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July 18, 2012

Dr. Stella Swanson
Dr. James F. Archibald
Dr. Gunter Muecke
Joint Review Panel
Deep Geological Repository
Low and Intermediate Level Radioactive Waste

Dear Drs. Swanson, Archibald and Muecke,

Some time ago, after I presented a seminar at the CNSC, Dr. Michael Binder suggested that I contact you to apprise you of an approach that can utilize all of the heavy atoms in our currently stored CANDU fuel "waste". This would be an alternative to the planned DGR for high-level nuclear waste. As such I indicated to Dr. Binder that your focus currently is a DGR for low and intermediate level nuclear waste, but he thought the ideas might be related. Perhaps they are.

It was the work in 2000 of M.R. Jensen (1) on water-flow measurements at the Underground Research Laboratory in Pinawa, indicating a water travel distance of about 25 m in 7 days under unit pressure gradient, that made me look at alternatives to a deep geological repository for used CANDU fuel. As a result of my own calculations and of data in the literature I have come to the conclusion that a deep geological repository for the long-term disposal of used CANDU fuel is not necessary: The used fuel can be consumed in a fast-neutron reactor, now commercially available, with all of the actinides being converted to fission products with predominantly short decay times.

In brief, it is possible to consume nuclear fuel waste in a fast-neutron reactor potentially to about 35% (2,3 attached), such that with cycling of the fuel one can use up one reactor-full of spent CANDU fuel in about three cycles. This has been demonstrated in part to be so for three decades in the US EBR-II reactor at the Argonne Labs in Idaho starting in 1964 (4). That reactor achieved a burn-up already at that time of about 20% and recycled 34,000 used fuel pins to extract the fission products, where about 7000 pins constituted the core charge of the reactor. Thus, in total, that reactor consumed the equivalent of one reactor-full of nuclear waste in the equivalent of five cycles. The fuel cycle facility is still operating, processing the EBR-II fuel after the reactor was shut down in 1994. This approach can readily be extended to cycle and consume used CANDU fuel completely, leaving only fission products (FPs) whose radiotoxicity

will be decay in 300 years to levels lower than the natural uranium from which they were created in the reactor(3). Moreover, a fast-neutron reactor based on the EBR-II design is now commercially available from GE-Hitachi in the U.S.A as the PRISM.

This is perhaps where the repository for low and intermediate nuclear waste becomes of interest. A repository is required for the 300-year decay time of the fission products formed above. However, it should be built in such a way that the eventual stable FPs are easily retrievable. In looking at the amounts and composition of the atoms in the mix of fission products, it is easily shown that all of the FPs combined, which among others atoms contain palladium and rhodium among the platinum-group metals as well as increasingly scarce rare earths, would be worth about $2.5 million per tonne at today's prices. And these minerals would not even have to be mined, if properly stored. We currently have over 40,000 tonnes of used CANDU fuel stored at reactor sites, which could all be converted in this manner while the energy is extracted as the heavy atoms are split by fast neutrons.

I have carefully looked at the design and intent of operation of the proposed DGR for low and intermediate waste to see if such a design could be amenable to storage of fission products. At the moment it is not; but it could be. The current intent is not to retrieve materials after individual emplacement rooms are sealed, and certainly not after galleries are back-filled. Yet similar to fission products, most of the neutron activated reactor components will decay to background in "short" order. It is only the TRU contamination that is of long-term concern. Thus an initial sorting of the relevant constituents of the low and intermediate level wastes would make it possible to retrieve the ones that decay "early" and to re-use those materials quite safely at that time.

This concept could then be applied to emplacement of fission products as well. At $2.5 million per tonnes this is well worth considering. The repository might not have to be dug as deep, or perhaps not dug at all, since it would be in continual operation, constantly monitored as new waste is brought in while safely decayed materials are retrieved and brought out for re-use, emptying the corresponding galleries and vaults to receive subsequent radioactive loads for decay.

I would be pleased to come before you to enlarge on some of these ideas.

In the meantime I have attached two recent submissions on the subject of productive elimination of nuclear waste that are relevant to the ideas of a "cycling repository", one to the Annual Meeting of the Canadian Nuclear Society, the second to Engineering Dimensions, where it will appear in the July/August issue.

I would be pleased if you could schedule a time for me to appear before you.
Sincerely,
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2. Ottensmeyer P. Used CANDU Fuel Waste Consumed and Eliminated: Environmentally Responsible, Economically Sound, Energetically Enormous. Proc. Ann. Meeting Can. Nucl. Soc., Saskatoon, June 10-13, 2012 (attached).

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Used CANDU Fuel Waste Consumed and Eliminated: Environmentally Responsible, Economically Sound, Energetically Enormous

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Abstract

The 43,800 tonnes of currently stored CANDU nuclear fuel waste can all be consumed in fast-neutron reactors (FNRs) to reduce its long-term radioactive burden 100,000 times while extracting about 130 times more nuclear energy than the prodigious amounts that have already been gained from the fuel in CANDU reactors. The cost of processing CANDU fuel for use in FNRs plus the cost of recycling the FNR fuel is about 2.5 times less on a per kWh energy basis than the currently projected cost of disposal of 3.6 million used CANDU fuel bundles in a deep geological repository.

1. Introduction

Canada's used and stored nuclear fuel waste in 2011 is expected to be about 44,000 tonnes [1]. Only 0.74% of this fuel has been converted to fission products with the concomitant yield of energy [2, p.341], while the remaining 99.26% consists of uranium and other heavy metals which together contain 130 times more untapped nuclear energy. This energy can all be extracted from the used fuel using fast-neutron reactors (FNRs). Simple calculations indicate that the gross revenue from this 99.26% would be $39.3 trillion in electricity [3] plus useful cogenerated heat.

Of the 0.74% fission products in the used fuel 70% are non-radioactive, while the radioactivity of virtually all of the remaining 30% will decay to background levels in about 300 years. Of greater concern is a small fraction of transuranics (TRUs), atoms heavier than uranium such as plutonium, americium, and curium that are created in the reactor. Although the TRUs constitute only 0.4% of the used fuel, they do not decay to background levels for about 400,000 years. Their long-term safe-keeping constitutes the major focus in nuclear waste disposal proposals.

The complete consumption of the heavy atoms, leaving only fission products, has the attractive potential of eliminating the TRUs, and with them the concern about their long-term radioactivity. The 300-year radiation hazard from the resulting fission products is a much more manageable task. After that time the fission products, atoms roughly of atomic number 35 to 65, become a valuable source of platinum-group metals, rare earths and the like, extractable by ordinary means.

