YOUR NEW SMR MUST NOT BE THERMAL

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Abstract

All nuclear reactors extract about 200 MeV from the fission of a heavy atom. Therefore the choice of a reactor is determined by other factors: economics, expediency, opportunity, national pride, etc. The advent of SMRs permits us to re-examine our choices. All thermal reactors consume <1% of the heavy atoms in mined uranium. The rest of the fuel is considered waste. Is now the time to choose better reactor cores that, with fuel recycling, are capable of extracting the energy of all the heavy atoms in that fuel? Yes, it is. This opportunity may not come again.

1. Introduction

Since the advent of the generation of uranium-based civilian nuclear power with its first electricity generated in 1951 by the 200 kWe EBR-1 in Arco, Idaho [1], about 3,000,000 tonnes of uranium have been mined. Most of these, about 2,300,000 tonnes, were destined for creation of electricity in an increasingly large worldwide fleet of thermal nuclear reactors. Of this latter uranium, about 2,000,000 tonnes are now stored as left-over depleted uranium near enrichment facilities after these facilities provided about 300,000 tonnes of uranium fuel enriched from the 0.72% U-235 in mined natural uranium to about 3% to 4% U-235, depending on the reactor core requirement. Yet of the total 2.3 million tonnes of uranium only some 12,500 tonnes, or 0.55%, have actually been used, fissioned, to extract nuclear energy in those reactors.

In Canada, with the use of natural uranium as fuel in its CANDU reactors, some 60,000 tonnes of uranium fuel have passed through those thermal reactors since the beginning of Canadian nuclear energy generation 60 years ago, but only 0.74%, or 440 tonnes of the heavy atoms in the fuel have been fissioned to yield nuclear energy.

Both of those percentages, whether 0.55% or 0.74%, point to a rather inefficient use of uranium, particularly since every uranium atom, U-235 and also U-238, when fissioned directly, or indirectly after transmutation to plutonium, yields about 200 MeV of energy.

It is that rather large energy yield per heavy atom that has been the saving grace of nuclear power to date. It indicates an enormous energy density in the fuel. Each 200 MeV fission from a single heavy atom corresponds to a 40 million-fold energy advantage over the 5 eV of energy that is yielded as part of the chemical reaction of a single carbon atom when it is burned with oxygen. Therefore even using only 0.5% to 0.75% of the uranium fuel still leaves us with a 200,000-300,000-fold energy advantage over carbon atoms. And it is carbon-free energy.

As a result of that advantage, the industry has settled on this comfortable 0.5% or so of nuclear energy exploitation. But industry knows better --- or has forgotten that it knew better.

For over 60 years nuclear energy has been approached not as a cohesive whole, but as disparate separate fragmentary competitive undertakings from mining, refining, reactor design and construction, used fuel recycling, storage and disposal. This is done frequently with the invocation of a free market economy that is supposed to shake out a most economical result, in spite of the obvious need for governmental oversight and financial assistance for virtually all aspects of the nuclear process due to high initial capital costs, questions of national security and proliferation concerns, radiation protection and of safety.

As a result many barbs, myths, and criticisms have been leveled at the operation of the nuclear enterprise. Not the least of these in no particular order are

1) the cost of construction in time and money,
2) the pluri-generational highly radiotoxic waste
3) the non-renewable character of nuclear energy
4) the potential of accidents with long-term consequences
5) the potential of facilitating nuclear weapons production

Most of these can be eliminated by a much more integrated, holistic approach, to benefit not only the industry, but also society and the environment as a whole.

The potential deployment of small modular reactors (SMRs) offers an opportunity to do better, much better. Their small size has an immediate and obvious impact on capital outlay and time.

Moreover, with the right SMRs a holistic approach to nuclear energy is attainable that integrates fuel, reactor, recycling and reuse into an even safer, proliferation-resistant seamless whole.

The result is an over-one-hundred-fold gain in carbon-free energy yield from uranium fuel, an elimination of long-term, million-year, heavy-atom radiotoxicity of used fuel, and the additional benefit of exploiting even the residue of fission products (FPs). The latter contain immediately-stable non-radioactive platinum-group metals, Rare Earths, as well as useful radioactive FP isotopes, e.g. Sr-90 and Cs-137, with half-lives of a few decades.

The potential is not the same for all reactor cores. The differences and the underlying concepts are outlined below. The most important outcome is that a transition has to occur from the use of thermal neutrons to the adoption of fast-spectrum neutrons.

