The Centre for International Governance Innovation

NUCLEAR ENERGY FUTURES PAPERS

The Nuclear Energy Futures Project

Uranium Enrichment in Canada

David P. Jackson and Kenneth W. Dormuth

Nuclear Energy Futures Paper No. 5
May 2009

An electronic version of this paper is available for download at:
www.cigionline.org

Abstract

The environment surrounding nuclear power production is changing around the world, including in Canada. This paper discusses the Canadian mining of uranium, its subsequent processing, current enrichment technologies and the capital and operating costs of a modern centrifuge enrichment plant. On the basis of these reasoned estimates based on publicly available information, it is expected that enrichment in Canada is likely to be more profitable than exporting natural uranium and buying back enriched uranium. Assuming that an environmentally and socially acceptable enrichment site is selected, this report asserts that an environmental assessment would be unlikely to find significant adverse effects.

Canadian Centre for Treaty Compliance

CIGI's Nuclear Energy Futures Project is being conducted in partnership with the Centre for Treaty Compliance at the Norman Paterson School of International Affairs, Carleton University, Ottawa.

ISSN 1919-2134

Letter from the Executive Director

On behalf of The Centre for International Governance Innovation (CIGI), it is my pleasure to introduce the Nuclear Energy Futures Papers Series. CIGI is a non-partisan think tank that addresses international governance challenges and provides informed advice to decision makers on multilateral governance issues. CIGI supports research initiatives by recognized experts and promising academics; forms networks that link world-class minds across disciplines; informs and shapes dialogue among scholars, opinion leaders, key policy makers and the concerned public; and builds capacity by supporting excellence in policy-related scholarship.

CIGI's Nuclear Energy Futures Project is chaired by CIGI Distinguished Fellow Louise Fréchette and directed by CIGI Senior Fellow Trevor Findlay, Director of the Canadian Centre for Treaty Compliance at the Norman Paterson School of International Affairs, Carleton University, Ottawa. The project is researching the scope of the purported nuclear energy revival around the globe over the coming two decades and its implications for nuclear safety, security and nonproliferation. A major report to be published in 2009 will advance recommendations for strengthening global governance in the nuclear field for consideration by Canada and the international community. This series of papers presents research commissioned by the project from experts in nuclear energy or nuclear global governance. The resulting research will be used as intellectual ballast for the project report.

We encourage your analysis and commentary and welcome your thoughts. Please visit us online at www.cigionline.org to learn more about the Nuclear Energy Futures Project and CIGI's other research programs.

John English
Executive Director

Introduction

There is a rapidly changing environment for nuclear power production internationally, including in Canada. Until recently, it was anticipated that nuclear generation worldwide would decline towards the latter half of the century as aging nuclear reactors went out of service without replacement. However, concerns about greenhouse gas emissions, high oil prices and energy security have caused a major change in outlook, with projected increases in nuclear power production worldwide.[1] This in turn is likely to lead to increased demand for uranium.

Almost all of the world's 440 operating power reactors are of the thermal type, producing energy primarily by fission of the fissile uranium isotope U235. Most of these are Light Water Reactors (LWRs) requiring enriched uranium fuel to operate. Naturally occurring (natural) uranium as mined contains only 0.7 percent U235, the remainder being U238. Typically, for LWRs the U235 content needs to be between 3.5 and 4.5 percent. Some nuclear reactors, such as the CANDU (Canada Deuterium Uranium) reactor design of Atomic Energy of Canada Limited (AECL), use natural uranium for fuel. However, AECL is now marketing its next generation design, the Advanced CANDU Reactor (ACR), which also requires enriched uranium; so the use of natural uranium fuel in power reactors could be expected to decline as new reactors replace older ones.

Canada is at present the world's largest producer of uranium. Canada does not have uranium enrichment plants and hence, the uranium exported is not enriched. Enriched uranium is a value-added product that generally appears to be more profitable to export than natural uranium. In addition to a potential export market, there is likely to be an increasing Canadian domestic requirement for enriched uranium fuel. For example, Ontario (Howlett, 2008a) has initiated a procurement process for new reactors at Darlington, and New Brunswick Power has indicated interest in a new build at Point Lepreau. All the reactors being considered would use enriched fuel.

This report addresses the feasibility of enriching uranium in Canada. We first review uranium mining and the various steps in its subsequent processing. Enrichment technologies of three types are outlined and the capital and operating costs of a modern centrifuge enrichment plant estimated.

[1] The 2008 reference case of the United States Energy Information Administration projects global electricity generation to increase by 2.6 percent per year, from 17.3 TWh in 2005 to 33.3 TWh in 2030 (DOE, 2008). Electricity generation from nuclear power plants worldwide is projected to increase at an average rate of 1.4 percent per year, from 2.6 TWh in 2005 to 3.8 TWh in 2030. Over the next 20 years, China's and India's nuclear capacities are projected to increase at an average annual rate of 8.8 percent and 9.4 percent, respectively. The United States Nuclear Regulatory Commission (NRC), for example, is expecting to have applications for 34 or more new reactors by the end of 2010 (NRC, 2008).

Author Biographies

David Jackson

After a career as a research scientist, David Jackson served as director of Canada's National Fusion Program. He now sits on several International Energy Agency (IAEA) committees, was a technical reviewer for the Intergovernmental Panel on Climate Change's most recent report, is a past president of the Canadian Nuclear Society, a consultant to the IAEA, and former acting director of the McMaster Institute for Energy Studies. He currently consults for Natural Resources Canada, the Nuclear Waste Management Organization, and Sustainable Development Technology Canada, teaches energy courses in McMaster University's Department of Engineering Physics, and coauthored the book *Half Lives: a Guide to Nuclear Technology in Canada* (Oxford University Press, 2009).

Kenneth W. Dormuth

Ken Dormuth holds a PhD in theoretical physics from the University of Alberta and has more than 35 years experience in science and technology related to energy and the environment. He joined Atomic Energy of Canada Limited (AECL) in 1971, working in the areas of reactor physics, nuclear fuel cycle analysis, and environmental transport of radioactive materials. Eventually, he led the development of a risk assessment methodology for the geological disposal of radioactive waste. From 1994 to 1998, he was director of AECL's Nuclear Fuel Waste Management Program, responsible for leading AECL's participation as proponent in the public environmental review of its concept for nuclear fuel waste disposal. He retired from AECL in 2007 as director of Environmental and Radiological Sciences.

