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Fuel cycle analysis of Advanced Burner Reactor with breed-and-burn thorium blanket

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A B S T R A C T

The Seed-and-Blanket (S&B) Sodium-cooled Fast Reactor (SFR) core concept was proposed for generating a significant fraction of the core power from thorium fueled breed-and-burn (B&B) blankets without exceeding the presently verified radiation damage constraint of 200 Displacement per Atom (DPA). To make beneficial use of the excess neutrons from fast reactors, the S&B core is designed to have an elongated TRU transmuting (or "TRU burner") seed from which over 20% of the fission neutrons leak into a subcritical thorium blanket that radially surrounds the seed. The seed fuel is recycled while the blanket operates in a once-through breed-and-burn (B&B) mode. The objective of this paper is to compare the fuel cycle performance of the S&B reactor against an Advanced Burner Reactor (ABR) and a conventional Pressurized Water Reactor (PWR). For the fast reactors (SFR: ABR and S&B) the fuel cycle performance is evaluated based on a 2-stage PWR-SFR energy system while the reference nuclear system is made of once-through PWRs.

It was found that relative to the ABR, the S&B core has a lower fuel cycle cost, higher capacity factor, and comparable short-term radioactivity. The discharged seed fuel from the S&B core features lower fissile Pu-to-Pu ratio, higher ^{238}Pu-to-Pu ratio, higher specific plutonium decay heat, higher spontaneous fission rate, and lower overall material attractiveness for weapon use. Due to the significant amount of ^{233}U discharged from the breed-and-burn thorium fueled blankets, the S&B core has much higher long-term radioactivity and radiotoxicity. Since the thorium fueled blanket operates in the breed-and-burn mode and requires no fuel reprocessing, the discharged blanket fuel is unattractive for weapons application.

Compared with a PWR, the S&B core has a lower fuel cycle cost, much lower short-term radioactivity and radiotoxicity but higher long-term values, and higher proliferation resistance for the discharged plutonium. The natural uranium utilization of the 2-stage PWR-S&B system is approximately 60% higher than that of present PWRs; it is few percent higher than that of the 2-stage PWR-ABR system. Approximately 7% of the thorium fed to the blanket is converted into energy, which makes the thorium fuel utilization approximately 12 times the utilization of natural uranium in PWRs.

A comprehensive fuel cycle evaluation performed with the methodology developed by the recent U.S Department of Energy's Nuclear Fuel Cycle Evaluation and Screening campaign concludes that the PWR-S&B system has similar fuel cycle performance characteristics as the PWR-ABR system. The S&B concept may potentially feature improved economics and resource utilization relative to the ABR.

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1. Introduction

The Breed-and-Burn (B&B) fast reactor concept has been proposed to make beneficial use of the large stockpiles of depleted uranium (DU) without recycling the discharged fuel (Greenspan and Heidet, 2011; Ellis et al., 2010; Sekimoto et al., 2001; Driscoll et al., 1979). Previous neutronic analysis (Hou et al., 2016; Heidet and Greenspan, 2012) showed that the minimum average burnup required for sustaining the B&B mode of operation with DU fuel is close to 20% Fissions per Initial Metal Atom (FIMA). This corresponds to a peak radiation damage of approximately 500 Displacements per Atom (DPA). The previous studies also concluded that it is not possible to sustain a B&B mode of operation in a critical core that is fed with natural thorium (Zhang et al., 2014). The maximum radiation damage that cladding materials have been exposed to so far is ~200 DPA. While waiting for the development of a cladding material that can be certified to withstand ~500 DPA, it was

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proposed to start benefiting from the B&B mode of operation by using a Seed-and-Blanket (S&B) core configuration (Greenspan, 2012). Instead of using accelerator-driven spallation neutron sources (Brown et al., 2016; Heidet et al., 2015; Lin et al., 2017), the S&B core is designed to have a subcritical breed-and-burn thorium fueled blanket that is driven by the excess neutrons from a TRU transmuting seed without exceeding the 200 DPA constraint.

