Some Implications of Recycling CANDU Used Fuel in Fast Reactors

NWMO-TR-2015-11

December 2015

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Nuclear Waste Management Organization

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Document History

Title:	Some Implications of Recycling CANDU Used Fuel in Fast Reactors		
Report Number:	NWMO-TR-2015-11		
Revision:	R000	Date:	December 2015
Nuclear Waste Management Organization			
Authored by:	Mihaela Ion		
Verified by:	Mark Gobien		
Reviewed by:	Mike Garamszeghy, Neale Hunt, Frank Garisto		
Approved by:	Paul Gierszewski		

ABSTRACT

Title: **Some Implications of Recycling CANDU Used Fuel in Fast Reactors**
Report No.: **NWMO-TR-2015-11**
Author(s): Mihaela Ion
Company: Nuclear Waste Management Organization
Date: December 2015

Abstract

This report documents a high-level analysis of an advanced nuclear fuel cycle where the transuranic (TRU) elements from the CANDU used nuclear fuel (i.e., plutonium, neptunium, americium, and curium) are assumed to be burned (transmuted) in a fast reactor. The fast reactor considered in the analysis is based on the advanced burner reactor preliminary design developed at the Argonne National Laboratory, which is based on the 1000 MWth or 380 MWe SuperPRISM (S-PRISM) reactor designed by GE Hitachi Nuclear Energy.

Mass flow calculations are performed to estimate the impact of such a nuclear fuel cycle from a waste management perspective, i.e., in terms of amounts of generated waste, as well as to estimate the time that would be needed to use up all the transuranic elements in the CANDU used fuel. Input data is based on information available in the open literature.

Scenarios consider the deployment of fast reactors only (no further CANDUs) as a method for waste management and for electricity production. Calculations are performed for different core configurations and metal-fuel options with favourable conversion ratios. For a high TRU consumption rate, a very low conversion ratio would be desired in a fast reactor. A reactor with conversion ratios of 0.25, 0.5 or 0.75 is used to estimate the amount of waste resulting from the overall nuclear fuel cycle. The analysis focuses on the transuranic content as an aggregate, and does not specifically focus on the isotopic content.

Assuming that burner fast reactors and advanced reprocessing and fuel fabrication are practical, then the results indicate that the substantive burnup of the TRUs in CANDU used fuel would require roughly similar numbers of new power blocks of PRISM-type fast reactors (one power block is two 380-MWe S-PRISMs) as the original CANDU reactors. In essence, adopting FRs to burn TRUs is as much an electricity production strategy as a waste management strategy.

With respect to waste management, the mass balance presented in this analysis indicates that the reduction in mass of TRUs for disposal would be accompanied by a larger increase in the mass of fission products requiring long-term management. There is comparatively little reduction in the total amount of uranium that needs to be managed. Also, a relatively significant amount of TRU would still be in the FR cores, which would need to be managed at the end of the operating life of the fast reactors.

Note that this analysis provides an overall mass balance perspective, but does not comment on the practicality of these fast reactor related technologies, the deployment of fast reactors, the specific isotopic and reactor physics implications of these fuel cycles, nor the implications of the hazard of the different final waste products.

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1. INTRODUCTION

Research and development studies of advanced nuclear fuel cycles are being pursued through national and international collaborative projects. Once-through and/or closed fuel cycle scenarios are being considered using thermal reactors in combination with fast spectrum reactors (FRs) or accelerator-driven systems with an interest in the economics, waste management, proliferation resistance, and resource use of these cycles. Typically these studies focus on recycling or burning used fuel from the light water reactors (LWRs). Recent assessments of recycling CANDU used fuel in fast reactors have been provided by Lee and Kim (2015) and Ottensmeyer (2013).

This report documents a high-level analysis of an advanced nuclear fuel cycle where transuranic elements (TRUs), that is plutonium and minor actinides, from the CANDU used nuclear fuel are burned (transmuted) in FRs. Mass flow calculations are performed to estimate the impact of such a nuclear fuel cycle from a waste management perspective, i.e., in terms of amounts of generated waste, as well as estimating the time that would be needed to use up all the TRUs present in existing and future CANDU used fuel. The implications on near-term emissions and long-term waste management are not assessed in this report.

2. METHODOLOGY

2.1 KEY ASSUMPTIONS

2.1.1 Nuclear Fuel Cycle

A closed nuclear fuel cycle is considered (see Figure 1), where CANDU used fuel is reprocessed to recover the uranium, plutonium and minor actinides such as neptunium, americium, and curium, which are then used to fabricate the fresh fuel required for starting and operating a fleet of FRs. Once in operation, the FR used fuel is reprocessed and recycled continuously to produce energy.

FRs can be theoretically operated as either “breeders” or “burners”, depending on the conversion ratio (CR)[1]. A “breeder” FR is attractive in that it makes its own fuel once started, i.e., it can convert ordinary uranium into useful fissile fuel. Historically, this has been the focus of many fast reactor programs. In contrast, a “burner” FR requires a continuous external source of fissile material in addition to uranium, and the external fuel could include TRU from used thermal reactor fuel. In this mode, therefore, burner FRs have been proposed for waste management purposes. In a burner FR, some make-up amount will be required to replenish the FR and maintain its operation at equilibrium[2].

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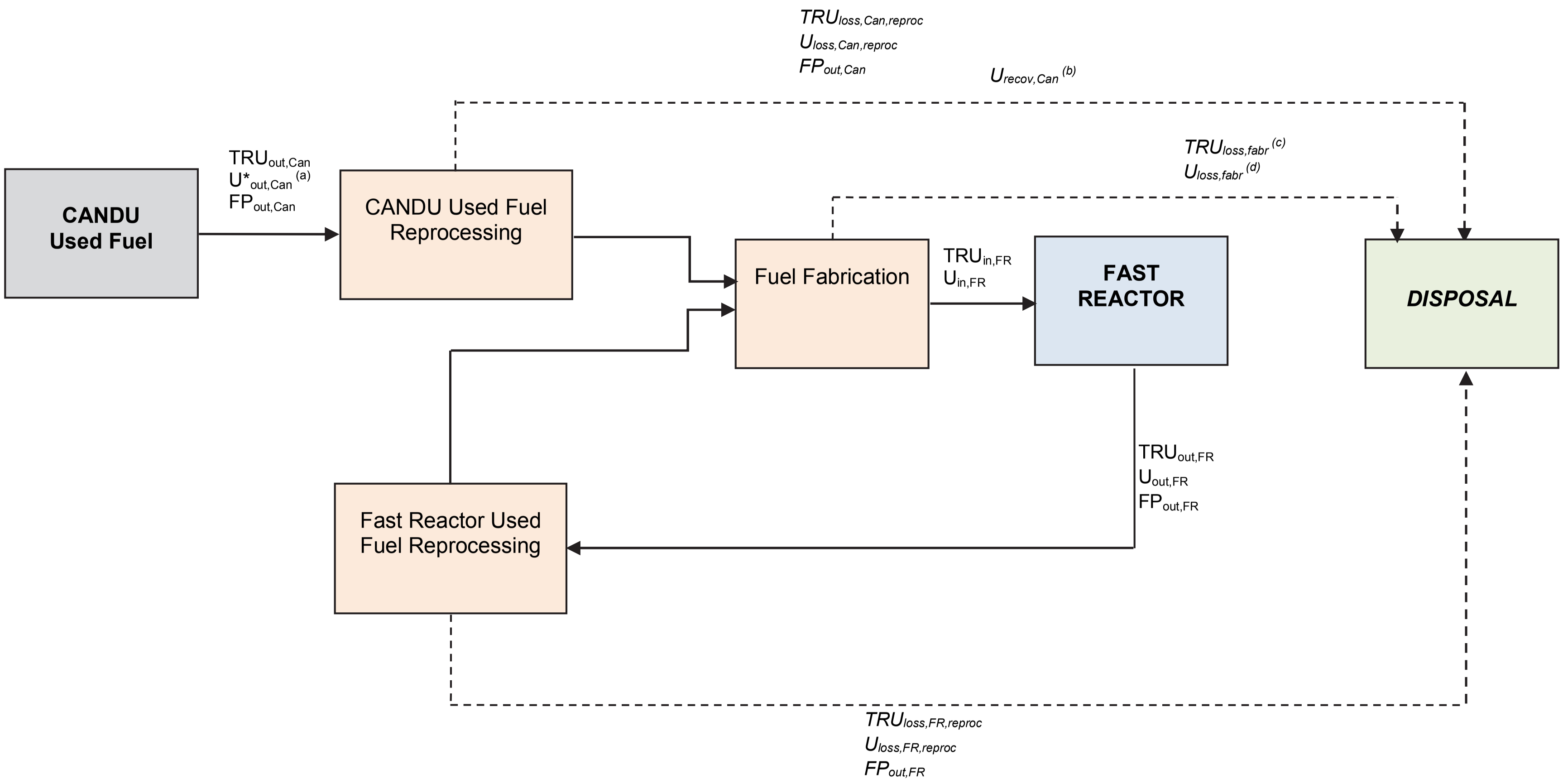
[1] “Conversion (breeding) ratio” is defined as the number of fissionable atoms produced to the number of fissionable atoms consumed in a reactor. If the ratio is less than 1, it is referred to as “conversion ratio”. If it is greater or equal to 1, it is referred to as “breeding ratio”. (Cacuci 2010, Sec.1.5.)

[2] “Equilibrium cycle” is considered to be reached when, after each refueling, the composition of materials remaining in the core after used fuel has been discharged and fresh fuel reloaded is the same as the composition of materials at the start of the previous irradiation cycle. (Waltar et al. 2012, Sec.7.2)



Notes:
a) $U^*_{out,Can}$ is the total amount of uranium available in CANDU used fuel, out of which a smaller quantity ($U_{out,Can}$) is used for reprocessing and for fabrication of the FR fuel.
b) $U_{recov,Can}$ is the amount of uranium recovered from reprocessing of CANDU used fuel, and not used for fabrication of the FR fuel, which could be either stored for future re-use as make-up in the fast reactor or sent for disposal.
c) $TRU_{loss,fabr}$ represents the total TRU losses from FR fuel fabrication using reprocessed CANDU and FR used fuels.
d) $U_{loss,fabr}$ represents the total U losses from FR fuel fabrication using reprocessed CANDU and FR used fuels.

Figure 1: Nuclear Fuel Cycle Considered in Analysis

In the present analysis, it is assumed the external supply for the make-up is reprocessed CANDU used fuel.