Uranium in Canada

Canada's uranium production in 2007 was 11,180 tonnes (U3O8) of which 9,476 tonnes was uranium metal. This is about 23 percent of world output (see Table 1). Canada's uranium ore reserves are about 9 percent of the world total with Australia's reserves around twice as large. The two big Canadian players in uranium are Cameco Corporation and AREVA Resources Canada Ltd.

A Cameco plant at Blind River, Ontario refines uranium oxide concentrate, yellowcake, to produce UO3 which is then processed at Port Hope, Ontario. The yellowcake comes from Canadian and foreign mines. The Port Hope plant converts about 80 percent of the Blind River output to UF6 which is then exported for enrichment elsewhere. The other 20 percent is reduced to UO2 for natural (unenriched) CANDU fuel. Zircatec Precision Industries (acquired by Cameco in 2006) at Port Hope and GE-Hitachi in Peterborough make CANDU fuel using about 1,900 tonnes of uranium per year in the form of UO2 fuel pellets.

Table 1: Uranium Production (tonnes U)*

Country	2002	2003	2004	2005	2006	2007
Canada	11,604	10,457	11,597	11,628	9,862	9,476
Australia	6,854	7,572	8,982	9,516	7,593	8,611
Kazakhstan	2,800	3,300	3,719	4,357	5,279	6,637
Russia (est.)	2,900	3,150	3,200	3,431	3,262	3,413
Niger	3,075	3,143	3,282	3,093	3,434	3,153
Namibia	2,333	2,036	3,038	3,147	3,067	2,879
Uzbekistan	1,860	1,598	2,016	2,300	2,260	2,320
USA	919	779	878	1,039	1,672	1,654
Total world	36,063	35,613	40,251	41,702	39,429	4,1279

*only the largest producing countries are shown.
Source: World Nuclear Association, 2008

In 1931 Gilbert Labine found pitchblende, a type of uranium ore, at Great Bear Lake, in the Northwest Territories. At that time the only interest in uranium ore was as a source of radium for medical applications and luminous dials. The radium market was sufficient to initiate a mine at Port Radium, Northwest Territories and later a radium refinery at Port Hope, Ontario.

During the Second World War, the Port Radium mine was nationalized, becoming Eldorado Nuclear, a crown company. The demand for uranium in the years following the war led to the development of additional uranium mines in Bancroft and Elliot Lake, Ontario. The latter became the centre of the industry in Canada and production continued into the 1990s driven by the expansion of civilian nuclear power in the 1960s and 1970s.

The balance in uranium mining in Canada began to shift to the Athabasca Basin in northern Saskatchewan in the 1970s and now all Canadian uranium mining is done there. The reason for this change was the very high percentage of uranium oxide found in this ore. Whereas 0.1 to 0.2 percent was typical of the earlier mines, the mines in Saskatchewan can have up to 21 percent uranium oxide (U3O8). In fact the ores are so rich and their radioactivity so high that special extraction techniques are needed. The ore is essentially encapsulated by an ice barrier, made into a slurry and pumped to the surface.

A succession of mining properties were developed in Saskatchewan as shown in Table 2. During this period various corporate changes occurred and only the present owners are shown in the Table. Currently, Cameco Corporation is the largest single uranium producer in the area, with the balance of production by AREVA.

The McArthur River and Cigar Lake mines contain large uranium reserves. Cigar Lake flooded in 2006 and it is not expected to be back in production until 2012. McArthur River was responsible for 75 percent of Canada's production in 2007.

Table 2: Summary of Saskatchewan Uranium Mines

Mine	Reserves*	Grade**	Owner	Dates of Operation
Beaverlodge			Eldorado	1953 - 1982
Rabbit Lake	782	1.3	Cameco	1975 -
Cluff Lake	20		AREVA	1980 - 2003
Key Lake	131	0.41	Cameco	1983 - 2001
McClean Lake	23	3	AREVA	1999 -
Cigar Lake	577	18	Cameco	2005 - ***
McArthur River	845	21	Cameco, AREVA	2000 -

* 1,000 tonnes ore ** % U3O8 *** not producing in 2008
Source: Tammemagi and Jackson, 2002

Pre-enrichment Processing

The first step in processing uranium ore is milling, which consists of grinding it into very fine particles at a mill, usually not far from the mine. Sulphuric acid is then added to this mixture and the uranium metal dissolved out (leached) from the ore into solution. The uranium-bearing solution is dried and the resulting precipitate is used to produce yellowcake, a yellow powder comprised of 70-90 percent U3O8 by weight. This is the end product of the milling done at the mills in northern Saskatchewan.

The environmental consequences of mine and mill tailings is project- and site-specific and has historically been of some concern. For example, the environmental review associated with the decommissioning of uranium mine tailings areas in the Elliot Lake area concluded that, "the tailings of the Elliot Lake uranium mines present a perpetual environmental hazard...the panel recommends that an adequate containment system must be supported in perpetuity by effective care and maintenance programs" (EAP, 1996). Today sequestration of the by-products (tailings) of mining and milling is highly regulated, and must be done in an environmentally responsible manner.

There are other uranium compounds present in yellowcake that must be removed at a refinery in a series of chemical separation processes. Initially the Canadian refinery was located at Port Hope, however, all uranium refining in Canada was moved to Blind River in 1983 due to environmental problems caused by the accumulated refinery tailings.

Refining consists of several steps beginning with dissolving the yellowcake in nitric acid to form a solution containing uranyl nitrate. This solution is purified and the uranyl nitrate is finally reduced to form uranium trioxide (UO3). This is the end product of the refining process, which is then shipped to Port Hope for further processing. As for milling, careful attention must be paid to reducing the environmental impacts of refining, including recycling the process chemicals and sequestering the tailings. Past difficulties in this regard are mentioned later in this report.

Conversion is the process of converting the uranium trioxide from the refinery into uranium dioxide, UO2, for use in natural uranium reactor fuel and into uranium hexafluoride, UF6, for enriched fuel. These steps are performed at Port Hope, where Cameco operates one of the largest uranium conversion plants in the world (see Table 3), the only one in Canada.

