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CANADIAN AMMONIA PRODUCERS

BENCHMARKING ENERGY EFFICIENCY AND CARBON DIOXIDE EMISSIONS



PREPARED FOR THE CANADIAN FERTILIZER INSTITUTE AND
NATURAL RESOURCES CANADA



CIPEC

Canadian
Industry
Program for
Energy
Conservation



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In co-operation with the Canadian Fertilizer Institute and the Canadian Industry Program for Energy Conservation

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Aussi disponible en français sous le titre : Les Producteurs Canadiens d'ammoniac – Analyse comparative de l'efficacité énergétique et des émissions de dioxyde de carbone

Library and Archives Canada Cataloguing in Publication

Canadian ammonia producers : benchmarking energy efficiency and carbon dioxide emissions / prepared for the Canadian Fertilizer Institute and Natural Resources Canada.

Published by the Canadian Industry Program for Energy Conservation.
Includes bibliographical references: p. 30

Cat. No. M144-155/2007E-PDF (Online)
ISBN 978-0-662-46150-0

1. Ammonia industry--Energy consumption--Canada. 2. Ammonia industry--Waste disposal--Canada.
3. Carbon dioxide--Environmental aspects--Canada. 4. Energy auditing--Canada. I. Canadian Fertilizer Institute II. Canadian Industry Program for Energy Conservation III. Canada. Natural Resources Canada
IV. Title: Benchmarking energy efficiency and carbon dioxide emissions.

TJ163.5.S83B46 2007

338.47661340682

C2007-980160-9

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I

INTRODUCTION



1. INTRODUCTION

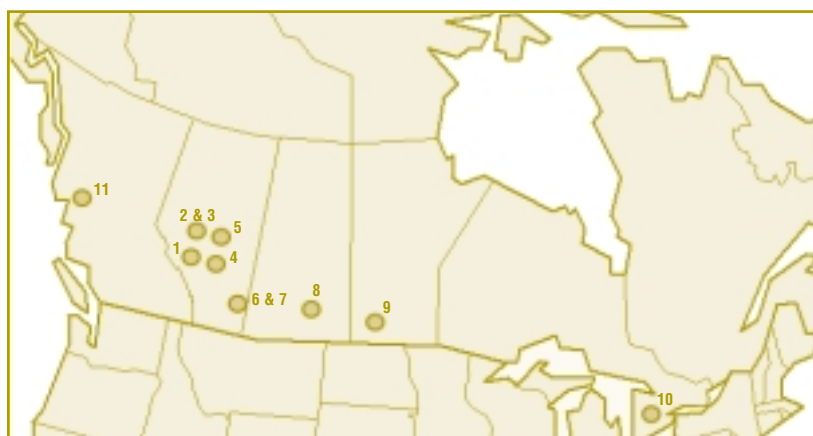
Canada supplies approximately 12 percent of the world's fertilizer materials. The fertilizer industry contributes over \$6 billion annually to the Canadian economy. Most Canadian fertilizer material production is in the form of either nitrogen or potash. Ammonia (NH_3) is an important nitrogen fertilizer and is the basic building block used in downstream nitrogen fertilizer production. Ammonia production is the most energy-intensive step in nitrogen fertilizer production.

Natural Resources Canada's (NRCan's) Office of Energy Efficiency (OEE) has worked with the Canadian Fertilizer Institute (CFI) by providing assistance for this study, which is part of NRCan's ongoing effort to promote more efficient energy use in Canada. This document presents the results of the energy efficiency and carbon dioxide (CO_2) emissions benchmarking of the Canadian ammonia production industry. The potash industry's energy benchmarking results are published under separate cover.

1.1 The Canadian Ammonia Industry

There are 11 ammonia plants located across Canada (Figure 1), producing between 4 and 5 million tonnes annually. Close to 25 percent of the ammonia produced in Canada is shipped to agricultural markets in North America for direct use. About 55 percent goes into the production of urea granular fertilizer, and approximately 20 percent is used to produce other nitrogen fertilizers and to meet a range of other industrial uses.

Figure 1: Canadian Ammonia Plants



1. Carseland AB
2. Fort Saskatchewan AB
3. Fort Saskatchewan AB
4. Joffre AB
5. Redwater AB
6. Medicine Hat AB
7. Medicine Hat AB
8. Belle Plaine SK
9. Brandon MB
10. Courtright ON
11. Kitimat BC

Canadian ammonia plants are located in Western Canada, with the exception of one plant in Ontario. All of the plants in Canada, except the Kitimat facility, are owned and operated by members of CFI.

1.2 Energy Consumption and Carbon Dioxide Emissions in Ammonia Production

Energy, in the form of natural gas, is a significant input into the production of ammonia in Canada. Natural gas costs represent between 70 and 90 percent of input costs, so ammonia producers are very focused on reducing consumption to stay competitive. The fertilizer industry consumes about 8 percent of the natural gas used in Canada.

Natural gas use in ammonia plants results in two major streams of carbon dioxide (CO₂) emissions – *fuel* and *process*. The *fuel*-generated CO₂ emissions result from the combustion of natural gas (or other hydrocarbon fuels) to supply heat for steam/gas reforming, steam boilers, process heaters, gas turbines and other equipment in the ammonia plant. During combustion, all of the carbon in the fuel is converted to CO₂ and is discharged to the atmosphere in the flue gas.

The *process*-generated CO₂ emissions result from the conversion of carbon in the natural gas feedstock to CO₂ and hydrogen during synthesis gas production. The hydrogen gas is combined with nitrogen from the air in a subsequent production process to form ammonia (NH₃). The plant's CO₂ removal system strips off the CO₂ from the process gas stream to avoid contamination of the ammonia synthesis catalyst. This relatively pure CO₂ is normally vented to the atmosphere unless some other use can be found for it.

Many facilities use part or all of the process-generated CO₂ for urea production. This is of great benefit since it reduces the amount of process-generated CO₂ emitted to the atmosphere. Canada is unique in that each of the participating ammonia plants is situated with one or more urea plants. Therefore, Canadian ammonia plants recover a higher percentage of their process-generated CO₂ emissions than do producers in other countries.

2

THE BENCHMARKING STUDY



2. THE BENCHMARKING STUDY

The Canadian fertilizer industry is committed to cost-effective reductions of CO₂ from ammonia plants, which contribute to greenhouse gases (GHGs). Consistent with this commitment, the Canadian Fertilizer Institute (CFI) is an active member of Natural Resources Canada's Canadian Industry Program for Energy Conservation (CIPEC).

