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Future Nuclear Power Generation in Canada: Transition to Thorium Fuelled SCWRs

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Abstract

The Canadian supercritical water cooled reactor (SCWR) is a heavy water moderated reactor concept, with supercritical light water coolant. A case in which the plutonium in used nuclear fuel from heavy water reactors (HWR) is mixed with thorium to fuel SCWRs has been analysed within the context of meeting future electricity demands in Canada. This case has been compared to a reference case in which all nuclear power is generated by uranium fuelled HWR in a once through fuel cycle. Fuel cycle simulations indicate that such a deployment of SCWRs would reduce uranium consumption and high level waste generation by 20%.

Keywords: Advanced fuel cycle, Scenario Analysis, Simulation.

1. Introduction

Advanced fuel cycles (e.g., based on thoria and/or recycled fuel) offer many potential benefits over conventional fuel cycles, including greater sustainability, and improved waste management characteristics. In this paper the deployment of thorium fuelled super-critical water reactors (SCWR) to meet future energy demands in Canada up to the year 2200 is investigated.

The possibility of reprocessing heavy water reactor (HWR) used nuclear fuel (UNF) in Canada has been acknowledged by the Nuclear Waste Management Organization (NWMO), which has recommended that an adaptive phased management approach be used to manage Canada's UNF such that it would be accessible for a period of time to allow the used fuel to be reprocessed if so desired [1].

In this report, two scenarios are compared: a reference scenario in which all nuclear power is generated by natural uranium (NU) fuelled heavy water reactors (HWR) in a once through fuel cycle, and a transition scenario in which the plutonium in UNF from NU fuelled HWRs is mixed with thorium to fuel SCWRs.

The supercritical water reactor is a heavy water moderated advanced reactor concept, with supercritical light water coolant. The main advantages of the SCWR over current reactor technologies are its enhanced safety and improved thermal efficiency [2]. The SCWR uses thorium based fuel, which should improve fuel cycle sustainability, as thorium is about three times more abundant in the earth's crust than uranium. Thorium is not fissile by itself and requires a driver fuel, for example, the fissile nuclide ^{239}Pu, which is produced during irradiation of uranium fuel and can be recycled from reprocessed UNF. Neutron capture by ^{232}Th leads to the production (via a series of decays) of ^{233}U, which is fissile. The reference Canadian SCWR concept uses reactor grade plutonium recovered from used light water reactor fuel. However, there is currently a significant amount of UNF from NU fuelled HWRs in Canada, the plutonium from which can be used to fuel the SCWRs.

In this study, a transition from a once-through, NU fuel cycle with HWRs to a mixed thorium/plutonium fuel cycle with the SCWR is studied, and various fuel cycle evaluation criteria such as uranium utilization and used fuel characteristics are examined. There are few fuel cycle systems studies in the open literature involving the reprocessing of UNF from NU fuelled HWRs. This is because of the relatively small proportion of fissile nuclides in the UNF, which renders such fuel cycles much less economical than those involving UNF from LEU fuelled light water reactors (i.e., more HWR UNF would need to be reprocessed to obtain the required amount of plutonium than with LWR UNF). In the Canadian context, however, the only domestic UNF that is available in large quantities is from NU fuelled HWRs. The reprocessing of UNF from NU fuelled HWRs may become economically competitive with the once-through fuel cycle if the savings in NU costs are larger than the added cost of reprocessing UNF.

This study proceeds by determining the fresh and used fuel compositions, fuel residence time in the reactor, and fuel burnup for each fuel type resulting from reactor physics calculations. These data are then used in a fuel cycle simulation to compute various fuel cycle evaluation criteria such as natural uranium consumed, and characteristics of UNF and high level waste (HLW) such as gamma and neutron emissions, and decay power.

2. Scenario description and inputs

This section presents a description of the scenario and the fuel cycle cases that were analysed.

2.1 Scenario parameters

There are a number of parameters that are needed to simulate the fuel cycle scenarios. These include:

- Reactor characteristics: thermal power, thermal efficiency, and capacity factor.
- The mass and age of legacy UNF in storage at the beginning of the scenario.
- The number of operating reactors at the beginning of the scenario, and their expected year of retirement.
- Expected total generating capacity of the fleet of reactors for each year of the scenario.
- The earliest year in which SCWRs can begin operation.
- The characteristics of each reactor type.
- The reprocessing capacity during each year of the scenario.

Each parameter is given a reference value that corresponds to the best estimate currently available. Each parameter is also given a lower and upper value, which will be used in a sensitivity analysis. The reference, lower, and upper value of each parameter are given in Table 1. Each parameter is described in the following paragraphs.

Table 1
The reference, low and high values of the scenario parameters.

