USED CANDU FUEL REASSESSED: A REACTOR'S FUEL WASTE – A LONG-TERM TREASURE TROVE FOR ONTARIO

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Abstract

Ontario's 50,000 tons of used CANDU fuel is 99.26% heavy atom fuel when recycled through available load-following fast-neutron reactors (FNRs) associated with fuel cycling facilities (FCFs). Such an FNR/FCF technology can produce $74 trillion of non-carbon electricity from that fuel, while avoiding 280 billion tons CO_2 emissions compared to using natural gas. That energy provides 4800 years worth of electricity at current power levels, or enough to supplant fossil fuels in transportation, industry and homes for an all-electric economy in Ontario for 900 years. It can replace volatile gas and wind generation with predictable load-following power on demand. Importantly, as the heavy atoms fission, their 400,000-year radiotoxicity is eliminated permanently. The fission product (FP) residue decays to uranium background levels in 300 years naturally, with special treatments possible for long-lived challenges. Surely such a proven FNR/FCF approach is environmentally friendlier, much more profitable, and more worth pursuing than burying a multi-trillion dollar fuel resource in an unprovable million-year DGR.

Keywords: used CANDU fuel, FNR, fuel recycling, fission products, DGR, CO_2, climate change

1. Introduction

The CANDU heavy-water reactor is the most neutron-efficient of the water-cooled reactors. Yet it extracts energy from only 0.74% of its natural uranium fuel [1], with the over 99% unused fuel currently being stored as high-level radioactive "spent" or "used" CANDU fuel at reactor sites. Light-water-cooled reactors (LWRs) are no better, utilizing only ~0.5% of the mined uranium.

Canada, primarily Ontario, has accumulated about 50,000 tons of used CANDU fuel from its ~20 CANDU reactors [2]. The USA with its 110 LWRs has ~70,000 tons of used fuel, plus another 500,000 tons of uranium depleted of its fissile U235 [3].

Most countries with nuclear reactors, including Canada, consider the used fuel to be waste of no value, or worse, a liability, since the fuel has become highly radiotoxic in the reactor and will remain so for about 400,000 years (Fig. 1). Canada and most other nuclear nations plan to bury the used fuel underground in deep geological repositories (DGRs) to sequester the material hopefully safely for hundreds of millennia. In Canada that cost is estimated at $20-40 billion.

It is puzzling that the nuclear industry should accept to discard over 99% of the uranium fuel. Can a greater percentage of the fuel be consumed before it is classified as waste? If so, is there a prudent alternative to summary burial of used fuel that constitutes a viable management strategy?

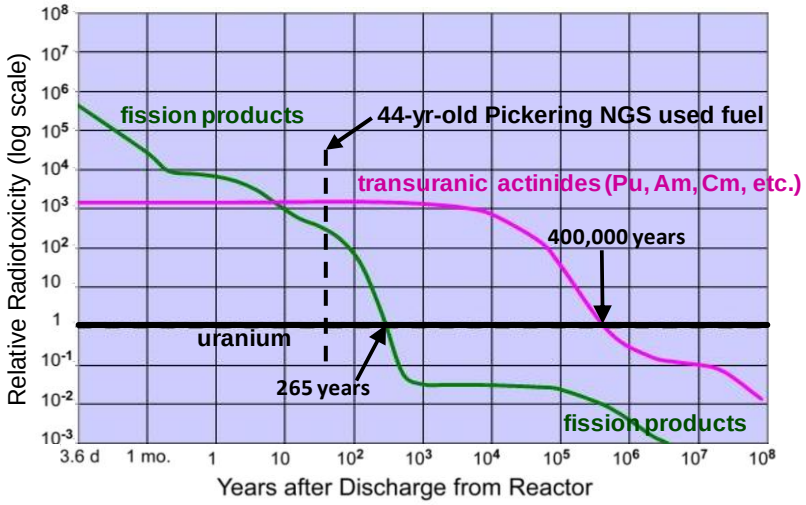


Figure 1. Evolution of Radiotoxicity from Used CANDU Fuel Components Relative to Natural Uranium.

Elimination of the transuranic actinides shortens the time of decay of radiotoxicity to background levels of natural uranium and lower from 400,000 years to 265 years. The broken line refers to the oldest used fuel (44 years) at the Pickering nuclear generating station (NGS). Note the log scales of both axes.

These questions are examined here, and both are answered in a resounding affirmative. It is possible to recycle the used fuel through available fast-neutron reactors (FNRs) and extract all of its energy. Indeed, it has been done [4]. Moreover, the consequences are so positive in terms of -- 1) massive additional reliable non-carbon energy available, 2) effective elimination of long-term radiotoxicity, 3) impact on lowering greenhouse gas (GHG) emissions for centuries, 4) valuable and scarce atoms and minerals extractable from fission products and 5) safety and proliferation concerns alleviated, -- that efforts towards DGRs worldwide should be redirected to the productive and profitable reuse of what is now considered "waste". The costs are similar to current nuclear operation, but the benefits to the industry and to society are huge.

