THE SMR CHALLENGE IN CANADA: ENRICHED FUEL; A SOLUTION: RECYCLING OF USED CANDU FUEL

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Abstract

The recently released Canadian Small Modular Reactor Roadmap (SMR Roadmap) expresses a concern about the availability and security of fuel for SMRs in Canada. This paper outlines an extraction/recycling approach that eliminates that concern. The small cores of SMRs engender a greater loss of neutrons than larger Canadian CANDU reactors that can operate on natural uranium fuel. That loss has to be compensated by an enriched fissile isotope concentration in the SMR fuel to permit neutron balance for operation of such small reactors. Canada has no enrichment facilities, with an imminent consequence that this country would henceforth have to rely on the good will of other nations, nuclear weapons states such as the USA, Russia, China, France or the UK to furnish SMRs in Canada reliably with such enriched, relatively expensive fuel. Alternatively Canada can maintain its fuel independence by recycling its stored used CANDU fuel to extract enough fissile transuranics (TRUs) from the current existing 60,000 tonnes of stored used fuel "waste" to furnish starting fuel for the equivalent of 24,000 MWe fast-spectrum SMRs. Business plans for such extraction/recycling facilities show that fuel enriched to 19.9% TRUs would be about half the cost, or less, of 19.9% low-enriched U235 purchased in the USA. Moreover, since the TRUs from used CANDU fuel are a mixture of isotopes that prevents weapons production without much further very costly isotope separation, concerns with weapons proliferation are effectively negligible. The extraction/recycling approach of used CANDU fuel would keep Canada independent and sovereign in nuclear fuel. Moreover, with a suitable choice of types of SMRs that can maintain or augment their fissile fuel components, this technology would provide fuel security for the Canadian nuclear industry for many centuries.

1. Introduction

The potential introduction of small modular reactors (SMRs) to Canada's energy mix would usher in an exciting new era of nuclear power in the country, different in technology both on a reactor level and on fuel aspects. Such SMRs require enriched fuel. Canada makes no such fuel.

Therefore the recently released Canadian Small Modular Reactor Roadmap [1] expresses a justifiable concern about the availability, national independence, and security of fuel for SMRs in Canada. This concern crystallizes the general realization that, according to the World Nuclear Association [2], Canada's 500,000 ton reserve of economically mined uranium, i.e. at US$ 130 per kg U, will be exhausted by 2050 if recent Canadian rates of mining and export continue.

The SMR Roadmap itself offers no way forward other than further studies. However, the background material of the Roadmap in the Technology Working Group Report [3] suggests fuel pathways that are more directive, but they are somewhat at odds with the recommendations of the main report on continued planned direct used-fuel disposal.

This paper takes an independent comparative approach by examining the general fuel use characteristics of several different types of SMRs compared to the CANDU reactor, after assessing the feasibility and cost of supplying that fuel via proliferation-resistant fuel recycling of used CANDU fuel with a modified PUREX technology, with electrorefining (pyroprocessing) and with a fluoride volatility approach.

In brief, the analyses indicate that a number of SMR designs examined act as pure burner reactors of fissile fuel while others operate as break-even reactors, i.e. maintain their fissile complement, or even augment their fissile content. All recycling approaches examined were feasible, and avoided proliferation concerns, but a modified PUREX approach was 2.0 times more costly than direct disposal. On the other hand, electrorefining and fluoride volatility approaches were found to be 2.7 to 3.3 times more economical than disposal, and also provided TRU-based fissile fuel at half the current price of commercially available enriched U-235 fuel.

The additional advantage of huge reductions in long-term radiotoxicity and the potential approach to fission products are not discussed here.

The results reveal the wisdom and also the greater economy of choosing "break-even" SMRs or better, and fueling them for centuries via recycling of our used CANDU fuel stockpiles.

