Scoping Study of a Thorium Reactor Driven by PWR-Derived Plutonium

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Abstract

This paper investigates the potential uranium savings from operating thorium-fuelled CANDU® reactors driven by PWR-derived plutonium and recycled ^{233}U. Because ^{233}U production in the thorium fuels is optimized at lower exit burnups, less external fissile driver material is required for the operation of the thorium reactors and natural uranium savings of the overall fuel cycle are increased. Assuming the same exit burnup is achieved by reactors with Pu+Th fuel and reactors with ^{233}U+Pu+Th fuel, it was determined that a 40 MWd/kg exit burnup yielded a 52% savings of natural uranium, compared to a scenario in which all power came from PWRs, while a 20 MWd/kg exit burnup increased the savings to 75%.

1. Background

Although not prevalent in modern power reactors, thorium can be used as a replacement for uranium fuel. One motivation for the shift to thorium is that it is three times more abundant in the Earth's crust than uranium [1]. However, even more importantly, thorium fuels can be used in a near equilibrium fuel cycle where the thorium can be recycled until nearly all of the ore has been fissioned. This can greatly reduce the demand for raw resources which has both economic and environmental consequences.

As thorium itself is not a fissile material, it needs a reactor with a good neutron economy in order to maximize conversion of thorium to fissile U-233. This makes CANDU reactors, which use heavy water as both coolant and moderator, the obvious starting point for the development of a thorium fuel cycle. A significant amount of work has been performed in the past on possible implementation of thorium in CANDU reactors [2-5]. In this paper, a thorium fuel cycle using pressurized water reactor (PWR)-derived plutonium as a driver fuel is investigated as a means for reducing uranium consumption, and fuel cycle systems are investigated that include reactors driven by Pu-driven and U-233 driven thorium fuel.

In the proposed fuel cycle, the plutonium produced from a PWR reactor is used in a $(Th,^{233}U,Pu)O_2$ matrix in a CANDU reactor, which is referred to as reactor A in this report. This reactor produces excess ^{233}U that is then used to compensate for ^{233}U losses in a $(Th,^{233}U)O_2$ fuelled CANDU reactor, which is referred to as reactor B. The fuel cycle is shown in Figure 1. This fuel cycle is self-sufficient in ^{233}U.

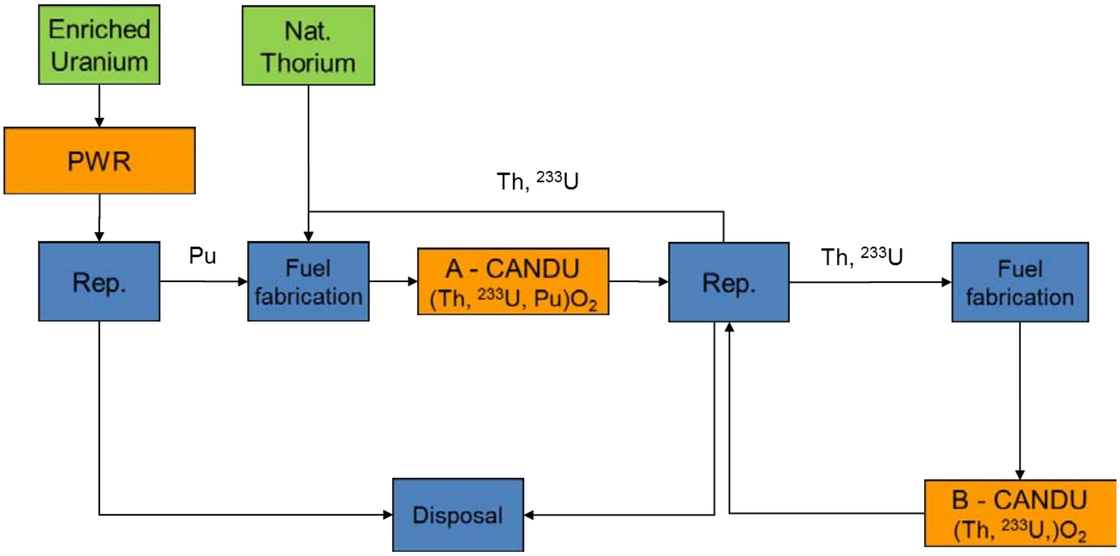

Figure 1 - The proposed thorium fuel cycle

There are many different schemes that can be used to generate the ^{233}U stockpile needed to initially load the thorium reactors. One option is to use ^{233}U generated from a $(Th,Pu)O_2$ once-through reactor. This paper assumes that the stockpile has already been created by some means and instead examines only the steady state resource consumption of the reactor park.

