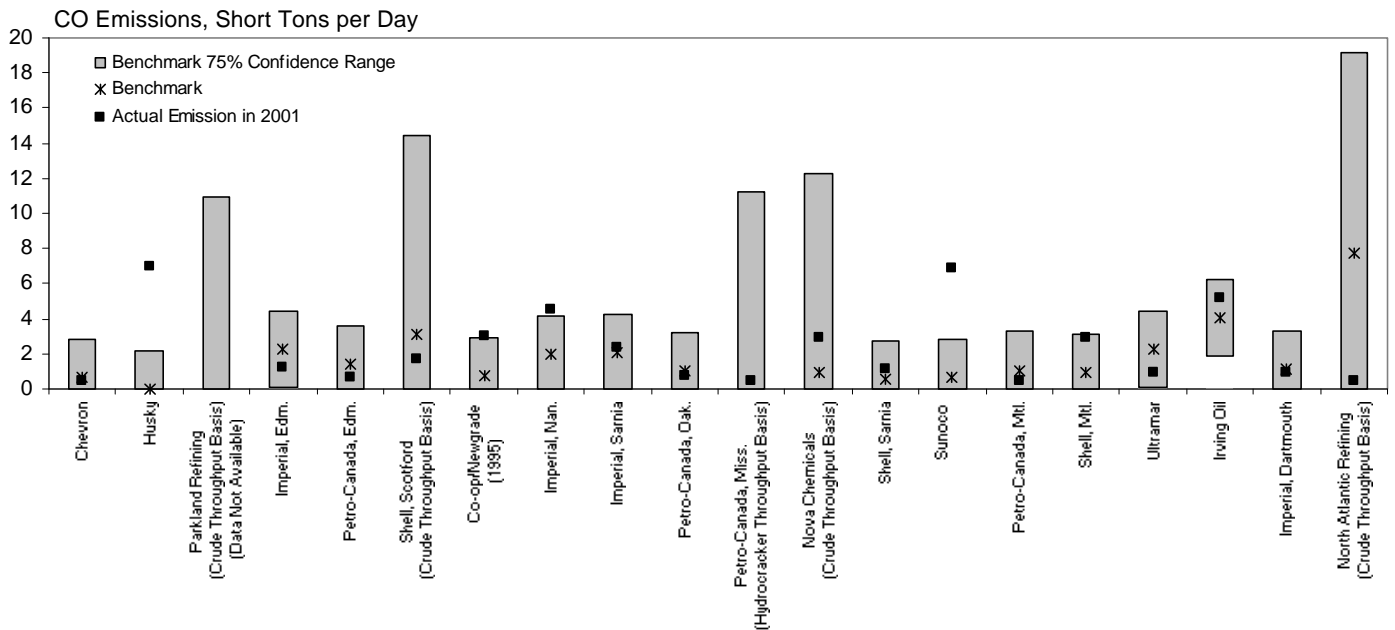


FIGURE S-5a: PM₁₀ EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES

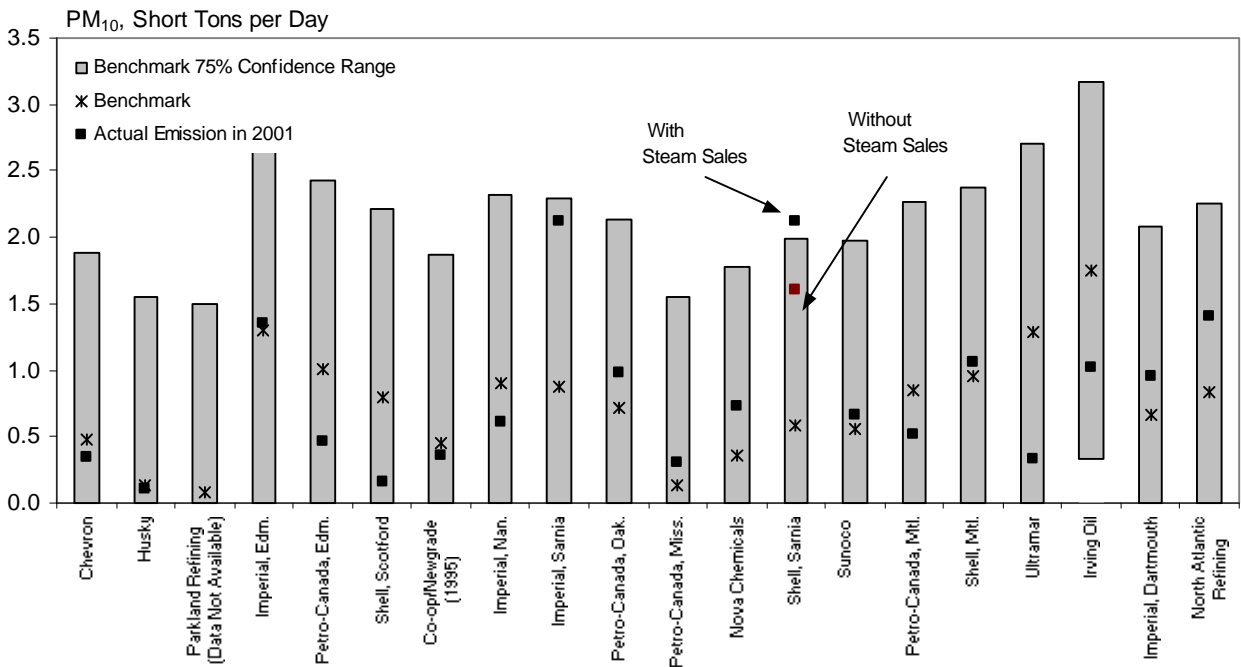
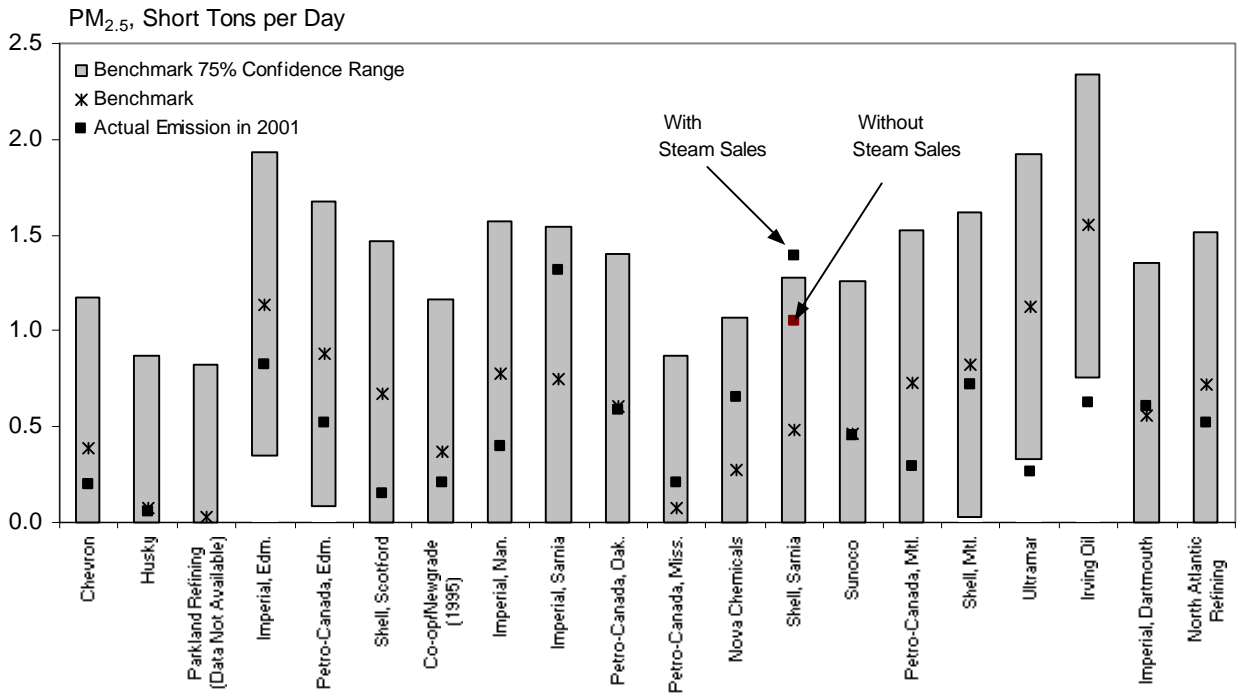


