15th International Conference on CANDU Fuel
Hilton Garden Inn/Homewood Suites by Hilton,
& Ajax Convention Centre, Ajax, Ontario, Canada
August 21-24, 2022

Used CANDU Fuel: Energy Independence and $ 1 Billion Carbon-Free Electricity Per Tonne

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ABSTRACT – All SMRs demand fuel enriched in fissile isotopes. Canada has no enrichment facilities. Therefore deployment of SMRs would make the country dependent on foreign fuel sources for its own energy needs. Yet Canada's 60,000 tonnes used CANDU fuel (UCF) contain 240 tonnes of transuranics that can furnish economical Canadian enriched starting fuel for fast-spectrum (fs) SMRs with a total power of 24,000 MWe. Such fs-SMRs, but not all, can, with recycling, replenish their fuel for centuries using only the remaining recovered uranium (RU) from the UCF stockpiles. Each tonne RU can create about $ 1 billion carbon free electricity, or $ 60 trillion from those 60,000 tonnes. The current plan is to bury this Canadian fuel resource.

1. Introduction

It requires only 6.25 fuel bundles in a CANDU reactor to produce one megawatt-year of electricity [1,p.394]. From this it can be estimated that since the beginning of nuclear energy generation in Canada 60 years ago, the accumulated 60,000 tonnes of used CANDU fuel have produced about $ 380 billion of fossil-free electricity and avoided the emission of 3.3 billion tonnes of CO_2.

Surprisingly, to deliver such huge amounts of energy, nuclear energy generation extracts less than 1% of the energy potential of uranium in its thermal reactors: generally close to 0.5% in light-water reactors, with 0.74% in heavy-water-cooled CANDU reactors being an industry best.

In Canada only 444 tonnes of the 60,000 tonnes of used heavy atom fuel have therefore actually been fissioned. The other over 99% unused heavy-atoms, suffused now with fission products (FPs), are considered "waste" and slated for permanent disposal in a deep geological repository planned since 2005 by the Nuclear Waste Management Organization and electrical utilities [1].

There is no other process that uses fuel so inefficiently, except in Nature for a few examples of photosynthesis. And even this is generally around 2%, reaching up to 8% in sugar cane [2,3].

Each heavy atom in the uranium fuel has the potential to yield almost 200 MeV of usable energy on being fissioned. Therefore it seems only logical that much more than the 1% be utilized.

This was and is possible, not with thermal reactors, but by cycling the heavy-atom fuel through certain types of fast-spectrum reactors, those that can maintain the fissile content of that fuel[4].

Canada's current exploration of small modular reactors (SMRs) provides a rare new opportunity to embark on a form of nuclear energy generation that can consume all of the heavy atoms in uranium fuel. With fuel recycling such a path can even re-utilize the over 99% heavy-atom content of Canada's 60,000 tonnes of used CANDU fuel "waste". The latter approach alone would provide Canada with fuel independence and sovereignty with home-grown enriched fissile starting fuel as well as with fuel replenishment for many centuries.

This paper explores the theoretical potential of extracting the energy of uranium fuel with neutrons over a range of energies, from thermal neutrons at 0.025 eV to nascent fission neutrons near 2 MeV. It does this by examining two interrelated fundamental ratios, each determined by the interplay of the neutron scattering cross sections of the constituent atoms in the reactor core: fuel, coolant/moderator, controls, and structural components.

The first ratio is the "New Neutron Ratio", or NNR. It is the ratio between the number of new neutrons produced by fission and the neutrons absorbed by all core components both in fission and radiative capture. For sustained power of a reactor this ratio must clearly be greater than 1.0, and for operation then brought to neutron equilibrium at 1.0 with absorptive control mechanisms.

The second ratio is the "Fissile Replacement Ratio", or FRR. This ratio considers the number new fissile atoms produced via neutron absorption and transmutation of fertile fuel atoms in the core versus the number of fissile atoms fissioned for energy production.

Ideally both ratios should be 1.0 or greater. The analysis below indicates that this is achievable only in the regime of high energy neutrons.

Yet even with high energy neutrons and fissile replacement the accumulating FPs eventually absorb too many neutrons to maintain neutron equilibrium. Thus periodically such FPs must be removed by fuel recycling and replaced with an equivalent mass of fertile fuel atoms.

A too brief discussion of fuel recycling indicates that the right technology, even with used CANDU fuel, can provide economical home-grown Canadian enriched fissile starting fuel via CANDU transuranic actinides (TRUs) at costs that are one third of used fuel "waste" disposal, and also at about half of the cost of importing such enriched fuel from foreign countries.

1.1 The Current State

Canada's nuclear power at present is generated in CANDU reactors fueled with natural uranium. This fuel contains 0.72% fissile U-235, with the bulk of the remainder consisting of U-238. At the end of a once-through fuel cycle the fissile content of the used fuel is still about 0.5%, of which almost half, 0.23%, remains as U-235, while 0.27% are fissile TRUs among a total of 0.4% of such actinides created in the reactor via the transmutation of U-238.