A fast-spectrum neutron technology is not alien to the field. Indeed the very first electricity produced by nuclear energy occurred using fast-spectrum neutrons in the small 200 kWe EBR-1 reactor in the USA in 1951 [2]. Such reactors, of different sizes, have been built and operated successfully for research and power generation since that time; to name but a few, the U.S. 20 MeV EBR-2 [3], the 350 MeV French Phenix [4], the Russian BN series from the BN-50, the BN-350, BN-600, to the most recent BN-800 [5]. Several fast-spectrum SMR designs are currently being considered in Canada: the ARC-100 by Advanced Reactor Concepts (U.S.A.) [6] and the SSR-waste-burner, a molten salt concept by Moltex in the U.K [7]. Further designs, that

can be added to this list, are the Natrium, a 345 MWe by U.S. TerraPower [8] and the 300 MWe PRISM by U.S. GE-Hitachi, the latter fueled with transuranic actinides (TRUs) [9,10]. The ARC-100, PRISM, and NATRIUM are all based on the EBR-2 reactor. The PRISM, offered to the UK for disposition of its excess store of plutonium, and the SSR reactor are the only reactors being offered commercially currently with some concepts of used fuel recycling. Although it is possible to fuel the ARC-100 with used-fuel-derived TRUs instead of U-235, this is not contemplated by ARC its First-Of-A-Kind reactor until after the first 20-year fuel cycle.

2 Neutron Interactions at Different Energies

To understand the importance, and the difference, of using neutrons of thermal or of fast-spectrum energies, it is instructive to revisit the generic reactor-independent fundamentals of neutron interactions with respect to their neutron energy.

The primary reason for the small, 0.5% to 0.75% fuel utilization in thermal reactors are the characteristics of moderated, low energy neutrons equilibrated to the thermal energies of their surroundings, e.g. 0.025 eV. Those low energy neutrons very efficiently fission U-235, or easily split only other *fissile* isotopes such as Pu-239 that are created in the reactor core from U-238.

In natural mined uranium the isotope U-235, at 0.72%, is the prime and only fissile target of such slow, low-energy neutrons. U-235 has a fission cross section σ(n,f) of some 950 barn per atom [11]. But the low natural concentration of U-235, that low 0.72%, reduces this number to an effective 4.2 barn (see the normalized cross sections in Fig. 1). But this is still some 250,000 times higher than the effective fission cross section $\sigma(n,f)_{eff}$ of the 99.28% U-238, at 0.000017 barn.

Thus it is clear that with pure uranium fuel, the only energy-yielding isotope is U-235, at 0.72%.

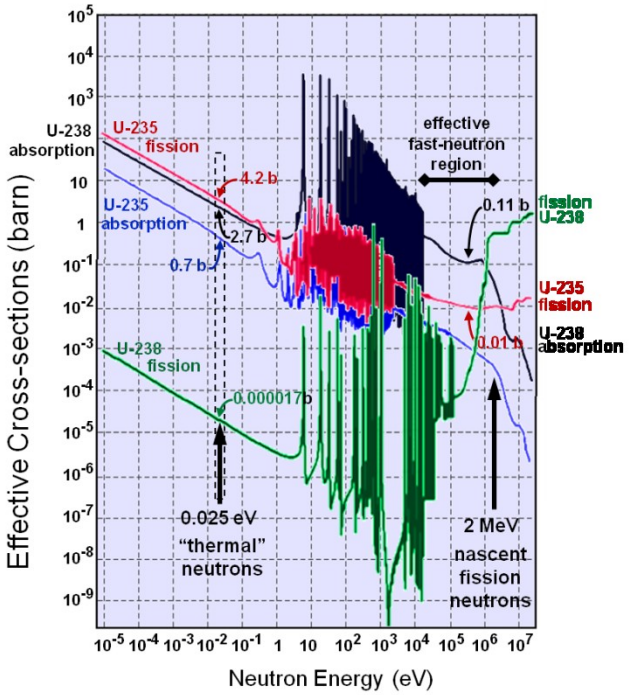

Figure 1. Relative effective neutron cross sections for natural uranium. Fission and radiative capture (absorption) of the two major uranium isotopes U-235 and U-238 over a range of energies including the high energies of nascent fission neutrons (average 2.1 MeV) and the low energies of moderated, thermally equilibrated neutrons at around 0.025 eV. Microscopic cross sections from the Brookhaven ENDF data bank [11] have been adjusted for the relative concentrations of the isotopes (i.e. 0.72% for U-235 and 99.28% for U-238).

