USE OF ENRICHED URANIUM IN CANADA'S POWER REACTORS

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ABSTRACT

Recent trends in Canadian nuclear power reactor design and proposed development of nuclear power in Canada have indicated the possibility that Canada will break with its tradition of natural uranium fuelled systems, designed for superior neutron economy and, hence, superior uranium utilization. For instance, the Darlington B new reactor project procurement process included three reactor designs, all employing enriched fuel, although a natural uranium reactor design was included at a late stage in the ensuing environmental assessment for the project as an alternative technology. An evaluation of the alternative designs should include an assessment of the environmental implications through the entire fuel cycle, which unfortunately is not required by the environmental assessment process. Examples of comparative environmental implications of the reactor designs throughout the fuel cycle indicate the importance of these considerations when making a design selection. As Canada does not have enrichment capability, a move toward the use of enriched fuel would mean that Canada would be exporting natural uranium and buying back enriched uranium with value added. From a waste management perspective, Canada would need to deal with mill, refinery, and conversion tailings, as well as with the used fuel from its own reactors, while the enrichment supplier would retain depleted uranium with some commercial value. On the basis of 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. Further, on the basis of environmental assessments for enrichment facilities in other countries, it is expected that an environmental assessment of a properly sited enrichment facility would result in approval.

1. INTRODUCTION

Traditionally, the design of natural-uranium-fuelled CANDU®[1] reactors has been aimed at providing electrical energy with excellent neutron economy and hence superior uranium utilization.[1] Nevertheless, the desire to improve operating characteristics has led to the proposed use of slightly enriched uranium in existing Canadian power reactors and to the design of the Advanced CANDU Reactor (ACR-1000), which employs enriched fuel.

The only reactors included in Ontario's 2008 request for bids on new reactors for Darlington B employ enriched fuel. The Ontario Ministry of Energy (MOE) initially considered reactor designs from both Canadian and foreign suppliers, including the Enhanced CANDU 6 (EC6), fuelled by natural uranium. To assist with its decision-making, MOE commissioned a study by McKinsey & Company, which concluded that there were clear differences in the estimated lifetime cost of power of the designs, "however, when taken together, these differences are not enough to rule out a contending design as fundamentally disadvantaged – save the EC6, which

[1] CANDU® is a registered trademark of Atomic Energy of Canada Limited.

would not benefit from the same economies of scale as its Generation III(+) competitors."[2] Subsequently, the EC6 was excluded from the continuing procurement process, which was ultimately narrowed to three designs for more detailed consideration: the ACR-1000, the Westinghouse Advanced Passive Reactor (AP1000), and the Areva Evolutionary Power Reactor (EPR). In the context of the present paper, we would note that the McKinsey & Company study compared the designs under three categories: (i) expected in-service date, (ii) levelized unit electricity cost, and (iii) macro-economic impact. These do not include explicit consideration of fuel cycle efficiency or environmental impact.

The MOE procurement process was suspended in June of 2009. Nevertheless, the Canadian Nuclear Safety Commission (CNSC) has proceeded with processing the request for a Site Preparation Licence. This has resulted in the establishment of a review panel under the Canadian Environmental Assessment Act, with OPG as the proponent. OPG has based its assessment on a "plant parameters envelope" (PPE) methodology, intended to bound the environmental aspects of the alternative plant designs.[3] The PPE used in the Environmental Impact Statement [4] was defined by three alternative designs, the ACR-1000, the AP1000, and the EPR, all of which are considered to be third-generation reactors. However, the CNSC subsequently requested that the review panel include the EC6 in its review [5], and it has since been included as an "alternative technology."[6]

In the following sections, we discuss some implications of the choice of continuing with natural-uranium-fuelled technology for Canadian nuclear power generation, or switching to a design employing enriched uranium. Given the increased interest in enriched reactors in Canada, we will also discuss the potential for providing enrichment at a Canadian facility.