Table 3: Uranium Hexafluoride (UF6) Conversion Facilities

Country	Company	Location	MTU/year
Brazil	IPEN	São Paulo	90
Canada	Cameco	Port Hope	10,500
China	CNNC	Lanzhou	400
France	COMURHEX	Pierrelatte	14,000
	AREVA	Pierrelatte	350
Iran	AEOI	Isfahan	193
Russia	ROSATOM	Ekaterinburg	4,000
		Angarsk	20,000
United Kingdom	BNFL	Springfields, Lancashire	6,000
United States	Honeywell (CONVERDYN)	Metropolis, Illinois	17,600
Total			73,133

Source: World Information Service on Energy, Uranium Project, 2008

During conversion, the UO3 is dissolved in nitric acid and after a sequence of reactions the UO2 is produced as a ceramic powder. UF6 production starts with UO2 which is mixed with hydrofluoric acid to make UF4 and then reacted with fluorine gas to yield UF6, liquefied for shipping. All the UF6 is exported to enrichment plants. About 80 percent of the uranium is exported as UF6 and the other 20 percent in the form of UO2 is used for natural uranium fuel, most of it for CANDU reactors.

The fabrication of CANDU natural uranium fuel is done at Zircatec (Cameco) at Port Hope and GE-Hitachi at Peterborough Ontario. These are the world's largest facilities of their kind.

Table 4: Heavy Water Reactor Fuel Fabrication Facilities

Country	Company	Location	MTU/ year
Argentina	CNEA	Ezeiza	160
Canada	Zircatec (Cameco)	Port Hope, Ontario	1,500
	GE-Hitachi Canada	Peterborough, Ontario	1,200
India	DAE Nuclear Fuel Complex	Hyderabad	135
		Trombay	135
South Korea	KEPCO	Taejon	400
Pakistan	Pakistan Atomic Energy Com.	Chashma	20
Total			3,550

Source: World Information Service on Energy, Uranium Project, 2008

This is the status of the "front end" of the nuclear fuel cycle in Canada. No enrichment plant or facility for the fabrication of LWR (light water reactor) fuel has yet been built in Canada. Both would be necessary if it were judged desirable to have the entire front end of the fuel cycle in Canada.

Enrichment Technologies

The objective of uranium enrichment is to produce fuels with an increased proportion of U235. Starting with natural uranium (0.7 percent U235) one can model enrichment processes in terms of the final degree of enrichment and the amount of U235 in the "tails" (the residual uranium, depleted in U235, left after enrichment). For a process of given efficiency, the higher the required enrichment (percentage of U235 in the product) the more natural uranium is required for a fixed percentage of U235 left in the tails. Similarly, higher enrichment percentages for a fixed amount of natural uranium and tails mean more energy must be expended in the separation process. Multiple stages with varying enrichment values for the input and output streams must also be taken into account. A quantity called the Separative Work Unit (SWU) is used as a measure of the energy used in enrichment given the masses and U235 contents of the feed, product, and tails. The dimension of the SWU is mass and thus, it is more correctly expressed as kg-SWU or tonne-SWU.

The SWU facilitates comparisons between various enrichment levels and their costs. For example, to enrich 1 kg of natural uranium to 3.75 percent U235 with 0.25 percent U235 left in the tails requires about 5.33 kg-SWU, no matter what enrichment process is used. The feed needed is 7.61 kg of natural uranium and the tails 6.61 of uranium depleted to 0.025 percent in U235. The differences between enrichment methods are reflected in the energy expended per SWU which in turn can be converted directly to dollars per SWU. The capacity of enrichment plants and the enriched uranium needed for a given reactor can also be expressed in terms of SWUs.

Present uranium enrichment methods exploit the small mass difference between U235 and U238 in the form of UF6. The technologies now in practical use are gaseous diffusion and centrifuge separation, with laser separation a promising new technology for the future.

Gaseous diffusion is the older technology and the first to become economically successful. It depends on the fact that in a gas of given temperature the lighter molecules, in this case the ones containing U235, travel faster than the heavier ones containing U238. If a gas flows past a porous membrane that allows the passage (diffusion) of molecules through it then gas on the other side of the membrane will be slightly enriched in the lighter molecule. The very small enrichment at each stage means that a succession of thousands of such stages, collectively called a cascade, must be used to achieve U235 enrichment levels of practical interest for nuclear power generation (up to 5 percent now but perhaps higher in future). The gas pressure must be brought back up after each stage to recover the pressure loss across the membrane. The compression used heats the gas which is then cooled. The net result is that large amounts of electricity are used to pump, compress and cool the gas. For example, a gaseous diffusion plant of 10 M kg-SWU/yr (10 million kg-SWU/yr) requires power of 2700 MW. Two large such plants are still in operation because the large capital investments made in them during the nuclear arms race of the Cold War have long ago been repaid. The largest is in the US at Paducah, Kentucky (11.8 M kg-SWU/yr) and another in France at Tricastin (10.8 M kg-SWU/yr).

Gas centrifuge technology, the second generation enrichment method, was developed in the 1960s and since then has been supplanting gaseous diffusion. All the enrichment plants built since that time have been based on gas centrifuge technology. The physical principle involved is to spin uranium hexafluoride in a high speed centrifuge, with the result that the centrifugal force exerted favours the migration of the heavier molecules to the outer radii of the centrifuge. An axial circulation

between the top and bottom of the centrifuge makes it possible to draw off a slightly enriched fraction at the top of the centrifuge and a correspondingly depleted fraction at its bottom. Again the enrichment in any one centrifuge is small and a cascade of them must be used. A significant advantage of this technology is that it is much more efficient in its use of electricity; a 10 M kg-SWU/yr centrifuge plant needs only 10 MW of power compared to the 2700 MW of a comparable gaseous diffusion plant.

Third generation enrichment technology is based on laser isotope separation and a variety of such techniques have been proposed. These rely on the fact that the energy levels in atoms and molecules vary slightly with mass, a phenomenon known as the "isotope effect." Lasers can be accurately tuned to a frequency that selectively excites an energy level of an atom or molecule containing, for example U235, but not one containing U238. For instance, excitation of one or more such energy levels can result in ionization of one of the isotope-containing species but not the other, allowing electromagnetic separation. Extensive research and development over many years, primarily in the United States, was devoted to developing such a method for uranium metal vapour, called Atomic Vapour Laser Isotope Separation (AVLIS), but in the end it proved impractical.