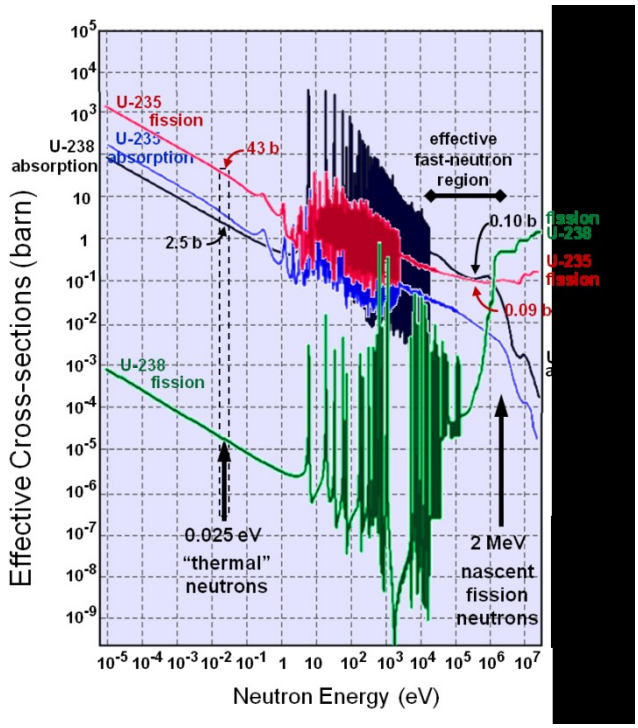

Figure 2. Relative effective cross sections for 7.3% U-235 enriched uranium fuel. Fission and radiative capture (absorption) cross sections of the two major uranium isotopes U-235 and U-238 over a range of energies from the high energies of nascent fission neutrons (average 2.1 MeV) to the low energies of moderated, thermally equilibrated neutrons at around 0.025 eV. Microscopic cross sections from the Brookhaven ENDF data bank [11] have been adjusted for the relative concentrations 7.3% U-235 and 92.7% U-238.

As irradiation proceeds a small amount of fissile plutonium is created within the reactor core from the transmutation of U-238 via its absorption of slow neutrons due to its radiative capture cross section σ(n,a) of 2.7 barn.

This is a beneficial effect that is most notable in the CANDU reactor, which derives almost equal amounts of energy near the end of its fuel cycle from fission of a decreasing amount of U-235 and fission of an increasing amount of plutonium created in the reactor [12, p.143]. At the beginning of the fuel cycle this beneficial transmutation effect depends on the relative ratio, 0.54, between the cross section of 2.7 barn for U-238, that creates a build-up fissile plutonium, and the effective 4.2 barn for fission of U-235 in sum with the transmutation of U-235 to non-fissile U-236 at 0.7 barn. Both latter effects on U-235 decrease the amount of fissile U-235 (abbreviated U5 in Equ. {1}). The ratio increases somewhat through the fuel cycle as various isotopes decrease or increase.

$$\text{Replenishment Ratio} = \frac{\sigma(n,a)_{U8} * \%_{U8} \ + \text{smaller terms}}{[\sigma(n,f)_{U5} \ + \ \sigma(n,a)_{U5}] \ * \ \%_{U5} \ \ + \ \text{smaller}} \qquad \{1\}$$

$$= \frac{2.7 * 99.28 \ + \text{smaller terms}}{[590 + 99] * 0.72 \ + \text{smaller terms}} \ = 0.54$$

For efficient use of all of the uranium in the fuel this ratio should be 1.0 or higher.

However enrichment of fissile U-235 actually decreases this beneficial effect of U-238 fuel transmutation. This becomes obvious from the data in Fig. 2, which depicts an enrichment of 7% U-235, even beyond the customary thermal reactor limit of 5% into the range of 5% – 20% of

"high-assay-low-enriched uranium" (HALEU) fuel required for most SMRs. In this case the higher concentration of fissile U-235 presents an almost 10-fold larger target size for interaction with neutrons, i.e. a 10-fold faster use of this isotope, at a relative rate corresponding to 50 barn. The replacement of fissile atoms via transmutation from U-238 suffers as a consequence even though its cross section is decreased only to an effective 2.5 barn, just lower than in the CANDU example above. The fissile replacement now occurs only at a relative ratio of 0.050, a more than ten-fold decrease from the ratio of 0.54 in the case for natural uranium in the CANDU reactor.