Parameter	Low	Reference	High
HWR thermal efficiency (%)	30	33	34
SCWR thermal efficiency (%)	44	47	50
Number of operating HWR: 2010-2025	15	17	19
Legacy HWR retirement start year	2025	2030	2035
Legacy HWR retirement period (years)	5	10	15
Growth in Nuclear generating capacity after 2025	No growth	Moderate Growth	High Growth (Moderate Growth % * 1.1)
Earliest year of operation for SCWRs	2040	2050	2060
HWR Reactor Lifetime (years)	25	30	45
SCWR Lifetime (years)	30	45	60
Average age of HWR legacy UNF in 2010 (years)	10	15	20

The reference electrical power and thermal efficiency of a HWR is 0.66 GWe and 33%, respectively, for a thermal power of 2 GWth [3]. To avoid additional reactor physics calculations, the lower and upper values of electrical power and thermal efficiency are chosen such that the thermal power of a reactor remains the same as the reference case. For HWRs, the lower and upper bound of the thermal efficiency is 30% and 34%, respectively. This results in lower and upper values of 0.6 GWe and 0.68 GWe, respectively, for the electric power of a HWR. The reference electrical power and thermal efficiency of a SCWR is 1.2 GWe and 47%, respectively, for a thermal power of 2.55 GWth. The lower and upper value of the thermal efficiency is 44% and 50%, respectively. This results in the lower and upper value of 1.1 GWe and 1.3 GWe, respectively, for electrical power. The capacity factor of HWRs and SCWRs is 85% [3].

There were 17 reactors that were operating in Canada in 2010 and 2011, and 19 in 2012 to 2014. Many of these reactors will be refurbished between 2015 and 2030, and some will be retired in 2020 [4]. The exact years in which reactors will be shut down for refurbishment or retirement are uncertain, therefore it is assumed that there will be an equivalent of 17 operating legacy reactors between 2010 and 2030, after which they will be retired at a linear rate over a 10 year period.

With no new reactors expected to be built prior to 2025, it is assumed that the generating capacity of the fleet will not increase between 2010 and 2025 [4]. After 2025, it is assumed that the generating capacity of the fleet will increase according to the rates for the “OECD90” region defined in [5].

Since the Canadian SCWR is in the concept phase of development, the earliest year that an SCWR can begin operation is highly uncertain. In this study it is assumed that SCWRs can begin operation no earlier than 2050.

The initial inventory of UNF from HWRs is calculated using the energy produced for each year for each reactor unit in Canada from [6], assuming a burnup of 7.5 $MW_{th}d/kg$ and 33% efficiency. According to this calculation there was approximately 38 kt of UNF from HWRs in storage at the beginning of 2010, the average age of which is 15 years. This amount compares reasonably well with the value arrived at by the NWMO of 44 kt [7].

2.2 Reactors and fuels

2.2.1 Natural uranium fuelled HWRs

The fuel bundle design for the currently operating NU fuelled HWRs is assumed to be the standard 37-element design. Since significant work has already been done with this design, lattice calculations were not performed for this fuel type. Instead, data on irradiated fuel compositions have been taken from [8]. The burnup of NU fuelled HWRs is 7.5 $MW_{th}d/kg$, and the fuel residence time in the reactor is 0.8 years.

2.2.2 Thorium fuelled SCWRs

The SCWR fuel is composed of 11% Pu from HWR UNF, which is shown in Table 2, with a burnup of 53.6 $MW_{th}d/kg$ and residence time of 3.2 years. The SCWR model and fuel depletion calculations are described in [9].

Table 2
The composition of plutonium in HWR UNF [7].

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
0.09%	69.25%	24.92%	4.72%	1.02%

2.3 Nuclear fuel cycle cases

Two fuel cycle cases were analysed to compare their fuel consumption, and used fuel.

- NU case: 100% of nuclear power is generated by NU fuelled HWRs for the duration of the scenario. All spent fuel is sent to wet storage for five years, after which it is placed in long-term storage for the remainder of the scenario.
- NU → Pu+Th: 100% of nuclear power is generated by NU fuelled HWRs until the earliest year of operation for SCWRs. After this year, Pu+Th fuelled SCWRs will be built if there is sufficient separated plutonium available to fuel them. If there is insufficient separated plutonium available then NU fuelled HWRs will be built instead. The HWR UNF is sent to wet storage for five years after which it is reprocessed if there is sufficient capacity to do so, otherwise it will be placed in dry storage until there is capacity available to reprocess it. The

reprocessing of HWR UNF will begin two years before the earliest year of operation of SCWRs so that the Pu+Th fuel can be fabricated on time to begin SCWR operation. This is done to limit the amount of ^{241}Am that would be built up from the post reprocessing decay of ^{241}Pu. The reprocessing capacity for HWR UNF is assumed to be 2300 t/yr, which is sufficient to reprocess all of the HWR UNF in dry storage by the end of the scenario. The SCWR UNF is sent to wet storage for five years, after which it is placed in long term storage for the remainder of the scenario.

