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THE TRAVESTY OF DISCARDING USED CANDU FUEL

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Abstract

The current plan worldwide for virtually all used nuclear fuels is costly deep burial to attempt to isolate their long-term radiotoxicity permanently. Alternatively Canada's 50,000 tons spent CANDU fuel, of which only 0.74% of the heavy atoms have been fissioned to extract their energy, could supply 130 times more non-carbon energy using proven economical recycling and fast-neutron technologies. The result in this country alone would currently be the creation of $74 trillion of reliable electricity on demand without greenhouse gas emissions. It would avoid adding 475 billion tons CO_2 to the atmosphere compared to the use of coal, to mitigate climate change. Worldwide recycling of stored spent nuclear fuel and replenishing with depleted uranium in fast-neutron reactors could avoid emitting over 20 trillion tons CO_2, or over six times the current total atmospheric CO_2 content. As added bonus the long-term radiotoxicity of the used CANDU fuel is effectively eliminated, making a long-term deep geological repository unnecessary. Even the shorter-lived radioisotope fission products become valuable stable atoms and minerals that would fetch $3 million per ton. Such an alternative is certainly worth pursuing.

1. Introduction

Nuclear power from thermal reactors, including Canada's CANDU reactors, produces prodigious amounts of energy. Curiously, such nuclear power creation is one of the most inefficient processes, converting less than 1% of the potential of nuclear fuel into usable energy.

This seeming paradox is well illustrated by a common analogy. Consider burning only the tinder-like bark off the birch log in your fireplace (Fig. 1). The bark flames up, with the flame providing a momentary satisfying heating glow. But it soon dies to make way for a new firebrand that repeats the procedure, while the old slightly charred unburned log, blackened with charcoal, soot and a few ashes, is discarded.

Surely you would personally quickly learn to build an efficient fire for you to enjoy, a fire that extracts the heat from the entire log, and burns down to a residue of ashes. No char left, no soot, and even the ashes provide fertilizer for the garden.

On a commercial scale operation one could scarcely envision burning only the birch bark tinder from reams of logs (Fig. 2) to make electricity. At an industrial scale such stored used charred logs could contaminate the soil and the environment with lyes from the ashes and with surface tars that leach harmful chemical residues including cancer-causing dioxins. Consider then being

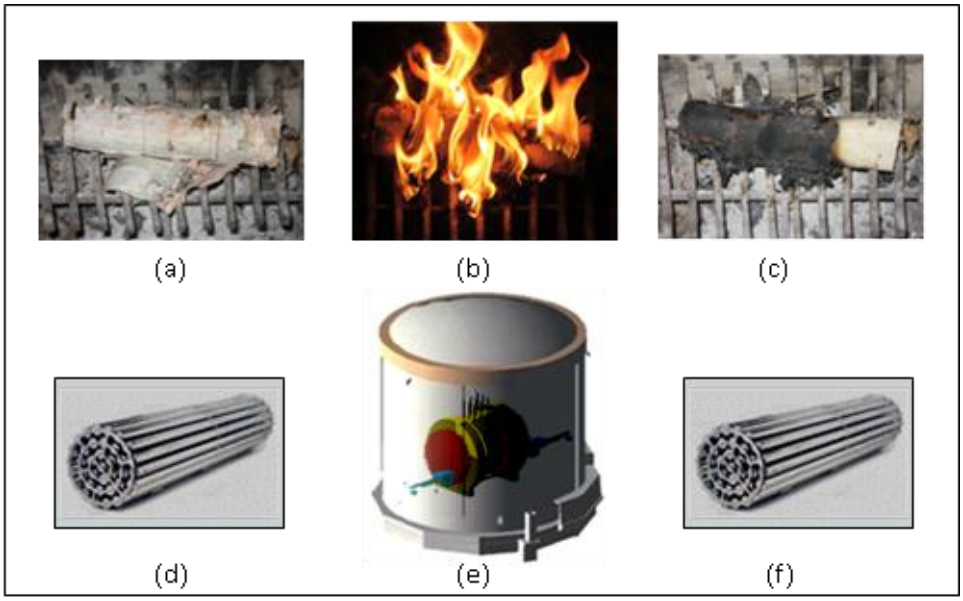

Figure 1. Analogy between birch log in fireplace and uranium fuel in CANDU reactor

(a) A fresh birch log with loose bark tinder, in analogy to fresh uranium fuel bundle with U-235 (d). (b) Lit bark tinder around log burning on grate in fireplace; (e) analogously U-235 in fuel bundle is consumed partially in the pressure tubes of the CANDU reactor (Note: the uranium is split to produce heat, but there is no fire). (c) Charred log, incompletely burned. (f) Spent fuel bundle, mostly U-238, with U-235 reduced from 0.72% to 0.23%, with 0.74% fission products ("ashes") and with 0.4% TRUs (invisibly inside the zirconium cladding of fuel rods)

asked to pay to bury the "contaminated" logs permanently in a cavern built deep underground to sequester them from the biosphere. You would likely soon find a company with a technology that would not only profitably use all components of the logs but that would also detoxify the tars and dioxins in the process.