The SILEX (Separation of Isotopes by Laser Excitation) process was developed in recent years in Australia. It relies on selective excitation to remove a fluorine atom from UF6 to convert it to UF5 to form a solid. This process is considered promising by investors and is being tested in a pilot scale plant in the United States under a licensing agreement with Silex Systems Limited.

In June 2008 a US subsidiary of Cameco, Cameco Enrichment Holdings LLC, bought a 24 percent holding in GE Hitachi Global Laser Enrichment (GLE), a subsidiary of GE Hitachi Nuclear Energy. This company is commercializing SILEX. Cameco's participation results in three leading companies supporting the commercialization of this laser enrichment technology. GE remains the majority owner, with 51 percent of GLE, while Tokyo-based Hitachi Ltd. which owns 25 percent (Canadian Press, 2008).

While the physical principles of all of these enrichment methods can easily be sketched, all of them incorporate advanced technologies that are closely held both for proprietary reasons and to prevent their use in illicit nuclear weapons programs, such technologies include alloys that can withstand the corrosive effects of uranium hexafluoride, specialized membranes for gaseous diffusion, centrifuges with magnetic bearings that can rotate at very high speeds without breaking up, and the precise details of SILEX. Most enrichment facilities are therefore owned by governments or organizations with close ties to governments.

World Enrichment Capacity

Table 5 shows the present world enrichment capacity. Most of the present enrichment capacity is in centrifuge plants but two large gaseous diffusion plants in France and the US still account for 38 percent of world capacity.

In addition to those listed, Russia in 2007 established an International Uranium Enrichment Centre at its existing Angarsk plant. To date only Kazakhstan has joined the Centre, but other countries are invited to participate (NEA, 2008). The initial plan was to expand this facility if there was sufficient demand from other participants. However, a report last year (BAS, 2008) indicated that a new plant with a 5M kg-SWU, to be operational by 2011, would be built on the basis of Kazakhstan's participation alone.

Table 5: Past and Projected World Enrichment capacity (1000 kg-SWU/yr)

Country	Company	2002	2006	2015
France	Areva	10,800*	10,800*	7,500
Germany-Netherlands-UK	Urenco	5,850	9,000**	12,000+
Japan	JNFL	900	1,050	1,500
USA	USEC	8,000*	11,300*	3,500+
USA	Areva	0	0	1,000+
USA	Urenco	0	0	1,000+
Russia	Tenex	20,000	25,000	33,000+
China	CNNC	1,000	1,000	1,000+
Other		5	300	300
total		46,500	58,450	62,800+
Requirements (WNA)			48,428	57,000 - 63,000

* Gaseous diffusion
** Urenco reached 10,000 in June 2008.
Including the US plant it expects to reach 15,000 in 2012
Source: World Nuclear Association, 2008

Table 5 shows that current world enrichment capacity exceeds requirements and will continue to do so until 2015. According to the World Nuclear Association, the source of Table 5, a capacity of 48.4 M kg-SWU/yr is needed today, whereas 58.4 is available. It also projects that by 2015

the requirements will be 57 to 62.8 M kg-SWU/yr and planned capacity increases now underway, if realized, will bring the total to 62.5 M kg-SWU/yr.

There would be no possibility of bringing a Canadian enrichment plant on line by 2015 and hence, it is the expansion of enriched uranium requirements beyond 2015 that is of most interest.

Complimentary Sources of Reactor Fuel

About one third of the world's used reactor fuel has been reprocessed to extract the substantial amounts of "unburned" uranium and plutonium it contains. However, there are difficulties in using the uranium from reprocessing as a consequence of undesirable uranium isotopes formed when the fuel was in the reactor. In order to use this uranium, it must be converted back to UF6 and re-enriched to a level great enough to counteract the effects of the unwanted isotopes. With the exception of the recycling of fuels from British reactor types, which ended in 1996, recycled uranium from previously used reactor fuel is not currently considered to be economical and "new" enriched uranium is cheaper.

The plutonium, mostly fissile Pu239, is a result of neutron capture in fission reactors and can be more easily recycled in the form of mixed oxide (MOX) fuel when blended with depleted uranium from enrichment plants. The plutonium-239 is the fissile component of MOX fuel, essentially playing the same role U235 plays in enriched uranium fuel. MOX fuel containing 7-9 percent plutonium (Pu239) would produce about the same amount of energy as uranium fuel enriched to 4.5 percent U235.

Commercial use of MOX started in the 1980s and now is about 2 percent of the fresh reactor fuel used worldwide, a proportion expected to increase to 5 percent by 2010. Around 30 reactors in Europe use MOX and it will soon be used in Japan for up to 20 reactors. Most of these reactors use MOX as one third of their fuel, but in many of them 50 percent MOX is possible.

In the Canadian context, the AREVA EPR and Westinghouse AP1000 reactors would be able to use 100 percent MOX fuel. It is not known what amount of MOX the AECL ACR-1000 reactor might accommodate. In order to produce MOX, a reprocessing plant would be required. We expect that this would be a more expensive and environmentally difficult undertaking than an enrichment plant, especially if the feed material to the reprocessing plant is used CANDU fuel, which has significantly less fissile plutonium per kilogram than used LWR fuel. It is estimated that some CDN$20-30 billion at today's commercial rates would be required to reprocess the existing accumulated CANDU spent fuel now in storage (Jackson, 2005) and thus, there are no plans to build a reprocessing plant in Canada.

The remaining complementary source of fissile material for reactor fuel is from dismantled nuclear weapons. Weapons grade plutonium can be blended into MOX for fuelling reactors in the same manner as the plutonium from reprocessing used reactor fuel, or it can be degraded to reactor grade by reactor irradiations. In either case it is taken out of the weapons inventory. There are estimated to be about 260 tonnes of surplus weapons grade plutonium available, mostly in Russia and the US.

Highly Enriched Uranium (HEU) from weapons can easily be blended with depleted uranium to produce reactor fuels. Agreements between the US and Russia on reducing nuclear weapons stockpiles have the effect of displacing 10,600 tonnes of mine production every year, which is about 13 percent of the world's requirements. The total available is around 2000 tonnes of HEU, about 12 times annual global production. Under the US/Russia "Megatons to Megawatts," Russian weapons material is used in US civilian power reactors. Surplus HEU from US weapons is also used in US power reactors. The current arrangement between the US and Russia will expire in 2013 (NEA, 2008), but there is a possibility that it may be extended.