2. ENVIRONMENTAL FACTORS

After including the EC6 design in the PPE for the environmental assessment and evaluating the implications relative to the assessment of the original set of three reactors, OPG concluded "no additional effects are anticipated, and no additional mitigating measures are required."[6] It was also pointed out, however, that the EC6 would require more storage space for used fuel than the other reactors. We believe that such an evaluation is incomplete in that it ignores the comparative influence of the alternative designs on other parts of the fuel cycle. Although such considerations are important, they are not required by the environmental assessment process and would not necessarily be a consideration in selecting a nuclear reactor design for this or other Canadian projects. Further, as has been pointed out elsewhere [7], "although it is clear that high burnup is beneficial in terms of reducing the volume and mass of spent fuel per unit of electricity generation, the corresponding repository storage volume savings is still uncertain because of the higher decay heat generation and radioactivity associated with each assembly of the higher-burnup spent fuel."

As part of a study conducted at the request of the Canadian Electricity Association (CEA) and National Resources Canada, some of the life cycle effects of the existing Darlington CANDU reactor system were compared to a conventional light boiling water reactor (LBWR) system located conceptually at the same site.[8] In particular, it was found that the CANDU system had 62% lower energy resource depletion than the LBWR. The difference resulted from the large amount of energy required to enrich uranium for the LBWR, and the LBWR's relatively inefficient use of fuel. It should be pointed out that this analysis was based on the assumption that the enrichment was provided by gas diffusion, a heavy user of energy, but not expensive because the capital cost of the diffusion plants was written off long ago. The assumption is, however, consistent with the current enrichment technology employed in North America. As the primary energy supply to the diffusion plant is provided by coal, significantly higher atmospheric emissions were attributable to the power plant fuelled with enriched uranium.

The point is that this is an environmental factor that would not be noticed without examining the effects of the power plant throughout the fuel cycle. In our view, such considerations should be included in determining environmental effects that are affected by the reactor design, independent of whether or not they are reflected in a great difference in the levelized unit energy cost, and whether or not these effects occur near the nuclear power plant.

3. FUEL CYCLE CONSIDERATIONS

Figure 1 gives a flow diagram for a once-through nuclear fuel cycle, showing some important environmental factors. Those stemming from the reactor component are dealt with in the environmental assessment by means of the PPE. They would also be dealt with for the specific selected reactor design in a subsequent licensing process. In neither case would it seem, however, that they are formally considered in the evaluation and selection of the reactor technology.