The fuel cycle is optimized to include the maximum number of reactor Bs. The number of reactor A's will be chosen so that they can support the rate of ^{233}U consumption in reactor B. Likewise, the number of PWRs will be chosen so that they can support the rate of plutonium consumption in reactor A.

The thorium reactors are simulated using a single-cell lattice in WIMS-AECL version 3.1.2.1 [6] with the ENDF/B-VII-based cross-section library [7], with appropriate boundary conditions to represent a whole reactor. The base case assumes the following reactor characteristics:

PWR

Parameter	**Value**
^{235}U Enrichment	4.11%
Exit burnup	42.16 MWd/kg
Tails enrichment	0.25%
Thermal efficiency	33%
Reprocessing losses	0.5%

CANDU

Parameter	**Value**
Power	20 W/g
# of elements	37
Parasitic absorption	30 mk
Lattice pitch	28.575 cm
Thermal efficiency	32.36%
Reprocessing losses	0.5%

Table 1 - Characteristics of base case

The power density chosen for this study is significantly lower than the power density of current generation CANDU reactors, 32 W/g. The low power density was initially selected to insure a low flux and minimize neutron absorption in ^{233}Pa. The fuel cycle's sensitivity to this assumption is investigated later in the paper.

Spent PWR fuel is assumed to contain 1.13% plutonium by weight with the following plutonium vector [5]:

Isotope	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
wt%	2.5	54.2	23.8	12.6	6.8

Table 2 - Plutonium vector from spent PWR fuel

Although thorium is not fissile, it can transmute to the fissile ^{233}U by the following process:

(1)

To drive the transmutation, an initial source of neutrons is required. One example is to include some amount of ^{233}U in the fresh fuel. If the mass of ^{233}U at discharge is equal to the initial mass requirement, (or slightly greater to account for losses during reprocessing), then the fuel can be recycled without the addition of new fissile material. This is referred to as a Self-Sustaining Equilibrium Thorium cycle (SSET). However, the SSET cycle is only achievable in a CANDU reactor for low exit burnups that may require an unrealistic amount of reprocessing. This can be compensated for by adding a small amount of fissile material, such as ^{239}Pu and ^{241}Pu, to the initial fuel. In this scenario, an equilibrium, but not self-sustaining, thorium fuel cycle is still achievable if the ^{233}U output exceeds the input. The conversion ratio (CR) is a measure of a reactor's ability to produce ^{233}U and is given by the following formula:

(2)

where M_i is the percentage by weight of isotope i. A CR greater than 1 implies a net production of ^{233}U while a CR less than 1 implies a net consumption. After reprocessing losses, the excess ^{233}U produced in reactor A, P_U, is then given by:

(3)

where P_U is in kg/MWdth, L is fraction lost in reprocessing, and BU is the exit burnup in MWd/kg.

The amount of ^{233}U that is loaded into reactor B is chosen so that reactors A and B have an equal exit burnup. As will be demonstrated later in the paper, the exit burnup of the thorium reactors is limited by the available reprocessing capacity. It is fair to assume that both the thorium reactors will be limited by the same reprocessing capacity and therefore will have the same exit burnup. For a given exit burnup, reactor B consumes a specific amount of ^{233}U, C_U (see figure 2). Therefore, the electric capacity from reactor B that can be supported by the electric capacity of reactor A is given by the support ratio, $SR_{A:B}$:

(4)

where e_i is the specific power of reactor *i*.

If M_{Pu} is the mass fraction of plutonium in reactor A, then the rate of plutonium consumption, C_{Pu}, in kg/MWd can be given by:

(5)

Therefore, the support ratio of PWR to reactor A, $SR_{PWR:A}$, is then given by:

(6)

where P_{Pu} is the rate of plutonium production in the PWR and is calculated using values from the literature and ignores reprocessing losses. From equations (5) and (6), it can be seen that the ratio of power produced in the PWRs to total power produced is given by:

(7)

It follows then that the NU consumption for the entire fuel cycle in kg/MWd is given by

(8)

where NU_{PWR} is the rate of NU consumption in the PWR.

2. Conversion Ratio

With no driver fuel, reactor B will have a conversion ratio less than 1 for all exit burnups greater than approximately 10MWd/kg. This is shown in Figure 2.

