FULL ARTICLE

FUEL CYCLE IMPLICATIONS OF DEPLOYING HTGRS IN HYBRID ENERGY SYSTEMS AS RESERVE POWER GENERATION IN ONTARIO

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Nuclear power plants could potentially be deployed in a type of nuclear hybrid energy system (NHES) in which their power is used primarily to drive an industrial process but can be diverted to meet demands for electricity when needed. The purpose of this study is to analyze the effects of deploying NHESs as reserve power for the transmission grid in Ontario on the overall Canadian fuel cycle. In this scenario, the fuel cycle demands of 2 high-temperature gas-cooled reactor (HTGR) concepts are analyzed with respect to costs, resource consumption, and enrichment requirements. One HTGR concept is a 30 MW-thermal (MW$_{th}$) reactor that is based on the UBattery concept, and the other is the Xe-100, which is a 200 MW$_{th}$ reactor. Calculations indicate that such a deployment of HTGRs would have a substantial effect on the fuel cycle in Canada. In particular, NU and enrichment demands would be greatly affected. Beginning this HTGR deployment in the year 2030 would more than double the annual NU demands in Canada, and deplete the uranium resources with extraction costs of <\$80/kgU by the year 2142. The uranium enrichment demands of this fleet would be >35% of the US capacity for uranium enrichment.

Nomenclature

NHES	nuclear hybrid energy system
HTGR	high temperature gas-cooled reactor
NPP	nuclear power plant
NGPP	natural gas-burning power plant
GHG	greenhouse gas
TRISO	tri-structural isotropic
NU	natural uranium
HALEU	high assay low enriched uranium
SWU	separative work unit
DU	depleted uranium
WNA	World Nuclear Association
MW$_{th}$	megawatt thermal unit of power
kgU	kilograms of uranium atoms
gU	grams of uranium atoms
tU	metric tonnes of uranium atoms
MSWU	millions of SWU
wt.%	percent by mass
MWd/kgU	thermal energy produced in megawatt days per kg of uranium consumed
MW$_{th}$y	megawatt year of thermal energy
UF$_6$	uranium hexafluoride
U$_3$O$_8$	triuranium octoxide
UO$_3$	uranium trioxide
^{235}U	a fissile isotope of uranium with 143 neutrons in its nucleus
^{238}U	an isotope of uranium with 146 neutrons in its nucleus
x_t	proportion of ^{235}U in DU tails from uranium enrichment
x_f	proportion of ^{235}U in the uranium feed to the enrichment process
x_p	proportion of ^{235}U in enriched uranium product
R	ratio of NU feed to enriched uranium product
S	SWU required per kg of enriched uranium product
x_t^*	the value of x_t that minimizes the cost of enriched uranium
U_N	the mass (kg) of NU that is consumed to fuel a reactor over its lifetime

P	thermal power capacity of a reactor in MW
N_{fs}	number of fuel spheres in the core of a reactor
B	average exit burnup of reactor fuel (MWd/kgU)
L	operational lifetime of a reactor
M_{fs}	mass of uranium in each fuel sphere (gU)
F_c	mass of uranium in the core of a reactor (kgU)
F_r	monthly mass of uranium refuelling (kgU)
F_L	mass of uranium fuel consumed over the lifetime of a reactor (kgU)
F_E	mass of uranium fuel consumed per unit generated energy (kgU/MW$_{\mathrm{th}}$y)

1. Introduction

Nuclear power plants (NPPs) have been primarily used as a source of baseline power generation on large electricity transmission grids due to economic and technological factors that make it desirable to maximize the power generated over the lifetime of NPPs. Alternatively, NPPs could potentially be deployed in a type of nuclear hybrid energy system (NHES) in which their power is used primarily to drive an industrial process but can be diverted to meet demands for electricity when it is profitable to do so [1]. Thus, it could be economically feasible to deploy NPPs as reserve power generation for a transmission grid. High-temperature gas-cooled reactors (HTGRs) are well-suited for deployment in a NHES due to their high temperature thermal power output, which can be either converted to electricity with high efficiency, or used in industrial processes that require high temperatures. An important consideration for the deployment of NPPs is the long-term sustainability of the nuclear fuel cycle.

In Ontario, natural-gas-burning power plants (NGPPs) provide a large portion of the reserve power generation capacity on the transmission grid, which typically remain idle until needed. The purpose of this study is to analyze the effects on the fuel cycle in Canada of deploying NHESs as reserve power in place of NGPPs for the transmission grid in Ontario. Such a deployment would not only reduce greenhouse gas (GHG) emissions from the generation of electricity, but also provide low GHG emitting sources of power for industrial processes, such as the production of hydrogen [1]. In this scenario, the fuel cycle demands of 2 HTGR concepts are analyzed with respect to costs, and uranium and enrichment demands. One HTGR concept is a 30 MW-thermal (MW$_{\mathrm{th}}$) reactor that is based on the UBattery concept [2]. This reactor is being designed to operate without refuelling for extended periods of time. The other concept that is analyzed is the Xe-100, which is a continuously refuelled, 200 MW$_{\mathrm{th}}$, reactor with a pebble fuel configuration [3]. The purpose of analyzing the fuel demands of these 2 HTGR concepts is to demonstrate how these demands can vary among HTGR concepts with different fuel characteristics.