3. Greater Fuel Efficiency Not Possible for Thermal Reactor Cores

The above numbers of 0.05 and 0.54 for the possible initial replacement ratio of fissile isotopes encompass fissile isotope concentrations in all current thermal reactor cores. The numbers are derived from cores operating either with natural uranium at 0.72% fissile U-235 or with 7% U-235 enrichment. Some thermal SMRs require still higher U-235 enrichment, with its still higher propensity to absorb an even larger proportion of available thermal neutrons. This will result quite naturally in even lower fractions of neutrons transmuting U-238 to fissile isotopes.

Of course, augmentation by endogenously created fissile Pu-239 via transmutation during the fuel cycle increases the overall fissile replacement ratio somewhat [Note: the replacement ratio is called "conversion ratio" (CR) when considered at the end of the fuel cycle]. Splitting of Pu-239 on average provides a greater number of neutrons per fission than does U-235 in the ratio of 2.87 to 2.4[11]. But even in the CANDU reactor CR only is about 0.7 [24]; it is less than that in other thermal reactor cores. And it is still far removed from a value of 1.0 or greater that is required to make efficient use of the fertile potential of the predominant U-238 isotope in uranium.

Therefore there are no thermal uranium-based reactor cores in SMRs or full-sized reactors which do not require periodic input of new exogenous fissile isotopes, rare and therefore precious, to continue operation. Consequently the fuel-use efficiency of such reactors remains at a paltry 0.5% to 0.75% of mined uranium, even with the use of MOX (mixed oxide) fuel via extraction of plutonium in one, two or three rounds of recycling, as is done, for instance, in France [12, p.145].

3.1 Neutrons of Higher Energy

The situation is quite different with the use of neutrons of higher energies.

Nascent fission neutrons are created with a broad spectrum of energies around 2 MeV. In fast-spectrum reactors this neutron spectrum, instead of shifting quickly to low, thermal energies, shifts only slowly as high energy neutrons interact elastically and inelastically with fuel, coolant and structural atoms in the cores of those reactors. There are no specific neutron energy moderators, e.g. water or carbon, which are part of the normal make-up of thermal reactors. Close to and below the initial average neutron energy of 2 MeV the fission cross sections and the absorption (radiative capture) cross sections of fuel isotopes differ by orders of magnitude from their values at thermal energies, and also dramatically change values relative to each other.

For instance Fig. 1 (above), for natural uranium, shows that at thermal energies the transmutation cross section of U-238 is at 0.6 time the fission cross section of U-235, at 2.7 b and 4.6 b

respectively. However, in the region of high neutron energies between 0.1 MeV and 1 Mev the relationship is reversed, with transmutation of U-238 at 0.3 MeV being a factor of 11 higher than U-235 fission, in ratio of 0.11 b to 0.01 b.

This high ratio of transmutation to fission portends well if the only consideration were the use of U-238 as fuel via transmutation to fissile Pu-239. However, the fraction of neutrons that fissions U-235 in natural uranium is now so low in comparison that not enough new fission neutrons are created to sustain a chain reaction. At a neutron energy of 0.3 MeV (300,000 eV), for every 100 interacting neutrons, 91 are absorbed by U-238 to produce transmutation, while less than 8 neutrons produce fission. While each of these eight fission events produces 2.47 new neutrons on average, only 19 new neutrons would replace the 100 neutron used altogether.

A reactor with such a low replacement of neutrons will not sustain a chain reaction. Calculations show that to replace the 100 spent neutrons with 100 new, nascent fission neutrons requires an increase in fissile fuel concentration, with a U-235 enrichment up to 6.8% or higher (Fig. 2).

It is this feature, the replacement of neutrons used in order to maintain a chain reaction that is the primary characteristic of every reactor. For equilibrium operation the ratio between the new neutrons created by fission and the neutrons used up in the combination of fission of fuel isotopes plus all other neutron absorption mechanisms in fuel, structural components and coolants in the core, has to be controlled to be 1.0. But for power regulation and power maintenance the potential should exist for the ratio to be greater than 1.0. Of course, once the ratio drops to less than 1.0, other than for deliberate power reduction or shut-down, the reactor needs to be refueled.