To dispose of current and future used nuclear fuel waste, the world of nuclear nations, including Canada, has primarily concentrated on the potential use of deep geological repositories (DGRs)

in whatever suitable rock strata are locally available, with retrieval possibilities or with eventual permanent closure. In Canada to build such a DGR is expected to cost between $16 and $24 billion, with total life-cycle costs estimated to be from $24.4 to $40.7 billion [1; 2, p163; 20, p3].

The extraordinary potential of fast-neutron reactors to eliminate the long-term radiation hazard of used CANDU fuel and at the same time deliver about 130 times more carbon-free nuclear energy from the used fuel, begs for at least a preliminary analysis of the costs associated with such an approach in comparison to the cost of Canada's planned DGR. Both approaches are or would be self-funding via revenue-producing reactors: CANDUs or FNRs. Therefore, while some of the characteristics of an FNR facility are discussed, the emphasis will finally be on the comparative cost of the non-productive aspects: the DGR versus the fuel cycle facility that is an additional integral part of such an FNR facility.

The comparison shows that the cost of constructing and operating a fuel cycle facility for pyroprocessing of metal fuel for a sodium-cooled FNR is up to 2.5 times smaller than the cost of the planned Canadian DGR. This cost does not consider the additional benefits of the elimination of the long-term radioactive burden via the FNR facility nor of the long-term non-carbon energy potential of already-stored used nuclear fuel.

2. Evolution of Radioactivity

Figure 1 shows the radioactivity of used CANDU fuel relative to that of natural uranium over time following removal from the reactor. The evolution of radioactivity of the fission products in the fuel has two major components. Most constituents decay to background levels (and below) at around 300 years (solid green line). A few, including Zr-93, I-129, and Cs-135, together constitute a long-lived component, but are very close to background (dashed green line).

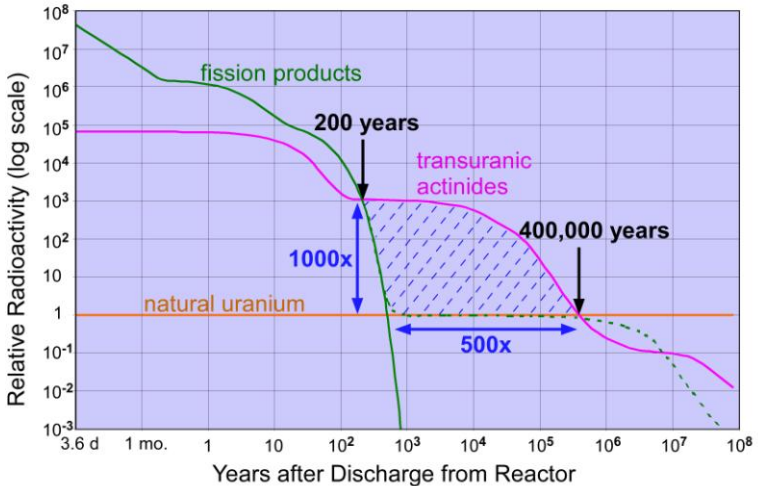

Figure 1. Evolution of Radioactivity from Used CANDU Fuel. Removal of the transuranic actinides (purple line) in fast-neutron reactors results in a 100,000 times reduction in radiation burden between 200 and 400,000 years (hatched area).

After about 200 years the major contributors to the radioactivity are the TRUs, which do not reach background levels for about 400,000 years. However, consuming the used fuel in an FNR in several fuel cycles has the consequence of eliminating TRUs and changing them to fission products (FPs). When the used FNR fuel is sent through the FNR-associated fuel cycling facility (FCF), pyroprocessing separates the fission products from the actinides (see Section 4. below), and reduces the concentration of uranium and TRUs in the FPs by a factor of 1000 [4]. This is in general sufficient to bring the TRUs to background levels after the short half-life Pu-241 isotope among the TRUs has decayed for about 100 years (Fig. 1). If further reduction of the TRU concentration is required then processes such as chromatographic separation with immobilized ligands specific for the actinides can be considered in future [5,6]. The Japanese, using amidoxime chelating groups fixed to polyethylene sheets, are extracting uranium from seawater with a concentration of 3 parts per billion [7]. This suggests strongly that lower concentrations of actinides in the extracted fission products can be achieved.

The relative benefit that can be derived from pyroprocessing alone, due to the 1000-fold reduction in TRU concentration in the used FNR fuel is very evident in the period from 200 years to 400,000 years (Fig. 1). Integrating between the original curve of TRUs and the curve for the FPs indicates that a reduction of 100,000 times can be obtained in long-term radiation burden.

3. Fuel Consumption in Fast-Neutron Reactors

3.1. Experimental Limits Achieved

Sodium-cooled FNRs in Russia (BN-350, BN-600), and France (Phenix) generally use mixed oxide fuel, and achieved 10-11% utilization of fuel. One reactor, the metal-fuelled EBR-II in the USA, regularly achieved 20% fuel utilization before refueling [8,9]. This facility has provided the greatest insight into fuel consumption, metal-fuel cycling, and FNR safety (Sections 4/5).

While, elsewhere, metal fuel was rejected early on due to swelling of the fuel under irradiation and subsequent deleterious fuel-cladding interactions at 1%-3% fuel consumption, EBR-II scientists at the Argonne National Labs systematically altered fuel charge, fuel canister, and fuel composition to achieve a safe 20% fuel consumption [8]. To avoid fuel-clad interactions the fuel slug was reduced in cross-sectional area to about 75% of the inner area of the fuel canister. To provide thermal contact between the now-smaller fuel slug and the wall of the canister, sodium, liquid at operating temperatures, was introduced as a thermal bond. When the canister burst at about 5% to 8% fuel consumption due to build-up of internal pressure from gaseous fission products, the sealed canister was provided with an empty volume (plenum) above the fuel. However, sharp indentations in the cladding, designed to prevent the fuel slug from rising into the plenum, resulted in stress failures even at 8% fuel consumption. They were replaced by spherical indentation. At the same time the steel of the canister was changed from 316 stainless steel to stronger HT9 ferritic steel. One further change was a change in fuel composition to the eventual use of 10% zirconium, to increase the melting temperature of the fuel, a

uranium/plutonium/zirconium alloy. These changes produced a fuel consumption of close to 20% without failure of any of 34,000 fuel pins used thereafter [9,10].

This suggested that the EBR-II was able to operate with fuel that before refueling contained about 20 wt% fission products.