The total energy harvested from the uranium has come from the fission of 0.74% heavy atoms, as measured by the quantity of FPs generated.

Light-water reactors are apparently more efficient. But this is a false impression. A typical pressurized water reactor that is fueled with 3.3% fissile U-235 derives power from the fission of 3.4% of the heavy atoms. This seems better than the energy yield from the CANDU heavy water reactor. However, the enrichment process to obtain the 3.3% U-235 extracts only about 0.5% U-235 from each reactor fuel volume of mined natural uranium, leaving 99.5% of the uranium unused as "depleted uranium". To arrive at an enrichment of 3.3% U-235 for the reactor fuel, a total of 6.6 fuel volumes of natural uranium have to be used [5, p.144ff]. Therefore the energy yield from 3.4% fission of the reactor fuel volume has to be normalized by a factor of 6.6, to become 3.4% / 6.6 = 0.51% of the mined natural uranium. This is substantially less even than the small yield obtained in the CANDU reactor.

In France the plutonium in the transuranics created in the used fuel is extracted for reuse in MOX fuel (fuel mixed oxide fuel). This increases the total energy yield only from 0.51% to 0.65%.

Can the energy yield from uranium be increased in thermal reactors? The total 65 years of commercial nuclear energy, with all such reactors extracting <1% of the uranium energy potential, implies that this technology cannot produce a greater energy yield. The analysis leading to Fig. 4 in Section 3 confirms this.

1.2. The Imminent Future

The recent interest in small modular reactors (SMRs) has stimulated an examination of different designs of thermal reactors and also of fast-spectrum reactors. Due to their small core size such SMRs require fuel enriched in fissile components.

Canada, by historical choice, has no enrichment facilities for U-235. This creates a dilemma for Canada, a challenge: fuel independence vs. reliance on potentially fickle foreign sources for its energy needs. But it is also an opportunity.

Over the last 55 years Canada's CANDU reactors produced 60,000 tonnes used fuel, which contain 240 tonnes of transuranic actinides (TRUs) that can be economically extracted as a group. With no further purification these TRUs, 75% fissile, can become fuel for such SMRs.

These accessible fissile TRUs are a finite home-grown resource. They are sufficient to start a total of about 24,000 MWe of PRISM-like fast-spectrum reactors or other equivalent SMRs. However, without replacement and recycling they would be exhausted after the first fuel cycle.

What approach would permit the best use of such a finite Canadian fissile reserve?

The analysis below strongly suggests that for long-term Canadian fuel independence and sovereignty the only path is fuel recycling through fast-spectrum SMRs (fs-SMRs) that can maintain or augment the fissile contents of their cores. No thermal reactors are capable.

The result would be fuel self-sufficiency with centuries of Canadian carbon-free energy and minimal temporary shielded storage for the short-lived radioactive FP residue.

2. Reactor operation and fissile fuel replacement

Given the components and dimensions of a reactor core, it is relatively straightforward to calculate a few fuel-related important characteristics. Two such characteristics come to the fore:

1) Will the reactor operate, i.e. are enough new neutrons produced by fission to continue the chain reaction?

This question is of course crucial. Without new neutrons from enough fissile fuel atoms there is no operating reactor. In a world with an unlimited supply of inexpensive fissile uranium fuel the answer is affirmative and is also sufficient. Indeed, since the start of operation of the first commercial thermal reactor in Shippingport in 1958 [6] the world of civilian nuclear power seems to have carried on under this assumption of unlimited fissile fuel availability.

Only a few countries have considered uranium to be in limited supply. Fuel recycling and reuse along the lines of extraction of fissile plutonium by the aqueous PUREX process (**P**lutonium/**UR**anium **EX**traction) as originally developed by the military has been adapted for civilian used fuel, primarily in France and Russia[7]. India, Japan and Korea[8], countries without indigenous uranium resources have built or are considering recycling facilities as well as reactors that are more efficient in their use of fissile isotopes. The USA had early on developed similar efficient reactors, starting with the EBR1, a concept initiated by Enrico Fermi and designed and constructed at the Argonne National Laboratories by Walter Zinn, a Canadian expatriate from Kitchener [4,p.20].

The relevant second question is:

2) Are sufficient fissile fuel isotopes maintained in the core of the reactor to continue operation into a new fuel cycle without the addition of extraneous fissile fuel?

Both questions can be answered at the same time given the reactor core characteristics. Figure 1 shows a representative arrangement for the make-up of a CANDU reactor core [9], while Figure 2 is a cross section through an equivalent fuel assembly in a PWR (Pressurized Water Reactor) or, with slightly different dimensions, in a BWR (Boiling Water Reactor)[10].