CIPEC helps Canadian industry boost its bottom line by using energy more efficiently. CIPEC is a unique government-industry collaboration between the Government of Canada and industry that offers a number of services to help each of Canada's industrial sectors develop energy efficiency goals and action plans. Together with industry, CIPEC defines sector-specific energy efficiency targets, develops and implements action plans to achieve them, and measures and reports on progress in its annual report.

In October 2003, CFI and CIPEC jointly engaged Plant Surveys International, Inc. (PSI), a firm recognized for its expertise in worldwide benchmarking of ammonia plants and CO₂ emissions, to produce *Energy Efficiency and CO₂ Emissions Benchmarking Study of CFI Ammonia Producers 2000–2002*. Ten Canadian ammonia plants, operated by six companies, participated in the study.

2.1 Objectives of the Study

The benchmarking study helps Canadian ammonia plants identify what opportunities exist for energy efficiency improvements and emissions reductions when compared with their global competitors. The objectives of the study were as follows:

- Provide historical knowledge of ammonia plant energy efficiencies and actual CO₂ emissions
- Benchmark ammonia plant energy efficiencies and CO₂ emissions against those of other regions around the world
- Develop an awareness of best-in-class performance and Canada's position within the international market
- Estimate future energy efficiency performance for "world top" and Canadian ammonia plants

2.2 Methodology

Data collection and calculation

Each plant submitted its annual performance data for the operating periods of 2000, 2001 and 2002 using a PSI data questionnaire in Microsoft Excel format. See Appendices A and B for more information on data conversion, collection activities and required calculations.

Performance data included production volumes, gas compositions, energy imports and exports, CO₂ distribution, production conditions, and other plant data. In this report, process CO₂ emissions are determined by subtracting the process CO₂ used in urea production from the process-generated CO₂.

Ammonia plant efficiencies and CO₂ emissions are presented as individual plant and industry averages for the three-year period. CO₂ emissions are presented as mass emissions (tonnes) and specific emissions (t CO₂/t NH₃). Year-by-year trend data (2000, 2001 and 2002) are presented as industry averages.

Data adjustments

Energy efficiency data were normalized in order to provide a common basis for comparison. Adjustments were made for such items as product ammonia conditions, and steam imports and exports. A complete explanation of this normalization methodology is presented in Appendix B.

Energy efficiencies are indicated throughout this report on the basis of a lower heating value (LHV), which is also called net heating value, and efficiencies are per tonne of ammonia. The annual average LHV of each stream is used to convert the volumetric usage to gigajoules (GJ). See Appendix B for details of LHV adjustments.

3

BENCHMARKING RESULTS



3. BENCHMARKING RESULTS

The results of the benchmarking project are presented in three sections:

Section 3.1: Benchmarking Energy Efficiency and CO₂ Emissions of Canadian Ammonia Producers (2000–2002)

This section provides an overview of the data for the Canadian industry, describes the operations involved in the project and presents data on energy efficiencies and CO₂ emissions for the sector.

Section 3.2: Global Energy Efficiency and CO₂ Emissions Comparisons (2002)

Canadian ammonia plant energy efficiencies and CO₂ emissions were compared with those of other ammonia plants throughout the world. Results were reported by global regions. Ammonia and urea productions used in this report are based on the International Fertilizer Development Center's worldwide plant capacity data.

Section 3.3: “World Top” Performance and Future Projections

This section reviews where Canadian facilities rank versus “world top” performance. A look at future low-energy designs is also included.

Factors that influence energy efficiency and CO₂ emissions production

A number of factors influence the energy efficiency and CO₂ emissions production of each operation, and no attempt has been made to correct for differences related to the following:

Catalyst conditions: plant efficiency declines as operating catalysts age.

Catalyst reductions: as old catalysts are replaced, some new catalysts require a reduction procedure before they can be placed into service. Frequently, this involves an energy loss when reduction gases are vented.

Climatic conditions: plants operate in cold or warm climates or at high or low elevations.

Environmental energy requirements: various plants operate supplemental systems to reduce emissions, such as process condensate stripping and steam injection to gas turbines.

Equipment performance: poor equipment performance can adversely affect the plant's operational energy efficiency.

Feedstock pre-treatment requirements: some feedstocks have higher sulphur content than others and may require additional pre-treatment.

Feedstock quality: some feedstocks have high inert levels or excessive levels of high molecular weight hydrocarbons; any compression requirements are considered to be inside battery limits.

Internal recycle streams: through the prudent recycling of off-gases and hydrogen, the plant's energy efficiency can be enhanced.

Operating factor: this is the percent of the year that the plant is operating and producing ammonia (i.e., no provisions are made for shutdowns or production cutbacks).

Process technology used to produce ammonia: some processes are more energy efficient than others (e.g., ICI-Katalco LCA process, Kellogg KAAP process).

Section 3.1: Benchmarking Energy Efficiency and CO₂ Emissions of Canadian Ammonia Producers (2000–2002)

Currently, there are 11 ammonia plants operating in Canada. A list of the 10 Canadian ammonia plants operated by six companies that participated in the benchmarking study and the corresponding rated production capacity are provided in Table 1 below.