2.4 VISION model

The cases described above were implemented using the VISION model version 4. VISION is a dynamic simulation model of the nuclear fuel cycle built on the PowerSim platform [10]. It models the interaction of the various components of the fuel cycle, including fuel fabrication, nuclear power plants, used fuel storage, used fuel reprocessing, and long-term disposal.

3. Fuel Cycle Simulations

The cases described in the previous section were simulated in VISION to compare their fuel consumption and UNF characteristics.

3.1 Reference NU → Pu+Th case

In this section the NU → Pu+Th case is compared to the NU case with all of the parameters in Table 1 set to their reference values.

3.1.1 Reactor fleet

The cases that were simulated are represented graphically by plotting the power generated from each reactor/fuel type over time, as are shown in Figures 1 and 2. In the "NU → Pu+Th" scenario (Figure 2), approximately 20% of the total electricity was generated from Pu+Th fuelled SCWRs over the entire scenario. Note that the first SCWR does not come online until the year 2061 despite the fact that SCWRs can begin operating as early as 2050. This is because no new reactors are required between the years 2050 and 2061, either to replace retiring HWRs or to add capacity to meet growing electricity demands.

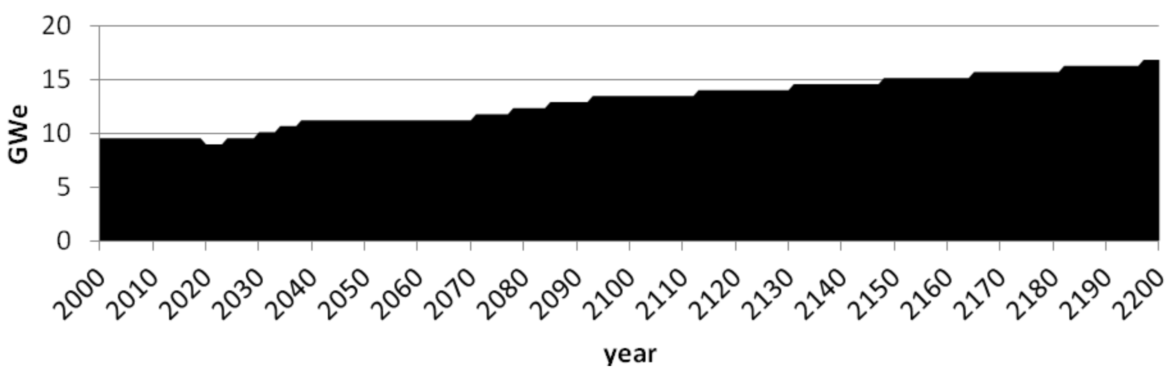


Figure 1 The power generated in the NU case.

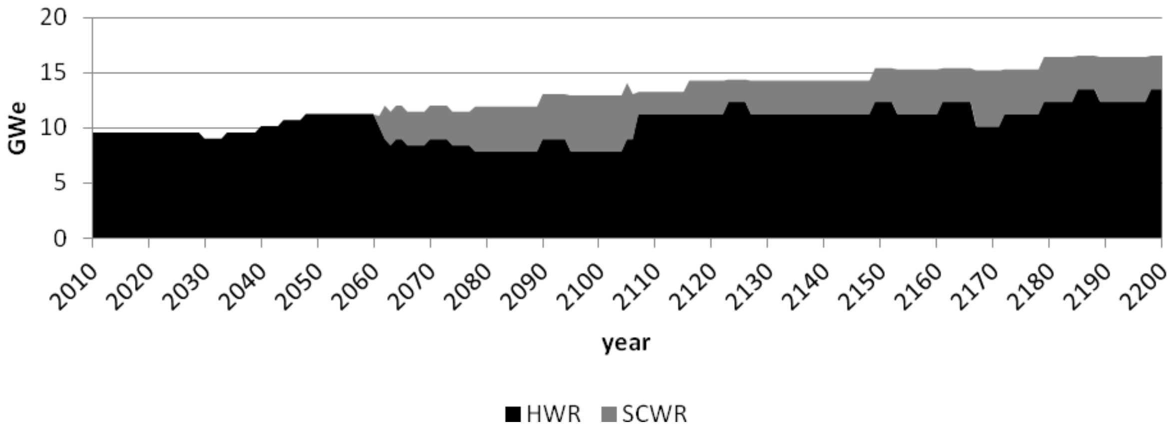


Figure 2 The power generated in the NU → Pu+Th case.

3.1.2 Natural Resource Consumption

The cumulative mass of NU consumed per cumulative electricity produced is shown in Figure 3. This figure shows how the total NU consumed divided by the total energy produced up to each year of the scenario is nearly constant until the beginning of the transition to SCWRs in the year 2060, after which it slopes downward over the first 45 years of SCWR operation before becoming nearly constant again until 2130. The nearly constant values between 2105 and 2130 correspond to the proportion of operating SCWRs decreasing slightly during this period due to the availability of separated plutonium. After 2130 the cumulative NU consumed per electricity produced decreases by a relative small amount by the end of the scenario, a consequence of the increased proportion of HWRs between 2105 and 2130 resulting in an increase in the amount of plutonium in the fuel cycle. By the year 2200, the NU case consumed 3.4 kt (20%) more NU than the "NU →Pu+Th" scenario per TWh electricity generated. In the Pu+Th case, the SCWRs consume 8.1 kt of thorium by the year 2200.