Typical Sodium-cooled Fast Reactor (SFR) cores have a core height of approximately one meter and feature an axial neutron leakage probability of over 20%. The large neutron leakage enables passive safety by reducing the positive coolant voiding reactivity feedback and increasing the negative reactivity feedback to the radial core expansion and axial fuel expansion. Besides the safety reason, there is no constructive use of these axially leaking neutrons. Early studies (Zhang and Greenspan, 2014; Zhang et al., 2013, 2015) found that it is feasible to design passively safe S&B cores to have a large height-to-diameter TRU burner seed. The elongated configuration maximizes the fraction of seed neutrons that radially leak into the blankets and reduces the neutron loss via axial leakage. The seed fuel is recycled whereas the thorium fueled blanket operates in the once-through B&B mode. There is a unique synergism between a low conversion ratio (CR) seed and a thorium B&B blanket (Zhang and Greenspan, 2014; Zhang et al., 2013, 2015). It is possible to design such an S&B core in which over 50% of the core power is generated from the thorium blanket (Zhang et al., 2017a). Since the blanket fuel requires no reprocessing and remote fuel fabrication, its cost is orders of magnitude smaller than that of the seed fuel. The seed loaded with high TRU content fuel features a low DPA/burnup ratio such that it can discharge the fuel at very high average burnup without exceeding 200 DPA. As a result of the high seed discharge burnup and the high fraction of core power generated by the blanket, the reprocessing capacity required for such an S&B core can be as low as one-fifth that of a conventional ABR core with comparable transmutation capability. Therefore, the fuel cycle cost of the S&B core is expected to be lower than that of the ABR. While the leaking neutrons from the seed "drive" the blanket fuel in the B&B mode, the reactivity gained in the blanket over the cycle partially compensates for the reactivity loss in the seed. The reduced burnup reactivity swing, along with the low power density in the blanket, enables the cycle length to be much longer than that of a typical ABR. The longer cycle is expected to increase the capacity factor and further reduce the cost of electricity generated by the S&B SFR. Due to the unique physics of the thorium fuel cycle, the thorium fueled blanket also makes the void reactivity worth of the S&B core less positive than that of a compact ABR core and provides adequate negative Doppler reactivity coefficient even when using inert matrix fuel for the seed (Zhang et al., 2017a).

The objective of this study is to quantify the fuel cycle performance of the S&B core concept relative to Argonne National Laboratory's (ANL) ABR and a conventional PWR. Section 2 describes the representative reactors used for the comparisons. Section 3 summarizes the methodologies used for the fuel cycle study. Section 4 compares the performance characteristics of the equilibrium fuel cycle, fuel cycle cost, waste characteristics, proliferation resistance of the discharged fuel, natural resource utilization, and a comprehensive fuel cycle evaluation. Conclusions of this study are summarized in Section 5.

2. Descriptions of S&B ABR, and PWR energy systems

2.1. Reference S&B core

The specific S&B core used in this fuel cycle study is the annular seed design (Zhang et al., 2017a) illustrated in Fig. 1 and Table 1.

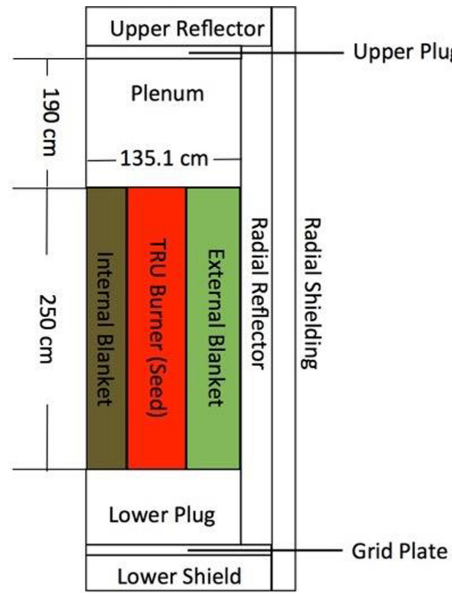

Fig. 1. Schematic configuration of the S&B core.

