Canadian Energy Research Institute

The Canadian Nuclear Industry: Contributions to the Canadian Economy

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

A. Introduction

The nuclear energy industry has experienced a worldwide renaissance in recent years. Industry development had slowed dramatically over the past quarter century, primarily because of public concern over the safety of nuclear power. But as energy demand has risen, as hydrocarbon energy supply appears increasingly tenuous, as global warming has become a prominent issue, as important nuclear products continue to be developed, and as nuclear safety issues are being addressed, the world is taking a new look at nuclear energy. This report examines and updates the history of nuclear research and development (R&D) and nuclear power generation in Canada; moving on to discuss the implications for the national economy of further domestic nuclear industry development and of the export of Canadian nuclear products and technology to the rest of the world.

B. Canadian Nuclear Development

Critical to any nuclear industry is the availability of uranium. Although Canada holds large reserves of the world's highest-grade uranium, and uranium has been mined in the Northwest Territories and Ontario, all present mining is taking place at three sites in northern Saskatchewan. Ore is taken to a mill where it is ground and concentrated into uranium oxide (U_3O_8), referred to as "yellowcake". At the refinery, the yellowcake is processed into purified uranium trioxide (UO_3), mostly for export, although some is converted into either uranium dioxide (UO_2) for use in CANDU® (CANada Deuterium Uranium) heavy-water reactors or into uranium hexafluoride (UF_6) for subsequent enrichment and conversion to uranium dioxide (UO_2) suitable for light water reactors. Canada does not enrich uranium; however other countries that use light-water reactors do have enrichment facilities. Each year, approximately 10 percent of the uranium mined is used domestically, while the rest is exported.

The Canadian nuclear industry began in 1945 when nuclear fission was controlled for the first time in a reactor at Chalk River, Ontario. Chalk River has been central to the industry ever since. CANDU reactors were first developed there, the Tandem Accelerator and Super Conducting Cyclotron were built there, as was the Tri-University Meson Facility (TRIUMF). It was also at Chalk River that the radioisotopes cobalt-57, gallium-67, and indium-111 were developed for medical applications.

There are presently eight research reactors operating in Canada: the National Research Universal (NRU) reactor and the Zero Energy Deuterium (ZED-2) test reactor at Chalk River and six other small reactors at various research institutions and universities — McMaster, École Polytechnique de Montréal, Dalhousie, University of Alberta, Saskatchewan Research Council, and the Royal Military College. The Chalk River facilities are operated under the aegis of Atomic Energy of Canada Limited (AECL), a crown corporation involved in all aspects of the industry — from R&D,

to facility maintenance, to waste management, to CANDU operations and sales. The university reactors operate mainly for Neutron Activation Analysis (a means to test for concentrations of certain chemical elements in a sample), commercial service, teaching, and training.

For the purpose of generating electrical power, Canada now has 18 reactors online, all heavy-water, all using CANDU technology. Sixteen reactors operate in the province of Ontario, with one in New Brunswick, and another in Quebec. The total capacity of these reactors is over 12,000 megawatts (MW), and yearly generation adds up to more than 85 terawatt-hours (TWh) of electricity, making Canada the world's 8th largest nation in terms of nuclear power capacity and 7th largest in terms of nuclear power generation. Nuclear power represents 11 percent of Canada's domestic electrical generation capacity.

Nuclear power generation has seen slightly negative growth over the past decade in Canada, largely because no new reactors have been commissioned during that time. However, since 1996, AECL has delivered seven new CANDU reactors to other nations (three to South Korea, two to China, and two to Romania), contributing to the very high rate of power generation growth in these countries. There are no reactors being built in Canada at the present time, though initial plans have been announced in Alberta, New Brunswick, and Ontario. Two reactors are undergoing refurbishment at the Bruce A nuclear generating station.

C. The Nuclear Industry's Economic Impact on the Canadian Economy

The nuclear industry has in the past had considerable impact on the Canadian economy — in terms of Gross Domestic Product (GDP), employment, and government revenue. For the purposes of this study, a Canadian Energy Research Institute (CERI)-developed Input-Output Model has been used to assess the economic impact of the following activities: i) construction of nuclear reactors; ii) electricity generation from nuclear power plants; iii) export of nuclear reactors; and iv) export of uranium.

In 2001, CERI collected investment data on two 720 MW-capacity CANDU 6 reactors (for a total capacity of 1,440 MW) to assess the economic impact of reactor construction, electricity generation from power plants, and the export of nuclear reactors. These data were updated to 2005 dollars for this study. To gauge the economic impact of uranium mining and milling, CERI used information available for the gross value of Canada's uranium exports in 2005 (see Table E.1).

Clearly, the Canadian nuclear industry is a significant contributor to the Canadian economy in terms of GDP, government revenue, and employment. Considering that the construction of a pair of new reactors similar to those analyzed in this study — either for domestic use or for export — could create substantial employment, billions of dollars in GDP, and hundreds of millions in government revenue, the potential rewards are considerable.

Table E.1
Estimates for Two 720 MW CANDU 6 Nuclear Reactors, 2005

Total cost of two CANDU 6 reactors	$3.742 billion
GDP generated by investment in two CANDU 6 reactors	$5.973 billion
GDP generated by export of two CANDU 6 reactors	$1.03 billion
Employment created by construction of two CANDU 6 reactors	80,233 person-years*
Employment created by export of two CANDU 6 reactors	17,039 person-years*
Government revenue resulting from construction of two CANDU 6 reactors	$1.604 billion
Government revenue resulting from export of two CANDU 6 reactors	$260 million
Canadian Nuclear Industry Totals, 2005	
Value of Canadian nuclear energy sold	$4.988 billion
GDP generated by Canadian nuclear power plant operation	$6.303 billion
GDP generated by Canadian export of uranium	$381 million
Employment created in Canada by nuclear power plant operation	66,694 jobs*
Employment created in Canada by export of uranium	4,898 jobs*
Government revenues resulting from Canadian nuclear power plant operations	$1.417 billion
Government revenues resulting from Canadian export of uranium	$100 million

* Note that employment figures refer to direct and indirect employment created.

D. The Risks of Nuclear Development

But with the potential rewards comes the element of risk. This paper considers many of the safety and environmental issues that surround nuclear energy. In terms of safety within Canada, the Canadian Nuclear Safety Commission (CNSC) oversees and regulates all nuclear activity. Construction of new reactors requires federal licensing and is subject to regulatory guidelines established by Ottawa in 2006 — including an 18–36 month environmental assessment. Regulations on spent fuel and waste are also stringent; while new, safer approaches to long-term waste management are being developed and implemented by the Nuclear Waste Management Organization (NWMO).

This paper points out that the accident at Chernobyl in 1986 is not representative of the industry's safety record over the years — a record that has been exemplary in comparison to other energy production and even to other human activities generally deemed safe.[1] More recently, concerns have been raised about the possibility of a terrorist attack at a nuclear facility; safeguards have been taken to fortify reactors against the impact of commercial aircraft and other threats. Commercial insurance is still available for nuclear plants, an indication that confidence remains in the structural integrity of reactors and the measures taken to protect them from attack.

[1] For example, the number of immediate fatalities caused worldwide by the nuclear industry between 1970 and 1992 totalled 31. In the hydroelectricity industry, however, a total of 4,000 people died over the same period, and in coal, the number was 6,400.

E. Economic Conclusions on Future Nuclear R&D

To draw quantitative conclusions about the merit of nuclear R&D in Canada, CERI has performed an economic case study using the logic model approach. There are three steps to this study: i) calculating the total cost of the program; ii) determining the benefits of the program and placing a dollar value on them; and iii) calculating a benefit-to-cost ratio. In this kind of study, for an option to be feasible, the benefit-to-cost ratio should be greater than 1. CERI compares nuclear energy with natural gas in Ontario (16 of Canada's 18 power-generating reactors are located in the province) and the sensitivity analysis determines that nuclear R&D is feasible with a 5 percent discount rate and unfeasible when the discount rate is set to 10 percent.

Table E.2
Nuclear R&D Benefit-Cost Analysis
(millions of dollars)

	5%	10%
Benefits	83,966	67,984
Costs	56,478	282,617
Ratio	1.486703	0.240552

CERI takes the position that the 5 percent discount rate is most appropriate today and that nuclear R&D is economically feasible. CERI has also estimated the discount rate at which costs begin to outweigh benefits to range between 5.8 and 6.9 percent. It should be observed, however, that the above analysis does not take into account the considerable social benefits derived now and in the future from nuclear R&D, some of which are more quantifiable than others: declining health care costs as fewer pollutants are released into the atmosphere; increasing quality of life as large amounts of clean electricity enter the grid, new and permanent jobs are created, and the problem of climate change is more directly addressed; and lives saved by new applications of nuclear technology in the field of medicine. What all this means is that even if the ratio of benefits to costs at a specific discount rate eventually works out to something less than 1, society may ultimately deem nuclear R&D to be worthwhile because of benefits derived above and beyond the economic.

CHAPTER 1
INTRODUCTION

1.1 Background

Canada became the second country in the world to control fission in a reactor at Chalk River, Ontario in 1945. Commercial production of radioisotopes for medical purposes began there in 1949, and the first nuclear electricity generation in Canada occurred in 1962 at the Rolphton Nuclear Power Demonstration (NPD) plant, near Chalk River. The NPD utilized CANada Deuterium Uranium (CANDU) heavy water technology and was designed and constructed jointly by Ontario Hydro and Atomic Energy of Canada Limited (AECL). Canada currently holds a strong position in the development and commercialization of heavy water nuclear reactors, while other countries have pursued the development of light water units. The distinguishing benefit of Canada's CANDU reactor technology is its ability to use natural uranium or uranium enriched to a lesser extent compared to other nuclear reactor technologies, making fuel acquisition, preparation, and handling cheaper and safer. Canada is a pioneer in developing nuclear energy for peaceful uses. The industry spans the nuclear fuel cycle, and includes uranium mining, electricity production, nuclear research and development, the application of nuclear technology in the medical field, and the management of nuclear fuel-waste. The federal government has funded nuclear research and development for several decades. Government support has enabled Canada to develop its own nuclear reactor technology and other related technologies. Within this context, the Canadian Nuclear Association (CNA) is interested in identifying the implications for the national economy attributable, directly and indirectly, to the operation of the nuclear industry.

1.2 Objective and Scope of the Study

The overall objective of this study is to assess the contribution of the Canadian nuclear industry to the overall Canadian economy. The detailed objectives of the study are the following:

- To provide an update on the development of the nuclear industry in Canada, including uranium mining and milling, nuclear power, domestic use and exports of nuclear reactors and medical use of nuclear products, such as medical isotopes.

- To analyze the economic impact of construction of nuclear power plants (reactors), electricity generation from the plants, exports of nuclear technology and exports of uranium. The economic impact is measured in terms of gross domestic product, employment generation and government revenue generation within the Canadian economy. The impact includes direct, indirect and induced effects.

- To evaluate the historical contribution of the nuclear industry, particularly research & development activities, to the Canadian economy. The evaluation includes an analysis of R&D expenditure since the early 1950s and assesses how this expenditure contributed to the economy, for example through the development of CANDU and Advanced CANDU Reactor (ACR) nuclear technologies, employment generated, and the medical use of nuclear technologies.

1.3 Methodology

The updates on the development of the nuclear industry in Canada, including uranium mining, construction and export of nuclear reactors, and nuclear power generation have been carried out based on the latest relevant literature and on information provided by the Canadian Nuclear Association.

The economic impact of the nuclear industry — including construction of nuclear power plants, electricity generation from nuclear power stations, exports of nuclear technology, and exports of uranium — is assessed using an input-output (I-O) model.[2] The model, which is based on national and provincial I-O tables produced by Statistics Canada, contains 19 economic sectors. Please see Chapter 5 for more details on the I-O model used for this study.

To begin with, this study analyses in detail Canadian nuclear R&D activities and corresponding products based on information provided by the Canadian Nuclear Association (CNA). This is followed by a comprehensive literature review on the various methodologies available to evaluate public R&D activities. Based on the literature review and the requirements of this study, the Logic Model has been selected to assess the impact of R&D activities in Canada.

1.4 Organization of the Report

Chapter 1 defines the scope and objectives of the study.

Chapter 2 presents an overview of the development of the nuclear industry in Canada, focusing mainly on institutional development of the industry. It also highlights safety issues related to the nuclear industry.

Chapter 3 compares the Canadian nuclear industry to nuclear industries in other countries. It includes comparisons in terms of the historical growth of nuclear power, total nuclear capacity, nuclear power generation, and nuclear fuel consumption. The chapter also discusses nuclear electricity generation and uranium requirements within Canada at the national and provincial levels.

Chapter 4 presents an analysis of the Canadian nuclear industry, focusing on uranium mining and nuclear products — principally the medical use of nuclear technology.

[2] The input-output model is an analytical tool pioneered by Professor Wassily Leontief in 1936. For his work, Professor Leontief was awarded the Nobel Prize in Economics in 1973. This modelling approach has been extensively used in both the developed and developing worlds in the fields of energy and environmental policy and activity analysis, regional economic planning and development, as well as resource planning and management.

Chapter 5 is the principal component of the study. It presents the economic impact of the nuclear industry on the Canadian economy. Direct, indirect, and induced impact of various activities such as nuclear plant construction, nuclear power generation, and uranium mining are analyzed using the CERI input-output model.

Chapter 6 pulls together descriptions of research and development activities in the Canadian nuclear industry. It covers R&D for nuclear power and other uses, particularly medical uses, of nuclear technology.

Chapter 7 quantifies the impact of nuclear R&D on the Canadian economy.

Chapter 8 presents the key conclusions of the study.

Appendix A presents a quantitative evaluation of nuclear R&D in Canada.

CHAPTER 2
THE NUCLEAR INDUSTRY IN CANADA

2.1 The Nuclear Industry in Canada

Canada has a long, rich history in the field of peaceful nuclear energy. Canada's nuclear research program was originally located in Montreal in 1942; and subsequently moved to Chalk River, 200 kilometres north of Ottawa, in 1944.[3] While the Montreal laboratory closed shortly thereafter — in 1946 — the Chalk River facility still remains at the core of Canada's nuclear research. Starting with the Zero Energy Experimental Pile (ZEEP) reactor in 1945, Canada became only the second country in the world to control atomic fission.[4] The success of ZEEP paved the way for further nuclear research and established Canada as a pioneer of nuclear technology.

The valuable information provided by the ZEEP experiment led to the creation of the National Research Experimental (NRX). At 25 megawatts (MW), it was the most powerful research reactor in the world at that time.[5] The NRX was a heavy-water-moderated, light-water-cooled, research reactor, primarily used to develop new isotopes, test materials and fuels, and to produce beams of neutral particles. Built in 1947, the reactor was shut down in 1992.

With the conclusion of World War II, the Government of Canada eschewed any aspirations to become a nuclear power and embarked on the development of peaceful uses of nuclear technology. In 1952, Atomic Energy of Canada Limited (AECL) was created to take over the Chalk River Nuclear Laboratories from the National Research Council (NRC). With Chalk River as the hub of research and development, AECL was charged with the development of technology for nuclear electricity generation. AECL's research and development program included work needed to ensure that CANada Deuterium Uranium (CANDU) technology had a solid technical base, and applied programs that resulted in qualification of equipment, processes and systems for power and research reactors.[6] AECL's research has focused primarily on eight key areas of expertise:

- safety
- fuel and fuel cycles
- fuel channels
- components and systems
- heavy water production and processing

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3 Bothwell, R. *Nucleus: The History of Atomic Energy of Canada Limited*. University of Toronto Press, 1998, pp. 59–66.
4 Bothwell, pp. 40–1.
5 http://science.uwaterloo.ca/~cchieh/cact/nuctek/canhistory.html (accessed June 26, 2008).
6 CERI. *Economic Impact of the Nuclear Industry in Canada*. Submitted to CNA, July 2003, p. 9.

- environment, emissions and waste management
- control and information
- constructability

The National Research Universal (NRU) reactor started up in 1957, soon after the creation of AECL. At nearly 200 MW, the NRU was a much larger reactor than the NRX. The NRU, also located at Chalk River, is still known today for its versatility and high neutron flux.[7] Like its predecessor, the NRU uses natural uranium and is heavy-water-moderated. According to the Canadian Neutron Beam Centre, there are plans to further refurbish the NRU, enabling operation to continue to around 2012.

Following the mandate to develop nuclear energy for peaceful purposes, the first nuclear electricity generation in Canada occurred in 1962 at the Rolphton Nuclear Power Demonstration (NPD) plant. The Rolphton NPD, located near Chalk River, was the first CANDU-type reactor. Using heavy water technology and natural uranium, the reactor was designed and constructed jointly by Ontario Hydro (now Ontario Power Generation), Canadian General Electric (GE Canada Inc.), and AECL.[8] The unique benefit of AECL's CANDU reactor technology is its ability to use uranium enriched to a lesser extent than other nuclear reactor technologies, thus making fuel acquisition, preparation, and handling cheaper and safer.[9] The NPD ushered in a new era of commercial reactors and was decommissioned in 1987.

Douglas Point commenced operating in late 1966. The large prototype CANDU reactor had a net-installed-capacity of 208 MW and was decommissioned in 1984. Pickering A's four units went into operation between 1971 and 1973 and Bruce A, a station with four 900 MW class units, came online in 1977. More CANDU power plants were constructed during the 1980s: a 600 MW class unit at Point Lepreau, New Brunswick; a similar unit at Bécancour, Quebec; four 600 MW class units at Pickering B in Ontario; and four 900 MW class units at Bruce B in Ontario. As well, the four 935 MW units at Darlington station in Ontario were completed in 1993.

Prior to the 1990s, AECL had sold and built five CANDU reactors outside of Canada (see Table 2.1), one in Pakistan (1971), two in India (1972 and 1980), one in South Korea (1983), and one in Argentina (1984). AECL has built six additional reactors outside Canada since the late 1990s: three in South Korea (Wolsong), two in China (Qinshan) and two in Romania (Cernavoda), the second one commissioned on October 5, 2007. Romania is considering two more CANDU units at the same location.

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7 http://science.uwaterloo.ca/~cchieh/cact/nuctek/canhistory.html (accessed June 26, 2008).
8 Bothwell, R. *Nucleus: The History of Atomic Energy of Canada Limited*. University of Toronto Press, pp. 228–232.
9 Timilsina, Govinda et al. *GHG Emissions and Mitigation Measures for the Oil & Gas Industry in Alberta*. CERI, 2006.

Table 2.1
CANDU Reactors Outside Canada

Reactor	Country	Capacity (net MW)	Year in Service
KANUPP	Pakistan	1 x 125	1971
Rawabhata 1	India	1 x 90	1972
Rawabhata 2	India	1 x 187	1980
Wolsong 1	Korea (South)	1 x 629	1983
Wolsong 2	Korea(South)	1 x 629	1997
Wolsong 3	Korea (South)	1 x 629	1998
Wolsong 4	Korea (South)	1 x 629	1999
Embalse	Argentina	1 x 600	1984
Cernavoda 1	Romania	1 x 629	1996
Cernavoda 2	Romania	1 x 629	2007
Qinshan 1	China	1 x 665	2002
Qinshan 2	China	1 x 665	2003

Sources: International Energy Agency (IEA), *Energy Policies of IEA Countries: Canada 2004 Review*, p. 142; World Nuclear Association's web site, www.world-nuclear.org

Currently, six of the 30 nuclear units under construction worldwide use Pressurised Heavy Water Reactor (PHWR) technology. This includes a CANDU unit in Romania, as well as construction in India using technology borrowed from Canada. India has 16 nuclear generating units in operation, 14 of them employing heavy water technology. The Tarapur-3 and Tarapur-4, located in Maharashtra, began operation in June 2006 and June 2005, respectively. India has a further seven reactors under construction, four of them employing heavy water technology.

China has 10 nuclear generating units in operation, two of them employing CANDU technology. With a total installed capacity of 7,572 MW, China is embarking upon an ambitious nuclear construction program. According to the World Nuclear Association (WNA), China is planning to increase its nuclear capacity fivefold by 2020. China has developed its own nuclear design and construction capability, although it also encourages international cooperation. It has selected Pressurised Light Water Moderated and Cooled Reactor (PWR) as the main, but not sole, reactor type. The 1,000-MW Tianwan-1 began operation in May 2006 while the Tianwan-2 began operation in August 2007.

South Korea has 20 nuclear units on line (four of them employing CANDU technology) totalling 16,840 MW. Currently, four additional units are under construction and a further four are planned to come on line by 2015, none of which are PHWR. Argentina is also constructing a PHWR reactor, the Atucha-2, which is to be completed in 2010.

2.2 Atomic Energy of Canada Limited (AECL)

As previously mentioned, AECL was created in 1952 to take over the Chalk River Nuclear Laboratories from the National Research Council. AECL was charged with the development of technology for nuclear electricity generation. AECL's research and development program included work needed to ensure that CANDU technology had a solid technical base and applied programs that would result in qualification of equipment, processes, and systems for power and research reactors.[10]

In 1994, the federal government altered AECL's mandate, requiring it to concentrate on "its role as a reactor designer and vendor."[11] In addition, AECL was forced to streamline operations to make it more cost-effective.

AECL is still responsible for most nuclear R&D occurring in Canada, including the development, marketing and management of the construction of CANDU power reactors, one of its core business products. AECL is currently pursuing detailed work on a "next generation" design of the CANDU reactor — the ACR-1000® — which is expected to have lower capital costs, shorter construction time, and produce less waste than the current generation of CANDU reactors. AECL also provides engineering and consulting services to owners of CANDU reactors, as well as other reactors at home and abroad, and offers radioactive waste management products and services.

AECL currently maintains a comprehensive R&D program that supports the CANDU reactor design and its product development. Together with partners mentioned in the previous section in the Canadian nuclear industry and private-sector companies in other countries, AECL has designed, engineered, and supplied components of CANDU units in North America, South America, Europe, and Asia. AECL also manages the building and servicing of CANDU units.

Sales of CANDU reactors abroad have a positive impact on AECL and the Canadian economy to the extent that goods and services used in their construction are imported from Canada, including reactor components which are manufactured in Canada and licence fees, project management and other consulting services sold by AECL to the importing country.

2.3 Nuclear Reactors in Canada

According to the Canadian Nuclear Association (CNA),[12] as of July 2006, there are 22 CANDU reactors in Canada, of which 18 are operating. The remaining reactors are shut down, having their operating life extended, or have been put into safe storage. Nuclear electricity generation in Canada is discussed in detail in Section 3.3. Nuclear research reactors in Canada are discussed in Chapter 7.

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[10] CERI. *Economic Impact of the Nuclear Industry in Canada*. Submitted to CNA, July 2003, p. 9.
[11] AECL. *Report of the AECL Research & Development Advisory Panel for 2001*. p. 8.
[12] CNA. *Nuclear Energy Technology in Canada: Nuclear at a Glance*." July 2006.

2.4 Safety and Environmental Issues

2.4.1 Canadian Regulations for Nuclear Power Plants

Nuclear activities in Canada are regulated by the federal government, under the direction of the Canadian Nuclear Safety Commission (CNSC). The CNSC describes itself as the "nuclear energy and material watchdog in Canada,"[13] and is responsible for the regulation of nuclear power reactors, uranium mines and mills, fuel fabrication and processing facilities, and waste management facilities.

There is considerable interest in new build nuclear reactors in Ontario, New Brunswick, and even Alberta where there are presently no reactors. Any new reactors would follow the regulatory guidelines detailed in the February 2006 document, *Licensing Process for New Nuclear Power Plants in Canada*.[14] The process requires a proponent to apply for licences for site preparation, construction, and operation of a nuclear reactor. In addition, a positive decision on an Environmental Assessment (EA) under the *Canadian Environmental Assessment Act* is required in order for a new nuclear reactor to be built in Canada. This process is anticipated to take anywhere from 18 to 36 months from start to finish, depending on a number of factors, as outlined in the 2006 document. The licences can be applied for in a parallel process while the EA is being carried out.

2.4.2 Regulations on Spent Fuel and Waste

The safety of nuclear energy in Canada can be separated into two generic categories: High and Low level "waste". High level waste consists primarily of spent nuclear fuel. Low level waste consists of all other radioactive waste streams that are not associated with spent fuel. The focus of this section will be on spent nuclear fuel as this accounts for the vast majority of radioactivity generated by nuclear power generation.

Spent nuclear fuel can be defined as irradiated fuel bundles that are discharged from operating nuclear reactors in Canada. These reactors all use CANDU technology, as described in the previous section. Spent fuel is also discharged from research reactors.

Currently in Canada, spent fuel is being kept on licensed facilities at reactor sites located in Ontario, Quebec, New Brunswick and Manitoba. Spent nuclear fuel is removed from reactors and then stored in wet storage for 7–10 years to reduce heat and radioactivity. It is then transferred into concrete dry storage containers that have a life span of 50 years. In December 2004, there was a total of 1.4 million fuel bundles in wet storage, and 0.3 million bundles in dry storage facilities in Canada.[15] It is possible to reprocess spent nuclear fuel to generate additional energy. A single nuclear fuel bundle, used in a CANDU 6 reactor, can be reprocessed multiple times, with

[13] www.nuclearsafety.gc.ca/eng/about_us/ (accessed February 7, 2007).
[14] www.nuclearsafety.gc.ca/pubs_catalogue/uploads/INFO-0756_e.pdf (accessed June 26, 2008).
[15] OPA. *Ontario's Integrated Power Systems Plan, Discussion Paper 4: Supply Resources*. November 9, 2006, p. 21.

the final high-level waste product the size of a golf ball, or 0.5 percent of the original size of a CANDU 6 fuel bundle. Reprocessing is generally not considered to be economic unless the price of uranium exceeds US$300/lb.[16] For security of supply reasons, reprocessing is taking place in France, UK, Belgium, Japan, and Russia.

Due to the high public interest and concern for long-term spent nuclear fuel management, the Government of Canada developed the *Nuclear Fuel Waste Act*, which came into force in November 2002. Following the Act's implementation, the federal government formed the Nuclear Waste Management Organization (NWMO). The NWMO has a mandate to recommend an approach for Canada's long-term management of spent nuclear fuel.[17]

The NWMO has completed a comprehensive study on the potential options for spent fuel management in Canada.[18] The study has been sent to the Government of Canada for consideration as part of Canada's long-term plan for spent fuel management. The study concludes that a process called *Adaptive Phased Management* be used for the long-term management of spent fuel in Canada. Adaptive phased management consists of both a technical method and a management system.

The Adaptive Phased Management approach is broken down into three phases. Phase 1 is preparing for the central used fuel management, using public awareness programs over a 30 year period. Phase 2 is central storage and technology demonstration. This phase would take 30 years and would require technology plans to be finalized and construction to be under way. Phase 3 is the long-term containment, a process by which spent nuclear fuel is moved to a central repository for Deep Geological Storage. Isolation and monitoring would last for at least 60 years.

Deep Geological Storage would involve placing spent nuclear fuel underground in the Canadian Shield. It would rely on natural and engineered barriers to isolate the spent fuel from humans and the surface environment over its hazardous lifetime. The central site could be designed to allow removal of spent nuclear fuel for reprocessing.

2.4.3 Nuclear Power Related Fatalities

New construction in the nuclear energy industry in North America ground to a halt in the late 20th century. In Canada, interest rates and inflation constitute two reasons why Ontario nuclear power plants experienced massive cost overruns. Similar problems occurred throughout the United States during the 1980s, contributing to the nuclear industry's stagnation. Another reason for the halt was the Chernobyl reactor accident, the worst nuclear power plant disaster in history.

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[16] Bunn, M., S. Fetter, J. Holdren, and B. van der Zwaan. *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*. Managing the Atom Project, Belfer Center for Science & International Affairs, Harvard University, December 2003.

[17] NWMO Mandate, www.nwmo.ca/default.aspx?DN=18,1,Documents&l=English (accessed June 26, 2008).

[18] NWMO, www.nwmo.ca/default.aspx?DN=20,1,Documents&l=English (accessed June 26, 2008).

Chernobyl does not provide a representative case of the nuclear industry's safety record. Documented cases of deaths associated with nuclear power since its origins consist of 28 Chernobyl plant personnel who died in 1986 from radiation exposure, three who died from the explosion and burns, and three children in the Chernobyl area who subsequently died from thyroid cancer; one Japanese plant worker died in 1999 in an incident at the Tokaimura nuclear fuel processing plant; and four plant workers died in 2004 from scalding at the Mihama nuclear power plant — for a total of 34 deaths at Chernobyl and 5 deaths elsewhere.

The most damaging nuclear incident in North America happened at the twin unit Three Mile Island Nuclear Generating Station (TMI) in the state of Pennsylvania, in the United States. TMI-2, the second unit, suffered an incident in 1979 that resulted in severe damage to the core of the facility. There were no fatalities from TMI-2, and the concept of reactor containment was proven effective in preventing the release of harmful radiation beyond the containment facility. This key feature differentiated it from the Chernobyl reactor that had no containment facilities. All modern reactors have containment facilities that are designed to prevent releases of radioactivity from the reactor core, a feature proven effective at TMI.

An appropriate way of comparing the mortality track record of different energy sources is to relate them to the amount of electricity generated. This is the approach taken in Table 2.2, which expresses the mortalities on a terawatt-year basis. One terawatt-year is the equivalent of the yearly output of 20 nuclear power plants the size of one CANDU or PWR plant.

Table 2.2
Comparison of Accident Statistics in Primary Energy Production

Fuel	Immediate fatalities 1970–92	Who?	Deaths per TWa* of electricity
Coal	6,400	Workers	342
Hydro	4,000	Public	883
Natural gas	1,200	Workers and public	85
Nuclear	31	Workers	8

Source: World Nuclear Association, compiled from Ball, Roberts & Simpson, Research Report #20, Centre for Environmental & Risk Management, University of East Anglia, 1994; Hirschberg et al., Paul Scherrer Institut, 1996; in: IAEA, *Sustainable Development and Nuclear Power*, 1997; *Severe Accidents in the Energy Sector*, Paul Scherrer Institut, 2001.

* TWa is an abbreviation for terawatt-year (a = annum).

A more comprehensive comparison of all hazards, prepared by the US Census Bureau, and reproduced by Garwin and Charpak (2001)[19] is presented in Table 2.3. Garwin and Charpak's risk calculations for normal nuclear operation at Three Mile Island and Chernobyl, are given in Table 2.4.