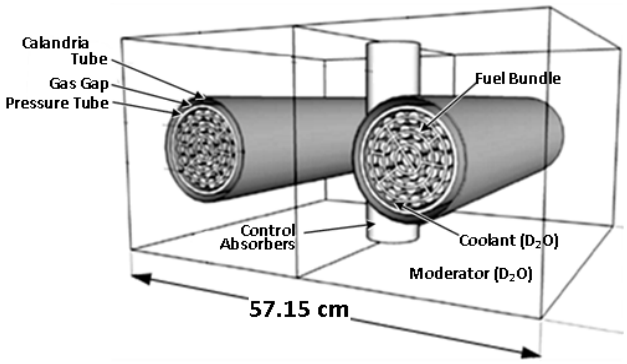

Figure 1. Representative arrangement of two pressure tubes as part of the core of a heavy-water-cooled CANDU reactor. Dimensions and composition from [9].

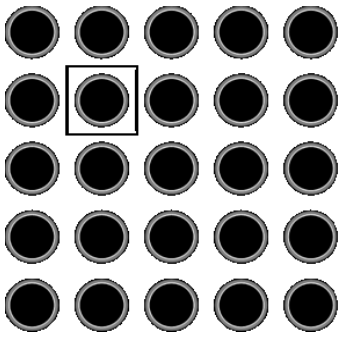

Figure 2. Representative arrangement of fuel elements inside a fuel assembly of either a PWR or BWR light water reactor. Dimensions and composition from [10].

Specific physical characteristics extracted from the material composition and dimensions of such reactors are summarized in Table 1.

It is clear in Columns 6 and 9 of Table 1 that both the CANDU reactor and the PWR are designed with enough fissile fuel to keep the neutron levels well above the operating equilibrium value of 1.0, i.e. **1.34** and **1.61** respectively, to permit not only control of power levels but also a reasonably long period of operation before refueling is required.

Those two columns show also that for these reactors there are rather low fractions of neutrons that are absorbed by U-238, 0.336 and 0.143 for the CANDU and the PWR respectively, to transmute the U-238 isotopes into usable fissile transuranics. With fractions of 0.546 + 0.086, or 0.632 of the neutrons reducing fissile U-235, the fissile replenishment ratio via U-238 for the CANDU reactor is only 0.336/0.632, or 0.532. For the PRW that replacement ratio it is even less, only 0.189. The major differences between the two design characteristics are a 33-fold higher neutron absorption by the light water coolant/moderator compared to heavy water, and a ten-fold larger neutron absorbing U-235 concentration (col. 3 and 7). Both effects siphon neutrons away from interacting with U-238.

Table 1: Characteristics underlying neutron replenishment by fission and production of new fissile isotopes by transmutation in CANDU and PWR cores at 0.025 eV

1	2	3	4	6	7	8	9
		CANDU			**PWR**		
Substance	Cross section (barn)	Relative # of atoms (%)	Relative interactions (2 x 3) norm'ed to 1.0	**New neutrons** or new fissile per neutron used	Relative # of atoms (%)	Relative interactions (2 x 7) norm'ed to 1.0	**New neutrons** or new fissile per neutron used
U-235 (fission) U-235 (abs'n)	605 95	0.029 0.029	0.546 0.086	**1.34**	0.323 0.323	0.654 0.103	**1.61**
U-238 (fission) U-238 (abs'n)	1.7×10^{-5} 2.70	4.009 4.009	2.1×10^{-6} 0.336	$\mathbf{5.3 \times 10^{-6}}$ 0.336	15.82 15.82	9.0×10^{-7} 0.143	$\mathbf{2.3 \times 10^{-6}}$ 0.143
O_2 (abs'n)	1.9×10^{-4}	8.076	4.8×10^{-5}		32.29	2.1×10^{-5}	
Zircon. alloys	0.250	3.762	0.029		10.05	0.0084	
Heavy water	0.00108	84.12	0.0028		0	0	
Light water	0.666	0	0		41.46	0.092	
CO_2 He	3.9×10^{-3} 6.6×10^{-4}	0.0034 0	4.1×10^{-7} 0		0 0.056	0 1.2×10^{-7}	
			Sum = 1.0			Sum = 1.0	
New neutrons per fission	for U-235 = 2.46 for U-238 = 2.50						

Are there conditions which can maintain the high level of nascent fission neutrons required for economical operation and at the same time increase the level of U-238 transmutation to fissile transuranic elements?

Clearly the concentration of fissile U-235 has a major desirable effect on the level of new neutrons created. However, as more U-235 atoms are used up in fission and also in transmutation to U-236, more fissile transuranic atoms need to be created via transmutation from U-238.

3. Energy dependence of new neutron ratio and fissile isotope replacement: CANDU Model

A second approach is suggested from plans to operate reactors at higher temperatures to take advantage of the ensuing thermodynamic benefits of harvesting more energy from the generated higher temperature steam. That brings the reactor into a perithermal region of slightly higher neutron energies with neutron cross sections altered somewhat. Figure 3 shows such changes in fission and absorption (radiative capture) cross sections for the perithermal region and beyond, up to energies of nascent fission neutrons, for most relevant atoms in a reactor core [11].