Table 1. Identified conventional uranium resources in Canada [5].

Recovery cost (US$/kgU)	Mass (tU)
<40	263 500
<80	310 400
<130	514 400
<260	846 400

2. HTGR Fuel Cycle

Both HTGR concepts analyzed in this study are fuelled with high assay low enriched uranium (HALEU) in the form of tri-structural isotropic (TRISO) particles [4]. As such, the HTGR fuel cycle in this study includes natural uranium (NU) mining and milling, NU conversion, uranium enrichment, and fuel fabrication.

2.1. Natural uranium

With respect to deploying HTGRs, an important consideration is how this deployment would be constrained by uranium resources and production in Canada. There are nearly 850 000 tonnes (tU) of conventional uranium resources that have been identified in Canada as of 2018 [5]. The mass and recovery costs of these resources are shown in Table 1. In 2018, active uranium production capacity in Canada was 6922 tU/year. At that time, there was also 11 924 tU/year of production capacity that was idled due to low NU prices [6, 7].

2.2. Conversion

Uranium enrichment requires feed uranium in the form of uranium hexafluoride (UF$_6$). In Canada, uranium conversion takes place in 2 stages [6]. The first stage converts triuranium octoxide (U$_3$O$_8$) to uranium trioxide (UO$_3$) at a refinery with 24 000 tU/year capacity. The second stage converts UO$_3$ to UF$_6$ at a facility with capacity of 12 500 tU/year.

2.3. Uranium enrichment

HALEU is uranium that has been enriched to between 5 and 20 wt.% ^{235}U [8]. The deployment of HTGRs in Canada, therefore, would require reliance on uranium enrichment, a component of the fuel cycle that is unnecessary for the NU fuelled heavy-water moderated reactors currently operating in Canada. Since there are no enrichment plants in Canada at this time, the deployment of HTGRs would require the import of HALEU or the construction of an enrichment plant in Canada. Also, there is currently no large-scale commercial production of HALEU anywhere in the world, and commercial production of HALEU in the United States is expected to begin in the year 2022 [8].

Uranium enrichment involves the separation of ^{235}U from ^{238}U. The most advanced, commercially available uranium enrichment technology is gaseous centrifugation. An enrichment facility accepts NU in the form of UF_6, and produces enriched uranium product and depleted uranium (DU) tails. The DU tails contain a smaller proportion of ^{235}U than the uranium feed, are typically stored on site, and would likely require conversion to U_3O_8 and disposal in a low-level waste repository [9].

While the NU demand per unit generated energy in a NU fuelled reactor does not vary much during its life, this is not necessarily the case for enriched uranium fuelled reactors. In the latter case the NU demand of a given reactor depends on the uranium enrichment process that was used to produce the fuel, which can vary substantially. In particular, the NU consumption depends on the proportion of ^{235}U in the DU tails (x_t), a parameter that is set by the enrichment plant operator. Higher values of x_t correspond to higher NU demands and lower amounts of separative work units (SWUs) required per unit mass of enriched uranium produced. The choice of x_t depends on many factors, including the cost of NU and SWUs, and available SWU capacity.

2.4. TRISO fuel fabrication

TRISO fuel is designed to withstand high temperatures and long irradiation times while not releasing significant amounts of fission products. Unlike fuel for conventional water-cooled reactors, which is in the form of ceramic rods, TRISO fuel is in the form of small (<1 mm) particles. Two common forms of TRISO fuel assemblies for HTGRs are spherical pebbles, and cylindrical compacts [9].

There are currently no TRISO fuel fabrication facilities in Canada. In fact, there is no large-scale TRISO fuel fabrication facility currently operating anywhere in the world [9], only small facilities in China (2.1 tU/year) and Japan (0.4 tU/year) [10]. In the United States, a TRISO fuel fabrication facility is operating at an engineering scale, and there are plans to increase its capacity to commercial scale by 2023 [10].

3. Analysis Methodology and Data

The analysis methodology and data used in this study are presented in this section.

3.1. Fuel demands

In this study only once-through fuel cycles with enriched uranium are considered for fuelling the HTGR-UB and Xe-100 reactors, the fuel demands of which are calculated using the methods described in the remainder of this section.