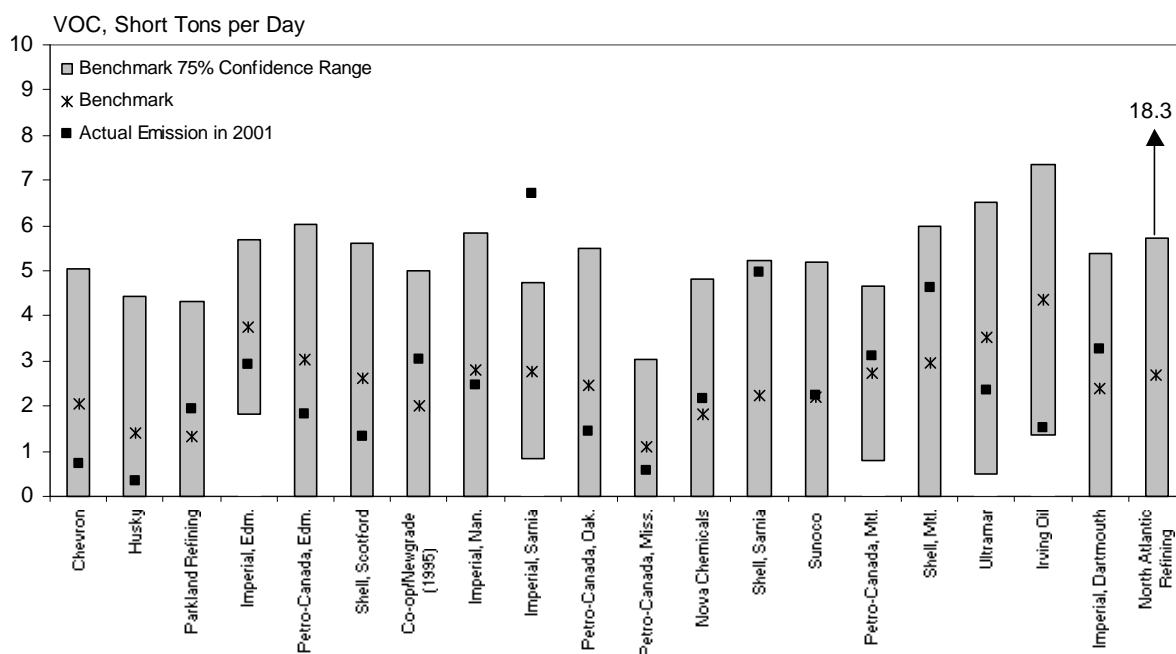
FIGURE S-5b: PM_{2.5} EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES



VOC

Benchmark VOC emissions were established using correlations which normalize VOC emissions to crude throughput for all U.S. refineries that do not have lube plants [VOC-1a] and all U.S. refineries that have lube plants [VOC-2a]. These correlations exhibited R^2 values of 0.18 and 0.72, respectively. Imperial Oil's Edmonton and Sarnia refineries, Petro-Canada's Mississauga lube plant, and Shell's Montréal refinery have lube plants, while the remaining refineries do not. Figure S-6, shown below, compares the actual Canadian refinery VOC emissions to the benchmark range determine using the U.S. refinery emissions data. For VOC, 18 refineries have emissions within the range, and two are above.