While not exhaustive in the space permitted, this analysis touches on the overarching potential energy value of Canada's used CANDU fuel, on FNRs and their special neutron physics, used fuel cycling and the elimination of long-term radiotoxicity, safety and proliferation, costs, economic impacts for Ontario, and implications for nuclear waste management.

2. The potential value of used CANDU fuel

2.1 Energy from heavy elements

The current 2.6 million used CANDU fuel bundles contain about 50,000 tons of uranium and other heavy elements [4,5]. The fuel in every 6.25 bundles has produced 1 MW-yr of electricity [1]. At the current Ontario mid-peak time-of-use consumer rate of 13.2 ¢/kWh [6, 7] this would correspond to $ 9.7 million/ton from only 0.74% of the heavy atoms in the fuel. The energy could be extracted from the remaining 99.26% of the heavy atoms by fuel cycling through available FNRs (see Section 4 below). Indeed, this has already been done elsewhere [4]. With such a technology the value of that remaining fuel would be an additional 134 times as much, or

$1.47 billion per ton. The total currently stored used CANDU fuel would then yield $73.7 trillion at today's consumer rate, corresponding to 63,700 GW-years of electricity.

To put this in perspective, Ontario's fossil energy needs in 2013 were around 70 GW-yr (see Figure 6, below) [8]. These needs could all be met for 900 years by electric power from the heavy atoms in currently stored used CANDU fuel "waste" alone.

2.2 Fission products

As the 50000 tons of heavy atoms are split (fissioned) in FNRs to extract their energy, 50000 tons of fission products (FPs), atoms about half the size of uranium, would be generated. 70% of these are non-radioactive while the other 30% would decay such that in 265 years their collective radiotoxicity would drop below that of the uranium from which they were generated (Fig. 1). Indeed, only two isotopes, Sr-90 and Cs-137 contribute to the major radiotoxicity near that time, others having decayed well before that. The total FPs, stable plus radioactive, have a mass distribution shown in Figure 2. Current values from international vendors for each element are shown normalized to the corresponding mass distribution in the same figure. The average value for the FPs overall is $3.1 million/ton, or $157 billion for 50000 tons of fission products. The fact that stable fission products are already being extracted and sold [9] indicates that the approach must be profitable for some isotopes even without waiting for a 300-year total decay.

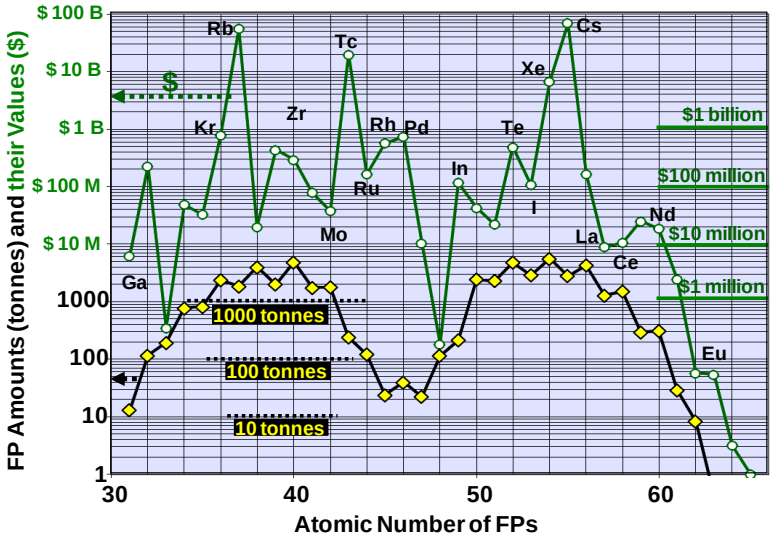


Figure 2. Distribution of amounts (black line) and values (green line) of fission products resulting from consuming 50,000 tons of nuclear fuel completely.

3. The wrong reactors

Why is not more than 0.5% to 0.75% of the fuel consumed? The simple answer is that some sixty years ago the world chose the wrong type of power reactor to use on land. The water-cooled reactor chosen as power plant for submarines by Admiral Rickover of the US Navy was logical, since these vessels operate in an aqueous environment. It was economically expedient for business to follow the research and development by the military and to copy such successful reactors. But in hindsight there are now weighty long-term radiotoxic consequences to past and future use of a wasteful water-cooled technology on land.

Water in the reactor core very efficiently slows down the 2 or 3 neutrons that are emitted with high speeds and energies (~2 MeV) during fission. Slow neutrons, with ~ 0.025 eV energies, split atoms of uranium-235 (U235) very effectively, about 1000 times better than the newly emitted fast neutrons do (Fig. 3). This is the advantage of water-cooled reactors. However, U235 exists only to 0.7% in natural uranium, with the rest of uranium being virtually entirely U238. This U238 isotope captures slow neutrons, transmuting to heavier atoms, but is split about 50 million times less often (Fig. 3). Once most of the small amount of U235 is consumed, water-cooled reactors have to be refuelled. For all water-cooled reactors their remaining fuel is now "waste".