This scenario in all aspects is effectively the situation of natural uranium fuel use in what I consider the most efficient current thermal reactor design, the CANDU reactors. Once most of the easily lit "nuclear tinder", the small amount of fissile U-235 in the fuel, is consumed in this reactor, a new fuel bundle is requisitioned to replace the old, leaving behind equivalent amounts of fission products ("ashes"), and virtually all of the "nuclear heartwood", the fertile U-238. A small amount of the U-238 is converted to highly radioactive transuranics (TRUs), atoms heavier than uranium (equivalent to the charred and tarred portion of the birch heartwood with its poisonous and carcinogenic dioxins). Only a small portion of the TRUs, consisting of fissile and fertile atoms, is consumed to create energy.

This process has not changed in principle since the first CANDU reactor was built, with used fuel bundles now amounting to a "pile" of 50,000 tons of over 99% still-usable fuel accumulating in pools and in dry storage (Fig. 2d).

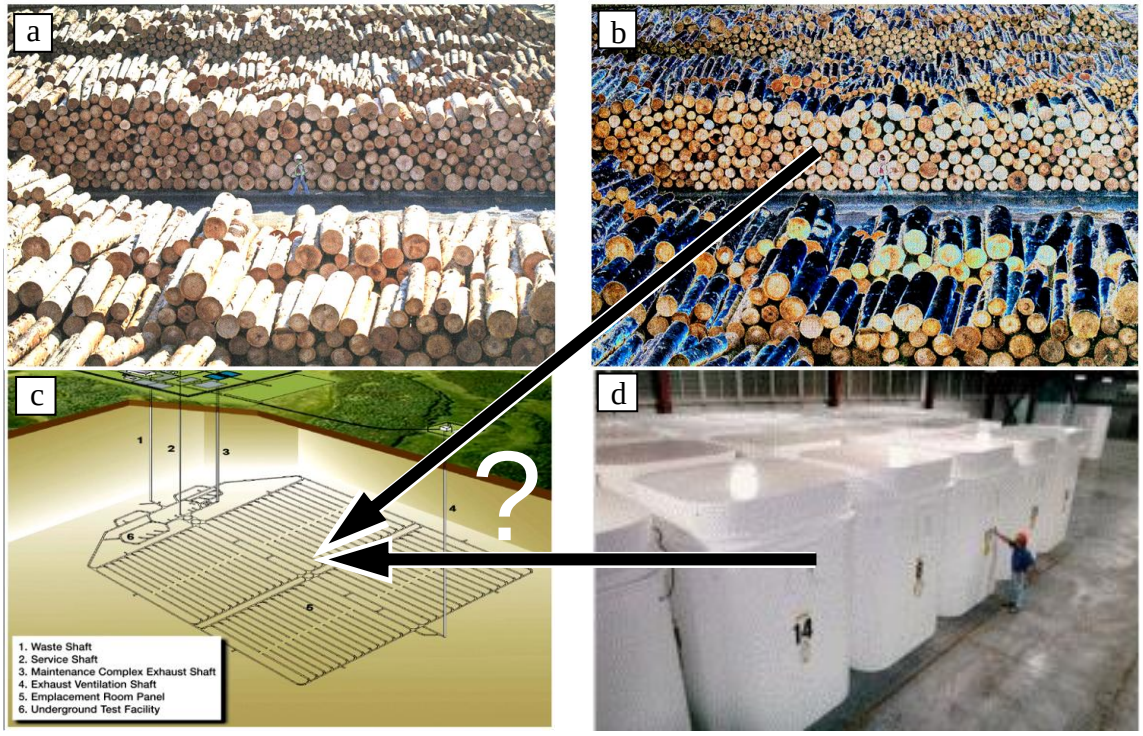

Figure 2. (a) Representative massive pile birch logs. (b) The same pile with the surface bark burned, leaving a charred surface (via image processing). (c) A potential planned deep geological repository. (d) Accumulating used fuel bundles stored dry in concrete castors.

Why does the nuclear industry permit the use of a process that only partially burns the 0.72% fissile U235, the "tinder" in natural uranium, while leaving the 99.68% U238, the massive nuclear heartwood of the fuel, virtually untouched? Worse still, since the consumption of that small amount of uranium leaves only a tiny residue fraction of powerful long-lasting radiotoxins associated with the fuel, why are we asked to pay to bury not only that small fraction but also all of the remaining unused fuel.

Since there is a much better alternative, used fuel cycling through fast-neutron reactors, something is wrong in our nuclear thinking.