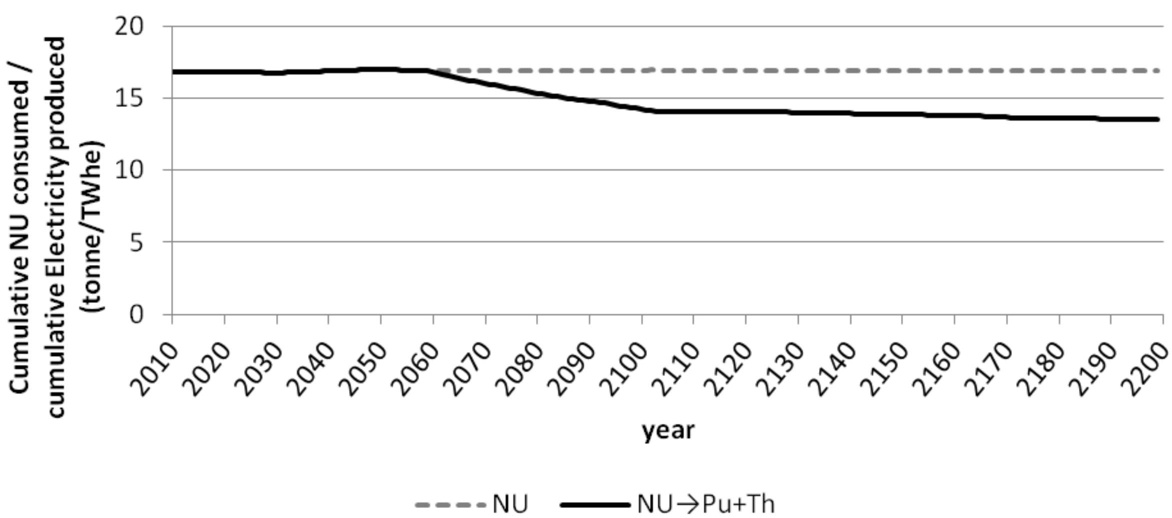


Figure 3 Cumulative mass of NU consumed per unit generated electricity.

3.1.3 Used fuel characteristics

This section compares the UNF and waste products resulting from each scenario. The total mass, gamma and neutron emissions and long-term decay power of UNF and waste produced in each scenario are compared. Gamma and neutron emissions from UNF have implications on water radiolysis in UNF storage, on shielding requirements for UNF and on worker dose (and shielding requirements) for handling, transportation, storage and disposal facilities, and possible reprocessing facilities. Decay power on a mass basis has more impact on handling and storage facilities. Decay power per unit energy impacts the size of the disposal facilities (disposal cost per unit energy).

The mass of HLW per unit electricity produced for each scenario is shown in Figure 4. By the year 2200, the transition to Pu+Th fuelled SCWRs resulted in a 3.1 kt (18.4%) reduction of HLW produced per TWh versus the NU case. Note that the SCWRs end up producing 2.1% of the total HLW by the end of the scenario.

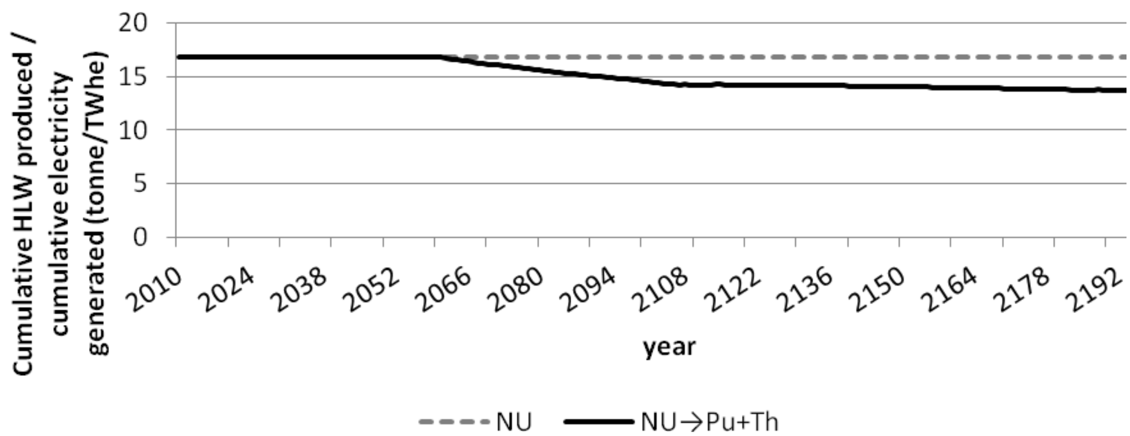


Figure 4 HLW produced per unit generated electricity.