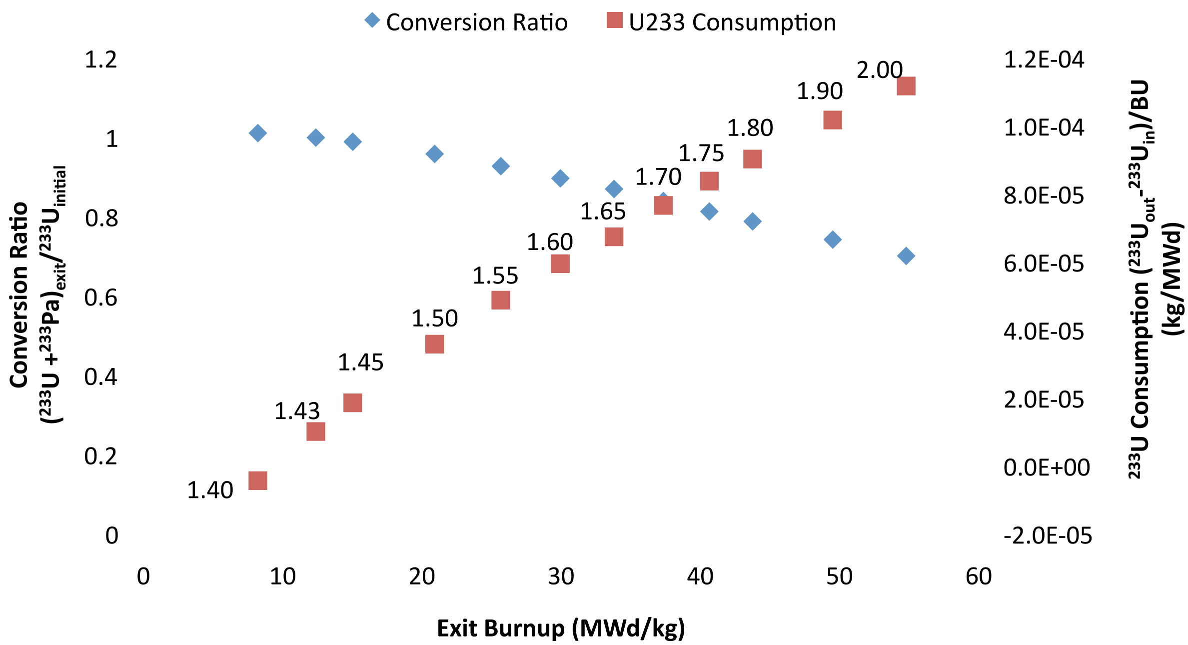

Figure 2 - CR and rate of ^{233}U consumption for reactor B. The initial ^{233}U concentration (wt%) in reactor B is shown on the graph. Note that a negative consumption implies a net production of ^{233}U.

To determine the ^{233}U consumption at an arbitrary exit burnup, a 2nd order polynomial was fit to the data. This gives $P_{U,}$ which can be used in equation (4).

Figure 3 shows that, although the conversion ratio decreases with increasing ^{233}U concentration, the same is not necessarily true for increasing plutonium concentration. This allows reactor A to achieve reasonably high burnups and have a conversion ratio greater than 1.