Table 2.3
Deaths and Death Rates for 1994 in the US
All Races, Both Sexes, Population = 261 million

Cause of death	Total number	Probability per year per 100,000 population
Cardiovascular diseases	2,286,000	876
Malignancies	534,000	205
Accidents and adverse effects	90,000	34
Motor vehicles	42,524*	16
Falls	13,450	5.15
Accidental poisoning by drugs and medicines	7,828	3.00
Fire and flame	3,986	1.53
Drowning	3,404	1.30
Inhalation and ingestion of objects	3,065	1.17
Complications due to medical procedures (approximate)	2,700*	1.03
Firearms (unspecified)	1,123	0.43
Air and space transport	1,075	0.41
Water transport	723	0.28
Gases and vapours	605	0.26
Railway	635	0.24
Electric current	561	0.26
Other solids and liquids	481	0.18
Handguns	233	0.09

Source: US Census Bureau, quoted by Garwin and Charpak.
* A 1999 Institute of Medicine study indicated that 49,000 to 98,000 Americans die each year due to "medical errors in hospitals" — more than die in motor vehicle accidents.

Table 2.4
Garwin and Charpak's Risk Calculations for Normal Nuclear Operation

Cause of death	Probability per year per 100,000 population
Normal operation of nuclear fuel cycle (6 per year x 300 plants / 10 billion people)	0.02 (200 per billion)
Three Mile Island (~3 deaths / [20 years x 220 million people])	0.00007 (0.7 per billion)
Chernobyl (30,000 deaths / [20 years x 250 million people])	0.6 (6,000 per billion)

Source: Garwin and Charpak.

[19] Garwin, R.L. and G. Charpak. *Megawatts and Megatons*. New York, Knopf, 2001, p. 202.

Clearly, the point Garwin and Charpak make is that the risk of immediate death due to normal nuclear operations is statistically very small — posing much less hazard than many other human activities.

Following the events of September 11, 2001, concerns have been raised about whether nuclear power plants are vulnerable to attack by large commercial aircraft. International and domestic regulations, as governed by the International Atomic Energy Agency, and the CNSC (respectively), are being continuously improved to address issues related to domestic and international terrorism. Although nuclear power plants have not been designed specifically to handle an event such as a plane crash, they are designed to withstand such extreme events as earthquakes, tornadoes and hurricanes.

2.4.4 Terrorism Threats to Nuclear Power

In December 2004, the Government of Canada commissioned Dr. John Gittus — expert in nuclear insurance and risk — to provide an assessment of the appropriate premiums for the reinsurance coverage for third party nuclear damage arising from acts of terrorism.[20] This comprehensive analysis concludes that the risk of a terrorist incident damaging a reactor and resulting in the release of radioactivity is still deemed to be sufficiently low. The risk of a commercial airliner being crashed into a nuclear facility has increased since 2001, but has not increased sufficiently to result in the defuelling and decommissioning of the world's nuclear power stations. In fact commercial insurance is still readily available, along with the traditional government insurance, for acts of terrorism at Canada's nuclear power plants.

Nuclear installations have been strengthened against terrorist attacks. Specific security measures available for current and potential new builds in Canada are highly sensitive and provided on a need to know basis. As such, they are unavailable for publication. While each government has its own unique response protocols, Western reactor designs have been proven to be hardened targets. According to the study prepared by Gittus in December 2004, the Government of Canada stated that nuclear power plants are designed to withstand the impact of a commercial airline but require added security against water-borne vessels that may carry explosives. Trials in Japan and the United States concluded that containment structures could withstand the impact of a commercial airline; containment damage would depend on the point of impact, and the balance of the plant would likely suffer considerable fire damage.

The availability of commercial insurance, the industry's excellent safety record, and a renewed global commitment to nuclear energy is helping drive a global "nuclear renaissance."

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[20] Dr. J.H. Gittus. *Review of the Premium for Government Reinsurance of Terrorist Coverage under the Canadian Nuclear Liability Act, (NLA)*. December 16, 2004.

2.4.5 Environmental Issues Related to Nuclear Power

As most developed countries are moving towards some form of greenhouse gas (GHG) reductions and emission-control strategies, nuclear is taking centre stage as a clean source of energy. There is, however, information available that nuclear energy is not a zero-emitting source of GHGs, rather a near-zero emitting source. When the life cycle of any energy option, including renewables, is considered, none is carbon-free. Consider specifically carbon dioxide (CO_2), a GHG considered to be the major culprit behind global warming. In the case of nuclear energy, no harmful gases are emitted while a reactor is generating — this is the critical point of differentiation between nuclear and fossil fuels: coal and gas emit substantial greenhouse gases during power generation while nuclear does not. It is at other points in the nuclear life cycle that emissions occur: mining and manufacturing of fuel for the power plants produce carbon dioxide and other GHGs, and there are inevitable emissions during the construction phase, as well. However, this also holds true of other energy options.

A Canadian-based environmental think tank, the Pembina Institute, recently published a report examining the environmental impact of nuclear energy.[21] According to the Canadian Nuclear Association, the report is "unbalanced,"[22] not taking into account GHG mitigation technologies used by the industry during the mining and manufacture of fuel bundles, and during the construction of nuclear reactors and support facilities.[23] According to an ongoing multipart study by the Ontario Power Authority (OPA), "The operation of nuclear power plants is virtually GHG emission free, and GHG emissions associated with uranium mining and transport and power plant construction and decommissioning are mitigated on a per unit energy basis, due to the high energy production capacity of nuclear plants."[24] CERI has also recently studied the issue and in a forthcoming report reaches the conclusion that "nuclear's greenhouse gas emissions are at least two orders of magnitude lower than those of fossil fuels — ranking with wind and solar energy."[25]

Like many developed nations struggling with carbon mitigation, the United Kingdom has been aggressively reviewing their available options. The UK's Sustainable Development Commission recently came out in support of nuclear as a favorable option for the UK. According to their conclusions, on a per unit of output basis, nuclear energy emits the least amount of carbon[26] when compared to the UK's energy alternatives: wind, biomass, natural gas and coal.[27]

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21 Pembina Institute. *Nuclear Power in Canada: An Examination of Risks, Impact, and Sustainability*. December 2006.

22 CNA President Murray Elston interview with the Canadian Broadcasting Corporation (CBC), December 14, 2006. www.cbc.ca/technology/story/2006/12/14/nuclear-study.html (accessed June 26, 2008).

23 Concerns of the CNA are based upon private communications with the CNA, December 14, 2006.

24 OPA. *Ontario's Integrated Power System Plan, Discussion Paper 6: Sustainability*. November 10, 2006.

25 CERI. *Nuclear Power in Canada: A Review of a Critique,* p. xiv.

26 Sustainable Development Commission. *The role of nuclear power in a low carbon economy*. SDC Position Paper, Continental SuperGrid, March 2006.

27 HM Government, UK Department of Trade and Industry. *The Energy Challenge*. July 2006.

Since there has been limited work on the Life-Cycle Assessment for nuclear energy in Canada, and such an assessment is outside the scope of this project, the Pembina Institute's estimates will be used for comparison with the cleanest hydrocarbon available — natural gas. Their report concludes that between 468,000 and 594,000 tonnes of carbon dioxide are emitted by the nuclear sector in a given year — including the fuel cycle and plant construction.

As previously mentioned, there are 18 nuclear reactors operating in Canada, and the uranium mining industry exports in excess of 90 percent of their uranium output to other countries. A single combined cycle-gas turbine (CCGT) produces approximately 290 kg CO_2/MWh according to the OPA.[28] This implies that a 750 MW natural gas CCGT facility would produce approximately 1.9 million tonnes of CO_2 in a given year, which is approximately 320 percent higher than the nuclear sector emits in a given year in Canada. On a per MWh basis, the OPA has reported contrasting numbers to the Pembina report. According to the OPA, nuclear emits 12 kg CO_2/MWh. For a 750 MW nuclear power plant (equivalent to the Enhanced CANDU 6), natural gas would emit some 2,400 percent more carbon. Based upon information from the OPA, the Pembina Institute, and sources from the UK, it can be concluded with reasonable certainty that the nuclear sector in Canada emits far less carbon dioxide than the cleanest hydrocarbon.

[28] OPA. *Supply Mix Advice and Recommendations, Volume 2 Analysis Report*. December 2005.

CHAPTER 3
WORLD AND CANADIAN NUCLEAR POWER

This chapter presents the latest statistics and analysis of Canadian nuclear power, comparing it with nuclear power in other countries. Divided into four sections, the first presents world nuclear power capacity and generation, followed by the world's uranium requirements for power generation in section two. Nuclear electricity generation capacity in Canada at the national as well as provincial levels is discussed in the third section. Finally, nuclear electricity generation and uranium requirements at the national and provincial levels are discussed in the last section.

3.1 World Nuclear Power

Table 3.1 tabulates the nuclear power capacity (MW) and generation (TWh) of all countries along with their GDP and population. Also presented in the table are the technologies employed for nuclear power generation in those countries.

The first commercial nuclear power stations started operation in the early 1950s. By 2006, 441 nuclear power reactors were in service around the world in 31 countries, with a combined generation capacity of 369,122 MW (see Table 3.1). Today, nuclear power supplies about 16 percent of the world's electric energy.

As shown in Table 3.1, approximately 55 percent of total global nuclear power capacity is located in three industrialized countries: the United States (26.6 percent), France (17.2 percent), and Japan (12.9 percent). Canada is in 8th position with a total capacity of 12,599 MW. China and India, the two most populous countries in the world, hold 3 percent of global nuclear capacity.

In 2004, about 2,619 terawatt-hours (TWh or billion kWh) of electricity were generated around the world. The three top producers of nuclear electricity were the United States (30 percent), France (16 percent) and Japan (10 percent). Canada was in 7th position with generation of 85 TWh (3.28 percent).

Table 3.1
2006 Economic and World Nuclear Power Indicators

Country	GDP (billions $US)	Population (millions)	Nuclear generation capacity (MW)	Nuclear generation (TWh)	Technology
US	12,980	298.4	98,145	788.53	PWR/BWR/LMFBR/HTGR
France	1,871	62.8	63,363	425.83	GCR/PWR/GCHWR/LMFBR
Japan	4,220	127.5	47,593	271.58	BWR/HWLWR/PWR/GCR
Russia	1,723	142.9	21,743	137.47	PWR/LGR/LMFBR/BWR
Germany	2,585	82.4	20,339	158.97	PWR/BWR/LMFBR/PHWR/ GCHWR/HTGR
Republic of Korea	1,180	48.8	16,810	124.18	PWR
Ukraine	356	46.7	13,107	82.69	LGR/PWR
Canada	1,165	33.1	12,599	85.87	PHWR
UK	1,903	60.6	11,852	73.68	GCR/AGR/PWR/LMFBR/ HWLWR
Sweden	285	9.0	8,910	73.43	PWR/BWR
China	10,000	1,314	7,572	47.95	PWR/BWR
Spain	1,070	40.4	7,446	60.43	PWR/BWR/GCR
Belgium	330	10.4	5,824	45.80	PWR
Taiwan	668	23.0	4,904	37.94	PWR
Czech Republic	221	10.2	3,368	25.01	PWR
Switzerland	253	7.5	3,220	25.61	PWR/BWR/GCHWR
India	4,042	1,095	3,040	15.04	PHWR/BWR
Bulgaria	77	7.4	2,722	15.60	PWR
Finland	172	5.2	2,676	21.55	PWR/BWR
Slovakia	96	5.4	2,442	16.18	PWR/GCHWR
Brazil	1,616	188.1	1,901	11.60	PWR
South Africa	576	44.2	1,800	14.28	PWR
Hungary	173	10.0	1,755	11.32	PWR
Mexico	1,134	107.4	1,310	8.73	BWR
Lithuania	54	3.6	1,185	14.35	LGR
Argentina	599	39.9	935	7.31	PHWR
Slovenia	46	2.0	656	5.21	BWR
Romania	197	22.3	655	5.27	PHWR
Netherlands	512	16.5	449	3.63	BWR
Pakistan	427	165.8	425	1.93	PHWR/PWR
Armenia	16	3.0	376	2.21	PWR
Total	**50,549**	**4,034**	**369,122**	**2,619**	

Source: *CIA Fact Book* (2006 GDP and POP), Y. Sokolov and A. MacDonald, *Nuclear Power – Global Status and Trends*, (2006 Capacity), International Nuclear Safety Center (2004 Generation and Technology).

Notes:
PWR — Pressurized Light Water Moderated and Cooled Reactor
BWR — Boiling Light Water Cooled and Moderated Reactor
PHWR — Pressurised Heavy Water Moderated and Cooled Reactor
HWLWR — Heavy Water Moderated, Boiling Light Water Cooled Reactor
LGR — Light Water Cooled, Graphite Moderated Reactor
LMFBR — Liquid Metal Fast Breeder Reactor
GCR — Gas Cooled, Graphite Moderated Reactor
GCHWR — Gas Cooled, Heavy Water Moderated Reactor
HTGR — High Temperature Gas Cooled Reactor
AGR — Advanced Gas Cooled, Graphite Moderated Reactor

It is also interesting to note how the nuclear power industry has been growing around the world. Growth rates of nuclear generation by country are shown in Table 3.2. CERI has estimated average annual growth rates (AGR) of nuclear power generation for the periods of 1990 to 2004 and 1995 to 2004 from available data.

From 1995 to 2004, three developing countries demonstrated the highest annual growth rates in nuclear power generation: Brazil (17.1 percent), Pakistan (14.5 percent) and China (14.5 percent).

Table 3.2
Growth Rates of World Nuclear Power Generation

Country	1990 (TWh)	1995 (TWh)	2000 (TWh)	2004 (TWh)	Annual growth rates 1990–2004 (%)	Annual growth rates 1995–2004 (%)
Brazil	1.9	2.4	4.9	11.6	12.66	17.09
Pakistan	0.4	0.5	0.4	1.9	11.75	14.52
China	NA	12.4	15.9	47.9	NA	14.50
India	5.6	6.5	14.1	15.0	6.79	8.82
Czech Republic	NA	11.6	12.9	25.0	NA	7.97
Republic of Korea	50.2	63.7	103.5	124.2	6.21	6.91
Slovak Republic	NA	10.9	15.7	16.2	NA	4.06
Russia	NA	94.3	122.5	137.5	NA	3.84
Belgium	40.6	32.3	45.8	45.8	0.81	3.56
Lithuania	NA	10.6	8.0	14.3	NA	3.03
South Africa	8.4	11.3	13.0	14.3	3.56	2.37
Ukraine	NA	67.0	71.1	82.7	NA	2.13
France	298.4	358.4	394.4	425.8	2.40	1.74
Finland	18.3	18.3	21.4	21.5	1.11	1.67
US	576.9	673.4	753.9	788.5	2.10	1.59
Spain	51.6	52.7	59.1	60.4	1.06	1.38
Slovenia	NA	4.6	4.5	5.2	NA	1.35
Taiwan	31.6	33.9	37.0	37.9	1.24	1.12
Sweden	64.8	66.4	54.5	73.4	0.84	1.01
Germany	145.4	145.4	161.1	159.0	0.59	0.89
Mexico	2.8	8.0	7.8	8.7	7.89	0.85
Switzerland	22.4	23.7	25.1	25.6	0.89	0.80
Argentina	7.0	7.1	6.0	7.3	0.26	0.34
Japan	192.2	276.7	305.9	271.6	2.33	-0.19
Bulgaria	13.5	16.4	17.3	15.6	0.95	-0.50
Netherlands	3.3	3.8	3.7	3.6	0.58	-0.50
Canada	69.2	93.0	69.2	85.9	1.44	-0.79
UK	62.5	84.5	80.8	73.7	1.11	-1.36
Hungary	13.0	13.3	13.5	11.3	-0.94	-1.61
Armenia			1.8	2.2	NA	NA
Romania			5.2	5.3	NA	NA
Total	**1,680**	**2,203**	**2,450**	**2,619**	**3.00**	**1.75**

Source: Energy Information Administration
Notes: NA (not available, mainly due to changes in national boundaries)

Nuclear capacity, nuclear generation, GDP, and population by country are presented in Table 3.3. The last two columns of this table relate each country's nuclear capacity and generation to the world total.

Table 3.3
World Nuclear Power Capacity and Generation Per Unit GDP and Per Person

	Nuclear capacity		Nuclear generation		% World nuclear power	
Country	KW per billion $ GDP	KW per 1,000 persons	KWh per $1,000 GDP	KWh per person	Capacity share	Generation share
Argentina	1,561	23.4	12.2	183.1	0.25	0.28
Armenia	23,515	126.3	137.9	740.8	0.10	0.08
Belgium	17,627	561.1	138.6	4,412.7	1.58	1.75
Brazil	1,176	10.1	7.2	61.7	0.52	0.44
Bulgaria	35,291	368.6	202.2	2,112.0	0.74	0.60
Canada	10,815	380.6	73.7	2,594.4	3.41	3.28
China	757	5.8	4.8	36.5	2.05	1.83
Czech Republic	15,212	329.1	113.0	2,443.9	0.91	0.96
Finland	15,585	511.5	125.5	4,118.6	0.72	0.82
France	33,866	1,009.7	227.6	6,785.9	17.17	16.26
Germany	7,868	246.8	61.5	1,928.8	5.51	6.07
Hungary	10,162	175.8	65.6	1,134.5	0.48	0.43
India	752	2.8	3.7	13.7	0.82	0.57
Japan	11,278	373.4	64.4	2,130.6	12.89	10.37
Lithuania	21,932	330.5	265.5	4,000.9	0.32	0.55
Mexico	1,155	12.2	7.7	81.3	0.35	0.33
Netherlands	877	27.2	7.1	220.1	0.12	0.14
Pakistan	995	2.6	4.5	11.6	0.12	0.07
Republic of Korea	14,246	344.1	105.2	2,542.3	4.55	4.74
Romania	3,320	29.4	26.7	236.3	0.18	0.20
Russia	12,619	152.2	79.8	962.0	5.89	5.25
Slovakia	25,345	448.9	167.9	2,974.4	0.66	0.62
Slovenia	14,236	326.3	113.1	2,592.6	0.18	0.20
South Africa	3,123	40.7	24.8	323.2	0.49	0.55
Spain	6,959	184.3	56.5	1,495.9	2.02	2.31
Sweden	31,252	988.2	257.5	8,143.4	2.41	2.80
Switzerland	12,732	428.0	101.3	3,404.1	0.87	0.98
Taiwan	7,338	213.2	56.8	1,649.5	1.33	1.45
UK	6,228	195.5	38.7	1,215.7	3.21	2.81
US	7,561	328.9	60.7	2,642.1	26.59	30.11
Ukraine	36,838	280.6	232.4	1,770.3	3.55	3.16

The top 10 nuclear power producing countries are ranked in Figures 3.1 and 3.2: 1) by generation per $1,000 GDP, and 2) by generation per person. These rankings are expected to change over the next 10 to 20 years due to expansion, replacement of retiring nuclear power plants in some countries, and the phasing out of nuclear power in other countries: Sweden, Spain, Italy, Belgium, and Germany have passed nuclear phase out laws. It is unclear at this time the extent to which they intend to implement them, only Italy and Sweden have closed reactors as a consequence of their phase out laws. Contrastingly, other nations such as Iran, North Korea, India and Pakistan may develop their first nuclear generating capacity or expand from an existing base. There appears to be a trend of developing nations advancing nuclear generation while some developed nations phase it out.

Figure 3.1
Top 10 Countries in Nuclear Generation per $1,000 GDP

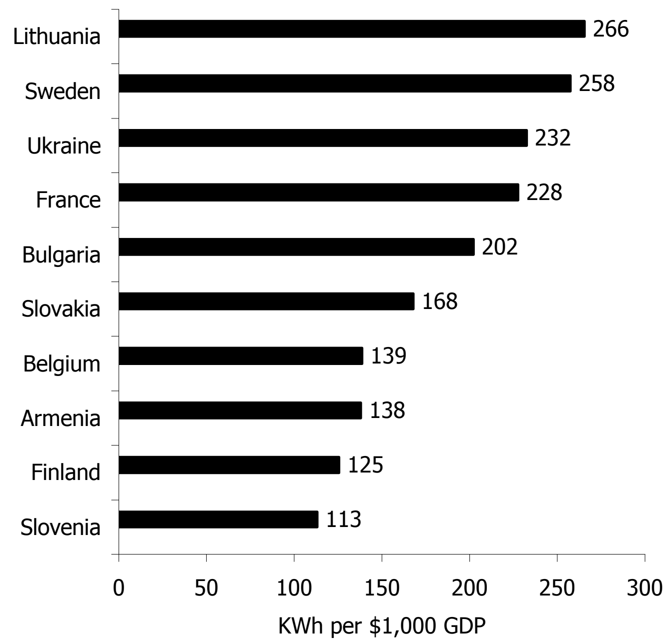
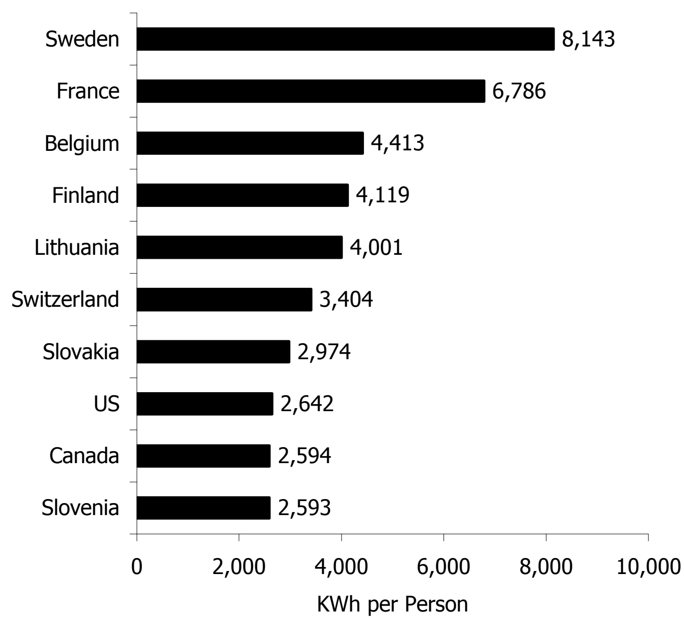


Figure 3.2
Top 10 Countries in Nuclear Generation per Person



Source: Table 3.3, Figure 3.1, and Figure 3.3 are derived from Table 3.1

3.2 World Uranium Consumption

In 2006, nuclear power plants with a combined capacity of 369,122 MW (Table 3.1) used approximately 66,500 tonnes of uranium, equivalent to 78,500 tonnes of U_3O_8 (yellowcake) from mines.

Nuclear fuels are produced from mined uranium or supplied from secondary sources, including civilian stockpiles; re-enriched depleted uranium tails; recycled uranium and plutonium from spent fuel; and uranium from dismantled military weapons.

Re-enriched uranium tails are derived from depleted uranium, which is a byproduct of the enriching of natural uranium for use in light water nuclear reactors. When most of the fissile radioactive isotopes of uranium are removed from natural uranium, the residue is called depleted uranium. It is estimated that 1 kg of enriched uranium requires 11.8 kg of natural uranium,[29] and leaves about 10.8 kg of depleted uranium with only 0.3 percent uranium-235. In 2002, the world's depleted uranium stock was estimated to be 1.2 million tonnes.

Spent fuel reprocessing to produce a fuel consisting of mixed oxides of uranium and plutonium (MOx) is undertaken in a number of countries including France and the United Kingdom, with a world capacity of over 4,000 tonnes of spent fuel per year. The product from reprocessing and MOx facilities re-enters the fuel cycle after being fabricated into fresh MOx fuel elements. Each year, approximately 200 tonnes of MOx is used in nuclear power plants, equivalent to less than 2,000 tonnes of yellowcake (U_3O_8) from mines.

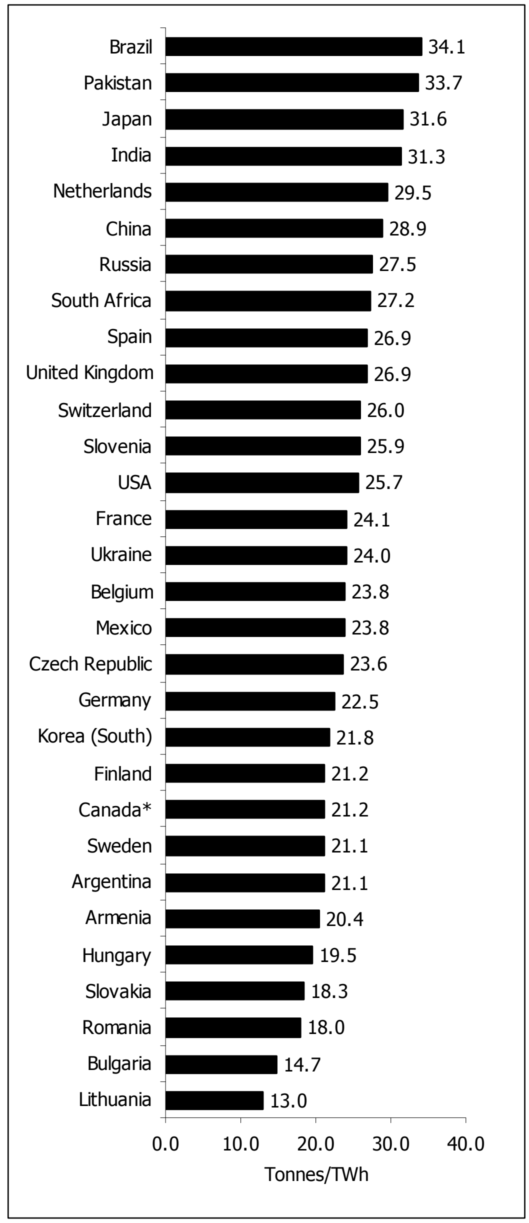
Military uranium for weapons is enriched to much higher levels than is required for power plants. Low enriched uranium (LEU) for power plants can be derived from high enriched uranium (HEU) in nuclear weapon stockpiles. HEU has been available to the nuclear power industry since 2000 as a result of disarmament treaties signed by the US and nations of the former Soviet Union. As of September 2007, the uranium from these stockpiles is displacing 10,600 tonnes of U_3O_8 from mines every year, meeting approximately 13 percent of the world's nuclear reactor requirements.[30]

The entire secondary uranium supply from all sources accounts for 35 percent of total supply, but this is projected to decline below 25 percent by 2010 and 12 percent by 2020.

The world's top three consumers of uranium for nuclear power generation are the United States, France and Japan (Figure 3.3). The available statistics suggest that Brazil has the highest rate of uranium consumption in terms of tonnes per terawatt-hour (use rate of 34.1) and Lithuania, the lowest (use rate of 13).[31]

[29] http://en.wikipedia.org/wiki/Depleted_uranium (accessed June 26, 2008).
[30] www.uic.com.au/nip04.htm (accessed June 26, 2008).
[31] There is a possibility of overestimating use rates due to availability of nuclear generation data in 2005 and estimated uranium requirements in 2007.

Figure 3.3
World Uranium Requirements by Country and by Electricity Generation



Source: World Nuclear Association, world-nuclear.org/info/reactors.htm

It is expected that annual worldwide demand for uranium use for electricity generation will increase for several reasons, notably the fuel requirements of the 27 new reactors presently under construction worldwide, with a combined capacity of 21,421 MW.

The price of uranium has been through two increasing price regimes: one in the 1950s, driven by military procurement; and the second in the 1970s, driven by commercial electric power. Uranium's price peaked in 1979 at US$45 per pound amid forecasts of an indefinite growth in demand of 3 to 4 percent per year; when this demand growth failed to materialize, a flood of new mines ended up with a huge buildup of inventories.

This boom was brought to an end by the Three Mile Island (1979) and Chernobyl (1986) incidents, which led to a moratorium on new nuclear power plants in the US and a construction slowdown worldwide. In 1993 the price declined to US$7 per pound, but in early 2004 it rebounded to more than US$15. Uranium spot prices in November 2007 peaked at US$92 per pound, two-and-a-half times the price at the start of 2006.[32] Many factors have influenced the rapid increase in uranium prices. These include surging fossil fuel prices, declining commercial uranium inventories, anticipated increase in demand for uranium mainly due to reactors under construction, cost of exploration, and decline in the value of the US dollar compared to the currencies of uranium producing countries.

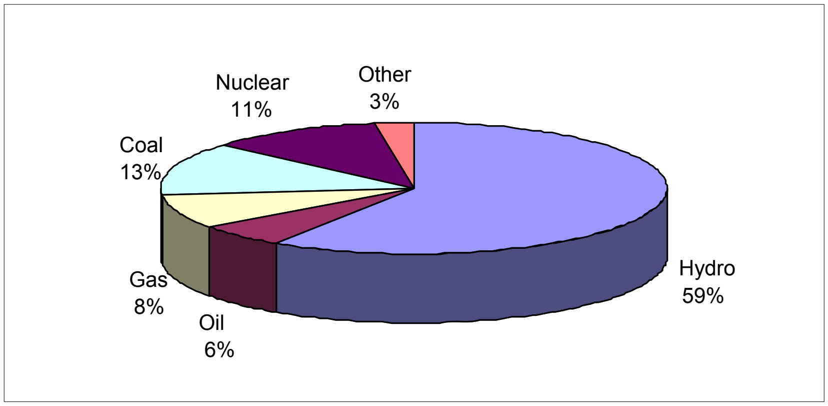
3.3 Nuclear Electricity in Canada

Nuclear energy is an important component of the energy mix required for providing low-cost and reliable electricity to meet Canada's baseload demand. The most notable product of Canada's nuclear energy industry is the unique CANDU (CANada Deuterium Uranium) reactor design, the centrepiece of Canada's nuclear program. The CANDU system, unlike US light water reactors, uses natural uranium as fuel.

In 2005, total electricity generation capacity in Canada, as shown in Figure 3.4, was 121,481 MW of which nuclear power was the third largest source with an 11 percent share after hydro (59 percent) and coal (13 percent).

[32] "Uranium stockpile to get more glow." January 3, 2007. www.allianceresources.com.au/IRM/Company/ShowPage.aspx?CPID=1065&PageName=The+Age+-+Uranium+stockpile+to+get+more+glow (accessed June 26, 2008).