The wastes from reprocessing of CANDU used fuel and FR used fuel are sent for deep geological disposal, due to their long lived radionuclide content and heat generation rate. These are primarily fission products and metal cladding hull wastes. The latter are neglected in the following analysis, although they will contain significant quantities of long-lived activation products, such as Zr-93 and Nb-94. In addition, as reprocessing and fuel fabrication are not 100% efficient, a small amount of TRU and U are also lost and sent with the wastes for disposal. These are not significant from an overall mass balance consideration, but they may affect the long-term safety of the wastes to be disposed and it is important to include them. A large quantity of uranium is also recovered during reprocessing of CANDU used fuel; this uranium can be either stored for potential future re-use as make-up in the fast reactor or sent for disposal.

Reprocessing is expected to also generate a significant volume of low-level waste and intermediate-level waste. However, only the inventory in the system (i.e., the closed nuclear fuel cycle) that would constitute high-level waste (HLW) is considered in the mass flow calculations.

The irradiated FR fuel in the reactor core is also considered in the analysis as part of the overall system inventory of long-lived radioactive wastes. This is in addition to the amount present from CANDU used fuel and from reprocessing wastes sent for disposal. This core material would need to be managed at the end of the operating life of the fast reactors.

It is assumed that a defined quantity of CANDU used fuel is available in storage and it is used for starting up and operating two or more FRs. The FRs are assumed to start operation in year 1, and operate for a period of 60 years. Reprocessing of stored CANDU fuel is assumed to start sufficiently in advance of year 1 in order to supply the initial core loading.

Reprocessing and Fuel Fabrication

Reprocessing is a key process in a closed fuel cycle. Various technologies are presently being considered, such as aqueous, pyro, and fluoride volatility processes. They are at various stages of development, ranging from conceptual phase to in use at industrial scale. For example, aqueous reprocessing of LWR spent fuels is presently commercial; the largest reprocessing plant, AREVA La Hague, is operating with two production lines with a total reprocessing capacity of 1700 t_{HM}/yr (AREVA 2013)[3]. On the other hand, pyroprocessing is still to be demonstrated at an industrial scale. Argonne National Laboratory (ANL) has demonstrated pyroprocessing feasibility (i.e., 0.1 t_{HM}/yr capacity) through treatment of the Experimental Breeder Reactor-II spent fuel, and currently is in the process of developing the conceptual design of a 100 t_{HM}/yr scale facility (Chang 2009, 2014).

The pyrometallurgy reprocessing ("pyroprocessing") technology is considered in this analysis for both CANDU and FR used fuels; however, this is not critical to the conclusions drawn here. In comparison with the aqueous technology, the pyroprocessing offers a number of advantages, such as: better proliferation resistance, as the minor actinides are recovered together with no separation of pure plutonium, greater radiation-resistance due to use of high-temperature salts

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[3] "t" in this report represents "tonnes" or "metric tons".

and metals, criticality safety, and overall potential economic superiority (for example, the equipment is more compact requiring less facility space; for metallic fuels, the reprocessing and fuel fabrication can be integrated) (Yoo et al. 2008, Sec. 1; Kok 2009, Sec. 11.6.1). Some of its limitations reported in the literature are: low throughput in each unit due to a batch process approach; contamination with rare earth elements in the separation of the TRUs; and safety provisions needed to handle higher dose rates compared with those of the pure plutonium products obtained from the aqueous process (Yoo et al. 2008, Sec. 1).

For the purposes of this report, it is assumed that the pyropocessing rate of CANDU used fuel is not limiting and all CANDU fuel can be reprocessed quickly enough to supply the needs of the FRs.

Theoretical pyroprocessing flowsheets have been developed to estimate the material balances for recycling actinides from the LWR spent fuel for use in fast reactors (OECD 2012, Williamson and Willit 2011, Berger and Benedict 2011, Yoo et al. 2008). The efficiencies assumed for the recovery of the actinides are typically within 99.0 – 99.9 wt% (OECD 2012, Yoo et al. 2008, Nuclear Fuel Cycle Options Catalog 2014). Some studies assume a very high efficiency, such as 99.9 wt%, which would maximize the amount of actinides recovered from pyroprocessing (OECD 2012, Sec. 2.4; Williamson and Willit 2011, Sec. 2). Others explore the implications of using different recovery efficiencies for the TRU and U streams, for example, 97 wt% efficiency for TRU recovery and 98 wt% for uranium, based on experimental results and technical information available in the open literature (Yoo et al. 2008). Lee and Kim (2015) recently reported results of a case study assuming different TRU recovery efficiencies (i.e., 99.9 – 99.9999 wt%) for recycling TRUs from CANDU used fuel for use in fast reactors.

The present analysis assumes 99.5 wt% for recovery of TRU elements and 99.0 wt% for the recovery of uranium, respectively. Note that this is an overall efficiency; the analysis does not consider the efficiencies associated with each individual step of the reprocessing technology. Other losses from reprocessing are neglected. It is assumed that all fission products in the used fuel are removed and sent for disposal.

The overall fabrication efficiency for TRU elements and uranium during fuel fabrication is assumed to be 99.9 wt%.

Fast Reactor

The fast reactor considered in this analysis is the advanced burner reactor preliminary design developed at ANL, which is based on the 1000 MWth or 380 MWe SuperPRISM (S-PRISM) reactor designed by GE Hitachi Nuclear Energy[4] (Hoffman et al. 2006, Dubberley et al. 2003a, Dubberley et al. 2003b).

S-PRISM (or PRISM) is a pool-type, sodium-cooled fast reactor designed to operate at near breakeven or as a breeder (Dubberley et al. 2003a, 2003b). The core configuration of the reactor can be modified, however, such that PRISM can be used as burner as well (Triplett et al. 2012, Table II). This modification as evaluated by ANL is considered in the present report.

The characteristics of the fast reactor used in this analysis are presented in Table 1. Three core configurations of the burner FR are considered, each with the same power output but with

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[4] The current reference PRISM reactor has a rated thermal power of 840 MW and an electrical output of 311 MW (GEH 2015, Triplett et al. 2012).

different CRs (0.25, 0.5 and 0.75). Figure 2, reproduced from Figure 4.3 in Hoffman et al. (2006), presents the three core configurations for illustrative purposes only.

The reference fuel for the PRISM reactor is an alloy metal containing a combination of uranium, plutonium, and zirconium. The composition of the fuel as well as the configuration of the reactor core depend on how the reactor is designed to operate, i.e., as burner, breakeven or breeder (Triplett et al. 2012, Sec. II.B). The characteristics of the FR fuel are provided in Sec. 2.1.2.

The operating lifetime of the reactor is assumed to be 60 years.

Table 1: Fast Reactor Characteristics

Thermal Power [MWth]	1000		
Thermal Efficiency [%]	38		
Conversion Ratio	0.25	0.5	0.75
Discharge Burnup [GWd/t_{HM}][1]	186.9	131.9	99.6

Note:

1) The discharge burnup is from Table 4.13 of the ANL report (Hoffman et al. 2006).

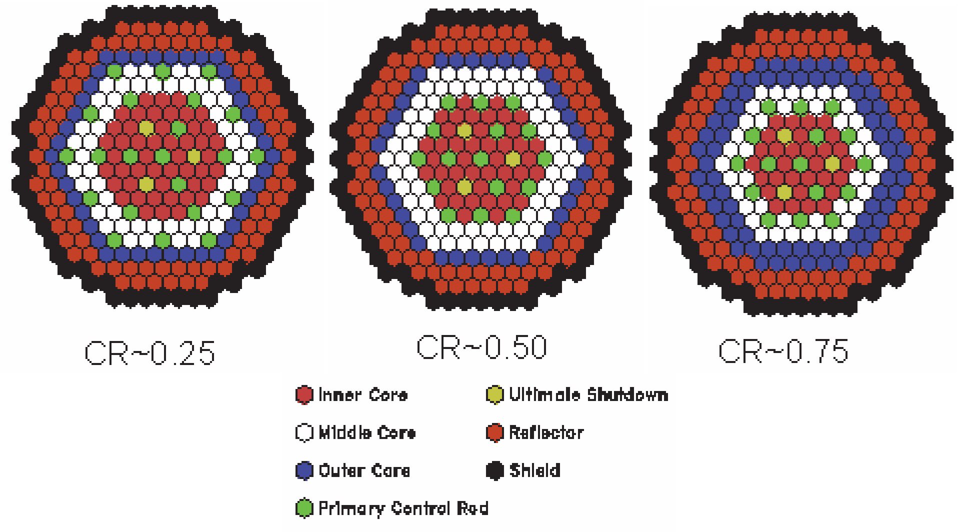

Figure 2: Burner Fast Reactor (ANL Preliminary Design) Core Configurations for Three Conversion Ratios (0.25, 0.5, and 0.75) (reproduced from Hoffman et al. 2006)

In developing the burner core preliminary designs, Hoffman et al. (2006) assume that the overall assembly dimensions for various core configurations remain unchanged. To achieve different CRs, the number and size of the fuel pins within each assembly are adjusted. For example, the number of fuel pins is adjusted to modify the linear power, whereas the fuel pin diameter is adjusted to change the fuel volume fraction. A reduction in the diameter of the fuel pin results in a decrease in the overall fuel volume fraction, which would require an increase in the TRU enrichment (i.e., TRU fraction in heavy metal) for the same fuel cycle. A higher TRU enrichment increases the TRU fission relative to U-238 capture, which would reduce the TRU conversion ratio (Hoffman et al. 2006, Sec. 2.0).

From a waste management perspective, an advanced burner FR with a very low CR, for example as low as 0.25, would be advantageous in a nuclear fuel cycle as it would require a larger amount of external fuel, therefore maximizing the burnup of TRUs from the wastes. However, a low conversion ratio requires a high TRU enrichment, beyond current irradiation experience with FR fuels. Based on current technology, the CR would be more likely in the range of 0.5 - 0.6 (Richter et al. 2006, Sec. 2). Conversion ratios greater than approximately 0.65 are within the plutonium enrichments of the U-Pu-10Zr fuel used in the US Experimental Breeder Reactor-II and Fast Flux Test Facility metal-fuel irradiation test programs (Hoffman et al. 2006, Sec. 1.0).

An advanced burner FR with a very low CR, such as 0.25, would require a more advanced design, which currently involves significant engineering challenges. As Richter et al. (2006) noted in Sec. 2 of their report, examples of such challenges include the following:

- “Fuel enrichments[5] on the order of 50% for which there is no fast reactor fabrication or irradiation experience. On the other hand, high fuel enrichments are not beyond the realm of consideration as the French did consider fuel enrichments as high as 45% for Super Phenix, but fabrication and irradiation were not completed due to the shutdown of the reactor;
- For smaller reactors, these high fuel enrichments produce significant reactivity swings during operating cycles, which in turn require a large number of control rods to manage this reactivity swing;
- The large number of control rods may produce a configuration in which essentially every fuel assembly is adjacent to a control rod, which in turn implies significant gradients in the neutron flux;
- This in turn implies that the fuel and therefore the coolant temperature vary from assembly to assembly and do so continuously throughout the core;
- This in turn implies significant differences in exit coolant temperatures between adjacent core locations, which in turn produces an effect called thermal striping. Thermal striping is a term used to characterize adjacent hot and cold sodium coolant steams leaving the core and impacting on the upper metal structures above the core;
- Small flow oscillations in these streams, which occur continuously in the radial and azimuthal directions, produce cyclical temperature changes in the metallic structures above the core and thereby subject them to thermal cycling and thermal fatigue.”