3.1.1. HTGR-UB

HTGR-UB is a HTGR model that was developed at Canadian Nuclear Laboratories for the purpose of evaluating computational tools for Small Modular Reactors. HTGR-UB is based on the UBattery design [2, 11], but with a nominal power of 30 MW_{th} and uranium enriched to 19.75%. The Monte-Carlo neutron transport code Serpent 2.1.26 [12] was used for full core analysis with time-dependent burnup calculations. A continuous energy nuclear data library based on the ENDF/B-VII.0 (Evaluated Nuclear Data File) distribution [13] was used in these calculations.

The descriptions of UBattery lacked the lattice pitch of the burnable poison micro-particles, and the radius of the control rods. Thus, computational experiments were conducted to determine their appropriate values. These experiments indicated that a lattice pitch of 0.035 cm for the burnable poison micro-particles and a radius of 3.5 cm for control rods worked well.

With these parameters, calculations indicate that over 10 years of operation can be achieved while maintaining criticality via a sequence of control rod movements. The HTGR-UB parameters used in this study are taken from the Serpent model, and are shown in Table 2. The thermal-electric efficiency of HTGR-UB used in this study is taken from the UBattery design [2].

The fuel demand per unit generated energy is calculated using Equation (1).

$$F_E = \frac{F_c}{P \times L} = 3.14\ \mathrm{kgU/MW_{th}y} \tag{1}$$

3.1.2. Xe-100

The Xe-100 is a HTGR being developed by X-energy [3], which has applied for prelicensing vendor design review with the Canadian Nuclear Regulatory Commission [14]. The Xe-100 parameter values used in this study are provided by X-energy, and are shown in Table 3.

The approximate mass of uranium in the initial core of each Xe-100 module is calculated using Equation (2), where N_{fs} and M_{fs} are the number of fuel spheres in a core and the mass of uranium in each fuel sphere, respectively.

TABLE 2. HTGR-UB parameters.

Thermal power P (MW)	30
Thermal-electric efficiency (%)	40
Core mass F_c (kgU)	960
Fuel enrichment (wt.%)	19.75
Fuel burnup (MWd/kg)	117.5
Core lifetime L (y)	10.2

TABLE 3. Xe-100 module parameters [4].

Thermal power P (MW)	200
Thermal-electric efficiency (%)	38
Number of fuel spheres N_{fs}	220 000
Fuel enrichment (wt.%)	15.5
Fuel burnup B (MWd/kg)	160
Design life L (y)	60
Uranium mass in each fresh fuel sphere M_{fs} (gU)	7

$$F_c = N_{\mathrm{fs}} \times \frac{M_{\mathrm{fs}}}{1000} = 1540\,\mathrm{kgU} \tag{2}$$

Xe-100 is designed to be refuelled continuously online. In this study the approximate monthly fuel demand is calculated using Equation (3), where P is the thermal power and B is the fuel burnup.

$$F_r = \frac{P \times 365\mathrm{days/year}}{B \times 12\mathrm{months/year}} = 38\mathrm{kgU/month} \tag{3}$$

Given a design lifetime L, the total fuel demand during the lifetime of a module is calculated using Equation (4), assuming that the first reload of fresh fuel occurs 1 month after start-up. The average fuel demand per unit generated energy is calculated using Equation (5).

$$F_L = F_c + (12L - 1)F_r = 28877\,\mathrm{kgU} \tag{4}$$

$$F_E = \frac{F_L}{P \times L} = 2.41\ \mathrm{kgU/MW_{th}y} \tag{5}$$

3.2. Uranium enrichment calculations

The equations that are used in this study for calculating enrichment quantities are taken from Glasstone and Sesonske [15]. The 2 quantities that are important with respect to uranium and SWU demands are the ratio of feed uranium to enriched uranium product (R), and the quantity of SWUs required to produce 1 kg of enriched uranium (S). The values of R and S are calculated using Equations (6–8), which depend on the proportion of ^{235}U in the feed, product, and tails uranium streams.

$$R = \frac{x_p - x_t}{x_f - x_t} \tag{6}$$

$$V(x) = (2x - 1)\ln\left(\frac{x}{1 - x}\right) \tag{7}$$

$$S = V(x_p) - V(x_t) - (V(x_f) - V(x_t))R \tag{8}$$

where x_f is the uranium feed to the enrichment process, x_p is the enriched uranium product, and x_t is the DU tails.

TABLE 4. Fuel costs in 2017 US$ [9].

	Low	Mode	High
Natural uranium ($/kgU)	34	86	296
Conversion ($/kgU)	6.5	13	19
Enrichment ($/SWU)	70	100	120
Fabrication ($/kgU)	3300	10 900	29 400

While the values of x_f and x_p are dictated by the available uranium feed and the reactor fuel demands, respectively, the value of x_t can be set to any positive value that is less than x_f. In an analysis of the economics of fuel cycles, Bunn et al. set the value of x_t to minimize the cost of enriched uranium. The method used by Bunn et al. [16] to calculate x_t^*, the proportion of ^{235}U in depleted uranium tails that minimizes the cost of enriched uranium, is used in this study. The value of x_t^* is calculated using Equations (9) and (10), assuming no uranium losses during conversion and enrichment. C_s, C_u, and C_c are the cost of enrichment ($/SWU), NU ($/kgU), and NU conversion ($/kgU), respectively.

$$\chi = \frac{C_s}{C_u + C_c} \tag{9}$$

$$x_t^* = 10^{-0.1631\log_{10}(\chi)^2 + 0.47055\log_{10}(\chi) - 2.6453} \tag{10}$$

The ratio of feed uranium to enriched uranium product R is also used to calculate the NU consumption (U_N) over the lifetime of a reactor using Equation (11).

$$U_N = R \times F_L \tag{11}$$

3.3. Fuel cycle unit costs

The fuel cycle unit costs used in this study come from the 2017 edition of the Idaho National Laboratory advanced fuel cycle cost basis report [9] and are shown in Table 4. The cost of each fuel cycle stage is given as a most likely value (mode), and a range (low and high), to indicate its uncertainty in the future.

The cost estimates associated with NU, conversion, and enrichment, are based on market conditions since there are many suppliers and consumers of these commodities. The cost estimate of TRISO fuel fabrication, in contrast, is based on estimates of process costs since the associated technology is relatively new with no commercial plants yet in operation.

4. Deployment Scenario

In this NHES deployment scenario, the target installed power of the NHES is derived from the total installed capacity of the NGPPs connected to the Ontario transmission grid in 2019, which was 10 277 MW-electric [17]. The deployment of HTGRs begins in the year 2030, and the total duration of the scenario is 120 years. Within this scenario 4 cases are analyzed: a reference case, a high deployment rate case, and a low and a high DU tails enrichment case.

4.1. Reference case

In the reference case, HTGRs are installed at a rate of 600 MW_{th} per year, which is equal to 50 MW_{th} per month. The enrichment plant is configured such that the DU tails enrichment is 0.227%, which corresponds to the optimal value for the mode fuel cycle costs in Table 4.

4.2. High deployment rate case

To assess the impact of a higher deployment rate on fuel cycle demands, a case is analyzed in which HTGRs are installed at a rate of 1200 MW_{th} per year.

4.3. Low and high DU enrichment cases

With uranium enrichment, the fuel cycle demands are sensitive to changes in fuel cycle unit costs, such as the cost of NU and enrichment, assuming that the enrichment plant is configured to minimize the cost of HALEU. Therefore 2 cases are analyzed with different tails enrichment. In one case the DU tails enrichment is 0.095%, which corresponds to the high NU, high conversion, and low enrichment costs from Table 4. In the other case, it is 0.347% which corresponds to the low NU, low conversion, and high enrichment costs from Table 4. These 2 cases represent the upper and lower bounds on NU and enrichment demands.

5. Results

The data and equations described in Section 3 are used to calculate the fuel cycle demands, fuel costs, and the impact of deploying HTGRs as reserve power in Ontario. The results of these calculations are presented in the remainder of this section.

5.1. Fuel cycle demands

HTGR-UB and Xe-100 require 3.1 $\text{kgU/MW}_{\text{th}}\text{y}$ and 2.4 $\text{kgU/MW}_{\text{th}}\text{y}$ of fuel, respectively. The NU and enrichment demands depend on the chosen DU tails enrichment. Setting the DU tails enrichment to its optimum value according to Equation (10) results in the NU demands shown in Figure 1 and the enrichment demands shown in Figure 2. The lower value of DU tails enrichment is calculated using the high NU, high conversion, and low enrichment costs from Table 4. The middle value of DU tails corresponds to the mode costs and the higher value to the low NU, low conversion, and high enrichment costs. These figures show the trade-off between NU and enrichment demands, where a lower DU tails enrichment reduces NU and increases enrichment demands.

The higher fuel, NU, and SWU demands of HTGR-UB fuel are due to its full core refuelling scheme, which results in lower average burnup and higher fuel enrichment required for long core lifetime.

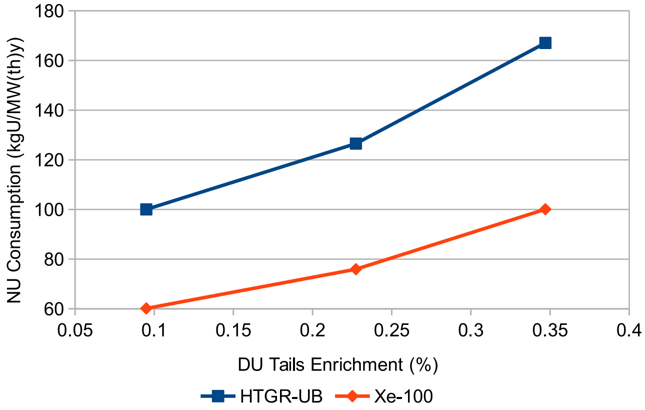

FIGURE 1. NU consumption versus DU tails enrichment.