Due to the very high energy density of nuclear fuel, this option had been highly successful for over half a century. However, the unused fuel "waste" of the reactors contains accumulated highly radioactive long-lived heavier atoms, the transmutations from neutron absorption by U238, transuranics (TRUs) neptunium (^{93}Np), plutonium (^{94}Pu), americium (^{95}Am), etc., with such longevity (Fig. 1) that storage and disposal management are now a challenge as stockpiles of used fuel mount. Fission products (FPs), the smaller atoms formed when heavy atoms are split (fissioned) by neutrons, are of lesser concern: they generally have much shorter half-lives.

4. The alternative: consume used fuel by cycling through fast-neutron reactors

A process to achieve more complete use of uranium fuel has existed since the beginning of the age of nuclear power: fast-neutron reactors (FNRs). Moreover, fuel cycling developed in conjunction with sodium-cooled metal-fuelled FNRs has shown that it is possible to fission all of the heavy atoms, including the TRUs [4]. Such an approach would eliminate the long-term concern from TRUs in used fuel. It would also offer >130 times more energy from the same CANDU fuel that has already provided Ontario with the lion's share of its electricity.

FNRs have a long history. The very first electricity produced via nuclear energy was made in 1951 via a liquid-metal-cooled FNR, the EBR-I, at the Argonne National Laboratories [10]. Its successor, the EBR-II, became a test-bed to refine the process, and achieved a burn-up of 20% of the fuel, compared to 0.74% in CANDU reactors currently [4]. Moreover, fuel cycling by electrolytic refining, developed for the metal fuel of the EBR-II to extract all fission products, resulted in all heavy atoms, uranium as well as the mixture of all TRUs, in being consumed.

By now over 400 FNR-years of experience have been achieved, most with sodium-cooled FNRs such as the US EBR-II, the French Phenix, and the commercial Russian BN300, BN600 and BN800 reactors. The International Atomic Energy Agency states that "since 1960, significant fast reactor development and deployment programmes have been implemented worldwide, bringing the knowledge about fast reactor and associated fuel cycle technologies to a high level of maturity. The most mature fast reactor technology is the sodium-cooled fast reactor" [3].

With such a history of development and application internationally it is no longer necessary for a potential user to begin with research and development. Indeed, a sodium-cooled FNR, the 300 MWe PRISM by General Electric-Hitachi (USA), with metal fuel suitable for cycling by electrolytic refinement, has already undergone preapplication safety evaluation review by the US Nuclear Regulatory Commission with the judgment that "no obvious impediments to licensing the PRISM design have been identified" [11]. Licensing is of course specific to every country, as it is in Canada by the Canadian Nuclear Safety Commission.

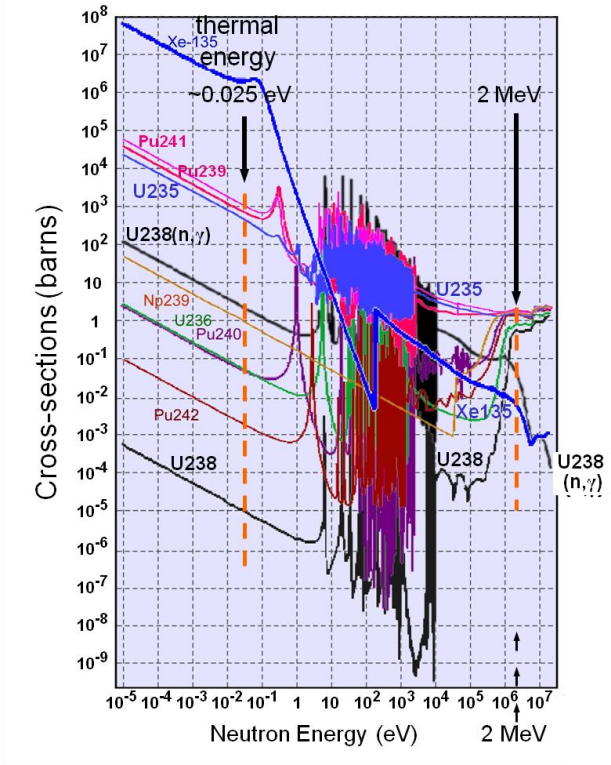


Figure 3. Neutron Interaction Cross Sections in Relation to Neutron Energy

Curves indicate fission cross sections for major fuel isotopes (plus radiative capture cross sections (U238(n,γ) and Xe135(n,γ). Regions of neutron energies in thermal reactors (0.025 eV) and of nascent fast neutrons (2 MeV) are indicated by the arrows. Data compiled from Brookhaven National Laboratories [12]. Note log scales on both axes.