Table 1: Canadian Ammonia Plants Participating in 2000–2002 Benchmarking Project

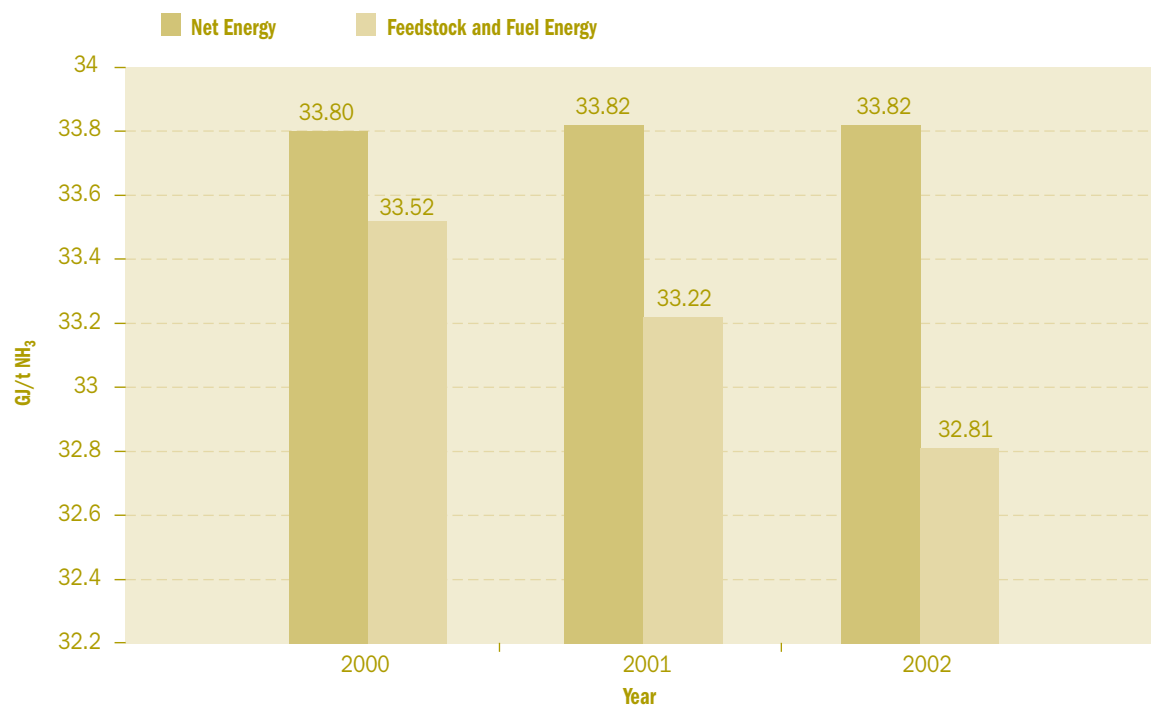
Company and plant name	Location	Rated production capacity (thousand metric tonnes/yr)
Agrium Carseland	Carseland AB	535
Agrium Fort Saskatchewan	Fort Saskatchewan AB	465
Agrium Joffre*	Joffre AB	450
Agrium Redwater #2	Redwater AB	950
Canadian Fertilizers Limited Medicine Hat 1	Medicine Hat AB	530
Canadian Fertilizers Limited Medicine Hat 2	Medicine Hat AB	530
Saskferco Ammonia	Belle Plaine SK	625
Sherritt Ammonia	Fort Saskatchewan AB	155
Simplot Brandon	Brandon MB	425
Terra Courtright 2	Courtright ON	412

* **Note:** All facilities use natural gas feedstock for ammonia production except Joffre, which uses by-product hydrogen stream. Joffre plant data are not included in inter-plant comparisons that include feedstock energy data.

3.1.1 Ammonia Production and Energy Use

Average annual net energy efficiency for the 10 Canadian plants over the three-year benchmarking study remained constant at 33.8 GJ/t NH₃, as shown in Figure 2. However, the feedstock and fuel energy has decreased from 33.5 to 32.8 GJ/t NH₃. This 2 percent improvement resulted in the same percentage reduction in CO₂ generation. Net energy remained constant since other energy use offset the reduction in feedstock and fuel energy.

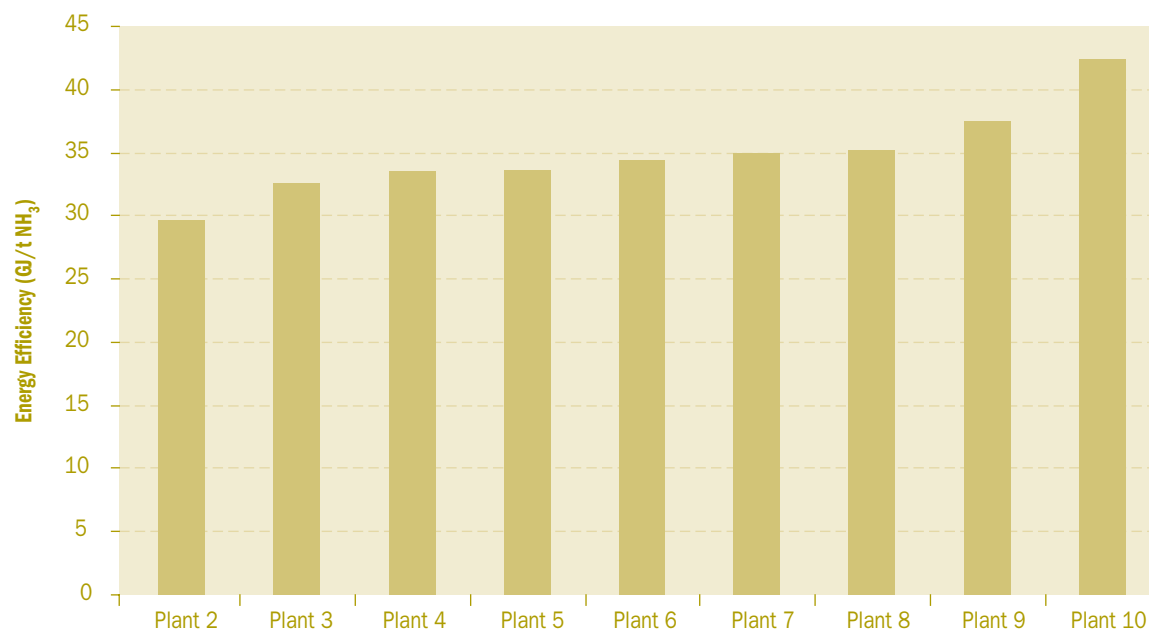
Figure 2: Canadian Ammonia Producers Average Efficiency Trend (2000–2002)



The three-year average *normalized* or *net* ammonia plant energy efficiencies for the natural gas feedstock Canadian plants are shown in Figure 3. The efficiencies of the nine natural gas-based plants range from 29.7 to 42.3 GJ/t NH₃, with an average for natural gas plants (NG) of 34.4 GJ/t NH₃. The group average is 33.2 GJ/t NH₃, with the hydrogen-based plant included. The most energy-efficient plant uses approximately 70 percent of the energy used by the least energy-efficient plant, per tonne of ammonia production.

Average* (GJ/t NH ₃)	High* (GJ/t NH ₃)	Low* (GJ/t NH ₃)
34.4	42.3	29.7

* NG: natural gas plants using lower heating value (LHV) for gas.