2. The Travesty

We proudly point to our CANDU reactors, our nuclear furnaces, as the most efficient uranium fuel consumers among thermal reactors. Heavy-water-cooled CANDU reactors extract about 0.75% of the energy in mined uranium. That is fully half again as much as is obtained in light-water-cooled reactors which manage to extract about 0.5%.

But that is still only an energy yield of 0.5 to 0.75% among all thermal reactors!

One would be hard-pressed to find as inefficient a fuel-to-energy extraction process anywhere in the world. Hydraulic power extracts about 90% of the falling water's energy. An electric motor converts 80%-90% or more of electrical energy to useful work. A Diesel engine drives 45-55% of the fuel energy into motion, with a gasoline engine, though being only half as efficient, still at 25-30%. Even solar panels convert 10-15% of the sun's energy falling on them to electricity, with laboratory specimens now at around 40%.

One has to go to nature to find something as inefficient as our thermal reactors: photosynthesis operates at 0.2% to 2% for most crop plants. And even there, the lowly sugar cane manages an 8% efficiency [1].

So why be satisfied with a nuclear energy yield of only 0.5 to 0.75%?

We have accepted that state perhaps because even a yield of nuclear energy this small results in a huge absolute amount of energy. While only 370 tons of the heavy atoms of the current 50,000 tons of stored used CANDU fuel have been split to extract their energy, those 370 tons have produced about 3500 TWh of electricity. At the current mid-time-of-use electricity rate that you and I currently pay in Ontario, those 3500 TWh would fetch $ 462 billion, although the utilities which produce the power get only about half that.

Since we currently accumulate about 1400 tons of used CANDU fuel per year, the gross revenue yield per year is ~$ 13 billion. That's $ 13 billion annually from only about 10 tons of split heavy atoms. The remaining yearly 1390 tons still sit there, idle.

These huge yields seem to blind us from the inefficiency of the process. Worse, although we are more familiar with radiation than most of the population, we seem nevertheless to be transfixed by fear of the fact that within the reactor the used fuel has become highly radiotoxic from the creation of long-lived heavier atoms in the fuel, the transuranics, and from the shorter-lived split atoms, the fission products. As a consequence the intent is to bury all current 50,000 tons of used CANDU fuel summarily and permanently for close to a million years in a deep geological repository (DGR) (Fig. 2c) at a cost of $ 24 to 40 billion [2, p.163; 3; 4, p.3], with a further 50,000 tons used fuel anticipated by the end of life of the current complement of reactors.

It would be a tragedy in today's era of climate change to bury such a virtually unused resource of non-carbon energy.

We already know how to extract the remaining energy. We also know how to eliminate the long-lived radiotoxicity, and have done so, by recycling the used fuel through fast-neutron reactors. We, internationally, have used the fast-neutron reactor technology since the 1950s [5]. We have developed the associated fuel cycle technology to help consume all of the used (or fresh) uranium fuel and by so doing to eliminate the long-term radiotoxicity of the heavy atoms [5, p. 167ff]. Indeed, the technology was developed with a strong Canadian content.

The travesty is that we have chosen to ignore these proven achievements that point to an effectively inexhaustible unending non-carbon energy future and have insisted instead on a path

down a deep hole, down into a DGR. The travesty is that we have acquiesced to paying $24.4 to $40.7 billion to build and fill such a DGR [2, p.163; 3; 4, p.3] that will rob us of the potential of $74 trillion in GHG-free electrical energy from just the current 50,000 tons used CANDU fuel alone. Those 50,000 tons of used fuel, converted into non-carbon heat and electricity, would avoid the emission of 475 billion tons of CO_2 in Canada alone, equivalent to about 15% of all the CO_2 currently in the entire atmosphere. Moreover, the process would permanently eliminate the "million-year" radiotoxicity of the heavy atoms in the fuel, and so avoid the use of an unproven and unprovable DGR. The travesty is that we are turning our backs on that potential.

3. The Wastefulness is our Choice

This flagrantly poor 0.75% efficiency has been accepted for at least three reasons. First, fresh uranium fuel is still relatively inexpensive, costing Ontario Power Generation (OPG) only 0.54 ¢/kWh currently [6], plus, depending on the calculating assumptions, an additional 0.2-0.4 ¢/kWh for disposal in a DGR [3]. Second, as mentioned above, the nuclear energy extracted from even as little as 0.5% - 0.74% of this non-carbon fuel is huge. It requires only 925 grams of the 125 kg uranium charge in 6.25 CANDU fuel bundles to produce 1 megawatt-year (8.76 million kWh) of non-carbon electricity in a CANDU reactor [2, p.351]. This is enough electricity for 900 households for a whole year [7]. To produce the same amount of electricity for those 900 homes from fossil fuels would take 2,800 tons of coal, or 28 hopper rail cars full of coal [8], and produce emission of 8000 tons of CO_2 [9]. The equivalent use of methane gas would be almost 50% better, but still emit 4700 tons CO_2 [10].