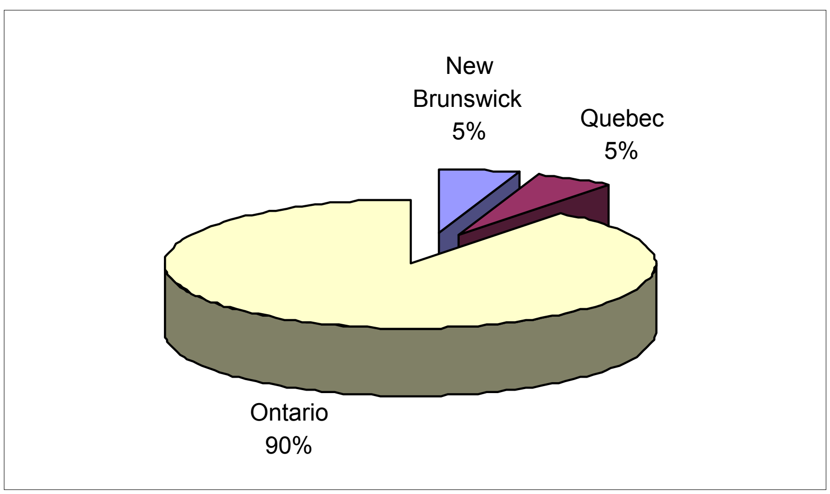
Figure 3.4
Canada's Generation Capacity by Resource, 2005
(121,481 MW)



Source: Statistics Canada, *Electric Power Generation, Transmission, and Distribution*, Catalogue no. 57-202-XIE, 2005, Table 1.

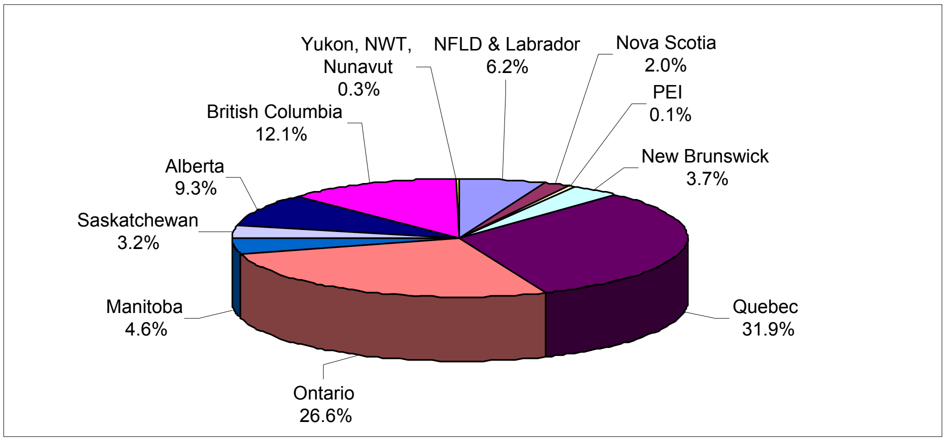
Most of the national total of 13,345 MW nuclear capacity is located in the province of Ontario, with 11,990 MW (Figure 3.5). Ontario has 16 operating reactors, plus two laid up and two others under refurbishment. Quebec and New Brunswick each have one reactor. Note that these three provinces account for about 62 percent of Canada's total electricity generation capacity (Figure 3.6).

Figure 3.5
Canada's Nuclear Capacity by Province, 2005
(13,345 MW)



Source: Statistics Canada, Catalogue no. 57-202-XIE and *Electric Power Generating Stations*, 2005, Table 1.

Figure 3.6
Canada's Electricity Generation Capacity by Province, 2005
(121,481 MW)



Source: Statistics Canada, Catalogue no. 57-202-XIE and *Electric Power Generating Stations*, 2005, Table 1.

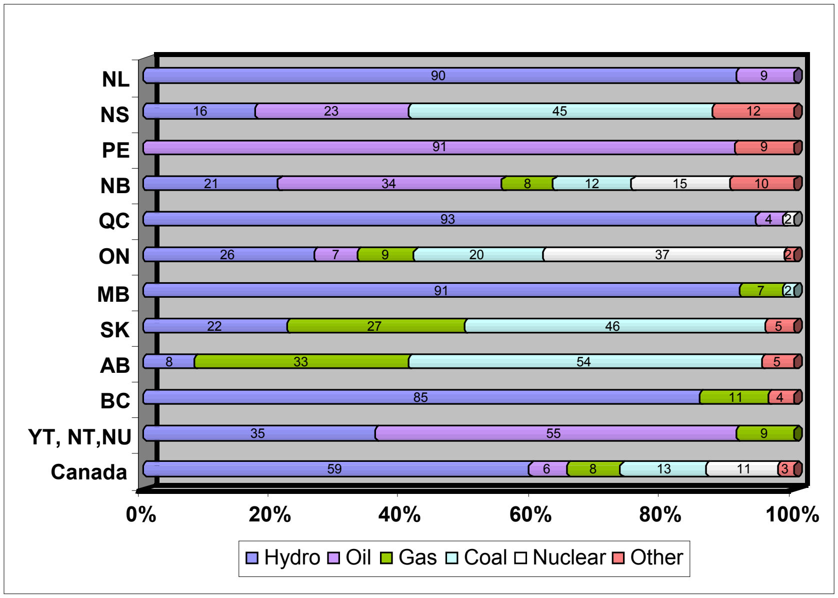
Table 3.4 and Figure 3.7 summarize electricity generation capacity by resource mix for each province in Canada, indicating that as of December 31, 2005, 37 percent of capacity in the province of Ontario was nuclear, compared to 15 percent in New Brunswick and 2 percent in Quebec.

Table 3.4
Canada's Electricity Generation Capacity by Province, 2005
(121,481 MW)

Provinces	Hydro	Oil	Gas	Coal	Nuclear	Other	Total
Newfoundland	6,777	674	43				7,494
Nova Scotia	404	554	98	1,097		299	2,452
Prince Edward Island		145				16	171
New Brunswick	930	1,546	350	541	680	447	4,494
Quebec	35,982	1,594	31		675	508	38,790
Ontario	8,473	2,126	2,822	6,337	11,990	509	32,257
Manitoba	5,024	10	372	98		42	5,545
Saskatchewan	855	0	1,054	1,790		175	3,873
Alberta	879	18	3,729	6,152		573	11,351
British Columbia	12,545	48	1,553			602	14,748
Yukon, Northwest Territories, Nunavut	109	170	27			1	307
Total	**71,978**	**6,896**	**10,079**	**16,014**	**13,345**	**3,169**	**121,481**

Source: Statistics Canada, *Electric Power Generation, Transmission, and Distribution*, Catalogue No. 57-202-XIE, 2005, Table 1.

Figure 3.7
Canada's Electricity Generation Capacity by Resource, 2005



Source: Statistics Canada, *Electric Power Generation, Transmission and Distribution*, Catalogue No. 57-202-XIE, 2005, Table 1.

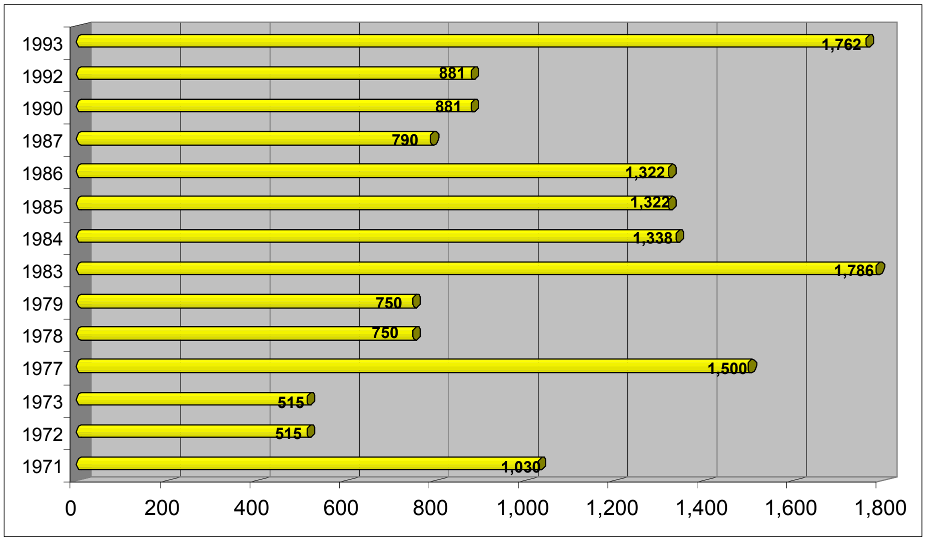
3.3.1 Provincial Nuclear Power Capacity

The first nuclear power station began its operation in Canada in 1962 at the Rolphton Nuclear Power Demonstration (NPD) plant; and Pickering, the first nuclear station still in service, began operating in 1971. This station is comprised of four CANDU reactors, each with capacity of 515 or 516 MW (Table 3.5).

Darlington, the newest Canadian nuclear power plant, was completed in 1993. Darlington is also located in the province of Ontario (Darlington) and features two CANDU reactors, each with capacity of 881 MW.

In 1993 Canadian nuclear power capacity (consisting of five nuclear power plants with 22 nuclear reactors) reached a peak of 15,142 MW. Currently, 18 out of 22 nuclear power reactors are operational with a combined capacity of 12,599 to 13,345 MW. Two of the four out-of-service nuclear reactors, each with a capacity of 750 MW, are expected to be refurbished and to restart operations in 2009 and 2010.

Figure 3.8
Nuclear Electricity Capacity Additions in Canada Prior to 2006
(MW)



Source: CANDU Owners Group Inc.

The capacity of the five nuclear power plants and their status are described below.

In Ontario, the Nuclear Power Demonstration (NPD) and Douglas Point plants have been retired from service. There are three nuclear power plants that are currently operational. These are:[33]

- Darlington Nuclear Generating Station with a total net capacity of 3,524 MW. This station has four units of 881 MW capacity each.

- Pickering Nuclear Generating Stations A and B. Each station has four CANDU reactor units with nameplate capacity of 4,124 MW and current operational capacity of 3,094 MW.

    - Pickering station A (four units) went into service in 1971 and continued in operation until 1997 when all four units were shut down. Pickering A Unit 4 returned to service in 2003, followed by Unit 1 in 2005.[34]

- The Bruce Nuclear Generating Stations A and B each have four CANDU reactor units that together have a nameplate capacity of 6,224 MW; current operational capacity is 4,724 MW. In May 2001, Ontario Power Generation leased the two generating units then in operation to Bruce Power Inc. for a period ending in 2018, with an option to extend the lease for a further 25 years. Bruce Power Inc. is considering adding two new reactors to the site.

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[33] www.2ontario.com/welcome/oout_903.asp (accessed June 26, 2008).
[34] www.opg.com/power/nuclear/pickering/unit1_details.asp (accessed June 26, 2008).

- The Bruce A, with four reactors, had a combined generation capacity of 3,000 MW. They were commissioned between 1977 and 1979 but between 1995 and 1998 all four reactors were removed from service. Later, two of them were restored. Bruce Power Inc. is in the process of refurbishing the other two.

- The Bruce B, with four reactors, has a combined generation capacity of 3,224 MW. The reactors were commissioned between 1984 and 1987.

In Quebec, Gentilly-2, with a generating capacity of 635 MW, is the only nuclear generating station in the province.[35] It went into commercial operation in late 1983. Gentilly-2 is located near a major electrical load centre and plays an essential role in stabilizing the Quebec grid. Gentilly-1, no longer in service, was a 250 MW generating unit that employed boiling water technology, unlike the CANDU reactors currently in service that use pressurized heavy water.

In New Brunswick, Point Lepreau Generating Station has one nuclear reactor, a CANDU 6, with a capacity of 635 MW. The unit supplies about 30 percent of total electricity generation in the province. New Brunswick Power[36] is refurbishing the reactor in 2008–09 to extend the station's life to 2032.[37]

[35] www.candu.org/hydroquebec.html (accessed June 26, 2008).
[36] New Brunswick Power Nuclear Corporation is a subsidiary of New Brunswick Power Corporation, the largest electric utility in Atlantic Canada. It operates the Point Lepreau Generating Station.
[37] www.candu.org/nbpower.html (accessed June 26, 2008).

Table 3.5
Canadian Nuclear Power Capacity by Province and Technology

Provinces	Unit	Net Capacity (MW)	Technology (reactor)	In-service year	Status
Ontario	Darlington 1	881	PHWR CANDU	1992	Operational
	Darlington 2	881	PHWR CANDU	1990	Operational
	Darlington 3	881	PHWR CANDU	1993	Operational
	Darlington 4	881	PHWR CANDU	1993	Operational
	Total	**3,524**			
	Pickering A — Unit 1	515	PHWR CANDU	1971	Operational
	Pickering A — Unit 2	515	PHWR CANDU	1971	Laid Up
	Pickering A — Unit 3	515	PHWR CANDU	1972	Laid Up
	Pickering A — Unit 4	515	PHWR CANDU	1973	Operational
	Pickering B — Unit 5	516	PHWR CANDU	1983	Operational
	Pickering B — Unit 6	516	PHWR CANDU	1984	Operational
	Pickering B — Unit 7	516	PHWR CANDU	1985	Operational
	Pickering B — Unit 8	516	PHWR CANDU	1986	Operational
	Total	**4,124**			
	Bruce A — Unit 1	750	PHWR CANDU	1977	Ref*
	Bruce A — Unit 2	750	PHWR CANDU	1977	Ref*
	Bruce A — Unit 3	750	PHWR CANDU	1978	Operational
	Bruce A — Unit 4	750	PHWR CANDU	1979	Operational
	Bruce B — Unit 5	806	PHWR CANDU	1985	Operational
	Bruce B — Unit 6	822	PHWR CANDU	1984	Operational
	Bruce B — Unit 7	806	PHWR CANDU	1986	Operational
	Bruce B — Unit 8	790	PHWR CANDU	1987	Operational
	Total	**6,224**			
Quebec	Gentilly-2	635	CANDU 6	1983	Operational
New Brunswick	Point Lepreau	635	CANDU 6	1983	Ref*

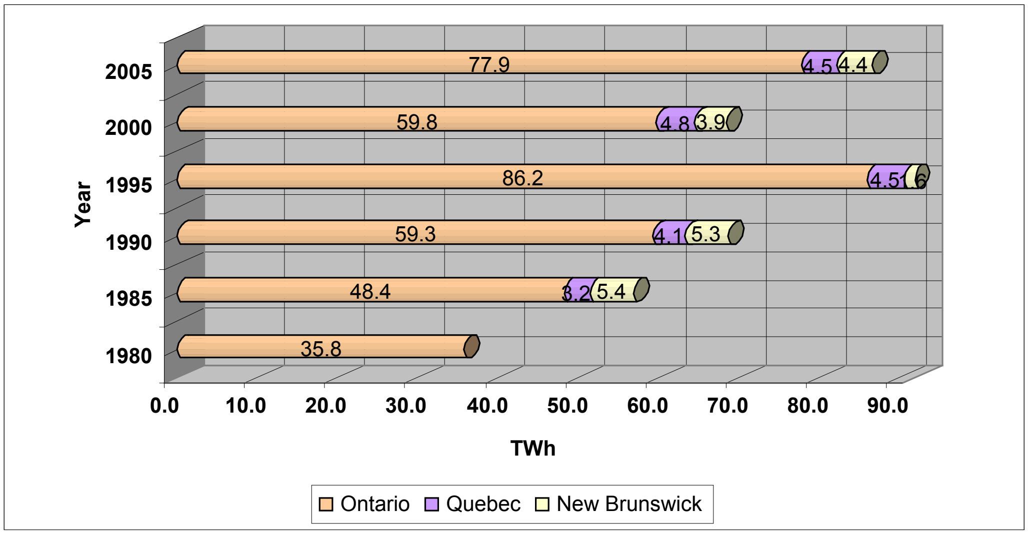
Source: CANDU Owners Group Inc.
* Note: Ref = undergoing refurbishment. Bruce A-1 is scheduled to restart in 2009 and Bruce A-2 in 2010.

3.4 Nuclear Power Generation and Uranium Consumption

The Canadian nuclear industry aims to ensure long-term and efficient production of electricity from existing reactors. It is actively addressing refurbishment and life extension issues, as well as operating and management practices and procedures. This effort is being conducted through programs under Ontario Power Generation Inc.'s Nuclear Asset Optimization Program, which has been underway since August 1997.

In 2005, approximately 77.9 TWh of nuclear power was generated in Ontario, 4.5 TWh in Quebec and 4.4 TWh in New Brunswick (Figure 3.9).

Figure 3.9
Provincial Nuclear Electricity Generation, 1980–2005

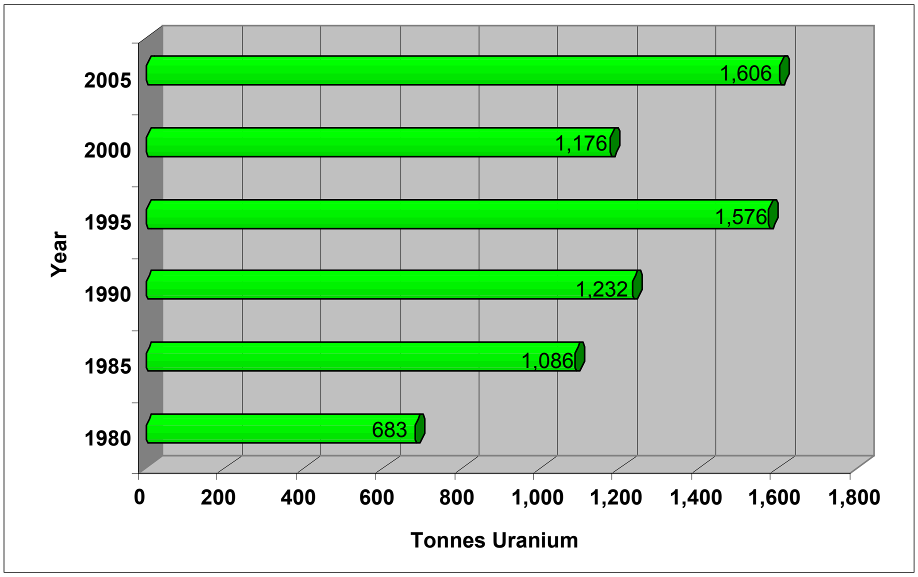


Source: Statistics Canada, *Report on Energy Supply-demand in Canada*, Catalogue no. 57-003-XIE, 2005, Tables 8-1 and 9.

Statistics Canada publishes data on supply and disposition of electricity and type of fuel requirements by utilities and industrial establishments which generate and/or distribute electric energy. The data show that Canada's uranium consumption for nuclear power generation has increased from approximately 683 tonnes in 1980 to 1,606 tonnes in 2005 (Figure 3.10), representing an average annual growth rate of 3.3 percent. Over the same period, Canada's nuclear electricity generation grew by 3.5 percent. The main reason for growth in nuclear generation was the construction of Bruce B, Pickering B and Darlington, along with the completion of Point Lepreau and Gentilly-2. Darlington was the last plant to come on line in 1993, and that signalled the end of rapid growth in Canada's uranium consumption.

Thermal efficiency gradually improved over this period. In 1980, the Canadian nuclear industry used approximately 19.07 grams of uranium per MWh of electricity generation; this ratio had declined to 18.2 grams by 2004. However, because of a 17,600 kJ/g reduction of the energy content of uranium, the fuel use rate increased again to 19 grams per MWh in 2005. Nevertheless, over the entire 25-year period, nuclear energy generation has grown and the fuel-use rate has declined.

Figure 3.10
Canada Uranium Consumption, 1980–2005
(tonnes/year)



Source: Statistics Canada, *Report on Energy Supply-demand in Canada,* Catalogue No. 57-003-XIE, 2005, Table 9; *Electric Power Generation, Transmission, and Distribution,* Catalogue No. 57-202-XIE.

According to Statistics Canada data (Catalogue 57-202-XIE), the 2005 unit cost of nuclear fuel for electricity generation was $111/kg; on a per-unit-of-output basis, the fuel cost for nuclear generation was approximately $2.05/MWh (Table 3.6). By way of comparison, Statistics Canada states that coal-fired utility generation had a fuel cost averaging $41.066/MWh and gas-fired utility generation came in at $54.06/MWh. Unit fuel costs for fossil fuel generation continue to be an order of magnitude higher than unit fuel costs for nuclear generation.

Table 3.6
2005 Major Descriptors of the Canadian Nuclear Power Industry

a. Nuclear generation	86,829,896 (MWh)
b. Uranium consumption	1,606,680 (kg)
c. Uranium energy content	687,947 (kJ/g)
d. Cost of uranium	$177,584,000
e. Uranium cost per kg (d/b)	$111 (kg)
f. Uranium use rate (1000*b)/a	19.0 (g/kWh)
g. Fuel cost (d/a)	$2.05 (MWh)
h. Fuel efficiency (3.6*a*1000)/(b*c)	28%

Source: Statistics Canada, *Electric Power Generation, Transmission, and Distribution*, Catalogue no. 57-202-XIE, Tables 2 and 6.

CHAPTER 4
OTHER NUCLEAR ACTIVITIES IN CANADA

4.1 The Uranium Mining Industry in Canada

Although Canada's uranium industry began at Port Radium in the Northwest Territories, and the Elliott Lake area of Ontario has had a long history of uranium mining, all uranium mining in Canada currently takes place at three mines in Saskatchewan: McArthur River, Rabbit Lake and McClean Lake. The first two are operated by Cameco Corporation, the third by AREVA Resources Canada Inc. The two prospective mines closest to beginning production — Cigar Lake (Cameco) and Midwest (AREVA) — are also in Saskatchewan. Production and reserves data for existing mines are shown in Table 4.1. The Athabasca Basin, where all of these mines (existing and prospective) are located, extends into Alberta. The Thelon Basin, which straddles the Nunavut/Northwest Territories border, is geologically similar to the Athabasca Basin, and has been the focus of prospecting activity in recent years.

Table 4.1
Reserves and Production of Uranium and Ores in Canada

	2006 reserves (as end of 2006)			2006 production			
Mine	U_3O_8 (tonnes)	Grade of uranium (%)	Total ore (tonnes)	U_3O_8 (tonnes)	Estimated grade uranium (%)	Estimated ore (tonnes)	Reserve/ production U_3O_8
McClean Lake	12,800	1.6	800,000	690	1.6	43,000	18.6
Rabbit Lake	8,700	1.2	725,000	1,962	1.2	164,000	4.4
McArthur River/ Key Lake	166,500	20.6	808,000	7,193	20.6	35,000	23.1
Subtotal	**188,000**	**8.1**	**2,333,000**	**9,845**	**4.1**	**242,000**	**19.1**
Cigar Lake (under construction)	102,600	20.7	496,000	0		0	
Midwest (before regulator)	15,000	4.8	312,000	0		0	

Source: Saskatchewan Mining Association for 2006 U_3O_8 production (www.saskmining.ca); Areva Resources web site www.arevaresources.com ("Reserves" under Publications — Uranium in Saskatchewan) for end-2005 reserves and associated grades; CERI estimate of 2006 total ore production based on reserves grades applied to 2006 production of uranium oxide (yellowcake) U_3O_8.

Canada leads the world in uranium production, followed by Australia and Kazakhstan, while Australia has the world's largest reserves of uranium, followed by Kazakhstan and Canada. The McArthur River Mine in Saskatchewan has the highest grade of uranium of any mine on Earth: 24.3 percent in U_3O_8 equivalent.[38] When the Cigar Lake Mine, also in Saskatchewan, comes on stream (currently slated for 2011) it will be the world's second-best in terms of ore grade. Earlier

[38] One tonne of pure uranium is equivalent to 1.17924 tonnes of U_3O_8.

estimations at Rabbit Lake indicated that reserves at the mine would be exhausted by the end of 2007. However, Cameco Corporation, which mines Rabbit Lake, has stated recently that incremental reserves have been found that should extend the life of the mine to at least 2011.[39] Prospects have also been identified for additional uranium in the vicinity of Rabbit Lake, and drilling to identify additions to reserves is ongoing.

The uranium reserves at Canada's existing mines averaged over 8 percent U_3O_8 at the end of 2006, as shown in Table 4.1, while the average grade of mined ore in 2006 was over 4 percent. The distribution of processed ore is different from that of mined ore because McArthur River ore is mixed with material from (mined-out) Key Lake stockpiles to reduce the uranium content to 4 percent U_3O_8 equivalent before processing. Figure 4.1 offers an apposite description of the McArthur River uranium mine written by *Time* magazine reporter Richard Martin.

Figure 4.1
The McArthur River Uranium Mine*

McArthur River isn't much to look at from above ground – just a cluster of green, corrugated-metal buildings, a company lodge and an airstrip — but the mine is an industrial marvel. The rocks underground are average 21% pure uranium, with pockets as concentrated as 80%, far richer than the typical 1% deposits at other mines. The ore at McArthur River is the richest in the world and is far too radioactive to handle conventionally; the miners extract it by remote control, using giant boring machines and scoop trams instead of pickaxes and shovels. On a recent winter day, more than 2,000 ft. below the surface of the McArthur River mine, Dale Powder operated a scoop tram from a niche in the rock wall 1100 ft. or so from the vehicle. Where Powder works, it's as dry as a bone, but a few hundred feet away, in a neighbouring tunnel, a perpetual fine rain falls. The porous sandstone that encases the mine's ore is saturated, even in winter, with water melting from the frozen surface. To keep the water from pouring into the mining shafts, Cameco's engineers have pulled off a remarkable feat: using one of the world's largest refrigeration plants, they have literally frozen the ground immediately surrounding the mine. Within the ice curtain, the walls and floors stay dry. Far underground, rock-bearing machines crumble and grind the ore and mix it with water to form a soupy slurry, which is piped to surface containers to await transport to the Cameco refining mill at Key Lake, about 50 miles away. This underground processing plant is McArthur River's third major innovation. "What we've done," says Doug Beattie, the mine's chief engineer, "is essentially bring the front end of the mill down to the mine". By mining just 140 tons of ore a day (a thimbleful compared with big copper- or iron-ore mines), McArthur River produces more than 18 million lbs. of uranium a year. That's 20% of the world's annual production, enough to run 40 standard 1,000-MW reactors for a year. That much uranium can satisfy fully 2% of the world's electricity demand.

Source: R. Martin, "Nuclear Rock: With Oil Supplies Uncertain, Uranium Mining Heats Up", *Time*, February 24, 2003.

* The text for this article is available in its entirety at:
www.time.com/time/magazine/article/0,9171,1004315,00.html

[39] www.cameco.com/media_gateway/news_releases/2007/news_release.php?id=203 (accessed June 26, 2008).

Jefferson et al.[40] note that the economic uranium resources in Canada "are 0.5 to 2 orders of magnitude higher in grade than all other deposits in the world." The average grade of uranium in Canadian mines has traditionally been higher than that of its major competitors, and has trended upward over time. This upward trend is expected to continue with Rabbit Lake and McClean Lake nearing the end of their lives and the commencement of mining of higher grades of ore at Cigar Lake and, presumably, Midwest. The ore grade from Canadian mines that have ceased production, as noted by Jefferson et al., ranges from just under 0.3 percent to almost 5.7 percent, measured as U_3O_8 equivalent. By way of comparison, the world-wide average grade is placed at 0.18 percent on the same basis.[41]

The other extreme is represented by Australia's Olympic Dam mine, the largest in the world in terms of reserves, with the world's lowest grade of just 0.07 percent (this grade would be considered uneconomic under normal circumstances, but at Olympic Dam uranium, gold and silver are by-products of copper output). The highest ore grade among Australia's three producing uranium mines is 0.21 percent U_3O_8 equivalent at the Beverley mine. In Kazakhstan, where uranium production is mainly by in situ leaching methods, the ore grades are similar to those of Australia.

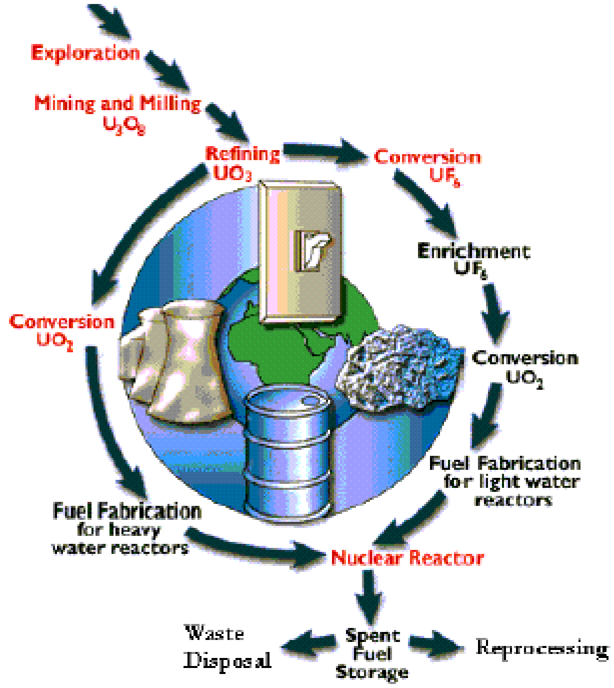
4.2 Uranium Refining, Conversion and Enrichment

The nuclear fuel cycle for both light water reactors and CANDU reactors is depicted in Figure 4.2 below. Uranium in the form of yellowcake (U_3O_8) is trucked from Saskatchewan milling operations to the world's largest uranium refinery, operated by Cameco, at Blind River, Ontario. There, it is refined to remove impurities and converted into uranium trioxide (UO_3), in a multi-step chemical and physical process using solvent extraction. From Blind River, most of the uranium trioxide goes to another Cameco facility at Port Hope, Ontario, where it is converted into uranium dioxide (UO_2) for use as natural uranium in existing CANDU reactors, or into uranium hexafluoride (UF_6) for enrichment and subsequent conversion to uranium dioxide for use in light water reactors. Natural uranium contains 0.7 percent U-235, the uranium isotope of interest; enrichment increases U-235 content to the 3 to 5 percent range required for light water reactors. No enrichment facilities exist in Canada; they are located in countries that have the capacity to build nuclear weapons.

[40] C.W. Jefferson et al. *Mineral Deposits of Canada: Unconformity Associated Uranium Deposits*. Available online at http://gsc.nrcan.gc.ca/mindep/synth_dep/uranium/index_e.php (accessed June 26, 2008). The world-wide average of 0.15 percent uranium noted by Jefferson et al. is restated as 0.18 percent on a U_3O_8-equivalent basis.

[41] J.W.S. van Leeuwen. *Energy from Uranium*. Oxford Research Group, July 2006.

Figure 4.2
The Nuclear Fuel Cycle



Source: Cameco Corporation.

Uranium dioxide, in either natural or enriched form, is pressed into cylindrical shapes and hardened by baking at high temperatures. It is then fabricated into pellets, which are made into bundles. At Port Hope, bundles are fabricated and assembled by Zircatec Precision Industries (a recently-acquired subsidiary of Cameco). Bundles are also fabricated in Toronto by General Electric Canada and then sent to GE Canada's Peterborough, Ontario facility for assembly. A fuel bundle for CANDU reactors contains either 28 or 37 rods of tubular zirconium alloy sheaths with uranium dioxide pellets inside, each rod being about 50 centimetres long. These fabrication facilities are largely devoted to the domestic market and to supplying CANDU reactors abroad, as the major uranium-importing countries have fabrication facilities of their own. Zircatec supplies the Bruce nuclear power plant, while GE Canada supplies Pickering and Darlington. In Cobourg, Ontario, Zircatec also manufactures zirconium tubing for fuel bundles, as well as certain CANDU reactor components and monitoring equipment.