Since their deployment is well controlled by international agreements, these complementary sources of enriched uranium and plutonium, while substantial, are not sufficient to significantly perturb the enrichment business. Therefore, they should have no effect on the decision of whether to do enrichment in Canada.

The Market for Canadian Enriched Uranium

Currently all of Canada's nuclear power reactors are of the CANDU type, using natural uranium for fuel. However, according to project descriptions submitted to the Canadian Nuclear Safety Commission (CNSC), some of these could be replaced by light water reactors (LWRs) using low enriched uranium.

Ontario is planning to maintain its installed in-service nuclear capacity to meet base load electricity requirements at a level not exceeding 14,000 MW. Partially in response to this plan, Ontario Power Generation (OPG) and Bruce Power (BP) have each applied to the CNSC for licences to prepare sites for up to four new nuclear reactors.

An announcement was made in June 2008 that at least two of the new reactors will be constructed at OPG's Darlington station (Ontario, 2008). An additional reactor has been proposed for New Brunswick. In addition, Bruce Power has submitted an application to prepare a site for the potential construction of new reactors in Alberta. Saskatchewan has also been exploring nuclear power.

The three reactor types under consideration in the Ontario competition are the Westinghouse AP1000, the AREVA EPR and AECL's ACR-1000. The Westinghouse and AREVA entries are light water reactors of the PWR (Pressurized Water Reactor) type, using natural water as both coolant and moderator. They are fueled with uranium typically enriched to an average of 3.75 percent. The AECL reactor will use heavy water as a moderator and light water as a coolant, with fuel said to be enriched to a level of about 2-2.4 percent U235. However, the design of the ACR-1000 will not be finalized until 2012.

Estimating the enriched uranium required for the light water reactors is relatively easy. The rule of thumb is that about 116,000 kg-SWU/yr are needed to fuel a 1,000 MW (electrical) reactor (Lamarsh and Baratta, 2001). The AP1000 is rated at 1,100 MW (e) and the EPR is even larger at 1,600 MW (e). Therefore, for the rough estimates needed for this paper, the separative work can be scaled to the reactor power:

- An AP1000 requires 127,600 kg-SWU/yr for its enriched uranium supply; and
- An EPR requires 185,600 kg-SWU/yr for its enriched uranium supply.

It is not possible at this time to estimate the enriched uranium requirements for the ACR-1000; the data required is not publically available and presumably will not be until the design is completed and the numbers are released in 2012.

It is possible to make estimates of the domestic market for enriched uranium by means of a few reasonable scenarios based on reactor type. For example, four new EPR reactors in Ontario would imply an enrichment requirement of 742,240 kg-SWU/yr, while four new AP1000 reactors would need 510,400 kg-SWU/yr. Add two or more LWRs in Alberta (Ermisch, 2008) and Saskatchewan (Howlett, 2008) and it is apparent that an enrichment plant of at least of 1 M kg-SWU/yr capacity could probably be supported by the domestic market alone when the new reactors come on stream in 2018 and after. This assumes that domestic supply would compete favourably with imported supply in terms of price and guaranteed long-term supply contracts.

As for the export market, an upper limit can be estimated if it is assumed that a significant portion of the UF6 now exported to foreign enrichment plants was diverted to Canadian enrichment plants before export. As shown in Table 1, Canadian uranium production in 2007 was 9,476,000 kg. Suppose that in the future approximately 80 percent of that amount was not exported as UF6, as it is now, but instead enriched to the 3.75 percent level with tails of 0.25 percent. This would require 6.822 M kg-SWU/yr, which establishes an approximate upper bound to the export potential for uranium enriched in Canada, assuming that production of Canadian uranium does not significantly increase. Comparison with Table 5 shows that one or two of the larger centrifuge plants would be possible for the domestic and export markets. This sets a notional upper limit for a possible enrichment business in Canada. Clearly, the actual level would be set by the domestic and international markets.

To further explore the economics of enrichment, consider the current market prices for both uranium and uranium-derived products as published by the UxC Consulting Company. At the beginning of November, 2008 the North American spot price for uranium oxide was US$45 /lb (US$ 99/kg), for conversion was US$8 /kg-U, and for enrichment was US$159 /kg-SWU (UxC, 2008). Historically, the price of uranium oxide has been relatively stable except for short-term fluctuations. It hovered around US$10 /lb (US$ 22/kg) for several years until about 2004 when it started to rise, reaching a high of US$135 /lb (US$298/ kg) in 2007. By November 2008 it was back down to US$45 /lb (US$99/ kg). The price of a kg-SWU has risen steadily from US$80 in 2000 to its November 2008 price of US$159.

Using the previous example of enriching 1 kg of natural uranium to 3.75 percent U235 with 0.25 percent U235 left in the tails, the total cost, according to current UxC prices, would be US$1,798.45 (see Table 6). Fuel fabrication has been omitted from this table because it is assumed that this would take place in the importing countries.

Table 6: Estimated cost of 1 kg of uranium enriched to 3.75 percent, tails 0.025 percent (November 2008 values)

	Unit Price	Units	Price US$
U3O8 Feed	$45/lb	19.78 lb	890.10
Conversion	$8/kgU	7.61 kg	60.88
Enrichment	$159/SWU	5.33 SWU	847.47
Total			$1798.45

Source: UxC Consulting Company, 2008

The figures in the feed and conversion lines in Table 6 represent the estimated price of Canadian uranium as currently exported; thus, the value added by enrichment is about 90 percent. Using 80 percent of the 2007 Canadian production as the amount exported and assuming the conditions of Table 6, gives a total value added of US$844 million per year. Of course, this is a very crude estimate. In addition to the many other assumptions made, it is based on spot prices and thus does not reflect price reductions that accompany the long-term contracts under which uranium is normally sold. Nevertheless, the important point is that annual returns in the order of hundreds of millions of dollars could be possible by exporting enriched uranium instead of natural uranium. Based on the assumption that the published price per kg-SWU reflects a reasonable return on investment for current producers of enriched uranium using centrifuges, this is likely to be a profitable undertaking. The foregoing assumes that a Canadian plant would be as cost-effective as current producers. Some existing plants, particularly those using old gaseous diffusion technology, have written off their capital costs long ago and therefore their profit margins are higher. New centrifuge installations with associated debt charge obligations will have different profitability calculations, but incorporate more economical fifth generation technologies that may offset to some extent the higher capital costs involved. Finally, the market is a dynamic one, which would normally mean that new entrants will struggle to gain a toehold. Profit-sharing may also be necessary, depending on who retains ownership of the technology.