That's a lot of non-carbon energy from very little uranium fuel. But compared to the 925 g, the remaining 124 kg (124,075 g) fuel in the same 6.25 used fuel bundles, if consumed completely by cycling through available fast-neutron reactors [5,11] would produce an additional 134 times the non-carbon electricity, or 134 MW-years worth, and avoid the emission of 1,000,000 tons of CO_2 compared to coal.

The 50,000 tons of used fuel replenishing fast-neutron reactors (FNRs) would provide almost 5000 years of nuclear energy for Ontario at our current nuclear power production. In contrast our thermal reactors will run out of economical fissile uranium fuel in Canada in about 40 years [12].

Thirdly, it is often assumed that recycling of used fuel brings with it an increased risk of nuclear weapons proliferation. Yet in over 60 years of commercial nuclear power worldwide no proliferation of nuclear weapons has occurred as a result of commercial fuel cycling. The used fuel from commercial reactors is very poor weapons materials. Moreover, in recycling, as described below, potential weapon materials, elements and isotopes, are not separated. Canada has had the wherewithal to build nuclear weapons since the 1940s and '50s even without fast-neutron reactors and without recycling, but has chosen not to do so. There is no reason to believe that adopting used fuel recycling through FNRs will change Canada's weapons philosophy.

Thus the wastefulness and inefficiency with respect to uranium fuel use is our choice rather than a technological or even geopolitical necessity. It appears that only our own inertia and our satisfaction with the *status quo* stand in the way of our doing better. Indeed, we are willing to spend $24 to 41 billion on a questionable million-year burial of Canada's current stored 50,000

ton energy resource of used CANDU fuel when the nuclear industry knows that the long-term heavy-atom radiotoxicity could be eliminated in 50 years or less with recycling in fast-neutron reactors (Fig. 5, below) [13,14].

4. The root cause of uranium fuel inefficiency: the wrong type of reactor

The uranium fuel inefficiency is inherent in the nuclear reactors that we now use, be they heavy-water-cooled CANDUs or light-water reactors (LWRs). Both types are "thermal" reactors using neutrons slowed down ("moderated" or "thermalized") to the same energy or "temperature" as the hydrogen or deuterium atoms in the water used to cool the reactors. Such slow neutrons very efficiently fission, or split, only a small isotopic component of the uranium, the 0.72% U-235 in mined uranium, while splitting the much larger component, the 99.28% U-238, about 50 million times less often, leaving it virtually untouched. A little of the U-238 is converted into heavier elements, some of which can also be consumed. (In the jargon of the field these properties make U-235 "fissile" and U-238 "fertile".) However, once most of the fissile U-235 is consumed the thermal reactors have to be replenished with fresh fuel.

With the massive power output of the reactors, often on the order of 1000 megawatts, the public and even many workers in the nuclear industry have been blinded to fact that so little of the uranium fuel is actually used up.

4.1 Fuel efficiency using fast neutrons

Clearly we have not accepted this type waste scenario for the utilization of wood. We have perfected efficient woodstoves, as well as learned to lay logs effectively for roaring campfires or economical cooking fires, utilizing every bit of fuel from log to scrap. Even the wood ash was used by our forebears to make soap, and is still used as a source of potassium in our gardens.

Indeed, a similar efficient scenario also exists in the nuclear field: fast-neutron technology with fuel cycling. It was started in the 1950s, fleshed out in depth in the USA in the '80s and '90s, and is now largely forgotten, overlooked, or taught as an historical footnote [5]. Few know that it was a fast-neutron reactor, the EBR-I, that produced the first nuclear-generated electricity in 1951.

The EBR-I successor, the EBR-II fast-neutron reactor (FNR), sodium-cooled to prevent thermalization or moderation of neutrons, was the test-bed from 1964 on for increased fuel utilization and for demonstrating passive safety of the technology [5, p.138ff]. It achieved 20% "burn-up" safely in the '80s, compared to 0.74% in CANDUs today. After the decommissioning of the EBR-II in 1994, fuel tests in the French Phenix FNR provided proof that 25% burn-up at least was possible.

These results indicated that not only was the physics of fast neutrons capable of delivering much higher fuel efficiencies than the physics of thermal neutrons, but also that the materials, the steels of the fuel rods and assemblies, were capable of withstanding the increased neutron fluxes at higher energies and at such high levels of fuel utilization.

Even the 25% fuel burn-up found experimentally in FNRs is not the theoretical limit, a limit that would ultimately be determined by neutron absorption in fission products (FPs) that build up in the fuel as more and more heavy atoms are split to extract their energy. That limit is closer to

35% (Fig. 3). To continue fission of heavy atoms beyond this limit it becomes necessary to extract the FPs, i.e. undertake fuel recycling. Such fuel cycling was put in place in conjunction with the EBR-II reactor, recycling about 35,000 fuel pins or five times the load of the reactor [15]. For a 20% fuel utilization achieved in that reactor, five such cycles would utilize the equivalent of 100% of a single reactor load, leaving nothing but FPs.