2. Background

Canada's early experience with neutron moderation by heavy water (deuterium oxide, D_2O) resulted in the design of the CANDU reactor (CANada-Deuterium-Uranium reactor) which permitted fueling using natural uranium with its normal content of 0.72% fissile uranium-235 (U-235) [4]. Since Canada has large uranium reserves, it has enjoyed nuclear fuel independence and fuel security in its utilization of CANDU-based nuclear energy over the last 60 years.

In contrast, other nations with light-water reactors need fuel with higher concentrations of fissile fuel components. As a consequence those nations would either have had to develop fairly huge and costly U-235 enrichment facilities, or be dependent for their fissile fuel supply on nations with excess capacity in such facilities developed normally for military nuclear weapons production. The expense of such facilities, coupled with their potential of acquiring nuclear weapons capabilities, has generally meant that non-weapons nations with nuclear power are dependent for their enriched U-235 fuel on existing nuclear weapons nations.

With the potential introduction of small modular reactors (SMRs) into Canada, this nation is at a cross-roads. The concern about the availability, national independence, and security of fuel expressed in the SMR Roadmap stems from the need of such small reactors for fuel enriched with fissile components such as U-235 well beyond the 0.72% of natural uranium.

Without building our own fissile-enrichment facilities, this uranium-producing country, Canada, would therefore also become dependent for such a U-235-enriched SMR fuel supply on the good will of nuclear weapons nations such as the USA, Russia, China, France or the UK.

Nonetheless, even with a costly foreign-enriched U-235 supply harvested from Canadian-supplied natural uranium, our base of fissile U-235 from our 500,000 tons of Canadian economic

uranium reserves would dwindle dramatically and also become much less economical around 2050 [2], if 2016 rates of uranium exports of 16,000 tons/year continue. Such a 3-decade span is much shorter than the lifetime of any modern nuclear reactor. After that time Canada would be dependent on foreign sources even for our current annual need of 2000 tons of CANDU fuel.

3. The alternatives

There are two complementary alternative approaches that solve both Canada's fissile fuel independence and also Canada's potential future fissile fuel shortage.

The most important path is predicated on the realization that Canada's current 60,000 tonnes of stored used CANDU fuel contain about 240 tonnes of a mixture of transuranic (TRU) elements, neptunium (Np), plutonium (Pu), americium (Am), etc., created during the sojourn of natural uranium in our CANDU reactors over the last 60 years. This TRU mixture as a whole, concentrated by extraction of fission products and excess uranium can serve as an exceedingly useful fissile fuel component for SMRs, since about 60% of the TRUs are fissile isotopes.

As an example, the 240 tonnes of TRUs are sufficient to start about 24,000 MWe fast-spectrum SMRs, adding almost two times Canada's current level of nuclear power of 13,500 MWe.

However, continuous fuel availability necessitates a second, parallel path involving the choice of SMRs. If added SMRs merely utilize and consume the fissile components of the fuel, i.e. are so-called "burners", without maintaining the level of that fissile material, such a course would correspond to a continuation of the current uranium exploitation, and would result in faster depletion of fissile fuel as more reactors are added, a depletion even of the TRU resource.

However, in the panoply of SMRs there are technologies that permit the maintenance of the fissile fuel component and can even augment it to supply fissile fuel for our CANDUs [23]. Except for some isolated geographic applications, it is such reactors, break-even reactors as a minimum, which must be chosen in order to safeguard the ability of the nuclear industry to deliver its non-carbon energy for years into the future, for over 4000 years at current nuclear power levels in Canada. Such reactors, once started, would replenish their fuel solely with the 59,300 tonnes depleted uranium stored in used CANDU fuel stockpiles.

If such a direction is not chosen, the demise of Canada's nuclear industry as an economical energy producer would be inevitable in a few decades.