Figure 3 shows the relationship for the CANDU reactor core of both the new neutron ratio and the ratio of the replacement of fissile atoms used with respect to the energy of the interacting

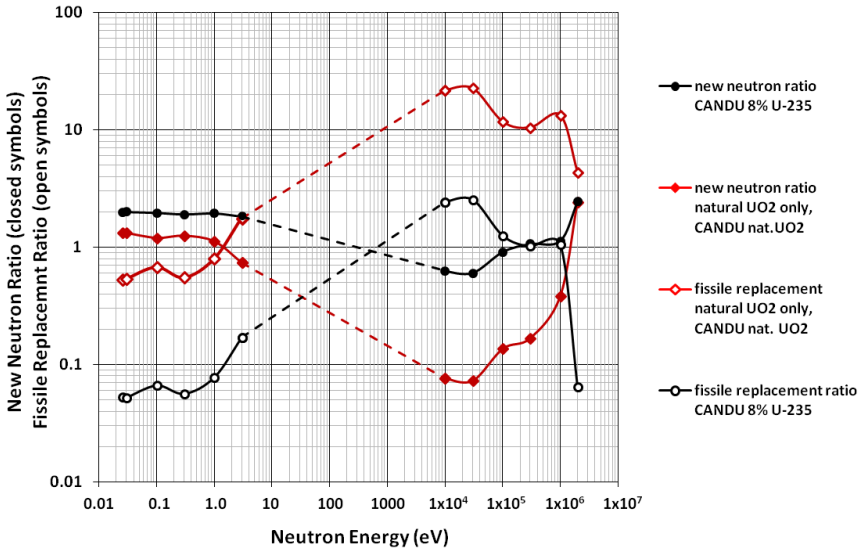

Figure 3. Variations at different neutron energies of the creation of new neutrons (new neutron ratio; closed symbols) and the creation of new fissile nuclei (fissile replacement ratio; open symbols) from 0.025 eV (thermal neutrons) to 2 x 10^6 eV (nascent fission neutrons). Dashed line indicates resonance region, not analysed (see text). Diamond symbols and red lines refer to natural uranium fuel (0.72% U-235); circle symbols and black lines refer to fuel enriched to 8% U-235.

neutrons. Two concentrations of fissile U-235 are represented: the 0.72% U-235 of natural uranium (the normal CANDU fuel) and a fuel arbitrarily enriched to 8 % U-235. Only two energy regions are considered: the low thermal/perithermal neutron energies, and the high energies of nascent fission neutrons from 2 MeV ($2x10^6$ eV) down to 10,000 eV. The rather severe fluctuations in cross sections in the so-called resonance region between those two energy regions (see Figs. 1 and 2) make reactor core design considerations and calculations for these intermediate energies exquisitely challenging. That resonance region was not part of the calculations and is merely indicated by the dashed lines.

The inner two lines (red, diamond symbols) give the results for 0.72% U-235 (natural uranium fuel) in the CANDU reactor core. The reactor can achieve neutron equilibrium for all low energies (new neutron ratio above 1.0; closed diamonds); but it does not replace the fissile U-235 used (replacement ratio only 0.5 or somewhat higher; open diamonds). At higher fissile content (8% U-235; circles) the two ratios separate. The new neutron ratio rises from 1.3 to 2.0 at 0.025 eV (thermal neutron region), but the fissile replacement ratio drops ten-fold from 0.53 to 0.053.

Increasing the neutron energy on the peri-thermal region up to 1.0 eV changes the ratios very little, as might be expected from the parallel nature of the cross sections seen in the low energy region in Figs. 1 and 2. Just above an energy of 1.0 eV both ratios tantalizingly cross each other near a ratio of 1.0 (theoretically an ideal result, though not practically so), and then diverge in opposite directions up to very high neutron energies (red lines; diamond symbols).

The cross-over and divergence of the ratios at higher neutron energies compared to their low energy characteristics results in rather beneficial high energy features. While at low energies increasing the fissile fuel concentration results in an increasing separation of the two ratios, the effect of fissile enrichment is to bring the two ratios together at high energies to a value close to 1.0 for both (see results in Fig. 3 for 8% U-235 between 0.1 MeV and 1.0 MeV).

If neutrons are used in this energy range, it would result in a fast-spectrum reactor core simultaneously capable of achieving neutron equilibrium (criticality), and also having a conversion ratio of 1.0.

Indeed, such conditions can be readily achieved with the use of coolants and structural components in the core that avoid the rapid reduction of neutron energy, i.e. avoid thermalization of high energy nascent fission neutrons. It has been calculated and observed that under such non-thermalizing conditions the energy spectrum of nascent fission neutrons shifts sufficiently slowly to lower energies to have a maximum in neutron-fuel interactions at around 0.3 MeV [12, p.232].