Figure 3: Normalized Plant Net Energy Efficiency (2000–2002)

3.1.2 Ammonia Production and CO₂ Emissions

Canadian ammonia plants generate 7 459 188 t/yr CO₂ (average over 2000–2002). All of the natural gas-based ammonia plants in Canada also produce urea. Urea production combines two molecules of ammonia with one molecule of CO₂ to form urea and water in solution. The urea solution is evaporated to form urea granular fertilizer. A total of 3 013 689 t/yr CO₂ is used for urea production. This is a 40 percent recovery factor for CO₂ that would otherwise be emitted to the atmosphere.

Specific CO₂ generation ranges from 1.66 to 1.98 t CO₂/t NH₃ for the natural gas feedstock ammonia plants (as shown in Table 2). The variability is primarily due to the energy efficiency of the plant and, to a lesser extent, the carbon content of the feedstock and fuel (see Factors that influence energy efficiency and CO₂ emissions production, page 10). More energy-efficient plants have a lower specific CO₂ generation since less fuel and feedstock are used to produce the same amount of ammonia.

Table 2: Canadian Ammonia Producers CO₂ Recovery Emissions (2000–2002)

	Average (NG) (t CO ₂ /t NH ₃)	High (t CO ₂ /t NH ₃)	Low (t CO ₂ /t NH ₃)
Total CO₂ Generation	1.68	1.98	1.66
Total CO₂ Recovered	0.61	1.11	0.30
Total CO₂ Emitted	1.07	1.68	0.55

The favourable impact of recovering some of the process-generated CO₂ is shown in Figure 4. Because all the natural gas-based plants are associated with urea plants, they recover otherwise vented CO₂ for urea production. Specific recovery ranges from 0.30 to 1.11 t CO₂/t NH₃ for an overall average of 0.61 t CO₂/t NH₃.

The resulting total CO₂ emissions from ammonia facilities (total generated – total recovered) range from 0.55 to 1.68 t CO₂/t NH₃, with average specific CO₂ emissions of 1.07 t CO₂/t NH₃ from natural gas-based plants. The specific CO₂ emissions levels for each plant are also presented in Figure 4.

Figure 4: CO₂ Recovery and Emissions – Specific Basis

Section 3.2: Global Energy Efficiency and CO₂ Emissions Comparisons (2002)

Canadian ammonia plant energy efficiencies and CO₂ emissions were compared with those of other ammonia plants throughout the world. There are 71 countries that produce ammonia and 58 that produce urea. For reporting purposes, these countries were grouped into 13 regions (Table 3). Ammonia and urea productions used in this report are based on the International Fertilizer Development Center's worldwide plant capacity data.

Table 3: Ammonia-Producing Regions

1. Africa	7. India
2. Asia (excluding China and India)	8. Mexico
3. Canada	9. Oceania
4. China	10. South America
5. Eastern Europe	11. Trinidad and Tobago
6. Former Soviet Union	12. United States
	13. Western Europe

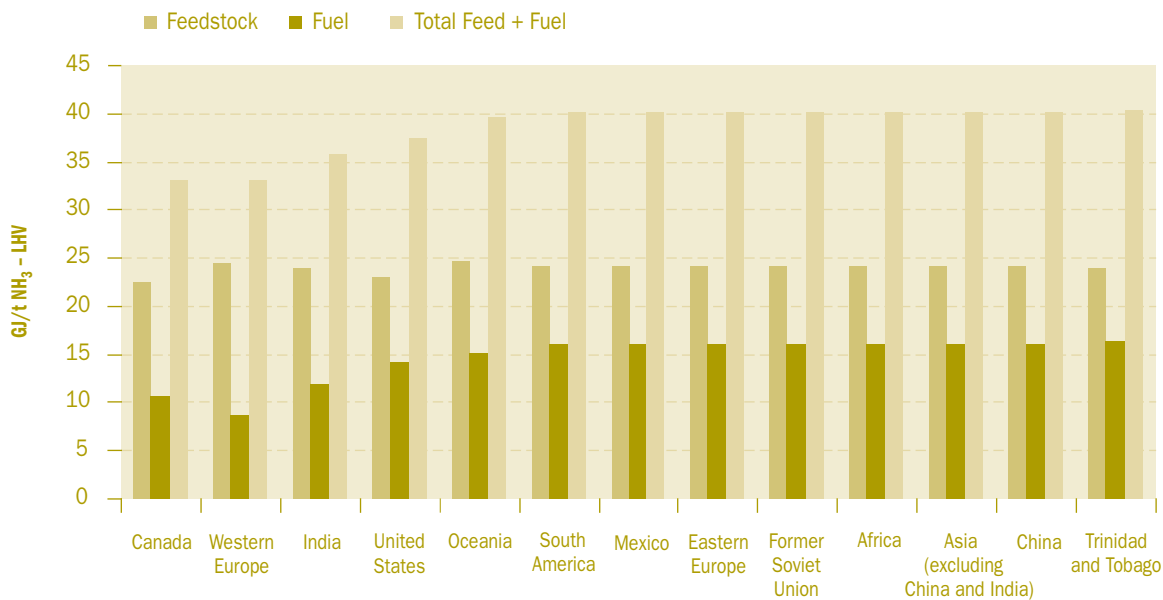
3.2.1 Ammonia Production Energy Efficiencies

CO₂ generation and emissions from ammonia plants are calculated using feed plus fuel energy (FFE) efficiencies rather than net energy efficiencies. FFE relates directly to the CO₂ generated within the ammonia plant, whereas *net* energy efficiencies include electrical usage and adjustments for other energy debits and credits, which can have associated offsite CO₂ emissions not directly from the ammonia plant.

Canadian plants rank first as the most feed-and-fuel energy-efficient plants in the world.

Estimated FFE efficiencies for each global region are shown in Figure 5 (on p. 16). These range from 33.1 to 40.4 GJ/t NH₃, with a world average of 38.6 GJ/t NH₃. Canada ranks first in having the most FFE-efficient plants. These plants generate the least amount of CO₂/NH₃ production.