The next section, Section 4, addresses recycling technologies of used CANDU fuel to provide relative cost estimates of these procedures. Section 5 then discusses in simplified form the neutron/fuel behaviour with respect to intrinsic fissile replacement within the core of several representative SMRs in relation to Canada's CANDU reactors, covering a light-water SMR, two different molten-salt designs, and two metal-cooled fast-spectrum reactors (FSRs).

4. Recycling of used CANDU fuel

Enrichment of fissile U-235 is costly and proliferation-prone, having been developed initially for the creation of nuclear weapons. However, the Moltex Energy (UK) literature indicates that its

SSR-W SMR (Stable Salt Reactor–Waste-burning) is specifically designed to consume the fissile isotopes in a mixture of transuranic (TRU) components such as those in used CANDU fuel [5,6]. This is a clear advantage over mere consumption of proliferation-sensitive PUREX-extracted plutonium used today as MOX fuel (Mixed Oxide) in large light-water reactors. The analysis of the PRISM FSR (Power Reactor Innovative Small Module), an SMR design from GE-Hitachi, USA, indicates that all TRU isotopes in used CANDU fuel can be readily consumed while maintaining and even augmenting fissile components by transmutation of its fertile U-238[7-9].

Hence Canada, which has no enrichment facilities, has the means to obtain local fissile starting fuel via the TRU content of its stored used CANDU fuel, if, as shown below, those TRUs can be extracted economically and in a proliferation-resistant manner.

It has been generally assumed that recycling of long-lived highly radioactive used CANDU fuel is "prohibitively expensive and would require decades of research", and that therefore such used fuel is "waste" and best discarded deep underground [10]. That conclusion was based on canonical PUREX-like reprocessing, and has been the standard thinking accepted for well over a decade without question. Data presented below indicate that with the challenges raised by the introduction of SMRs into the Canadian nuclear framework this standpoint must be reexamined.

4.1 Transuranics: used CANDU fuel as an economical fissile resource

All of the current reactors and reactor designs other than the CANDU-like reactors, whether full sized or SMRs, require enriched fissile material, normally considered to be enriched U-235. A few SMRs can operate with 3% enriched fissile fuel, but most, including for example the PRISM FSR from GE-Hitachi, aim for fissile concentrations of 15% up to the permitted limit of LEU (low-enriched uranium) of 20% out of necessity, since small reactor cores naturally lose more neutrons than large reactors before the neutrons find another fuel atom to fission.

While some SMR designs call for U-235, several have concentrated on the use of transuranics (TRUs) from used fuel as a source of fissile fuel material. This type of fuel is a step beyond the canonical MOX fuel, which consists of LWR-derived purified plutonium diluted with uranium depleted of U-235. TRU-based fuel contains all actinides, from uranium to higher atomic number elements such as $_{93}$Np, $_{94}$Pu, $_{95}$Am, $_{96}$Cm, etc. created in the core of a given reactor. This mixture of unpurified elements is essentially proliferation resistant, since fissile elements such as Pu-239 are effectively diluted with 30% fertile (non-fissile) elements such as Pu-240, which are virtually impossible to separate from the fissile components.

Is it economical to extract such highly radioactive mixed TRUs?

As a reference point, the current alternative is to bury the radioactive used CANDU fuel permanently in a planned deep geological repository (DGR). A recent estimate for the life cycle cost for such a plan, depending on the capacity of the DGR is between $ 18.3 and $ 28.4 billion [11]. The current management cost to the user of nuclear electricity per used CANDU fuel bundle can be estimated by considering that the total funds tithed from nuclear electricity up to 2017 are CAD 10.125 billion [13-15,24]. The stored number of fuel bundles in 2017 was 2.771 million [16], indicating a current used fuel management fund of

$3,654 per used CANDU fuel bundle.

How does this compare to the cost of recycling of the fuel bundles to extract the TRUs?