4.1 The fast-neutron advantage

Figure 3 shows that in the region of thermal neutron energies (slow neutrons, ~0.025 eV) there is a huge range in cross sections for fission (probability of fission) for different isotopes of fuel elements from a very low of 0.00001 barns for U238 through 0.002 to 1 barn for Pu240/242, U236, and Np239, to a high of 600 to 1000 for U235, Pu239 and Pu241. This property determines why only the latter three isotopes fission readily to produce energy (are fissile).

Fast neutrons, newly emitted in fission with energies around 2 MeV, have the ability to fission all heavy atom fuel atoms with approximately equal probabilities (0.56 barns to 2.1 barns). This includes the fissile isotopes as well as Pu240, Pu242, Np239, U236 and the abundant U238. Thus all fuel isotopes, including the long-lived, highly radiotoxic transuranic isotopes (TRUs) created and accumulated in used CANDU fuel, can be consumed in FNRs.

The results of calculations for two FNR refuelling models with used CANDU fuel are shown in Fig. 4 for isotopes up to americium-242 (Am242). At the end of each refuelling cycle FPs need to be extracted, else excessive neutron absorption due to FP build-up would stop the reactor.

Figure 4 shows that after two cycles or less, a dynamic equilibrium of concentrations of each of the heavy atom fuel isotopes, fissile and fertile, is maintained from cycle to cycle. This repeating pattern is crucial since it shows that:

1) no additional fissile components are required to maintain or re-establish operation, and
2) all fuel components in the replenishment with used CANDU fuel, i.e. uranium and all TRU isotopes, are completely consumed and converted to fission products at the end of each cycle.

In comparison to TRU-producing thermal reactors, the result of consuming used CANDU fuel in FNRs is a net reduction in radiotoxicity since the long-lived TRUs in the FNR-fuel replenishment are fissioned and eliminated in each fuel cycle. FP radiotoxicity is alike in both types of reactors.

4.1.1 High fuel utilization and ease of load-following -- no xenon effect

Two other characteristics of fast neutrons contribute strongly to higher fuel utilization. 1) More nascent neutrons are emitted in fission events caused by high energy neutrons than by slow, thermal neutrons [12]. 2) FPs absorb high energy neutrons much less frequently than they do slow neutrons, by orders of magnitude [12,13] (see Xe-135, Fig. 3). Both effects permit more fuel atoms to be split into FPs before neutron absorption by the build-up of FPs stops the reactor.

The same low FP absorption, particularly by Xe-135, also permits load-following by FNRs with delayed or immediate changes at all power levels. There is no "xenon-poisoning" in FNRs as seen in water-cooled reactors (more accurately the effect is reduced by a factor of 2600).

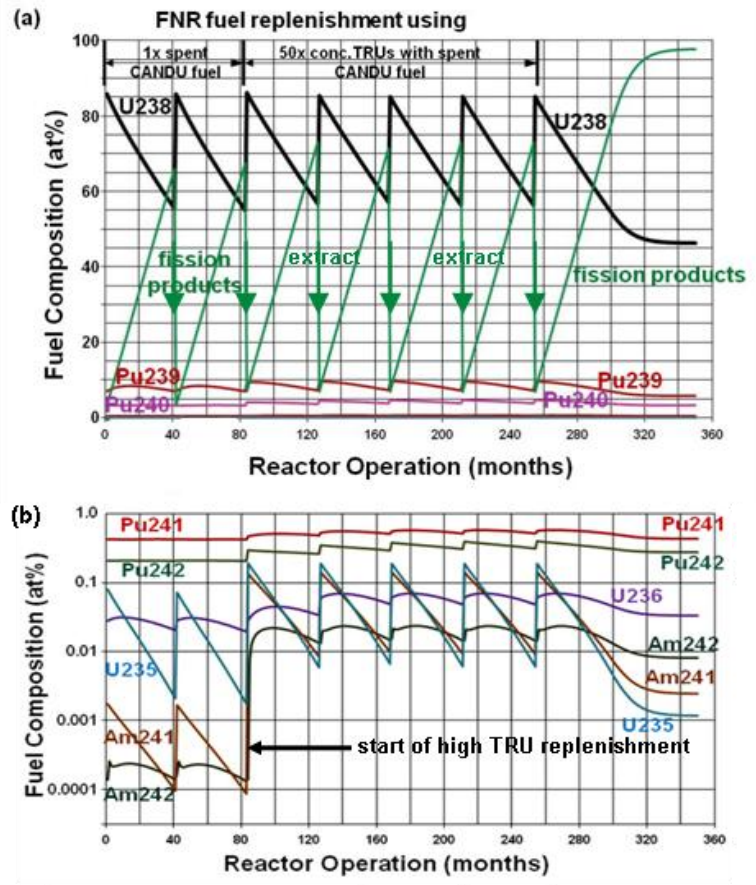


Figure 4. Fast-neutron reactor fuel behaviour under replenishment with two forms of used CANDU fuel stored for 26 years (2 Pu241 half-lives) after discharge

Spent FNR fuel is replenished with used CANDU fuel directly at months 1 and 41. Starting at month 82 FNR fuel is replenished with used CANDU fuel from which 90% of the uranium has been extracted to speed up the elimination of transuranic actinides over 50-fold [described in 13,14]. Panel (b) shows the same data as (a) below 1% on a logarithmic scale to accommodate the large variations in concentrations of the minor isotopes.