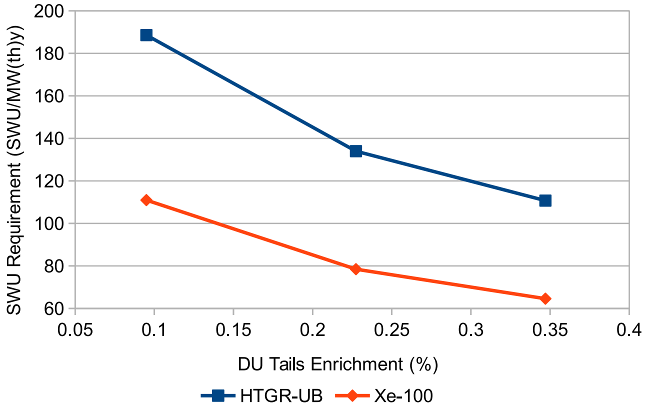

FIGURE 2. Enrichment demands versus DU tails enrichment.

5.2. Fuel cycle costs

The total cost of fuel is \$60 122/$\text{MW}_{\text{th}}\text{y}$ and \$41 592/$\text{MW}_{\text{th}}\text{y}$ for HTGR-UB and Xe-100, respectively. These costs are based on the assumptions that the fuel cycle unit costs are equal to the mode fuel cycle costs given in Table 4, the optimal tails enrichment is used, and that the fuel fabrication cost is the same for both concepts. A breakdown of the fuel cost (Figure 3) shows that fuel fabrication comprises a large portion of the total fuel cost, which is due to the very high unit fabrication costs relative to the other cost components. Figure 3 also shows the range of fuel costs for each HTGR concept based on the low and high unit costs given in Table 4. For HTGR-UB, the fuel cost is between \$24 642/$\text{MW}_{\text{th}}\text{y}$ and \$145 739/$\text{MW}_{\text{th}}\text{y}$. For Xe-100, the fuel cost is between \$16 380/$\text{MW}_{\text{th}}\text{y}$ and \$102 632/$\text{MW}_{\text{th}}\text{y}$.

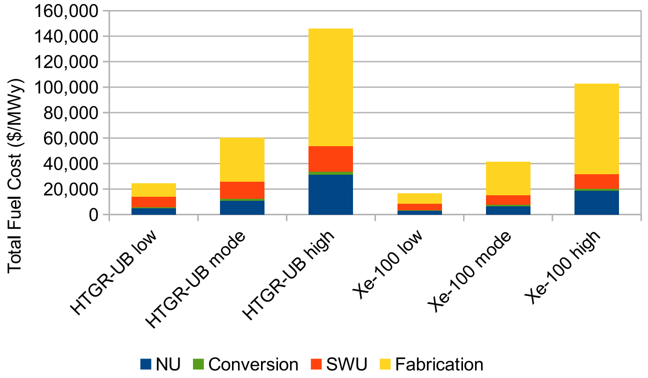

FIGURE 3. Fuel cost breakdown.

5.3. Deployment as Ontario reserve power scenario

The deployment of the NHES as reserve power in Ontario as described in Section 4 results in the annual installed power shown in Figure 4. The target installed power for HTGR-UB (40% thermal-electric efficiency) and Xe-100 (38% thermal-electric efficiency) is 25 693 MW_{th} and 27 045 MW_{th}, respectively. In the HTGR-UB_Ref and Xe-100_Ref cases the fleet reaches the target installed power in the years 2073 and 2075, respectively.

The reference HTGR-UB deployment case begins with the fuelling of 20 cores per year (Figure 5), which require a total of 19.2 tU of fuel per year (Figure 6). This fuel demand persists until year 2041, when there are 17 cores that require refuelling after 10.2 years of operation, in addition to the 20 newly installed cores. The number of refuelled cores then goes up to 20, for a total of 40 cores that require fuelling for the next 9 years. HTGR-UB deployment continues step-wise in this way until the target installed power is reached. Once fully deployed, the fleet of 857 HTGR-UBs requires 80.6 tU of fuel per year on average. The periodic spikes in the number of cores that require refuelling are due to the coincidence between the initial fuelling of new reactors and the refuelling of reactors every 10.2 years during the build up stage of the fleet. Aside from doubling fuel demands during the initial deployment of the fleet, doubling the deployment rate increases the magnitude of the periodic spikes in fuel demand.