An in-depth analysis was carried out as an entire fourth-year Chemical Engineering course in Plant Design at the University of Toronto to extract such TRUs specifically without separating and purifying plutonium to obviate proliferation concerns [17]. The analysis included 1) a modified PUREX approach (aqueous) that included an initial 75% extraction of pure uranium to reduce subsequent processing volumes, 2) electrorefining in molten salt (non-aqueous), and 3) fluoride volatility methods. The fluoride volatility study was repeated 5 years later with equivalent results. To provide a finite bound the analysis was arbitrarily limited to processing one annual CANDU reactor fuel load of 100 tonnes. For fluoride volatility the smallest equipment met this through-put criterion in 4 months, permitting a three-fold larger annual through-put with the same facility. The output in each case was in metal form ready to be adapted to specific fuel forms for different reactors. The results in summary form are shown in Table 1.

	Modified PUREX	Electrorefining (Pyroprocessing)	Fluoride Volatility
Capital - overnight cost (land, constr., license, indir. costs + contingencies ~30%)	186.9 M$	80.2 M$	11.5 M$
Total annual cost (OM&A, taxes, 5% interest for 40yrs)	37.2 M$	11.0 M$	5.6 M$
Annual thru-put (bundles)	5000	8050	5000
Cost per bundle	$ 7,432	$ 1,368	$ 1,114*
* see text			

Table 1. Cost breakdown of recycling used CANDU fuel by various methodologies

The PUREX-like processing, even modified to avoid extracting pure plutonium, is costly, about twice as expensive per used CANDU fuel bundle as funds currently set aside for direct disposal in a DGR. However, both the electrorefining and fluoride volatility technologies result in recycling costs that are considerably less, from 2.7 to 6.7 times less, than direct disposal.

A repeat of the study on fluoride volatility in 2017 took advantage of a 3 times larger though-put possible with the same equipment, resulting in a further reduction of costs to $ 412 per bundle. On the other hand a very much more conservative estimate [25] set the capital costs of fluoride volatility methods at $ 229 million. This would substantially raise the cost of borrowing and result in a total annual cost of $ 18.2 million. However, the greater through-put of this technology would result in a cost per bundle of $ 1,156, still near the least expensive management approach.

5. Neutron interaction results in representative SMR designs

Reactor designs are proprietary information. Thus the data shown in Table 2, needed to determine reactor properties, are based on calculations made using published information and

represent reasonable estimates but not necessarily exact characteristics. Therefore any representative reactor mentioned should be regarded at best as CANDU-like, NuScale-like, etc. This is particularly important where data was taken from a historical reactor such as the Oakridge DMSR (Denatured Molten Salt Reactor) as being representative of the IMSR (Integral Molten Salt Reactor) design of Terrestrial Energy. Corrections in the fundamental data in Table 2 could readily produce correspondingly more correct outcomes below, in Table 3 and 4.

isotopes/ atoms/ compounds/ alloys		Microscopic cross sections (barns)			Relative Number of Moles in Reactor Core (%)					
		Thermal 0.025 eV	100 keV	2 MeV	CANDU	NuScale	DMSR / IMSR	SSR-like	ARC-100	PRISM
U238	f *	0.0^4176	0.0^4403	0.480	4.023	14.49	0.534	3.835	32.612	26.26
	c *	2.63	0.172	0.0410						
U235	f	596	1.55	1.19	0.0295	1.274	0.017	0.0089	3.999	0.0613
	c	97.6	0.399	0.0568						
Pu239	f	770	1.54	1.95				1.870		2.100
	c	281	0.23	0.00766						
Pu240	f	0.0634	0.0745	1.677				0.748		0.597
	c	293	0.344	0.0627						
Pu241	f	1030	2.12	1.665				0.150		
	c	375	0.320	0.0718						
O	c	0.0^3368	0.0^476	0.0^4155	8.105	31.54				
H_2O	c	0.666				35.50				
D_2O	c	0.00116	0.0^4419	0.0^3208	84.09					
zircaloy/Zr	c	0.191	0.0175	0.0128	3.745	17.20		3.784		
CO_2	c	0.00432	0.0^4937	0.0^4377	0.00315					
Na	c	0.529	0.0311	0.0319				14.93	18.85	24.78
HT9	c	2.400	0.00689	0.00196				15.37	44.54	46.21
LiF	c	0.0633					4.290			
BeF_2	c	0.0285					0.957			
C	c	0.00931					94.20			
Cl	c	33.3	0.00192	0.0^4103				35.18		
F	c	0.00931	0.00375	0.0^4880				21.19		
K	c	2.13	0.00498	0.0^3253				2.838		
Hf	c	101	0.527	0.0763				0.095		