5. Electrolytic refinement of FNR used fuel by pyroprocessing: FP extraction

Processing of fuel from water-cooled reactors generally involves an aqueous procedure called PUREX (Plutonium/URaniumEXtraction) to recover plutonium (Pu) for reuse in mixed oxide fuel.

PUREX facilities are large, complex and expensive: the unfinished Rokkasho (Japan) facility by now cost $25 billion [15]. PUREX leaves radioactive working fluids and FPs mixed with other TRUs for long-term disposal. Since PUREX isolates pure Pu, it is a weapons proliferation risk.

For FNRs like the GEH PRISM [11], the recycling choice is non-aqueous electrolytic refinement in molten salt (pyroprocessing) developed at the Argonne National Labs for used metal fuel of the EBR-II [4]. It is compact and economical. Pyroprocessing does not isolate pure Pu [4,16]. It parts used fuel into 3 fractions (with the Zr sheath of the CANDU fuel pellets being a fourth).

1) pure uranium on an iron cathode (up to 95% of the total uranium); >>> FNR refuelling
2) a mixture of all TRUs plus the remainder of the uranium on a liquid cadmium cathode; >>> FNR refuelling
3) all FPs in the electrolyte, with <1part in 1000 heavy atoms [13]; >>> storage

Fission products are recovered by extracting them from the molten salt via chromatographic columns of zeolite. The salt is recycled back into the electrolytic refiner. In light of the value of the FPs (Fig. 2), Max Fratoni (University of Berkeley, personal communication) suggests that FPs be eluted from the zeolite and stored dry in salt form in suitable containment, possibly stainless steel canisters that permit easy recovery and economical chemistry some years hence.

6. Very long-lived fission products: iodine-129

The discussion above indicated that all TRUs could be effectively eliminated by cycling through FNRs. Radioactive fission products, however, take several decades to decay, with two major isotopes, Sr-90 and Cs-137 requiring almost 300 years to reach the background level of natural uranium (Fig. 1). Some seven minor very long-lived FPs at low radiotoxicity levels will remain for a million years or longer (Fig. 5). Of these, iodine-129 (I-129) with a 17 million-year half-life may be of biological concern even though its toxicity levels become almost 40000 times less than uranium, since, if ingested, iodine can concentrate in the thyroid gland about 10,000-fold [17].

This particular concern can be alleviated as part of normal FNR fuel cycling. During pyroprocessing at 500ºC, and again during casting and refabrication of new FNR fuel rods at about 1500 ºC, iodine, mainly I-129 and stable I-127, is volatile and is removed via condensation

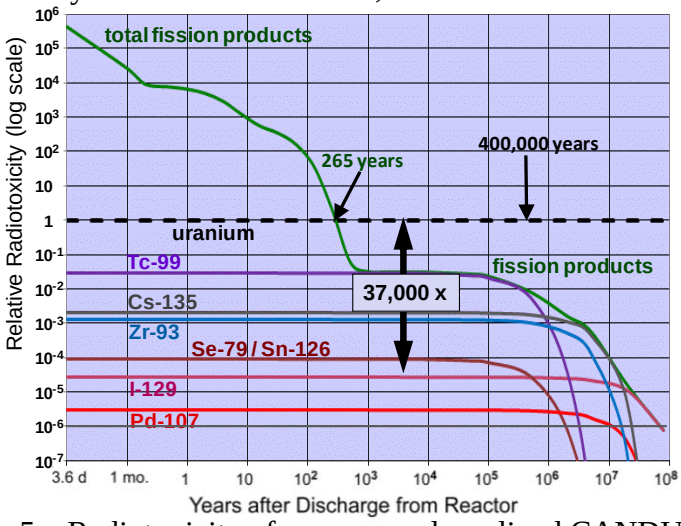


Figure 5. Radiotoxicity of seven very-long-lived CANDU fuel fission products after discharge from reactor

in cold-traps. I-129, with a neutron cross section of 30 b, can be transmuted in reactors to I-130.which has a half-life of only 12.3 hours, decaying to stable Xe-130. Some of the stable I-127 would become I-128, which decays in 25 minutes to stable Xe-128 [13]. Similarly, other iodine isotopes formed, e.g. I-130 to I-131, decay rapidly to their stable xenon analogues. In this way a million-year concern becomes a 12.3 hour non-problem transmuting into a valuable noble gas.