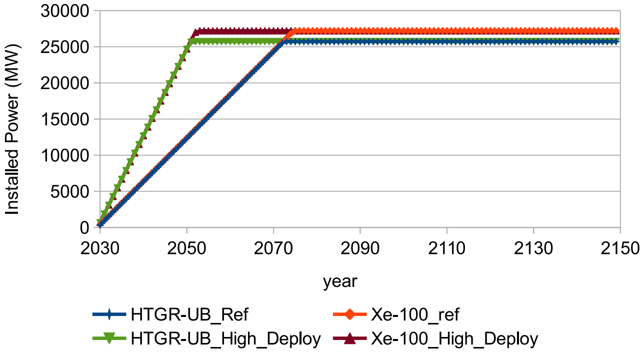

FIGURE 4. Average annual installed power.

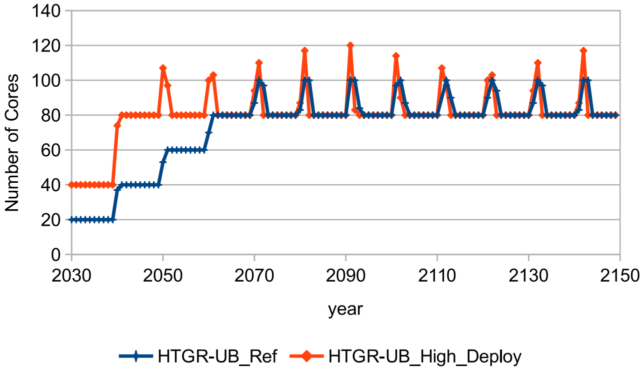

FIGURE 5. Number of HTGR-UB cores to fuel.

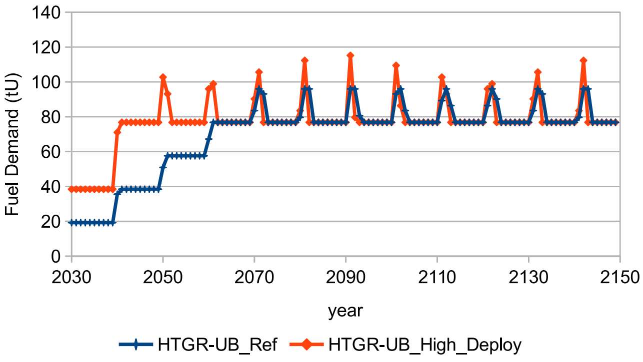

FIGURE 6. HTGR-UB fuel demands.

The deployment of the Xe-100 fleet begins with the fuelling of 3 initial cores per year for 45 years in the reference case, as is shown in Figure 7. As is the case for HTGR-UB, doubling the deployment rate, doubles the number of initial cores to fuel per year and halves the number of years until the fleet is deployed. After the initial full core fuel is loaded into the reactor, each Xe-100 unit requires additional fuel each year until the end of its life, after which a full core fuel load is required for its replacement. Thus, annual fuel demand during the initial deployment of the reference case Xe-100 fleet grows from 5.4 tU/year to a peak of 63.6 tU/year, as is shown in Figure 8, which corresponds with the growth in installed power. Once the fleet is fully deployed, annual fuel demand drops to a steady 62.1 tU/year until the first operating units reach the end of their life, at which time fuel demand temporarily increases to 66.6 tU/year as full core replacement fuel is required. In the case of the higher deployment rate, the duration in which full core replacement fuel is

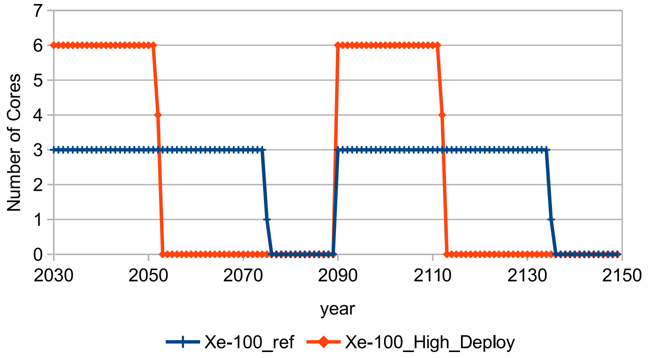

FIGURE 7. Number of Xe-100 initial and replacement cores to fuel annually.

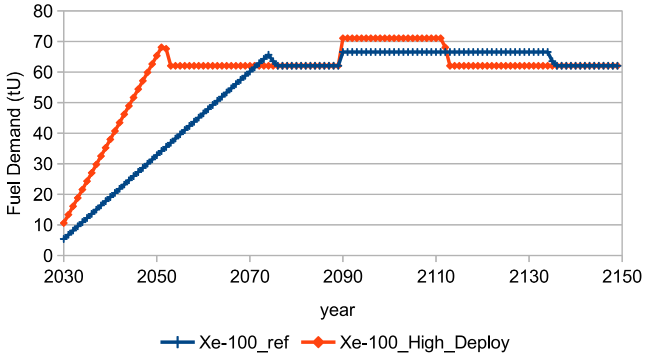

FIGURE 8. Xe-100 annual fuel demands.

required is reduced and the annual fuel demand during full core replacement is 71.1 tU/year.