Calculations in Table 1 were carried out for neutrons at thermal energies, nominally at 0.025 eV which corresponds to about 290 K or 17 °C. Such calculations can be carried out at any energy using available data such as that shown in Fig. 3.

Immediately obvious in Fig. 3 is the parallel nature of the cross sections from low energies to about 1 eV. The cross sections remain in the same ratio over this region, and any calculations involving those ratios will yield a virtually constant result. Only U-235 shows an incursion at around 0.3 eV, near 3000 °C, that is mimicked in the fission and the absorption cross sections.

Figure 4 shows the results of calculations of ratio of new neutrons to neutrons used, carried out for a hypothetical CANDU core, similar to those in Table 1. The number of new neutrons

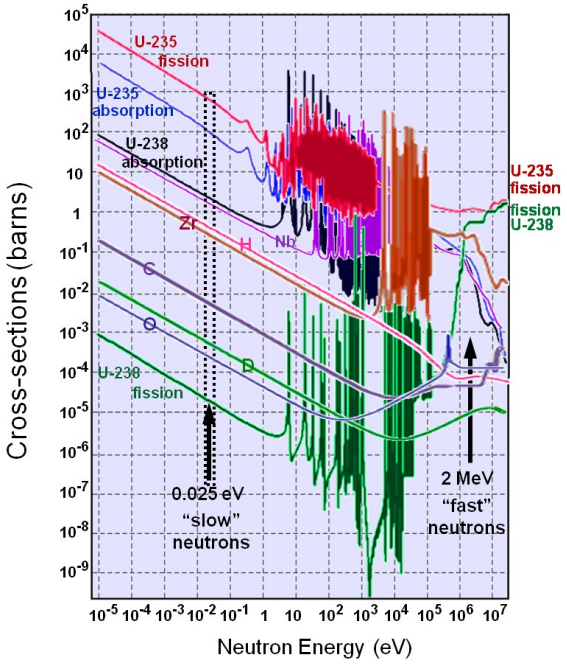

Figure 3. Fission and absorption (radiative capture) cross sections of uranium fuel isotopes and absorption cross sections of major atoms in reactor core structural materials, in coolant and in moderator [11].

produced due to fission of U-235 and U238 for an ambient energy of 0.025 eV are given in column 6 in bold type. That sum is plotted in Fig. 4 not just for thermal energies but for energies from 0.025 eV to 2 MeV (red line with closed diamond symbols), omitting the "resonance" energy region of wildly fluctuating cross sections seen in Fig. 3.

Similarly, using the absorption (radiative capture) cross sections of U-238 to derive the fraction of neutrons leading to transmutation of this isotope in relation to the fraction of fissile U-235 lost in fission and transmutation, the ratio of new fissile isotopes created to replace the fissile U-235 lost was calculated. This too is plotted in Fig. 4 for energies from 0.025 eV to 2 MeV (red line with open diamond symbols).

To examine the effect of changing the concentration of fissile U-235, calculations were carried out for natural uranium (0.72% U-235, red diamond symbols), for 2.5% U-235 (green triangles), and for 8% U-235 (black circles).

As anticipated from the constant ratios between all absorptive cross sections at low neutron energies (Fig. 3), the ratio for the creation of new neutrons per neutron used (Fig. 4, closed symbols) and the ratio for the replacement of fissile isotopes by transmutation per fissile U-235 lost to fission and radiative capture (Fig. 4, open symbols) were relatively constant in this region.

