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SYNERGISTIC FUEL CYCLES OF THE FUTURE

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Abstract

Good neutron economy is the basis of the fuel cycle flexibility in the CANDU reactor. This paper describes the fuel cycle options available to the CANDU owner with special emphasis on resource conservation and waste management.

CANDU fuel cycles with low initial fissile content operate with relatively high conversion ratio. The natural uranium cycle provides over 55 % of energy from the plutonium that is created during fuel life. Resource utilization is over 7 MWd/kg NU. This can be improved by slight enrichment (between 0.9 and 1.2 wt % U235) of the fuel. Resource utilization increases to 11 MWd/kg NU with the Slightly Enriched Uranium cycle. Thorium based cycles in CANDU operate at near-breeder efficiency. They provide attractive options when used with natural uranium or separated (reactor grade and weapons grade) plutonium as driver fuels. In the latter case, the energy from the U233 plus the initial plutonium content amounts to 3.4 GW(th).d/kg Pu-fissile. The same utilization is expected from the use of FBR plutonium in a CANDU thorium cycle. Extension of natural resource is achieved by the use of spent fuels in CANDU. The LWR/CANDU Tandem cycle leads to an additional 77 % of energy through the use of reprocessed LWR fuel (which has a fissile content of 1.6 wt %) in CANDU. Dry reprocessing of LWR fuel with the OREOX process (a more safeguardable alternative to the PUREX process) provides an additional 50 % energy. Uranium recovered (RU) from separation of plutonium contained in spent LWR fuel provides an additional 15 MWd/kg RU.

CANDU's low fissile requirement provides the possibility, through the use of non-fertile targets, of extracting energy from the minor actinides contained in spent fuel.

In addition to the resource utilization advantage described above, there is a corresponding reduction in waste arisings with such cycles. This is especially significant when separated plutonium is available as a fissile resource.

INTRODUCTION

The neutron economy of the CANDU reactor is a result of design features that minimise parasitic neutron absorption. The use of heavy water for the moderator and the coolant limits their parasitic load to 1.5 % (15 milli-k). On-power refuelling avoids the use of burnable poisons for reactivity suppression. Such features limit the fissile inventory in CANDU cores. To appreciate the extent of this advantage, the fissile inventory of 1 GW(e) FBR, LWR, CANDU (Natural Uranium) and the CANDU AB that burns the transuranics in sterile fuel is compared in Table 1. As expected, lower fissile inventory leads to a higher conversion ratio for the production of fissile material from fertile material.

Table 1

Fissile Inventory (te) of 1 GW(e) Cores

FBR	PWR	CANDU	CANDU AB
3 to 4	2 to 3	1	0.05

The ability of CANDU to burn fuel with low fissile content leads to resource extension by the recycling of spent LWR fuel. In addition, it creates a significant fissile resource by raising the conversion ratio. This is especially so for fuel cycles that use thorium as the fertile material. A variety of innovative fuel cycles, some of which illustrate the synergy between CANDU and other systems such as FBR and LWR are described below.

URANIUM BASED CYCLES

Natural Uranium

Currently operating CANDU reactors use a once-through natural uranium cycle. The low fissile content of natural uranium leads to a conversion ratio around 0.8. This provides a plutonium production rate that almost compensates for the depletion of U235. The reason for the reactivity drop with irradiation in this fuel cycle is the buildup of fission product absorbers. The fissile content of the fuel on exit (at about 7 MWd/kgU) is almost the same as in the fresh fuel. This high rate of plutonium production leads to a large (> 55 %) energy contribution by plutonium. At exit the energy contributed by plutonium is > 70 %. Resource consumption in this cycle is 157 te/GW(e).y, (Table 2). Waste arisings are correspondingly the same.