NU demands follow the same pattern as fuel demands, as is shown in Figures 9 and 10. These figures also show the NU demand for low (HTGR-UB_Low_DU, Xe-100_Low_DU) and high (HTGR-UB_High_DU, Xe-100_High_DU) values of DU tails enrichment, 0.095 wt.% ^{235}U and 0.35 wt.% ^{235}U, respectively. The HTGR-UB fleet demands are more than double the World Nuclear Association (WNA) reference projection in Canada [6], assuming that the demand beyond the year 2040 is equal to the WNA projected demand for the year 2040. Note that the WNA projected NU demand in Canada does not include the potential deployment of HTGRs, thus their demands would be in addition to the WNA projection. With 6922 tU/year of current NU production capacity, and 11 924 tU/year of idled capacity in Canada, it is likely that there will be sufficient NU production to meet the 3700 tU/year demands of the HTGR-UB fleet in the short-term.

Figure 11 shows the cumulative NU consumption due to HTGR-UB NU demands in addition to the WNA projected Canadian NU demands. Also shown are the 2018 identified NU resources in Canada, which are listed in Table 1 [5], and cumulative NU consumption in Canada without HTGR deployment. The identified NU resources are shown as horizontal lines according to their extraction cost. The HTGR-UB deployment would deplete the identified NU resources with extraction costs <$80/kgU by no

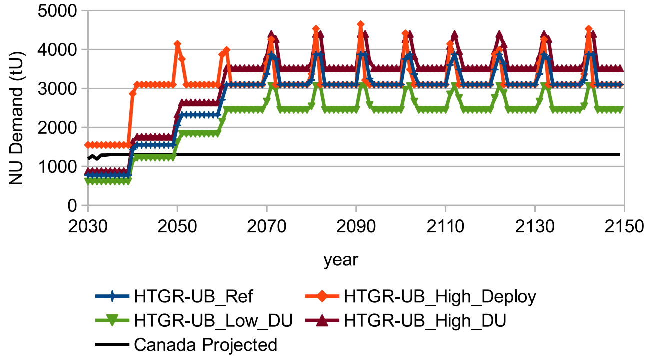

FIGURE 9. HTGR-UB NU demands.

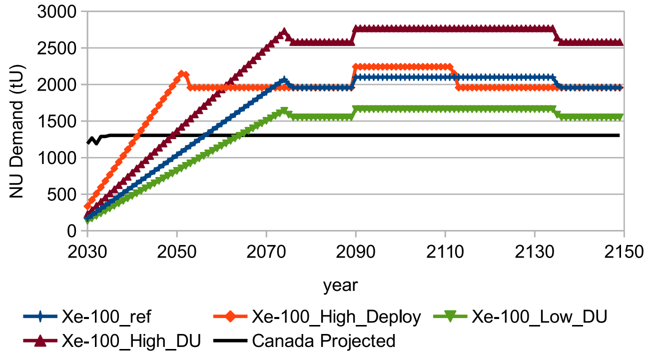

FIGURE 10. Xe-100 annual NU demands.

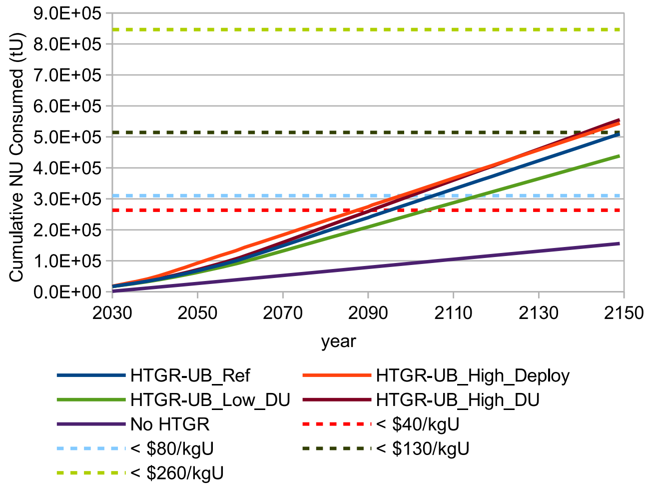

FIGURE 11. Projected cumulative NU consumption in Canada including HTGR-UB fleet.

later than 2120, whereas these resources would last beyond 2250 with no HTGR deployment.

Annual NU demands of the Xe-100 fleet ranges from slightly more than the WNA projected NU demands in Canada in the case of low DU tails enrichment, to double the WNA projected demand in the case of high DU tails enrichment. The cumulative NU consumption in Canada with the Xe-100 fleet (Figure 12) indicates that the identified NU resources with extraction costs <$80/kgU would be depleted by 2142. If over 75% of Canadian NU production continues to be exported [5], then there may not be sufficient identified NU resources in Canada to fuel the HTGR-UB or Xe-100 fleet past the year 2091 and 2108, respectively, unless new resources are identified.