Such conditions are met, for instance, in fast-spectrum reactor designs such as the ARC-100, the PRISM, or the NATRIUM, mentioned above, that can operate with starting fuel in the lower enrichment range of HALEU fuel or of TRU fissile fuel mixtures, e.g. 7.1% Pu-239 for the PRISM [12, p.141].

Figure 4 indicates that such simultaneous conditions of neutron equilibrium and fissile fuel replacement can be met in the modelled non-thermalizing core of the sodium-cooled ARC-100 with U-235 fuel enrichment to 7.4% [adapted from 12, p.167]. The effect is further enhanced in

such an ARC-100 core with the use of an 8.2% TRU mixture containing 5.7% fissile Pu-239/241 (Fig. 5), fuel that could be obtained directly by the recycling of used CANDU fuel.

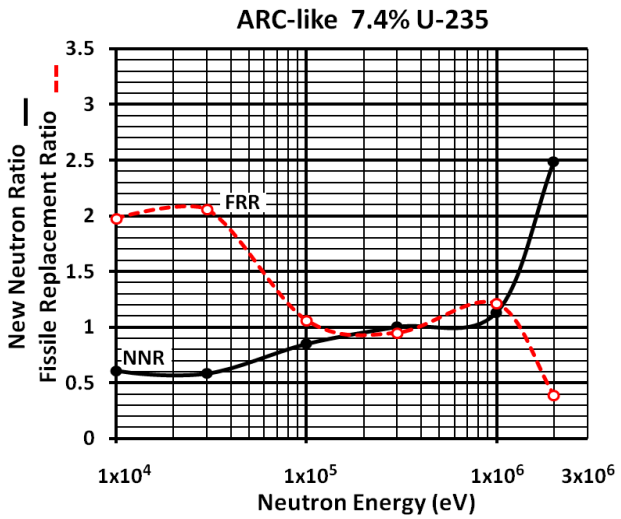

Fig. 4 Ratios for the creation of new neutrons and the replacement of U-235 atoms used with fissile TRUs, at energies indicated, in an ARC-like reactor core operating with a spectrum of high energy neutrons. Crucial ratios ≥1.0

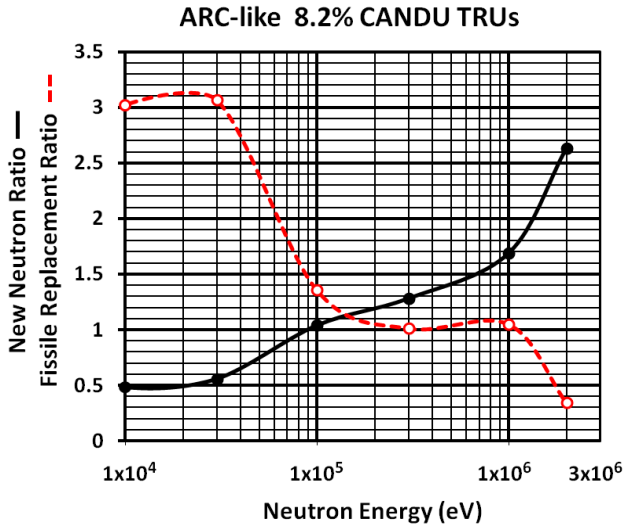

Fig. 5. Ratios for the creation of new neutrons and the replacement of fissile transuranic actinides used with further fissile TRUs, in an ARC-like reactor core operating with a spectrum of high energy neutrons. Crucial ratios ≥1.0.

Indeed the new neutron ratio in the $1x10^5$ eV to $1x10^6$ eV neutron energy range in Fig. 5 is so high that the enrichment of the fuel could be reduced somewhat with the result of an enhanced transmutation and conversion of U-238 to Pu-239. As was seen in Fig. 3, the ratios of neutron- and of fissile-creation move in opposite directions with changes in enrichment of fissile fuel.

4. Absolute Requirement for Fast-Spectrum Neutrons and Fuel Recycling

The above details on the energy dependence of the relative characteristics of fission and absorption (radiative capture) cross sections of the natural isotopes in uranium fuel indicate that neutrons of high energies are essential for efficient extraction of close to 100% of the nuclear energy in such fuel, i.e. for a conversion ratio of 1.0 or higher. Low energy neutrons such as those found in all thermal reactors cannot achieve this, and as a result, even with recycling, extract less than 1% of the energy in natural mined uranium, primarily from the sparse 0.72% U-235 isotope of this ore. Such thermal neutrons cannot do more.