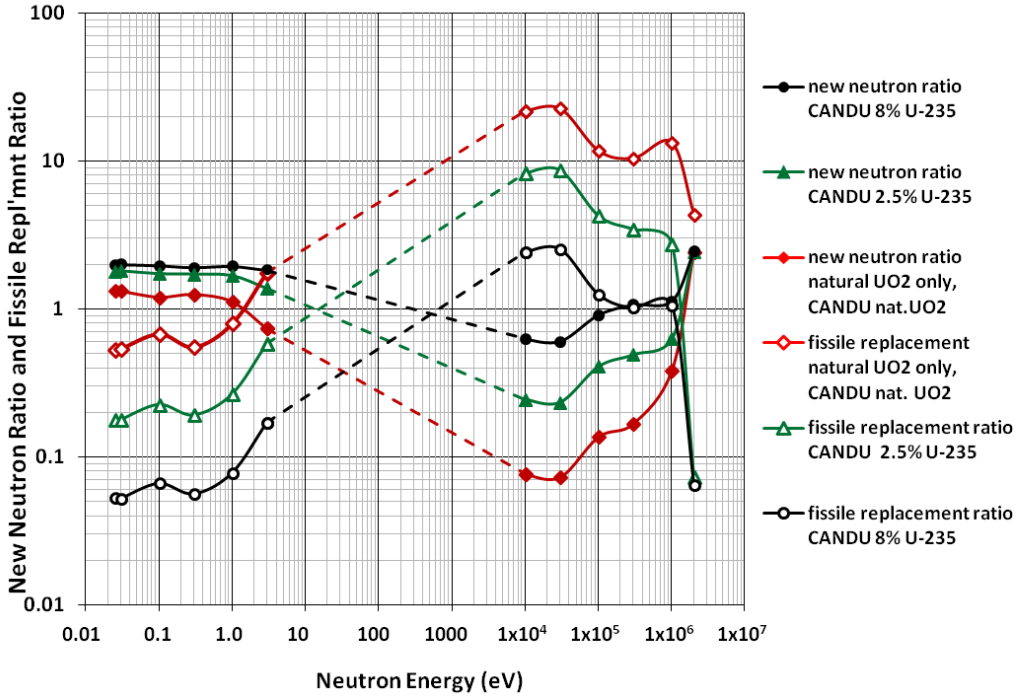

Figure 4. Variations in the relative values of the creation of new neutrons (new neutron ratio) and the creation of new fissile nuclei (fissile replacement ratio) with neutrons of different energies from thermal neutrons (0.025 eV) to nascent fission neutrons (2 x 10^6 eV). No losses of neutrons were assumed. Dashed line indicates resonance region (not analysed). Pairs of lines of the same colour (and the same open and closed symbols) refer to the same fuel concentration.

Thus increasing the operating temperature of the reactor to achieve a thermal neutron equilibrium at 0.1 eV (900 °C) or somewhat higher, did not result in a beneficial a more efficient utilization (greater degree of U-238 conversion).

Ideally the new neutron ratio and also the ratio for replacing fissile isotopes used should both be 1.0 or greater. In the thermal/perithermal region they are not.

While increasing the concentration of fissile U-235 had the anticipated benefit of creating more new neutrons by fission, it resulted in a large related decrease in transmutation and conversion of U-235 (green and black curves at low energies). Indeed the inverse behaviour of the two relationships suggests that a greater total uranium fuel utilization might be achieved by decreasing the U-235 concentration below that of natural uranium.

However, U-235 concentrations lower than the 0.72% in natural uranium would likely produce fewer neutrons than required for operation, since the moderation of nascent high-energy fission neutrons to thermal energies inexorably results in a non-fission capture of more than 10% of the neutrons in the fuel structure in spite of it being bathed in non-absorbing heavy water.

At high neutron energies, above 10,000 eV, a different picture emerges. The quantitative relationships between the various cross sections have changed (Fig. 3), both for a given isotope and also between isotopes. As a result the two relevant calculated ratios have reversed positions. At low concentrations of fissile U-235 the replacement ratio of fissile isotopes is now high, well above 1.0, but the ratio for the creation of new neutrons is so low that the reactor would not operate at all.

Nevertheless, increasing the fissile concentration has the same effect as before, in increasing the number of nascent fission neutrons and in decreasing the creation of new fissile isotopes due to transmutation of U-238. As a consequence the two curves move together and overlap in certain energy regions, in this case at a U-235 concentration of 8% and in the energy region between 0.1 and 1 MeV (Fig.4). Both ratios in this region are encouragingly close to 1.0.

Very similar results, both in the low energy and high energy regions were obtained using the geometries and constituents of a modelled PWR core. For both thermal reactors the properties of the light and heavy water coolant/moderator were arbitrarily maintained throughout. For high neutron energies this of course has to be substituted with a non-moderating coolant. Therefore similar calculations were carried out using the high energy cross sections of several fast-spectrum reactor designs, below.

4. Energy dependence of new neutron ratio and fissile isotope replacement: High energy region

Design parameters are available in published form for three fast-spectrum reactor designs with sufficient geometric and compositional information to calculate the new neutron and fissile replacement ratios at higher energies (the final designs may not have those identical parameters).