* f = fission cross section; c = radiative capture cross section

Table 2. Input parameters for calculations of neutronic and isotopic behaviour in the cores of several representative SMR designs in relation to CANDU reactors

Neutron cross section data were obtained from Brookhaven data files [18]. Superscripts in cross sections indicate numbers of zeros. Relative percentages of major reactor core component elements were calculated from published data [5-8,21-22].

The calculations of the parameters shown in Tables 3 and 4 took into account all the relevant fuel isotopes as well as structural components and heat transport fluids in a central portion of the core. Fresh fuel was assumed and no neutron losses were considered for that region.

For the CANDU-like core and for the SSR-like core the reactivity balancing of partly used and fresh fuel from geometrically opposite fuel directions is neglected at this stage with the result of somewhat higher calculated new-neutron ratios for those reactors.

5.1 Thermal reactor comparisons

In Table 3 the first line of calculated parameters (new-neutron ratios) for several thermal reactor designs indicates the expected capability of all controlled operating reactors to produce more neutrons from fresh fuel than required for neutron equilibrium. For constant power this ratio is controlled to be 1.0. Any number less than 1.0 results in the reactor shutting down.

	CANDU	NuScale	DMSR/ ISMR	SSR-like
Reactor type	Thermal	Thermal	Thermal	Thermal
Neutron energies	0.025 eV	0.025 eV	0.025 eV	0.025 eV
New-neutron ratio	1.34	1.95	1.77	1.27
# U-235 nuclei fissioned (normalized reference)	1	1	1	1
# New fissile ratio # Pu-239 from U-238 or Pu-241 from Pu-240	0.52	0.043	0.12	0.11

Table 3. Some operational core characteristics of representative thermal reactors.
CANDUs are heavy-water-cooled and NuScale-like reactors are light-water-cooled, while the DMSR/ISMR-like and SSR-like reactors are different molten salt designs.

The higher numbers of the NuScale-like and DMRS designs indicate a higher initial fissile fuel content which is largely compensated by controlled neutron absorption. For CANDU reactors and for SSR-like liquid-fuel reactors the high reactivity (high new-neutron ratio) of fresh fuel is primarily compensated by adjacent placement of used fuel with reactivities less than 1.0.

Once a controlled neutron equilibrium of 1.0 is achieved as part of the reactor design, a primary interest for efficient uranium fuel consumption is the ratio of the number of new fissile isotopes created for every fuel nucleus fissioned. This ratio is also referred to as the conversion ratio, or CR. It is shown in the last parameter line in Table 3. No thermal reactor fully replaces its fissile content at thermal energies (0.025 eV), but of these, the CANDU reactor is clearly the most fuel-efficient representative thermal reactor. For CANDU reactors this ratio increases during operation to reach about 0.75 as more U-238 isotopes are transmuted to fissile Pu-239. This isotope also yields 10% more neutrons per fission than fissile U-235.