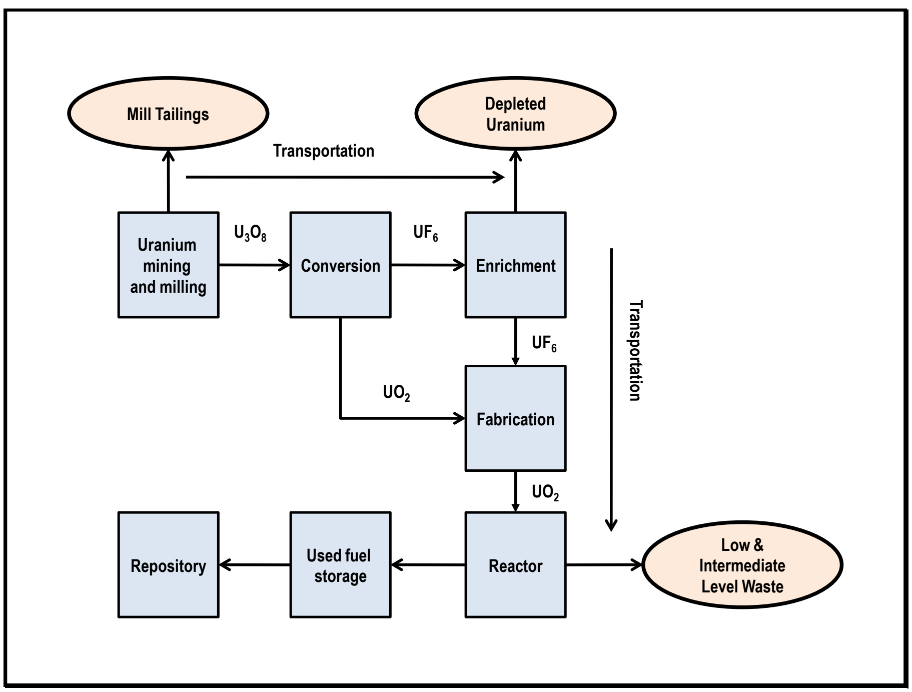

Figure 1. Once-through fuel cycle flow diagram

Some parameters for the reactors currently under consideration for the Darlington B new-build are given in Table 1. It should be noted that each stage of the fuel cycle requires energy input, the environmental implications of which should be taken into account in a full life cycle assessment.[9] The implications for the enrichment phase are considered in the following.

Table 1. Reactor parameters.

Description	ACR-1000	AP1000	EPR	EC6
Thermal power per unit[1] (MWth)	3200	3400	4590	2084
Net electrical output per unit[1] (MWe)	1085	1090	1600	689
Enrichment[2] (%)	2.5	4.8	5.0	0.711
Average Burnup[1] (MWd / MgU)	20,000	48,700	56,000	7,500[a]
Plant net thermal efficiency[1]	34%	32%	35%	33%

Sources:

1. Bruce Power, *Bounding Plant Envelope Technical Support Document: Bruce Power New Nuclear Power Plant Project Environmental Assessment*. 2008. [10]
2. Ontario Power Generation, *Nuclear Waste Management Technical Support Document: New Nuclear - Darlington Environmental Assessment*. 2009. [11]

a. Atomic Energy of Canada Limited, *Enhanced CANDU 6 Technical Summary*, http://www.aecl.ca/Assets/Publications/EC6-TS_Eng.pdf .

Table 2 gives fuel cycle quantities for 1 GWy_e (gigawatt-year electric) net electrical energy production for the four alternative reactor designs, calculated from the above parameters.

Table 2. Calculated fuel cycle characteristics per net GWy_e.

Description	ACR-1000	AP1000	EPR	EC6
Uranium ore to mill (MgU)	305	272	226	156
Conversion plant feed (MgU)	292	261	216	150
Enrichment plant feed (MgU)	290	259	215	N/A
Separative work (kSWU)[1]	138	161	135	0
Fabrication plant feed (MgU)	54.3	23.7	18.8	149
Fuel loaded to reactor (MgU)	53.7	23.4	18.6	148

Notes:

1. kSWU = 1000 kg-SWU

For these calculations, nominal values were used for loss in conversion (0.5%), loss in fabrication (1%), and ^{235}U content of depleted uranium from the enrichment process (0.3%).

Some environmental stressors attributable to the alternative reactor designs are given in Table 3. The separative work required by the three enriched-fuel reactors is calculated assuming gaseous diffusion enrichment. It is comparable for each of the enriched-fuel reactors: over 3% of the net electrical output of the reactor. Diffusion plants will eventually be replaced by centrifuge, which would lower the energy requirement by about 80%, albeit at increased costs due to the need to amortize new plant.

Table 3. Calculated fuel cycle environmental stressors per GWy_e.

Description	ACR-1000	AP1000	EPR	EC6
Separative energy[1] (GWh_e)	317	371	312	0
Solid mill tailings (Mg)	152	136	113	78
Conversion plant solid waste (Mg)	203	181	151	104
Conversion plant liquid waste (m^3)	1890	1690	1400	970
Depleted uranium - UF6 (Mg)	349	348	290	0
Used fuel (MgHE)	53.7	23.4	18.6	148

Note:

1. Gas diffusion enrichment at 2300 kWh_e per SWU is assumed.

Figure 2 is a comparative chart of solid fuel cycle wastes associated with each reactor type. The relative superiority of the EC6 is evident in all areas except as regards the mass of used fuel discharged. However, it should be noted that the fission products, minor actinides, and heat generation of the used fuel are also much lower for a given mass of discharged EC6 fuel than for the same mass of fuel discharged from the enriched fuel reactors, particularly the AP1000 and EPR with their very high burnup. In addition, there is no need for reactivity suppression to protect against criticality in used fuel storage for the discharged EC6 fuel.