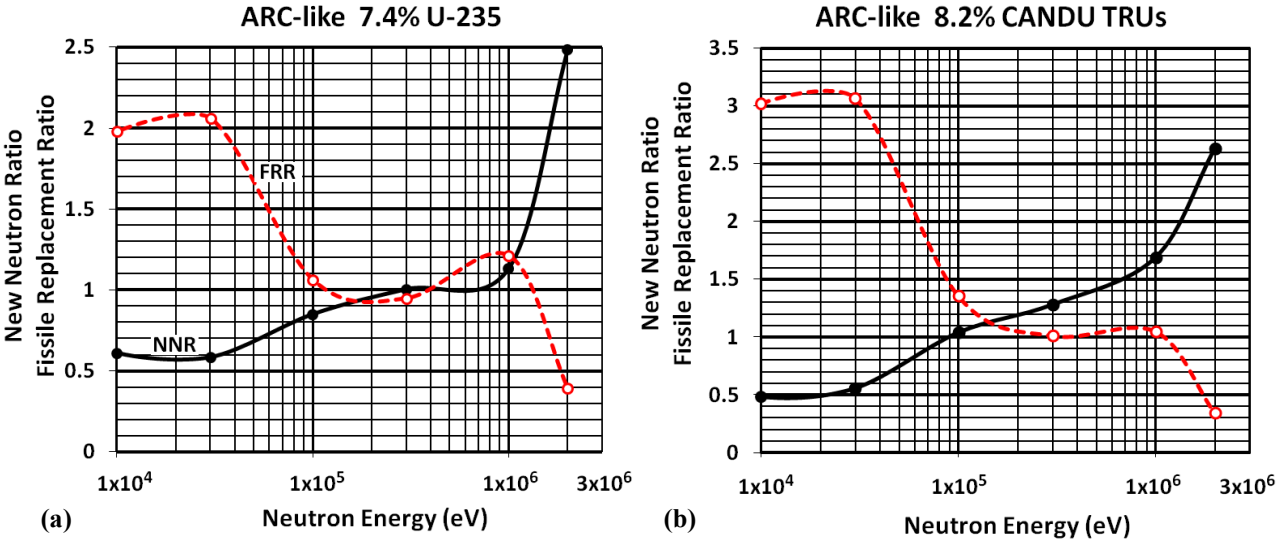

Figure 5. (a) An ARC-like fast-spectrum reactor fueled with enriched uranium optimized for simultaneous optimization of the creation of new neutrons and replacement of fissile nuclei used. (b) A similar optimization for uranium enriched with Pu-containing transuranics from used CANDU fuel.
FRR (dashed red line): fissile replacement ratio; NNR (solid black line): new neutron ratio.

Figure 5 shows the calculated two ratios for the 100 MWe ARC-100-like SMR from Advanced Reactor Concepts [12]. The reactor is planned to operate starting with a high concentration of U-235 to provide it with fuel for about 20 years without refueling. However, such a fissile load puts this fast-spectrum reactor clearly into a range of a "burner" with a fissile replacement ratio or conversion ratio less than 1.0. To achieve a ratio of 1.0 a more optimal enrichment is lower, close to 7.4% U-235 (Fig. 5a), for which both the new neutron ratio (NNR) and the fissile replacement ratio (FRR) are close to 1.0 for neutron energies from $1x10^5$ eV to $1x10^6$ eV.

The planned ARC-100-like reactor will slowly convert U-238 to fissile transuranics which are intended to be the major fissile source of fuel for the second fuel cycle. However, if the reactor is fuelled from the outset with transuranics from used CANDU fuel at a level of 8.2%, then an operation with internal full replacement of its core fissile complement can be achieved right from the start of operation (Fig. 5b).

Such a maintenance of fissile fuel is planned in the 300 MWe PRISM SMR (**P**ower **R**eactor **I**nnovative **S**mall **M**odular) from GE-Hitachi [13]. Its core is to be fueled with plutonium as its fissile source, with a fuel cycle of about 6 years. Calculations, using 7.73% transuranics from used CANDU fuel, indicate a near-optimal performance in terms of simultaneously having the NNR and the FRR being 1.0 or greater at neutron energies from $1x10^5$ eV to $1x10^6$ eV (Fig. 6).

The third fast-spectrum SMR examined was the Moltex Energy SSR-W, a 150 MWe modular unit with on-power refueling, operating with liquid uranium/plutonium chloride fuel and separate liquid FZrNaK-fluoride salt cooling [14]. As designed as a "waste-burner" the reactor is fueled with about 15% plutonium chloride derived from used CANDU fuel. This provides a very high

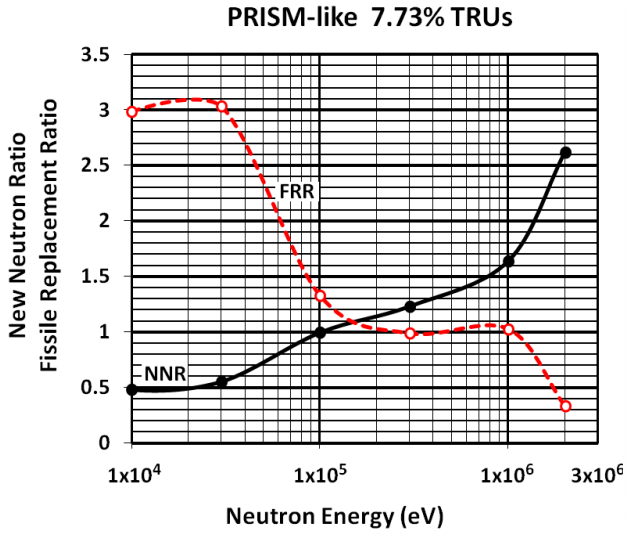

Figure 6. PRISM-like fast-spectrum reactor core model [7] fueled with an optimum concentration of used CANDU fuel TRUs at 7.73% for simultaneous new neutron and fissile replacement ratios greater than 1.0.