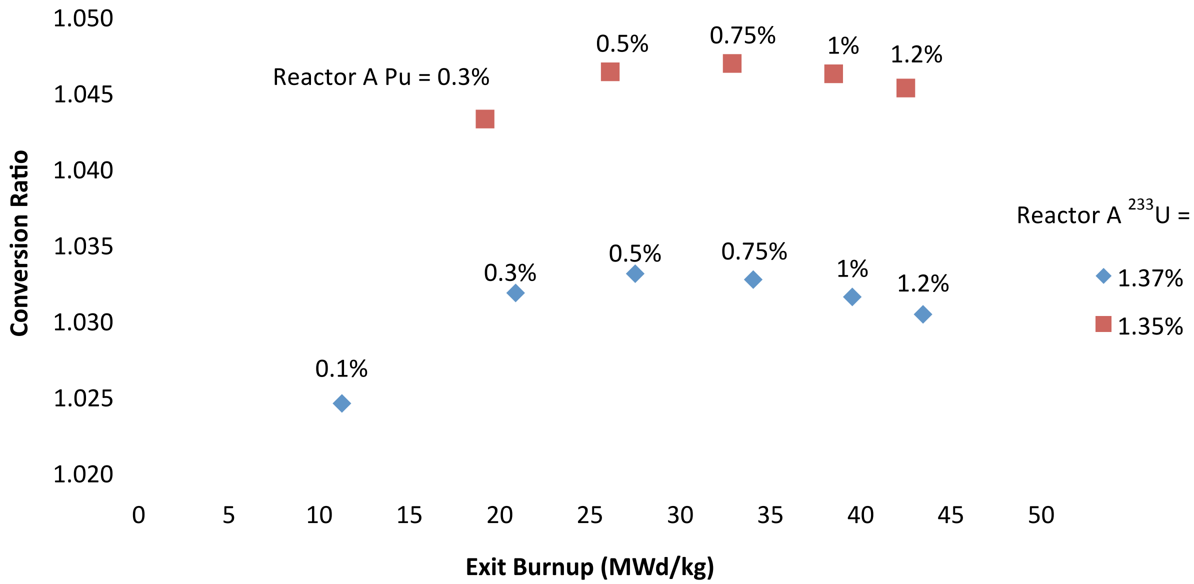

Figure 3 - The effect of enrichment on CR in reactor A. Initial ^{233}U concentration (wt%) of reactor A is shown in the legend and plutonium concentration is shown on the chart.

Figure 4 gives an explanation as to why a maximum CR can be seen in Figure 3. Although increased plutonium loading increases the CR for a given burnup, it does not necessarily lead to a higher CR at the exit burnup.

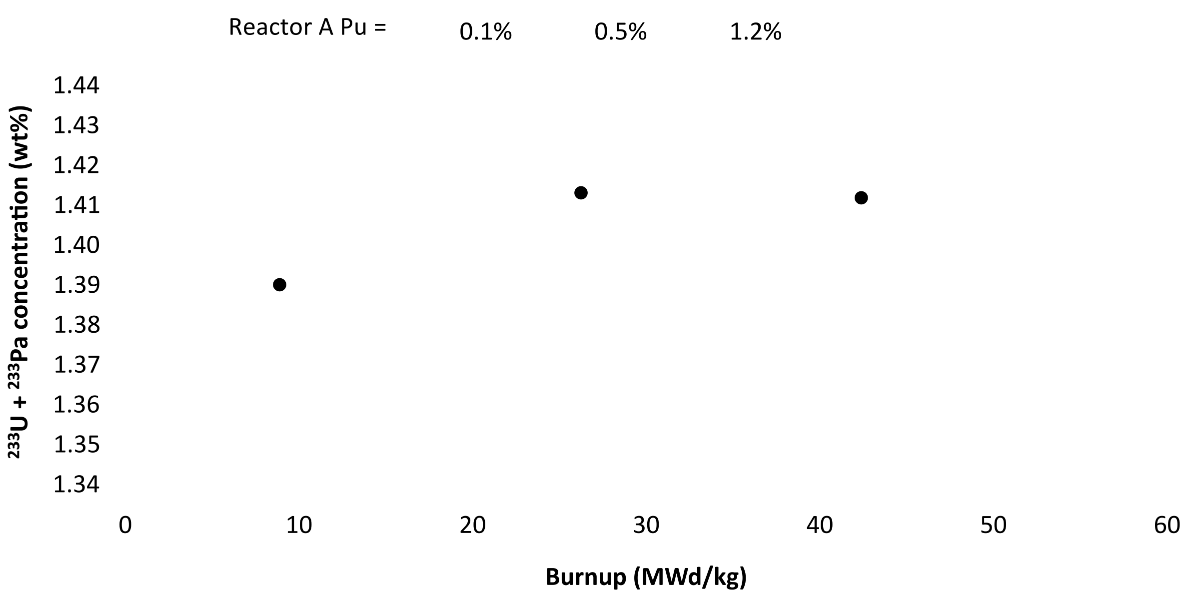

Figure 4 – The effect of plutonium loading on ^{233}U and ^{233}Pa concentrations at discharge for reactor A with a fixed initial ^{233}U concentration of 1.35%. The legend shows the initial plutonium concentration. The black dots show the exit burnup.

3. Natural Uranium Consumption

The reactor share is dependent on the exit burnup of the thorium reactors. Figure 5 shows the reactor share for 1.35% and 1.40% initial ^{233}U concentrations.