The core designs developed by ANL are based on a model that assumes no fuel shuffling and uses batch-average compositions. To produce a relatively uniform radial power distribution, Hoffman et al. (2006) assume three enrichment zones in the reactor core, i.e. the inner, middle and outer core (see Figure 2), with the enrichment levels increasing from the inner core towards the outer core. The enrichment of the middle core is assumed to be 1.25 times the inner core and the enrichment of the outer core is assumed to be 1.5 times the inner core (Hoffman et al. 2006, Sec. 2.0).

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[5] Note that “fuel enrichment” here refers to “TRU enrichment”, i.e., TRU fraction in heavy metal.

A capacity factor of 85% is assumed for all core configurations in this analysis[6]. The capacity factor will ultimately depend on the CR as the refuelling frequency, number of assemblies replaced per outage, and unplanned outages related to fuel failures, will differ from one core configuration to another.

2.1.2 Fuel Characteristics

The CANDU used fuel composition assumed in this analysis is presented in Table 2, and is based on the radionuclide inventory for actinides and fission products in the UO_2 fuel at a reference burnup of 220 MWh/kg U (Tait et al. 2000, Vol.2, Appendix A). The fissile Pu content (Pu-239 and Pu-241) is about 66 wt% of the total TRU content in the CANDU used fuel.

Table 2: CANDU Used Fuel Composition (weight fraction)

Uranium (U)	0.9857
TRU	0.0044
Fission Products (FP)	0.0099

The FR fuel composition assumed in this analysis, as a fraction of the initial heavy metal load, is presented in Table 3, and it is estimated from the ANL data. Note that the present report focuses on the TRU content as an aggregate, and does not specifically consider the isotopic content. The TRU includes the total plutonium, neptunium, americium, and curium content of the fuel. In practice, a certain amount of more fissile isotopes would be required in the core. The fissile Pu content assumed in the FR fresh fuel analysis was between about 39 wt% (for CR=0.25) to 54 wt% (for CR=0.75) of the total TRU content. Since the fissile Pu content in TRU from CANDU used fuel is higher than this, it is assumed that the CANDU TRU would be suitable for direct use in these FRs. However, it may be that some adjustment of the fuel may be needed, in order to make the reactor physics work.

Table 4 presents the heavy metal loadings assumed in this analysis at the beginning of the cycle for the fast reactor, which are based on the ANL equilibrium data used in their reference scenario. In that scenario, Hofmann et al. (2006) assume that the external supply of TRU make-up is spent fuel from light water reactors, irradiated to 1200 MWh/kg_{HM} (or 50 MWd/kg_{HM}) and stored for five years prior to reprocessing, and the make-up uranium is depleted uranium.

It is noted that Hofmann et al. (2006) also evaluated the impact on the performance of the CR=0.5 design at equilibrium for different sources of external supply for the TRU make-up. That is, the core configuration design remained unchanged while using different sources of TRU feed streams. The ANL analysis showed a minimal impact on the performance of the CR=0.5 design (Hoffman et al. 2006, Sec.4.5), and that results are not strongly sensitive to the exact mix of actinide isotopes present in the TRU recycled for use in the fast reactor.

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[6] A similar assumption of using 85% capacity factor for different CR designs was noted in mass flow calculations documented in the ANL report (Hoffman et al. 2006, Sec.4.3) and in the MIT Interdisciplinary Study (MIT 2011, Ch.6 - Fast Reactor Technical Characteristics).

Table 3: FR Fuel Composition As Fraction of Initial Heavy Metal Load

Conversion Ratio	**0.25**		**0.5**		**0.75**	
Start-up [1,2]						
	Fresh Fuel	Used Fuel	Fresh Fuel	Used Fuel	Fresh Fuel	Used Fuel
U	0.5432	0.4823	0.7054	0.6236	0.7947	0.7089
TRU	0.4568	0.3364	0.2946	0.2355	0.2053	0.1854
FP	0	0.1813	0	0.1409	0	0.1057
Equilibrium [3,4]						
	Fresh Fuel	Used Fuel	Fresh Fuel	Used Fuel	Fresh Fuel	Used Fuel
U	0.4400	0.3856	0.6667	0.5889	0.7878	0.7009
TRU	0.5600	0.4175	0.3333	0.2707	0.2122	0.1924
FP	0	0.1969	0	0.1404	0	0.1067
Irradiated Fuel in Core [5]						
	Equilibrium		Equilibrium		Equilibrium	
U	0.4128		0.6278		0.7444	
TRU	0.4888		0.3020		0.2023	
FP	0.0985		0.0702		0.0534	

Notes:

1) Fresh fuel composition for start-up is estimated from the detailed charge data in Table 4.16 of the ANL report.
2) Used fuel composition for start-up is estimated from the detailed five-year cooled data in Table 4.17 of the ANL report.
3) Fresh fuel composition for equilibrium is from the detailed charge data in Table 4.12 of the ANL report.
4) Used fuel composition for equilibrium is estimated from the detailed five-year cooled data in Table 4.13 of the ANL report.
5) Fuel composition for the irradiated fuel in core is estimated as the average of the fresh and used fuel, calculated as: ½ × *(equilibrium fresh fuel + equilibrium used fuel)*.

Table 4: Fast Reactor Heavy Metal Loadings

Conversion Ratio	0.25	0.5	0.75
Heavy metal loading[1] [t_{HM}]	6.169	9.449	13.436

Note:

1) Heavy metal loadings are from Table 4.12 of the ANL report.

2.2 MASS FLOW MODELLING

The mass flow diagram for the nuclear cycle considered in this report is shown in Figure 1. The mass flows shown in this figure, as well as others, are calculated using the equations shown below.

2.2.1 General

The mass of FR fuel used to generate 1 GWe·yr of electricity is calculated from the burnup and the reactor thermal efficiency:

$$m = \frac{365}{B_d\,\eta_{th}} \tag{1}$$

where: m = mass of FR fuel used to generate 1 GWe·yr, [t_{HM}/GWe·yr]

B_d = discharge burnup, [GWd/t_{HM}]

η_{th} = thermal efficiency, [%].

The amount of TRU in fresh fuel required for operation of the FR is obtained from recycled FR fuel as well as make-up from CANDU used fuel:

$$TRU_{in,FR} = \varepsilon_{TRU,r}\ \varepsilon_{TRU,f}\left(TRU_{out,Can} + TRU_{out,FR}\right) \tag{2}$$

where: $TRU_{in,FR}$ = mass of TRU in FR fresh fuel, [t/yr]

$TRU_{out,Can}$ = mass of make-up TRU reprocessed from CANDU used fuel, [t/yr]

$TRU_{out,FR}$ = mass of TRU reprocessed from FR used fuel, [t/yr]

$\varepsilon_{TRU,r}$ = TRU recovery efficiency from reprocessing, [%]

$\varepsilon_{TRU,f}$ = TRU recovery efficiency from fuel fabrication, [%].

2.2.2 Fast Reactor

The core loading of a FR will vary in mass and composition from the initial start-up load until an eventual equilibrium fuel cycle is reached. For simplicity, the first fuel start-up load is considered and then all other loadings are assumed at equilibrium conditions.

FR Fresh Fuel Composition

The TRU and U in FR fresh fuel at start-up of a new fast reactor are:

$$TRU_{in,FR(start)} = f_{TRU,start}\ m_{HM_{load}} \tag{3}$$

$$U_{in,FR(start)} = f_{U,start}\ m_{HM_{load}} \tag{4}$$

where: $TRU_{in,FR(start)}$ = mass of TRU in FR fresh fuel at start-up, [t]
$U_{in,FR(start)}$ = mass of U in FR fresh fuel at start-up, [t]
$m_{HM\ load}$ = mass of heavy metal loading [t] (Table 4)
$f_{TRU,start}$ = fraction of TRU in fresh fuel at FR start-up (Table 3)
$f_{U,start}$ = fraction of U in fresh fuel at FR start-up (Table 3).

The TRU and U in FR fresh fuel at equilibrium are:

$$TRU_{in,FR} = f_{TRU,in}\ m\ P\ CF \tag{5}$$

$$U_{in,FR} = f_{U,in}\ m\ P\ CF \tag{6}$$

where: $TRU_{in,FR}$ = mass of TRU in FR fresh fuel at equilibrium, [t/yr]
$U_{in,FR}$ = mass of U in FR fresh fuel at equilibrium, [t/yr]
m = mass of FR fuel used to generate 1 GWe·yr, calculated using Eq.1, [t_{HM}/GWe·yr]
$f_{TRU,in}$ = fraction of TRU in fresh fuel at equilibrium (Table 3)
$f_{U,in}$ = fraction of U in fresh fuel at equilibrium (Table 3)
P = electrical output per fast reactor, [GWe]
CF = capacity factor, [%].

The FR fuel is assumed to be fully recycled here. However some additional TRU and U are required to be added with each new FR fuel cycle. Starting with year 2, the make-up amount of TRU required to be reprocessed for the FR fresh fuel is determined based on Eq.2, as follows:

$$TRU_{mk,FR,n} = \frac{TRU_{in,FR,n}}{\varepsilon_{TRU,r}\ \varepsilon_{TRU,f}} - TRU_{out,FR,n-1} \tag{7}$$

where: $TRU_{mk,FR,n}$ = mass of make-up TRU reprocessed for FR fresh fuel at equilibrium for year *n* ($2 \leq n \leq 60$), [t/yr]
$TRU_{in,FR,n}$ = mass of TRU in FR fresh fuel at equilibrium for year *n,* [t/yr]
$TRU_{out,FR,n-1}$ = mass of TRU in FR used fuel at equilibrium, resulting from FR operation in year *n-1,* [t/yr]
$\varepsilon_{TRU,r}$ = TRU recovery efficiency from reprocessing, [%]
$\varepsilon_{TRU,f}$ = TRU recovery efficiency from fuel fabrication, [%].