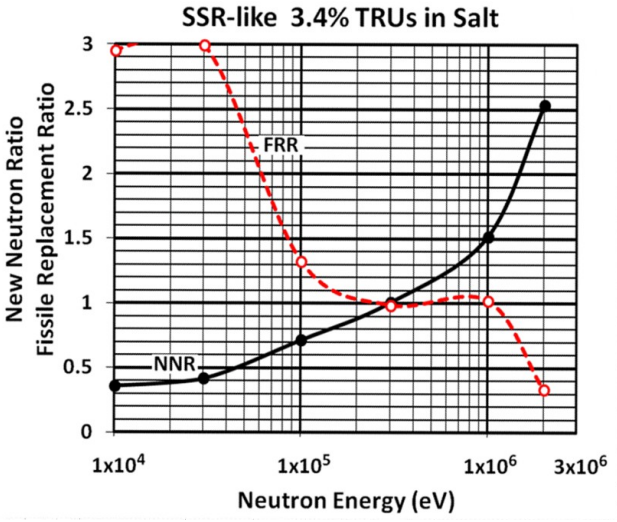

Figure 7. Stable-salt-reactor-like model core [8] fueled with 3.4% used CANDU fuel TRUs as optimum compromise for simultaneous large new neutron and fissile replacement ratios near 1.0.

new neutron ratio, but also a fissile replacement ratio well below 1.0., i.e. a low transmutation rate of U-238. However, by reducing the plutonium concentration by using a level of 3.4% transuranics (3.3% plutonium), the results shown in Fig.7 can be obtained. Both NNR and FRR are 1.0 or greater for neutron energies from $3x10^5$ eV to $1x10^6$ eV.

Below that energy range the number of new neutrons created are not sufficient for neutron equilibrium, although a more detailed calculation may indicate that the average number of neutrons created in the entire energy range may still be enough to operate the reactor. Raising the fissile concentration lowers the fissile replacement ratio below 1.0.

5. Towards recycling of used CANDU fuel

Given that Canada has no U-235 enrichment facilities and is unlikely to construct them in the near future, can enriched fissile fuel in the form of transuranic elements be extracted economically from Canada's 60,000 tonnes of used CANDU fuel?

Such used fuel can be considered as three distinct components with a content approximately of

98.88 % uranium, with 0.23 % being fissile U-235
0.74 % fission products
and 0.40 % transuranic elements (Np, Pu, Am, Cu,...) with 70% being fissile.

The U-235 is not separable currently other than in new physical enrichment facilities capable of handling highly radioactive input feedstock. It will not happen.

Planned deep geological disposal of used nuclear fuel is currently the major thrust in a number of nations with nuclear energy generating stations. In Canada funds sufficient for such a plan have been accumulating over many years as a small fraction, 0.26 ¢, of the consumer price per kWh

of electricity generated from nuclear power. These funds, recently stood at over $ 10 billion, derived at that time from about 2.8 million used CANDU bundles [15]. Normalizing that cost:

funds for nuclear waste management: $ 3,654 per fuel bundle.

To compare, cost estimates were made of three plant designs for fuel recycling of used CANDU fuel in a University of Toronto study that included this author, of PUREX-like aqueous processing (current standard), fluoride volatility methods, and electro-refining in molten salts (pyroprocessing). No pure plutonium was to be separated, to alleviate concerns of nuclear proliferation. Therefore the aim was to provide three fractions:

1) pure uranium (as stored feeder stock for future fuel cycling),
2) pure fission products (as the only material needing medium term shielded storage),
and 3) an impure blend of concentrated transuranics still mixed some 80% or more of diluting uranium and a small acceptable level residues of fission products.

Fraction 3) would serve as starting fuel for SMRs.

The cost for the three approaches included land, facilities, equipment, consumables, OM&A, capital borrowing expenses, licence, taxes, contingencies, etc. To provide a bound, the facilities were aimed at an annual throughput of 100 tonnes of used CANDU fuel, the approximate flow from one CANDU reactor. The resulting costs were normalized per used CANDU fuel bundle.

Those results were:	PUREX-like procedures	$ 7,430	per used CANDU bundle
	Electro-refining (pyroprocessing)	$ 1,370	”
	Fluoride Volatility methods	$ 1,120	”

Clearly two of the recycling/separation procedures are less costly by about a factor of three than long-term disposal of a used CANDU fuel bundle. Moreover, in creating fast-spectrum SMR fuel the heavy atoms from each used CANDU fuel bundle can deliver about $ 500,000 of carbon-free electricity per fuel cycle, which would be lost by disposal of the used fuel [5, p.172].