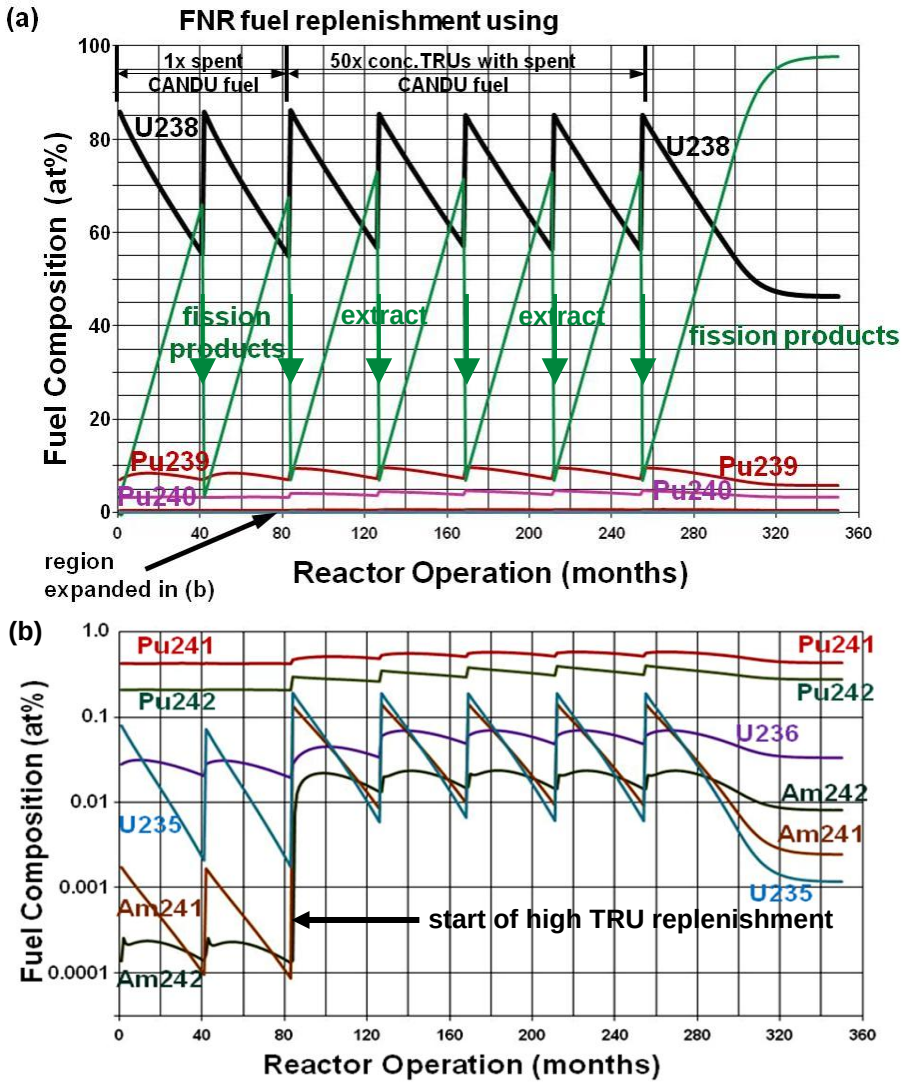

Figure 3 Fast-Neutron Reactor Fuel Behaviour under Replenishment with Two Forms of Used CANDU Fuel

The first two cycles show FNR fuel replenished with used CANDU fuel at months 1 and 41. Subsequent cycles starting at month 82 have FNR fuel replenished with used CANDU fuel from which 90% of the uranium has been extracted to increase the concentration of transuranic actinides (see text).
Panel (a) shows the major isotopes and FPs on a linear scale. Panel (b) is shows an expanded view of the lower 1% of Panel (a) with a logarithmic scale to accommodate the large variations in concentrations of the minor isotopes.

4.2 More fast-neutron advantages

4.2.1. Maintenance of fissile content

A particular design advantage of such an FNR is its internal maintenance of the level of fissile atoms required for operation. Thus after the 20% fission products are removed from the fuel at the end of one fuel cycle, the fuel has only to be replenished with any source of fissionable atoms that includes primarily fertile U-238, such as depleted uranium or used CANDU fuel. No additional fissile components are required. At the end of each such cycle, all of the fuel isotopes, uranium and transuranics, reach the same level as at the end of the previous cycle (Fig. 3). This includes the minor actinides such as Am-241 and Am-242, etc., as well as even-numbered major actinide isotopes such as Pu-240 and Pu-242 that accumulate in the used fuel of all thermal reactors. It is this property of FNRs that makes it possible to consume all of the heavy atoms in used CANDU fuel.