Slight Uranium Enrichment

The large (> 70 %) contribution to energy by plutonium at the end of fuel life points to the benefits of extending the fuel life without reducing the conversion ratio. Slight enrichment of the fuel extends the fuel life but reduces the conversion ratio. However, with enrichment levels below 1.2 wt % U235, there is a net positive gain in resource utilization. With an enrichment level of 1.2 wt % the exit burnup is 22 MWd/kg and the uranium consumption drops to 114 te/GW(e).d. More significantly, the waste arisings decrease to 49.8 te/GW(e).y.

Spent LWR Fuel

Synergy between LWR and CANDU is best illustrated by burning spent LWR fuel in CANDU. There is sufficient fissile content (about 1.6 wt %) in the spent fuel to provide, after removal of the fission products, an energy output of 27 MWd/kg in CANDU. This is in addition to the 35 MWd/kg obtained from the LWR cycle. It should be noted that the fissile utilization (1700 MWd(th)/kg fissile) is poorer compared to the case with an enrichment of 1.2 wt % U235. This is due to a larger reduction in conversion ratio at the higher enrichment level. The uranium consumption, 119 te/GW(e).y is about the same. But the major gain is the reduction in waste arisings, from 49.8 to 18.8 te/GW(e).y.

Table 2

Fuel Cycle Characteristics For LWR's and CANDU

	Fuel Cycle Option	Natural Uranium Requirements (Mg/GWy(e))	Fuel Disposal Requirements (Mg/GWy(e))
1.	Enriched-U in LWR	217	33.2
2.	LWR-Pu recycled in LWR	185	29.2
3.	LWR-Pu and re-enriched LWR-U recycled in LWR	157	24.7
4.	Natural-U in CANDU	157	157.0
5.	Slightly enriched-U in CANDU	114	49.8
6.	LWR-Pu recycled in LWR and recovered LWR-U in CANDU	151	23.8
7.	LWR-Pu and LWR-U recycled in CANDU	119	18.8
8.	Re-clad LWR spent fuel recycled in CANDU	125	19.7
9.	Actinides from LWR spent fuel annihilated in CANDU	0	1.2
10.	Re-clad LWR spent fuel recycled in CANDU/Thorium-U233 converter	98	17.4

There is an incentive to use dry reprocessing of the spent LWR fuel. Dry reprocessing is considered a more easily safeguardable alternative. In the DUPIC, (Direct Use of LWR Fuel in CANDU), the dry process does not remove all the fission product absorbers. The fuel burnup and utilization is less, (18 MWd/kg and 125 te/GW(e).y). This also affects the waste arisings, 19.7 te/GW(e).y.

With the current focus of recycling plutonium in LWRs, there is an opportunity for further resource extension through the use of the uranium recovered from the reprocessing plant. The recovered uranium has a U235 content between 0.8 and 1.0 wt %. It also has a significant U236 content which is a non-fissile absorber. (In a CANDU neutron spectrum which is considerably softer than the LWR neutron spectrum, the parasitic behaviour of U236 is reduced). Here again, the neutron economy of CANDU provides a conversion ratio above 0.7 and an energy contribution from plutonium that is comparable to the natural uranium cycle. Exit fuel burnup is between 15 and 17 MWd/kg of RU. The use of this CANDU fuel cycle together with recycling the plutonium in LWR, reduces uranium consumption from 185 te/GW(e).y to 151 te/GW(e).y.

THORIUM BASED CYCLES

The use of thorium as an alternative fuel to uranium has several attractions. Thorium is more abundant and widespread. Spent thorium fuel is less toxic (has few, if any, of the higher actinides present in spent uranium fuel) and has an ingestion hazard that is an order of magnitude lower. The main disadvantage of thorium is the absence of fissile material in it. This could rule it out as an option if enrichment or reprocessing technology is not available.

CANDU's neutron economy provides a larger advantage when thorium is used as a fertile material instead of uranium 238. The conversion ratio can exceed 0.95. U233 buildup is almost monotonic in CANDU thorium fuel. The fuel life is limited either by fuel performance or by excessive buildup of fission products. Consequently, thorium fuel provides rated power even in a subcritical lattice.