It is anticipated that during the 300-year decay of the other fission products a technology will be developed to manage and possibly find applications for the other six long-lived fission products.

7. Fast-neutron reactor safety

Despite the Chernobyl disaster that caused direct casualties, and the Fukushima and Three-Mile-Island accidents that had none from radiation, nuclear power is demonstrably the safest energy-generating modality [18]. Gen IV reactors, including FNRs, incorporate further safety features. Indeed a prototype Gen IV FNR, the US EBR-II was tested many times under full power with unprotected loss of cooling (control rods inactivated, cooling to the core shut off suddenly) [19]. The resulting brief temperature rise self-terminated without intervention, due to inherent negative reactivity feedback from a strong negative temperature coefficient, with no damage done (Fig. 6, [20]. The reactor also incorporated two passive (no-power) convection coolers, to remove fuel decay heat and lower temperatures within hours after the reactor was shut down (Fig. 7) [21].

With such intrinsic safety features the EBR-II would have avoided the accidents and disaster of Fukushima, Three-Mile-Island, and Chernobyl altogether. A commercial version based on the EBR-II design is being offered by General Electric-Hitachi (USA) as the modular factory-built 300 MWe sodium-cooled PRISM FNR [11].

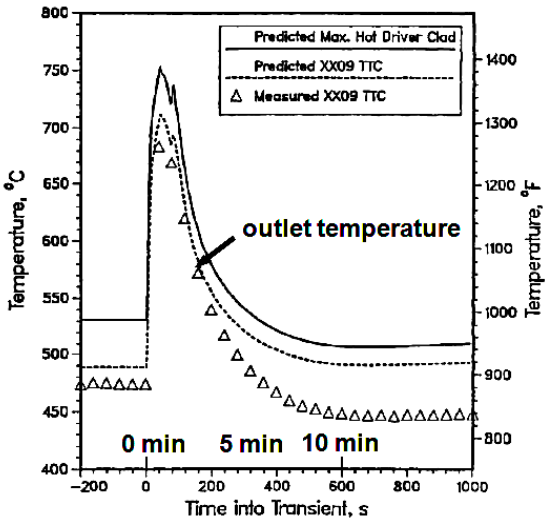


Figure 6. Passive safety. Unprotected (no scram) loss of flow (ULOF) experiment demonstrated in EBR-II fast-neutron reactor [20].

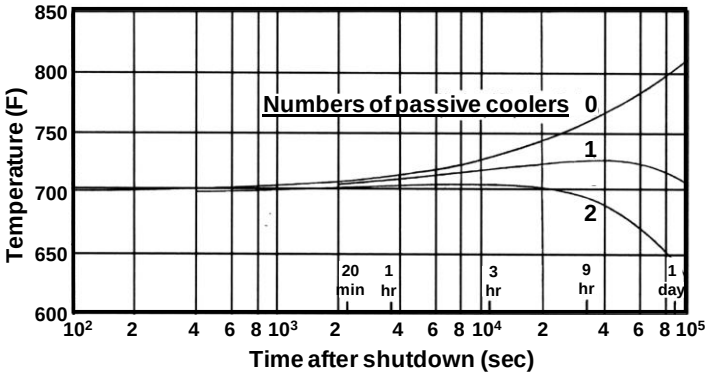


Figure 7. Passive removal of fission product decay heat after shut-down of EBR-II fast-neutron reactor. Temperature course using 0, 1, or 2 convection-based coolers [21].

8. Costs

The relevant comparison is between the current cost for acquisition and disposal of CANDU reactor fuel versus fuel recycling of used CANDU fuel with storage/disposal. FNRs are integral to the recycle process, but those reactors would merely replace other required reactors at the end of their design lives, or as needed new-builds. First-of-a-kind reactors come at a 50% cost premium. The Indian 500 MWe PFBR is quoted recently at a rather economical 5677 Crore, equivalent to CAD $2252/kWe [22]. The simplicity of the sodium-cooled FNR (no pressure vessels or tubes, operation at ambient pressure) is anticipated to bring the eventual cost of further reactors to about 70% of thermal reactors at equivalent power. It is reasonable to assume that operating, maintenance and administration costs would be similar for all kinds of reactors.

Pyroprocessing for FNR fuel is estimated to have a capital cost of $100 million for a facility associated with a 1000 MWe FNR [4,p.291], substantially lower than the $25 billion Rokkasho 800 ton/yr PUREX facility [15]. Running costs, including fixed 15% interest over 40 years, FP storage, and decommissioning are estimated at 0.44 ¢/kWh (a 3-fold capital cost of $300 million at 15% would raise this to 0.82¢/kWh, a mortgage-free facility lower it to 0.25¢/kWh) [4,p.292]. Canadian Nuclear Labs reported a mid-range estimate of 0.66 ¢/kWh [23]. Pre-processing for pyroprocessing (uranium extraction [14]) is expected to add 0.1-0.2 ¢/kWh. For comparison, OPG reports its fuel cost at 0.7 ¢/kWh (0.5 ¢/kWh fuel + 0.2 ¢/kWh fuel waste disposal) [24].