The neutron emissions per kg of UNF of each type of fuel at zero and five years after discharge are shown in Figure 5a. The Pu+Th UNF has higher neutron emissions relative to NU UNF, which is mainly a result of the larger amount of ^{242}Cm and ^{244}Cm isotopes. Both ^{242}Cm and ^{244}Cm are high neutron emitters. The neutron emissions per unit (MWd) of generated electricity, shown in Figure 5b, are also higher for Pu+Th than NU UNF.

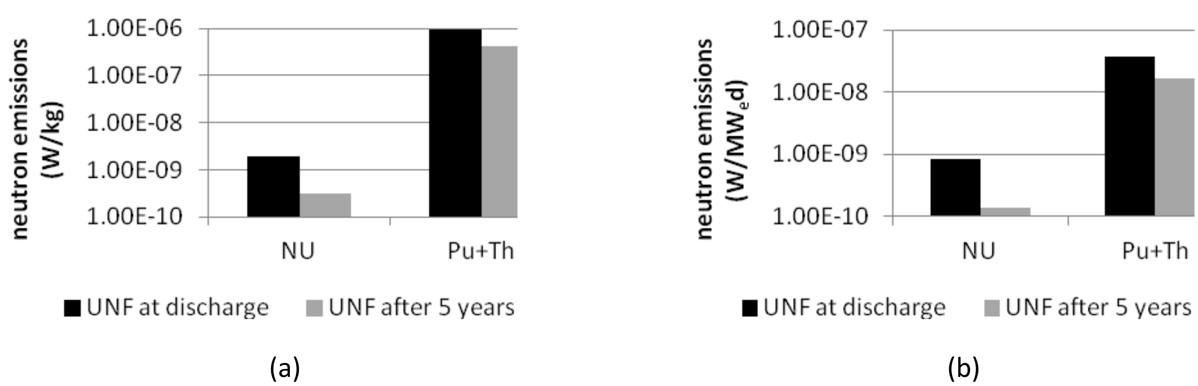
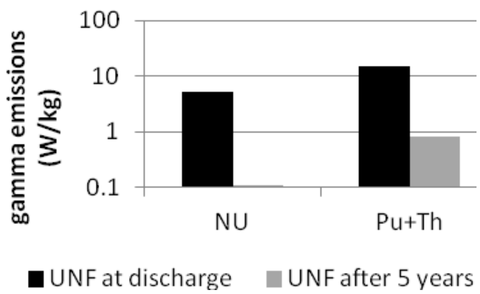
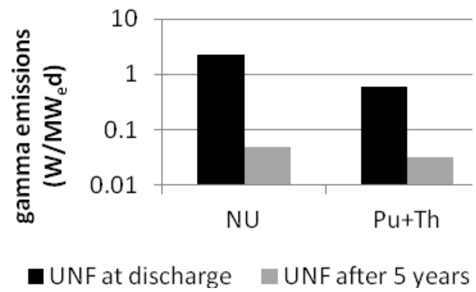


Figure 5 Neutron emissions of UNF per unit (a) mass and (b) generated electricity.

The gamma emissions per mass of and per electricity produced from each type of UNF are shown in Figure 6. After 5 years, the Pu+Th UNF has 620% more gamma emissions per mass than NU UNF. However, the gamma emissions per unit electricity produced for Pu+Th UNF are 34% less than NU UNF after 5 years. The lower gamma emissions of Pu+Th UNF per unit electricity produced are due to the higher burnup of Pu+Th fuel and higher thermal efficiency of the SCWRs.



(a)



(b)

Figure 6 Gamma emissions of UNF per unit (a) mass and (b) generated electricity.

The decay power per unit mass of NU and Pu+Th UNF is shown Figure 7. For the first 50 years after discharge, Pu+Th UNF has over 8 times the decay power per unit mass than NU UNF. This is due to the higher burnup and higher plutonium content of the Pu+Th fuel. The total long-term decay power per TWh of generated electricity of all HLW at the end of the scenario for each case is shown in Figure 8. The Pu+Th case resulted in an increase of between 16% and 37% in the decay power per unit generated electricity of HLW from 0 to 100 years, and a 41% increase at 100,000 years. The higher decay power up to 100 years is mainly due to the larger amount of ^{238}Pu in Pu+Th UNF. The higher decay power at 100,000 years is mainly due to the larger amounts of ^{233}U and ^{234}U in Pu+Th UNF. At 1000 and 10,000 years the decay power per unit generated electricity of HLW in the Pu+Th case is 7% and 40% lower than the NU case, respectively. These lower decay powers per unit generated electricity are mainly due to the higher burnup of Pu+Th fuel and higher thermal efficiency of SCWRs.