The Self-Sufficient Thorium Cycle

With some re-design of the lattice (and, albeit, with a narrower reactor operating regime) the Th232/U233 cycle in the CANDU reactor can be closed and operated with total independence of external fissile material. The exit fuel burnup is between 10 and 15 MWd/kgHE. This relatively low burnup demands a significant amount of reprocessing in order to recycle the U233 from the spent fuel. Furthermore, some fissile driver is required to startoff the production of U233.

Natural Uranium Driver

CANDU's neutron economy makes it feasible to use a low-grade driver fuel such as natural uranium. Natural uranium CANDU fuel is cheap and the manufacturing technology is well established and has been transferred to several clients. It is expected that thorium CANDU fuel will have the same features. The CANDU reactor provides the use of thorium as a fuel option to clients that do not have access to enrichment or reprocessing technology until the latter become available.

The resource utilization depends on the transition strategy used to implement the thorium cycle into a CANDU reactor that has been operating on natural uranium fuel. Some enhancement of the U233 buildup can be achieved by periodic cooling of the fuel between irradiations. Even in a subcritical lattice, the U233 buildup is sufficient to provide rated power from the thorium channels that are placed in the midst of natural uranium channels. The core thorium inventory is found to be limited by fuel handling capability. With current fuel handling capability, the thorium inventory of the core is limited to about 20 %. Loss of power from fresh thorium channels leads to a reactor power penalty of 12 % during the approach to equilibrium refuelling. Following equilibrium, there is no power penalty predicted. The reason for this (besides the long fuel life of the thorium fuel) is the random selection of channels for refuelling during equilibrium operation which results in a very small number of relatively fresh, i.e. low-powered thorium channels present in the core.

Thorium utilization is comparable to that of the Self-Sufficient Thorium Cycle assuming that a high-burnup thorium fuel is available. This makes the natural uranium/thorium cycle an option to consider by clients when they do not have access to enrichment or reprocessing technology to provide fissile material.

The DUPIC Driver

In the DUPIC/Thorium cycle, the DUPIC fuel replaces natural uranium as the driver fuel. Because of its higher fissile content compared with natural uranium (1.6 vs 0.72 wt %), this cycle permits a larger thorium inventory in the core, as much as 48%. The power penalty during the transition is significantly higher. Also the discharge burnup of the DUPIC fuel remains high, between 15 to 18 MWd/kgHE which implies that the U233 production is sufficient to compensate the neutron load of the thorium.

Reprocessed LWR Fuel

An increase in driver fuel reactivity and in thorium utilization is obtained if fission products are removed from the DUPIC fuel. The fissile content of the driver fuel is the same as DUPIC and the fissile plutonium remains unseparated. With this cycle, the thorium fuel burnup is limited by fuel performance.

The Plutonium-Driven Thorium Cycle

There are two kinds of Thorium/Pu cycles to be considered in CANDU. In the high plutonium utilization thorium cycle, the U233 that is produced during the irradiation of Thorium/Pu fuel is recycled together with a fresh feed of Thorium fuel. This feed may or may not contain fissile Pu as topping to extend fuel burnup. Without Pu topping, the fuel life is limited by lattice reactivity.

In this regard it should be noted that the buildup of U234 with subsequent recycles constitutes, due to the type of neutron spectrum in CANDU, a relatively low fuel burnup penalty. The equilibrium cycle burnup obtained is about 10 MWd/kgHE. Since current CANDU fuel achieves this level of burnup, such a cycle can be implemented without major fuel development.

An increase in initial fissile content is required to reduce reprocessing cost via increased fuel burnup. There are two conflicting requirements that emerge when considering such a cycle; high Pu utilization vs low reprocessing cost.

FBR-CANDU SYNERGISTIC CYCLES

One of the major incentives for the development of breeder reactors is to provide security of fuel supply. This incentive makes sense if the current relatively high cost of producing fuel from breeder reactors can be offset by the strategic advantage of independence, in the future, of uranium supply and cost. A major assumption that is implicit in this approach to ensure the security of fuel supply, is the technical feasibility of fast breeder reactors on a commercial scale. This has not been achieved to-date. Nor is it a certainty in the future. What is certain, however, is that fast breeders are technically feasible but at a high capital cost per installed kilowatt. The latest experience indicates that this cost is an order of magnitude higher than the cost of established thermal reactor power plants. With this cost differential, uranium cost must rise by two orders of magnitude (or its equivalent in commercial availability) to realize the cost benefit of fast breeders.