A few fuel pins were tested to canister failure, which occurred at about 23%-25% fuel consumption. Before further improvements in fuel design were made the reactor was shut down in 1994 by edict of the US Congress [11]. Nevertheless, Argonne scientists designed and tested fuel pins with a still larger plenum for potential safe 25% fuel consumption, and tested them successfully in the French Phenix FNR starting in 2007 [12]. The pins were not tested to failure.

3.2. Calculated Theoretical Limit

The safe fuel consumption up to 25%, resulting in 25 wt% content of fission products, was not necessarily a fundamental limit. Ultimately the build-up of fission products in the fuel pin should absorb sufficient neutrons to stop the chain reaction. To reach such a limit in practice the fuel pin would need to contain a large enough plenum such that the internal pressure from gaseous fission products would not stress the steel cladding beyond its elastic limit.

On the basis of that assumption calculations were performed examining the performance of a sodium-cooled fast-neutron reactor loaded with such ideal fuel pins. As a starting point the relative volume proportions of fuel, sodium bond plus coolant, and steel were taken from the sodium-cooled GE-Hitachi S-PRISM design [13]. Neutron cross-sections for elastic and inelastic scattering, fission and radiative capture were obtained from the ENDF data base [19] for uranium and plutonium isotopes in the fuel, for 18 fission products with the highest macroscopic capture cross-sections at thermal energies, as well as for sodium, for zirconium in the fuel, and for the constituents of HT9 steel. Energy transfer matrices for inelastic neutron scattering were obtained from Yiftah et al. [14]. These transfer matrices limited the high energy calculations to 12 groups from 3.668 MeV to 9.1 keV in equal logarithmic intervals of 0.5.

The energy loss history of the spectrum of nascent fission neutrons was followed for 202 rounds of neutron interactions with reactor fuel, fission products, sodium and steel atoms. At that time the 2% of the original fission neutrons remaining were assigned proportionately to macroscopic fission and capture cross-sections of all the components. A homogeneous reactor was assumed, since mean-free-paths were larger than the fuel assembly lattice pitch of the S-PRISM reactor.

The results in Fig. 2 are for several cycles after the fuel in the reactor has reached equilibrium compositions. At this stage all of the TRUs in the reactor remain constant from cycle to cycle, except for repeating variations within each cycle. As fission products build up to a point that they absorb too many neutrons to sustain the controlled chain reaction, constant power of the reactor can no longer be maintained, and the reactor shuts down slowly. At this point the fuel assemblies would be removed and substituted with a set of suitably prepared new assemblies.

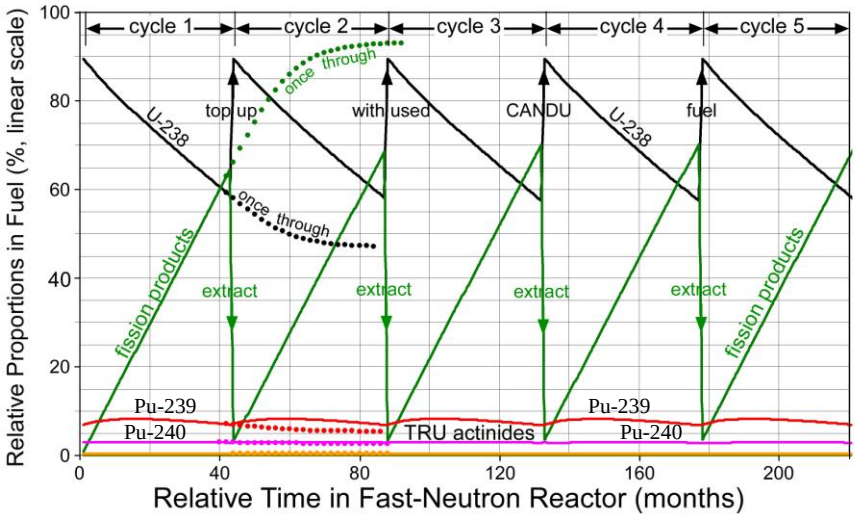

Figure 2 Consumption of uranium and behavior of other actinides

Figure 2 shows that for an ideal fuel pin the fuel charge is consumed about 35% before power is limited by fission product build-up even though the weight percent of the fissile actinides (e.g. the plutoniums) is equal to their proportion at the start of the cycle. To continue to consume the remaining actinides, the fission products must be separated from the actinides. This occurs in the fuel cycle facility (FCF) of the reactor complex by means of pyroprocessing (see Section 4).

3.3. Used CANDU Fuel Top-Up

The fission-product-free actinides from pyroprocessing, 65% of the original charge, would be topped up to 100% with used CANDU fuel which has been converted from the oxide to metal form. No separation of the CANDU fuel components is required, since the actinides from pyroprocessing contain sufficient components that are fissile at high neutron energy to restart the reactor. Moreover, the small percentage of fission products in used CANDU fuel, 0.74%, is too low to limit the reactor appreciably.

The experimental results from the EBR-II facility with 20% fuel consumption in one cycle indicate that in 5 cycles one reactor-core-full of used CANDU fuel uranium and TRUs could be consumed completely. For fuel pins built for the calculated limit of 35% fuel consumption only 3 cycles through the facility would be enough to use up one reactor-core-full of used CANDU fuel.

4. Pyroprocessing

The separation of actinides from fission products by pyroprocessing has been well-described [4,9]. In brief, used-fuel assemblies from the FNR are brought into a shielded fuel cycle facility, where all operations are sufficiently simple to be amenable to remote control. The fuel pins are disassembled, chopped into small cylinders and put into a wire mesh basket that becomes the anode of an electrolytic cell operating with molten chloride salts at about 500°C. The cell also

contains a bath of molten cadmium beneath the salt, and two cathodes suspended in the molten salt. One is solid iron, the other a vat of molten cadmium.

In the operation of the cell the various constituents in the chopped-fuel mesh basket dissolve in the salt or remain as solids that either stay in the basket or drop into the cadmium under the molten salt. These are the noble metals, such a rhodium and palladium, as well as zirconium. The actinides dissolve as chlorides in the salt bath, as do the rest of the fission products. The electrolytic process then plates out uranium on the iron cathode until a large proportion of it is removed from the molten salt. Due to the large difference in free energy between uranium and the other actinides in their chloride form, no other actinides plate out on the iron electrode.

However, this free energy difference is very much reduced when the molten cadmium cathode is put into operation. At this electrode all the actinides can form intermetallic compounds with cadmium and plate out together along with the remaining uranium.