FIGURE S-6: VOC EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES



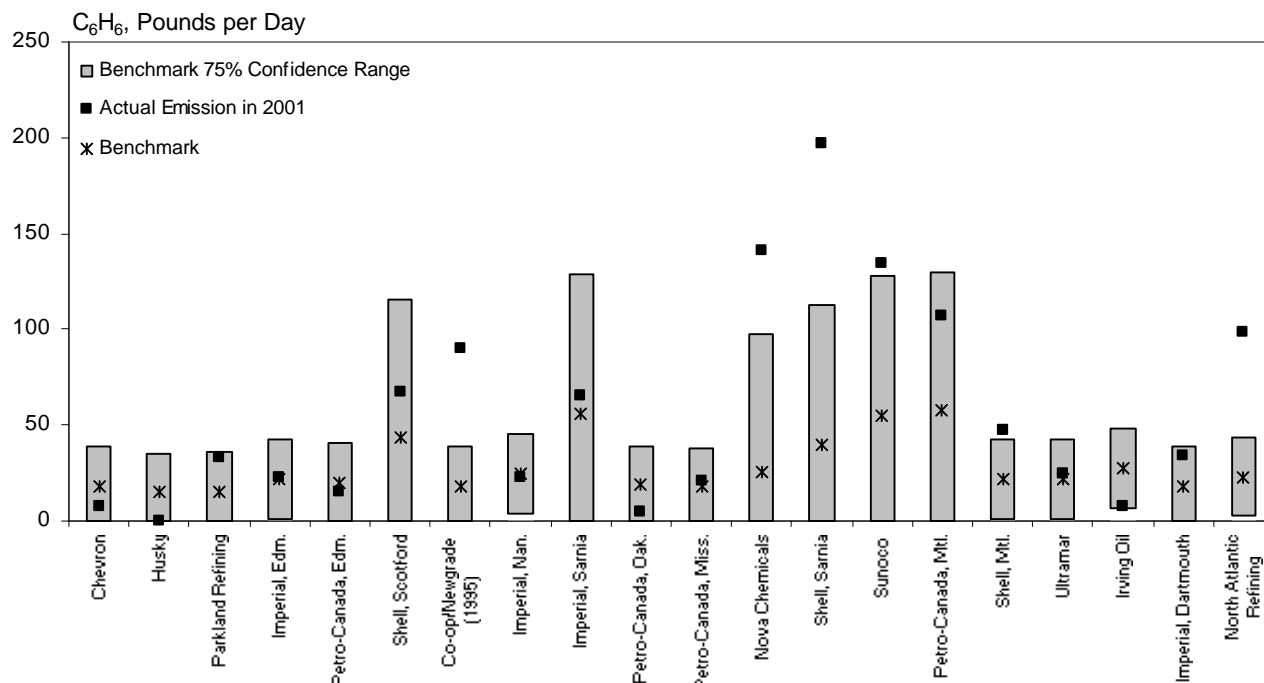
NH₃

The correlation developed for ammonia is [NH₃-1a], which normalizes emissions as a function of crude throughput, with an R^2 value of only 0.06. Canadian refinery emissions of ammonia were found to be well below refineries in the U.S. The higher U.S. ammonia emissions are likely due to ammonia slip from use in selective catalytic reduction systems for NO_x control. No benchmark is recommended for ammonia, as there does not appear to be a valid basis for comparison between Canadian and U.S. refinery ammonia emissions.

Benzene

Benchmark benzene emissions for each Canadian refinery were determined on the basis of reformer unit capacity for refineries without aromatics extraction, and reformer + aromatics extraction capacity for refineries with aromatics extraction ([C₆H₆-3a] and [C₆H₆-4a], with R^2 values of 0.22 and 0.28). The comparison of the actual emissions to the benchmark ranges is shown in Figure S-7, below. Six facilities have emissions above the range, and the remainder fall within the 75% confidence range of the benchmark prediction.

FIGURE S-7: C₆H₆ EMISSIONS BENCHMARKING FOR CANADIAN REFINERIES



OBSERVATIONS

A comparison has been made of Canadian refinery emissions performance, relative to U.S. refinery benchmarks. There are a variety of reasons why the comparisons may be subject to some uncertainty. In some cases, the refinery emissions reported for Canadian facilities are of less certainty. While the CPPI member company facilities have standardized their methods for preparing emission inventories, some variability may still exist from company to company or facility to facility. For the non-CPPI companies, data has been obtained from a variety of sources, ranging from testing and monitoring data reported under provincial permits and approvals, to provincial inventories, to national inventories dating back to 1995 for criteria air contaminants. For non-criteria contaminants, the NPRI was the main source of emissions data. NPRI data is based on company self-reporting, so may also be subject to some variability. It should be noted that the availability of Canadian emissions data should improve in future years, with the expansion of the NPRI to include both CACs and non-criteria air pollutants. It is expected that concerns about uncertainties in emission reporting will be examined in more detail by the NFPRER Monitoring and Reporting sub-group.

Differences in Canadian and U.S. refinery emission performance can also be explained to some extent by differences in the level of emission control, pollution prevention, and other practices which could impact on emissions. The effect of control technology differences on emissions performance are discussed in this report, where information is available. However, a review of refinery-specific controls and regulations is beyond the scope of this project. A companion study reviewing regulatory regimes for petroleum refineries in Canada, the U.S. and other parts of the world, is being conducted in parallel with this study. The regulatory regime study should be a

source of information on regulatory differences both between Canada and the U.S. and across regions in both countries.

Another issue is the various initiatives to reduce sulphur and benzene levels in liquid fuels, both in the U.S. and Canada. New regulations for fuel sulphur content are expected to impact on refinery emissions performance in future years. The removal of more sulphur from fuels is leading to new technologies and changing manufacturing processes at refineries and overall, it is expected that these processes will be more energy-intensive, potentially resulting in higher emissions of NO_x and greenhouse gases. For this study, the U.S. benchmarks have been developed using the most current emission data set (for 1999), while Canadian performance has largely been assessed using 2001 data. In comparing Canadian and U.S. performance, it should be noted that the two sets of data used may represent different stages of fuel desulphurization.

The scope of this study was to compare Canadian refinery emissions performance against U.S. benchmarks. However, the benchmarks developed in this study should not be construed as the eventual performance standards. Ultimately, the findings of the emission performance and regulatory regime benchmarking studies will feed into an overall process to develop performance-based standards for Canadian refineries. The overall development process is expected to be consultative, involving multiple stakeholders, and drawing on information from each of the NFPRER sub-groups. There is a wide range of other considerations in consulting on and developing the national framework, including but not limited to: facility caps; airshed caps; inter-pollutant and inter-facility offsets and trading; implementation time frames, phasing and grandfathering; circumstances specific to implementing jurisdictions; fairness, equity and competitiveness issues; and the implications of improving performance in the U.S., should that occur.