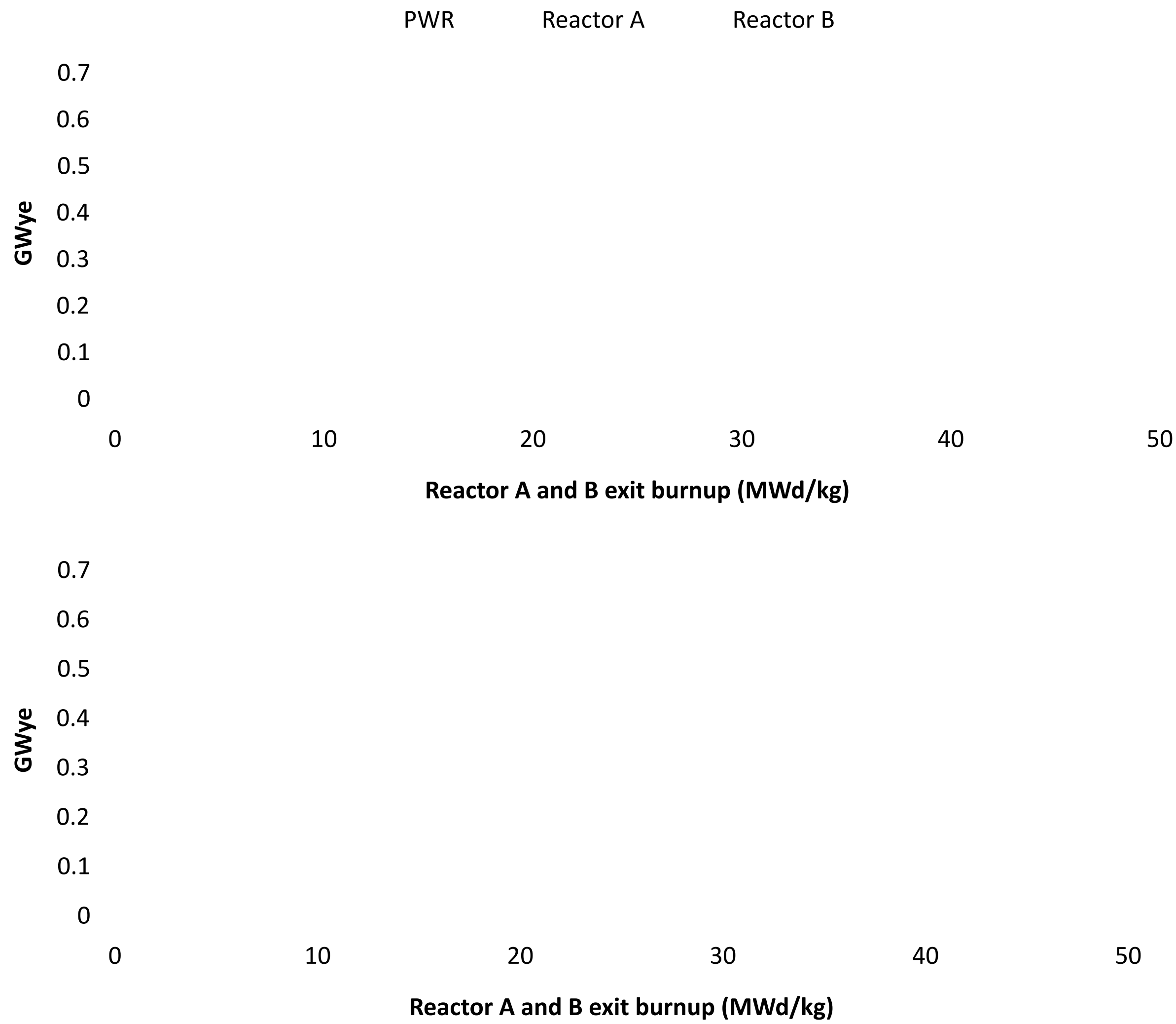

Figure 5 - Energy production from each reactor in a 1 GWye scenario where reactor A is initially loaded with 1.35% (top) and 1.40% (bottom) ^{233}U.

As was shown in Figure 2, the CR of reactor B approaches 1 at low exit burnups. If reactor B were to achieve a SSET cycle (i.e. have a CR $\geq$ 1), then no fissile feed would be required and the reactor park would have no PWRs or reactor A. Therefore, at low exit burnups the reactor park will be primarily comprised of reactor B. At higher exit burnups, reactor B consumes more ^{233}U. This requires a larger capacity of reactor A and, consequentially, a larger capacity of PWRs. This trend is shown in Figure 5. This is what leads to the counter intuitive trend of a less-sustainable fuel cycle for higher exit burnups that is shown in Figure 6. Also shown in the Figure 6 is the fact that natural uranium consumption is not strongly dependent on the specific concentration of ^{233}U and plutonium. Rather, it is dependent on the exit burnup achieved from the combination of the fissile components.