Similarly, the make-up amount of U required to be reprocessed for the FR fresh fuel is estimated as:

$$U_{mk,FR,n} = \frac{U_{in,FR,n}}{\varepsilon_{U,r}\ \varepsilon_{U,f}} - U_{out,FR,n-1} \tag{8}$$

where:

$U_{mk,FR,n}$ = mass of make-up U reprocessed for FR fresh fuel at equilibrium for year *n,* [t/yr]

$U_{in,FR,n}$ = mass of U in FR fresh fuel at equilibrium for year *n,* [t/yr]

$U_{out,FR,n-1}$ = mass of U in FR used fuel at equilibrium, resulting from FR operation in year *n-1,* [t/yr]

$\varepsilon_{U,r}$ = U recovery efficiency from reprocessing, [%]

$\varepsilon_{U,f}$ = U recovery efficiency from fuel fabrication, [%].

In year 1, when the FR is assumed to start operation, there is no recycled FR fuel available and all the initial fuel is provided from reprocessed CANDU used fuel.

FR Used Fuel Composition

The TRU in the FR used fuel is calculated as:

$$TRU_{out,FR} = f_{TRU,out}\, m\, P\, CF \tag{9}$$

where: $TRU_{out,FR}$ = mass of TRU in FR used fuel at equilibrium, which is also the mass of TRU reprocessed from FR used fuel for recycling in FR, [t/yr]

$f_{TRU,out}$ = fraction of TRU in FR used fuel at equilibrium (Table 3)

m = mass of FR fuel used to generate 1 GWe·yr, calculated using Eq.1, [t_{HM}/GWe·yr]

P = electrical output per fast reactor, [GWe]

CF = capacity factor, [%].

The U and FP amounts in FR used fuel are calculated in a similar manner.

Irradiated Fuel in FR Core

The TRU in the irradiated fuel in the FR core is estimated as:

$$TRU_{FR} = \frac{f_{TRU,in} + f_{TRU,out}}{2}\,(FR\ HM\ inventory\ -\ FR\ spent\ fuel)$$

i.e.:

$$TRU_{FR} = \frac{f_{TRU,in}+f_{TRU,out}}{2}\,(FR\ HM\ inventory - m\, P\, CF) \tag{10}$$

where: TRU_{FR} = mass of TRU in irradiated fuel in FR core at start of cycle, [t]

FR HM inventory = mass of heavy metal inventory in FR core at start of cycle, estimated from the mass of heavy metal loading at equilibrium, [t_{HM}] (Table 4)

m = mass of FR fuel used to generate 1 GWe·yr, calculated using Eq.1, [t_{HM}/GWe]

$f_{TRU,in}$ = fraction of TRU in fresh fuel at equilibrium
$f_{TRU,out}$ = fraction of TRU in FR used fuel at equilibrium
P = electrical output per fast reactor, [GWe]
CF = capacity factor, [%].

The U and FP amounts in the irradiated fuel in FR cores are estimated in a similar manner.

During year 1, when the FR is assumed to start operation, it is assumed that there is no irradiated fuel in the FR cores.

Waste from FR Used Fuel Reprocessing and FR Fuel Fabrication

The TRU losses from reprocessing of FR used fuel and from FR fuel fabrication are:

$$TRU_{loss,FR} = (TRU\ losses\ from\ FR\ used\ fuel\ reproc + TRU\ losses\ from\ fuel\ fabrication)$$

i.e.:

$$TRU_{loss,FR} = TRU_{loss,FR,reproc} + TRU_{loss,FR,fabr}$$

$$TRU_{loss,FR} = \left(1 - \varepsilon_{TRU,r}\right) TRU_{out,FR} + \left(1 - \varepsilon_{TRU,f}\right) \varepsilon_{TRU,r}\ TRU_{out,FR}$$

therefore:

$$TRU_{loss,FR} = \left(1 - \varepsilon_{TRU,r}\ \varepsilon_{TRU,f}\right) TRU_{out,FR} \tag{11}$$

Similarly, the U losses from reprocessing of FR used fuel and from FR fuel fabrication are:

$$U_{loss,FR} = \left(1 - \varepsilon_{U,r}\ \varepsilon_{U,f}\right) U_{out,FR} \tag{12}$$

The fission products removed from the FR used fuel during reprocessing are:

$$FP_{out,FR} = f_{FP,out}\ m\ P\ CF \tag{13}$$

2.2.3 CANDU Used Fuel

CANDU Used Fuel for Reprocessing

The TRU in CANDU used fuel required for reprocessing and FR fuel fabrication, which provides the annual make-up fuel to the FR, is equal to the make-up amount of TRU for the FR fresh fuel calculated in Eq. 7:

$$TRU_{out,Can} = TRU_{mk,FR} \tag{14}$$

The total mass of CANDU used fuel required for reprocessing is determined by the amount needed to supply the TRU in the make-up fuel:

$$m_{HM_{out,Can}} = \frac{TRU_{out,Can}}{f_{TRU,Can}} \tag{15}$$

where: $m_{HM\ out,\ Can}$ = mass of CANDU used fuel to be reprocessed, [t/yr]

$TRU_{out,Can}$ = mass of make-up TRU reprocessed from CANDU used fuel, [t/yr]

$f_{TRU,Can}$ = fraction of TRU in CANDU used fuel (Table 2).

The total amount of uranium available in the mass of CANDU used fuel required for reprocessing is estimated as:

$$U^{*}_{out,Can} = f_{U,Can} m_{HM_{out,Can}} \tag{16}$$

where: $f_{U,Can}$ = fraction of U in CANDU used fuel (Table 2).

Out of this total amount, a small quantity is reprocessed and used for fabrication of the FR fresh fuel, and is equal to the make-up amount of U for the FR fresh fuel calculated in Eq. 8:

$$U_{out,Can} = U_{mk,FR} \tag{17}$$

The remainder is recovered from reprocessing the CANDU used fuel, and a small quantity will be sent for disposal as waste resulted from reprocessing of the CANDU used fuel and from the FR fuel fabrication (see below).

Waste from CANDU Used Fuel Reprocessing and from FR Fuel Fabrication

The TRU losses from reprocessing of CANDU used fuel and from FR fuel fabrication are:

$$TRU_{loss,Can} = (TRU\ losses\ from\ CANDU\ used\ fuel\ reproc + TRU\ losses\ from\ fuel\ fabrication)$$

i.e.:

$$TRU_{loss,Can} = TRU_{loss,Can,reproc} + TRU_{loss,Can,fabr}$$

and they are estimated using a similar equation to Eq.11:

$$TRU_{loss,Can} = \left(1 - \varepsilon_{TRU,r}\ \varepsilon_{TRU,f}\right) TRU_{out,Can} \tag{18}$$

The U losses from reprocessing of CANDU used fuel and from FR fuel fabrication are:

$$\begin{aligned} U_{loss,Can} = {} & (U\ losses\ from\ CANDU\ used\ fuel\ reproc + U\ losses\ from\ fuel\ fabrication) \\ & + U\ losses\ from\ recovery\ of\ U\ during\ CANDU\ used\ fuel\ reproc \end{aligned}$$

that is:

$$\begin{aligned} & U\ losses\ from\ CANDU\ used\ fuel\ reproc + U\ losses\ from\ fuel\ fabrication \\ & = \left(1 - \varepsilon_{U,r}\ \varepsilon_{U,f}\right) U_{out,Can} \end{aligned}$$

$$\begin{aligned} & U\ losses\ from\ recovery\ of\ U\ during\ CANDU\ used\ fuel\ reproc \\ & = \left(1 - \varepsilon_{U,r}\right)\left(U^{*}_{out,Can} - U_{out,Can}\right) \end{aligned}$$

thus:

$$U_{loss,Can} = \left(1 - \varepsilon_{U,r}\, \varepsilon_{U,f}\right) U_{out,Can} + \left(1 - \varepsilon_{U,r}\right) \left(U^{*}_{out,Can} - U_{out,Can}\right) \tag{19}$$

The U recovered from reprocessing of CANDU used fuel is estimated as:

$$U_{recov,Can} = \varepsilon_{U,r} \left(U^{*}_{out,Can} - U_{out,Can}\right) \tag{20}$$

All fission products are assumed to be removed from the CANDU used fuel during reprocessing:

$$FP_{out,Can} = f_{FP,Can}\, m_{HM_{out,Can}} \tag{21}$$

2.3 RESULTS

Calculations are performed for two scenarios that consider the overall Canadian used fuel inventory.

- In Scenario 1, the construction of two fast reactors is considered as a deliberate method for long-term waste management of all of the CANDU used fuel in Canada's reactors. This generates some electricity in parallel, but that is not the primary intent.

- In Scenario 2, the construction of fast reactors is considered to replace the existing CANDU fleet electricity production. This is an energy supply scenario; however the analysis in this report is with respect to the implications of this scenario for waste management. It is assumed that only new FRs are built; there are no further CANDUs.

An advanced burner fast reactor based on the S-PRISM design described in Sec. 2.1 is considered for both scenarios. Two S-PRISM reactors typically constitute a power block that would be deployed in the nuclear energy system, with a combined output of 760 MWe (or 0.76 GWe). The second scenario assumes the number of FRs that would replace the current nuclear fleet by producing a similar electrical output. This would require 36 FRs, with a total net output of 13.7 GWe (13.5 GWe are currently generated by the existing reactors, based on information in Table A1, Garamszeghy 2015). All FRs are assumed to be available to start in year 1 and to operate for 60 years.

Three CRs are used in the calculations, i.e., 0.25, 0.5, and 0.75, for the scenarios involving one or more fast reactors used to burn the TRUs in the CANDU used fuel. A lower value of the CR is more advantageous for burning the TRUs, but requires a more advanced FR.

In all cases, it is assumed that the CANDU used fuel is available to be reprocessed into TRU and U streams to support FRs. Assuming an average of 20 kg heavy metal in a fuel bundle, the amount of CANDU used fuel considered to be available for further reprocessing is 103,000 t_{HM}. This is the estimate for the high scenario of projected nuclear fuel waste from the existing reactors, based on approximately 5.2 million bundles, assuming that most of reactors are refurbished with a new set of pressure tubes and other major components (Garamszeghy 2015, Table 2).

An example of a flowsheet showing the material balance within the system in presented in Appendix A.

2.3.1 TRU + Fission Products

The results focus on the total inventories of TRUs and FPs within the nuclear energy system for all scenarios, as these would need long-term management as high-level waste (HLW). The three primary "stores" for the TRUs and FPs are: 1) the remaining unreprocessed CANDU used fuel, 2) the FR cores, and 3) the amounts sent for disposal, which include losses from reprocessing and fuel fabrication. Fuel in transit between these "stores" is neglected.