As one crucial outcome, as the heavy atoms are fissioned, whether uranium or TRUs, they cease to exist and their long-term radiotoxicity ceases to exist. Short-lived FPs remain (see Section 5).

4.2.2 No xenon poisoning: load-following

Additionally, one practical operational advantage accrues from the fact that at high energies neutron absorption of any fission product, including Xe-135, is extremely low. At 1 MeV, absorption of Xe-135 is only 0.01 barns versus 2.6 million barns at thermal energies [16]. Therefore “xenon poisoning”, a problem caused by huge absorption of thermal neutrons by the build-up of Xe-135 via decay from I-135 after reactor shut-down, virtually does not exist at high energies (more accurately, the effect is reduced by a factor of 2600). Such reactors can therefore have their power levels changed at will. There would be no delay in powering up or restarting even after longer shut-downs that normally prevent the restart of thermal reactors until xenon absorption has decayed enough, after several 9.2 hr Xe-135 half-lives. Thus load-following of the daily variations in demand of energy could be readily accommodated by such reactors, opening the possibility of supplanting much GHG-emitting gas-fired electrical generation. (Note added: a referee rightly suggested that “no-xenon-effects” would likely have avoided the Chernobyl disaster. The strong positive feedback on Xe-135 burnout from a power increase in that reactor would not have occurred in an FNR with high energy neutrons; they cause no xenon effects).

5. Elimination of long-term radiotoxicity.

Long-term radiotoxicity is the prime reason cited for discarding used CANDU fuel and to sequester it from the biosphere for the requisite several hundred thousand years (Fig. 4). As pointed out above, using all of the heavy atoms and particularly the transuranic actinites (TRUs) as fuel in FNRs would eliminate the major portion of that future radiotoxicity.

However, since the practical limit of heavy-atom fuel burn-up in FNRs is not 100% but closer to 15-20% [11], the fuel must be recycled, with fission products being removed periodically. In such a process the efficiency of separating fission products cleanly from radiotoxic heavy atoms becomes important, as does the purity and volume of used chemicals after such separation.

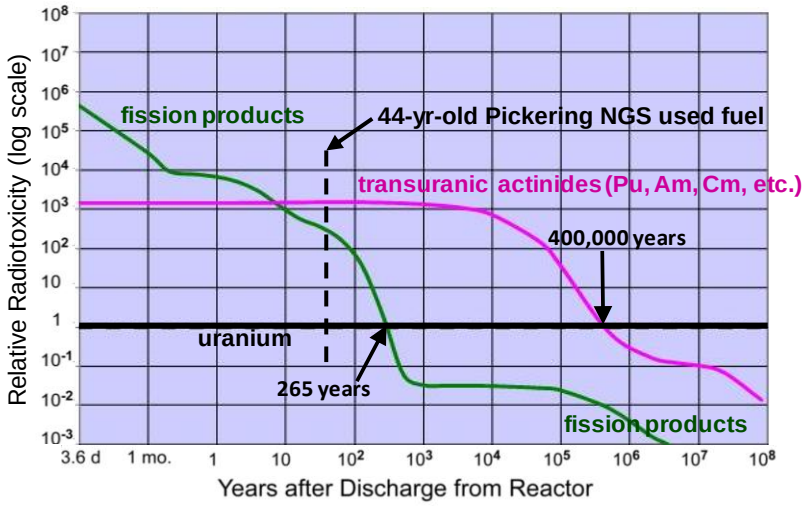

Figure 4 Evolution of Radiotoxicity from Used CANDU Fuel Components Relative to Natural Uranium.

Elimination of the transuranic actinides in fast-neutron reactors and extraction of uranium from the used fuel waste shortens the time of decay to background levels of natural uranium from 400,000 years to 265 years, and results in a reduction in radiotoxicity of used fuel waste of about 42,000X at 1000 years. After 265 years the radiotoxicity of the fission products is lower than that of the natural uranium from which they are created in the reactor. Broken line indicates current radiotoxic state of oldest used fuel (44 years) at the Pickering nuclear generating station. Note log scales of both axes.

5.1 Aqueous processing: PUREX and variants

The classical "recycling" procedure is the separation of fissile materials, specifically plutonium, using aqueous chemistry such as PUREX (Plutonium URanium EXtraction) or its modifications. Facilities used at La Hague in France, and Sellafield in the UK, for example, are huge, leave large volumes of radioactive liquids, and are expensive - the still unfinished Rokkasho (Japan) facility already cost $25 billion [17]. Moreover, with the focus on recovering and cycling only fissile isotopes, the amounts of radiotoxic materials are only minimally reduced.