Laidler et al. [4] indicate that less than 0.1% of the actinides remain in the salt that contains most of the fission products.

4.1. Proliferation Resistance

From the previous discussion it is clear that there is no separation of the actinides in pure form except for a large proportion of uranium. None of the plutonium is separated from the other actinides. Indeed, experimental operation of such a pyroprocessing cell on 4.5 tonnes of used fuel from the EBR-II indicates that plutonium plating out in the molted cadmium cathode contains not only the higher TRUs but also from 25% to 64% uranium [9, p189ff]. Moreover, from Figure 2 it can be seen that the plutonium is not isotopically pure, but contains about 26% Pu-240. Thus it would be difficult to utilize such material for explosive purposes, requiring large centrifugal enrichment facilities to separate the 74% Pu-239 from the 26% Pu-240.

Concerns with handling plutonium also impinge on the start-up of a fast-neutron reactor. Calculations resulting in Figure 2 indicate a requirement of about 7% Pu-239/241 to bring the reactor into neutron balance. It is conceivable that such plutonium may be obtained from dismembered-weapons stores. However, the sensitivity of such acquisition and transport may force a different start-up scenario. It is quite possible to start with a fuel mix containing low-enriched uranium with just less than 10% U-235 (see Figure 3). Figure 3a shows that fuel consumption, as represented by the usage of U-238, is not significantly different than when starting up with plutonium-enriched fuel. Figure 3b shows the detail of U-235 usage as well as the build-up in the reactor core of Pu-239/240/241, that serve to maintain neutron equilibrium. Changes in concentration of these actinides are substantial initially. However, after about two refuel cycles equilibrium of all actinides is reached at levels identical to starting with plutonium-enriched fuel. The difference is a slight remanent level of U-236 from radiative capture in the high initial concentrations of U-235.

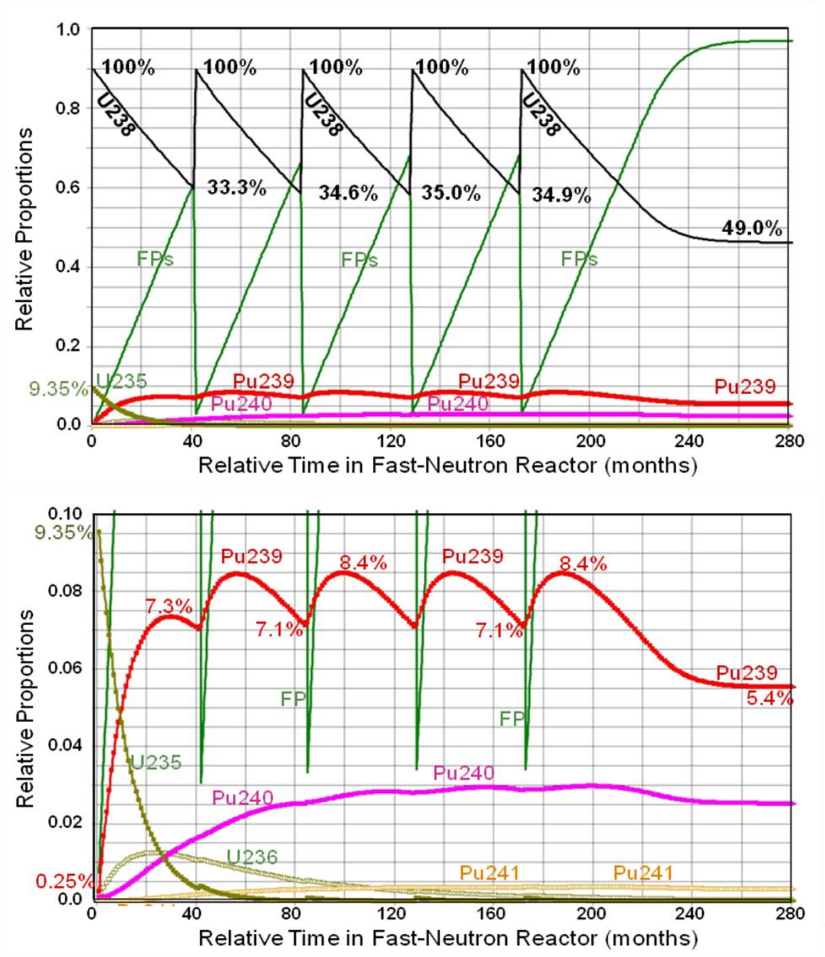

Figure 3. Fuel Consumption and Build-Up of Pu Isotopes in FNR on Start-Up with U235
Fig. 3a (top) Large scale. Fig. 3b (bottom) Expanded scale.

5. Safety

The safety characteristics of a sodium-cooled metal-fueled FNR, the US EBR-II, are described in detail by Till and Chang [9, Ch.7] and by Koch [10, p.24/25]. Only three characteristics will be mentioned here, most pertinent to the stressors of the kind that befell the reactors at Fukushima, Three-Mile-Island, and Chernobyl.

Two crucial experiments were performed in 1986 to test the passive safety characteristics of EBR-II reactor under full power that likely would not be done with thermal reactors: initiating an unprotected (no SCRAM) loss-of-flow (ULOF) situation in the core and letting the event run its course without automated or human intervention; and similarly initiating an unprotected loss-of-heat-sink (ULOHS), i.e. loss of cooling from the intermediate heat exchanger. In both cases the reactor shut down and reached a stable temperature in 300 to 500 seconds [9, p.148/150].

The third characteristic was the built-in passive cooling by two convective liquid metal heat exchangers in the reactor tank, called shut-down coolers, which carried fission product heat to

two convective atmospheric heat exchangers outside the reactor building at every normal shut-down of the reactor [10, p. 24].

While many redundant safety systems in current reactors work very well indeed, these characteristics as exemplified in the EBR-II would have provided a safe passive response to the events leading to the happenings at Chernobyl, Three-Mile-Island and Fukushima Daiichi.

6. Economics

Finally, if an FNR facility is to substitute for the use of a deep geological repository (DGR), it is important to compare the relative costs of the two approaches.