This suggests that fuel costs with recycling would be roughly the same as they are today: low.

For such equivalent costs, what value can be put on the potential of eliminating the long-term radiotoxicity of TRUs for future generation? Is it worthy of social acceptance? What value has the potential of a secure, predictable and affordable non-carbon energy supply for millennia? Or the avoidance during those millennia of GHG emissions equivalent to 15% of the CO_2 in the earth's entire atmosphere (see below)?

Is Canadian inexperience in FNRs or fuel recycling a drawback? Initially, perhaps. However, we did develop the CANDU reactor with no experience. And CNL has years of experience in processing highly irradiated fuel for analysis or for the extraction of medical isotopes. In addition, a worldwide 400 reactor-year experience with Na-cooled FNRs, and the potential of purchasing a mature commercial design means Canada would start from a good base.

9. Economic implications: Stimulation of the nuclear industry

The existing radiotoxic used nuclear fuel "waste" is an albatross around the neck of the nuclear industry. The major reduction and possible rapid elimination of the long-term radiotoxicity in a few decades by recycling the used fuel through FNRs (e.g. Fig. 9) removes that major societal objection to the continued or increased use of nuclear power. That potential, demonstrated, should stimulate the CANDU industry locally plus the Canadian nuclear industry in general.

10. Reliable predictable energy, affordable for industry, transportation and homes

Each ton of used CANDU fuel can produce $1.47 billion of electricity in fast-neutron reactors, over 130 times more than already extracted from the same fuel in our CANDU reactors. Can such a potential surfeit of additional electricity be incorporated in the Ontario economy now?

The 2013 Ontario Long Term Energy Plan predicts levelling of electricity demand, and even a reduction in nuclear power in our 20 GWe very-low-carbon electric sector [25]. But the recent emphasis worldwide and in Canada on greenhouse gas (GHG) reduction points to the need for reliable and affordable non-carbon electrical energy in other economic sectors; e.g. Ontario's transportation, industry and homes sectors use 70 GW of fossil fuel energy (Figure 8) [8]. Enticing those sectors to use non-GHG electricity would require massive affordable additional electric power. Nuclear, along with hydroelectric power, are Ontario's most affordable energy sources, produced at around 5.7-6.6 cents/kWh [7]. 70 GW reliable, affordable non-carbon energy could be readily furnished for centuries from Ontario's used CANDU fuel, recycled and consumed in FNRs. The existing stored 50,000 tons fuel "waste" alone would provide 63,700 GW-years of electricity, sufficient to replace all current fossil energy needs of those sectors with non-carbon electrical energy for over 900 years.

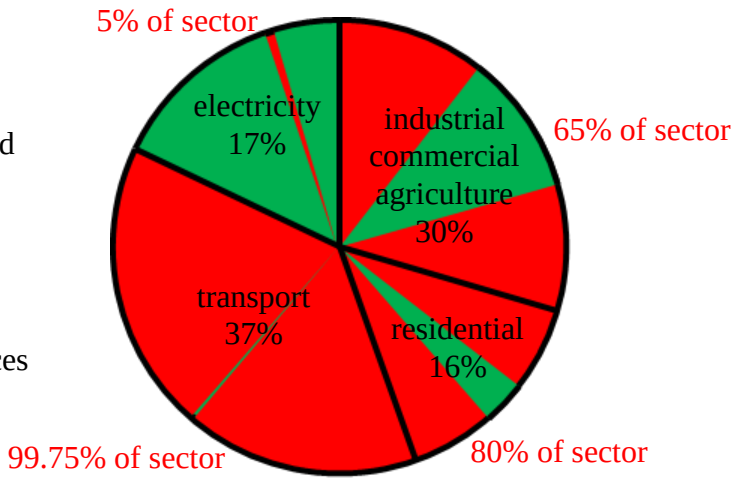
11. Environmental impact: huge GHG avoidance by cycling used CANDU fuel in FNRs

The use of coal in creating 1 megawatt-hour (MWh) of electricity releases 0.85 tons of CO_2 into the atmosphere [26]. One ton used CANDU fuel consumed in an FNR would create 11.2 million MWh and avoid the release of 9.5 million tons of CO_2. The 50,000 tons of used fuel would avoid the release of 475 billion tons of CO_2 (280 billion tons compared to natural gas). This enormous amount is equivalent to 15.5% of all the CO_2 currently in the entire atmosphere [27].

Figure 8.

Primary energy use in Ontario with proportionate use of fossil fuel indicated within each activity sector [8]. Total energy use = ~100 GW-yr in 2013.