Once fully deployed, the average annual enrichment demands of the HTGR-UB fleet are substantial, 3.1–4.8 MSWU/year, which is 62%–96% of the 2018 enrichment capacity in the US [6], as is shown in Figure 13. The enrichment demands of the Xe-100 fleet are between 35% and 60% the enrichment capacity in the US, as is shown in Figure 14.

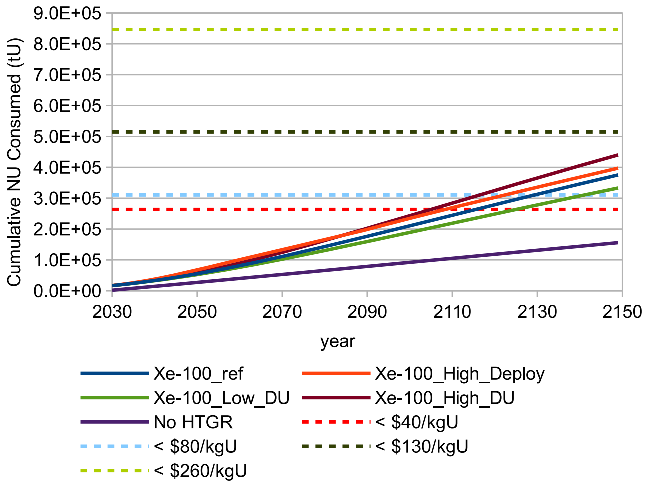

FIGURE 12. Projected cumulative NU consumption in Canada including Xe-100 fleet.

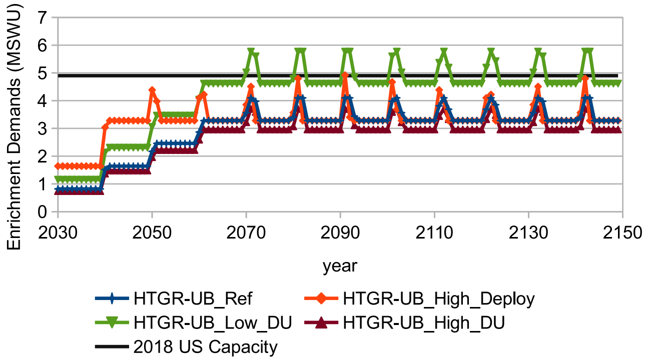

FIGURE 13. Annual enrichment demands of the HTGR-UB fleet.

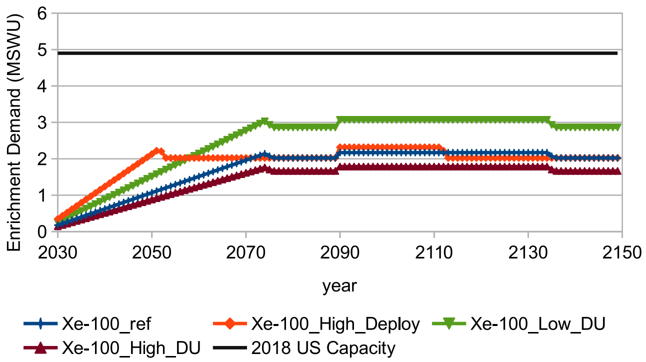

FIGURE 14. Annual enrichment demands of the Xe-100 fleet.

6. Conclusions

In this study, the fuel cycle of HTGRs was analyzed in the context of their deployment in a NHES as reserve power on the transmission grid in Ontario beginning in the year 2030. Two HTGR concepts were considered in this study: a 30 MW_{th} HTGR similar to the UBattery concept, and the 200 MW_{th} Xe-100 HTGR from X-energy. Calculations indicate that such a deployment would have a substantial effect on the fuel cycle in Canada. In particular, NU and enrichment demands would be greatly affected.

The deployment of this fleet of HTGRs would more than double the annual NU demands in Canada. Although there are more than sufficient identified uranium resources in Canada to meet these demands beyond the year 2150, the resources with lower extraction costs would likely be depleted by the year 2142 in the case of the Xe-100 fleet. The UBattery-type HTGR fleet would deplete these lower cost resources by the year 2120. These estimates assume that 100% of uranium resources in Canada are extracted for domestic use, whereas over 75% of extracted uranium is currently exported. If export of this proportion of extracted uranium persists, then the deployment of HTGR-UB and Xe-100 fleets would deplete all identified uranium resources in Canada by the years 2091 and 2108, respectively, unless more uranium resources are discovered by then. By this time it may cost less to meet the fuel demands of the HTGR fleet via the recycling of used fuel than to continue using enriched uranium.

The deployment of this fleet of HTGRs would introduce a substantial amount of uranium enrichment into the fuel cycle in Canada. The enrichment demands of this fleet would be a large fraction of the current uranium enrichment capacity in the United States.

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