It is significant that the other representative thermal reactors have conversion ratios as low 0.04 to 0.1 due to a much higher fissile U-235 content (enrichment). The high absorption for fission in

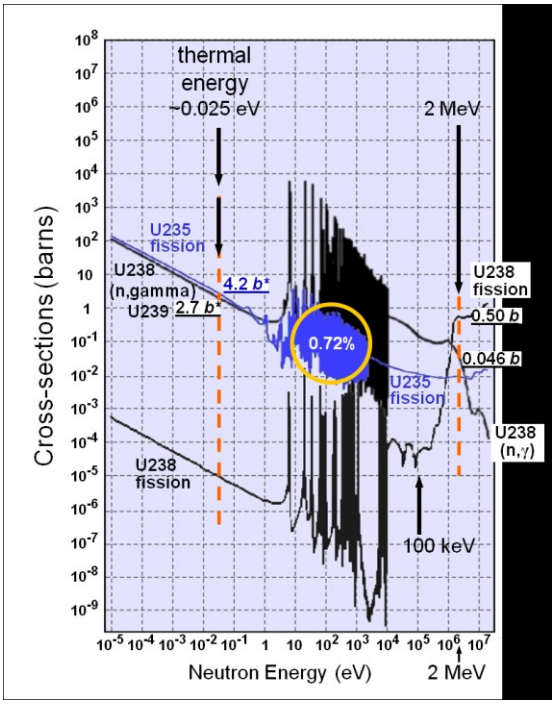
the high U-235 levels proportionately reduces the number of neutrons that are available to interact with and convert fertile U-238. Consequently this reduces the total fraction of mined natural uranium consumed in such reactors compared to CANDU fuel utilization.

5.2 CANDU neutrons at higher energies

Since the conversion ratio (new fissile nuclei ratio) is determined strongly by the macroscopic radiative capture cross section of fertile U-238 in relation to the fission cross-section of fissile isotopes such as U-235, Pu-239, or at high energies even fission of U-238 [18], it is of interest to examine the change in that ratio as individual cross sections change with energy (see Fig. 1). New, nascent fission neutrons have an average energy of about 2.1 MeV and are slowed down (moderated) primarily by heavy water in CANDUs until they reach thermal energies around 0.025 eV. If a neutron along this energy path enters a fuel rod, it can interact with the fuel.

A neutron on this path at an intermediate energy of 100 keV re-entering the fuel would produce a fission events so rarely in CANDU fuel that on average only 0.136 new neutrons are produced by it (Table 4). However, the macroscopic capture cross-section of U-238 is over ten times higher than fission by the low concentration of U-235 (Fig. 1), with about 12 U-238 nuclei converted eventually to Pu-239 for each rare U-235 fission event. But with so few new neutrons created the reactor would not operate at this energy.

The situation is vastly different for a 2 MeV neutron (Table 4). At this energy the fission probability is dominated by a high macroscopic fission cross section of normally fertile U-238 (Fig. 1), resulting in a total new-neutron yield of 2.4. U-235 fission is the lowest of the macroscopic fuel cross sections shown at this energy (Fig. 1), while a fairly high radiative capture cross section of the >99% U-238 in fresh CANDU fuel results in a conversion to fissile Pu-239, or a CR of 4.48.



The 2 MeV energy for nascent neutrons cannot be maintained in the CANDU core to produce a functioning fast-neutron CANDU reactor. Interactions with the many moles of surrounding D_2O very quickly slow down the neutrons to reach thermal energies. Even a single elastic scatter interaction with D_2O produces a neutron energy loss of almost 1 MeV with a resulting 20-fold loss in fission probability from U-238 (Fig. 1).

Figure 1. **Neutron interaction cross sections** for fission of U-238 and U-235 plus radiative capture in U-238. Adjustments for the prevalence of only 0.72% of U-235 in natural uranium provide a graphical representation of relative macroscopic cross sections. Effects of major changes in cross sections at energies of 100 keV and above are discussed in the text.