In 2006 Australia did a review of whether Australia, already a large producer of uranium, should branch out into conversion, enrichment and fuel fabrication (Switkowski, 2006). This review contained a very similar calculation to the simple one done above and found that an additional AUS$1.8 billion/yr would be added to Australian export revenue if these activities were done domestically. The Switkowski report did not consider any further analysis of costs and profitability. It advised the Australian government not to proceed with this concept on the grounds that it would be too difficult for Australian companies to enter the market. A variety of reasons were put forward to support this conclusion: it would be very difficult to get access to the technology; there was little Australian experience or expertise in nuclear fuel cycles; domestic legal restrictions on the uranium business would be hard to change; and, the Australian nuclear regulatory regime is localized and not organized to cope with a broadening of the uranium business. Canada's situation with respect to enrichment presents fewer barriers than Australia's. In fact, the key hurdle for Canada would be acquiring enrichment technology through licensing agreements with appropriate companies. The motivation to attempt this would only arise from a strong business case, very likely based on firm long-term supply contracts with domestic and international customers.

Another potential domestic market for enriched uranium could be in isotope production. For many years Canada has been the largest supplier of medical and industrial isotopes to the world. The main medical isotope is Mo99, produced in the National Research Universal (NRU) reactor at Chalk River, Ontario as a fission product in highly enriched uranium (HEU) targets. However, this market is unlikely to be a factor in a decision to site an enrichment plant in Canada, since the amounts of enriched uranium used are small compared to power reactor fuel, the future of the isotope business in Canada is uncertain with the cancellation of the MAPLE reactors intended to replace the fifty year-old NRU reactor and the additional expense for the necessarily stringent safeguarding and security of HEU may not be financially justified.

Cost of Potential Enrichment Plants for Canada

Capital costs

The costs associated with three new US enrichment plants under construction, as shown in Table 7, are most relevant to the assessment of the likely cost of building an enrichment facility in Canada.

Table 7: US Centrifuge Enrichment Plants under Construction

Organization	Location	M kg-SWU	US B$
National Enrichment Facility	New Mexico	3.00	1.50
American Centrifuge-USEC	Ohio	3.80	3.50
AREVA	Idaho	3.00	2.00

Source: Compiled from data in World Nuclear Association, 2008

Table 7 indicates that the estimated capital cost of a medium sized (3 M kg-SWU) centrifuge plant is in the range of US$1.5- 3.5 billion. Although these costs are large, they are less than the cost of one new 1,000 MW reactor, probably in the range of US$5-7 billion. The capital costs of a SILEX plant are not known at this time since the technology is still in the trial stage.

Using standard amortization methods we can use these numbers to compare the value added, in terms of the dollar value of the kg-SWU produced by the plants, with the amortization costs of the initial capital investment based on three representative interest rate values (5 percent, 10 percent, and 15 percent) for borrowing the capital (see Table 8). SWU output is valued at US$159 /kg-SWU. The amortization period is conservatively chosen as 30 years based on the excellent performance record of current centrifuge enrichment plants. It is concluded that the revenue calculated on the basis of the SWU value would offset the amortization costs even at a 15 percent interest rate.

Table 8: Estimate of Repayment of Capital Costs over 30 years for Enrichment Plants of Table 7 at Illustrative Interest Rates

	Output	SWU Value	Capital Cost	Level Annual Repayment (US$M/yr)		
	M kg-SWU	**(US$M/yr)**	**($M)**	**5%**	**10%**	**15%**
National Enrichment Facility	3	477	1,500	97.5	238.5	228.5
American Centrifuge-USEC	3.8	604.2	3,500	227.5	371	533.1
Areva	3	477	2,000	130.0	212	304.6

Energy is likely to be the main operating cost of a centrifuge plant, while other operating and maintenance costs are low. The operating costs of new centrifuge plants can therefore largely be derived from the energy consumed per SWU. The WNA (WNA, 2008) quotes the example of the UK centrifuge plant at Capenhurst operated by Urenco which in 2001-2 used 50 kWh/kg-SWU and an effective 62.3 kWh/kg-SWU for all costs. It is assumed that the wholesale electricity cost in Canada for a large industrial plant would about be $0.05 /kWh. Therefore, in order to produce 62.3 kWh/kg-SWU, a 3 M kg-SWU plant would cost about $9.35 million /yr to operate. Overall, O&M costs thus appear to be small compared to the likely debt service burden and are unlikely to play a significant role in making decisions on the viability of a Canadian enrichment plant.

Canadian access to technology

The issue of Canadian access to the technology of an enrichment plant based on Canadian soil is often raised. Centrifuge plants have been developed to such a high level abroad that it would seem there is little in the way of improvements that Canadians could add. For this reason and because of the need for safeguarding the technology due to the risks of nuclear weapons proliferation, we expect that a centrifuge plant in Canada would function as a "black box," meaning that the plant would be built, owned and operated by a foreign company. A Canadian company would supply the natural uranium feedstock and receive the enriched uranium for domestic use or export.

Because it is still in the prototype stage, costs cannot be estimated for the SILEX enrichment process. However, it would probably offer more scope for technical involvement because it is less developed than the centrifuge method and also because Cameco holds a substantial position in the

company developing it.

Environmental Impacts of Enrichment

In an enrichment plant with only natural uranium as input, the only radioactive materials present are those already contained in the feed. No other radioactive materials are produced as they would be in a nuclear reactor. The tails, like the natural uranium, are only mildly radioactive and are stored as depleted UF6, which must be converted for disposal. The main environmental concerns are chemical. UF6 reacts with water to form highly corrosive hydrofluoric acid, and trace amounts of arsenic and other heavy metals also need to be controlled. Thus chemical toxicity rather than radioactivity is the primary concern, and the safety systems are similar to those used in other chemical plants.

For example, the environmental impact study for the National Enrichment Facility in Lea County, New Mexico, found the environment impacts in all areas to be small, or at most moderate in a few areas such as transportation during construction and UF6 waste cylinder disposal. This project was approved and is now under construction (NRC, 2005). It would seem likely that an enrichment plant in Canada would be approved after a similar assessment, unless some aspects of the particular location being proposed made it unacceptable.