4.3 Other Nuclear Products

Uranium mining and the production of nuclear electricity are key activities in the Canadian economy, but there are a number of other important nuclear products either being developed or used in Canada. In areas such as medicine, nuclear products are saving lives; in agriculture they are increasing crop yields. Manufacturers use nuclear products to strengthen plastics and bond composites. Radioactive materials may also be found in photocopiers, smoke detectors, watches and other items in daily use by Canadians.

4.3.1 Medical Isotopes

Radioisotopes for medical and industrial applications have been produced at the Chalk River research facilities since the 1940s. In 1951 the world's first cobalt radiotherapy units for the treatment of cancer were produced and installed in hospitals in London, Ontario and in Saskatoon, Saskatchewan.

The main producer of isotopes in Canada is MDS Nordion, a company originally formed in 1946 as the radium sales department of Eldorado Mining and Refining (1944) ltd. It was soon transferred to AECL and began to market a variety of radioisotopes produced at the National Research Council's reactor in Chalk River. As a result of research and development conducted at AECL, the division began to produce isotopes for commercial use in 1972. In 1991 the commercial products division of AECL — known as Nordion International Inc. — was sold to MDS Health Group. Now known as MDS Nordion, it is the world's leading supplier of medical isotopes.

MDS Nordion specializes in the radioisotopes, radiation and related technologies that are used to diagnose, prevent and treat disease in over 70 countries. In the year ending October 31, 2005, 97 percent of its revenues — over $300 million — were derived from exports. The company's radiation therapy equipment is used in cancer clinics and hospitals around the world and in about 15 million cancer treatments every year. MDS Nordion supplies over two-thirds of the world's medical isotopes. An estimated 15 to 20 million nuclear medicine imaging and therapeutic procedures are performed globally each year.

The Ottawa-based company is also working with outside partners to develop and manufacture new radiopharmaceuticals to treat cancer, such as non-Hodgkin lymphoma, and to produce new proprietary treatments, such as for liver cancer. TheraSphere®, MDS Nordion's innovative new treatment, is a therapeutic medical device for the treatment of liver cancer. Consisting of tiny glass beads, TheraSphere® is injected by a physician into the main artery of the patient's liver using a catheter. The beads become lodged in the small blood vessels that feed the tumour and deliver a therapeutic dose of radiation directly to the cancer while minimizing impact on the patient's healthy tissue.

Canada accounts for some 75 percent of the world supply of cobalt-60, which is produced by irradiating naturally-occurring cobalt-59 with neutrons. Hospital supplies such as sutures, masks, surgical gloves, dressings, scalpel blades, catheters and syringes are passed through an irradiator containing a large cobalt-60 source, virtually eliminating bacteria, viruses and other living organisms without damaging the product. There are an estimated 1,200 cobalt-60 machines around the world, delivering about 15 million cancer treatments each year.

MDS Nordion is also the major supplier of molybdenum-99, which decays into technetium-99m, which in turn emits gamma rays and is the most widely used medical radioisotope for diagnostic medical purposes.

In addition to the radioisotopes discussed above, MDS Nordion supplies the following medical isotopes and radiopharmaceuticals for diagnostic or therapeutic purposes in cardiology, oncology and neurology:

cobalt-57	copper-64	Curicap® radiopharmaceutical (I-131)	gallium-67
indium-111	iodine-123	Glucotrace® radiopharmaceutical (F-18)	iodine-125
iodine-131	lucetium-177	palladium-103	phosphorus-32
rhenium-186	strontium-82	thallium-201	xenon-133
yttrium-90			

4.3.2 Electron Beam Technology

Acsion Industries Inc. of Pinawa, Manitoba markets electron beam technology for use in sterilization and processing. In addition to sterilization, electron beam technology serves the health care market through the cross-linking of medical plastics to improve performance properties such as stiffness of catheters and the wear properties of artificial joints. This technology is also used in the aerospace market for both the manufacture and repair of composite and metal bonded structures, including flight control surfaces, fairing panels, engine cowls, duct work and interior passenger and cargo compartment floor panels.

4.3.3 Neutron Radiography

Nray Services Inc. of Dundas, Manitoba, a spin-off from AECL, specializes in neutron radiography, a non-destructive testing technique that serves as an alternative to x-ray and ultrasound testing methods. Among the applications to date are reliability testing of detonators in explosive devices; testing of explosives for the presence of transmitters and receivers; testing for cracks, inclusions, voids, bubbles, density variations and misalignments; determining bonding flaws in adhesives; inspecting radioactive objects; inspecting artifacts from archaeological digs; testing for aluminum corrosion products; and testing for missing or misplaced o-rings.

4.3.4 Food Irradiation

Food irradiation is widely practiced, and makes food safer by eliminating such harmful bacteria as *e. coli* 0157:H7, salmonella, campylobacter and *listeria monocytogenes*. It also provides quarantine treatments for fruits and vegetables to ensure that insect pests are not transported across borders; and extends the shelf life of foods by destroying microorganisms that cause spoilage, by slowing the ripening process and by inhibiting the sprouting of root vegetables such as potatoes and onions. Irradiation has been approved for more than 50 food products in 40 countries. Cobalt-60 is often used as the source of radiation, in a process resembling the X-raying of luggage at airports. Worldwide, there are more than 170 gamma irradiators.

4.3.5 Insect Sterilization

In agriculture, harmful insects can be eliminated through sterilization of the males of the species using radiation. This approach has been used to bring the codling moth in British Columbia's apple orchards under control. Nuclear techniques are also used to measure the efficiency of fertilizer use by crops, and to monitor crop moisture content.

4.3.6 Common Uses of Nuclear Products

Photocopiers use small amounts of radioactive material to eliminate static and to prevent sheets from sticking together and jamming the machine. Most residential smoke detectors contain a low-activity americium-241 source that emits alpha particles to ionize the air and make it conductive. Cosmetics, hair products and contact lens solution are sterilized with radiation to remove irritants and allergens. Among the consumer items that contain radioactive materials, modern watches and clocks sometimes use a small quantity of tritium (hydrogen-3) or promethium-147 as a source of light, and some gas lantern mantles incorporate thorium-232. Emission of light from these mantles is produced through heating of the thorium by the burning gas.

4.4 Potential Applications — Hydrogen/Desalination

Among the possibilities identified for future development in Canada and elsewhere is the use of nuclear power plants in off-peak periods for desalination of ocean water or for supply of hydrogen to the widely-heralded hydrogen economy. The technical potential of nuclear desalination has been demonstrated in both Kazakhstan and Japan, although it has not yet been proven to be economically feasible. Currently, most desalination plants use fossil fuels. A nuclear combination of reverse osmosis and multistage flash technology, which requires both heat and electricity, appears promising.

Steam reforming of natural gas currently accounts for nearly all of the world's voluntary production of hydrogen. Electrolysis is "typically 25–35 percent efficient because of the inefficient generation of electricity."[42] A number of thermo-chemical configurations have been proposed to enhance the efficiency of hydrogen production from water. One such configuration is the Hybrid-Sulphur Process, in which the following reaction is promoted by electrolysis at a temperature of 80°C:

$$SO_2 + 2H_2O = H_2SO_4 + H_2$$

Although there is the added complexity of chemical plant, the power requirements of the Hybrid-Sulphur Process are much lower than those of direct electrolysis of water. Both the heat and the electricity required for the Hybrid-Sulphur Process could be supplied by nuclear facilities.

[42] U.S. Department of Energy, Office of Nuclear Energy, Science & Technology. *SuperGrid Concept Sparks Interest*. Available online at www.ne.doe.gov/hydrogen/thermochemical.pdf

Carbon-free production of hydrogen is one ingredient in a vision of the future known as the Continental SuperGrid, advocated by Chauncey Starr, President Emeritus of the Electric Power Research Institute. Although the roots of this concept date back to 1967, it is only in recent years that reasonably affordable superconducting materials have come into existence to make commercialization a serious possibility. Ausubel (2004) describes the Continental SuperGrid as follows:

> The fundamental design involves wrapping a superconducting cable around a pipe pumping liquid hydrogen, which provides the cold needed to maintain superconductivity ... The SuperGrid would not only transmit electricity but also store and distribute the bulk of the hydrogen ultimately used in fuel-cell vehicles and generators or redesigned internal-combustion engines.[43]

[43] Ausubel, J.H. "Big Green Energy Machines." *The Industrial Physicist*, Vol. 20, No. 5, Oct–Nov 2004, p. 23.

CHAPTER 5
ECONOMIC IMPACT OF THE NUCLEAR INDUSTRY IN CANADA

This chapter presents the economic impact of the nuclear industry in Canada. Considered in this chapter are impacts on: (i) gross domestic product (GDP), (ii) employment and (iii) government revenue. Impact is measured for various activities such as the construction of nuclear reactors (or nuclear power plants), the operation of nuclear power plants, the export of nuclear reactors, and the export of uranium. Before entering into a detailed analysis of economic impact, the chapter also discusses the model used for economic impact assessment, the data used, and the key assumptions made.

5.1 The Input-Output Model

5.1.1 Background

The input-output model (hereafter the I-O model) is an analytical tool pioneered by Professor Wassily Leontief in 1936. For his work, Professor Leontief was awarded the Nobel Prize in Economics in 1973. The modelling approach has been extensively used in both developed and developing countries in the fields of energy and environmental policy and activity analysis; regional economic planning and development; and resource planning and management. West[44] maintains that the I-O model is the "bread-and-butter model" for regional economic planning exercises. Miller and Blair (1985) developed foundations to use I-O models in the field of energy and environmental policy, and in development analyses.[45]

A large number of studies have employed the I-O approach for analyzing the impact of nuclear power on the economy. Below are a few examples:

- *Alternative Technologies for New Nuclear Power Plants: Economic Impact*, Atomic Energy Canada Limited, August 2005.
- *Economic Benefits of the Duke Power-Operated Nuclear Power Plants*, Nuclear Energy Institute, December 2004.
- *Economic Benefits of Palo Verde Nuclear Generation Station*, Nuclear Energy Institute, November 2004.
- *Economic Impact of the Nuclear Industry in Canada*, Canadian Nuclear Association, Ottawa, Canada, July 2003.

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[44] West, G. "Comparison of Input-Output, Input-Output + Econometric, and Computable General Equilibrium Impact Model at the Regional Level." *Economic System Research*, Vol. 7, No. 2, 1995. pp. 209–227.

[45] Miller, R.E. and P.D. Blair. *Input-Output Analysis: Foundations and Extensions*. Prentice-Hall, Inc., New Jersey, 1985.

The United Nations has also promoted the I-O model as a practical planning tool for developing countries and has sponsored a standardized system, the "System of National Accounts" (SNA), to develop a database that is useful for I-O analysis.

5.1.2 The I-O Model Used in This Study

The nuclear industry has contributed, directly and indirectly, to the Canadian economy through various activities: in particular, the construction of nuclear reactors (i.e. nuclear power plants), the operation of nuclear electricity plants, the export of nuclear technology (e.g. nuclear reactors), and the export of uranium. This study assesses the economic impact of each of these activities separately. Although other activities are being carried out — such as the production and export of nuclear isotopes, the refining of uranium and the manufacturing of fuel bundles — the impact of these activities are not included in this chapter; rather, the impact of these activities is discussed later in Chapters 7 and 8.

In order to assess the economic impact of nuclear reactor construction, CERI first collected investment data on two CANDU 6 reactors of 720 MW capacity each (a total of 1,440 MW). The details of the data are presented in Section 5.2 of this chapter. The domestic components of goods and services purchased and labour expenditure serve as the key input to the I-O model to assess the economic impact of nuclear power construction. Similarly, to estimate the economic impact of power generation, CERI collected data on the total value of electricity sales produced from all nuclear power generation units (17 units) in year 2005. Data on exports of various goods and services were used as the key input to assess the economic impact of nuclear reactor exports. Finally, the total value of exported uranium was used as the main input to the I-O model assessing economic impact of uranium exports.

The I-O model used in this study is based on the national I-O table produced by Statistics Canada.[46] The model has 19 sectors, as presented in Table 5.1.

[46] Statistics Canada. *The Input-Output Structure of the Canadian Economy, 1999-2000*. Catalogue No. 15-201-XIE, July 2004.

Table 5.1
Sectors/Commodities in CERI I-O Model

Serial no.	Sector or commodity	Examples of activities under the sector or commodity
1	Agriculture	Farming of wheat, corn, rice, soybeans, tobacco, cotton, hay, vegetables and fruits; greenhouse, nursery, and floriculture production; cattle ranching and farming; dairy, egg and meat production; fishing, hunting and trapping
2	Forestry	Timber tract operations; forest nurseries and gathering of forest products; logging
3	Other mining	Mining of iron, gold and silver ores; copper, nickel, lead, and zinc mining; sand, gravel, clay, ceramic, limestone and granite mining; potash, soda, borate and phosphate mining
4	Crude oil	Conventional oil, oil sands and service incidental to conventional oil and oil sands
5	Natural gas	Natural gas and service incidental to natural gas
6	Coal	Coal and service incidental to coal mining
7	Manufacturing	Food, beverages and tobacco; textiles and apparel; leather and footwear; rubber and plastics; furniture and fixtures; pulp and paper; petroleum refinery; drugs, chemicals and fertilizer; lime, glass, clay and cement; iron, aluminum and other metals; fabricated metal, machinery and equipment, electrical, electronic and transportation equipment
8	Construction	Construction of residential, commercial and industrial buildings; highways, streets and bridges; gas and oil pipelines; water and sewer systems; power and communication lines
9	Transportation and communications	Road, rail, air and water transportation services; postal and warehousing; information and communication
10	Electricity utility	Electric power generation, transmission and distribution
11	Gas utility	Natural gas distribution
12	Wholesale	Wholesale activities
13	Retail	Retail activities
14	Finance, insurance and real estate (FIRE)	Banking, insurance and credit companies; real estate, renting and leasing
15	Business services	Architectural, engineering, and related services; legal and accounting services; management, environmental, research and development and advertising services; employment and business support services
16	Education	Educational services; business schools and training
17	Health	Hospitals; nursing and residential care facilities; medical laboratories; child and senior care services
18	Food and accommodation service	Hotels; recreational vehicle (RV) parks and recreational camps; food services and drinking places
19	Other services	Public administration; arts, entertainment, and recreation; personal and laundry services; repair and maintenance services; waste management and remediation services; water and sewage systems

As is the case for standard I-O models, the impact of the nuclear industry is calculated by modelling the relationship between output and final demand as follows:

$$\Delta GO = [I - DNB]^{-1} \times DN\Delta F$$

Where:

I	Identity matrix (a matrix with diagonal elements 1 and rest of the elements 0).
∆GO	Vector of change (or increase) in gross output due to a nuclear activity (e.g. reactor construction, power generation, reactor exports, uranium exports).
B	The input coefficient matrix. An element of this matrix is derived dividing the value of a commodity used in a sector by the total output of that sector. The element represents requirements of a commodity in a sector to produce one unit of output from that sector.
N	Matrix of domestic shares in the total supply of a commodity. This matrix converts the input coefficient matrix [B] to an input coefficient matrix of domestically-produced goods and services [NB].
D	Matrix of sectoral shares in the total commodity production; an element of this matrix is derived by dividing production of a commodity from a sector to the total production of that commodity in the economy. It represents the fraction of a commodity produced by a sector. This matrix is used to convert delivery of commodity to delivery of a sectoral output.[47]
∆F	Vector of change (or increase) in final demand of a commodity or commodity directly demanded (or purchased) by an activity (e.g. construction of a nuclear reactor, electricity generation, export of a nuclear reactor or uranium).

Once the impact on output (change in output) is calculated using the relationship mentioned above, the calculations of impact on GDP, employment, and government revenue are straightforward. These impacts are estimated at the industry level using the ratio of each (i.e. GDP, employment) to gross output.

[47] Since the scope of the study is to assess economic impact at the sectoral (or industry) level, an industry by industry requirement matrix is needed. An element of DNB_{ij} matrix represents demand for a good/service domestically produced by industry i in order to produce one unit of output from industry j.

5.2 Input Data

Since the economic impact assessment is focused on four activities, construction of nuclear reactors, electricity generation from nuclear power plants, exports of nuclear reactors, and uranium mining, detailed expenditure data are needed for each of these activities. Instead of starting from scratch, this study is based on a previous CERI study carried out in 2003.[48] In the previous study, CERI relied on detailed cost information in 2001 Canadian dollars on construction and operation of CANDU nuclear generating units supplied by AECL. No new cost engineering information was gathered in the preparation of this study, assuming that the real cost structure would not be altered significantly. Instead, CERI adjusted the 2001 costs from the previous study to 2005 Canadian dollars using price indices from Statistics Canada. For example, electrical generators and motors were estimated to cost $130 million in 2001. This cost has changed to $156 million in 2005; calculated by applying the ratio of index numbers (CANSIM v1575754) for electrical generators — 128.4 for 2005 divided by 107.3 for 2001. In a few cases the latest available index number is for 2004; in such cases, the 2004 index number is adopted without any further adjustment.

5.2.1 Input Data for the Assessment of Economic Impact of Nuclear Reactor Construction

The data needed for this analysis are mostly taken from the July 2003 CERI study, *Economic Impact of the Nuclear Industry in Canada* and have been adjusted using commodity price indices and the labour cost index. Table 5.2 presents cost estimates for construction of a pair of CANDU 6 units in Canada in the years 2001 and 2005.

5.2.2 Input Data for the Assessment of Economic Impact of Nuclear Power Generation

The data were estimated in the same manner as in the case of construction of nuclear reactors. However, the derivation of these data required an additional step. As illustrated in Table 5.3, the costs for 2001 expressed in 2005 Canadian dollars were scaled upward in proportion to the increase in Canada's nuclear electricity generation from 2001 to 2005. The implicit assumption here is that the real cost of electricity generation per unit of electricity output remained constant between 2001 and 2005. However, nominal unit costs did change. The study has considered the price of Bruce Power ($58/MWh) as the representative price for nuclear electricity generated in Canada. The total nuclear electricity sold to grids multiplied by the representative price of nuclear power provides the total value of nuclear electricity in a year. This total value is then divided into costs of various goods and service inputs, labour input and other operating surplus — including profits and taxes. Table 5.3 presents the input cost structure of generating electricity from all existing power plants in the years 2001 and 2005.

[48] CERI. *Economic Impact of the Nuclear Industry in Canada*. Submitted to CNA, July 2003.

Table 5.2
Domestic Construction Costs of Two 720 MW CANDU 6 Reactors

Description of cost element	Value per 2003 study ($ millions at 2001 price)	Adjusted to 2005 prices ($ millions at 2005 price)	Import content (%)	Import value ($ millions at 2005 price)
Commodity				
Other iron and steel pipes and tubes	11	13	50	7
Other iron and steel pipe fittings	95	108	36	39
Metal tanks	46	58	45	26
Power boilers	100	121	0	0
Iron and steel structural materials	42	53	7	4
Prefabricated metal structures	162	219	0	0
Metal doors and windows	13	14	0	0
Other hardware	34	35	0	0
Valves	48	53	42	22
Pumps, compressors, fans and blowers	59	61	68	42
Industrial trucks and material handling equipment	5	6	0	0
Other industry specific machinery	12	10	0	0
Air conditioning equipment, wall and window	8	8	0	0
Power generation and marine prop., non-electric	194	200	0	0
Electrical generators and motors	130	156	75	117
Transformers and converters	18	19	0	0
Industrial electric equipment, including safety	10	11	0	0
Wire and cable, insulated, excluding aluminum	9	10	0	0
Measuring and controlling instruments	30	31	22	7
Service				
Truck transportation	61	65	0	0
Telephone and other telecommunications	4	3	0	0
Non-life insurance	15	16	5	1
Accounting and legal services	2	2	0	0
Data processing services	6	6	10	1
Computer systems design and related services	40	42	10	5
Other professional, scientific and technical services	18	19	37	7
Other administrative and support services	28	30	10	3
Other goods and services	21	22	0	0
Subtotal	**1,221**	**1,393**		**280**
Wage, tax and operating surplus				
Indirect taxes on products	27	45	0	0
Indirect taxes on production	28	30	0	0
Wages and salaries	1,277	1,364	0	0
Supplementary labour income	403	431	0	0
Other operating surplus	448	479	0	0
Subtotal	**2,183**	**2,349**	**0**	**0**
Total	**3,404**	**3,742**		**280**

Table 5.3
Distribution of Nuclear Power Revenue
to Various Expenditures and Operating Surplus*

	Per 2003 study ($ millions at 2001 price)	Adjusted to 2005 prices ($ millions at 2005 price)	Scaled to2005 generation ($ millions at 2005 price)	Import content (%)	Import value ($ millions at 2005 price)
Commodity					
Radioactive ores and concentrates	159	511	623	0	0
Advertising flyers, catalogues, directories	11	11	14	5	1
Electrical generators and motors	197	236	287	75	215
Deuterium oxide (heavy water)	10	17	20	0	0
Service					
Repair construction	10	10	12	0	0
Non-life insurance	63	67	82	5	4
Architect, engineering, and related services	186	198	241	37	89
Accounting and legal services	53	58	70	0	0
Data processing services	164	173	211	10	21
Computer systems design and related services	186	196	239	10	24
Investigation and security services	88	94	114	0	0
Other professional, scientific and administrative services	22	23	28	0	0
Other administrative and support services	59	63	76	10	8
Spare parts and maintenance supplies	8	9	11	15	2
Sale of other government services	22	23	28	0	0
Subtotal	**1,238**	**1,688**	**2,055**		**363**
Wage, tax and operating surplus					
Indirect taxes on products	94	155	189	0	0
Wages and salaries	560	598	728	0	0
Supplementary labour income	140	150	182	0	0
Other operating surplus	646	1,507	1,834	0	0
Gross value of nuclear electricity at busbar	2,678	4,098	4,988		363
Total nuclear generation (GWh)	70,652	70,652	86,000		
Busbar Price (Bruce Power)	$38/MWh	$58/MWh	$58/MWh		

* Includes all existing nuclear power generating stations in Canada.

Imports in both of the preceding tables were estimated by applying percentages to the estimated 2005 costs.

5.2.3 Input Data for the Assessment of Economic Impact of Nuclear Reactor Exports

The data for the year 2005 were derived in a similar manner as discussed in Section 5.2.1. The costs in 2001 from the previous study were adjusted with corresponding price indices to 2005 costs. The input data needed to assess the economic impact of exports of a pair of CANDU 6 reactors are presented Table 5.4.

Table 5.4
Canadian Content of an Export Order for Two 720 MW CANDU 6 Reactors

Description of cost element	Per 2003 study ($ millions at 2001 price)	Adjusted to 2005 prices ($ millions at 2005 price)
Commodity		
Other iron and steel pipes and tubes	5	6
Other iron and steel pipe fittings	59	67
Metal tanks	24	30
Iron and steel structural materials	39	49
Metal doors and windows	4	4
Other hardware	7	7
Valves	36	40
Pumps, compressors, fans and blowers	9	9
Industrial trucks and material handling equipment	5	6
Other industry specific machinery	68	56
Air conditioning equipment, wall and window	1	1
Electrical generators and motors	2	2
Transformers and converters	10	11
Industrial electric equipment, including safety	5	5
Wire and cable, insulated, excluding aluminum	2	2
Measuring and controlling instruments	24	25
Industrial safety equipment	13	14
Service		
Truck transportation	6	6
Telephone and other telecommunications	4	3
Paid charges, banks and other dep. acc. intermed.	25	27
Management fees of companies and enterprises	19	20
Non-life insurance	17	18
Architect, engineering, and related services	303	322
Accounting and legal services	2	2
Data processing services	6	7
Computer systems design and related services	34	37
Other administrative and support services	15	16
Other goods and services	19	20
Total	**763**	**815**

5.2.4 Input Data for the Assessment of Economic Impact of Uranium Mining and Milling

The economic impact of uranium mining and refining to serve Canadian nuclear power plants has already been captured as indirect and induced impacts of nuclear electricity generation. Exports of uranium in various forms also create indirect and induced impacts on the Canadian economy. The input required to estimate this impact is the gross value of Canada's uranium exports. In its online publication *Nonferrous Metals Outlook, December 2006*[49] Natural Resources Canada gives $1,775,064,000 as the value of Canada's total exports of uranium and thorium minerals and mineral products (Stages I to IV) in 2005. Natural Resources Canada distinguishes these stages as follows:

Stage I — Primary. Involves the discovery of ore, ore extraction and processing to the concentrate stage. Scrap material, ash and tailings have been placed in this category.

Stage II — Smelting and Refining. This stage refers to the metallurgical extraction process, the product of which is a relatively pure mineral, a metal or an alloy. Some of the activities related to this stage are smelting and refining, roasting, calcining, direct reducing and leaching. Products classified under this stage include powders, flakes, dusts, cathodes, ingots, pig, blocks and plates.

Stage III — Semi-Fabricated. This stage involves the manufacturing or processing steps required to bring products to a semi-finished or semi-fabricated stage or form, or to a state for use as input in other industries. Products related to Stage III include rods, plates, sheets, thin strips, pipes, rails, wires, metal-based structural forms and a number of chemicals and compounds. Also included are ingot moulds.

Stage IV — Fabricated. This stage includes products of Stage III that have undergone further processing, such as elements produced by the metal framing industry, hardware items, tools and cutlery. This stage includes products such as pipe fittings, forged and cast parts, grinding balls and rail parts.

Statistics Canada also gives a lower figure for Saskatchewan's uranium exports in 2005: $381 million. CERI understands that this figure relates specifically to Stage I, exports of uranium ores and concentrates, because the other stages would take place in Ontario.

[49] Natural Resources Canada. *Nonferrous Metals Outlook, December 2006*. Available online at: www.nrcan.gc.ca/mms/pdf/nfo/nfo06_e.pdf (accessed June 26, 2008).

5.3 Impact on GDP

5.3.1 Impact on GDP of Nuclear Reactor Construction

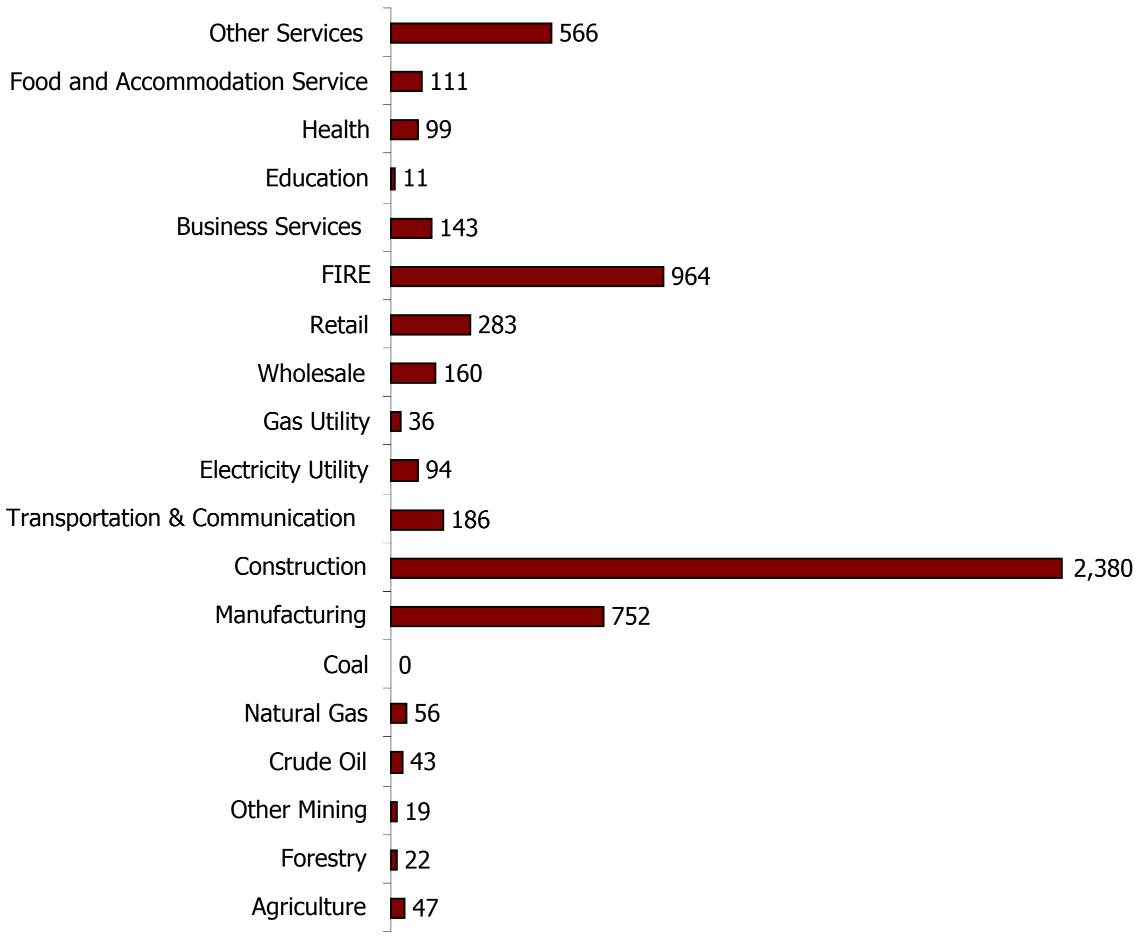
This study has considered construction of two CANDU 6 reactors of capacity 720 MW each. The total construction costs of these two reactors were estimated to be $3,742 million at the 2005 price. This implies an overnight construction cost of about $2,600/kW. The investment would have created a total value added of $5,973 million. If the total GDP impact is expressed in terms of per unit capacity constructed, it turns to be $4.15 million per MW of installed capacity. Note that the investment or overnight construction cost of one MW of nuclear capacity is $2.6 million at 2005 price.

Figure 5.1 shows the distribution of GDP impact to various sectors. As expected, the construction sector would have received the highest impact, $2,380 million which accounts for 40 percent of the total GDP impact. This is followed by finance, insurance and real estate (FIRE), and manufacturing. These sectors account for 16 percent and 13 percent of the total GDP impact, respectively.

Note that the impact is of two 720 MW nuclear units. As of December 31, 2006, total nuclear capacity in Canada was between 12,599 and 13,345 MW (see Chapter 3 for more details). It could be interesting to gain an approximate idea of how much the construction of all nuclear power plants has contributed to the Canadian economy until today. A precise estimation of such impact is beyond the scope of this study as it is too complex and constrained by data availability. Detailed construction expenditure profiles are needed for all nuclear units, as well as I-O models for each of those years. Hence, what has been estimated here is the GDP impact of all nuclear units if their overnight construction costs equal those of year 2005 and if the economic structure of Canada equals that of year 2000.