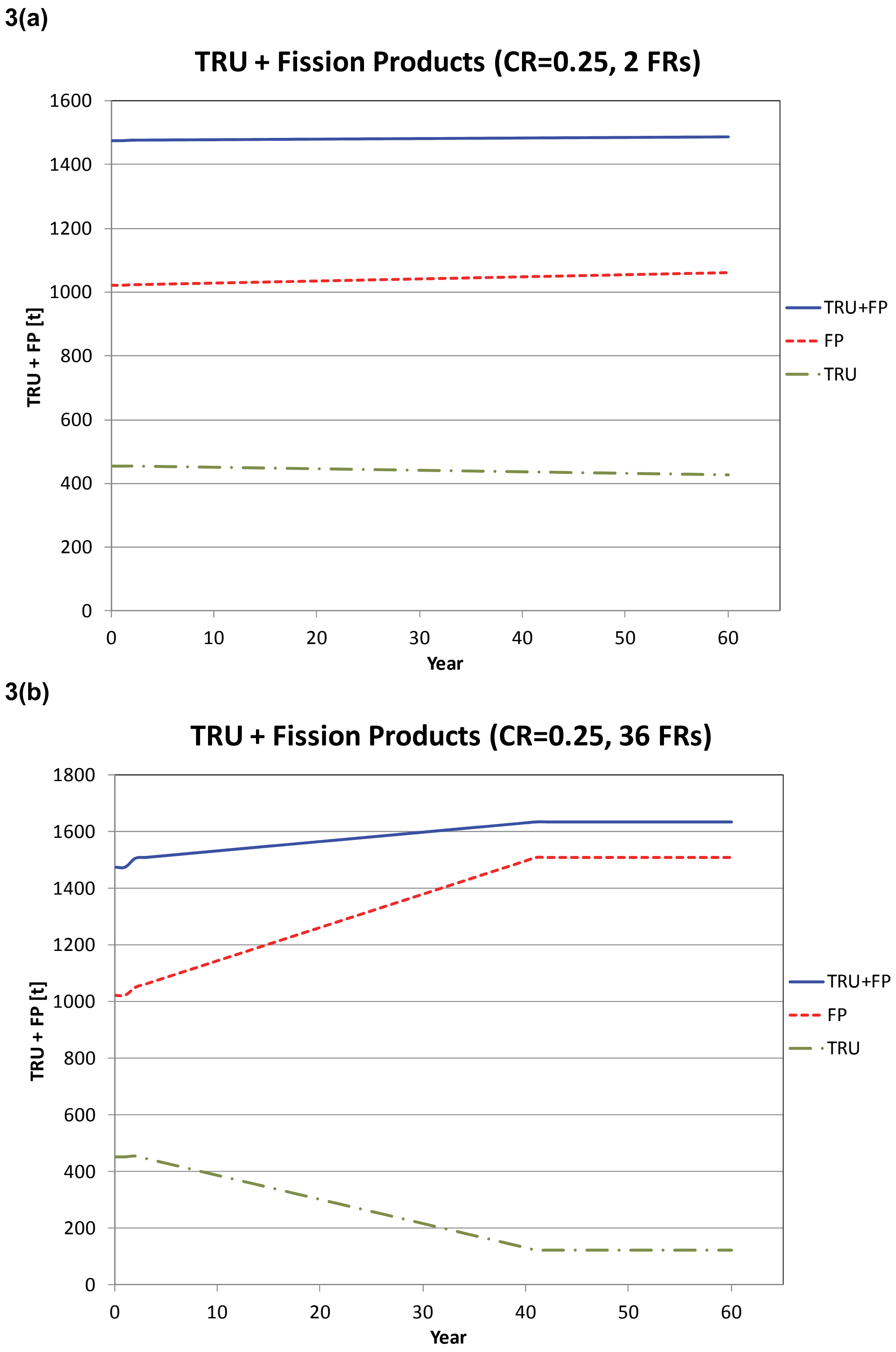
Figure 3 shows the total amount of TRU and fission products within the system considering the operation of fast reactors with a favourable very low conversion ratio, CR=0.25, starting from 103,000 t_{HM} CANDU used fuel. Figure 3(a) shows the results for Scenario 1, with a two-FR site dedicated to waste management. Figure 3(b) shows the results for Scenario 2, where 36 FRs are built in order to maintain the current nuclear electricity supply.

- The results for Scenario 1 presented in Figure 3(a) show that a 2-FR site would not provide fast reduction of the existing CANDU TRU inventory. Extending the analysis from Figure 3(a), it is estimated that it would take almost 1000 years for a 2-FR site to burn all TRUs in 103,000 t_{HM} of CANDU used fuel. As the operating life of a FR is assumed 60 years, this means that approximately 15 generations of 2 FRs (or 30 FRs) would be needed to burn the entire amount of CANDU used fuel. During this period, there would also be continuous production of fission products.
- The results for Scenario 2 presented in Figure 3(b) show that a large fleet of FRs could consume the total CANDU TRU inventory within about 50 years, allowing also for time to consume the significant TRU inventory remaining in the reactor cores. Although there would be insufficient TRU amounts in the remaining unreprocessed CANDU used fuel to continue operation of all the FRs after slightly over 40 years, there would still be significant TRU amounts in the FR cores. This could be consumed by continued longer operation of 1 or 2 FRs (not shown in Figure 3b).

Figure 4 and Figure 5 show the total amount of TRU and fission products for the same conditions as Figure 3, except considering the operation of fast reactors with a conversion ratio of 0.5 and 0.75 respectively. Figure 4(a) and Figure 5(a) show the results for Scenario 1, with a two-FR site dedicated to waste management. Figure 4(b) and Figure 5(b) show the results for Scenario 2, where FRs are built sufficient to maintain current nuclear electricity supply.

- The results presented in Figure 4(a) and Figure 5(a) show that a 2-FR site with a conversion ratio of 0.5 or 0.75 respectively, would still not provide fast reduction of the total CANDU TRU inventory, similar to Figure 3(a). The differences between operating FRs with either of the three CRs in this case are insignificant.
- The results for Scenario 2 presented in Figure 4(b) and Figure 5(b) show that a large fleet of FRs would not consume the CANDU TRU inventory within their assumed operating lifetime of 60 years.

For both scenarios and for all conversion ratios, the total amount of TRU plus FPs that would have to be managed as HLW in Canada increases with time, reflecting the steady production of FP at a rate that is faster than the TRU consumption. The nature of the HLW will change over time as the TRU fraction decreases, and becomes more fission product based. The preliminary implications of that on long-term safety and heat generation have been assessed in in a separate report (Gobien 2015).

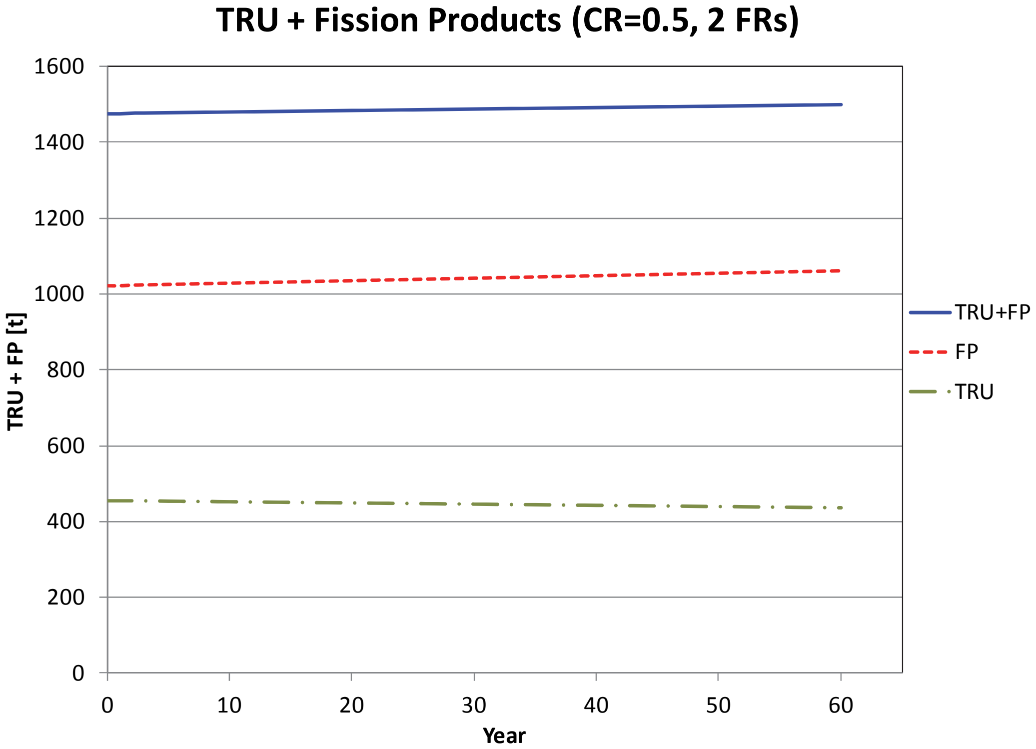


TRU + Fission Products (CR=0.25, 2 FRs)

TRU + Fission Products (CR=0.25, 36 FRs)

Figure 3: Total TRU and Fission Products System Inventory for Scenario with Fast Reactors with a Favourable Very Low Conversion Ratio (CR=0.25), Starting from 103,000 t_{HM} CANDU Used Fuel, (a) 2 FR; (b) 36 FR

4(a)



4(b)

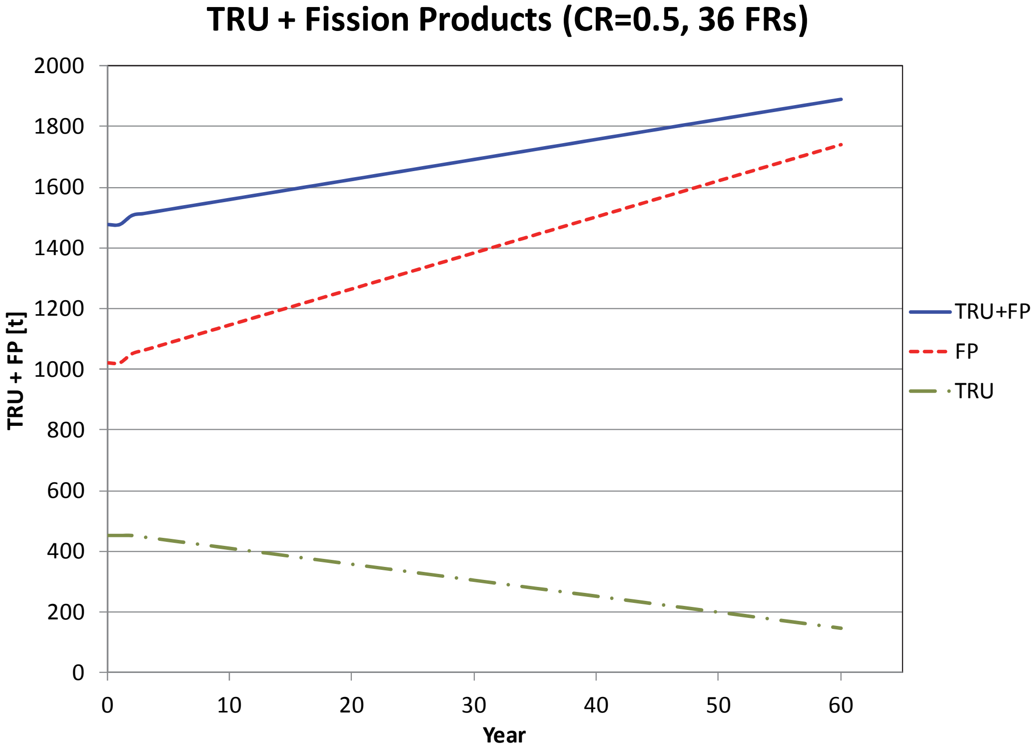


Figure 4: Total TRU and Fission Products System Inventory for Scenario with Fast Reactors with a Low Conversion Ratio (CR=0.5), Starting from 103,000 t_{HM} CANDU Used Fuel, (a) 2 FR; (b) 36 FR