Particular attention might be given to the implications of the reactor type for the generation of uranium tailings, which have been of some concern in the past. For example, the environmental review associated with the decommissioning of uranium 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.”[12]

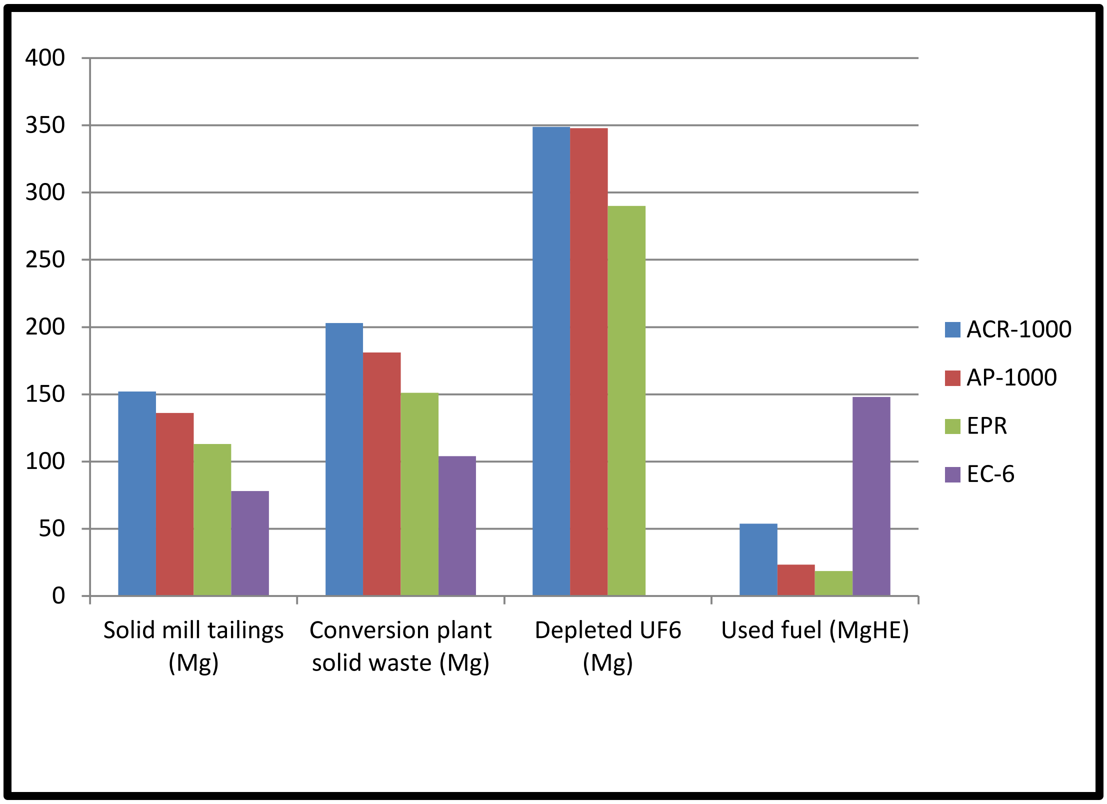

Figure 2. Once-through fuel cycle waste per GWy_e.

Environment Canada, with technical support from the Canadian Nuclear Safety Commission (CNSC), has determined that "uranium and uranium compounds in effluent from uranium mines and mills were entering the environment in quantities or concentrations or under conditions that have or may have an immediate or long-term effect on the environment or its biological diversity."[13] Consequently, it was recommended that investigations of options to reduce exposure to uranium from these sources be considered a high priority. The CNSC has identified risk management activities for each facility and annual reports are produced outlining their progress. Even before these steps were taken, environmental management at more modern mines and mills in Canada has been recognized as much improved. It should be noted, however, that the toxicity of the environmental hazard of the mined uranium is dominated by chemical rather than radiological toxicity, and the hazard does not diminish significantly with time.

Table 4 gives three derived fuel cycle parameters attributable to each reactor design. It is clear that when compared to the other three reactors, the EC6 has far superior uranium utilization (thermal energy produced per unit mass of uranium from the mill), and a competitive overall fuel cycle efficiency.