However, while fast-spectrum neutrons in suitable non-moderating reactor cores convert the copious fertile isotope U-238 to fissile isotopes as quickly as fissile isotopes are used up in the creation of nuclear energy, the process does not go to completion in a single fuel cycle. Fission of heavy atoms produces a residue of fission products that like all matter, absorb neutrons. The slowly increasing amounts of fission products eventually absorb sufficient total neutrons to leave not enough free neutrons to continue the chain reaction of neutron- and energy-producing fission events.

As a consequence it becomes imperative to extract such fission products periodically from the used fuel in order to continue the nuclear energy harvest from the remainder of the fuel.

An ideal separation process would selectively remove only the fission products in the used fuel of fast-spectrum reactors; all heavy atoms can still deliver energy at 200 MeV per fission. Since in such reactors the fissile heavy atom content of the fuel is maintained during reactor operation, those extracted fission products would only need to be replaced with an equal weight of fertile U-238 in order to re-establish the starting conditions for a further round of reactor operation.

Such a separation procedure solely for fission products currently does not exist, since the thought processes in the nuclear field have focused almost exclusively on extraction of fissile U-235 and fissile Pu-239/241 as the definitive fuels, as indeed they are in thermal reactors.

But are existing recycling procedures cost effective enough to produce enriched SMR starting fuel from the used fuel of thermal reactors?

Civilian extraction procedures historically followed the military lead on the separation of plutonium with PUREX (Pu/U Extraction), or with modified PUREX to yield an unseparated proliferation-resistant mix of Pu and U, as potential mixed oxide (MOX) fuel in thermal reactors. These processes are expensive (see below) and also leave substantial volumes of radioactive working fluids for disposition.

A much better alternative was developed at the Argonne National Laboratories in the 1980s for cycling of used metal fuel from the EBR-2 fast-spectrum reactor: electro-refining in molten salt at 400°C (pyroprocessing) [13, p.167ff]. This technology utilized the conducting used metal fuel rods of the EBR-2 as anodes in an electrolytic cell, with the purified uranium metal and also the transuranic actinides (TRUs) in metal form plating out separately on two cathodes, an iron cathode for the uranium and molten cadmium for a TRU/uranium mix [13, p.171]. The two metal forms were then recast as new fuel rods in the desired proportions of uranium and TRUs.

Fission products (FPs), separated as a group, were left in the salt electrolyte, from which they were cleared periodically by chromatography, with the salts returned to the electro-refiner for continued use. This left virtually no working fluids for disposition. The separated FPs are currently in short-term shielded storage, but could be separated further as stable and as radioactive fractions.

The costs of these methodologies (as well as fluoride volatility methods) were analysed in a full course study in 4th-year Chemical Engineering at the University of Toronto for potential use of separating used CANDU fuel into three fractions: pure fission products, pure uranium, and a mixture of TRUs with some impurities of both uranium and traces of fission products [14].

On the basis of financing, construction and operation for an annual through-put of about 50,000 used CANDU fuel bundles the costs were determined for a modified PUREX method (no Pu separation) and for electro-refining. They were [15]:

	per 20 kg fuel bundle	USA expert estimates	
Modified PUREX	$ 7,432	$ 8,460	[13, p.285]
Electro-refining	$ 1,368	$ 1,690	[13, p.289]

As a basis for comparison, the monies set aside by 2017 for permanent disposition of used CANDU fuel bundles in a deep geological repository were $ 10.125 billion for 2,771,000 bundles [16-20], or normalized per fuel bundle:

towards DGR disposition $ 3,654 per 20 kg fuel fundle.

From the above results a comparison can be made for the cost of purchasing starting fuel for the ARC-100 or PRISM fast-spectrum reactors, each requiring approximately 20,000 kg HALEU fuel* with 20% U-235 enrichment [21,22], or alternatively making the equivalent fuel with used CANDU TRUs by electro-refining [15]:

Purchase of enriched U-235	$ 152 million
Extraction of TRUs (electro-refining)	$ 62.2 million

* currently commercially available only from Russia

5. Fast-Neutrons and Recycling: Fuel Galore, Much Reduced Radiotoxicity

The results above on the fundamental characteristics of neutrons at different energies and the analysis of the cost of recycling suggest that nuclear energy generation can, and indeed must move in a new and exciting direction.