Red = energy from fossil fuels
Green = energy from non-carbon sources



12. Time for TRU Elimination and Nuclear Exit

How quickly can the TRUs in used CANDU fuel be sequestered and eliminated using FNRs? The short answer is: only a few decades. The advantage of FNRs in this process is two-fold. First, they can use the TRUs as starting fuel (20% of the core load). Second, they can then use further TRUs as fuel replenishment at close to 15% of the core-load in each six-year fuel cycle. As an example, depicted in Fig. 9, PRISM-like FNRs replacing the 3000 MWe power output in Pickering would require 20 tons TRUs as starting fuel, obtained from 5360 tons of the 15000 tons stored used CANDU fuel expected by 2020. They would consume 1.4 tons TRUs from a further 360 tons each year. Thus in about 27 years after the start of operation there would be no further TRUs in any of those original 15,000 tons of used CANDU fuel. After that time the fuel in the reactors and their successors can be replenished for several millennia at ~5 tons per year from the many tons of depleted uranium separated early during the recycling of the used CANDU fuel.

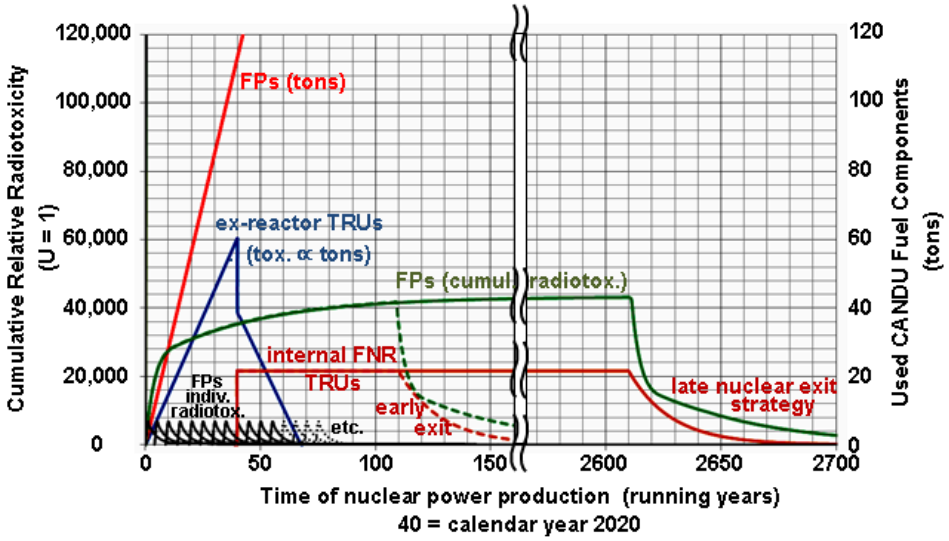


Figure 9. Evolution of radiotoxicity upon recycling of 15,000 tons used CANDU fuel stored at the Pickering Nuclear Power Plant using FNRs of 3000 MWe total power. Details in text. .

For each year of operation there would be a further 4.6 tons FPs added to the 110 tons existing FPs that require safe interim storage before their value (Fig. 2) can be accessed. But, the total radiotoxicity or heat-load, would not increase substantially. Due to its rapid decay (see individual FP-load contributions in Fig. 9) it is already at 75% of its maximum attainable cumulative value.

If a better source of energy is found in future, an early or late exit from FNR nuclear power (Fig. 9) is best achieved by measures such as the gradual diminution of the number of FNR reactors at a rate equal to the fuel use in each cycle, e.g. ~15% for PRISM-like reactors. In such ways the eventual amounts of long-term TRUs left are driven to a minimum.

13. Concluding remarks

The advantages of the FNR/FCF approach suggest that it should be incumbent on the NWMOs of the world to embrace that pathway as management strategy for used nuclear fuel. Fuel cycling through FNRs has already been proven internationally, and offers an actual elimination of the long-term radiotoxicity of used fuel heavy atoms as they are fissioned, with copious non-carbon energy created as a bonus. Moreover, the definition of "management" in the Canadian Nuclear Fuel Waste Act that created our NWMO not only includes fuel "disposal", but also "conditioning" and "storage", [28], procedures such as applied in conjunction with the EBR-II, and still employed, to process and store used fuel for that type of reactor. Thus used fuel processing can be a legitimate logical prime activity of the Canadian NWMO.

In contrast, many years of international effort and many millions have been spent, including in this county since our Hare Report of 1977 [29], with no currently existing proven or functioning DGR for used fuel, worldwide. Indeed, the effectiveness of any long-term DGR is practically unprovable. However, the certainty exists, with the current intent of burying used fuel, of an inevitable squandering of a still-growing non-carbon energy resource that in Canada already embodies close to $74 trillion ($74,000,000,000,000) in potential GHG-free electricity for Ontario. That resource wisely used by its current custodians is a long-term treasure trove of non-carbon energy for the province.

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