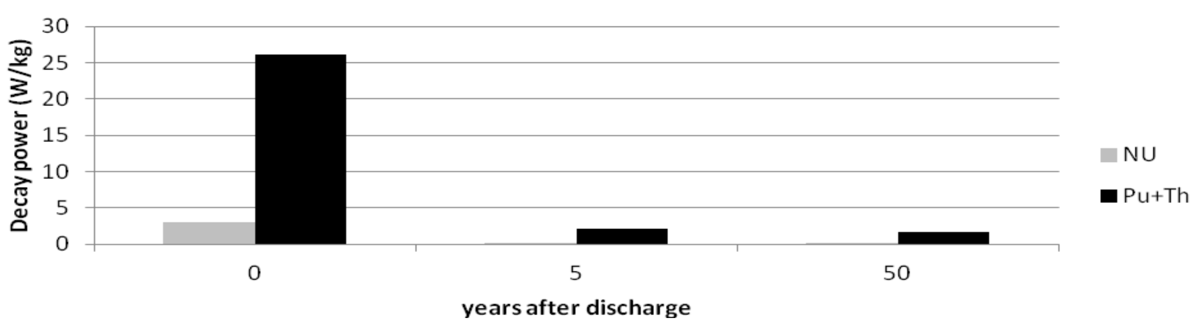


Figure 7 The decay power of NU and Pu+Th UNF per unit mass.

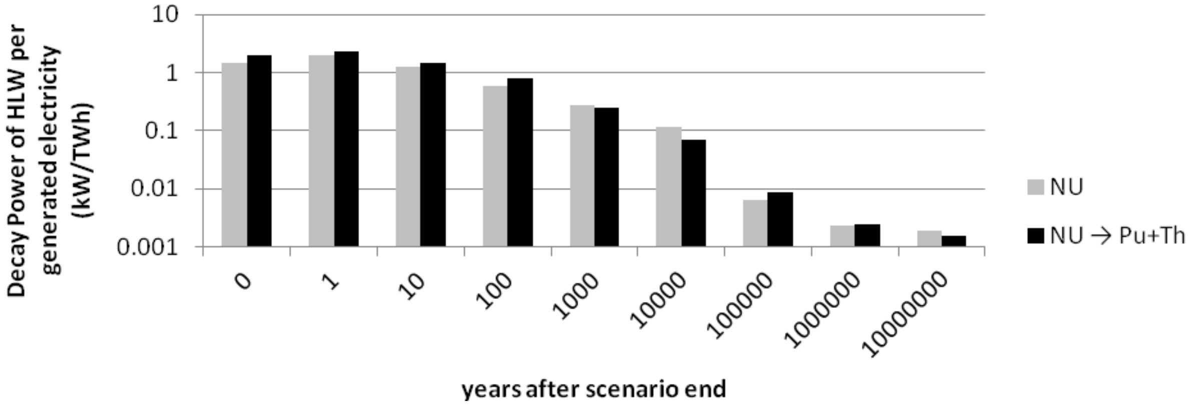


Figure 8 Long-term decay power per unit generated electricity of HLW at the end of the scenario.

The Pu+Th case requires the reprocessing of UNF, thus requiring the addition of reprocessing capacity to the fuel cycle. Figure 9 shows the mass of NU UNF that is sent to reprocessing every year in the Pu+Th case. The amount of UNF reprocessed is a constant 2300 t/year between the years 2048 and 2190, after which the reprocessing rate reaches a new steady value of 1820 t/year until the end of the scenario. This drop in throughput corresponds with the point at which all of the UNF that leaves wet storage goes directly to the reprocessing plant (i.e., there is no longer any NU UNF in dry storage as shown in Figure 10). Put into perspective, the reprocessing plant operated by AREVA at La Hague has a capacity of 1700 t/year [11], which is 600 t/year less than the reprocessing capacity in this scenario.

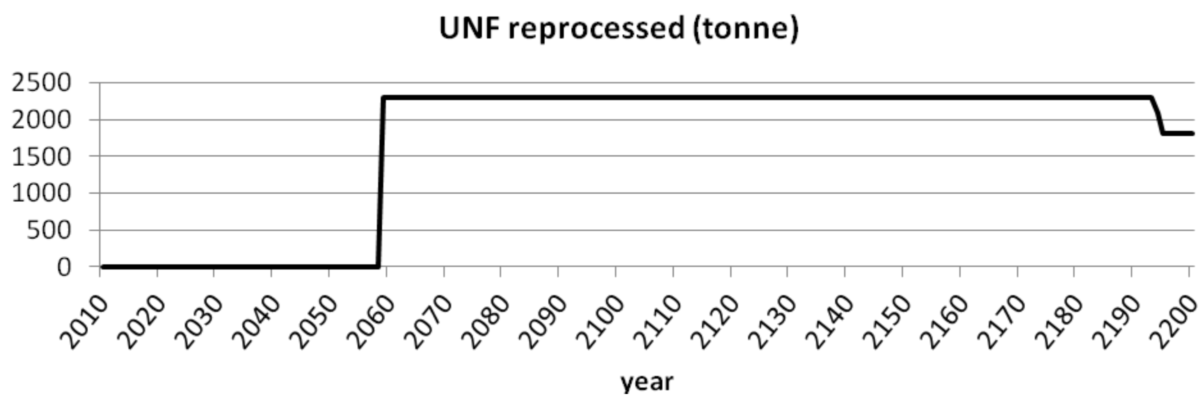


Figure 9 NU UNF reprocessed per year in the NU→Pu+Th case.