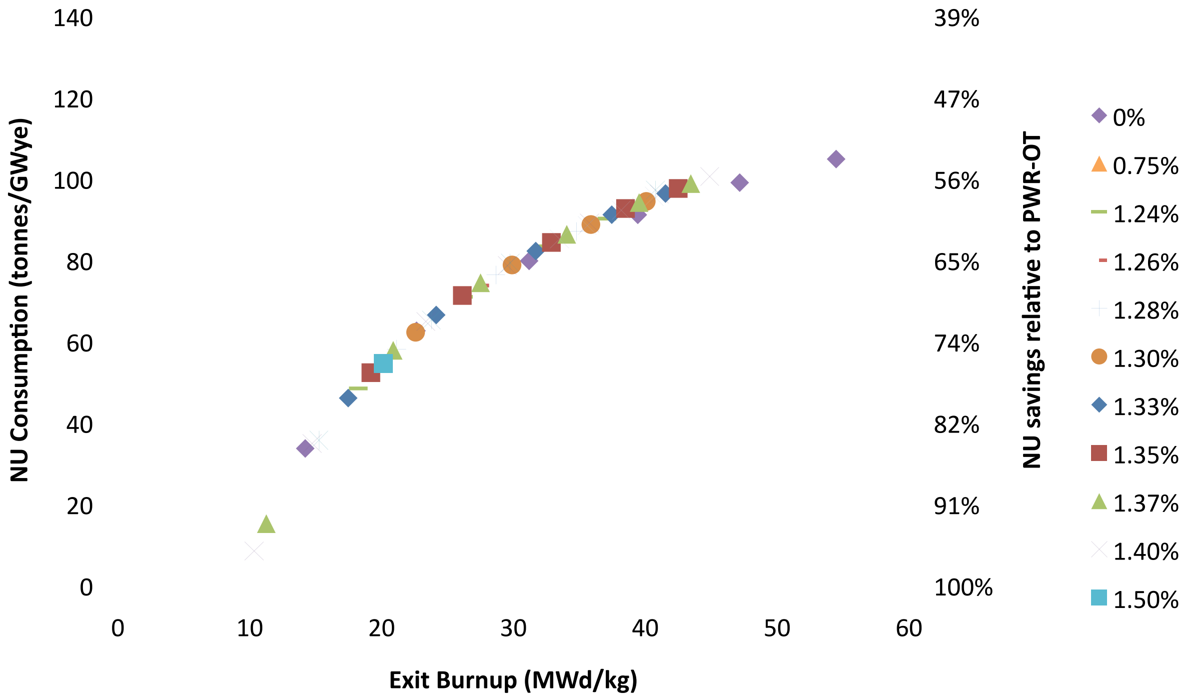

Figure 6 – NU savings relative to an all PWR once-through fuel cycle. The initial ^{233}U concentrations are shown in the legend. For a given initial ^{233}U concentration, the plotted points vary by initial plutonium concentration,

At an exit burnup of 20 MWd/kg, the thorium recycling scheme reduces the natural uranium consumption by 75% relative to the PWR once-through fuel cycle but the savings decrease with increasing exit burnup. The obvious disadvantage of lower burnup fuel is the increased burden on reprocessing. This is shown in Figure 7.