If the total GDP impact is expressed in terms of per unit capacity constructed, it turns out to be $4.15 million per MW of installed capacity. Considering the total nuclear capacity constructed in Canada until today, which is over 12,000 MW, the total GDP impact of all nuclear units constructed in Canada would be $52.3 billion in 2005 dollars.

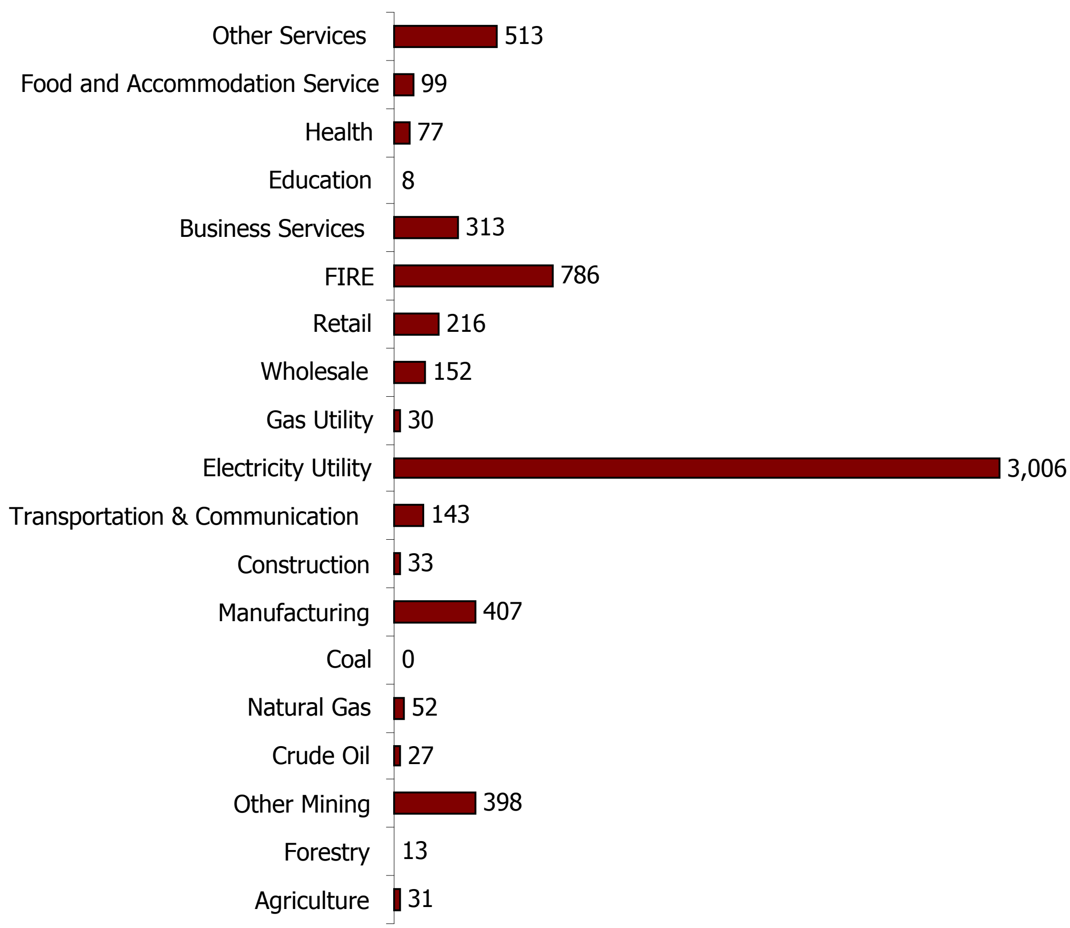
Figure 5.1
GDP Impact of Construction of Two 720 MW CANDU 6 Reactors in Canada
(millions of dollars)



5.3.2 Impact on GDP of Nuclear Power Generation

While assessing economic impact of electricity generation from nuclear power plants, the study has considered all operating units. As of the end of year 2005, there were 17 units with total capacity of 12,767 MW. In 2005 these units generated 86,000 gigawatt-hours (GWh). The value of total electricity sold from these units was estimated to be $4,988 million in 2005. The operation of these power plants would have created a total GDP of $6,303 million in that year. Figure 5.2 illustrates the distribution of GDP impact to various sectors resulting from the operation of nuclear power plants. As expected, the electricity sector would have received the highest impact, $3,006 million, which accounts for almost a half of the total GDP impact. This is followed by finance, insurance and real estate (FIRE) and manufacturing. These sectors account for 12 percent and 7 percent of the total GDP impact, respectively. Note also that the total GDP impact of the other mining sector that includes uranium mining and refining is $398 million, or 6 percent of the total.

Figure 5.2
GDP Impact of Production of 86,000 GWh of Electricity from 17 Nuclear Power Generation Units in Canada in 2005
(millions of dollars)

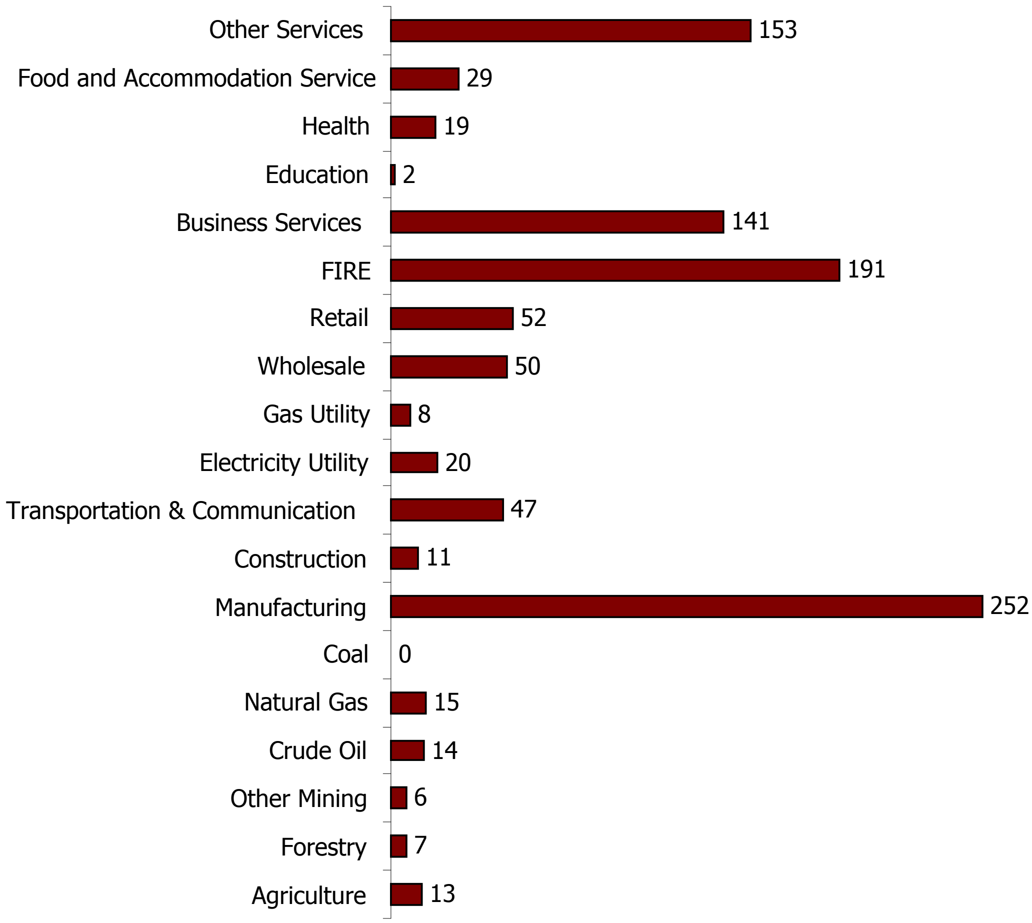


5.3.3 Impact on GDP of Nuclear Reactor Exports

Exports of a pair of CANDU reactors (720 MW from each unit or a total of 1,440 MW) have been considered while assessing the economic impact of nuclear reactor exports. The export of reactors would contribute to the economy in various ways such as increased sales of reactor components, services to install the reactor, among others. It is estimated that Canadian entities (private and public) would directly receive $815 million through the export of a pair of nuclear reactors and the associated services needed for the construction of nuclear power plants. This amount would cause a spin-off effect on the Canadian economy. It is estimated that the export of a pair of nuclear reactors would add $1,030 million to the Canadian GDP.

Figure 5.3 presents the distribution of GDP impact resulting from the export of a pair of nuclear reactors. The manufacturing sector would receive the highest impact, $252 million, or about one quarter of the total GDP impact. This is followed by finance, insurance and real estate (FIRE), business services and other services. These sectors account for 19 percent, 15 percent and 14 percent of the total GDP impact, respectively.

Figure 5.3
GDP Impact on Canada of Exports of Two 720 MW CANDU 6 Reactors
(millions of dollars)

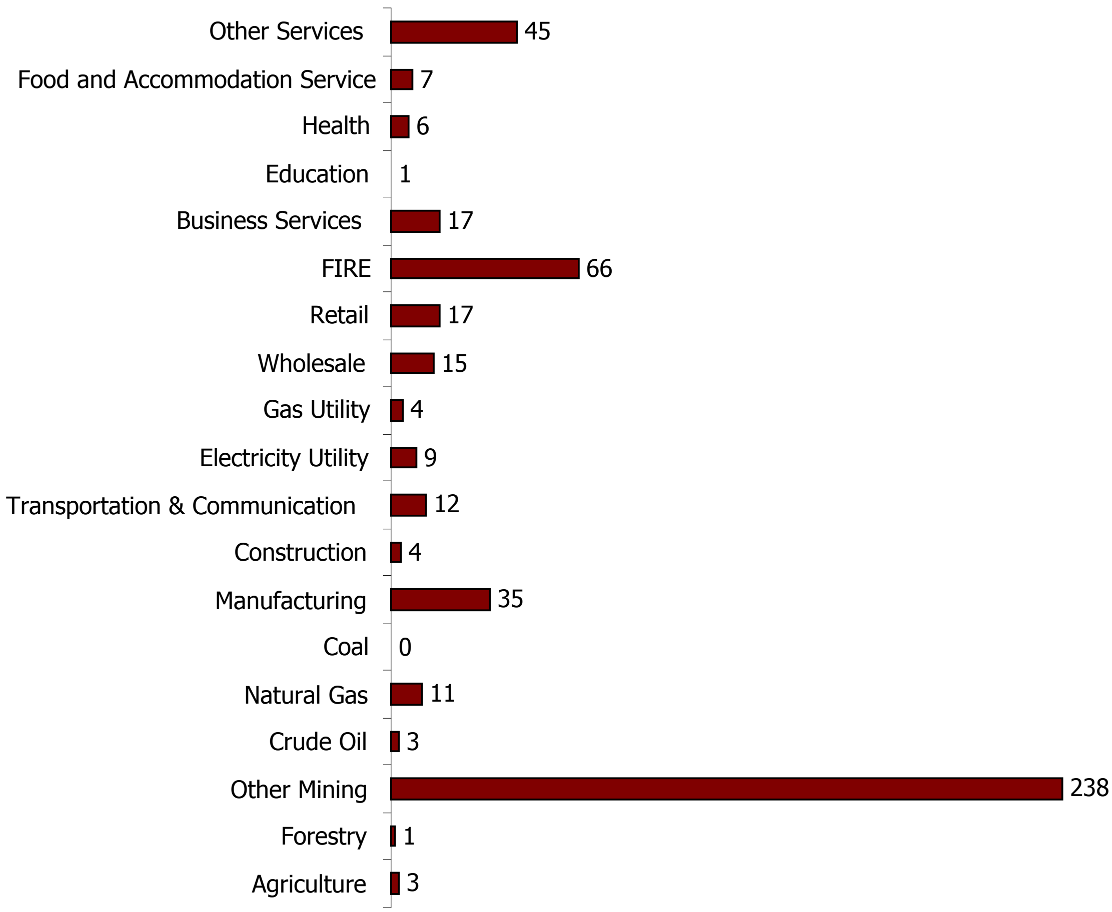


5.3.4 Impact on GDP of Uranium Exports

The impact of uranium exports has been assessed slightly differently from the economic impact of nuclear reactor construction, power generation and nuclear reactor exports. Whereas the total investment in the case of nuclear reactor construction and the total value of electricity sales or the value of nuclear reactor exports were distributed to corresponding purchases of goods and services, labour, and operating surplus, such distribution could not be done in the case of uranium exports because of lack of data. Instead, total value of uranium exports was treated as an output of the other mining sector, which includes uranium mining and refining. This implicitly assumes that uranium mining also uses goods and services in the same manner as the metal and mineral mining industry does. In other words, the impact assessment of uranium exports may not be as precise as the impact assessment of other nuclear activities considered in this study. Note also that the impact of uranium mining for domestic nuclear power plants has already been covered in the impact of nuclear electricity generation. The impact discussed here is related to uranium mining for exports.

In 2005, Canada exported uranium valued at $381 million. This export would have added $494 million, directly and indirectly (i.e. indirect and induced impact) to the GDP. Figure 5.4 shows the distribution of GDP impact resulting from the export of uranium in 2005. As expected, the other mining sector, which includes uranium mining, would have received the highest impact, $238 million or almost a half of the total GDP impact of uranium exports.

Figure 5.4
GDP Impact of Exports of Uranium in 2005
(millions of dollars)



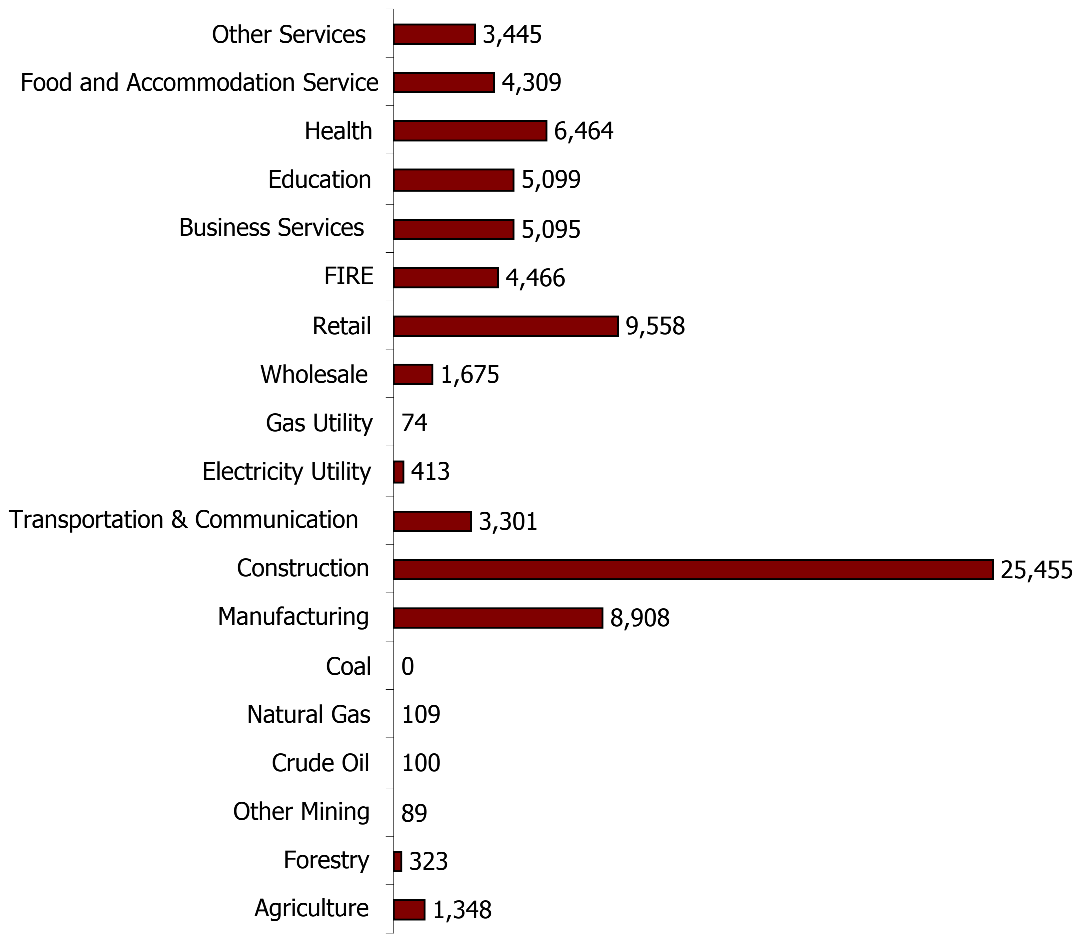
5.4 Impact on Canadian Employment

5.4.1 Impact on Canadian Employment of Nuclear Reactor Construction

Construction of a pair of nuclear reactors (i.e. nuclear power plants), would create 80,233 person-years of employment, directly and indirectly in 2005. If the impact is expressed in terms of per MW capacity of nuclear power unit, it turns out to be 56 person-years of employment per MW of nuclear capacity.

Figure 5.5 portrays the sectoral employment impact of nuclear reactor construction. Intuitively, the construction sector would create the largest number of person-years of employment — 25,455, accounting for 32 percent of total employment creation. Other sectors, such as retail and manufacturing, also create significant employment. These sectors each account for approximately 12 percent of the total employment creation, directly and indirectly, due to the construction of nuclear power plants.

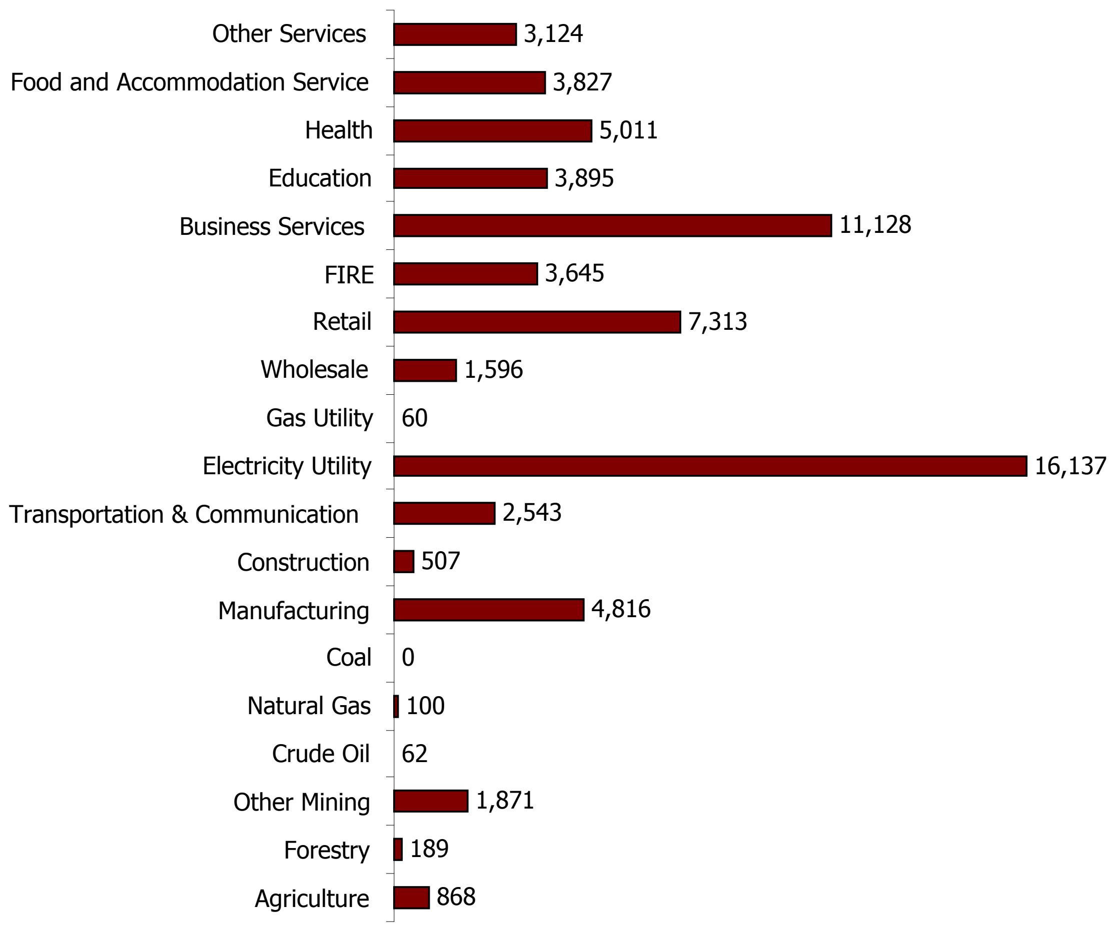
Figure 5.5
Employment Impact of Construction of Two 720 MW CANDU 6 Reactors in Canada in 2005
(person-years)



5.4.2 Impact on Canadian Employment of Nuclear Power Generation

Operation of the existing 17 nuclear units (total capacity of 12,767 MW), would have provided 66,694 full-time jobs, directly and indirectly, in Canada. Figure 5.6 illustrates the sectoral employment impact resulting from the operation of nuclear power plants. Obviously, the electricity sector (i.e. nuclear plants) would have provided the highest employment, 16,137, representing one quarter of the total employment created, directly and indirectly, by the operation of the nuclear power stations in 2005. Other sectors such as business services and retail also would have provided significant jobs, 17 percent and 11 percent, respectively.

Figure 5.6
Employment Impact of Production of Electricity from 17 Nuclear Power Generation Units in Canada in 2005 (jobs)

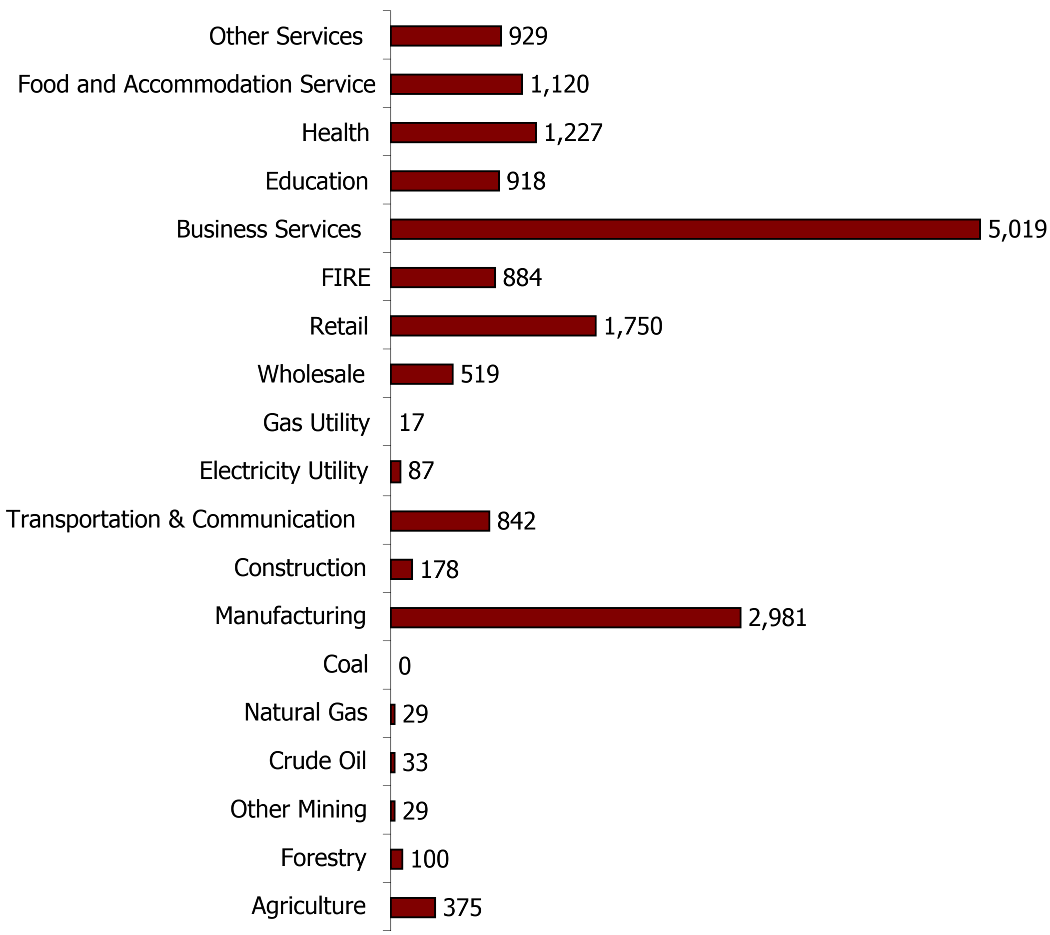


5.4.3 Impact on Canadian Employment of Nuclear Reactor Exports

Nuclear reactor exports also create employment in Canada. Our model shows that exports of a pair of CANDU reactors (720 MW each unit or a total of 1,440 MW) would create, directly and indirectly, 17,039 person-years of employment in Canada. On a per unit basis, exports of 1 MW of nuclear reactor would create 12 person-years of employment in Canada.

Figure 5.7 presents the distribution of employment impact across various economic sectors resulting from the export of a pair of nuclear reactors. The business service sector would create the highest employment impact with 5,019 person-years or about 30 percent of total employment created.

Figure 5.7
Employment Impact on Canada of Exports of Two 720 MW CANDU 6 Reactors (person-years)

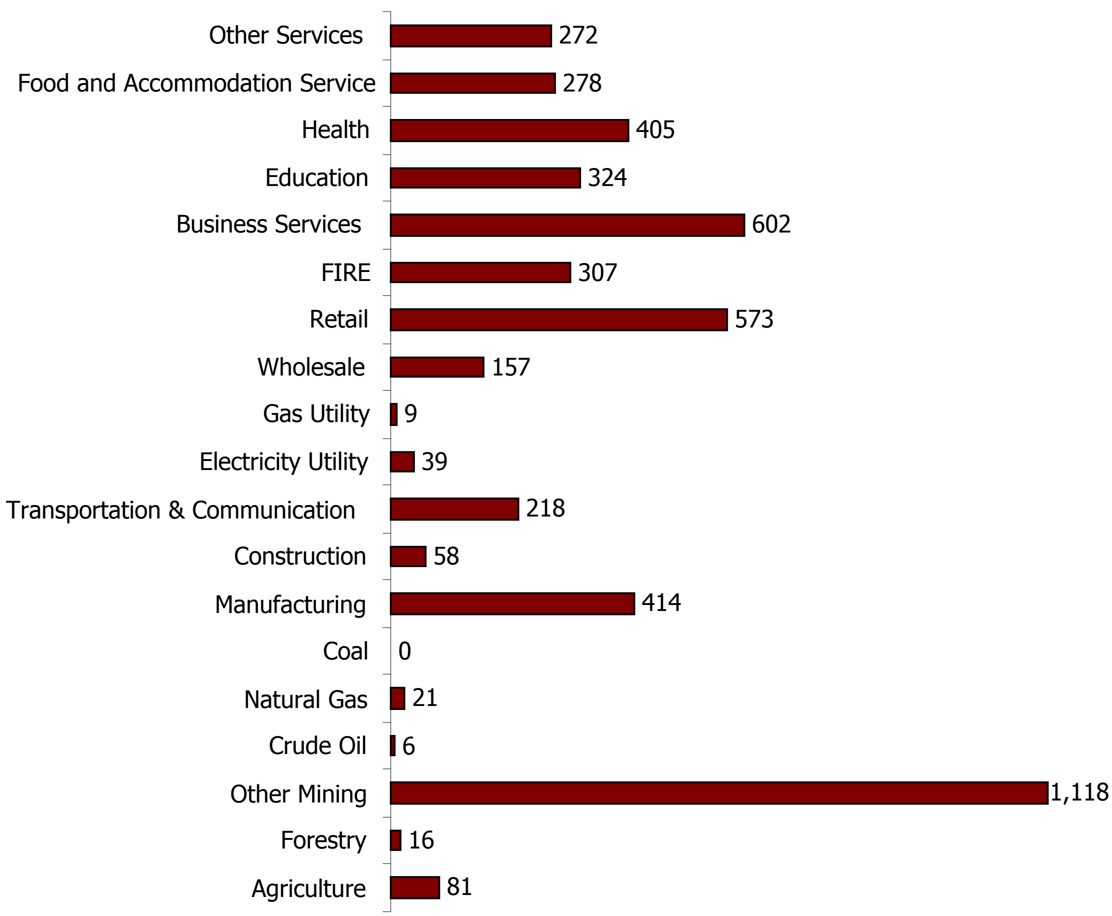


5.4.4 Impact on Canadian Employment of Uranium Exports

Like the exports of nuclear reactors, exports of uranium also provide employment to a large number of Canadians. In 2005, Canada exported uranium valued at $381 million. The mining and refining of uranium to export would have provided 4,900 jobs, directly and indirectly. Note that the employment impact of uranium mining used by domestic nuclear power stations has already been captured in the employment impact assessment of nuclear electricity generation (Section 5.4.2).

Figure 5.8 shows the distribution of employment impact resulting from the export of uranium in 2005 across various economic sectors. As expected, the other mining sector, which includes uranium mining, would have provided the highest employment, 1,118 persons (or 23 percent of the total employment generated by the export of uranium in 2005).

Figure 5.8
Employment Impact in Canada of Exports of Uranium in 2005
(jobs)



5.5 Impact on Government Revenue

Government revenue is another important indicator of the economic impact of an activity. Government revenue is generated through various sources such as indirect taxes, including GST, PST and property taxes; corporate income taxes and personal income taxes. Most of these tax revenues are generated indirectly. For example, the nuclear industry creates a job and the job holder pays income tax. Similarly, the nuclear industry causes output of uranium mining to increase, thereby increasing the corporate income tax paid by uranium mining companies.

5.5.1 Impact on Government Revenue of Nuclear Power Construction

Table 5.5 presents government revenue impact of construction of a pair of nuclear power units with a capacity of 720 MW each. The construction activity would generate, directly and indirectly, a total of $1,604 million in government revenue. Of the total revenue generated, about 60 percent (or $957 million) comes through personal income tax revenue. Indirect tax and corporate income tax revenues account for 24 percent ($389 million) and 16 percent ($257 million).