Basic cost analysis shows that it will be commercially viable to supplement the breeding power of fast reactors with that of established thermal reactor systems to offset the high capital cost of fast reactors in achieving security of fuel supply. In this approach, fissile material from FBRs is used to produce the relatively inexpensive fuel that is currently used in thermal reactors. The range of uranium cost over which commercial viability is achieved in this case will be determined by the conversion ratio of the thermal reactor.

CANDU provides several options to burn fissile material from FBRs. These options are attractive for two reasons. First, the high conversion ratio of a CANDU lattice maximises the energy extracted from the bred fuel. Second, due to the low capital cost of CANDU relative to FBR, an FBR-CANDU system minimises TUEC for a wide range of increased uranium cost. There are several options that are available for the use, in CANDU, of fissile material from FBRs. These options include the direct use of fissile material from FBRs in the MOX, Pu/Th and the Pu/Minor Actinide fuel cycles in CANDU. They also include the indirect options which burn reprocessed spent LWR/MOX fuel in CANDU. The main features of these fuel cycles are given below, starting with the cycle that provides the highest utilization of FBR bred plutonium.

Plutonium driven thorium fuel cycles in CANDU using thorium fuel with low plutonium content (0.9 to 1.1 w% fissile Pu) provide the best utilization of FBR bred plutonium. The low fissile content preserves the near-breeder feature of the Thorium/U233 lattice in CANDU. The plutonium can be used either to initiate a self-sufficient Thorium/U233 cycle in CANDU with subsequent recycling of U233, or it can be used as an integral part of the Thorium/U233 cycle in CANDU to achieve high fuel burnup. In the former option, the fuel life is limited by the lattice reactivity. In the latter, it is limited by fuel performance. In the former case, the fissile plutonium utilization is higher and determined by the buildup of U234 in subsequent reprocessings of spent CANDU fuel. In the latter case it is about 3.5 GW(th).d/kg provided the fuel can achieve 55 MWd/kgHE. Excess plutonium from a 1 GW(e) IFR will support 1.5 GW(e) CANDU installed.

Use of FBR bred plutonium in MOX CANDU fuel provides a fissile utilization of 1.5 GW(th).d/kg in a once-through cycle. This is the result of a lower U238 to Pu239 conversion ratio compared with Thorium. However, it is significantly higher than using the MOX fuel in LWRs. This means that excess fissile plutonium from a 1 GW(e) IFR will support 0.7 GW(e) CANDU.

Use of FBR bred plutonium via the LWR-CANDU tandem fuel cycles improves the overall fissile utilization but it remains less than that provided by the direct MOX CANDU option. The difference is significant if reprocessing of LWR fuel is limited as in the DUPIC (Direct Use of PWR Spent Fuel in CANDU) cycle where the presence of the fission products from the LWR stage restricts the burnup that is achievable in CANDU.

The recycling of fissile material from CANDU spent fuel into FBRs (see Figure 1 attached) is an option that may become available if costs allow the reprocessing of the large volume of CANDU fuel. With one such recycling, supportable CANDU capacity would increase from 0.7 to 1.3 GW(e) with a U/Pu cycle.

Studies of fast reactor cycles show that use of U233 together with Pu239 have higher breeding ratios and lower fissile requirements. Sodium void coefficients are not affected, (1). Using thorium in the blanket but not in the core has the additional advantage of eliminating the reactivity transient associated with Pa233 decay to U233 and reducing the U232 content of U233.

Based on the above, the use of U233 from spent CANDU Th/Pu fuel in FBRs and the subsequently bred Pu in CANDU Th/Pu cycles is a synergistic cycle to be considered.