The FNR facility requires a reactor plus a fuel cycle facility. Of these the reactor cost is probably less crucial, since the FNR creates heat and electricity similar to any thermal reactor, and so would be revenue-producing. Nevertheless, such a nuclear-waste-consuming reactor should not have a completely unreasonable price. While comparisons are difficult, since FNRs have only been built so far as first-of-a-kind, and relatively few thermal reactors have been constructed lately, recent textbooks put the cost of a "mature" FNR at between 1.1 and 1.25 times the cost of a thermal reactor [15, p.42]. First-of-a-kind FNRs in the field appear to cost a low of 1.26 times the cost of established thermal reactors on the Asian continent (Table 1) to a high of 2.1 times as much (France) on a $/kWe basis. Second and further reactors of the same type are estimated to drop in cost to as low as 0.7 times thermal reactors per kWe (Table 1; Japan, Russia) to 1.05 times (France). Discounting their waste-consuming advantage, this puts initial FNRs on a relatively reachable level, with further FNRs equally or less costly than mature thermal reactors.

Table 1
Cost of Commercial Size Fast-Neutron Power Reactors versus Mature Water-Cooled Reactors

Country	Reactor		FNR Cost or Cost Ratio	Reference Reactor Cost	
France	SuperPhenix	(1,240 MWe)	2.1	1.0	French PWR
[9, p.275ff]	SuperPhenix II	(1,500 MWe)	1.05		
Russia	BN-600	(560 MWe)	1.5	1.0	Russian LWR
[9, p.276]	BN-800	(under construction)	1.35 (estimate 2011)		
	BN-1800	(under development)	0.72 (estimate 2011)		
India	PFBR	(500 MWe)	$2,500/kWe	$1,978/kWe	CANDU in China
[16]			1.26	1.0	[21]
				$1,840/kWe	PWR in China
			1.36	1.0	(Framatom ANP)
Japan	JSFR	(1500 MWe)	$2,600/kWe	$1,769/kWe	CANDU in China
[17]	Design, fist of a kind		1.47	1.0	[21]
	Nth reactor (projected)		$1,300/kWe	$1,840/kWe	PWR in China
			0.70	1.0	(Framatom ANP)

The additional expense associated with a waste-consuming FNR is the shielded fuel cycle facility (FCF) required both for processing used CANDU fuel into a metal form suitable for the FNR and for cycling the used fuel from the FNR itself. From their experience at the FCF associated with the EBR-II in the Integrated Fast Reactor facility, which is still operating and processing fuel from the EBR-II after the reactor was decommissioned, Till and Chang [9, p292] estimate that for a 1000 MWe reactor the associated shielded FCF would cost about $100 million.

Their breakdown of the fuel cycle cost components is, in mill/kWh:

Capital fixed charges at 15%	1.90
Operating and maintenance	1.27
Process consumables, etc.	0.76
Disposal fee (300 year storage)	0.50

The total is 4.43 mill/kWh with construction capital charges, and 2.52 mill/kWh without.

Till and Chang [9, p.292] have assumed a disposal fee for storage of fission products from the FNR of 0.5 mill/kWh, half the 1 mill/kWh for planned repository disposal in the USA. Studies in Japan indicate that partitioning of fission products and transmutation of minor actinides can reduce the disposal repository size by a factor of 4 to 5; moreover, additional separation and storage of cesium and strontium can reduce the size by more than a factor of 100 [15, p.19].

The numbers by Till and Chang permit a comparison on a mill/kWh basis with the costs of disposal of used CANDU fuel in a planned Canadian deep geological repository (DGR) in the Canadian Shield at the site of a willing host community [1, p.15]. It is estimated that the total lifetime cost of this DGR, a first-of-a-kind facility, will be $24.4 billion for the Adaptive Phased Management option adopted [2, p163]. Under consideration currently is increasing the capacity of the DGR from 3.6 million bundles of used CANDU fuel to 7.2 million bundles [1, p.104]. This produces some economies of scale, with an increase of only 67% in cost for doubling the capacity [20, p3]. The cost of either DGR is to be met by the tithing of the revenue from the consumer of electricity produced from nuclear energy on a mill/kWh basis. The initial charges are to be low, but are to ramp up later, in the years closer to the construction of the DGR [18].

In 2010 the total used CANDU fuel accumulated at various reactor sites in Canada amounted to 2.2 million used fuel bundles [1, p11]. On the basis that 6.25 bundles would have produced 1MW-year of electricity [2, p351], the electrical energy produced by those fuel bundles is 3.07×10^{12} kWh. The funds collected from fees on this electricity, and put in trust accounts, were $2.28 billion, averaging to 0.74 mill/kWh up to the present.

To meet the total lifetime-cycle costs of the smaller DGR, to be filled with 3.6 million used fuel bundles, $24.4 billion have to be tithed in total, requiring a further $22.12 billion above the current $2.28 billion already in trust. This amount has to be obtained from 1.4 million bundles above the currently accumulated 2.2 million bundles. If the DGR is built to accommodate 7.2 million bundles, its total life-cycle cost in proportion to the 67% increase of the repository cost

Table 2
Future Average Mill Rate Required to Meet DGR Costs

Total Life Cycle Cost	Outstanding Balance	DGR filled with 3.6 million bundles tithe from 1.4 million* or 1.96×10^{12}kWh** Avg. mill rate needed	DGR filled with 7.2 million bundles tithe from 5.0 million* or 6.99×10^{12} kWh** Avg. mill rate needed
$24.40 billion	$22.12 billion	11.29	
$40.75 billion	$38.47 billion		5.50

* 2.2 million bundles have been tithed to date
** Electrical energy yield calculated on basis of 6.25 bundles per 1 MW-year (2, p351)

would be $40.75 billion, requiring the collecting of $38.47 billion above the $2.28 billion currently accumulated. This can be levied on 5.0 million future bundles. Table 2 shows the average mill rates required from now on, going forward, to meet the costs of the DGR under these conditions. Since the effective mill rate for 72,999 used fuel bundles in 2010 [1, p197] was 1.46 mill/kWh, a planned slowly escalating mill rate to the start of construction of the DGR will result in much higher final rates in the later years than the averages shown in Table 2.

Comparison between these costs and the cost of processing and cycling used CANDU fuel for use in an FNR, above, indicates that the processing costs of 4.43 mill/kWh are a factor of 2.5 lower than the average future mill rate for a DGR accommodating 3.6 million used CANDU fuel bundles, and still 24% lower than the costs of a DGR accommodating 7.2 million used fuel bundles. However, a similar saving from the economies of scale as for a larger DGR likely applies to the fuel cycle facility which can as readily be scaled for several FNRs on the same site.