Table 5.5
Government Revenue Impact of Construction of Two 720 MW CANDU 6 Reactors in Canada

Type of revenue	Amount ($ millions)	Amount (%)
Indirect tax (e.g. GST, PST, property taxes)	389	24.28
Corporate income tax	257	16.04
Personal income tax	957	59.68
Total	**1,604**	**100.00**

5.5.2 Impact on Government Revenue of Nuclear Power Generation

The operation of the existing 17 nuclear units (total capacity of 12,767 MW), would have provided, directly and indirectly, $1,417 million in revenues to governments in 2005. Table 5.6 presents government revenue impact of operation of nuclear power stations in Canada in 2005. It is interesting to note that it is personal income taxes that would have contributed the highest tax revenues generated, directly and indirectly, through the operation of nuclear power stations in Canada in 2005.

Table 5.6
Government Revenue Impact of Production of Electricity from 17 Nuclear Power Generation Units in Canada in 2005

Type of revenue	Amount	
	($ millions)	(%)
Indirect tax (e.g. GST, PST, property taxes)	457	32.29
Corporate income tax	274	19.37
Personal income tax	685	48.34
Total	**1,417**	**100.00**

5.5.3 Impact on Government Revenue of Nuclear Reactor Exports

Exports of a pair of CANDU reactors (720 MW each unit, or a total of 1,440 MW) would create, directly and indirectly, $260 million in government revenues in Canada (see Table 5.7). No tax is imposed on the exports of a nuclear reactor and accessory services.

Table 5.7
Government Revenue Impact of Exports of Two 720 MW CANDU 6 Reactors

Type of revenue	Amount	
	($ millions)	(%)
Indirect tax (e.g. GST, PST, property taxes)	57	22.00
Corporate income tax	57	21.76
Personal income tax	146	56.24
Total	**260**	**100.00**

5.5.4 Impact on Government Revenue of Uranium Exports

Like the exports of nuclear reactors, exports of uranium also generate government revenue. It is estimated that the exports of uranium would have generated $100 million government revenue in 2005 (see Table 5.8).

Table 5.8
Government Revenue Impact of Exports of Uranium in 2005

Type of revenue	Amount	
	($ millions)	(%)
Indirect tax (e.g. GST, PST, property taxes)	27	26.54
Corporate income tax	21	20.80
Personal income tax	53	52.66
Total	**100**	**100.00**

CHAPTER 6
RESEARCH AND DEVELOPMENT ACTIVITIES IN NUCLEAR TECHNOLOGY

This chapter provides a brief review of the structure and the players of nuclear research and development programs and facilities in Canada. In addition, types of funding and activities will be discussed throughout this chapter. Nuclear research in Canada is conducted by a number of institutions including Atomic Energy of Canada Limited (AECL), the CANDU Owners Group Inc. (COG), the National Research Council (NRC), the nuclear power generating companies, MDS Nordion, other private sector companies, universities, and other institutions. The main sponsor of research and development, however, is the federal government. As such, Section 6.1 details federal government, AECL and NRC spending.

Section 6.2 reviews nuclear research facilities that are used for research and development and other purposes in Canada. This section is further divided into two segments. The first briefly reviews nuclear research reactors. These nuclear reactors are not used for power generation. Two such reactors are operated by AECL in Chalk River; the remaining six are owned and operated by various universities across Canada. The second section discusses other facilities, both university and industry, that are active in nuclear research and development.

Section 6.3 reviews research and development activities on nuclear energy. This section is divided into three parts. AECL's activities are discussed, followed by a review of nuclear power generating companies and the CANDU Owners Group (COG). While COG has several international members, this section focuses on utility providers such as Ontario Power Generation (formerly Ontario Hydro), Bruce Power, New Brunswick Power, and Hydro-Québec. Also discussed briefly is the role of university research and development programs.

Section 6.4 reviews research and development in nuclear medicine. This section is in turn divided into four parts: AECL, the NRC, MDS Nordion and university research and development programs.

6.1 Main R&D Sponsors

The federal government is the main entity to support nuclear R&D in Canada, a role that remains unchanged since the early years of the Canadian nuclear industry. Ottawa continues to be the most significant financial supporter of the industry, from which AECL and the NRC are the two players that have received the largest federal R&D funds. Since its creation in 1952, AECL has received most of the federal government funding. Although its nuclear assets were transferred to AECL in 1952, the NRC continues to support academic nuclear R&D programs through universities and independent researchers. The NRC was an integral part of the Canadian nuclear industry in its early days, and was heavily involved with the design of the Zero Energy Experimental Pile (ZEEP) reactor at Chalk River in 1946. At present the NRC is important to facilitating nuclear science in Canada, operating a neutron beam laboratory at Chalk River, not as a facility for "nuclear R&D" as such, but to use neutrons from the Chalk River nuclear research reactor to probe materials of all kinds and extract information about molecular structures and dynamics.

Table 6.1 illustrates the R&D money received by AECL since 1952; it is important to note that these numbers are in nominal dollars. The main sources for this data are *Canadian Nuclear Subsidies: Fifty Years of Futile Funding*[50] by Dave Martin and *Federal Government Subsidies to Atomic Energy Canada Limited*[51] by Tom Adams.

Table 6.1
Federal Government R&D Funding to AECL
(millions of dollars of the year)

Year	R&D	Year	R&D	Year	R&D	Year	R&D
1952	12.1	1966	52.7	1980	114.7	1994	161.5
1953	21.4	1967	58	1981	123.1	1995	169.5
1954	19.6	1968	66.5	1982	145.7	1996	164.3
1955	29.5	1969	68.6	1983	169.9	1997	167.4
1956	30.3	1970	69	1984	184.5	1998	132.2
1957	30.5	1971	68.9	1985	192.4	1999	102.4
1958	23.8	1972	77	1986	172.7	2000	105.7
1959	26.6	1973	78.2	1987	176.8	2001	108.9
1960	24.7	1974	87.9	1988	143.3	2002	136.3
1961	26.5	1975	85.9	1989	135.9	2003	106.6
1962	29.1	1976	93.6	1990	141.5	2004	103
1963	37.1	1977	96.8	1991	154.3	2005	99
1964	44.9	1978	101.7	1992	162.1	2006	98.8
1965	45.2	1979	110.3	1993	167.3		

As demonstrated in Table 6.1, federal government financial support for nuclear R&D programs through AECL has substantially increased over time in nominal terms, peaking in 1995. From that year forward, the funding decreased dramatically until 2006 when it reached its lowest level since 1977. The peak of federal government funding to AECL occurred, in actual terms, in 1985 at $192.4 million. Federal government funding was highest in the period between 1983 and 1987.

To shed more light on actual R&D spending, the real R&D support for AECL is calculated. Table 6.2 illustrates real R&D funds, at the 2005 price level, and in so doing, uses the Consumer Price Index (CPI) reported by the Bank of Canada. Federal government spending to AECL peaks between 1968 and 1972. While remaining over the $300-million level until the mid-1980s, federal government spending decreased gradually. Current spending is slightly higher than spending in 1952, but is at the lowest level in decades. The federal government spending in research and development to AECL has not exceeded the $200-million level since 1998, and 2006 represents the first year since the inaugural year of AECL that spending has not exceeded the $100-million level.

[50] Martin, D. *Canadian Nuclear Subsidies: Fifty Years of Futile Funding*. Campaign for Nuclear Phase-Out, January 2003. www.cnp.ca/resources/nuc-subsidies-at-50-ex-sum.html, full text available at: www.cnp.ca/resources/nuclear-subsidies-at-50.pdf (accessed June 26, 2008).

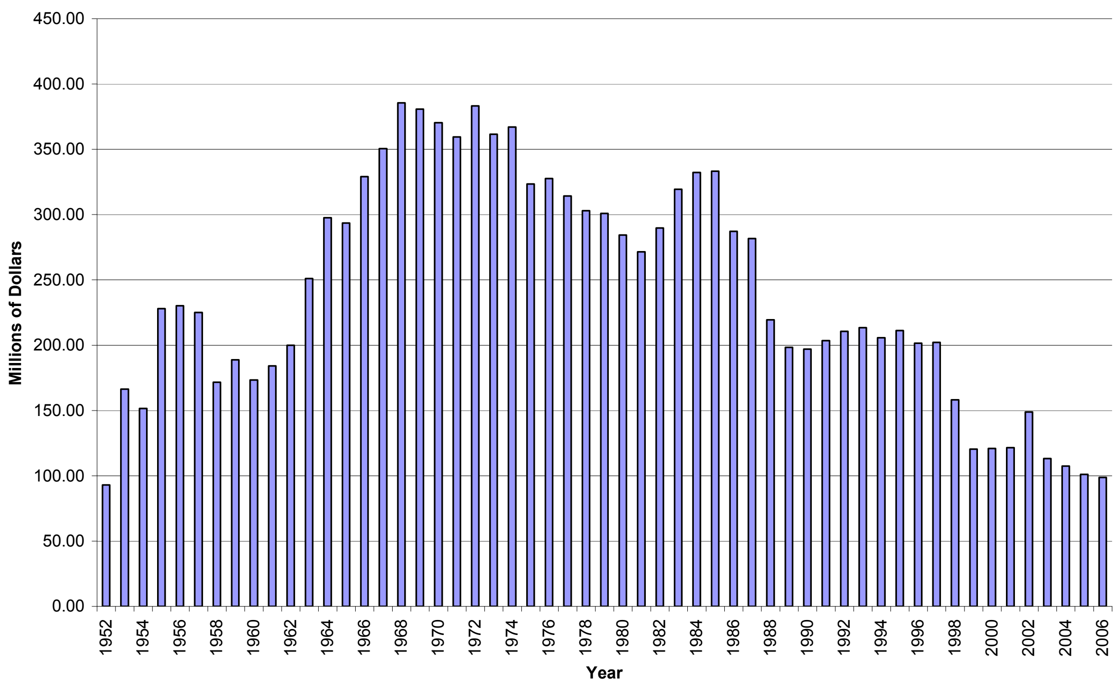
[51] *Energy Probe*, January 11, 2006. Using available AECL annual reports CERI double-checked these figures and found them to be reasonable and conservatively calculated.

Table 6.2
Federal Government R&D Funding to AECL
(millions of 2005 dollars)

Year	R&D	Year	R&D	Year	R&D	Year	R&D
1952	93	1966	329.1	1980	284.3	1994	205.6
1953	166.4	1967	350.4	1981	271.4	1995	211.3
1954	151.5	1968	385.6	1982	289.8	1996	201.5
1955	228.1	1969	380.8	1983	319.3	1997	202
1956	230.1	1970	370.3	1984	332.4	1998	158.1
1957	225.1	1971	359.4	1985	333.2	1999	120.3
1958	171.7	1972	383.2	1986	287.2	2000	120.9
1959	188.8	1973	361.5	1987	281.8	2001	121.5
1960	173.4	1974	367.1	1988	219.5	2002	148.7
1961	184	1975	323.4	1989	198.3	2003	113.2
1962	200	1976	327.7	1990	197	2004	107.3
1963	251	1977	314.3	1991	203.4	2005	101
1964	297.5	1978	303	1992	210.5	2006	98.8
1965	293.5	1979	301	1993	213.4		

Figure 6.1 illustrates federal government's nuclear support through AECL, in 2005 dollars.

Figure 6.1
Real R&D Funds
(2005 dollars)



Cumulative federal government spending (1952–2006) on nuclear R&D through AECL is about $13.26 billion in 2005 dollars.

6.2 Nuclear Research Facilities

6.2.1 Research Reactors

Research reactors comprise a wide range of civil and commercial nuclear reactors that are generally not used for power generation. The primary purpose of research reactors is to provide a neutron source for research and other purposes. For research purposes, the Chalk River reactors are categorized as industry reactors. The Chalk River reactors are the 135 MW National Research Universal (NRU), and the 250 W ZED-2, a zero-energy test reactor.

There are currently eight operating research reactors in Canada: two at AECL's Chalk River Laboratories and six at universities and research institutions (McMaster, École Polytechnique de Montréal, Dalhousie, University of Alberta, Saskatchewan Research Council, and the Royal Military College). These non-power reactors, shown in Table 6.3, have a wide range of uses, including analysis and testing of materials and production of radioisotopes. Due to their multi-disciplinary nature, their roles in Canada's nuclear research and development are quite different and may be too complex to differentiate or to generalize their role in Canadian R&D. For example, a reactor, such as the SLOWPOKE-2 (Safe Slow Power Critical Experiment), is used for research and training, materials testing, or the production of radioisotopes for medicine and industry.

Table 6.3
Research Reactors in Canada

Non-power reactors	Total staff	Annual operating cost ($ millions)	Owner	Status
Chalk River (NRU)	200	20	AECL	Operating
Chalk River (ZED-2)	5	0.3	AECL	Operating
McMaster University (MTR-type research reactor)	10	1.1	McMaster University	Operating
École Polytechnique de Montréal (SLOWPOKE-2)	4	0.22	Université de Montréal	Operating
Dalhousie University (SLOWPOKE-2)	3	0.12	Dalhousie University	Operating
Saskatchewan Research Council (SLOWPOKE-2)	6	0.05	SRC	Operating
University of Alberta (SLOWPOKE-2)	4	0.1	University of Alberta	Operating
Royal Military College of Canada (SLOWPOKE-2)	8	1	Royal Military College	Operating

Source: International Atomic Energy Agency (IAEA). www.iaea.org/worldatom/rrdb/, accessed September 2002.

Chalk River is an important hub for AECL's R&D activities. Recall that the development of CANDU reactors started in Chalk River, an evolution from the creation of the ZEEP, NRX and NRU reactors. Other important developments in nuclear physics occurring in Chalk River were the first phase of the Tandem Accelerator and Super Conducting Cyclotron (TASCC) completed and entered into operation in 1991, as well as the Tri-University Meson Facility (TRIUMF), established in 1975 by physicists in Chalk River to conduct particle physics in Canada. Incidentally, this facility operates in collaboration with the University of British Columbia, the University of Victoria, Simon Frasier University and the University of Alberta, creating ion beams shot onto special targets to study the subatomic fragments that result from collision. TRIUMF produces radioisotopes such as cobalt-57, gallium-67, and indium-111. MDS Nordion in turn markets these radioisotopes.

The university research reactors include five 20 kW SLOWPOKE-2[52] reactors and one 5 MW MTR-type reactor.[53] The 20 kW reactors are located at the University of Alberta (Edmonton), Saskatchewan Research Council (Saskatoon), Royal Military College (Kingston), Dalhousie University (Halifax), and École Polytechnique de Montréal. The 5 MW MTR-type reactor is located at McMaster University (Hamilton). A Canadian-supplied SLOWPOKE-2 is also operated at the Centre for Nuclear Sciences, in Kingston, Jamaica, and an additional two SLOWPOKE-2 units — the original prototype at the University of Toronto and one at MDS Nordion's facility in Kanata — have been shut down. AECL also designed a scaled-up version (2–10 MW) of SLOWPOKE for district heating.

The main advantages of the SLOWPOKE reactors are the reliability and ease of use of their design and the reproducibility of the neutron flux. They are operated mainly for neutron activation analysis (NAA), in research and as a commercial service, but also for teaching, training, and irradiation studies. The SLOWPOKE research reactor was visualized at AECL's Whiteshell Laboratories in the late 1960s.

The reactor at McMaster University, often called McMaster Nuclear Reactor (MNR), is the only research reactor in Canada that is not a SLOWPOKE-2. The 5 MW reactor has the highest flux of any university reactor in Canada.

AECL was commissioning the MAPLE 1 and 2 reactors. When built, their combined capacity would have been approximately 20 MW. The MAPLE is a pool-type reactor with a compact core of low-enriched uranium fuel surrounded by a vessel of heavy water. The MAPLE reactor project was cancelled in May, 2008.

In addition, AECL's Whiteshell Laboratories has decommissioned two reactors: a 60 MW WR-1, organic-cooled reactor and a 2 MW SLOWPOKE Demonstration reactor. Whiteshell Laboratories (WL), established by AECL as a nuclear research centre in 1963, was closed in 1998.[54]

Whiteshell Laboratories was an important nuclear research facility for AECL R&D activities. Located at Pinawa, Manitoba, WL provided research for the deep underground disposal of spent

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[52] The SLOWPOKE-2 is a low-energy, pool-type research reactor designed by AECL. It uses passive cooling and safety systems, and is licensed to run unattended for short periods of time (e.g. overnight).

[53] www.cns-snc.ca/nuclear_info/canadareactormap.gif (accessed June 26, 2008).

[54] Bothwell, R. *Nucleus: The History of Atomic Energy of Canada Limited*. University of Toronto Press, 1988, pp. 265–71.

nuclear fuels. Lessons from WL are now applied around the world. The SLOWPOKE were also studied and developed at WL. Although many university research reactors are SLOWPOKE, due to a lack of market interest, the idea and research were abandoned. WL was also home to research in food irradiation; hydrogen safety and performance; materials science for satellites and high performance aircraft; nuclear reactor design; and reactor safety and waste management. Many of these activities ceased following AECL's decision to close the site in 1998. Following cost-cutting measures, AECL is now planning the decommissioning of Whiteshell Laboratories.

Despite this fact, WL still supports a viable Waste Technology Unit (WTU) that manages the Underground Research Laboratory (URL). The URL is used to research the concept of permanent disposal of used nuclear fuel in a deep geological vault and performs this research for both Canadian and international clients. The reactor safety research conducted at WL is in the process of being consolidated to Chalk River Laboratories.[55]

6.2.2 Other Research Facilities

AECL: As mentioned in Section 6.1, AECL is the epicentre of nuclear R&D activity in Canada. Besides operating several non-power generating reactors (NRU, ZED-2), there are a variety of nuclear facilities located at Chalk River Laboratories. Many are crucial to nuclear R&D in Canada.

The R&D programs include underlying work to ensure that CANDU technology has a solid technical base; there are also other applied programs that result in qualification of equipment, processes and systems for power and research reactors.[56] Following are the AECL programs:

- Research and Development
- Safety Technology
- Software Performance
- Physics and Fuel
- Fuel Channels Technology
- Reactor Chemistry and Systems
- Hydrogen and Heavy Water
- Environmental Emissions and Health Physics
- Control and Information

[55] Tammemagi, H. and D. Jackson. *Unlocking the Atoms*. McMaster University Press, 2002.
[56] www.aecl.ca/Science/RD.htm (accessed June 26, 2008).

Below are a number of nuclear research facilities that are operated by AECL. There is also a short review (above) of Whiteshell Laboratories, which is now defunct.

Chalk River Laboratories is the hub of nuclear R&D in Canada and is home to several major nuclear facilities. The many laboratories and facilities can be divided into the following:

- Research reactors (discussed earlier)
- Isotope production reactors (discussed earlier)
- Shielded facilities (hot cells)
- Nuclear materials production
- Nuclear labs and experimental facilities
- Shops for radioactive materials

Important facilities include the Recycle Fuel Fabrication Laboratory, Nuclear Fuel Fabrication Facility, Universal Cells and Fuels and Materials Cells. There are several fuel fabrication laboratories that are used to fabricate fuel for irradiation experiments in research reactors. For example, the Nuclear Fuel Fabrication Facility produces both low- and high-enriched uranium fuels. There are also various other facilities at Chalk River that include thermo-hydraulics test facilities, environmental test facilities, surface science laboratories, and fission product research laboratories.

University and Other Research Facilities: There are currently six nuclear research facilities in Canada located at universities and other institutions. These facilities, like the nuclear research reactors, have a wide range of uses, including analysis and testing of materials, and production of radioisotopes.

In addition to the 5 MW pool-type MTR nuclear research reactor, McMaster University is home to an advanced nuclear engineering program. The University's facilities are complemented by joint research with AECL at Chalk River. Current projects include two 3 million electron-volts (MeV) Model KN Van De Graaf Accelerators and two 1.25 MeV Tandetrons. The university also has a Single-Ion μMicrobeam and is proposing a 30MeV Cyclotron. The KN accelerators date back to the early days of the McMaster Accelerator Lab in the 1970s.

The University of Western Ontario (UWO), like McMaster University, possesses a Van De Graaf Accelerator as well as a Tandetron. UWO's Tandetron is 1.7 MeV, slightly larger than McMaster's Tandetron. The accelerator provides ion beams, used for both modification and materials analysis.[57] UWO's Van De Graaf Accelerator is 3 MeV. The Université de Montréal also has one Van De Graaf Accelerator and one 1.7 MeV Tandetron.

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[57] www.uwo.ca/isw/facilities/Tandetron/tand_acc.htm (accessed June 26, 2008).

The University of Guelph, Queen's University and Laval University each operate an accelerator. The University of Guelph operates a Pelletron Accelerator, which provides a 3-MeV proton beam of energy. The accelerator is part of the Guelph PIXE Group, which is involved in physics research. Queen's University operates a particle accelerator in the High Energy Physics Laboratory building. The Van De Graaf accelerator is linked with nuclear physics and astrophysics research. Queen's University also is taking a leading role in the Sudbury Neutrino Observatory project. Laval University operates a single 7.5 MeV Van De Graaf Accelerator.

The NRC operates two accelerators, both used by the Ionizing Radiation Standards Group. The first is a clinical linear accelerator, the Elekta Philips Precise. The second is the 35 MeV Vickers Electron Linear Accelerator. The Elekta Precise Linac is a standard clinical radiotherapy machine with photon beams of 6, 10 and 25 MeV and five electron beams with energies between 4 and 22 MeV.[58] Acsion Industries Inc. also operates a particle accelerator. It is located in Pinawa, Manitoba, the site of AECL's Whiteshell Laboratories. While Ascion Industries is involved in providing health care and aerospace products, they also provide R&D related to electron beam processing and manufacturing.

6.3 Research and Development on Nuclear Energy

To reiterate, Canadian nuclear energy R&D spending has resulted in the unique CANDU heavy water reactor system, which unlike light water reactors, uses natural uranium as fuel. The main supporter for nuclear energy R&D in Canada, as mentioned above, is the federal government. The main recipients of government funding are AECL and the NRC. This section, however, investigates R&D on nuclear energy and science. As such, this section will discuss AECL, nuclear power companies and the CANDU Owners Group Inc., as well as university research programs.

6.3.1 AECL

AECL employs its resources to enhance the design of CANDU power reactors, and explore continuous improvements in its products and services.

Today, AECL focuses on eight key technologies: safety; software performance; physics and fuel; fuel channels; components and systems; hydrogen and heavy water; environmental emissions and health physics; and control and information.[59] These R&D programs include underlying work to ensure that CANDU technology has a solid technical base for applied programs.

The most recent and ambitious project is to develop two advanced reactors, the Advanced CANDU Reactor (ACR-1000®) which is a 1,200 MW class pressure-tube reactor and the Enhanced CANDU 6 which is a 700 MW class reactor.

The ACR-1000® reactor core consists of fuel and light-water coolant in pressure tubes with a heavy water moderator. The reactor is expected to have a 60-year design life.

58 http://inms-ienm.nrc-cnrc.gc.ca/calserv/ionizing_radiation_e.html (accessed June 26, 2008).
59 www.aecl.ca (accessed June 26, 2008).

The CANDU 6 was designed specifically for electricity production, unlike other major reactor types that evolved from other uses. This focused development is one of the reasons that CANDU has such high fuel efficiency. The first CANDU 6 plants went into service in the early 1980s as leading-edge technology, and the design has continuously evolved to maintain superior technology and performance.

AECL's nuclear platform research and development program maintains and enhances the CANDU safety, licensing and design basis. In addition, it supports public policy for nuclear technology, develops pre-commercial CANDU technology and preserves the capability and expertise needed to address future issues.

AECL's expertise also supports improvements in plant performance and licensing for CANDU utilities. Generic support — part of the safety, licensing and design basis — is provided through cost-shared programs with the CANDU Owners Group. AECL continues to advance its research vision of providing components, systems and technology that will ensure CANDU's long-term safety and performance competitiveness in global markets.

6.3.2 Nuclear Power Companies and the CANDU Owners Group

In the realm of nuclear R&D activities, nuclear power companies and the CANDU Owners Group (COG) are discussed together in this study, as their activities are very closely interlinked. The nuclear power companies in Canada are Ontario Hydro (now Ontario Power Generation), Hydro-Québec and New Brunswick Power. COG was formed in 1984 by an agreement among the Canadian CANDU-owning utilities. COG membership includes five Canadian members (AECL, Ontario Power Generation, Bruce Power, Hydro-Québec, New Brunswick Power Nuclear Corporation) and six offshore members (Argentina, Romania, Pakistan, India, South Korea and China), all of which own CANDU units.

The purpose of COG is to provide programs for co-operation, mutual assistance and exchange of information for the successful support, development, operation, maintenance, and economics of CANDU technology.

Under the original agreement, the former Ontario Hydro was the administrator of COG, reporting to a Directing Committee comprised of representatives of the four Canadian members. However, in 1999 COG was registered as a not-for-profit corporation, and a Board of Directors was appointed to replace the previous Directing Committee.

The COG Research & Development Program addresses current and emerging operating issues to support the safe, reliable, and economic operation of CANDU reactors in the areas of licensing; fuel channels; health, safety and environment; and chemistry, materials and components.[60] In this chapter COG's involvement in R&D programs and the scope of the support that this group has provided for nuclear R&D are discussed.

[60] www.candu.org/programs.html (accessed June 26, 2008).

COG supports its members through different technical assistance. The main goal for COG is to ensure the safety and reliability of CANDU reactors within Canada and around the world.

6.3.3 Universities

University nuclear programs are closely linked to COG's objectives. Industry and university interactions are discussed briefly in this section, which is in turn divided into the four current R&D programs, as indicated in the previous section: chemistry, materials and components; fuel channels; safety and licensing; and, finally, health, safety and environment.

It is important to note that all universities mentioned below are members of the University Network of Excellence in Nuclear Engineering (UNENE), an alliance of prominent Canadian universities and the nuclear industry. UNENE is an industry driven initiative. Further research funding stems from grants received from the National Sciences and Engineering Research Council of Canada (NSERC).

The University of Toronto, University of New Brunswick and Queen's University assist COG in researching chemistry, materials and components. The University of Toronto is researching Nano-engineering of Alloys for Nuclear Power Systems. The university received federal funding of $1,019,000 over five years for the NSERC/UNENE Industrial Research Chair at the University of Toronto. The Chair will examine the capabilities of materials that are critical to extending the life of nuclear power plants. UNENE will contribute an additional $922,000 in cash and $542,000 in-kind over five years.

The University of New Brunswick, on the other hand, assists COG researching Chemistry and Corrosion. Research is conducted under the leadership of Dr. Derek Lister. Problems can arise from the generation of corrosion products, which transport around the circuits and deposit on surfaces. Heat transfer may be impeded and, in reactors, primary coolants associated with radioactivity lead to the build-up of radiation fields around components.[61] The project is also funded by NSERC. Queen's University is researching Advanced Nuclear Materials. Dr. R. Holt is the Industrial Research Chair of Nuclear Materials. NSERC announced in September 2002 that it is providing $1.15 million over five years with the partners jointly contributing $1.05 million.[62] The project is in partnership with Ontario Power Generation, COG and Nu-Tech Precision Metals Inc.

The second division of current R&D is in Nuclear Fuels. The Royal Military College and McMaster University are researching Nuclear Fuels. Dr. Brent Lewis and the RMC are preparing the project, which is in partnership with COG. McMaster University is researching Thermal Hydraulics under Dr. John Luxat. Boiling heat transfer from cylindrical nuclear fuel elements and fuel channel calandria tubes is an important factor in CANDU reactor accidents.[63]

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[61] www.nserc.gc.ca/partners/profile_detail_e.asp?pid=342 (accessed June 26, 2008).
[62] www.nserc.gc.ca/news/2002/p020919.htm (accessed June 26, 2008).
[63] http://engphys.mcmaster.ca/faculty_staff/faculty/luxat/index.htm (accessed June 26, 2008).

McMaster University is also active in Safety and Licensing. Again this research is in partnership with COG. Under Dr. John Luxat and Associate Chair Dr. Dave Novog, McMaster University is researching Nuclear Safety Analysis. "Best estimate models of physical processes, best estimate plant states, and most probable system configurations and failure events provide the most realistic representation of plant behaviour and consequences during accidents."[64]

The University of Ontario Institute of Technology is involved with COG in researching Health, Safety and Environment under Dr. Anthony Waker.

6.4 Research and Development on Nuclear Medicine

This section discusses current R&D activities in nuclear medicine. This section is divided into four parts: AECL; NRC; private companies; and universities.

6.4.1 AECL

AECL has been responsible for many developments in the use nuclear technology in medicine, especially for cancer treatment. In fact the idea of employing cobalt-60, positron emission tomography and thermo luminescence was originally developed and applied in Chalk River. In 1990, AECL developed the world's first dedicated reactor to produce medical isotopes, the MAPLE.

AECL was in the phase of commissioning a dedicated medical isotopes production facility (DIF) at the Chalk River Laboratories. The DIF was to consist of the MAPLE 1 and MAPLE 2 reactors — which would have provided a long-term secure supply of isotopes. The focus of these project activities included licensing, commissioning, and preparations for operations. Currently the 50-year old NRU reactor supplies MDS Nordion with medical isotopes. The importance of this reactor is discussed further in Section 6.4.3. AECL terminated the MAPLE project in May 2008.

6.4.2 NRC

The National Research Council (NRC) operates the Canadian Neutron Beam Centre (CNBC) in Chalk River. Using the NRU reactor, the NRC operates a suite of five neutron beam instruments within this international facility where researchers and students carry out experimental measurements on a wide range of materials in all physical science disciplines. Independent users from industry also benefit from the centre. Besides managing the neutron beam, the CNBC investigates new areas of neutron beam technology to ensure that Canada maintains its technological edge in the industry around the world.

The CNBC continues to play a key role in funding and establishing the Canadian Neutron Facility, which will use the NRU at Chalk River Laboratories until 2011 to assist Canadian universities, government laboratories and industrial users in their research. This facility will be the main testing centre in the development of the new generation of CANDU power reactors.

[64] http://engphys.mcmaster.ca/faculty_staff/faculty/luxat/index.htm (accessed June 26, 2008).

The long list of projects and experiments that have been undertaken at CNBC is beyond the scope of this chapter, but can be accessed through the CNBC web site.[65] For the year 2005–06, the CNBC ran more than 78 projects. Along with Canadian scientists from all over the country, researchers from nine foreign countries were involved.

6.4.3 MDS Nordion

MDS Nordion is the world's leading producer of medical and industrial isotopes. In fact MDS Nordion produces two-thirds of the world supply of reactor-produced isotopes using the NRU reactor at Chalk River.

MDS Nordion uses nuclear technology to prevent, diagnose and treat diseases. The company employs more than 1,000 people and operates in North America, Europe and Asia. Its R&D program developed the radioisotope cobalt-60, which is used to treat products and destroy harmful microorganisms. MDS Nordion is the main supplier of cobalt-60 in the world. The company was the first to build a commercial irradiator in 1964; today, irradiators are used in more than 45 countries to sterilize medical supplies. The Canadian Irradiation Centre, as a part of MDS Nordion, continues to advance radiation processing through R&D.