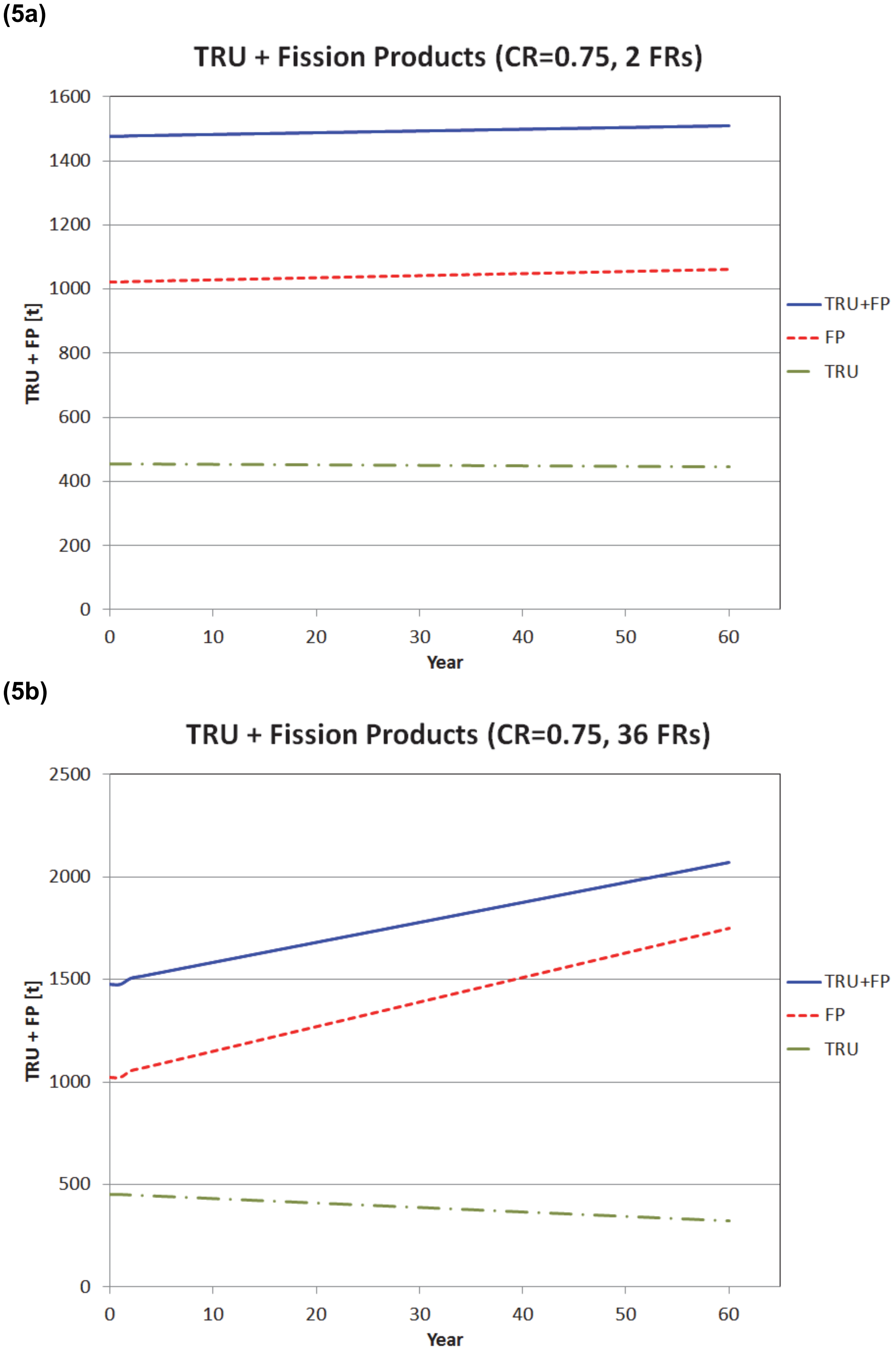


Figure 5: Total TRU and Fission Products System Inventory for Scenario with Fast Reactors with a Conversion Ratio CR=0.75, Starting from 103,000 t_{HM} CANDU Used Fuel, (a) 2 FR; (b) 36 FR

2.3.2 Uranium

Results are presented for the total inventory of uranium in the nuclear energy system, as this would require long-term waste management as well. The total inventory of uranium in the system is available in four “stores”, which are: 1) the remaining unreprocessed CANDU used fuel, 2) the FR cores, 3) the amounts sent for disposal, which are losses from reprocessing and fuel fabrication, and 4) uranium recovered from reprocessing of CANDU used fuel.

Figure 6 shows the total uranium system inventory for Scenario 2 with 36 FRs using 103,000 t_{HM} CANDU used fuel, for all CRs (0.25, 0.5, and 0.75).

The results indicate that there is little reduction in the total amount of uranium in the system inventory that would need to be managed, for any of the CRs considered. It is observed that a large amount of uranium will be recovered during the reprocessing of CANDU used fuel, which could be either stored for future re-use as make-up in the fast reactor or sent for disposal.

2.3.3 System Inventory

The total amounts of uranium, TRUs, and FPs in the CANDU used fuel available in the system initially, at start up of the FRs, as well as their remaining quantities after operating the FRs for a number of years, are provided in Table 5. The results are presented for Scenario 2 with 103,000 t_{HM} CANDU used fuel and 36 FRs, for all conversion ratios.

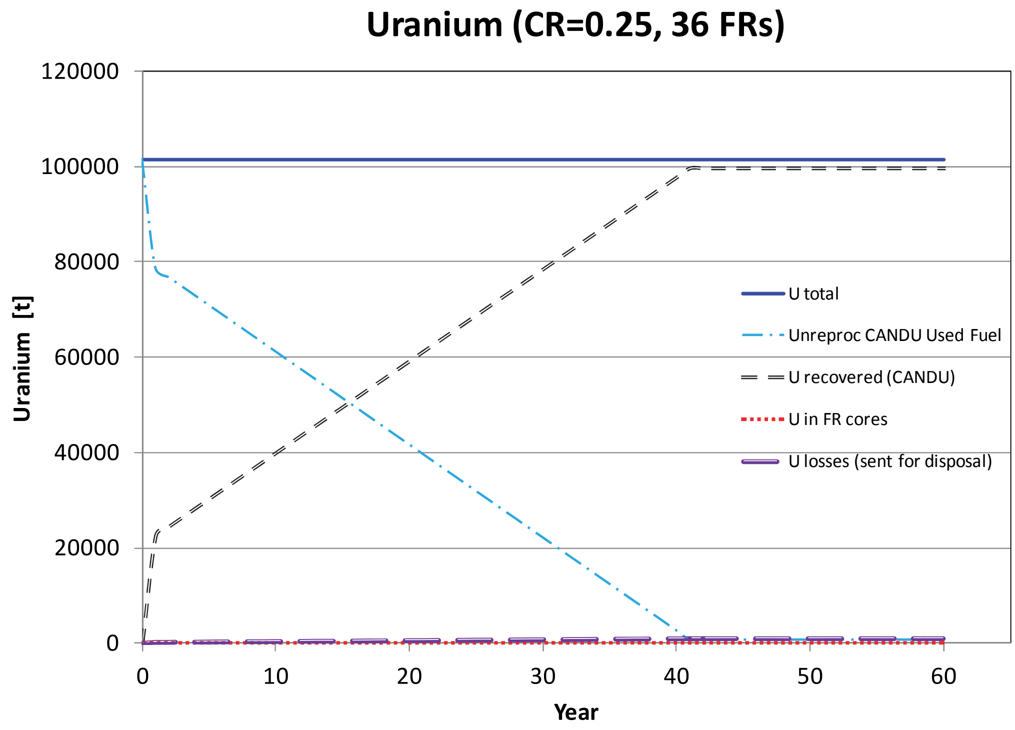
In case of a very low conversion ratio, CR=0.25, it is noted that the system inventory would have insufficient TRU amounts in the unreprocessed CANDU used fuel to continue operation of the FRs after slightly over 40 years, and at that point another source of TRUs or fissile material would be needed, or the fast reactors would need to be converted to breeder reactors, in order to continue supplying electricity.

A larger amount of TRU however, about 20-25% of the initial CANDU used fuel TRU inventory, is noted to still be present in the FR cores. This TRU would need to be managed at the end of the operating life of the fast reactors. It could be reduced through use as fuel in a smaller number of FRs with an extended operation life not shown in these analyses.

The small amount of TRU remaining for disposal after the various fast reactor scenarios is the cumulative residual amount due to reprocessing of both CANDU and FR used fuels and due to fresh fuel fabrication inefficiencies.

During reprocessing of the CANDU used fuel, a large quantity of uranium is estimated to be recovered, which could be either stored for future re-use as make-up in the fast reactor or sent for disposal.