Global Ammonia Plant Energy Efficiency			
Average (GJ/t NH ₃)	High (GJ/t NH ₃)	Low (GJ/t NH ₃)	Canada (GJ/t NH ₃)
38.6	40.4	33.1	33.1

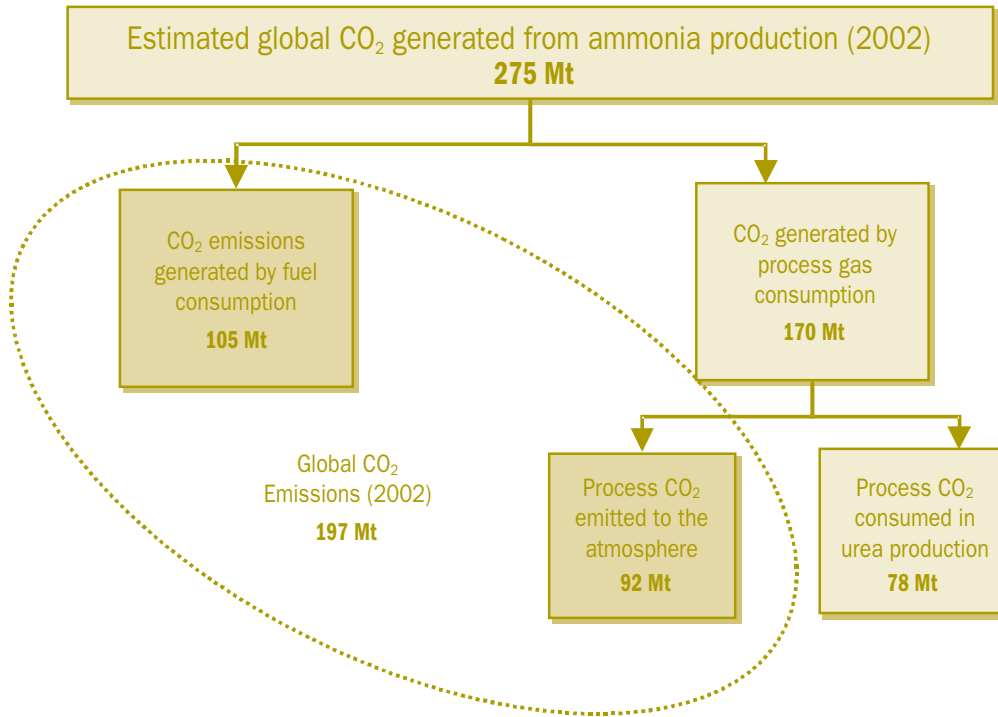
Figure 5: Estimated Ammonia Plant Energy Efficiency by Global Region

3.2.2 Estimated CO₂ Emissions From Ammonia Production

CO₂ emissions were calculated using ammonia and urea production estimates and a 79.5 percent capacity utilization for each global region. Canadian estimates were based on actual 2002 production from the nine natural gas-based ammonia plants. CO₂ emissions from ammonia production are derived from the combustion of natural gas used as a fuel and from the steam reformation process used to derive the hydrogen stream from the natural gas used as a feedstock. These CO₂ emissions streams are referred to as fuel and process (or feed) respectively.

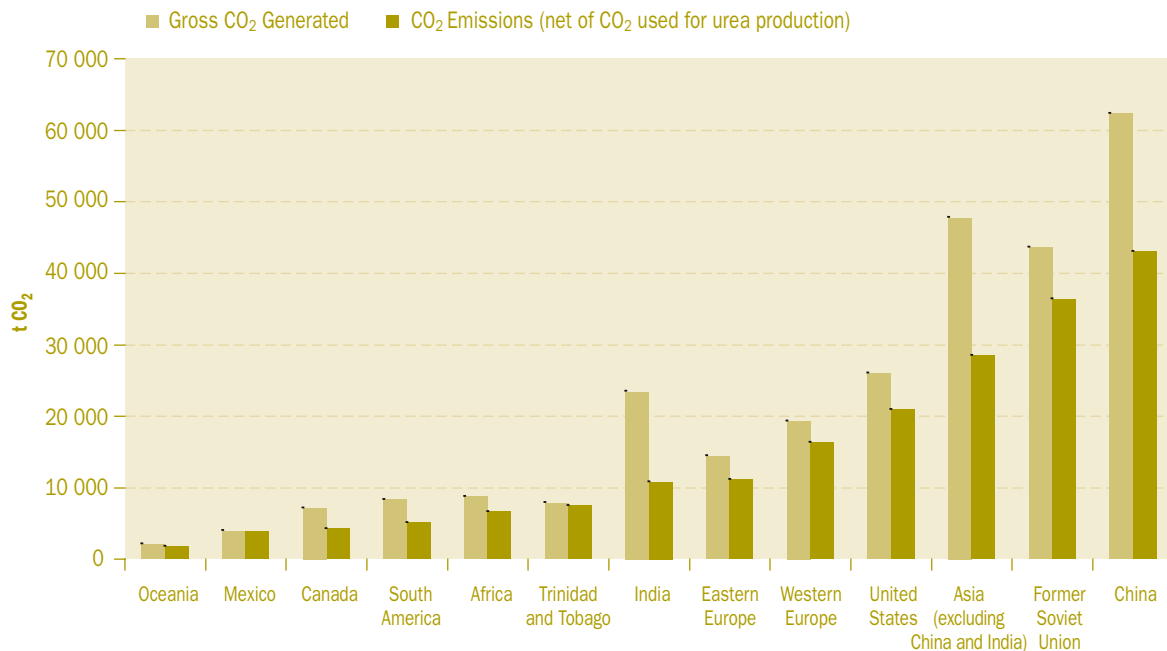
Total world ammonia production for 2002 is estimated to be 128 megatonnes (Mt). Total CO₂ generation from these ammonia plants is estimated to be 275 Mt. Approximately 62 percent, or 170 Mt CO₂, is process- or feed-related. A significant amount (28.5 percent) of total CO₂ generated is recovered for use in urea production, leaving CO₂ emissions of 197 Mt from ammonia plants throughout the world. The global CO₂ generation and emissions estimates for 2002 are summarized in Figure 6.

Figure 6: CO₂ Generation and Emissions From Ammonia Plants



Gross CO₂ generation from ammonia plants and emissions net of CO₂ used in urea production in the various regions of the world are shown in Figure 7. China ranks first with the highest CO₂ emissions (21.9 percent), and Oceania has the least. Canada is among the regions with the least CO₂ emissions, ranking 11th (highest to lowest), and emits 2.2 percent of the world’s total CO₂ from ammonia plants.