While there is perhaps no urgency for the next month or so, at the speed with which changes in the acceptance of nuclear technology occur, new directions must be taken now to avoid a potential collapse of the industry from lack of fissile fuel a few decades hence.

This seems like a dire statement, but the World Nuclear Association indicates that Canada's 500,000 tonnes of economically accessible natural uranium reserves will be exhausted within 30 years at the rate that it is being mined and exported for use in the World's U-235-consuming thermal reactors [23]. World uranium reserves for fissile U-235 are expected to last somewhat longer, but will also be gone around 2090 [23]. The U-235 depletion will only be faster with the introduction of SMRs and more full-sized reactors.

To avoid such a predicament a transition away from thermal reactors is imperative, with the adoption of U-238-transmuting fast-spectrum SMRs. However, to gain the benefit of such reactors, the shift has to be coupled with efficient and clean recycling of used nuclear fuel.

The latter process is ready to be deployed and, as shown above, is economical. It should already be put in place, early, to process existing used CANDU fuel, so that the required enriched fissile SMR starting fuel is ready when those reactors come on line.

Canada's current 60,000 tonnes of used CANDU fuel can yield 240 tonnes TRUs with enough fissile content to provide "home-grown" Canadian starting fuel for about 24,000 MWe fast-spectrum SMRs equivalent to the 300 MWe PRISM. For Canada's own energy needs that approach obviates the reliance on foreign countries for such strategic fuel as LEU (low-enriched uranium) from the USA, France, or China, or HALEU from the Russia.

But this is not the only benefit of fast-spectrum SMRs coupled with recycling of used fuel.

Canada's CANDU reactors have produced carbon-free energy for about 60 years by splitting only 440 tonnes of the current 60,000 tonnes of used fuel. Fast-spectrum SMRs with recycling can split the remaining existing 59,560 tonnes of heavy atoms to yield 134 times more carbon-free energy, to provide such carbon-free energy at today's power levels for about 5,200 years; or to replace all fossil fuels in Ontario for about 1000 years; or to provide carbon-free energy for all of Canada for about 300 years. Future mined uranium can yield proportionately more.

But a further crucial major societal benefit of fast-spectrum SMRs coupled with fuel recycling is the elimination of the long-term multigenerational radiotoxic legacy of used CANDU fuel actinides and their need for a long-term storage or repository. The extraction of the TRUs also removes the million-year radioactivity that is intrinsic to the TRUs and therefore part of the current 60,000 tonne stockpiles of used CANDU fuel. Such TRUs can be removed expeditiously in decades, to be subsequently sequestered and eliminated in the cores of SMRs. Separated from the bulk of the uranium, the TRU mass is only 0.4% of the used fuel. Moreover, up until sequestration and use in reactors the TRUs can be usefully shielded by the simultaneously separated 98.9% heavy-atom uranium, which in pure form requires little shielding itself.

Fission products are extracted concurrently. They constitute only a small 0.7% of the used CANDU fuel, 440 tonnes. About 70% of them are stable immediately, while the remainder decay in days, weeks, months or a few years. Most are valuable mid-sized atoms that include platinum group metals, exceedingly useful as catalysts, or Rare Earths needed for solar panels or wind turbines. Only two major isotopes, Sr-90 and Cs-137 have half-lives as long as 30 years. And extracting these separately makes them useful, respectively, as gamma sources similar to Co-60 and as long-term thermoelectric generators for Arctic or space applications, like Pu-238.

6. Canada's Next Step

The direction into fast-spectrum SMRs coupled with used fuel recycling is a major new direction for Canada. Yet it is not without precedent. Over half a century ago Canada entered the nuclear age by successfully developing a radical new reactor design, the CANDU reactor, cooled with heavy water and fueled with natural uranium. It was different from enriched-fuel-requiring light water reactors of all other countries. And it extracted energy from uranium about 50% better than any other water-cooled reactor.

At that time Canada had no enriched fissile isotopes, nor the facilities to make them. Yet in the decades since then those CANDUs have slowly provided the means in the form of used CANDU fuel. The TRUs in that fuel, proliferation resistant in isotopic composition, now allow Canada to extract and concentrate them as starting fuel for even better reactors, fast-spectrum SMRs.

Those reactors, with recycling, can then consume all of Canada's used fuel actinides, including U-238, for an energy yield over 100 times better than any thermal reactor. That's carbon-free energy for centuries.

It is a giant step beyond our CANDUs; a giant step beyond all thermal reactors. A step we must take. Gladly.

7. References

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