This is not to say that accidents at such plants cannot happen. In July, 2008 a uranium waste leak at Tricastin in France, resulted in 6 cubic metres of water containing uranium to be spilled into two local rivers. Tricastin is the site of France's large gaseous diffusion plant, but it also has four power reactors that supply electricity to the enrichment plant. It is not known whether the spill was directly associated with enrichment or with some other part of the operation.

Port Hope has had problems with uranium operations for many decades. It has some 2 million cubic metres of historic refinery wastes mixed with soil dating from the 1930s to the 1970s. The waste is only mildly radioactive but was used in certain parts of the town for fill in building a variety of structures, resulting in a radon hazard that came to light in the 1970s. The Atomic Energy Control Board (now the Canadian Nuclear Safety Commission) cleaned up some of the worst affected areas between 1975 and 1982. There is also a waste management area in nearby Port Granby used from the 1940s to 1988. A variety of plans has been proposed for dealing with this waste since the 1980s, including one, abandoned in 1996, to ship all the historic wastes to Chalk River. At this time there is a project called the Port Hope Area Initiative undertaken by the Low Level Radioactive Waste Management Office, an Agency of Natural Resources Canada (LLRWMO, 2008), funded by the federal government. The project aims to construct waste management facilities for remediation of the waste sites, and provide long-term monitoring and maintenance of the facilities.

Leakage from the large UF6 conversion facility at Port Hope was found in 2007. Uranium, arsenic and some fluorine compounds had been leaking into the soil under the plant, probably for many years. Contamination of the harbour may also have occurred from contaminated groundwater flowing under the plant. Extensive remediation was undertaken and the plant was re-opened in September 2008. Later that year the UF6 plant closed and its near-term operations remain uncertain due to questions about the supply of hydrofluoric acid.

Significant greenhouse gas (GHG) emissions are often attributed to nuclear power in the US because of the large amounts of electricity used by the Paducah, Kentucky, gaseous diffusion plant; this electricity is mostly generated from coal. A Canadian enrichment plant is most likely to be located in Ontario or Saskatchewan. Assuming it was a modern Capenhurst-type plant with a capacity of 1 M kg-SWU, using electricity in the order of 50kWh/SWU, the GHG emissions can be calculated depending on the electricity generation mix of the province in which it is sited. In 2005 Environment Canada (EC, 2005) calculated CO2 equivalent emissions per kWh of electricity for each province by weighting the emission per-unit-energy for each generation technology by the percentage use of that technology in electricity production. Saskatchewan electricity is produced mainly from coal and gas and the emission per kWh is 880g. Ontario generates about 75 percent of its electricity from nuclear and hydro, and the average emission per kWh is 220g. Total annual emissions from a Capenhurst-type enrichment plant of 1 M kg-SWU size would thus be about 11,000 tonnes of CO2 for Ontario and four times that for Saskatchewan. This is a relatively small amount compared to the 34 M tonnes emitted by the Ontario electricity generation system as a whole. As CO2 emissions from all provincial electricity generation systems are expected to decrease in the future, we do not expect that the secondary emissions due to energy consumption by a single enrichment plant would be judged to be significant in an environmental assessment.

While there is no experience of exporting significant amounts of low enriched uranium from Canada, transportation of UF6 from Canada to the US has been routine. According to the US Argonne National Laboratory,

"Historically, no transportation accidents involving a release of UF6 have occurred" (ANL, 2008). From a chemical point of view, an accident involving UF6 would be a greater hazard than an accident involving enriched uranium. We expect that, with appropriate mitigation measures, transportation effects would not be determined to be significant in an environmental assessment of an enrichment plant in Canada. However, it might be argued that security for shipments of enriched uranium should be higher than for shipments of uranium ore.

Non-Technical Considerations

Public acceptance of a new nuclear facility might be problematic in some Canadian communities. However, an enrichment plant with its relatively low environmental impact should be attractive to communities interested in the local economic benefits, and there appears to be some level of public support for an expanded nuclear fuel business, particularly in Saskatchewan.

There also appears to be at least some potential for international initiatives to affect the prospects for uranium enrichment in Canada. For example, Canada is a member of the Global Nuclear Energy Partnership (GNEP). Although states participating in this partnership do not give up any rights, GNEP aims, as one of these objectives "to establish international supply frameworks to enhance reliable, cost-effective fuel services and supplies to the world market…and fostering development while reducing the risk of nuclear proliferation by creating a viable alternative to acquisition of sensitive fuel technologies" (DOE, 2008). It would appear that the possibility exists for establishment of coordinated international supply networks and management of technology. It is not clear how such developments would affect the economic attractiveness of establishing enrichment in Canada.

Discussions about whether Canada could perform uranium enrichment would also need to be held with the 45- member NSG (Nuclear Suppliers Group). This was the group that recently sanctioned the resumption of nuclear trade with India and it has been reported that Canada has been lobbying the NSG to allow Canadian enrichment plants with full Canadian access to enrichment technology (that is no black box) (Squassoni, 2008), (Cheadle, 2008).

Conclusions

This report does not purport to be a rigorous economic analysis; rather it presents reasoned estimates based on published data. We do not believe that our analysis can be taken any further without well-defined project specifications, including many details that are both unknown and unlikely to be released for both non-proliferation and proprietary business reasons. For example, precise costs of enrichment plants are not publicly available. These costs would depend on factors such as where the plant was located, in terms of land, transportation and power costs; environmental assessments and regulatory fees; the licensing agreement between the technology supplier and the operator; the interest rate structure of project financing; and a myriad of other factors.

We do not believe that it would be useful to try to guess these factors, because the range of project parameters is too large to make inferences of more validity than those provided by our estimates. Our view is that any possible enrichment plant would have to be a private undertaking on the part of AREVA and/or Cameco or some other entity, perhaps a public-private partnership. In principle, we see no necessity for the participation of Canadian governments in such a partnership, but we would not exclude the possibility.

The reality is that Cameco, AREVA or some other firm considering an enrichment plant in Canada would have to build a hard-nosed and well-founded business case using precise information rather than publically available estimates. They would also have to make well-informed predictions about competition, future enrichment markets and prices to arrive at the best decision possible.