7. Summary and more

Fast-neutron reactors based on the design of the US EBR-II have the capability of consuming used nuclear fuel waste from CANDU reactors and other water-cooled reactors, reducing the long-term radioactive burden about 100,000 times, and shortening the radioactive lifetime of the current used fuel from 400,000 years to reach background to as little as 300 years. As an added bonus, such FNRs can extract about 130 times more energy from used CANDU fuel than the prodigious amounts of nuclear energy that have already been extracted. Since the used fuel already exists, stored at reactor sites, the energy can be considered to be carbon-free, devoid of fossil fuel energy associated with the mining and manufacturing of fresh fuel.

A fast-neutron reactor, required for the consumption of used fuel waste, has an additional advantage to those mentioned above. It can readily adjust power. This makes it possible to follow the variations in energy demands during any given day, and also to partner in the mix of non-

carbon renewable energies that are sporadic, such as wind or solar. These reactors, in contrast to thermal reactors, do not exhibit a xenon effect nor samarium poisoning that cause a delay in start-up or else require large compensating positive reactivity insertions. This is clearly understood from the radiative capture cross sections for high energy neutron interactions (Fig. 4) of xenon (major blue line), samarium, indeed of all fission products. Such cross sections are low at energies of nascent fission neutrons, and all are clustered below the fission cross sections of all of the actinides. Thus the decay of one fission product into another, e.g. Te-135 into I-135 into Xe-135, that is of great consequence at thermal energies, has little effect on total neutron absorption at high energies. This is a very useful characteristic that permits ready load-following by FNRs.

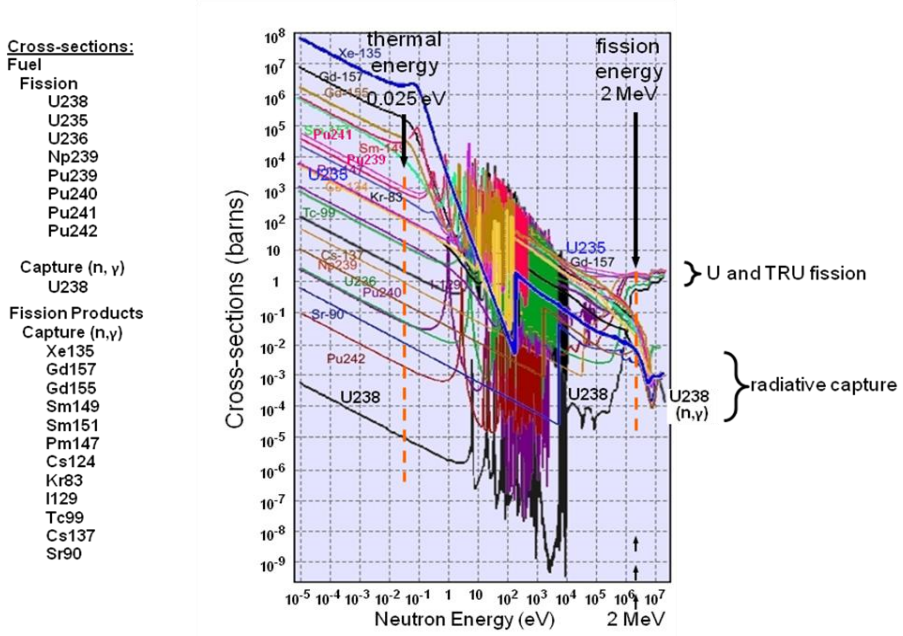

Figure 4. Combined Radiative Capture and Fission Cross Sections of Selected Isotopes [from 19]. Nascent fission neutrons have an average energy of 2 MeV.

Processing of the used CANDU fuel is required to convert it to the metal form for consumption in an FNR, and also for fuel cycling by pyroelectroprocessing in molten salts. However, the analysis above shows that the cost associated with such processing is up to 2.5 times less than the currently projected costs of disposal of used CANDU fuel in a deep geological repository.

Building and operating a DGR in a willing northern community is expected to provide local jobs for three to four decades, primarily in service-related employment [1, pp.53/56/90]. In comparison, an FNR facility built at that site would additionally provide energy to use and to sell, with an associated stimulation of the local economy and a raised standard of living for centuries.

Therefore taking advantage of a nuclear-waste-consuming fast-neutron reactor facility to consume CANDU nuclear fuel waste instead of disposing the used fuel in a DGR is economically sound and has huge societal and ecological benefits.

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Professional Engineers of Ontario
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POLICY ENGAGEMENT

CANDU Fuel Waste Re-Used, Recycled, Eliminated:
$48 Trillion of Carbon-Free Electricity via Fast-Neutron Reactors

By Peter Ottensmeyer PhD

One major concern about nuclear power generation is the management of used nuclear fuel waste which is highly radioactive for 400,000 years. Burial in deep geological repositories is universally contemplated. Yet this "waste" from CANDU reactors is still more than 99% fuel[1] that can create energy in proven fast-neutron reactors (FNRs). Simultaneously this reduces the long-term radiotoxicity 1.5 million times so that it reaches background levels of natural uranium in less than 300 years rather than 400,000.

In FNRs the energy yield from the currently stored 43,660 tonnes[2] of used CANDU fuel would create $48.4 trillion of non-carbon electricity. That alone would provide 4200 years of power at today's rate of nuclear energy production. Furthermore, FNRs can rapidly change power to follow changing demands for electricity, and therefore, unlike thermal reactors, can readily complement intermittent renewable wind and solar energy sources.

What fundamental principles make this possible? How is it done with today's technology? Is the technology safe? Is it economically viable? The rather positive responses follow.

Used Nuclear Fuel Waste 101

CANDU reactors generate energy using slow neutrons to split heavy atoms such as U235 in natural uranium fuel into two roughly equal halves which fly apart at great speed. As the split-atom halves slow down their kinetic energy is converted to heat that is converted to electricity.

For each U235 atom split by a neutron, more than two new neutrons are emitted. One of these must split another heavy atom to continue the chain reaction. However, there is less than 1% U235 in the uranium. Therefore the extra neutrons enter other atom nuclei, such as the 99% U238, which do not split but which become heavier atoms called transuranics or TRUs. U238 becomes neptunium, which turns into plutonium, then americium, curium, etc., as more neutrons are absorbed. The TRUs are all radioactive, primarily emitting high energy alpha particles (helium nuclei that become helium gas). TRUs are the major concern, since they need 400,000 years to decay to background. (Figure 1).