Table 4. Derived plant parameters.

Description	ACR-1000	AP1000	EPR	EC6
Uranium utilization[1] (MWd_e/MgU_{mill})	1200	1340	1620	2340
Separative energy relative to plant net electrical output[2]	3.6%	4.2%	3.6%	0
Overall fuel cycle thermal efficiency[2]	33%	31%	34%	33%

Note:

1. Uranium utilization is given as megawatt-days electric (net) per tonne of uranium from the mill.
2. Gas diffusion enrichment at 2300 kWh_e per SWU is assumed.

4. POTENTIAL FOR CANADIAN ENRICHMENT CAPABILITY

Canada is at present the world's second largest producer of uranium, supplying reactors here and in other countries (

Table 5), most of which use enriched uranium. After conversion, Canadian uranium intended for enriched fuel reactors is exported as natural UF_6 for enrichment and fabrication. A study conducted for the Centre for International Governance Innovation [14] discusses the market, cost, and environmental aspects of instead providing enrichment in Canada.

Table 5. Uranium production from mines (MgU)*

Country	2003	2004	2005	2006	2007	2008	2009
Kazakhstan	3300	3719	4357	5279	6637	8521	14 020
Canada	10457	11597	11628	9862	9476	9000	10173
Australia	7572	8982	9516	7593	8611	8430	7982
Namibia	2036	3038	3147	3067	2879	4366	4626
Russia	3150	3200	3431	3262	3413	3521	3564
Niger	3143	3282	3093	3434	3153	3032	3243
Uzbekistan	1598	2016	2300	2260	2320	2338	2429
USA	779	878	1039	1672	1654	1430	1453
World	**35 574**	**40 178**	**41 719**	**39 444**	**41 282**	**43 853**	**50 772**

* Only the eight largest producing countries are shown

Source: World Nuclear Association

Table 6 shows the present world enrichment capacity, most of which is provided by centrifuge. However, two large gaseous diffusion plants in France and the US still account for about 37% of production.

Table 6. Past and projected enrichment capacity (kSWU/a)

Country	Company / Plant	2008	2015
France	Areva, Georges Besse I & II	10,800*	7000
Germany-Netherlands-UK	Urenco: Gronau, Germanu; Almelo, Netherlands; Capenhurst, UK.	11,000	12,200
Japan	JNFL, Rokkaasho	150	750
USA	USEC, Paducah & Piketon	11,300*	3800
USA	Urenco, New Mexico	0	5900
USA	Areva, Idaho Falls	0	>1000
USA	Global Laser Enrichment	0	2000
Russia	Â Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	25,000	33,000
China	CNNC, Hanzhun & Lanzhou	1300	3000
Pakistan, Brazil, Iran	various	100	300
TOTAL		**59,650**	**69,000**
Requirements (WNA)		**47,600**	**55,400**

* Gas diffusion technology
Source: World Nuclear Association

World capacity exceeds requirements and will continue to do so until 2015 at least. Based on the World Nuclear Association (WNA) reference scenario, a capacity of 55,400k SWU/a will be needed in 2015, while 69,900 kSWU/a is projected to be available. As there would be no possibility of bringing a Canadian enrichment plant on line by 2015, it is the expansion of enriched uranium requirements beyond 2015 that is of most interest here.

About one third of the world's used reactor fuel has been reprocessed to extract the substantial amounts of uranium and plutonium that it contains. In order to use this uranium, it must be converted back to UF_6 and re-enriched to a level great enough to counteract the effects of unwanted isotopes produced while the fuel was in the reactor. Thus, recycled uranium from previously used reactor fuel is not currently considered to be economical. The plutonium can be more easily recycled in the form of mixed oxide (MOX) fuel when blended with depleted uranium from enrichment plants.

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 or EC6 reactors 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.[15] Accordingly, there are no plans to build a reprocessing plant in Canada

Highly Enriched Uranium (HEU) from dismantled nuclear weapons can easily be blended with depleted uranium to produce reactor fuels. Agreements between the US and Russia on reducing nuclear weapons stockpiles could have the effect of displacing 10,600 Mg of mine production every year for about 12 years. The current arrangement between the US and Russia will expire in 2013, 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, and they should have no effect on the decision of whether to develop enrichment capacity in Canada.