WASTE ANNIHILATION CYCLES

The Pu/Minor Actinide Cycle

The Pu/Minor Actinide fuel cycle in CANDU is a relatively low utilization cycle that is designed to annihilate minor actinide inventories resulting from fuel reprocessing. To achieve high burnup of actinides, this cycle, unlike the FBR, operates without fertile material in the fuel. This prevents the formation of actinides during the fuel life and provides relatively high net actinide annihilation. Annihilation rates in CANDU are compared in Table 3 with several design concepts. The annual annihilation rate in CANDU is equivalent to the actinide production from an installed capacity of 3.6 GW(e).

Table 3

CANDU-AB PERFORMANCE

	kg Annihilated
ALMR (SPENT LWR FUEL)	273-413
ALMR (Pu FUEL)	825
ALMR (SMALL BURNER)	99
ALMR (LARGE BURNER)	144
LMFBR (ENHANCED SAFETY)	387
PWR (STANDARD)	657
PROTON LINEAR ACCELERATOR	1016
CANDU-AB	1227

Long-Lived Isotope Transmutation

The relatively high neutron flux level in the CANDU reactor, which is a result of its low fissile inventory, is effective in the transmutation of long-lived fission products such as Tc 99 and I 129. The feasibility of this option is enhanced by the space available in the CANDU core due to its large lattic pitch and also the low operating pressure of the moderator system. The annihilation rates shown in Table 4 are based on using Tc 99 as the absorber material in the reactor control elements.

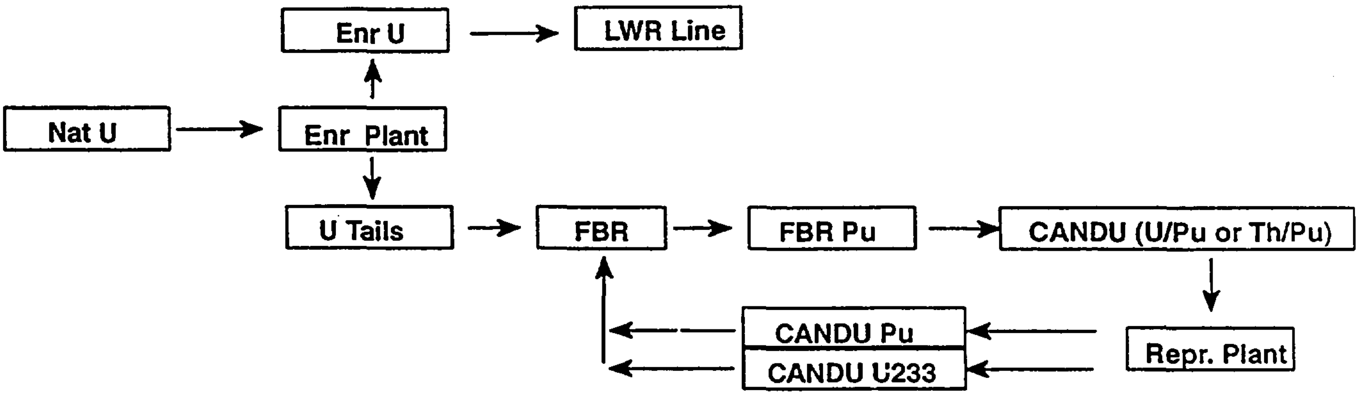
Table 4

TRANSMUTATION RATES FOR Tc99

CASE	FUEL ENRICH-MENT (wt%)	NEUTRON FLUX (n/cm^2/s) x 10^{14}	TRANSMUTATION RATE (kg/a)	TRANSMUTATION HALF-LIFE (a)
Central Fuel Pin Metallic Tc99	0.94	1.51	35	44.2
9 Outer Pins	0.95	0.91	40	40.3
Adjuster Rod	1.3	0.91	81	24.5
Moderator Poison	3.2	1.36	207	11.0

Reactor Power 935 MW(e)

Figure 1: FBR/CANDU Synergy



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