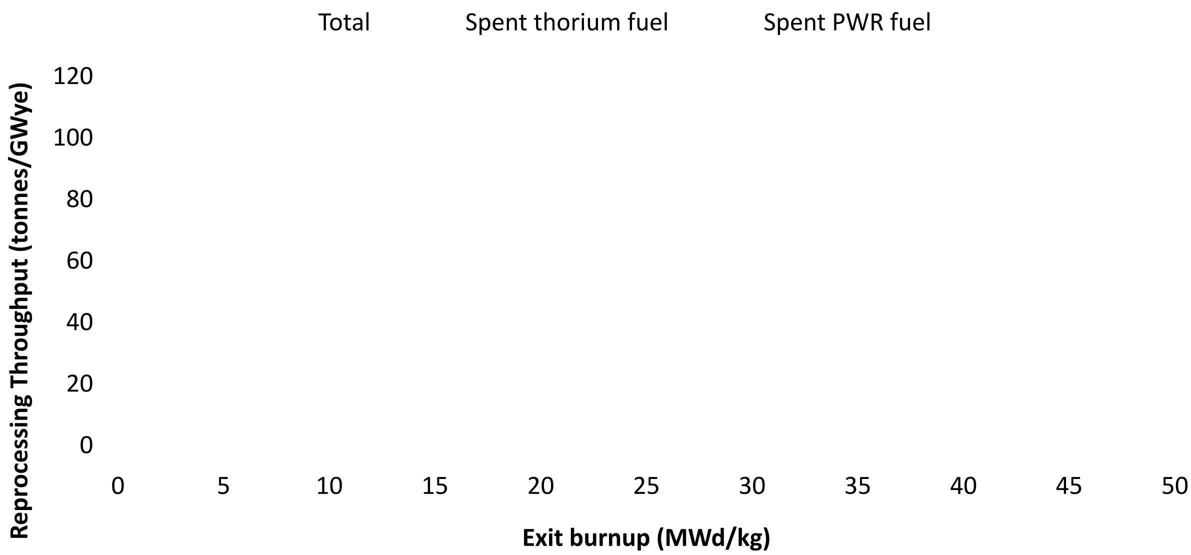

Figure 7 - Reprocessing demands for spent thorium and PWR fuels

Due to the presence of some strong gamma emitters in the spent fuel and the novelty of the technology, it is likely that thorium reprocessing will be several times more expensive than conventional uranium-based fuel reprocessing (e.g., the PUREX process). For a typical MOX reprocessing plant that can reprocess 120 tHM/y, the capital cost is approximately $2.5B (US) [8]. This suggests that a practical implementation of the fuel cycle may have to compromise uranium utilisation with reprocessing costs.

4. Sensitivity

The base case, as outlined in Table 1, was tested for sensitivity to the following changes and the results are summarized in Figure 8 and Table 3:

- Parasitic absorption increased to 35 mk from 30 mk
- Reprocessing losses doubled to 1%
- Reactor power at 18, 22, and 32 W/g
- The lattice pitch changed to 26cm and 30cm
- The ^{239}Pu and ^{241}Pu concentrations in spent PWR fuel varied by ± 10%