6(a)



6(b)

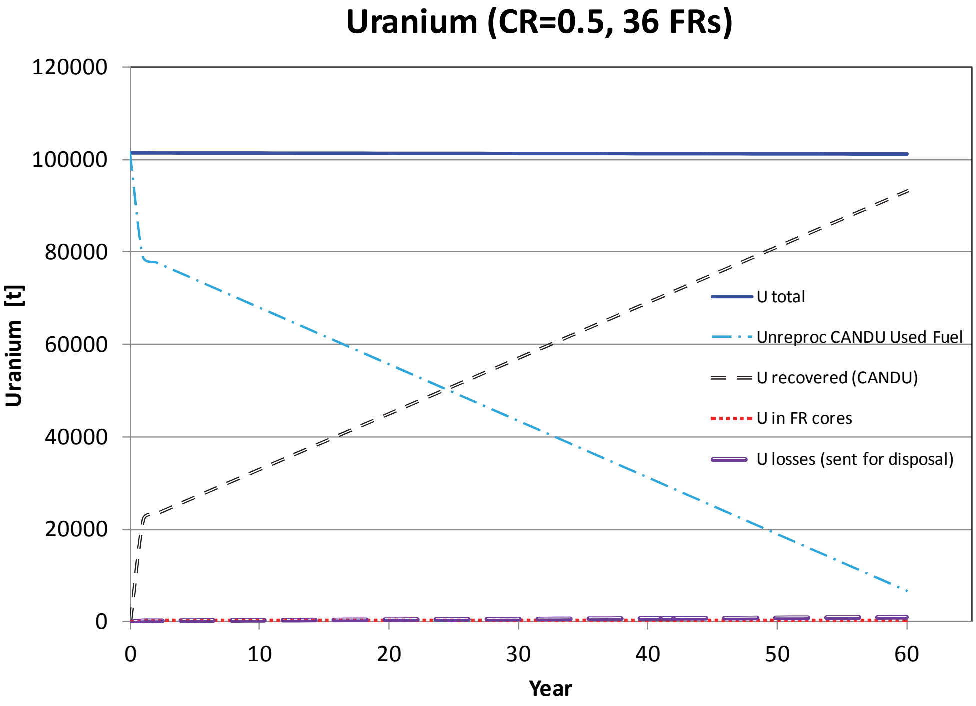


Figure 6: Total Uranium System Inventory for Scenario with 36 Fast Reactors Starting from 103,000 t_{HM} CANDU Used Fuel, for Three Conversion Ratios (0.25, 0.5, 0.75)

6(c)

Figure 6 (cont.): Total Uranium System Inventory for Scenario with 36 Fast Reactors Starting from 103,000 t_{HM} CANDU Used Fuel, for Three Conversion Ratios (0.25, 0.5, 0.75)

2.3.4 Reprocessing Rates

The amounts of reprocessed CANDU and FR used fuel required to start-up or operate FRs are estimated for the three scenarios previously described. Table 6 presents the results for a very low conversion ratio, CR=0.25. It is assumed that CANDU and FR used fuel would be reprocessed in separate plants, with different reprocessing capacities.

For Scenario 1, with two FRs constructed for long-term waste management of all of the CANDU used fuel, the results show the reprocessing rates for both CANDU and FR used fuel would be at technologically practical levels. A 110 t_{HM}/yr reprocessing plant for CANDU fuel would be sufficient to support the FR operations, but would need to start about 12 years ahead of the FR to build up enough TRUs to support the initial FR core loading. A much smaller capacity plant of about 10 t_{HM}/yr could be used to reprocess the FR used fuel.

For Scenario 2, with 36 FRs constructed to replace the existing CANDU fleet and produce the same electricity, the results show that to support FR operation, two reprocessing plants of about 1000 t_{HM}/yr reprocessing capacity each would be required, and these would need to start about 12 years ahead of the FR start-up to produce the initial core load. The FR used fuel could however be reprocessed in a 60 t_{HM}/yr plant.

Table 5: System Inventory for Scenario 2 with 36 FRs and 103,000 t_{HM} CANDU Used Fuel

		Initial	Final		
			CR=0.25 (41 yrs)[1]	**CR=0.5** (60 yrs)[2]	**CR=0.75** (60 yrs)[2]
Unreprocessed CANDU Used Fuel [t]	U	101,524	714.4	6786.8	47990.5
	TRU	454	3.2	30.4	214.6
	FP	1022	7.2	68.3	483.3
FR Core(s) [t]	U	0	93.3	216.9	364.9
	TRU	0	112.8	105.4	99.0
	FP	0	16	17.9	19.8
Reprocessing and Fuel Fabrication:					
• Waste Sent for Disposal [t]	U_{loss}[3]	0	1018.5	980.4	587.3
	TRU_{loss}[4]	0	8.7	10.7	9.1
	FP	0	1485.8	1655.4	1245
• Uranium Recovered from Reprocessing of CANDU Used Fuel Stored for Re-use or Sent for Disposal [t]	$U_{recov,Can}$[5]	0	99540.2	93128	51986.6
	Total U [t]	101,524	101,366	101,112	100,929
	Total TRU [t]	454	125	146	323
	Total FP [t]	1022	1509	1742	1748

Notes:

1) At the end of year 41, there will be insufficient TRU in the unprocessed CANDU used fuel to continue operation of the FRs with CR=0.25.
2) It is assumed that the operating lifetime of the FRs is 60 years.
3) U_{loss} represents uranium losses from reprocessing of CANDU and FR used fuel, plus losses from fuel fabrication.
4) TRU_{loss} represents TRU losses from reprocessing of CANDU and FR used fuel, plus losses from fuel fabrication.
5) $U_{recov,\ Can}$ represents uranium recovered during reprocessing of CANDU used fuel which could be stored for future re-use as make-up in the fast reactor or sent for disposal.

Table 6: Reprocessing Rates for FR Start-up or Operation, for CR=0.25

Scenario	FR Start-up	FR Operation
2 FRs	1290 t_{HM} CANDU used fuel	110 t_{HM}/yr CANDU used fuel
		4 t_{HM}/yr FR used fuel
36 FRs	23,220 t_{HM} CANDU used fuel	1980 t_{HM}/yr CANDU used fuel
		60 t_{HM}/yr FR used fuel

All reprocessing rates presented above would be within the capacity rates of the current aqueous processing technology. For example, the reprocessing capacity at La Hague (France) is about 1700 t_{HM}/yr. This technology has been extensively used to reprocess LWR fuel but has not been applied to CANDU used fuel. Pyroprocessing has been demonstrated to be feasible at engineering-scale (i.e., 0.1 t_{HM}/yr capacity), with a conceptual design being currently developed by ANL for a 100 t_{HM}/yr pilot plant for LWR spent fuel (Chang 2009, 2014).

3. DISCUSSION

Current CANDU used fuel inventory is about 50,000 t_{HM}. If all existing operating reactors were refurbished and operated to end-of-extended life, the used fuel inventory would increase to 103,000 t_{HM}.

This report documents a high-level analysis of an advanced nuclear fuel cycle where the TRUs from the CANDU used fuel were assumed to be burned in a S-PRISM based fast reactor. Mass flow calculations were performed to estimate the impact of such a nuclear fuel cycle from a waste management perspective, i.e., in terms of amounts of generated waste, as well as estimating the time that would be needed to use all the TRUs in the CANDU used fuel.

Calculations were performed for a FR design with different core configurations, developed by ANL for metal-fuel options with conversion ratios less than 1 (i.e., “burners”). For a high TRU consumption rate, a very low conversion ratio would be desired in a FR. A reactor with conversion ratio of 0.25 was thus used to estimate the amount of waste resulting from the overall nuclear fuel cycle. As operation of a FR with such conversion ratio would involve significant engineering challenges, calculations were also performed considering reactors with conversion ratios of 0.5 and 0.75, which would be more likely to be developed based on existing technology.

Scenarios considered the deployment of fast reactors only (no further CANDUs) as a method for waste management and for electricity production, with all reactors assumed to start operation simultaneously. If fast reactors were started up in some sequence, as would be likely, the net effect at the level of detail of the present analysis would be to extend all the time frames proportionately.

All calculations were based on the assumption that the amount of reprocessed CANDU used fuel is not limiting and that all CANDU fuel can be reprocessed quickly enough to supply the needs of the FRs.

The total amount of TRUs and FPs that would constitute HLW from the advanced nuclear fuel cycle was calculated. This total includes the amount remaining in the unreprocessed CANDU used fuel, the amount in FR cores, and the amount in wastes intended for disposal.

With one power block of two S-PRISM type fast reactors (0.76 GWe) in operation, it was noted that the yearly consumption of the TRUs was very small, whether the FRs were operating with a conversion ratio of 0.25, 0.5 or 0.75. Further, for two FRs operating with CR=0.25, it was estimated that it would take almost 1000 years to consume the entire amount of TRUs in 103,000 t_{HM} of CANDU used fuel. However, as the operating life of a FR was assumed to be 60 years, this means that approximately 15 generations of 2 FRs (or 30 FRs) would be needed to burn the entire amount of TRUs in the CANDU used fuel. During this period, there would also be continuous production of fission products.

If the current nuclear fleet was replaced with fast reactors, it would require 36 S-PRISM type fast reactors to produce 13.7 GWe annually. If all these reactors were assumed to start operation simultaneously at year 1 with a favorably low conversion ratio of CR=0.25, it would take within about 50 years to burn the TRUs in the 103,000 t_{HM} of CANDU used fuel. Although there would be insufficient TRU amounts in the remaining unreprocessed CANDU used fuel to continue operation of all the FRs after slightly over 40 years, there would still be significant TRU amounts in the FR cores. This could be consumed by continued longer operation of 1 or 2 FRs. For the same scenario (36 FRs) and considering a more practical conversion ratio (CR=0.5), the CANDU TRU inventory would not be consumed within the assumed 60 years life of these fast reactors.

More generally, it may be noted that the approximate number of power blocks of PRISM-type FRs needed to consume the TRUs in the CANDU used fuel is similar in units of GWe-yr to that of the original CANDU reactors, with the exact correspondence depending on the assumed FR conversion ratio. In essence, adopting FRs to burn TRUs is as much an electricity production strategy as a waste management strategy.

In all these cases, the total amount of TRUs plus FPs from the advanced nuclear fuel cycle in Canada increases with time, reflecting the steady production of FP at a rate that is faster than the TRU consumption. That is, neither of these scenarios results in a net loss of the hazardous component of used fuel within Canada. The nature of the resulting high-level waste will change over time as the TRU fraction decreases, and becomes more fission product based. The implications of that on long-term safety, radiotoxicity, and heat generation have been assessed in a separate report (Gobien 2015).

It is also noted that the amount of TRUs in the FR cores could be an appreciable fraction of the initial amount in CANDU fuel, and this amount would require to be managed at the end of the operating life of the fast reactors.

The total amount of uranium in the system was also estimated for the scenario of 36 FRs using 103,000 t_{HM} CANDU used fuel, for all conversion ratios. In all cases the results showed that there was an insignificant reduction in the total amount of uranium system inventory, which would require management.

As previously mentioned, all scenarios considered in this analysis were based on the assumption that the amount of reprocessed CANDU used fuel would not impose any practical limitations on the overall nuclear fuel cycle. The CANDU and FR used fuel required to be reprocessed to provide sufficient fuel for start-up and subsequent operation of the FRs were estimated. All reprocessing rates would be within the capacity rates of the current aqueous processing technology, which has been extensively used to reprocess LWR fuel only (i.e., 1700 t_{HM}/year at AREVA's La Hague plant). For pyroprocessing, although demonstrated to be feasible, a conceptual design is currently being developed by ANL for a 100 t_{HM}/yr pilot plant for LWR spent fuel.