Figure 7: CO₂ Generated and Emitted by Region (2002)



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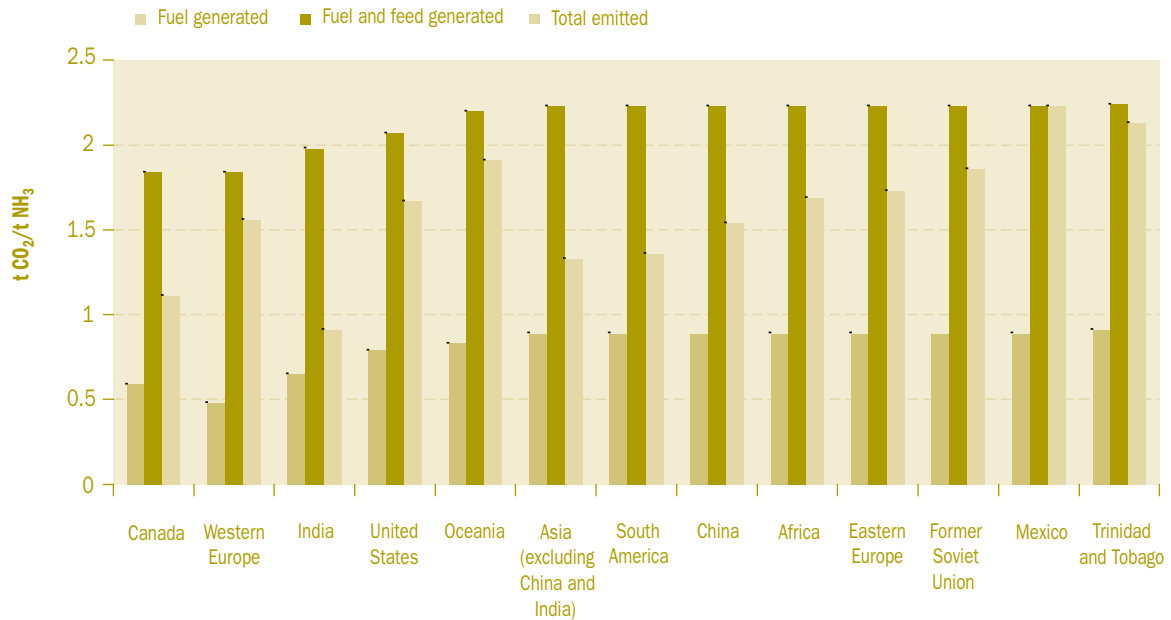
On a per tonne of production basis, CO₂ generation from ammonia production ranges from 1.84 to 2.24 t CO₂/t NH₃, with a world average of 2.14 t CO₂/t NH₃. Canada and Western Europe are the most efficient regions, with generation factors of 1.81 and 1.84 respectively.

	Average (t CO ₂ / t NH ₃)	High (t CO ₂ / t NH ₃)	Low (t CO ₂ / t NH ₃)	Canada (t CO ₂ / t NH ₃)
Global CO₂ Generated per Tonne of Ammonia Production	2.14	2.24	1.81	1.81
Global CO₂ Emitted per Tonne of Ammonia Production	2.14	2.23	0.91	1.11

When the CO₂ that has been captured and used in urea production is accounted for, total CO₂ emissions from ammonia production range from 0.91 to 2.23 t CO₂/t NH₃. Canada is the second-lowest region in terms of emissions per tonne of ammonia production, at 1.11 t CO₂/t NH₃. Figure 8 presents the specific CO₂ generation and emissions rates by region for 2002.

Canada and Western Europe are the most efficient regions, with generation factors of 1.81 and 1.84 respectively.

Figure 8: Specific CO₂ Generation and Emission Rates (2002)



Section 3.3: “World Top” Performance and Future Projections

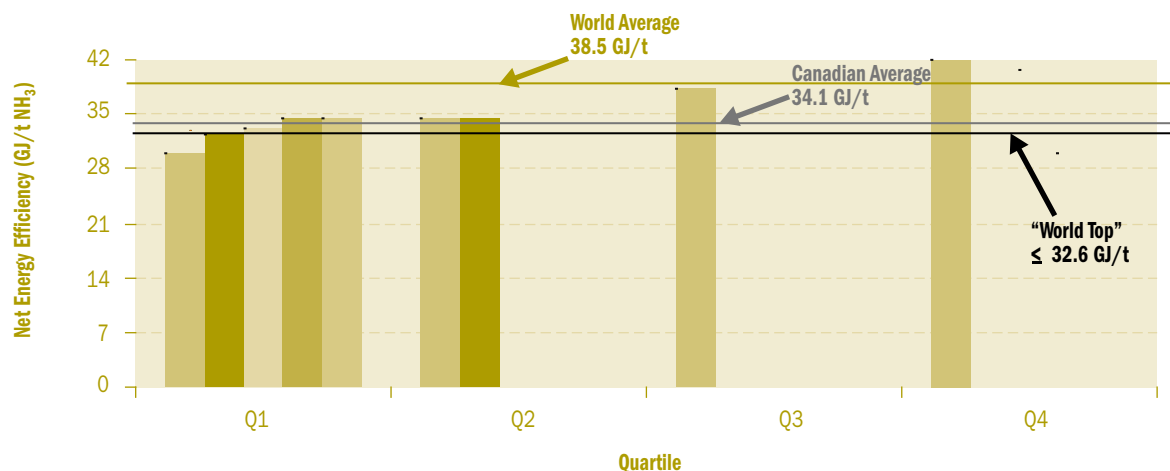
3.3.1 Worldwide Benchmarking

Nearly all the worldwide commercial production of ammonia is from hydrocarbon feedstocks and fuels. As mentioned previously, improving the energy efficiency of ammonia production is an important strategy to reduce CO₂ emissions.

Two of the Canadian plants are “world top” plants – those that rank in the top decile globally in terms of energy efficiency.

Benchmarking the energy efficiency of individual ammonia plants is an effective way to measure plant performance against other producers and determine the best performers in the world. It provides a quantitative measure of what is possible with today’s technology and can be used to assess the feasibility of making improvements. Figure 9 shows the performance of the individual Canadian ammonia plants against other plants around the globe.