The split-atom halves, called fission products (FPs), are smaller atoms generally between atomic numbers 35 and 65. About 70% of these are stable atoms. The other 30% are radioactive, emitting

predominantly electrons. The radioactivity of the FPs needs only 300 years to decay to background levels (Figure 1), not 400,000. After that time the FPs become a valuable source of minerals like platinum-group rhodium and palladium, and increasingly expensive rare earth elements used for batteries, electronics, solar panels and wind-turbine generators.

Compared to alpha particles, the biological impact or radiotoxicity of FP electrons of the same energy is 20 times smaller[3]. Therefore the radiotoxicity of the FPs drops below that of natural uranium after as few as 265 years. Four of the fission products (zirconium-93, cesium-135, technetium-99 and iodine-129) have very long half-lives; however, their combined radiotoxicity is about 30 times less than that of the natural uranium from which they were created in the reactor.

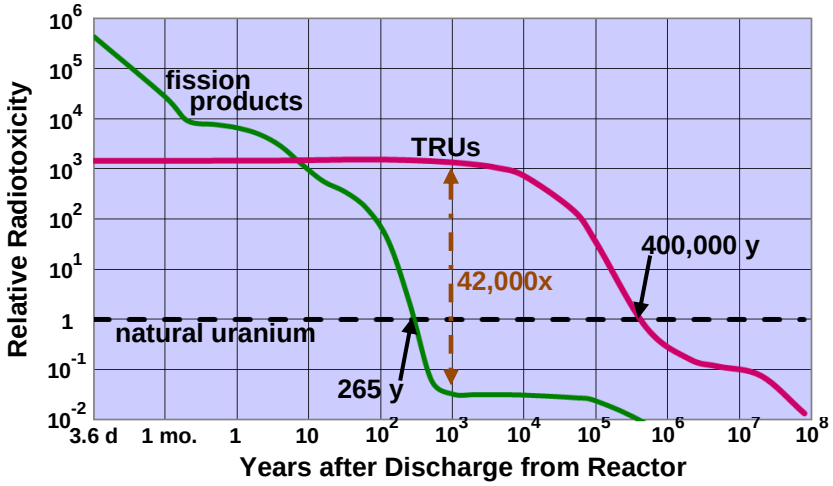

Figure 1. Evolution of Radiotoxicity from Used CANDU Fuel Components Relative to Natural Uranium. Consuming of the transuranics (TRUs) and of uranium (dashed horizontal line) in fast-neutron reactors results in a huge reduction in radiotoxicity of used fuel waste (about 42,000-fold per unit time at 1000 years) and also shortens the time of decay to background levels from 400,000 years to 265 years. After 265 years the radiotoxicity of the fission products is lower than that of the mined natural uranium from which they are created in the reactor. Note the log scales of both axes.

Biological and Economic Benefits of Consuming Spent Nuclear Fuel

Figure 1 shows that consuming all of the long-lived TRUs and the uranium in the CANDU fuel waste to convert them to fission products would eliminate their radioactivity and reduce the decay time of the waste 1,500 times, from 400,000 years to less than 300 years. The resulting reduction in radiotoxicity is a remarkable 42,000 times at 1,000 years, and averages to 2,260 times between the 265 and 400,000 years. The integrated radiotoxicity in this time interval would be 3.4 million times less than that of current nuclear waste. However, the required chemical separation of FPs from the TRUs (see below) can currently reduce the TRU concentrations in the FPs only by a factor of 1000,[4] such that the integrated biological advantage would be just 1.5 million, a smaller but still very worthwhile goal.

The biological advantage of eliminating the TRUs is huge. However, used CANDU fuel in an FNR also yields over 100 times the enormous nuclear energy that we have enjoyed since June 1962, the beginning

of nuclear power in Canada.[5] In 2008 alone, CANDUs using up only 0.74% of 1390 tonnes of uranium fuel [6,7] produced $11.5 billion of electricity at Ontario's current mid-peak time-of-use consumer price of 10 ¢/kWh. In FNRs the remaining 99.26% fuel in 43,660 tonnes of current CANDU fuel waste[2] could produce $48.4 trillion of non-carbon electricity, plus cogenerated heat[6]. This is equivalent to 4,200 years of nuclear electricity at 2008 production rates.[6]
An additional economic benefit is available once the FPs decay to background levels, after 265 years. The value of all FP atoms derived from 43,660 tonnes of used fuel waste, the rhodium, rare earths, etc. that are extractable then by ordinary means, would be over $100 billion at today's prices.

Fast-Neutron Reactors
In CANDU reactors the 99% U238 does not fission, nor do TRUs such as the long-lived Pu240 and Pu242 that accumulate in the fuel. Once most of the 0.72% U235 in natural uranium is consumed by the slow neutrons in the reactor, the fuel has to be replenished even though less than 1% of the energy of the uranium has been extracted.

The advantage of FNRs is the ability to split all isotopes of uranium, U238 and U235, and to fission all of the TRUs in used fuel waste. Furthermore, very low absorption of fast neutrons by the FPs means that FNRs can consume more of the fuel before refueling becomes necessary. In addition, this low absorption by the FPs makes large, quick changes in power output possible. Thus an FNR can usefully act as carbon-free back-up power for today's intermittent wind and solar energy sources.

Research FNRs have been built since the 1950s in England, France, Germany, Russia, India, Japan and the USA. Russia also has commercial FNRs. These reactors predominantly used uranium/plutonium oxide fuels, achieving a fuel utilization of 10-11%[7,8,9]. Used fuel was normally not recycled, since fresh uranium fuel was and remains relatively inexpensive. Moreover, used fuel waste volumes were so small at the time that management and disposal were not a major concern. They are now.

One reactor, the metal-fuelled EBR-II in the USA, regularly achieved 20 per cent fuel utilization. It recycled about 34,000 used fuel pins, equivalent to five complete reactor refuelings during its 30 years of operation ending in 1994.[10] The 20 per cent fuel utilization in the EBR-II represented no fundamental limit but was determined by the pressure build-up from gaseous FPs inside the sealed fuel container.[10] Calculations for more ideal fuel containers with large gas-expansion spaces indicate that 35 per cent fuel utilization can be obtained before reactor refueling becomes necessary.[11] Those calculations indicate that it should be possible to consume one reactor-full of used CANDU fuel in three cycles (Figure 2).

Fast-Neutron Reactor Safety: the EBR-II
The characteristics of the sodium-cooled metal-fueled US EBR-II are described in detail by Till and Chang[12] and Koch.[13] Liquid sodium replaced water for cooling in FNRs, since in contrast to water it does not slow down fast neutrons appreciably. Sodium reacts chemically very strongly with water, but it was used safely in the EBR-II under power for 30 years without incident. There is no water in the reactor.