The very low conversion ratio (CR=0.25) considered in this analysis would require a high TRU enrichment, which is beyond the current irradiation experience with plutonium-based fast reactor fuels. It has been reported that based on current technology, the CR would be more likely in the range of 0.5 - 0.6 for such a reactor. The core designs used in this analysis are those developed by ANL, which are based on assumptions of high TRU enrichment for low CRs, with significant engineering challenges and uncertainties associated with the detailed fuel design, as well as potentially additional concerns regarding nuclear proliferation.

A FR capacity factor of 85% was assumed for all core configurations in this analysis. The capacity factor will ultimately depend on the CR as the refuelling frequency, number of assemblies replaced per outage, and unplanned outages related to fuel failures, will differ from one core configuration to another. It is likely that FRs with lower CRs would have lower capacity factors due at least to the higher rate of fuel shuffling required.
Also as noted earlier, this analysis assumes that the isotopic composition of TRUs from used CANDU fuel are sufficient for ensuring appropriate reactor criticality and stable reactivity.

It is noted that it is expected that reprocessing of used fuel is expected to generate a significant volume of metal cladding hull wastes, low-level waste and intermediate-level waste. This was not evaluated in this report.

REFERENCES

AREVA. 2013. Processing for Recycling. AREVA Website: http://www.areva.com/EN/operations-3024/nuclear-used-fuel-processing-reduction-in-the-volume-of-waste.html (accessed April 23, 2015).

Berger, J. and R. Benedict. 2011. An Integrated Mass Balance Model for Pyrochemical Processing. Nuclear Technology 175, 450-459.

Cacuci, D.G. (Ed). 2010. Handbook of Nuclear Engineering, Vol. 1 - Nuclear Engineering Fundamentals. Springer Inc. USA.

Chang, Y.I. 2009. Integral Fast Reactor and Associated Fuel Cycle System. Part 3. Status of Pyroprocess Development. Joint ICTP/IAEA School on Physics and Technology of Fast Reactors Systems. Trieste, Italy.

Chang, Y.I. 2014. Fuel Cycle Based on Integral Fast Reactor and Pyroprocessing. International Symposium on “Present Status and Future Prospective for Reducing Radioactive Waste ~Aiming for Zero Release~”. Tokyo, Japan.

Dubberley, A.E., T. Wu and S. Kubo. 2003a. S-PRISM High Burnup Metal-Fuel Core Design. For Session 3: Future Deployment Programs and Issues. Proc. ICAPP ’03. Cordoba, Spain.

Dubberley, A.E., C.E. Boardman, D.G. Carroll, C. Ehrman and C.E. Water. 2003b. S-PRISM Fuel Cycle Study. For Session 3: Future Deployment Programs and Issues. Proc. ICAPP ’03. Cordoba, Spain.

Garamszeghy, M. 2015. Nuclear Fuel Waste Projections in Canada – 2015 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2015-19. Toronto, Canada.

GEH. 2015. How PRISM Works. GE Hitachi Nuclear Energy Website: http://gehitachiprism.com/what-is-prism/how-prism-works/ (accessed April 1, 2015).

Gobien, M. 2015. Preliminary Hazard Assessment of Waste from an Advanced Fuel Cycle. Nuclear Waste Management Organization Technical Report NWMO-TR-2015-22. Toronto, Canada.

Hoffman, E.A., W.S. Yang and R.N. Hill. 2006. Preliminary Core Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios. Argonne National Laboratory report ANL-AFCI-177. Argonne, USA.

Kok, K.D. (Ed). 2009. Nuclear Engineering Handbook. CRC Press. USA.

Lee, Y.-K. and M.-H. Kim. 2015. Performance Evaluation of a Transmutation Sodium-Cooled Fast Reactor in Recyling Scenarios. Actinide and Fission Product Partitioning and Transmutation, Proc. Thirteenth Information Exchange Meeting, NEA/NSC/R(2015)2. Seoul, Republic of Korea.

MIT. 2011. The Future of the Nuclear Fuel Cycle, An Interdisciplinary MIT Study. Massachusetts Institute of Technology. Cambridge, USA.

Nuclear Fuel Cycle Options Catalog. 2014. https://inlportal.inl.gov/portal/server.pt/community/nuclear_science_and_technology/337/online_nuclear_fuel_cycle_options_catalog (accessed July 15, 2015).

OECD. 2012. Spent Nuclear Fuel Reprocessing Flowsheet. A Report by the WPFC Expert Group on Chemical Partitioning of the NEA Nuclear Science Committee. NEA/NSC/WPFC/DOC(2012)15. Paris, France.

Ottensmeyer, P. 2013. Accelerated Reduction of Used CANDU Fuel Waste with Fast-Neutron Reactors: Fuel Cycle Strategy Cuts TRU Waste Lifespan from 400,000 Years to Less than 80 Years. Proc. 34rd Annual Conference of Canadian Nuclear Society. Toronto, Canada.

Richter, B., D.C. Hoffman, S.K. Mtingwa, R.P. Omberg, J.L. Rempe and D. Warin. 2006. Report of Advanced Nuclear Transformation Technology Subcommittee of the Nuclear Energy Research Advisory Committee. US Department of Energy. USA.

Tait, J.C., H. Roman and C.A. Morrison. 2000. Characteristics and Radionuclide Inventories of Used Fuel from OPG Nuclear Generating Stations, Volume 2 – Radionuclide Inventory Data, Appendix A. OPG Report 06819-REP-01200-10029-R00. Toronto, Canada.

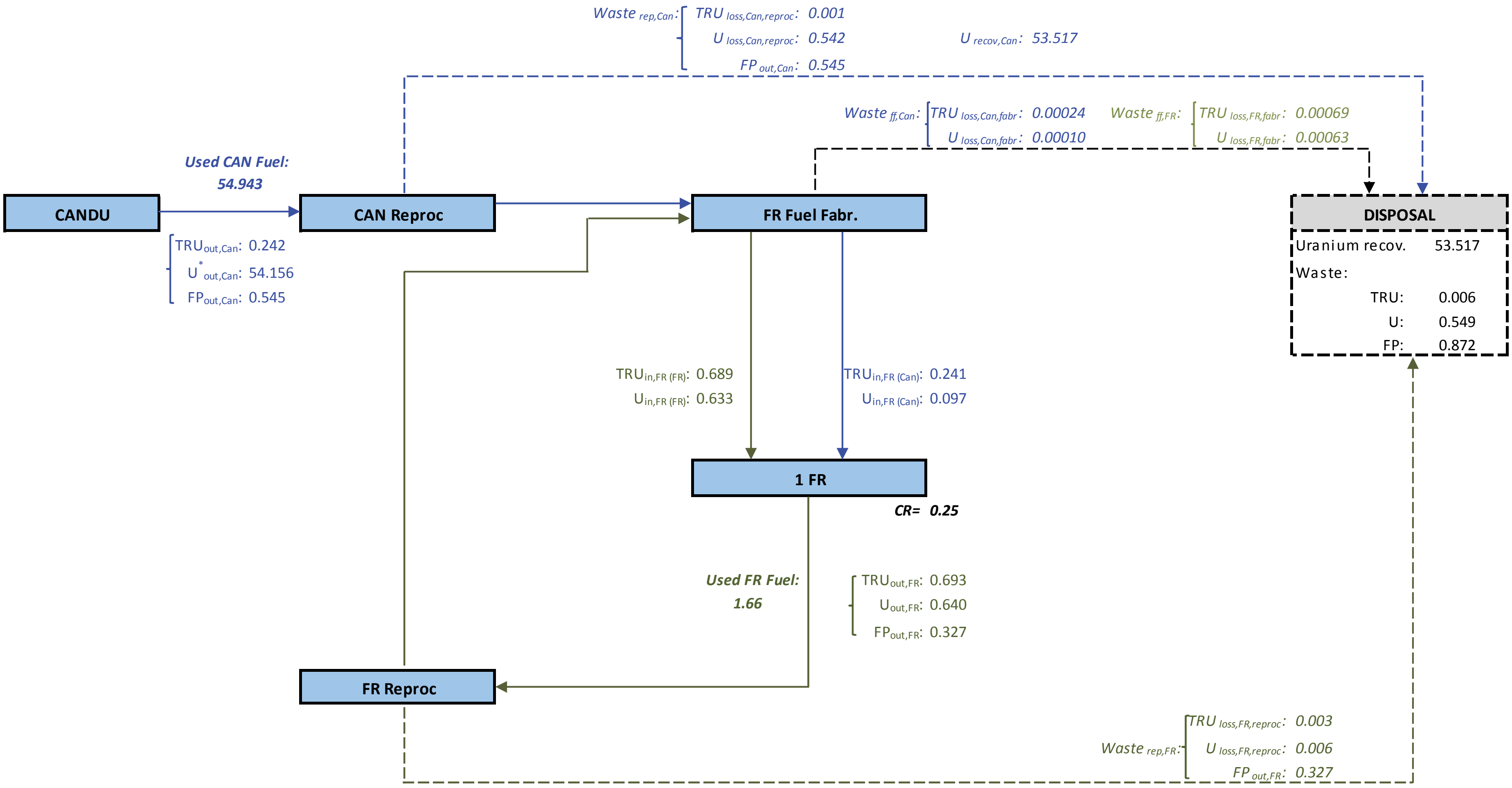
Triplett, B.S., E.P. Loewen and B.J. Dooies. 2012. PRISM: A Competitive Small Modular Sodium-Cooled Reactor. Nuclear Technology 178, 186-200.

Waltar, A.E., D.R. Todd and P.V. Tsvetkov (Eds.). 2012. Fast Spectrum Reactors. Springer Inc. USA.

Williamson, M.A. and J.L. Willit. 2011. Pyroprocessing Flowsheets for Recycling Used Nuclear Fuel. Nuclear Engineering and Technology, 43(4), 329-334.

Yoo, J.-H., C.-S. Seo, E.-H. Kim and H.-S. Lee. 2008. A Conceptual Study of Pyroprocessing for Recovering Actinides from Spent Oxide Fuels. Nuclear Engineering and Technology 40, 581-592.

APPENDIX A: RECYCLING CANDU USED FUEL IN FAST REACTOR - SAMPLE FLOWSHEET



Notes:

*** The uranium recovered from reprocessing of CANDU used fuel can be either stored for future use or sent for disposal**

**** All quantities are in t/yr**

Figure A.1: Sample Flowsheet of an Advanced Fuel Cycle for a Scenario with 1 Fast Reactor (CR=0.25) at Equilibrium