5.1.1 Aqueous processing: two other drawbacks

Even discounting the expense, aqueous processing results in products that are particularly sensitive to weapons proliferation. PUREX was intentionally designed by the military to produce pure weapons-grade plutonium. However, even derivatives of PUREX, such as COEX, UREX, GANEX, etc., provide products that are relatively pure mixtures of alpha-emitting transuranics and uranium which are amenable to being easily handled directly without shielding, and therefore open to being readily diverted for further nefarious purification.

In addition, any accidental leakage of the aqueous radioactive solutes and solvents might result in seepage into ground water before a clean-up could be instituted.

5.2 Non-aqueous recycling: pyroprocessing

A better approach, specifically designed for recycling used metal fuel from FNRs, is non-aqueous pyrometallurgical electrolytic separation, or "pyroprocessing", developed at the Argonne National Laboratories, and still operating [5, p.181]. The cost of a full sized facility is estimated at $ 0.1 billion [5, p.291]. This procedure produces three fractions from the fuel: 1) pure uranium, 2) a mix of all TRUs with a few fission products (FPs) as impurities plus any remaining uranium, and fraction 3): all other FPs. There is no separation of plutonium, or any other TRU. Fraction 1) and 2) contain heavy atoms that are recycled into the FNRs. Fraction 3), the FPs, are put into medium-long storage to decay further for a maximum of 300 years (Fig. 4), although most become stable after a few decades. Useful stable or radioactive isotopes can be extracted, and many are already for sale [18]. Zirconium, even long-lived radioactive Zr-93, can be recycled into FNR metal fuel, while activated iron casings are compacted and treated like FPs, for decay. Molten salt electrolytes are recycled, leaving effectively no process wastes for disposal.

Any spillage of the hot molten salt solutions would result in almost immediate solidification to make clean-up relatively easy.
Still, this non-aqueous separation process is not perfect. Laidler et al. [19] indicate that pyro-processing achieves a separation of better than 99.9% of the actinides from the fission products. This does not result in a complete elimination of the long-term TRU radiotoxocity in fraction 3), but the degree of separation would lower the toxicity of the TRUs over 1000-fold to the level of the original natural uranium or below (cf. Fig. 4).

This TRU level among the fission products may be considered sufficient to obviate the need for a long-term DGR. If not, one has effectively 300 years to search for a better separation method before those remaining TRUs would become the dominant radiotoxic component of fraction 3).

Furthermore, the less than perfect separation of FPs from the TRUs in fraction 2 makes clandestine diversion for nefarious purposes particularly difficult. This fraction, still being highly radioactive, has to be shielded and processed remotely to make new FNR fuel. This necessity imparts a very high degree of proliferation resistance to the pyroprocess..

5.3 Accelerated detoxification of TRUs

One additional advantage of the non-aqueous pyroprocess is its ready potential to accelerate the long-term detoxification of existing used nuclear fuel. Since one fraction, fraction 2), contains the long-lived TRUs, this fraction can be recycled into FNRs preferentially as fuel to eliminate the TRUs without a major effect on the operation of the reactors. This is demonstrated in Fig.3, which from month 82 on depicts the replenishment of FNR fuel using a 50-fold increase in the use of pyroprocess fraction 2), i.e. the mixture of all TRUs plus some uranium (see also [13]).

This approach can be remarkably effective and quick. It can be calculated that with such a procedure it would take only ~27 years to eliminate the small (0.4%) long-term radiotoxic TRU component from the 15,000 tons of used CANDU fuel that would be stored at the Pickering