Three crucial safety features were built into the EBR-II. One was passive removal of FP-generated heat by two heat exchangers that operated by natural convection alone, without power. They functioned at each reactor shut-down. The other two features were tested under full power. In one, the cooling pumps to the reactor core were shut off after the control rods were deliberately inactivated. The reactor shut itself down without human or automated intervention. In the third, cooling to the heat exchanger in the reactor tank was shut off. Again the reactor shut itself down due to its inherently strong negative temperature feedback.

These features by themselves would have prevented the Chernobyl disaster as well as the melt-down of the Three-Mile-Island and Fukushima reactors.

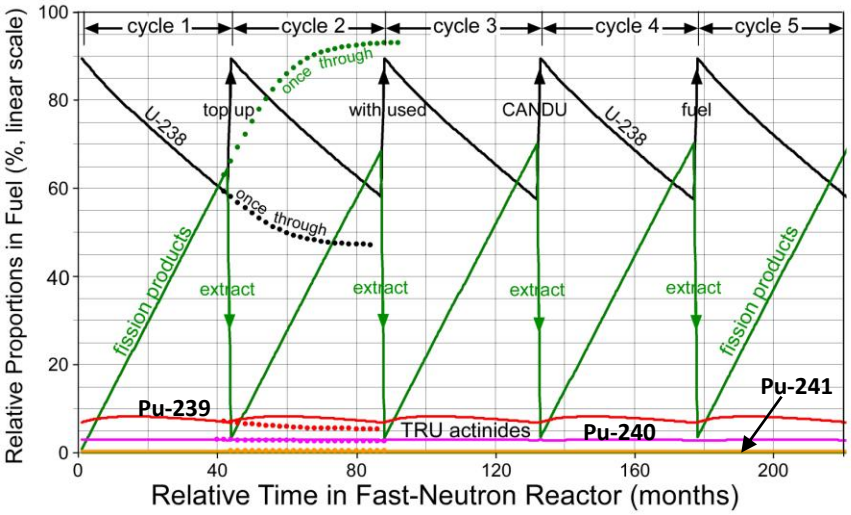

Figure 2. Calculated Cyclic Consumption and Build-up of Fuel Components in an EBR-II-like Fast-Neutron Reactor.

Only the levels of U238 are shown along with fission products and several representative TRUs. Every other type of atom in the reactor, including structural steel and coolant was also part of the calculation. Transuranics (TRUs) represented by three plutonium isotopes (Pu-239/240/241) remain at an equilibrium concentration in the reactor, whereas uranium and TRUs brought in with the ~35% top-up load of used CANDU fuel are completely consumed at the end of each fuel cycle. Fission products accumulate, but are separated and extracted at refueling.

Economics

All FNRs have been "first-of-a-kind" designs, with costs being about 50% higher than conventional thermal reactors, e.g. $2500/kWe (kilowatt of electrical power output) for the Indian 500 MWe PFBR FNR in Kalpakkam[14] versus the CANDU reactors in Qinshan, China, at $1978/kWe.[15] Subsequent FNRs of the same design should match costs of thermal reactors.[12] Clearly, building such reactors at sites of currently stored used CANDU fuel near existing CANDU reactors would obviate fuel transportation costs and potentially reduce expenses for extensive environmental assessments and other hearings required at virgin sites.

Using highly radioactive fuel waste in FNRs is more costly than fueling with fresh uranium at current prices of natural uranium. However, the lifetime cost of discarding used CANDU fuel in a proposed Canadian deep geological repository (DGR) is also substantial, estimated at $24.4 billion for a DGR holding 3,600,000 fuel bundles[1], and $40.75 billion for twice that capacity,[16] disregarding the lost revenue from this valuable resource. These DGR costs can be compared directly to the cost of converting and recycling used CANDU fuel in an FNR facility.

The cost of construction, filling, and eventual closure of the DGR is being met by a levy on each kWh of electricity generated at about 0.16 MW-years per fuel bundle.[1] To date $2.28 billion have been charged and put in trust from 2.2 million used fuel bundles.[17] To meet the cost of the smaller DGR an average charge of 1.13 ¢/kWh has to be levied from now on (see Table 1); the future cost of a DGR with twice that capacity would be 0.55 ¢/kWh.

Table 1

Future Average Rate Required to Meet DGR Costs

Total Life Cycle Cost	Outstanding Balance	**DGR filled with 3.6 million bundles** tithe from 1.4 million* or from 1.96×10^{12} kWh** Avg. rate needed (¢/kWh)	**DGR filled with 7.2 million bundles** tithe from 5.0 million* or from 6.99×10^{12} kWh** Avg. rate needed (¢/kWh)
$24.40 billion	$22.12 billion	1.13	
$40.75 billion	$38.47 billion		0.55

* 2.2 million bundles used fuel are stored and have been tithed to date ($ 2.28 B[17])
** Electrical energy yield calculated on basis of 6.25 bundles per 1 MW-year[1]

Till and Chang, on the basis of their EBR-II experience, have calculated the cost of cyclic pyroprocessing of used fuel as 0.44 ¢/kWh in a dedicated facility associated directly with a 1000 MWe FNR.[12] This includes capital costs for the processing facility plus 300 year storage of the FPs. This cost is about 2.5 times less than the smaller planned Canadian DGR, and 20% less than the larger DGR.

Conclusion

The current worldwide approach to highly radioactive used nuclear fuel waste disposal is to discard it in as yet unproven deep geological repositories which in Canada will cost an estimated $24.4 billion to $40.75 billion. The alternative presented here is the elimination of the long-term radioactivity of CANDU fuel waste using fast-neutron reactor facilities successfully tested and operated for three decades before 1995. This approach is up to 2.5 times less costly than burial of the used fuel. Moreover, it would result

in a virtual elimination of long-term radiotoxicity of the waste and a shortening of its radioactive decay time to background from 400,000 years to 300. At the same time the 43,660 tonnes of currently stored used fuel waste would provide $48 trillion of carbon-free electricity plus cogenerated heat from that waste alone, equivalent to more than 4000 years of nuclear-generated electricity at today's level of production. Moreover, after 300 years the fission products emerging from such a reactor facility would become valuable minerals extractable by ordinary means. No waste at all.

The option is ours: a $40 billion burial of a 400,000-year nuclear waste hazard or the elimination of that hazard via the creation of an economic base of $48 trillion of steadfast dependable and green electrical energy for homes, industry and transportation for many centuries.

Is there a choice?

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