Estimates of recycling used fuel in the U.S. environment indicate a cost near USD 330/kg HA for aqueous PUREX-like processing [4, p. 285ff], while pyroprocessing costs were about 20% of this. These convert today to $ 8,460 and $ 1,690 respectively, per used CANDU fuel bundle. These numbers are not too different from the $ 7,430 and $ 1,370 established in the above study.

But is it economical or even profitable to furnish fissile SMR starting fuel from used CANDU fuel compared to buying foreign enriched U-235?

A PRISM-like fast-spectrum reactor load of 20 tonnes of heavy-atom fuel would require about 4 tonnes of U-235. Its purchase from USA sources would cost between $ 145 and 155 million[16]. The equivalent charge using transuranics from used CANDU fuel via pyroprocessing, above, would be half that price, costing $ 77 million.

6. Summary

The joint analysis of fertile isotope transmutation (FRR) and neutron production (NNR) over a neutron energy range of 0.025 eV to 2 MeV shows that uranium fuel use can be increased from the current 0.5 – 0.75 % to close to 100% only by recycling the fuel through fast-spectrum

reactors that maintain the fissile complement of the fuel. No thermal reactors have that capability. Such-spectrum fast reactors exist, and have existed since the 1950s. Similarly, recycling technologies have been developed that produce minimal waste streams and are also economical. Such technologies applied to Canada's 60,000 tonnes used CANDU fuel would deliver cost-effective home-grown enriched fissile starting fuel for reactors with a total power of 24,000 MWe and provide Canada with fuel security and fuel sovereignty for centuries.

7. Acknowledgement

The author thanks the University of Toronto Chem. Eng. Dept. for permission to use the results of the CHE430 Plant Design course. The author had a supervisory role in the study.

8. References

[1] Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel. Final Study. NWMO, 22 St. Clair Avenue East, Sixth Floor, Toronto, Ontario, M4T 2S3 Canada www.nwmo.ca/studyreport/?action=downloadfile&id=341
[2] Govindjee, R. "What is photosynthesis". https://www.life.illinois.edu/govindjee/whatisit.htm
[3] Miyamoto K. "Chapter 1 - Biological energy production". Renewable biological systems for alternative sustainable energy production (FAO Agricultural Services Bulletin - 128).
[4] Till C.E. and Chang Y.I. "Plentiful Energy", publ. CreateSpace (Amazon), 2011.
[5] Ottensmeyer P, "Neutrons at the core", Kindle Direct Publishing, Amazon. 2021.
[6] Clayton J.C., "The Shippingport pressurized water reactor and light water breeder reactor". 25th Central Reg. Meet. Am. Chem. Soc., Pittsburgh, PA, Oct. 4-6, 1993. https://inis.iaea.org/collection/NCLCollectionStore/_Public/25/025/25025940.pdf
[7] World Nuclear News. Reprocessing contract signed for fast reactor complex. Jan. 11, 2022. https://www.world-nuclear-news.org/Articles/Reprocessing-contract-signed-for-fast-reactor-comp
[8] McGoldrick F., The new peaceful nuclear cooperation agreement between South Korea and the United States. Sep. 2015. http://keia.org/wp-content/uploads/2015/12/KEI_Special-Studies-2015-FINAL.pdf
[9] CANDU lattice pitch: The Essential CANDU. http://www.nuceng.ca/candu/pdf/4%20-%20Reactor%20Statics.pdf
[10] NUREG- 1754. A New Comparative Analysis of LWR Fuel Designs 2001. https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1754/; https://www.nrc.gov/docs/ML0136/ML013650469.pdf
[11] National Nuclear Data Centre. https://www.nndc.bnl.gov/sigma/tree/index.html
[12] Wade DC, Walters L. "ARC-100: A sustainable, modular nuclear plant for emerging markets". ICAPP'10, San Diego, CA, USA, June 13-17, 2010. Paper 10079.
[13] Dubberly AE, Boardman CE, Wu T, Yoshida K. "GE superPRISM oxide and metal fuel core design," 8th Int'l Conf. Nucl. Eng., ICONE 8, April 2-6, 2000, Baltimore MD.
[14] Khuttan A, Owens A, O'Sullivan R, Scott I. "Molten salt reactor thermohydraulics & economics of linear reactor design". Moltex Energy: 50 Fenchurch St, London EC3M3JY https://www.moltexenergy.com/technology-suite/
[15] NWMO Annual Report 2017. Moving towards partnership; AECL Nuclear Waste Trust Fund, 2017; Hydro-Québec Trust for Management of Nuclear Fuel Waste; Garamszeghy M. "Nuclear Fuel Waste Projections in Canada – 2017", https://www.nwmo.ca/
[16] Nuclear fuel cost calculator. http://www.wise-uranium.org/nfcc.html; UxC Fuel Quantity & Cost Calculator. https://www.uxc.com/p/tools/FuelCalculator.aspx