With the foregoing discussion in mind, we conclude, on the basis of our estimates, that enrichment in Canada is likely to be more profitable than exporting natural uranium and buying back enriched uranium. We expect that a significant domestic market for enriched uranium will arise in the years following 2012 when new reactors using enriched fuel are expected to be built in Canada. As similar enrichment plants have been assessed elsewhere and found to have low to moderate environmental affects, we expect that, as long as an environmentally and socially acceptable site is selected, an environmental assessment of a Canadian enrichment plant would be unlikely to find significant adverse environmental effects. A major barrier might be acquiring the technology needed for enrichment or persuading an existing enrichment company to set up a plant in Canada, as enrichment technology is closely held both for non-proliferation and business reasons.

Works Cited

ANL (2008). Argonne National Laboratory, Depleted Uranium Guide. Available at: http://web.ead.anl.gov/uranium/guide/health/transport/index.cfm

Bodansky, David (2000). Nuclear Energy: Principles, Practices and Prospects, 2nd edition. New York: Springer. BAS (2008). Bulletin of the Atomic Scientists. April 28.

Canadian Press (2008). "Cameco pays US $123.8M to join GE-Hitachi uranium enrichment venture." June 20.

Cheadle, Bruce (2008). "Tories mum on nuclear enrichment strategy," Globe and Mail. May 7.

DOE (2008). US Department of Energy/Energy Information Administration, DOE/EIA-0484.

EAP (1996). Decommissioning of Uranium Mine Tailings Management Areas, Report of the Environmental Assessment Panel. Minister of Supply and Services Canada,

EC (2005). Environment Canada, National Inventory Reports: Inventory of Green House Gas Sources and Sinks in Canada. Available at: http://www.ec.gc.ca/pdb/ghg/inventory_report/2005_report/a9_eng.cfmof

Ermisch, M. (2008). "Alberta nuke plans on track: Bruce Power CEO believes Saskatchewan plant also an option," Calgary Sun. November 28.

Howlett, K. (2008a). "Ontario to build Darlington reactors by 2012; critics accuse government of low-balling estimated $26 billion cost for nuclear upgrades," Globe & Mail. June 17.

————(2008b). "With two proposed reactors; Saskatchewan joins nuclear Renaissance," Globe & Mail. June 18.

IAEA (2008). Energy, Electricity and Nuclear Power Estimates for the period up to 2030. International Atomic Energy Agency.

Jackson, David (2005). Implications of Reprocessing, Partitioning and Transmutation on Long-Term Management of Used Nuclear Fuel. Nuclear Waste Management Organization. Available at: www.nwmo.ca

Lamarsh, John R. and Baratta, Anthony, J. (2001). Introduction to Nuclear Engineering, 3rd edition. Upper Saddle River, NJ: Prentice Hall.

LLRWO (2008). Low Level Radioactive Waste Management Office. Available at: http://www.llrwmo.org/en/porthope/historicllrw.html

NAS (2007). Review of DOE's Nuclear Research and Development Program. National Academies of Science. Available at: http://www.nationalacademies.org/includes/NERBa.pdf

NEA (2008). Market Competition in the Nuclear Industry, Document #6246. Nuclear Energy Agency.

NRC (2005). U.S. Nuclear Regulatory Commission, Environmental Impact Statement for the Proposed National Enrichment Facility in Lea County, New Mexico - Final Report, NUREG-1790). Available at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1790/

NRC (2008). "Expected new nuclear power plant applications," updated December 17. Available at: http://www.nrc.gov/reactors/new-reactors/new-licensing-files/expected-new-rx-applications.pdf

MOE (2008). Ontario Ministry of Energy. Available at: http://www.energy.gov.on.ca/index.cfm?fuseaction=english.electricity

Squassoni, Sharon (2008). "All eyes on the Nuclear Suppliers Group: Will the nonproliferation main stream shift? Carnegie Endowment. August 18. Available at: http://www.carnegieendowment.org/publications/index.cfm?fa=view&id=20394

Switkowski, Z. (2006). "Uranium mining, processing and nuclear energy — opportunities for Australia?" Australian Government.

Tammemagi, Hans and Jackson, David (2002). Unlocking the Atom: The Canadian Book on Nuclear Technology. Hamilton: McMaster University Press.

UxC (2008). The UxC consulting Company LLC. Available at: http://uxc.com/

WISE (2008). World Nuclear Fuel Facilities.World Information Service on Energy, Uranium Project. Available at: http://www.wise-uranium.org/efac.html

WNA (2008). "World Uranium Mining." World Nuclear Association. Available at: http://www.world-nuclear.org/info/inf23.html

The Centre for International Governance Innovation
Centre pour l'innovation dans la gouvernance internationale

Who We Are

The Centre for International Governance Innovation is an independent, nonpartisan think tank that addresses international governance challenges. Led by a group of experienced practitioners and distinguished academics, CIGI supports research, forms networks, advances policy debate, builds capacity, and generates ideas for multilateral governance improvements. Conducting an active agenda of research, events, and publications, CIGI's interdisciplinary work includes collaboration with policy, business and academic communities around the world.

CIGI's work is organized into six broad issue areas: shifting global order; environment and resources; health and social governance; international economic governance; international law, institutions and diplomacy; and global and human security. Research is spearheaded by CIGI's distinguished fellows who comprise leading economists and political scientists with rich international experience and policy expertise.

CIGI was founded in 2002 by Jim Balsillie, co-CEO of RIM (Research In Motion), and collaborates with and gratefully acknowledges support from a number of strategic partners, in particular the Government of Canada and the Government of Ontario. CIGI gratefully acknowledges the contribution of the Government of Canada to its endowment Fund.

Le CIGI a été fondé en 2002 par Jim Balsillie, co-chef de la direction de RIM (Research In Motion). Il collabore avec de nombreux partenaires stratégiques et exprime sa reconnaissance du soutien reçu de ceux-ci, notamment de l'appui reçu du gouvernement du Canada et de celui du gouvernement de l'Ontario. Le CIGI exprime sa reconnaissance envers le gouvernement du Canada pour sa contribution à son Fonds de dotation.

CIGI is located in the historic former Seagram Museum in Waterloo, Ontario, Canada.

The Centre for International Governance Innovation

Centre pour l'innovation dans la gouvernance internationale

57 Erb Street West
Waterloo, Ontario N2L 6C2, Canada
tel +1 519 885 2444 fax +1 519 885 5450
www.cigionline.org