Along with the above-mentioned products, the company has introduced and continues to introduce new products to the market every year; the list of these products is available through the company's web site.[66] Furthermore, the researchers at MDS Nordion contribute to academic literature through publishing papers and preparing scientific reports. A list of these publications is also available though MDS Nordion's web site.[67]

6.4.4 Universities

As mentioned earlier, there are six Canadian universities conducting nuclear R&D using SLOWPOKE reactors. Radioactive isotopes are produced in abundance inside these reactors; some of which are sold for use in medicine, science and industry (Canada is the world's largest supplier of molybdenum-99 and cobalt-60). In fact, researchers use these reactors for a broad range of studies, including issues in archaeology, material science, fusion research and environmental science. This chapter will most closely review the benefits of SLOWPOKE nuclear R&D on medical science.

Several of the Canada's nuclear research reactors are discussed in the following section.

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[65] http://neutron.nrc-cnrc.gc.ca (accessed June 26, 2008).
[66] www.mds.nordion.com
[67] www.mds.nordion.com/eLibrary/elibrary-research-articles.html (accessed June 26, 2008).

McMaster University Reactor

As a multidisciplinary facility, McMaster University is home to research in a variety of areas in nuclear science, engineering, and health and radiation physics. The experiments at the facility include neutron beam, isotope production, neutron activation research and neutron radiography research. This reactor is also an educational facility for graduate students of engineering, science and physics.

The KN accelerator is used for experiments in many different areas. In the Medical Physics field, tests are conducted on irradiated samples of simulated human teeth and tissue, and used to obtain information on radiation exposure to body parts and to help contribute research in finding cures for diseases.

Various departments inside the university benefit from the McMaster facility; the departments of Biology, Physics, and Radiology along with the University Medical Centre and the Hamilton Regional Cancer Centre are among these. Facilities available at the Cancer Centre include various optical and ionizing radiation sources and detectors, linear accelerators, cobalt-60 treatment machines, a Cs-137 cell irradiator and various nuclear and radiographic imaging devices. Also on the University campus are radiobiology laboratories for studying radiation-induced DNA damage and repair in human cells and photodynamic therapy. McMaster's faculty and graduate student research ranges from curiosity-driven basic science in the laboratory, to clinical research at the bedside and in the community, to cost-effectiveness of particular therapies and the efficiency of health care delivery.[68]

University of Alberta

The SLOWPOKE Nuclear Reactor Facility is located on the main campus of the University of Alberta. The facility houses a SLOWPOKE-2 nuclear reactor that was designed and built by AECL and commissioned in 1978. The reactor is used as a source of neutrons for radionuclide production, Neutron Activation Analysis (NAA), research, and teaching. The facility has gamma spectrometers to analyze radioactive materials from many different sources.[69]

École Polytechnique de Montréal

The École Polytechnique de Montréal's nuclear engineering program began in 1970. Research is conducted using mainly the SLOWPOKE nuclear. It is used mainly for neutron activation analysis (NAA) and the production of radioactive tracers. NAA is a type of non-destructive chemical analysis used for measuring the concentrations of chemical elements in solids and liquids.

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68 http://mnr.mcmaster.ca/ (accessed June 26, 2008).
69 www.ualberta.ca/~slowpoke/ (accessed June 26, 2008).

The SLOWPOKE Laboratory and the chemical engineering department are cooperating in the production and use of radioactive tracers for the study of flow dynamics in multiphase chemical reactors. In a number of ongoing collaborations in medicine and pharmacy, radioactive tracers are used in animals and humans for the study of medication dissolution in the digestive system and distribution to various organs. The list of other scientific activities using the SLOWPOKE Laboratory is available through their web site.[70]

Dalhousie University

The Dalhousie reactor was installed in 1976. This reactor has been used for Neutron Activation Analysis at the Trace Analysis Research Centre and has become the frontier for the study of analytical chemistry. The research resulted in gamma energy spectrum, which can be used to identify the elements in an unknown sample. This reactor has also been used to produce isotopes for medical research as well as training students and assisting faculty members to conduct their research.[71]

[70] www.polytechnique.edu/page.php?MID=152&LID=1&PID=96 (accessed June 26, 2008).
[71] http://chemistry.dal.ca/Research/Centres_and_Facilities/SLOWPOKE.php (accessed June 26, 2008).

CHAPTER 7
NUCLEAR FUNDING: AN ASSESSMENT OF VALUE

Previous chapters have addressed the overall contribution to the economy attributable to the nuclear energy industry. This study has also outlined the research activities that relate to or rely on the nuclear sector; and now turns to a more specific assessment as to whether or not the funding provided by the federal government over past decades can be justified based on the direct benefits that resulted from that funding. The assessment of both government programs and specific project evaluation is relatively complex and is treated in greater detail in the Appendix**.** In this chapter, a simplified summary of the government's contribution over the years and the associated costs and benefits of the resulting activity is provided. The discussion requires some technical context, as discussed below.

The federal government has been the primary source of funding for AECL and other vehicles for nuclear research since 1952. Over that time, significant annual funding has been allocated for research and development in the nuclear sector. Have those funds resulted in appropriate benefits? To answer that question, one has to consider all of the benefits that resulted from the expenditure, to the extent that data on such benefits is reasonably available. As well, any other costs that were necessary to realize those benefits have to be included.

<u>The Basic Issue</u>

Since this study encompasses a long period of time and must include the likely benefits that will accrue for some reasonable period into the future, methods must be found to make all of the annual expenditures comparable. That will be accomplished by adjusting all expenditures to remove the effects of inflation so that dollars spent in every year are reported on a comparable basis.

Because of the long time span involved, it is also necessary to evaluate the annual expenditures in a way that allows for what is often termed the time value of money. This is handled by calculating the present value of the stream of costs and benefits (or alternatively, by calculating the future value of an annual stream of costs and benefits). The calculation of present or future value involves discounting future revenue by a discount factor or compounding past revenue by the same factor that is calculated directly from the discount rate. This allows the addition of the value of benefits over a long time period, and the comparison of that sum to that of all the costs over the same time period. Some straightforward rules to assess the result can then be applied.

For example, if the net present value (NPV) of all the costs associated with nuclear activity is calculated over a certain time period followed by the same for the benefits, this simple rule could be considered; if the discounted benefits exceed the costs, the project has net benefits and is, in some sense, justifiable, since there are more benefits than it cost to produce them.

The mathematical depiction of the process is as follows:

$NPV = \sum benefits/(1 + r)^{t-T} - \sum costs / (1 + r)^{t-T}$

Where $\sum$ = the sum of, T = Reference year, t = year cash flow occurred, and r = discount rate

The discount rate r is important in the interpretation of this formula. The formula says that given a discount rate r, the NPV is the sum of the discounted benefits minus the sum of the discounted costs. If the NPV is positive, the benefits outweigh the costs and of course, if the NPV is negative the costs outweigh the benefits. The case where the two are equal yields a zero net present value. In this case, the discount rate is often interpreted as the internal rate of return (IRR) for the project. Given a stream of revenues and costs, the discount rate that equates the two streams of values is the percentage return that results from spending the costs to earn the benefits.

The discount rate used in this calculation is important because it can be interpreted as one of the indicators of the desirability of a project. The higher the discount rate used, the lower the present value of both costs and benefits. Another way to interpret this approach is that a positive discount rate means that future values are given less weight than current values. The choice of an appropriate rate of discount is a matter of some debate in the economic literature. A simple characterization of the issue is to what extent present generations should consider the welfare of future generations when making current investment decisions. Low discount rates may favour future generations by justifying high levels of current investment, the benefits of which are realized by future generations. High discount rates favour the present by discouraging investment and releasing current income for consumption, the benefits of which accrue to current generations.

Some argue that the current market interest rate should be used since that rate represents the opportunity cost of allocating funds to any specific investment. Others argue that the current market rate is unfair to the future, since it reflects current preferences and opportunities only, and that a lower rate, sometimes referred to as a "social discount rate" is more appropriate.

Complicating Factors

This approach is complicated in application for several reasons. First, it is not always easy to quantify either the costs or the benefits of actions. On occasion both costs and benefits can be somewhat intangible. For example, the costs of burning fossil fuels include the environmental implications, which are currently hard to quantify. As well, the benefits of research, very important to the current review, are not always translatable into dollars and cents.

Another complication relates to how the results of the calculation are interpreted. The easiest result to interpret is one where at any rate of discount, the costs outweigh the benefits so the NPV is negative. In general, when costs exceed benefits the investment is not advisable, though some uncertainty can attach even to this case.

When the NPV is positive, there is a question as to what discount rate was applied. If the discount rate is equal to or larger than the prevailing market rate, there is usually a broad consensus that the project is attractive. When the discount rate is between zero and the market rate, the issue is less clear. Some argue, as noted above, that a lower social discount rate is appropriate because it gives a higher weight to the welfare of future generations. Even a zero discount rate would be acceptable to some, if it leads to a positive NPV, because that implies the interests of the future are valued equally to those in the present. Others argue that some version of a market rate should be used to ensure efficient allocation of resources. If you accept rates of return lower than the market rate, you implicitly forego better investment opportunities. This is discussed in greater detail with respect to the current review in the Appendix.

Evaluating Nuclear Funding in Canada

This leads to the case at hand, an evaluation of the historical funding of the nuclear sector by the federal government. Historical costs have been estimated based on the reported contributions of the federal government beginning in 1952. This time series of annual funding provides the amounts allocated to Atomic Energy of Canada Limited (AECL), the National Research Council (NRC), and the CANDU Owners Group (COG). The series allows a consistent estimate of the cost side of the equation.

The benefits side is a bit more complicated. The first component of the benefits is the net revenue to AECL from both domestic and export activities. Since net revenue is used, the cost to provide those services has been netted out and is, therefore, implicitly included in the analysis. The second component of the benefits is a contribution to lower costs in electricity generation that would not have occurred in the absence of the nuclear sector. These benefits are estimated using a model of Levelized Unit Energy Cost that is applied to plants using coal, natural gas, and nuclear as fuels. The savings from using nuclear are then incorporated on an annual basis.

Because the benefits from existing nuclear generation facilities would continue even if all federal funding were terminated in 2006, those continuing benefits have been included over the life of the plants in question. That means an assumption that plants in New Brunswick and Quebec are in operation until the year 2033, and plants in Ontario are assumed to retire at various dates up to 2043. This is laid out in detail in the Appendix.

Finally, the total annual benefit is estimated as the sum of these two components — the saving from nuclear generation and the AECL benefit. This gives the stream of benefits to be compared to the stream of costs associated with the federal funding of nuclear R&D over the years. After adjusting for inflation, this stream can be used to calculate the internal rate of return or it can be discounted using varying rates, to determine the net present value of the federal investment.

The real internal rate of return for the "R&D Investment Project" was calculated to be within a range of 5.8 to 6.9 percent. This is a very reasonable return in a world where inflation is running close to 2 percent and real interest rates are in the 4–5 percent range. Based on this discussion, and using a 5 percent discount rate and considering natural gas as the alternative to nuclear energy, the benefit/cost ratio works out to be 1.49. This clearly indicates a viable project because a ratio greater than 1 demonstrates benefits exceeding costs. For a more detailed discussion of the analysis, see the Appendix.

Other Considerations

Aside from the emissions uncertainty that could enhance the comparative economics of the nuclear option, there are uncertainties in measuring benefits that should be noted. The authors were unable to get a reliable estimate of benefits related to nuclear R&D in any of the areas discussed in Chapter 6. While there are significant levels of such benefits, particularly with respect to MDS Nordion, reliable estimates to augment the benefits numbers could not be obtained. As well, there are research reactors and universities doing fundamental research that are hard to pin down in dollar terms but are certainly generating benefits. And finally, although the environmental costs that are not included in this study have been noted, it should be emphasized how important those could be. For example, if the climate change issue, pursuant to fossil fuels emissions is very significant, the implied benefit to switching generation sources to nuclear is very high indeed. Such benefits would likely dwarf the analysis presented here and make nuclear, wherever possible, the predominant choice for energy supply.

CHAPTER 8
CONCLUSIONS

That AECL has only sold reactors abroad over the past decade points to a worldwide trend in nuclear energy: developing nations with rapidly expanding industrial bases are hungry for energy and appear more willing than developed nations to embrace nuclear power; for fast-growing economies, nuclear power is a cost-effective addition to the energy mix. Developed nations, on the other hand, have now lived with nuclear energy for two generations, and there is cautious public sentiment towards further development — safety being the main concern.

However, this study demonstrates that in 2007 the risks of an accident at a Canadian nuclear facility are comparatively small; nowhere in the world has there been a radiation-caused fatality or notable radiation leak causing environmental damage at an operating CANDU reactor. Canadian nuclear reactors are subject to stringent regulation, and both the technological and safety standards are being continually improved. Even outside of the Canadian industry, nuclear power operations have proven safe, especially when considered against production of other forms of energy such as coal and hydroelectricity. The accident at Chernobyl is a reminder of the potential perils of nuclear energy generation, but because it was an isolated incident that has not been repeated, it also indicates that the industry today operates reliably and safely. As for the threat of terrorism, both governments and insurance companies consider the threat to be low. Reinforcements of existing facilities have been made and new facilities are being designed with terror threats in mind.

For any project the scale of nuclear reactor construction, the economic impact on national and local economies is bound to be substantial. This study considers construction of two 720 MW CANDU 6 reactors costing $3.742 billion and has found the various impacts on Canadian GDP to add up to over $5 billion, direct and indirect employment would increase by more than 80,000 person-years, and government revenues would exceed $1.6 billion. The export of two reactors would also impact the Canadian economy significantly, with over $1 billion GDP created, 17,000 person-years of employment added domestically, and government revenues increased by $260 million.

If Canada were never to build another CANDU reactor, the domestic nuclear energy industry would still contribute notably to GDP, employment, and government revenue for many years to come. In 2005, Canada's 18 nuclear reactors sold energy worth almost $5 billion, contributed a total of over $6 billion to GDP, and created $1.4 billion in government revenue. The industry employed, directly and indirectly, over 66,000 people.

CERI has performed a sensitivity analysis concerning the economic benefit of nuclear R&D. Using available information from Ontario, the province with 16 of Canada's 18 nuclear power facilities, CERI projects that at a 5 percent discount rate, nuclear R&D yields economic benefits. Moreover, these figures do not take into account several difficult-to-quantify positive externalities, mainly improvements in quality of life, that society may judge to be more important than the economic bottom line; indeed, if nuclear R&D brings cleaner air, reduces the rate of global climate change, and sees breakthroughs in medicine, the social benefits gained may outweigh economic considerations. A number of agencies and corporations are drawing similar provisional conclusions; in Ontario, New Brunswick, and Alberta plans are being presented for new nuclear power plant construction projects.

Though the trend has been towards establishing and expanding nuclear power in developing countries, it is not entirely surprising that developed nations such as Canada are now considering new reactors. Recent years have seen high global demand for energy and increasing tightening of supply. Climate change has also been on the front pages of late, so reducing worldwide CO_2 emissions caused by the burning of fossil fuels has become a public concern. The nuclear industry — which is capable of producing energy reliably, in large amounts, at low cost, and at a near-zero CO_2 emission rate — can play a leading role in ameliorating these problems. In Canada, the nuclear industry has made major contributions to society and the economy for decades. This study has demonstrated both the economic feasibility and the social benefits of future nuclear R&D; whether or not Canadian society accepts a greater role for nuclear power is a question that continues to be debated and remains to be answered.

APPENDIX A
QUANTITATIVE EVALUATION OF NUCLEAR R&D IN CANADA: METHODOLOGY AND ANALYSIS

A.1 R&D Evaluation Framework: An Overview

By definition, evaluation is the systematic investigation of the value or merit of an activity. There are two types of evaluations, the project evaluation and the program evaluation. Project evaluation focuses on the particular project, whereas program evaluation looks at the impact of a collection of activities.

A.2 Evaluation Methods

The use of different methods of evaluation is closely related to how a program is positioned relative to the market and how mature it is. Some methods are relatively useful when an R&D program is in its initial steps, while others are better suited to closer-to-market programs. In general, as an R&D program matures and moves towards commercialization, there are more methods available to capture its impact. In this case, employing an evaluation program that allows actual data to reveal the impact of the R&D program is a wise approach.

Below, the most common approaches in evaluating an R&D project are revised based on information from the Advanced Technology Program evaluation cookbook. These methods are discussed briefly along with their advantages and disadvantages.

- Analytical/conceptual modelling of underlying theory
    - This is an essential step for program operation, which gives early stage knowledge to formative management and evaluation procedures. It helps to build and design a long-term comprehensive evaluation program on programs impact.

- Survey Method
    - This method gathers aggregate data based on a uniform set of questionnaires from all parties on activities, plans, relationships, accomplishments, values and impact. Surveys provide statistical analysis on multiple projects rather than on project details.
    - The advantage of using this method is that it allows the gathering of aggregate data on a program in the early stages. It is economical and also reveals information that is not usually available through other resources.
    - The disadvantage is that surveys do not provide detailed information on specific individual projects, which are of great interest to stakeholders and project managers.

- Descriptive Case Study
    - This type of evaluation is an in-depth analysis of a specific program. This analysis is especially useful in understanding and identifying fundamental relationships and variables. Furthermore, it is helpful in the exploratory phase of an R&D program.
    - The advantage of this type of analysis is that it helps decision makers to easily understand a program.
    - The disadvantage of this method is that it lacks the robustness of quantitative methods. As well, because the results tend not to be general, they do not always apply to other cases.

- Economic Case Study
    - The economic case study usually uses descriptive analysis along with quantification of costs and benefits of an R&D program and analyzes economic impact in terms of distribution of costs and benefits.
    - This type of study gives an in-depth and case-specific understanding of a project. There are two types of economic case studies, the retrospective study which uses historical data to estimate the past effects and the prospective study which is based on projected future effects.
    - This method is highly developed and most common in evaluating commercialized R&D projects.
    - The advantage of this method is its emphasis on ultimate impact rather than on immediate outputs alone. It also covers the effects of a program throughout its lifetime.
    - The approach also has some downsides. Sometimes it is not an easy task to quantify the impact of a project. Also, some benefits and costs cannot be measured in monetary terms.
    - Different methods involved in this method will be explored since this approach is used as one of the tools for the analysis in nuclear R&D evaluation.

- Econometric and Statistical Methods
    - This approach employs econometric model building techniques to estimate and perform hypothesis testing by using extensive historical data. Due to the complexity of R&D effects, the application of this method requires considerable care and skill. In fact identifying the corresponding variables and their relationship throughout the lifetime of an R&D project is not an easy task.
    - The advantage of this method is obvious; it empowers analytic evaluators with quantitative information. It also produces valuable information on the particular variables and parameters of a model which helps identify the quantitative importance as well as establishes sensitivity analysis for the value of the estimated parameters.

- o The main disadvantage is the fact that not all effects can be capture by pure and highly quantitative methods. Also, the results might not be very informative for some audiences who are not familiar with econometrics.

A.3 Economic Case Study: Methods and Implications

The economic case study usually employs monetary units of costs and benefits. Thus, the researcher should identify these units through the lifetime of a project. To adjust for the difference in time, and have a consistent base for comparison, one has to eliminate the effect of any price changes from the estimated cash amounts. The application of a "real discount rate" is the most common approach. An alternative approach is to use the current costs and benefits and then employ the "nominal discount rate" to adjust for the combination of opportunity costs and price changes.

There are a number of measures one can take to evaluate the costs and benefits of R&D expenditure. In fact these methods can be used to evaluate the project performance. The most common measures are as follows and will briefly be reviewed below:

- Net benefit measure
- Benefit-to-cost ratio
- Internal rate of return (IRR)
- Payback period

The net benefit measure is calculated as the difference between time-adjusted benefits and time-adjusted costs. If net benefit is greater than 0, the project is potentially desirable.

The benefit-to-cost ratio is also another measure for R&D performance. This ratio is calculated by dividing benefits by costs. It measures the benefit of $1 realized cost. If the ratio is greater than 1, there is an indication of a project's worthiness. In other words, a ratio greater than 1 means the benefits are greater than the costs.

The next measure is the internal rate of return (IRR). This is the interest rate which equates the streams of benefits and cost. The problem with this measure is that it might reveal more than one IRR equating the costs and benefits. The "non uniqueness" has its roots in the methodological defect of this approach. In particular; the assumption of a constant rate of return throughout the project life might not be an appropriate assumption. In this method, the rate of return in the initial stages of the project is assumed to be the same for every other stage. In spite of the possible drawbacks, in practice the rate of return is widely used as an indicator of project acceptability.

Payback period measures the required time for the accumulated discounted benefits to become sufficient to cover the discounted costs. This measure has its own shortcomings with its emphasis on the break-even point, rather than the net benefit of the whole project.

For most publicly funded projects, it is recommended to use the net benefit approach, supplementing it with the other measures when they are useful in defining the value of the activity being assessed.

A.4 Econometric and Statistical Method: Methods and Implications

The econometric and statistical method usually employs historical data and tries to quantify the mathematical relationship between input and output of an R&D project. Econometrics requires model building, estimation, and hypothesis testing. Model building is an essential part of any econometric evaluation procedure. The more complex the project, the more difficult it is to build an appropriate model which addresses all its aspects and impact. It is important to note that one cannot expect to capture all effects by means of the econometric and statistical methods. In fact these methods will add some analytical capabilities to evaluators. There are at least three distinct types of econometric methods when it comes to project evaluation, regression and correlation analysis, production function and productivity measurement, and macroeconomic modelling.

Regression analysis is based on estimating a linear or non-linear relationship between a set of dependent and independent variables. It uses historical data on dependent and independent variables to estimate the unknown coefficients in a model. For instance, a regression analysis can be used to test the effects of an increase in an R&D spending program on the numbers of patents issued by, say, the nuclear industry. One has to avoid drawing a conclusion that the regression analysis by itself can prove a cause-and-effect relationship. Instead it reveals the extent of a change caused by each variable.

The production function estimation is another form of evaluating an R&D program. A production function is a mathematical relationship between input and output of an economic system. Through econometric analysis the R&D production function can be estimated and at the same time, the effectiveness of R&D spending be measured. The problem with this approach is that the form of the production function is unknown and there is no agreement on its exact specification among economists.

The third method in using an econometric approach is to construct a macroeconomic model based on national input-output tables, using the structural equations to model the economic relationships and study the effects of an R&D program on increasing productivity or product innovations. This method requires extensive effort to construct the fundamental equations and estimation of these equations, which in most cases is not a feasible option for specific programs.

A.5 Canadian Nuclear R&D Evaluation, Methodology

To evaluate economic effects of nuclear R&D in Canada, CERI will employ the economic case study method and emphasize the benefit-to-cost ratio. In doing so the logic method approach is used to identify the costs and benefits for nuclear R&D. Table A.1 is an itinerary sketch of the logic model for nuclear R&D in Canada. This matrix will be used to quantify the cost and benefits for each year of the nuclear industry in Canada according to data availability.

Table A.1
The Logic Model for the Canadian Nuclear R&D Program Evaluation

Resources	Activities	Outputs	Consumers reached	Outcomes
R&D spending including AECL, NRC, COG, MDS Nordion and private companies	Basic research	Research labs	Federal and private researchers	New generation of CANDUs
	Fund grants	CANDU reactors	Power plants	Technological support
	Technical assistance	# of swards	Nuclear-related manufacturing firms	Cost efficiency in building new CANDUs
	Training staff	Medical isotopes	Universities	Cost efficiency in electricity generation
	Construction of CANDU	Graduate programs	Electricity users	New medical isotopes
	Refurbishment of CANDU	Papers published	Hospitals	Contracts for refurbishments
	Life extension of CANDU	Nuclear electricity generation	Patients receiving nuclear treatments	Contracts for life extensions
	Design research labs	Research reactors	Foreign countries received nuclear products and services	New staff training
				More basic research

A.5.1 The Logic Model

The logic model has been a tool for program evaluators over the past 25 years. McLaughlin and Jordan[72] claim that the logic model provides a solid base to evaluate the expected performance of a program under certain conditions. Wholey[73] identifies the elements of the logic model as resources, activities, outputs, consumers reached, and outcomes. Wholey, Rush and Ogborne,[74] Jordan and Mortensen[75] among many others apply the logic model to measure and evaluate program performance.

According to McLaughlin and Jordan, the benefits of employing the logic model include:

- Providing a conclusive understanding of the program, expectations for the resources and outcomes.
- Helping to design the program or to improve and modify.
- Identifying goals and limitations along with inconsistent linkages among program elements.
- Identifying the key performance measurement points which improve data collection and help the evaluation process.

As mentioned before, there are at least five components for a logic model: resources, activities, outputs, consumers reached, and outcome.

Resources include financial and human along with any others necessary to support the program. Activities consist of those steps required to produce program outputs. Outputs are the direct goods and services produced for consumers of the program. Montague[76] added the concept of "consumers reached" to the logic model to identify the users of a product or services from the program; this enables the program's evaluator to identify conclusions and the population groups the program intends to serve. Outcomes are the changing of benefits resulting from activities and outputs. The changes and benefits are normally sequential and take place over the lifetime of the program.

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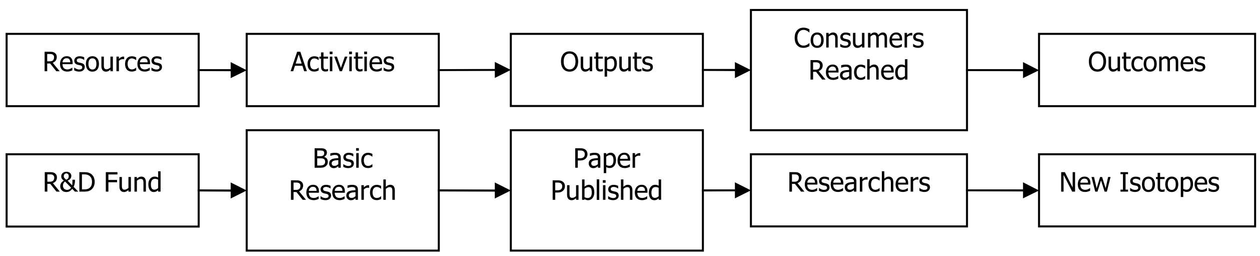
[72] McLaughlin, J. and G. Jordan. "Logic models: A tool for telling your program's performance story." *Evaluating and Program Planning*, 22, 1999, p. 65–72.
[73] Wholey, J. "Evaluability assessment: Developing program theory." In L. Bickman, (ed.), *Using Program Theory in Evaluation, New Directions for Program Evaluation*. San Francisco, CA: Jossey-Bass Publishers, 1987, p. 77–92.
[74] Rush, B. and A. Ogborne. "Program logic models: Expanding their role and structure for program planning and evaluation." *The Canadian Journal of Program Evaluation*, 6 (2), 1991.
[75] Jordan, G. and J. Mortensen. "Measuring the performance of research and technology programs: A balanced scorecard approach." *Journal of Technology Transfer*, 22 (2), 1997, p. 13–20.
[76] Montague, S. *The Three Rs of Performance: Core Concepts for Planning, Measurement, and Management*. Performance Management Network Inc., 1997.

Figure A.1 illustrates a logic model for the Canadian nuclear R&D program. This logic model is the basis for CERI's evaluation procedure.

To clarify the nuclear R&D logic model in Table A.1, see Figure A.1, in which the logic behind the elements of the logic model becomes clearer.

For each item in the logic model, a linkage as in Figure A.1 can be established. This logic will help determine the exact relationships between the resources and the final outcomes when evaluating the performance of the R&D program.

Figure A.1
The Logic Model Linkage with an Example



A.5.2 Measuring Performance

Measuring performance is the second piece in the evaluation procedure. In fact the logic model establishes the basis for the measurement to take place. The depth of the measurement analysis depends on data availability and the scope of the evaluation program. According to Weiss,[77] the measurement should "track the steps of the program." In the logic model each cell indicates the step and each arrow, connecting the cells, represents the hypothesized linkages or causal relationships among the steps. In fact, McLaughlin and Jordan claim that the logic model provides the hypothesis of how the program is supposed to work to achieve intended results.

The approach taken is to use the economic case study method to evaluate the R&D program. Therefore, the costs and the benefits of nuclear R&D spending must be identified. The logic model in Figure A.1 enables the identification of this information throughout the lifetime of the program. The costs of the program appear under "resources" in the logic model. Measuring the benefits of the R&D program is not an easy task. The crucial step is to identify the extent of the evaluation procedure. The benefits can be seen as the outputs and/or the outcomes in the logic model.

[77] Weiss, C. *Evaluation*. 2nd Edition, Upper Saddle River, NJ: Prentice Hall, 1998.

A.5.2.1 Cost-Benefit Analysis

As stated earlier, CERI uses the economic case study analysis to evaluate the Canadian nuclear R&D program. In doing so, CERI uses the logic model approach and follows the following three steps:

1. Calculate the total cost of the program.

2. Determine the benefits of the program and place a dollar value on those benefits.

3. Calculate the desired indicator: benefit-to-cost ratio, net present value, or internal rate of return.

From an economic point of view, for each dollar spent on the nuclear R&D program, the federal government (or any other entity which supports this program) has a choice of alternative investment. In particular, the opportunity cost of every dollar spent on the program should be taken into consideration in the evaluation procedure. In order to incorporate the concept of opportunity cost, CERI adopts the usual practice and employs present value analysis which converts all program costs and benefits to their present value at the end of the evaluation year, say 2006.

The opportunity cost to supporting entities is the real rate of return, available to that entity each year. The net present value (NPV) in year 2006, can be expressed by the following formula:

$$PV(B)_T = (B_0) * (1 + r_0)^T + (B_1 \ ) * (1 + r_1)^{T-1} + ... + (B_T)$$

$$PV(C)_T = (C_0) * (1 + r_0)^T + (C_1 \ ) * (1 + r_1)^{T-1} + ... + (C_T)$$

B_i and C_i are the benefits and costs incurred in year i respectively. T is year 2006 and r_i is the real rate of return available in year i.

It is important to note that the costs and benefits are in real terms. Also, the nominal costs and benefits have been adjusted by inflation rate. The real rate of return, r, is also adjusted for inflation.

This analysis is very sensitive to the choice of the real rate of return, i.e. the discount rate.

A.5.2.2 Measuring Benefits

As mentioned before, the outputs column in the logic model has been used to identify the benefits. Below is an explanation of how to calculate the benefits from the outputs in the logic model and put dollar values on those benefits.