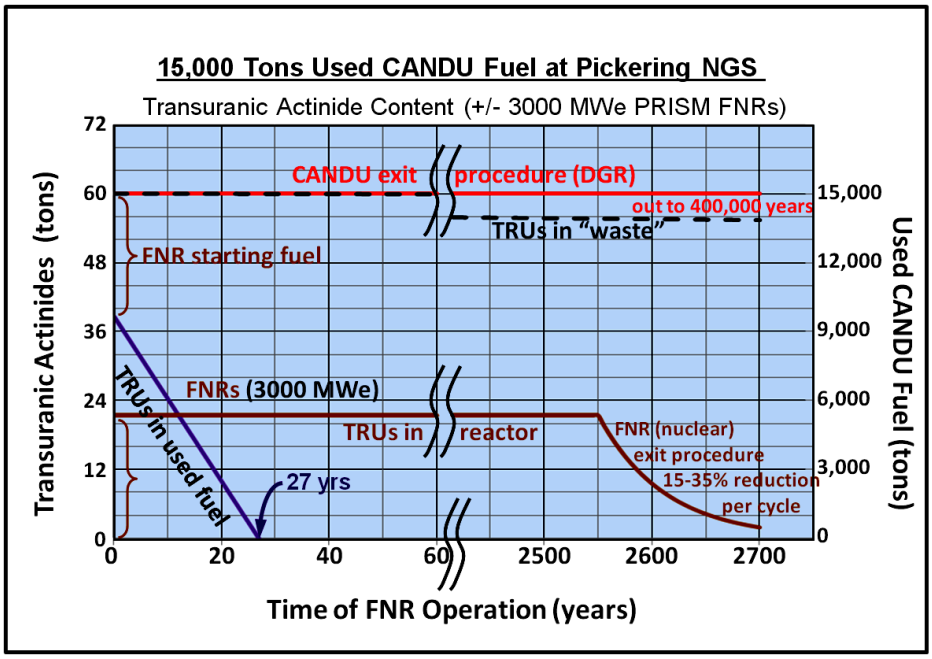

Figure 5 Accelerated consumption of long-lived transuranic actinides in 15,000 tons used CANDU fuel with recycling through 10 PRISM-like 300 MW fast-neutron reactors.

nuclear reactors after their shutdown in 2020 (Fig. 5) [13]. Part of those TRUs would become the required constant "in-reactor" fissile fuel component of the FNRs until their decommissioning.

After the 27 years to eliminate the "out-of-reactor" TRUs in the stored used CANDU fuel, the FNR fuel could be replenished for centuries with stored pure depleted uranium from fraction 1) since FNRs can conserve their fissile fuel content. The requirement would be a fleet of FNRs equal in output to the current 3000 MW Pickering plant along with a fuel cycling complex that included a 50 ton/year pyroprocessing facility and a feeder pre-treatment plant to extract 90% pure uranium from the stored used CANDU fuel. Both components of the fuel cycling complex would be about 10-fold smaller than the existing PUREX plants mentioned in Section 5.1 above.

If a better fuel source is found in future, then at any time after the use and consumption of TRUs from the stored spent CANDU fuel, from 27 years in the Pickering case to over 2500 years (Fig. 5), the best exit strategy for the FNRs would be to diminish the number of reactors at each fuel cycle in proportion to the fuel consumed in the reactors in that cycle, e.g. ~15% for PRISM-like FNRs. In this way the eventual amounts of long-term TRUs left within the reactors are driven to a minimum of less than the fuel charge of the final single reactor.

6. Long-lived fission products

As is evident in Fig. 4, beyond 300 years fission products contain isotopes that are also long-lived. Even though their total radiotoxicity is well below that of the uranium from which they were formed, concern exists about specific isotopes that are biologically important and might require special handling. The treatment and elimination of only 7 isotopes, either early or perhaps

more easily after 300 years, would bring the toxicity level to about 1 million times lower than the toxicity of natural uranium. Only iodine-129 ($T_{½}$ = 17 M y) with a toxicity level 40,000 less than its natural uranium parent, will be mentioned, since it can accumulate in human thyroid tissue.

The pyroprocess of fuel recycling runs at about 500ºC. At this temperature iodine is volatile and consequently I-129 is captured as a vapour in cold traps. With a neutron absorption of 30 barns it can be relatively easily transmuted to I-130 in a thermal reactor. I-130 decays with a half-life of 12.3 h to stable Xenon-130. Thus a 17 M-year concern is changed to a 12.3-hour non-problem.

The other isotopes require different approaches for isolation and transmutation; or they can be re-used, such as zirconium, including Zr-93, as alloying element in FNR metal fuel (section 5.2).

7. Cost of recycling

Till and Chang have estimated the cost of recycling FNR fuel at 0.44 ¢/kWh, including capital, operation and storage of fission products. Bushby at the Canadian Nuclear Laboratory estimates a mid-price of 0.66 ¢/kWh for recycling alone [5,p.292; 20]. This suggests that FNR fuel cycling is similar in cost to purchase by OPG of fresh fuel plus its cost for disposal (0.5 + 0.2 ¢/kWh [21]).

8. Conclusion

In today's climate of reduce, re-use, and re-cycle, along with a strong worldwide emphasis on increasing the use of carbon-free energy, it seems utterly wrong to focus on the permanent disposal of Canada's used CANDU fuel which can currently provide about $74 trillion of non-carbon electrical energy over centuries. Its use can avoid the emission of about 275 billion tons of CO_2 to the atmosphere compared to the use of natural methane gas (470 billion for coal). That fuel resource requires no mining, and is already stored at reactor sites ready to be exploited.

If there were no other choice, and no further energy could be easily extracted by known means, one could condone burial of the used fuel, since it is highly radioactive and will be for millennia. But we, the nuclear establishment, know how to eliminate the long-term radiotoxicity by recycling the fuel through energy producing FNRs; and have done so. We therefore have that choice. Neutron physics created the radioactive material, and neutron physics has the ability to destroy it. It has been proven and has been accomplished safely -- with the help of Canadians [5].

Surely this is the path we should follow. It is a path on which we can lead the world. Now.

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