5.3 Fast-spectrum reactor comparisons

However, it is possible to diminish the energy loss of nascent high energy neutrons by replacing light-atom coolants/moderators such as D_2O and H_2O with non-moderating heat transfer liquids (coolants) constituted of heavier atoms, such as molten lead, molten lead/bismuth eutectics, or in

	CANDU*			ARC-100			PRISM			SSR-like		
Reactor type	Thermal			Fast			Fast			Fast		
Neutron energies	0.025 eV	100 keV	2 MeV	100 keV	500 keV	2 MeV	100 keV	500 keV	2 MeV	100 keV	500 keV	2 MeV
New-neutron ratio	1.34	0.136	2.40	1.12	1.24	2.46	1.09	1.55	2.64	1.05	1.54	2.59
# U-235 nuclei used (norm'zed reference)	1	1	1	1	1	1	1	1	1	1	1	1
# New fissile ratio												
# Pu239 from U238 + Pu241 from Pu240	0.517	12.0	4.48	0.720	0.685	0.268	1.18	0.806	0.257	0.209	0.131	0.036

Table 4. Operational core characteristics of representative small fast-spectrum reactors compared to a CANDU-like reactor

* While neutrons in CANDU reactors interact primarily at 0.025 eV, two other energies were considered along the path from nascent to thermal neutrons (see text).

principle any other heavy-atom liquid that is stable and has minimal neutron-absorbing characteristics. Currently the most prevalent such liquid coolant is sodium, with a melting point of 98°C and a boiling point of 883°C. Liquid sodium (Na) has been used successfully for well over 400 reactor-years since the early 1960s in fast-spectrum reactors from 20 MWe (EBR-II, starting in 1964) to 800 MWe (BN-800, starting in 2016).

Two fast-spectrum liquid-Na SMR designs are examined in Table 4, a 100 MWe ARC-100-like reactor (Advanced Reactor Concepts) and a 300 MWe PRISM-like reactor (Power Reactor Innovative Small Module, GE-Hitachi), plus a liquid salt reactor that comes in thermal form (Table 3) as well as a fast-neutron design (Table 4). The fast-spectrum reactors have high fissile starting concentrations, high in enriched U-235 for the ARC-100 and high in Pu-239 and other TRUs for the PRISM and SSR. Perhaps unexpectedly at 2 MeV the reactors have a relatively low conversion ratio (few new fissile nuclei produced). This is caused by the high macroscopic fission cross sections of the high fissile concentrations, which also include U-238 fission, and by relatively the low macroscopic capture cross section of U-238.

At lower energies, down to 100 keV the fission cross sections of U-235 and of Pu-239 remain fairly constant, while U238 fission drops but its capture cross section increases (e.g. Fig. 1). This results in more conversion of U-238 to fissile Pu-239, i.e. a rising CR, with the PRISM reactor attaining an augmented fissile content (CR > 1). The 100 keV energy level is important, since the neutron energy utilization spectrum in fast-neutron reactors peaks around this energy [26].

The ARC-100-like reactor, on the basis of the number of new fissile nuclei in Table 4, appears not to have achieved fissile isotope equilibrium or "break-even" status (CR=1). However, there is a shift from fissile U-235 isotopes with a neutron yield of 2.55 per fission at 2 MeV to U-238-

derived new Pu-239 isotopes with a substantially higher neutron yield of 3.17 at this energy. This provides the important neutron equilibrium (reactivity =1.0) with a neutron ratio higher than the new fissile ratio. This neutron yield difference advantage is maintained at lower energies.

The SSR-like reactor never achieves a high enough conversion ratio to maintain its fissile complement. This is caused by two effects. One is a low fuel to salt ratio, with the total macroscopic heavy atom fuel cross section only being 6.8% of the total. Second, the fissile fuel component is almost 30%, while fertile U-238 comes in at a low 56%, much lower than the 89% and 92% fertile fuel components of the ARC-like and PRISM-like reactors. Thus the SSR-like fast-neutron reactors operates as a "burner", like its thermal counterpart.

To reiterate, the representative small modular reactors of different designs all require enriched fissile fuel. Most designs simply consume that increasingly precious fissile component of uranium fuel to a substantially larger extent than the Canadian standard reactor, the CANDU.