Figure 9: Net Energy Efficiencies (Normalized)



3.3.2 Canada in “World Top” Rankings

A “world top” rating ranks plants in 10 groups according to energy efficiency. If a plant is ranked in the top group, it is considered world top. An ammonia plant with an energy efficiency of 32.6 GJ/t NH₃ or lower is considered to be world top. As noted previously, Canadian ammonia production is energy efficient. Comparing global regions, the nine Canadian ammonia producers are the second-most efficient, following the Western European producers. The average net energy efficiency of the nine Canadian producers is 34.1 GJ/t NH₃. This is 11 percent better than the world average of 38.5 GJ/t NH₃.

The Agrium plant in Joffre, Alberta, is an excellent Canadian example of inter-plant integration. A by-product hydrogen stream from an adjacent facility replaces the need for steam reforming of natural gas to supply the feedstock for ammonia production.

3.3.3 The Future of Ammonia Plant Low-Energy Designs

Modern ammonia production technology began in the 1960s. The energy efficiency of these plants was typically 39.5 GJ/t. The efficiency of newly designed plants improved substantially, as numerous innovative concepts were developed. Designs of 28.0 GJ/t became available in 1991. Since then, improvements have continued but at a much reduced rate. Currently, low energy designs approaching 27.0 GJ/t are being offered.

The best estimate of future improvements in the efficiency of low-energy ammonia plants comes from *Ammonia: Principles and Industrial Practice*. After an extensive review of the history of industrial ammonia production and current technologies, the author, Max Appl, makes the following broad predictions:

- Natural gas will remain the preferred feedstock for at least the next 10 to 15 years. Coal gasification will not play a major role in ammonia production in that period.
- The present ammonia technology will not change fundamentally, at least in the next 10 to 15 years. Even if there are radical, unforeseeable developments, they will take time to reach commercial introduction.
- With the traditional concepts, the margins of additional improvements have become small after years of intensive research and development.
- Only minor improvements of individual steps, catalysts and equipment are expected.
- There is unlikely to be any further significant reduction in the energy consumption of the natural-gas-based steam-reforming ammonia process; figures between 27 and 28 GJ/t are already close to the theoretical minimum, which is 20.9 GJ/t.
- For the next 10 to 15 years, the bulk of ammonia production will still be produced in world-scale plants of 1000–2000 tonnes per day NH_3 . Small capacity plants will be limited to locations where special logistical, financial or feedstock conditions favour them.
- New developments in ammonia technology will mainly reduce investment costs and increase operational reliability. Smaller integrated process units contribute to this reduction and give additional savings by simplifying piping and instrumentation. Reliability may be improved by advances in catalyst and equipment quality and by improved instrumentation and computer control.

With this forecast in mind, the improvement in the consumption of fuel energy of new low-energy design plants is estimated to continue at a slower rate than that experienced over 1991–2003, where the Energy Improvement Factor (EIF) averaged 1.0 percent of the fuel per year. From now through 2014, it is estimated that the fuel consumption improvement will be 35 percent less than that during the previous decade. This equates to a 0.65 percent per year EIF. The energy efficiency of these low-energy designs is expected to drop from 6.2 to 5.8 GJ/t, while process efficiency will remain fixed by chemistry. The total energy efficiency in 2014 will be 26.7 GJ/t.

Recently completed Process Integration (PI) studies at Canadian ammonia production facilities have highlighted opportunities to improve the integration between ammonia and urea plants. By looking for opportunities to further include PI methodologies during the design phase of new ammonia and urea plants, future plants can be built with even greater energy efficiency and at lower or minor incremental capital cost.

APPENDICES



APPENDIX A: ABBREVIATIONS

- G – giga – 10^9
- J – joule
- k – kilo – 10^3
- M – mega – 10^6
- t – metric tonne
- m^3 – cubic metre

Conversion factors for greenhouse gas emissions from fuels		
To convert	To	Multiply by
Natural gas (GJ)	Tonnes CO ₂ equivalent	0.0513
Diesel (litres)	Tonnes CO ₂ equivalent	0.00276
Gasoline (litres)	Tonnes CO ₂ equivalent	0.00249
No. 2 fuel oil (litres)	Tonnes CO ₂ equivalent	0.00284

Source: *Canada's Greenhouse Gas Inventory, 1990–2000*. Greenhouse Gas Division, Environment Canada (June 2002).

APPENDIX B: PLANT SURVEYS INTERNATIONAL'S AMMONIA PLANT ENERGY EFFICIENCY NORMALIZATION METHODOLOGY

Energy Efficiency

One of the primary reasons for benchmarking is to compare performance results. In some cases, it is desirable to make adjustments to performance measurements so that plant processes are compared on a common basis. Such is the case for ammonia plant energy efficiencies, where adjustments are made to arrive at a standardized or normalized plant. The method used to make these adjustments is shown in the table below.

Normalized Ammonia Plant Energy Efficiency Example Calculation	
	GJ/t (Lower Heating Value)
Total feed	25.1
Total fuel	8.2
Total Feed + Fuel	33.3
Electric import (40%)	1.2
Nitrogen (N ₂) imports (40% electric)	- 0.0
Oxygen (O ₂) imports (40% electric)	0.0
Total steam imports (90%)	0.0
Total steam exports (90%)	- 1.1
Total other energy imports	0.0
Total other energy exports	- 0.0
Ammonia (NH ₃) product adjustment	0.1
Cooling water (CW) energy adjustment	0.3
Boiler feedwater (BFW) energy adjustment	0.0
Other Energy	0.5
Net Energy Efficiency	33.8

Energy Efficiency Normalization

Basis

- Actual plant calendar year data are used. All quantities are on an annual basis. Annual ammonia production and all feedstock and fuel energy consumed by a plant during the year are recorded. This includes the energy to produce ammonia, as well as the energy used during start-ups, shutdowns, catalyst reductions, etc. The ammonia plant fuel energy includes energy for reformer firing, auxiliary boiler use, gas turbine use and process heater use.
- The lower heating value (LHV), also called the net heating value, is used throughout. The annual average LHV of each stream is used to convert the volumetric usage to gigajoules (GJ).