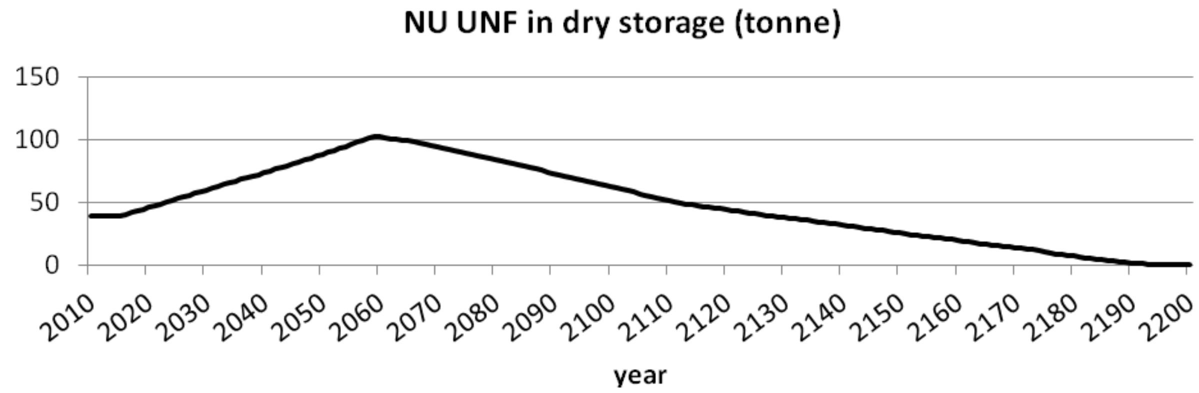


Figure 10 NU UNF in storage that is available for reprocessing in the NU→Pu+Th case.

3.2 Sensitivity analysis of the NU→Pu+Th case

This section presents the sensitivity of NU consumption in the NU→Pu+Th case to changes in the parameters given in Table 1.

The sensitivity of the total NU consumed per unit generated electricity to each parameter is shown in Figure 11. The reference NU consumed per unit generated electricity is indicated by the position of the vertical axis, and its sensitivity to changes in each parameter while keeping all other parameters at their reference values is shown as horizontal bars. The thermal efficiency of HWRs has by far the largest effect on the consumption of NU per unit generated electricity: the lower thermal efficiency increased the uranium consumption by 7.4%, and the higher thermal efficiency decreased the uranium consumption by 5.5%. The parameter with the next largest impact on uranium consumption, the thermal efficiency of SCWRs, affected the uranium consumption by less than 2%.

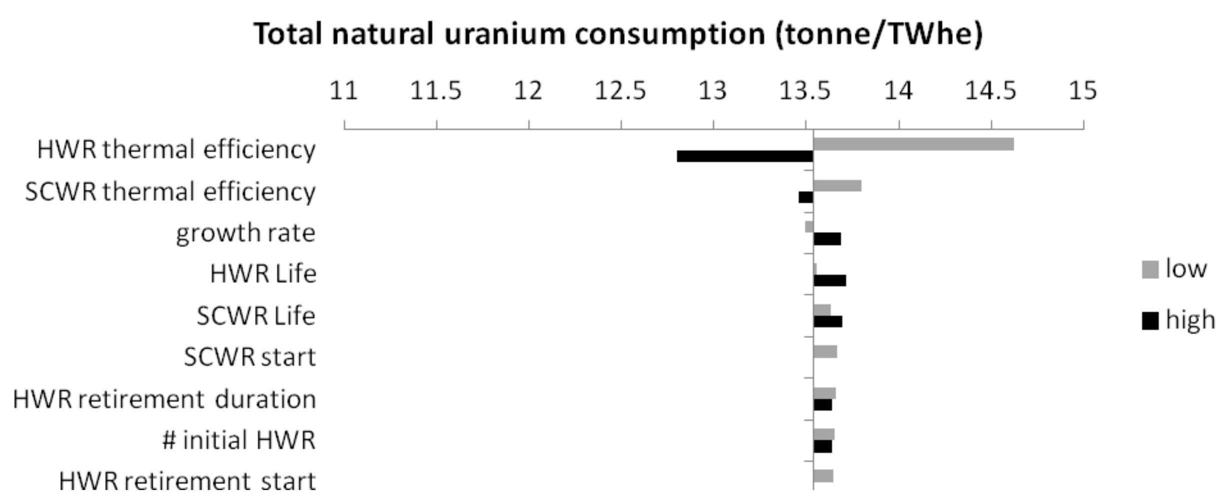


Figure 11 The total NU consumed per unit generated electricity in the "NU → Pu+Th" case, and its sensitivity to changes to each parameter.