The exceptions to this are the two representative fast-spectrum reactors, the ARC-100-like and the PRISM-like reactors. Even though both also require an enriched fissile fuel component, Table 4 at the 100 keV energies shows that this component is maintained, even augmented between fuel cycles. Once this type of reactor is started, the consumable fuel in effect consists of fertile U-238 and non-fissile isotopes of the TRUs, i.e. Pu-240, Pu-242, Am-241, etc., fissioned directly at high energies or transmuted and converted to maintain the level of fissile isotopes consumed.

6. Fuel cost implications

Barring a Canadian decision to develop uranium enrichment facilities, the acquisition of fuel for SMRs is a choice between foreign sources of enriched U-235 and locally recycled transuranics from used CANDU fuel recycled via the two more economical technologies indicated in Table 1, electrorefining or fluoride volatility methods.

	total charge tonnes	fissile/TRU content tonnes	CANDU used fuel bundles	Cost per bundle CAD	Total Cost CAD million
20% U-235 enrichment	20	4			157.34 [19] 146.65 [20]
20% TRUs electrorefining	20	4	50,000	1,368	68.40 77.19*
20% TRUs fluoride volatility	20	4	50,000	1,114	55.70 62.85*
* corrected for fissile content in TRUs (see caption)					

Table 5. Comparison of enriched-fuel costs for SMRs
Costs were calculated for a hypothetical fuel requirement of 20 tonnes of uranium fuel with 20% enriched U-235 from sources in the USA [19,20] and the same amount enriched with 20% total transuranics obtained from used CANDU fuel via two economical methods analysed in Table 1. The latter results were then corrected to adjust for the difference in reactivity (neutron yield) between U-235 and the mixture of TRUs.

The fuel costs shown in Table 5, derived from the analyses above, are nearly linearly related to the enrichment required and to the number of tonnes of enriched fuel needed to charge the reactor core. Therefore the amounts in Table 5 are arbitrary, assuming a 20 tonne fuel core fuel requirement at the low-enriched U-235 limit of 20% versus the same charge with 20% TRUs.

This corresponds approximately to the requirement of the GE-Hitachi PRISM fast-spectrum reactor. Costs of other amounts and levels of enrichment can be scaled from values in the table.

On the basis of the above calculations Table 5 shows that SMR starting fuel enriched locally with fissile isotopes in a mixture of TRUs derived from the recycling of used CANDU fuel is between a factor of 1.9 and 2.5 times more economical, i.e. many millions of dollars more economical, than purchasing the equivalent U-235-enriched fissile fuel in the USA.

7. Summary and Conclusion

The study above shows that the concern about long-term fuel security and Canadian enriched uranium fuel autonomy engendered by the future introduction of small modular reactors can be addressed locally and independently with two complementary lines of attack.

The first line is the local establishment of available economical recycling capabilities for used CANDU fuel stockpiles to provide TRU-based enriched fissile SMR starting fuel (which facilities would also recycle future used SMR fuel). This approach provides fuel autonomy.

The second path is the choice of SMRs that can maintain their fissile fuel component or even augment it during their fuel cycle. Such reactors in effect consume fertile fuel components such as U-238. This second approach provides long-term fuel security since the used CANDU fuel stockpiles contain enough fertile uranium to power the reactors for many centuries.

Appropriate SMR designs are available for consideration. Two have been analysed above.

The above examination of fuel recycling technologies for used fuel management suggests that two methods, electrorefining and fluoride volatility approaches, are about 3 times more economical than direct disposal of used CANDU fuel bundles, and produce TRU-based enriched fissile fuel for SMRs at 50% of the cost of commercially available equivalent U-235-enriched uranium.

It would be wise to adopt such approaches for fuel security and independence, and at the same time eliminate the long-term radiotoxic TRUs from the stored used CANDU fuel stockpiles.

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