Like any other industry, the nuclear industry uses different resources to produce outputs. The outputs can be categorized into two different products, new outputs and ongoing outputs. The new outputs are those that have been produced for the first time in the industry. The ongoing products are those that were developed in the past and experience continued production by industry. Following this terminology, it can be argued that the new products are the results of the R&D programs. For the ongoing outputs, the efficiency increase of the production process is the result of such programs. Thus, the benefits of the nuclear R&D program can be seen in terms of the new products and the efficiency increase of the ongoing outputs.

CERI maintains that the difference between the cost of production and the market value for a new product is the economic benefit of the R&D program. In the same line, any decrease in the cost of production for the ongoing outputs would be the benefits for R&D spending. In particular, new and ongoing products in the Canadian nuclear industry are tracked since 1954. If there is any new output in a particular year, the difference between the cost of production and the market value will be considered as a benefit of the R&D program in the particular year. For the ongoing outputs, the cost of production has been tracked and if any decrease in the cost is observed, it will be considered a benefit of the R&D spending.

Following this methodology, there is a time series of R&D benefits which are used to calculate the present value of the benefits for year 2006.

A.5.2.3 <u>Measuring Costs</u>

In the logic model for the nuclear R&D program, the resources column includes those inputs that are directly used as resources. In particular, the federal government and other entities' spending on nuclear R&D programs are considered a resource. This simplification allows the tracking of costs in a consistent manner. Adjusting the spending in each year according to the inflation rate makes a series of real costs over the period of study, 1954–2006. The next step is to calculate the present value of the costs using the sample formulation to calculate this present value of the benefits.

A.5.2.4 <u>Benefit-Cost Ratio</u>

As the present values of benefits and costs are calculated, the final step of reporting the desired indicator, such as the benefit-cost ratio, comes about. For economically beneficial programs, this ratio should be greater than 1. In this case, the real present value of benefits would be greater than the real present value of costs respectively. If the program is uneconomic, then this ratio would be less than one.

It is of interest to note that the benefit-cost ratio is a tool to calculate the economic costs and benefits of a program. It is obvious that most R&D programs, like nuclear R&D, have greater impact on society, the environment, politics, geopolitics and the security of a country. Measuring the costs and benefits of these impacts is beyond the scope of this study, despite their importance in the process of decision making from policy makers' and politicians' points of view.

A.6 Quantitative Analysis

This part lays out the quantitative evaluation of nuclear research and development in Canada. CERI's approach is to evaluate the benefits and costs associated with nuclear R&D in Canada, based on the logic model discussed earlier. In doing so, the evaluation begins in 1954 with the early days of the Canadian nuclear industry, and assumes that R&D spending ends in 2006, while benefits continue for several more decades. The rationale for this approach is a simple one: if spending stops on nuclear R&D, benefits from the investments that have been made in the past will continue.

The next section quantifies R&D spending in the nuclear industry, followed by a discussion of the benefits from this spending. Such benefits include opportunities for AECL — as measured by non-R&D cash flows, and lowering the costs of nuclear electricity generation, among others. The measurement of total benefits and costs is the subject of the subsequent section, and the final section reports the results of the cost-benefit analysis.

A.6.1 R&D Spending

The R&D funds received by AECL, COG and NRC from 1954 to 2006 are used to calculate R&D spending in the Canadian nuclear industry. Using 2003 prices, the constant-dollar (real) values of these expenditures can be calculated in each year.

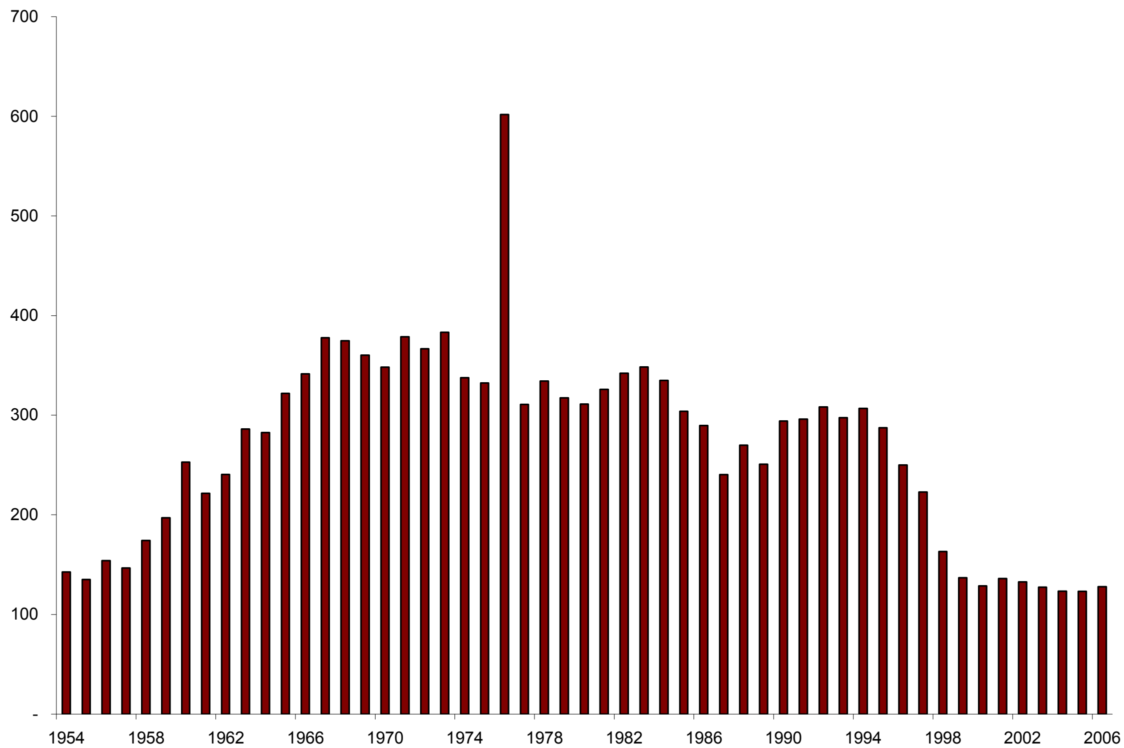
The total real value of R&D spending in each year is the sum of the amounts reported by these three organizations converted to Canadian dollars of 2003 purchasing power. Figure A.2 shows real R&D spending for the period of 1954 to 2006.

A.6.2 AECL Benefits

Using the logic model previously discussed, AECL cash flows can be identified to calculate the benefits of the R&D spending accruing to this organization. In general, there are two kinds of outputs in AECL: the services provided to Canadian customers (domestic sales) and the exports. It can be argued that the benefit from R&D is the difference between the value of these outputs and their associated costs, because without R&D those transactions would not have taken place. AECL's annual reports identify the revenue generated in domestic sales and exports. Because costs associated with exports and domestic sales are not separately identified in the annual reports, the cost-revenue ratio[78] has been used to allocate those costs. Net export revenues are then used as the measure of benefit from R&D associated with AECL's exports. In fact the simple assumption is applied that the net value added in the export sector is derived from investment in R&D.

[78] The total commercial revenue has been divided by total cost to calculate this ratio.

Figure A.2
Real R&D Expenditure
(millions of 2003 dollars)

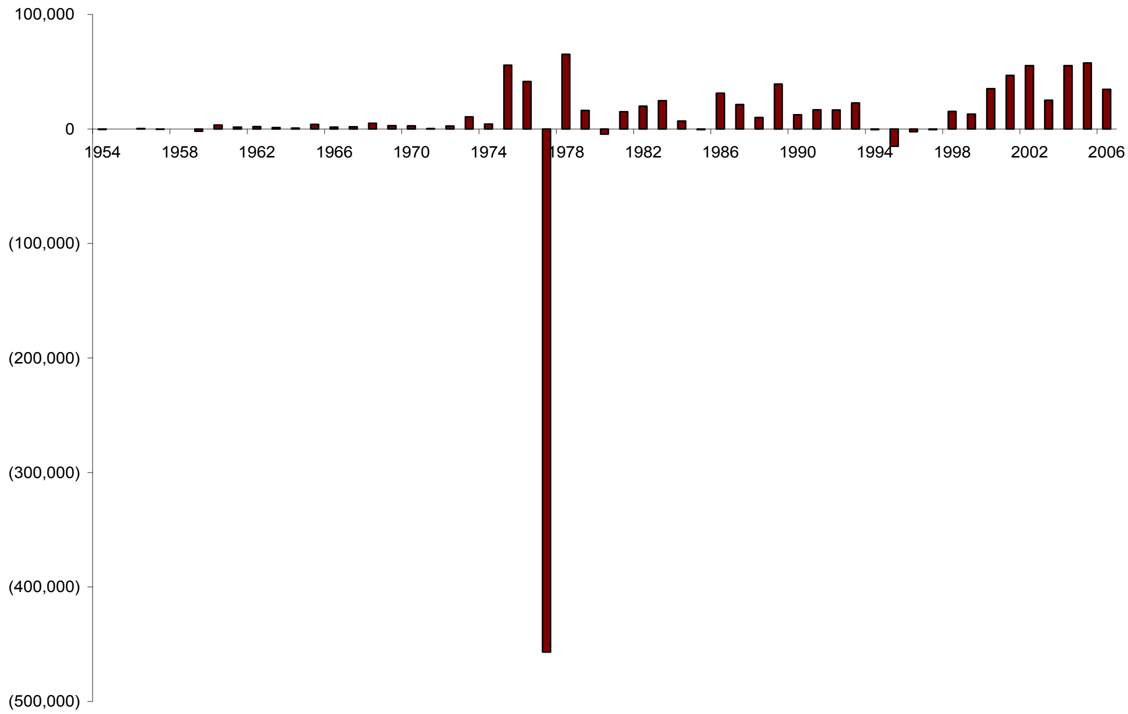


Source: AECL Annual Reports.

The same method is used to determine the domestic benefits. Using AECL annual reports, the net domestic benefit are calculated as the difference between the commercial revenue and cost. The total benefit, then, is the sum of the domestic benefit and export benefits in each year. Figure A.3 presents R&D benefits in AECL expressed in 2003 dollars.

In principle, one should treat non-R&D capital outlays in such an analysis as cash flows required to reap benefits from commercial operations. The data available did not permit this. The depreciation of non-R&D expenses included in the accounting version, however, captures part of this cost in an implicit fashion. The benefit stream present value, incorporating an incomplete treatment of non-R&D capital outlays, is somewhat overstated. However, this affects a relatively small portion of the benefits included in the analysis. The lion's share of benefits is attributable to generation cost savings — discussed in Section A.6.3 below. In almost every year, the generation benefits exceed the benefits to AECL by one or two orders of magnitude. The bias associated with treatment of non-R&D capital outlays is therefore small.

Figure A.3
Real Benefits Accruing to AECL
(thousands of 2003 dollars)*



* In 1976 there was a one-time extraordinary loss in foreign commercial operations.

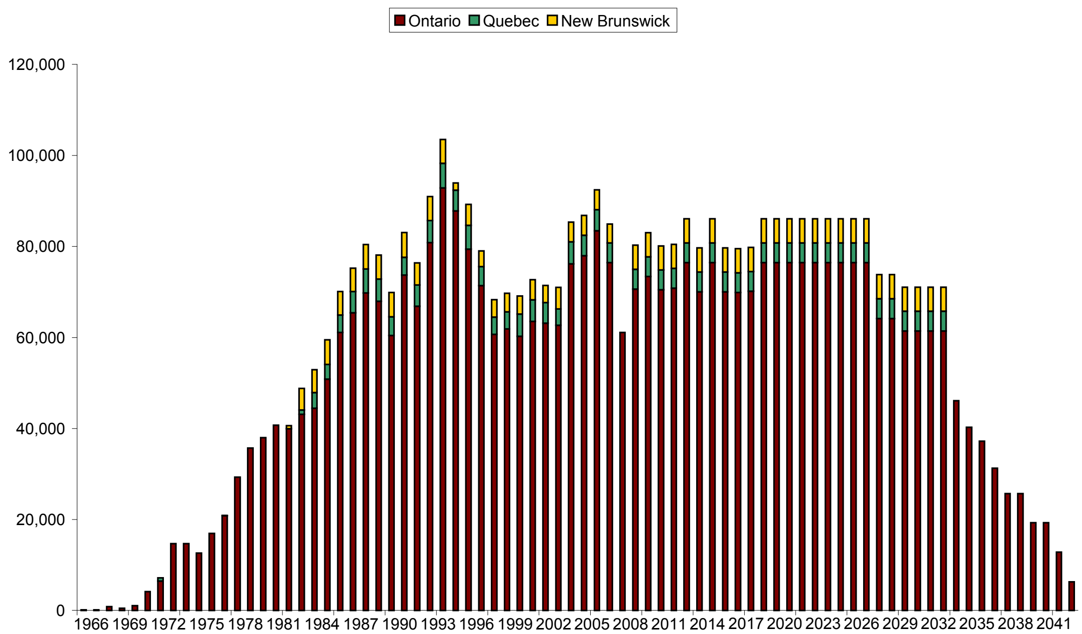
A.6.3 Electricity Benefits

The International Atomic Energy Agency (IAEA) database[79] is used to calculate electricity generation in Canada, supplemented with Statistics Canada data prior to 1970. The IAEA database has detailed information on the history, capacity, output and load factor for each power plant in Canada. The information on electricity generation and load factor for each nuclear power plant and for the national fleet is extracted from this database. Canada's first commercial nuclear electricity was generated in Ontario in 1968. Some nuclear units constructed since then have been retired or laid up, but most are still in service. For those plants that are operating it is assumed that they are refurbished in their 25th year of operation, stop generating for one year during refurbishment, and then resume operating for another 25 years. Since the data end in 2006, it can be assumed that each unit's 2006 output will be sustained in every subsequent year until retirement, except for the refurbishment year.

[79] www.iaea.org/programmes/a2/index.html (accessed June 26, 2008).

If there were to be no further investment in nuclear power construction in Canada after 2006, the current plants with one-time refurbishment in their 25th year of operation would produce electricity until 2033 in New Brunswick and Quebec, and 2043 in Ontario. Figure A.4 depicts actual electricity generation for Canada and these provinces from 1970 to 2006 and projected generation for the years 2007 to 2043.[80]

Figure A.4
Nuclear Generation by Province
(MWh)



Source: Statistics Canada; IAEA

The study assumes that the nuclear R&D benefit to electricity generation is the cost savings associated with nuclear electricity generation. In particular, the cost saving is the reduction in the cost of generation that has occurred in the Canadian economy due to employing nuclear technology, rather than relying on coal or natural gas. To quantify these benefits, the Levelized Unit Energy Cost (LUEC) approach is applied to estimate cost savings. LUEC is defined as the discounted average unit cost of producing electricity from a power plant. It takes into account the total discounted cost of producing the energy and the total amount of energy produced over the life of the plant, and distributes these costs over the anticipated operating life of the station. Canadian data in 2003 dollars has been used for the LUEC of nuclear, natural gas (combined cycle) and coal generation based on 5 percent and 10 percent real discount rates[81] as reported by the International Energy Agency. The results, converted to Canadian dollars, are summarized in Table A.2.

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[80] The analysis does not include the return of Bruce 1 and 2 to operation after their refurbishment.
[81] International Energy Agency. *Projected Costs of Generating Electricity, 2005*.

Table A.2
IEA's LUEC Comparison of Coal, Natural Gas and Nuclear Generation in Canada

Discount Rate	Fuel	Investment	Op/Mtce	Fuel	Total LUEC
		2003 dollars per megawatt-hour			
5%	Coal	14.6	8.7	17.1	40.5
	Gas	6.9	3.4	41.8	52.1
	Nuclear	17.6	11.6	4.7	33.8
10%	Coal	27.9	8.7	17.0	53.6
	Gas	11.6	3.4	412.8	56.8
	Nuclear	32.0	11.6	4.7	48.3

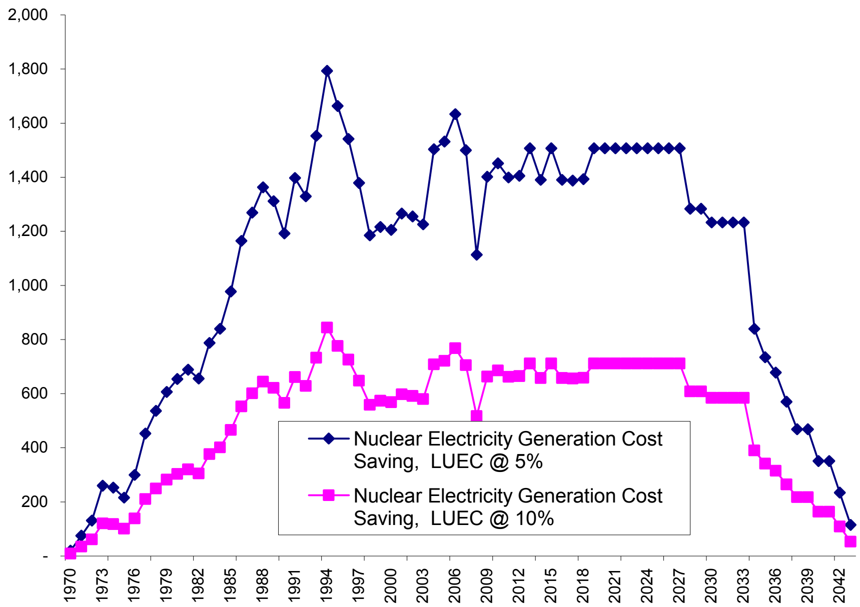
The generation cost saving associated with nuclear electricity generation is found by applying the following formula:

$$CS^{t} = (LUEC_{Alternative} - LUEC_{Nuclear})E_{Nuclear}{}^{t}$$

where CS^{t} is the cost-saving at time t, $LUEC_{Alternative}$ is the LUEC for the best alternative to nuclear generation[82] and $E_{Nuclear}$ is nuclear energy generation. Figure A.5 depicts the real cost savings due to nuclear electricity generation in Canada from 1970 to 2043 in 2003 constant dollars. As discussed earlier, for years beyond 2006, estimated electricity was used.

[82] It is assumed that coal generation is the best alternative in New Brunswick, while gas generation is taken to be the best alternative in Quebec, where coal has never been used. Gas generation was not available in New Brunswick until recently. Although gas has never been used to generate electricity on a large scale in Quebec, it was taken as the alternative since hydro costs are highly site-specific and therefore lack reliability. Although coal would actually be cheaper than gas in Ontario on a LUEC basis, the assumption that coal would have been used in the absence of nuclear implies a quadrupling of coal-fired generation in 2004, for example, relative to what actually occurred. Given Ontario's commitment to phasing out coal, it appears unlikely that coal would have been allowed to take nuclear's place.

Figure A.5
Nuclear Electricity Generation Cost Saving
(millions of 2003 dollars)



A.6.4 Total Benefits

In each year, the total benefit of R&D spending is the sum of cost-saving benefit from nuclear electricity generation and the AECL benefit. The price index is employed to calculate values of these benefits in dollars of 2003 purchasing power. Since a dollar spent in year 1954 has a different value than, say, a dollar spent in 2000, these outlays in dollars of constant purchasing power have been expressed before applying a discount factor to take into account the time value of money. The following formula calculates the future values of the benefits acquired between 1970 and 2006 and the present values of the benefits that are expected to happen from 2007 to 2043 — with all of these values adjusted to a 2003 reference year:

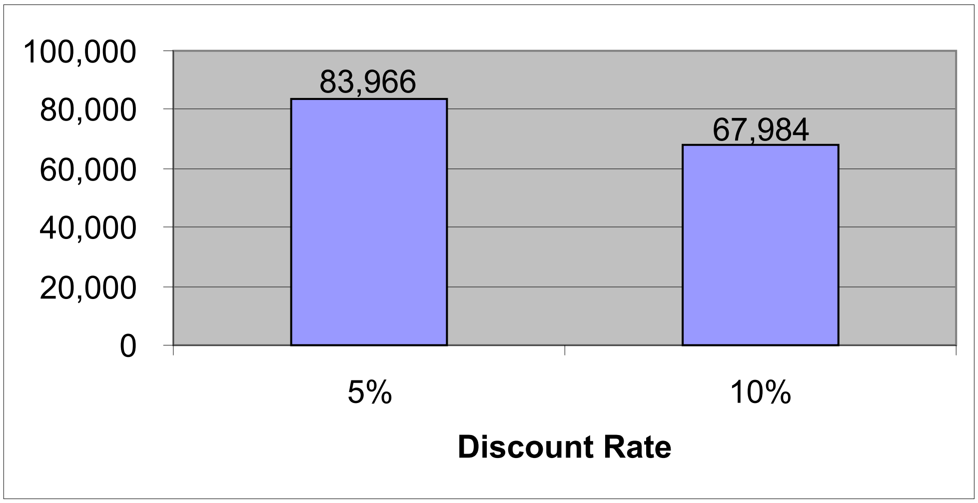
$$FV_T = PV_t(1+r)^{T-t}$$

where FV_{T-t} is the value at reference date T=2003, PV_t is the present value of the cost saving at time t when generation occurs and r is the real discount rate of 5 percent or 10 percent,[83] as employed by the IEA in its LUEC calculations.

[83] The nominal Government of Canada bond yield has been volatile in this period. It increased from 3 percent in the 1950s to almost 13 percent in the mid-1980s. It then dropped to about 5 percent in the 1990s and has recently dropped below 4.5 percent. What counts for the purposes of selecting a real discount rate is the real or inflation-adjusted yield. The most recent yield on federal government "real return" bonds is 2.05 percent, compared to the 4.42 percent yield on ordinary long-term market-issue federal government bonds, a difference of more than two percentage points. The generating utilities are shareholder-owned companies and Crown corporations. The long-term nominal yield on corporate bonds is 5.82 percent, or 1.4 percentage points higher than on federal government market issue bonds. The real return on long-term corporate bonds can therefore be estimated to be about 3.5 percent. As for Crown corporations, the applicable long-term nominal yield is on provincial bonds, coming in at 5.07 percent or 0.65 percentage points higher than equivalent federal bond yields. Thus the real yield on provincial government bonds is about 2.7 percent. A shareholder-owned utility typically would have a

The total real discounted R&D benefit is then calculated as the sum of the real discounted R&D benefits in each year, during 1954 to 2043. Figure A.6 shows these benefits at 5 percent and 10 percent discount rates.

Figure A.6
Present Value of Benefits to 2003 from Nuclear Research and Development (millions of 2003 dollars)



A.6.5 Total Cost

The cost of nuclear R&D spending in a given year is converted to 2003 dollars of purchasing power, and then compounded at 5 percent and 10 percent annual rates to the reference year 2003, using the future value formula described above; the results are shown in Figure A.7.

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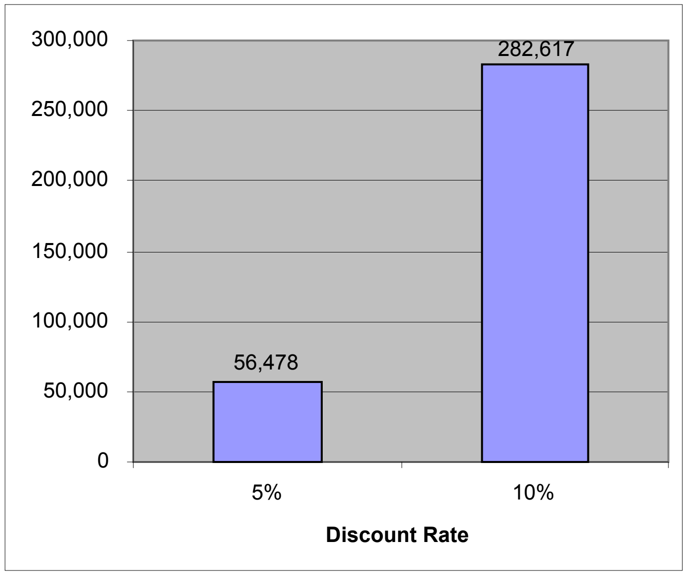
capital structure consisting of about two-thirds debt and one-third equity. Allowed return on equity for Ontario utilities is currently about 8.5 percent nominal, or 6.1 percent real. In order to pay for the corresponding income taxes at a combined federal/provincial rate of 36.1 percent, the ratepayers would have to pay correspondingly more: about 9.6 percent real. Thus the required real return on rate base for ratepayers of an investor-owned utility is estimated to be two-thirds of 2.7 percent plus one-third of 9.6 percent, or 5.0 percent. For ratepayers of a Crown corporation, the required real return on rate base is lower, both because the interest rate on debt is lower and because there are no income taxes to pay. From a residential ratepayer's perspective, the main point of contact with financial markets is in residential mortgages. Long-term mortgages are currently available at an interest rate of about 7 percent nominal, or close to 5 percent real. The conclusion is that an appropriate real discount rate for comparing generation alternatives today would be 5 percent or somewhat less. In the past, real interest rates tended to be somewhat higher. On the other hand, all of Canada's nuclear power plants were built under Crown corporation ownership; even today Bruce Power is the lessee of the Bruce power plant owned by Ontario Power Generation, a Crown corporation.

Figure A.7
Present Value to 2003 of Nuclear Research and Development Costs
(millions of 2003 dollars)



A.6.6 Cost-Benefit Analysis

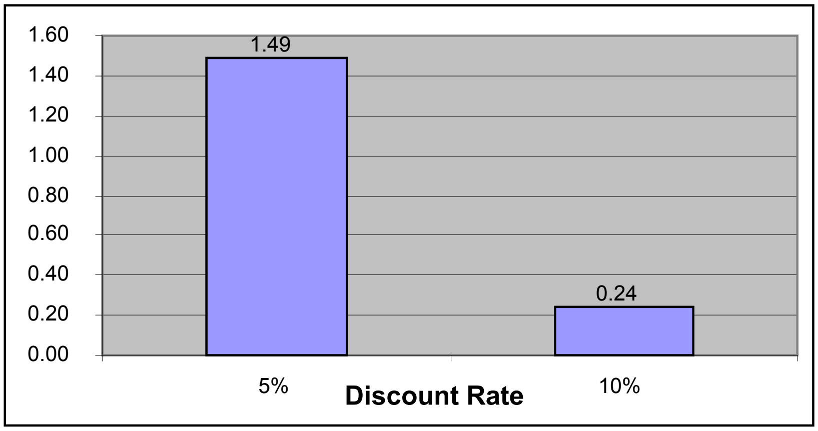
The last part of this analysis relates the benefits of nuclear R&D to the costs, in the form of a benefit/cost ratio. Since cost and benefits are both expressed in dollars of reference year 2003, the calculation of this ratio is straightforward. The benefit-cost ratios calculated in this manner are shown in Figure A.8 and Table A.3. It is CERI's position that a 5 percent discount rate and a comparison of nuclear with natural gas in Ontario are most appropriate, but the corresponding figures for nuclear-versus-coal in Ontario and the use of a 10 percent discount rate are shown for comparative purposes. CERI has estimated the discount rate that obtains a benefit/cost ratio of 1: this number falls within a range of 5.8 to 6.9 percent.[84]

Table A.3
Ratio of Discounted Benefits to Discounted Costs

Discount Rate	5%	10%
Coal as Ontario's nuclear alternative	0.60	0.16
Natural gas as Ontario's nuclear alternative	1.49	0.24

[84] As IEA calculations are available only for the discount rates of 5 percent and 10 percent, the range for the discount rate has been estimated.

Figure A.8
Benefit/Cost Ratio for Nuclear Research and Development



Although CANDU generating units constructed abroad in recent years have come in on or ahead of schedule and on or under budget, a long-term resident of Ontario who is aware of the historical cost overruns, particularly at Darlington, may wonder how those overruns have been incorporated into the analysis. Those cost overruns, amounting to billions of dollars, have been traced to a number of causes, of which cost estimation procedures are relatively unimportant.[85] Irrespective of cause, however, cost overruns are still costs, and they serve to reduce the historical benefit from the lowering of generation costs. The LUEC procedure described above is based on design numbers, so cost overruns beyond the cost engineer's contingency provisions are not formally incorporated. Even so, it is appropriate in a retrospective analysis to look at the treatment of not just capital costs but fuel costs as well in judging whether, all things considered, prospective future costs from a LUEC analysis are a reasonable way of gauging past costs. Historically, the difference in unit fuel costs between natural gas and nuclear was generally larger than the $37.09 per MWh difference in fuel costs between nuclear and natural gas derived from the IEA's LUEC analysis, as illustrated in Table A.4.

[85] Various estimates of the capital cost of the Darlington nuclear power plant were made along the way. In 1981, with engineering work 15 percent completed, a "definitive estimate" of $7.4 billion was announced. The final cost came to $14.4 billion. The manifold reasons for the $7 billion in subsequent cost overruns are described in A. Nixon's paper *The Canadian Nuclear Power Industry*, available online at http://dsp-psd.pwgsc.gc.ca/Collection-R/LoPBdP/BP/bp365-e.htm (accessed June 26, 2008); and J. Whitlock's paper *Why Was the Cost of Ontario's Darlington Plant So High?* available online at www.nuclearfaq.ca/cnf_sectionC.htm#darlington

Table A.4
Historical Fuel Cost Differentials: Natural Gas versus Nuclear

Year	Natural gas fuel cost ($/MWh)	Nuclear fuel cost ($/MWh)	Fuel cost differential ($/MWh)	Fuel cost differential (2003 $/MWh)
1975	10.17	0.94	9.23	32.75
1980	31.03	2.64	28.39	66.24
1985	83.52	4.97	78.55	128.16
1990	63.84	5.27	58.57	76.81
1995	26.97	1.93	25.05	29.40
2000	42.25	2.34	39.91	43.00
2003	54.43	2.00	52.42	52.42
2004	35.87	2.00	33.87	33.26

In discussions of the role of nuclear while Darlington was under construction, the fuel savings from nuclear units already in operation at that time are often overlooked. Based on the unit fuel costs recorded by Statistics Canada, it can be estimated that during the period 1979 to 1988, when Darlington was constructed and before it generated any electricity, the generation of electricity from nuclear units then in service saved $27.6 billion in fuel costs (computed in dollars of the day, not 2003 dollars) relative to the natural gas alternative. The equivalent estimate of fuel saving from the IEA's LUEC costs, adjusted downward to reflect the general price levels prevailing in those years is $9.5 billion. The $18.1 billion underestimate of historical fuel costs inherent in the IEA fuel costs clearly outweighs the Darlington capital cost overrun. The estimates of benefits in Figure A.6 and the benefit/cost ratios of Figure A.8 are therefore conservative.

About CERI

The Canadian Energy Research Institute (CERI) is a co-operative research organization established through an initiative of government, academia, and industry in 1975. The Institute's mission is to provide relevant, independent, objective economic research and education in energy and related environmental issues. Related objectives include reviewing emerging energy issues and policies as well as developing expertise in the analysis of questions related to energy and the environment.

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