For the purpose of this discussion, we will assume that current announced intentions for nuclear power expansion at Darlington will be fulfilled and that MOX fuel will not have a significant impact on Canadian requirements for fresh fuel.

Table 7 gives estimates for the separative work required for the Darlington B project for the maximum expected project size of 4800 MWe. The estimated requirement is 472 - 600 kSWU per full-power-year, depending on the reactor design. If other projects that have been suggested were to go ahead, the 600 kSWU per year could be exceeded. Thus we believe it is reasonable to expect that a 1000 kSWU per year plant would meet domestic requirements when new reactors come on stream in 2018 and beyond. This assumes that domestic supply would compete favourably with imported supply in terms of price and guaranteed long-term supply contracts. It is also conceivable that Canada would undertake to provide enrichment for export by diverting a significant fraction of the UF_6 that is currently exported to Canadian enrichment plants prior to export. If we assume that roughly 80% of the 2009 annual Canadian uranium production (10173 MgU from

Table 5), were enriched to 4% with 0.25% enrichment tails, we would require about 6 MSWU/a. This added to the roughly 1 MSWU/a for the domestic market gives about 7 MSWU/a as the upper limit of an enrichment market, which would be satisfied by one or two of the larger centrifuge plants. 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.

Table 7. Estimated separative work

Description	ACR-1000	AP1000	EPR
Net electrical output per unit (MWe)	1085	1090	1600
Separative work per GWy_e (kSWU)	138	131	122
Separative work per full-power-year (kSWU)	150	143	195
Units for 4800 MWe project	4	4	3
Separative work per full-power-project year	600	472	585

The estimated capital cost of a medium sized (3000 kSWU) centrifuge plant is in the range of US$1.5- 3.5 billion. Although these costs are large, it is estimated that the revenue calculated on the basis of the SWU value would offset the amortization costs even at a 15 percent interest rate.[14]

We turn finally to some environmental implications of the decision whether or not to undertake enrichment in Canada. If Canada were to purchase enrichment for its domestic power reactors from other countries, it would be retaining all the major fuel cycle wastes except (presumably) the depleted uranium, which has some commercial value, albeit small. For this benefit, Canada would be buying back enriched UF_6 with a large value added for its reactors.

In an enrichment plant with only natural uranium as input, the main environmental concerns are chemical. UF_6 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 by the USNRC.[16] 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.

Significant greenhouse gas (GHG) emissions are attributed to enrichment in gaseous diffusion plants, which require a large amount of electricity (about 2300 kwh_e per SWU). In the US in particular, 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 CO_2 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 CO_2 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.

5. CONCLUSION

The environmental review of new power reactors for Canada has evidently not considered the relative implications across the complete fuel cycle of the alternative reactor designs. The relative merit of designs under consideration is also obscured by use of a plant parameter envelope approach rather than comparative design-specific analysis. The broad environmental implications for Canada of a shift to the use of enriched fuel would require examination of the environmental effects in all parts of the fuel cycle for each design. Despite the different locations of the effects in different parts of the cycle, they are none the less attributable to the decisions regarding the nuclear generating station.

Although the natural uranium fuelled Enhanced CANDU 6 was only included in the environmental review at a late stage as an alternative technology, it would appear to have some significant advantages over the designs employing enriched fuel when viewed from the perspective of the once-through fuel cycle as a whole.

If a decision is made, nevertheless, to move to an enriched fuel cycle, consideration should be given to enriching uranium in Canada. From a waste management perspective, Canada would otherwise need to deal with mill, refinery, and conversion tailings, as well as with the used fuel from its own reactors, while the enrichment supplier would retain depleted uranium with some commercial value. On the basis of 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. Further, on the basis of environmental assessments for enrichment facilities in other countries, it is expected that an environmental assessment of a properly sited enrichment facility would result in approval.

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