Adjustments

- Imported off-gas streams are valued at their LHV. Typically, these are a small percentage of the total feed and fuel usage. However, in the case of hydrogen imports that constituted the bulk of the feedstock requirement, an estimate of the energy needed to produce this hydrogen is included in the feedstock energy.
- Imported electricity is converted to a heat equivalent at a 40 percent (LHV fossil fuel basis) efficiency (1 kWh = 9000 kJ LHV). This is a typical overall efficiency for fossil fuel utility-based electric generation and distribution. The purpose of the electrical efficiency adjustment is to reflect the fossil fuel use associated with its production. This conversion does impact a plant's energy efficiency calculation, but it has no effect on a plant's CO₂ emissions calculation. Only carbon-bearing streams directly used in a plant are used in the CO₂ emissions calculations. Electricity exports are valued at 100 percent conversion efficiency (1 kWh = 3600 kJ LHV). A high efficiency conversion rate is used for internal generation of electricity for export because it is considered to be incidental to the process and normally represents the recovery of waste heat.
- Process nitrogen imports (nitrogen for process use) are based on actual energy used for production and delivery to the ammonia plant. Otherwise, an estimate of the electricity needed to produce and supply the nitrogen to the ammonia plant is used based on production from an air separation plant using a 40 percent LHV electrical conversion efficiency. No energy debit is made for the import of nitrogen for utility use, such as for inert gas blanketing needs and purging of vessels.
- Process oxygen imports (oxygen for process use) are based on actual energy used for production and delivery to the ammonia plant. Otherwise, an estimate of the electricity needed to produce and supply the oxygen to the ammonia plant is based on production from an air separation plant using a 40 percent LHV electrical conversion efficiency.

- Steam imports and exports are based on their actual enthalpy at plant battery-limit conditions (defined below). Export steam must have a valid use. Vented steam and other such uses do not qualify as export steam. A conversion efficiency of 90 percent is used ($\text{enthalpy}/0.90 = 1.11 \times \text{enthalpy}$). This is typical of condensing steam systems. Plants have the option of using their actual utilization efficiencies in cases where they significantly differ from the default 90 percent conversion. **Note:** 90 percent conversion efficiency is based on inlet water at 15°C where enthalpy is 63 kJ/kg.
- Other energy imports and exports are valued at their LHV.
- Ammonia product adjustments are made to normalize ammonia production to liquid at atmospheric pressure (−32°C), using the difference in enthalpy. Gaseous ammonia is converted to liquid using a heat of vaporization of 1148 kJ/kg. Liquid ammonia above −32°C is adjusted using a specific heat of 4.63 kJ/kg °C. This results in a minor adjustment for most plants and a more significant adjustment for those plants producing a high percentage of gaseous product.
- The basis for cooling water is that the energy for producing and pumping all cooling water is included in the plant’s energy usage. Where a plant imports cooling water (from a cooling tower, river water, sea water, etc.), the pumping energy and cooling fan energy (for cooling towers) is added as an energy debit. Actual energy usage is used, if known. Otherwise, estimates are used where the pumping energy is based on using a single-stage, double-suction centrifugal pump with an 85 percent efficiency. Coupled with a large 96 percent efficient electric motor, the resulting pumping efficiency is 82 percent. An additional energy load of 44 kWh/km³ is used for cooling tower fan operation. The net energy usage for cooling water is then determined by using a 40 percent electrical conversion efficiency.
- Boiler feedwater (BFW) adjustments are made for those plants importing BFW. The actual electrical pumping energy is used, if known. Otherwise, pumping energy is estimated using a multi-stage centrifugal pump with a 65 percent efficiency. Coupled with a large 96 percent efficient electric motor, the resulting pumping efficiency is 62 percent. The net energy usage is then determined by using a 40 percent electrical conversion efficiency.

Plant Battery Limit

Battery limit is the “fence” around an ammonia plant. Inside the battery limit (ISBL), ammonia is manufactured and the energy efficiency is determined from measurements of feedstocks and energy flows across this boundary. Important utilities to support the manufacture of ammonia are typically produced outside battery limit (OSBL) and delivered to the plant. Commonly, hydrocarbon feedstocks and fuels, electric power and (sometimes) steam are produced OSBL and delivered to the ammonia plant.

Standard ammonia plant configuration**ISBL**

- Boiler feed water production
- Cooling water production and circulation
- Feedstock pre-treatment
- Feedstock compression
- Process flares
- Process condensate treatment

OSBL

- Electrical power generation
- Ammonia storage and handling
- Ammonia storage flare

In a normalized ammonia plant, cooling water production is ISBL. In plants using offsite cooling water, the pumping and cooling (tower fan) energy for all of the circulating cooling water must be determined since the entire circulating flow crosses the battery limit. Ammonia storage and handling are considered to be OSBL.

APPENDIX C: HISTORICAL DATA

There are more than 400 ammonia plants throughout the world. Plant Surveys International, Inc. (PSI) has historical data on about one fourth of these plants. The most accurate data are in global regions where PSI has considerable data, such as Western Europe, the United States, Trinidad and Tobago, Oceania and Canada. In regions where there are limited data, the bottom-half average listed in the table below was used.

Historical Ammonia Plant FFE* Efficiencies From PSI Benchmarking Records GJ/t NH ₃ LHV			
Average	Feedstock	Fuel	Total feed + fuel
1 Quartile	23.3	8.2	31.6
2 Quartile	23.6	11.0	34.7
3 Quartile	23.5	13.7	37.2
4 Quartile	24.9	18.2	43.1
Bottom Half	24.2	16.0	40.2
World	23.8	12.9	36.7

*Note: FFE = Feed + Fuel Energy (hydrocarbon basis)

APPENDIX D: REFERENCES

- ¹ International Fertilizer Development Center, *Worldwide Ammonia Capacity Listing by Plant* (FSR-10), (September 2003).
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- ³ Plant Surveys International, Inc., *1997–1998 Worldwide Ammonia Plant Benchmarking Study*.
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- ⁵ Nand, Dr. S., “Downtime in India Ammonia and Urea Plants,” The Fertilizer Association of India, AIChE paper (September 1999).
- ⁶ Nand, Dr. S. and Goswami, Manish, “On-Stream and Energy Efficiency of Indian Ammonia and Urea Plants – An Analysis,” The Fertiliser Association of India [ABSTRACT] presented at the Ammonia Symposium (2004).
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- ⁸ Appl, Max, *Ammonia: Principles and Industrial Practice* (Wiley-VCH, ISBN 3-527-29593-3, 1999).
- ⁹ European Fertilizer Manufacturers Association, “Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry,” Booklet No. 1 of 8, “*Production of Ammonia*” (second edition revised in 2000).
- ¹⁰ G.P. Williams with Kellogg Brown and Root (private correspondence), Design Efficiency for Proposed CNCC plant for Hainan Island, China.