4. Summary and Conclusions

A Canadian transition scenario from NU fuelled HWRs to thorium-plutonium fuelled SCWRs was simulated and compared to a reference once through scenario with NU fuelled HWRs. This comparison was with respect to resource consumption and used fuel characteristics. A summary of the results is shown in Figure 12. These results indicate that 20% of the nuclear power in Canada can be generated from Pu+Th fuelled SCWRs, which have the following benefits:

- Decreased NU consumption by 20%.
- Decreased short-term gamma of UNF per unit generated electricity by 34%.
- Decreased HLW produced per unit generated electricity by 20%.
- Decreased decay power per unit generated electricity of HLW for 1000 and 10000 years after discharge by 7% and 40% respectively.

These benefits come with the following disadvantages:

- Increased short-term neutron emissions per unit generated electricity by over 10,000%.
- Increased decay power of HLW between 0 and 100, and 100,000 years after discharge by up to 37% and 41% respectively.

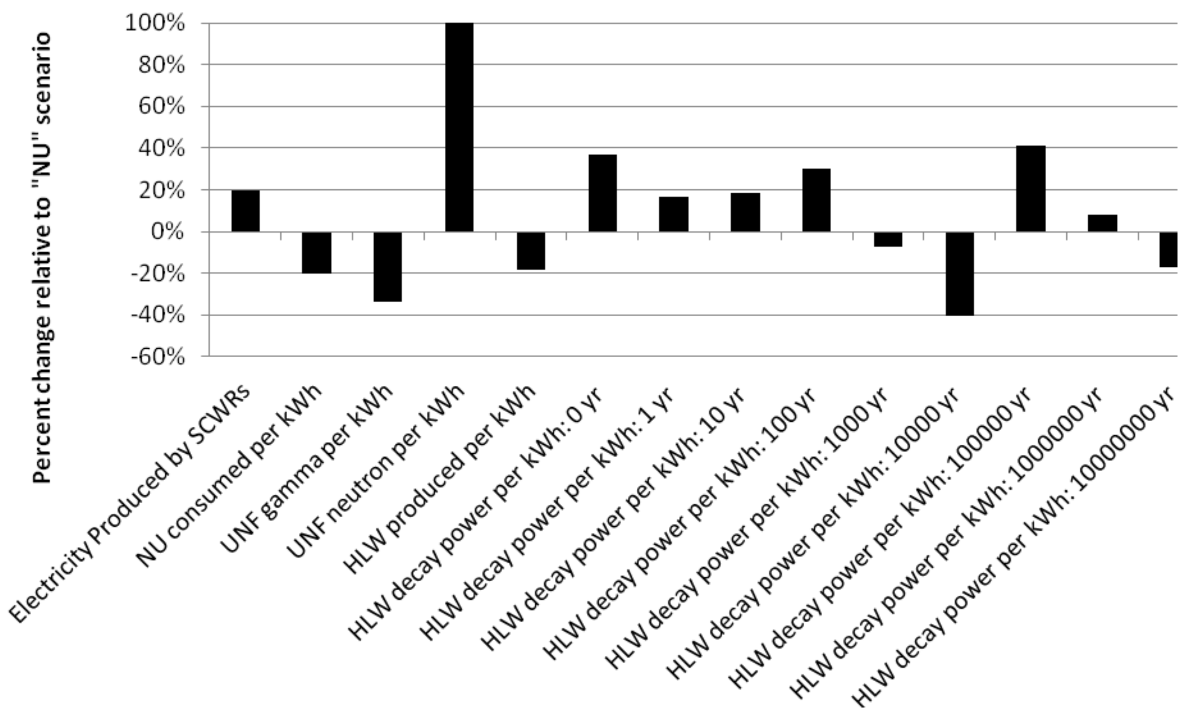


Figure 12 The % change in fuel cycle metrics of the Pu+Th case relative to the NU case.

An analysis was also performed to determine the sensitivity of the transition to Pu+Th fuelled SCWRs to changes in the scenario parameters. This analysis showed that the NU consumption is most sensitive to the thermal efficiency of HWRs. Changing the thermal efficiency of HWRs from the reference value to the lower value resulted in the largest change to the NU consumed per unit generated electricity (8% increase), the second largest change (5.5% decrease) occurred when the thermal efficiency was changed to its upper value. Changes to each of the other parameters under consideration resulted in changes to the fuel cycle metrics of no more than 2%.

It should be noted that other countries with HWRs are actively pursuing the reprocessing of UNF due to the scarcity of indigenous NU reserves. For example, India currently reprocesses UNF from its fleet of HWRs to extract plutonium to fuel fast neutron reactors [12].

5. References

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