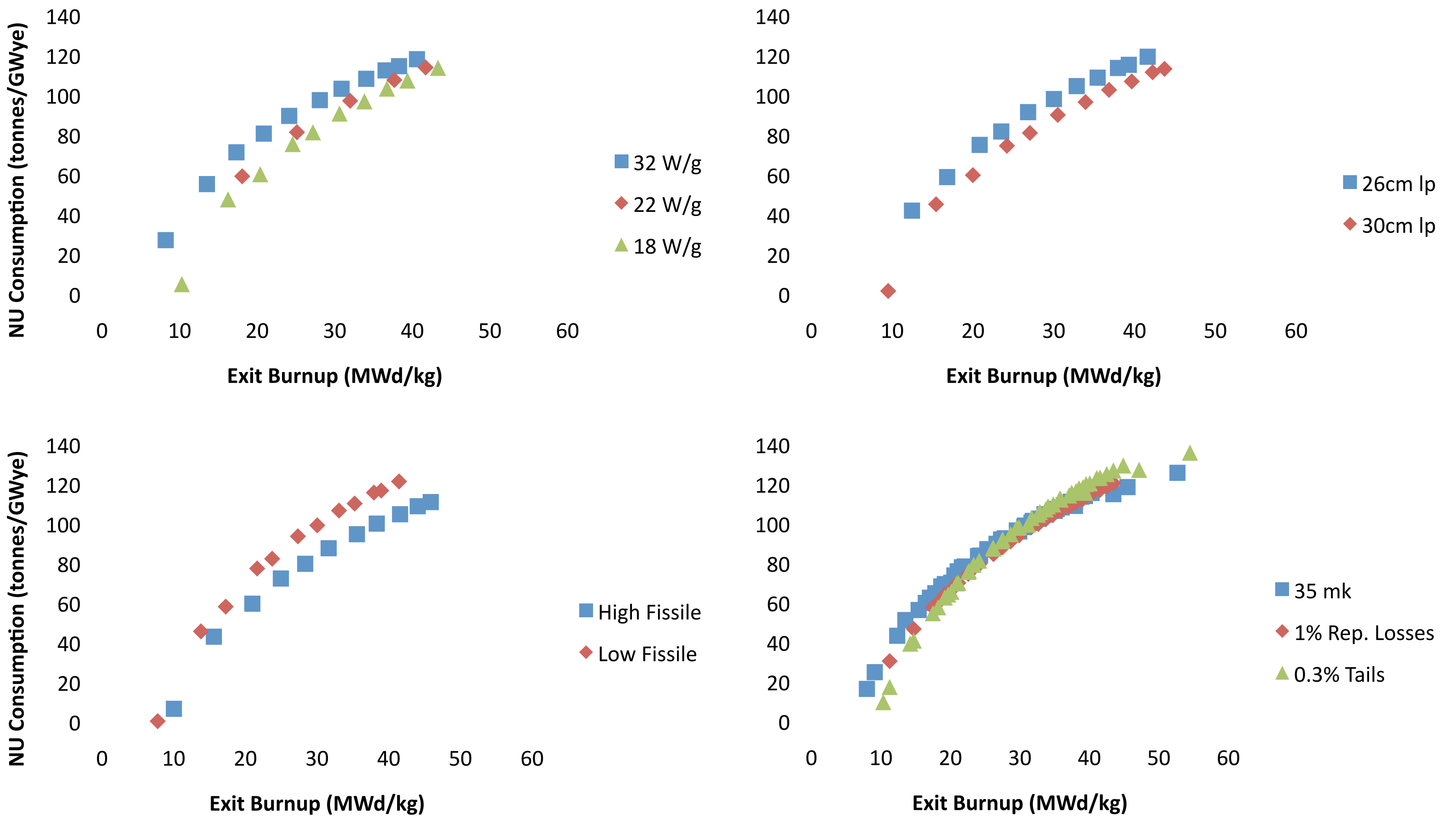

Figure 8 – Sensitivity analysis of NU consumption. The black line shows the base case. High/low fissile refers to an increase/decrease in the concentration of ^{239}Pu and ^{241}Pu in spent PWR fuel

Parameter changed	Change in NU Consumption at Exit Burnup	
	20 MWd/kg	40 MWd/kg
Increase in parasitic absorption from 30 mk to 35 mk	23.22%	4.89%
Reprocessing losses doubled to 1%	14.78%	4.58%
Reactor power decreased from 20 W/g to 18 W/g	-0.11%	-0.90%
Reactor power increased from 20 W/g to 22 W/g	14.69%	1.89%
Reactor power increased from 20 W/g to 32 W/g	34.89%	5.57%
Lattice pitch decreased to 26 cm	23.21%	6.48%
Lattice pitch increased to 30 cm	-0.49%	-3.95%
Fissile Pu increased by 10%	-5.08%	-5.04%
Fissile Pu decreased by 10%	20.17%	7.42%
Tails enrichment increased from 0.5% to 1%	10.87%	10.72%

Table 3 – The effect on overall NU consumption of changes to various reactor characteristics for two different exit burnups.

Natural uranium CANDU reactors operate with 35 mk of parasitic absorption. However, a thorium fuelled CANDU reactor can likely operate with removed control rods and, therefore, would have less parasitic absorption. The sensitivity study shows that, at an exit burnup of 20 MWd/kg, increasing the parasitic absorption by 5 mk increases the natural uranium consumption by as much as 23%. The increase in power corresponds to an increase in neutron flux, which will increase the parasitic absorption on Pa-233, thus increasing the fissile requirements. This highlights the need for a reactor with a good neutron economy.

As mentioned earlier, the power density of the base case is significantly lower than that of a current generation CANDU reactor. The sensitivity study shows that, while it may result in significantly higher uranium consumption, more realistic power densities are plausible.

Decreasing the lattice pitch is a common means for suppressing the coolant void reactivity (CVR). For a lattice pitch of 26 cm, the uranium consumption increases by approximately 23% at an exit burnup of 20 MWd/kg and 6% at an exit burnup of 40 MWd/kg, due to the hardening of the neutron spectrum. The effect of decreasing the lattice pitch has on CVR must be investigated in order to justify the added uranium consumption.

The isotopic composition of spent PWR fuel varies between reactors so it is important to quantify the effect of varying isotopics. For an exit burnup of 40 MWd/kg, the uranium consumption increases by 7% for a 10% decrease in the fissile concentration in the plutonium. For an exit burnup of 20 MWd/kg, the uranium consumption increases by 20%.

Reprocessing losses are speculative as commercial scale thorium reprocessing plants are yet to be developed. Current uranium reprocessing plants have reprocessing losses between 0.5% and 1%. Tails enrichment can be chosen to balance reprocessing costs and resource consumption. Doubling the tails enrichment increases the natural uranium consumption by approximately 10%.

5. Conclusions

The thorium fuel cycle presents the opportunity to reduce the demand for uranium by as much as 75%. In both Canada and abroad this can have large consequences financially and environmentally. Therefore, PWR-derived plutonium should be further investigated as a potential driver fuel for the CANDU thorium reactors. In the future, this study will continue to investigate the potential viability of thorium fuel cycles, including; CVR calculations, a comparison to other potential driver fuels, an analysis of the characteristics of the spent thorium fuel, and fuel cycle optimizations with remove the requirement for equal burnup in the two reactor options.

6. References

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