Table 1
Dimensions and composition of the components in S&B cores (Zhang et al., 2017a).

Property	Component	Value (cm)	Material (vol%)
Axial Dimension	Upper Reflector	60.0	50% HT9 – 50% Na
	Upper End Plug	2.5	22% HT9 – 78% Na
	Upper Plenum	191.1	Design variable[a]
	Active core	250.0	28% Fuel – 21% HT9 – 51% Na (seed) 51% Fuel – 22% HT9 – 27% Na (blanket)
	Lower End Plug	111.7	22% HT9 – 78% Na
	Grid Plate	5.2	50% HT9 – 50% Na
	Lower Shielding	30.0	47% B4C - 21% HT9 - 32% Na
Radial Dimension[b]	Active Core OD[c]	270.3	Design variable[d]
	Reflector OD	326.2	50% HT9 – 50% Na
	Shielding OD	354.1	47% B4C – 21% HT9 – 32% Na
Assembly Geometry	Assembly Pitch	16.124	–
	Duct Gap	0.432	–
	Duct Wall Thickness	0.394	–

[a] Same volume fractions for cladding and coolant are applied as those in active core region.
[b] Approximate value for R-Z model.
[c] Outer Diameter (OD).
[d] The fractions of fuel/cladding/coolant depend on the P/D ratio of fuel assemblies.

Both seed and blanket are designed to operate with multi-batch fuel management scheme: half of the seed fuel is discharged and recycled after each cycle; the innermost batch of the internal blanket is discharged; the other blanket batches are shuffled inward (the innermost batch of the outer blanket is shuffled to the outermost batch of the inner blanket); and fresh thorium fuel is loaded into the outermost blanket batch. The seed region is loaded with inert matrix TRU-10wt%Zr and transmutes TRU at a rate of 383.3 kg/GWe-EFPY.[1]

The high fissile content in the nearly zero CR seed minimizes the number of required seed fuel assemblies and enables to use a

[1] The TRU transmutation rate is normalized by the power of the seed. EFPY means Effective Full Power Years.

large pitch-to-diameter ratio (P/D). Both features maximize the fraction of seed fission neutrons that leak into the subcritical blanket. As a result, the fraction of core power generated by the thorium blanket is the highest at – 57.7%. The higher TRU concentration of the CR ~0.0 seed also results in a lower flux amplitude for a given fission density and therefore more than twice the average discharge burnup than that of the reference ABR without exceeding the radiation damage constraint of 200 DPA. The high average discharge burnup of the seed fuel along with the large fraction of core power generated by the blanket reduces the reprocessing capacity and the fuel cycle cost. A detailed description of this core design is given in Zhang et al. (2017a).

The reference S&B core considered for this fuel cycle analysis was designed to set upper bounds on the S&B core performance by using larger core height and pressure drop than those of typical SFR designs and using unproven inert matrix fuel for the seed. A sensitivity analysis was undertaken to quantify the tradeoff between S&B core design variables and the core performance (Zhang et al., 2017a). The design variables considered include the Zr content in the TRU-Zr inert matrix fuel, the active core height, the core pressure drop, and the cladding radiation damage (Zhang et al., 2017a). The seed fuel in the high transmutation core was changed from TRU-10Zr to TRU-40Zr that has been successfully irradiated in the past (Hayes et al., 2015). The higher Zr content in the non-fertile fuel raises the solidus/liquidus temperature. As a result, the fraction of core power generated from the blanket decreases from 57.7% to 50.7%. However, due to its higher Zr and lower TRU concentrations, the new seed has a softer spectrum and can achieve a higher discharge burnup for the same radiation damage constraint. The reprocessing capacity required per unit of electricity generated is slightly lower in the seed with TRU-40Zr than the reference S&B core. However, the application of TRU-40Zr reduces the cycle length from 1550 EFPD to 840 EFPD; this cycle length is still almost four times longer than of the reference ABR.

In another sensitivity analysis, the core height was reduced in steps from 250 cm down to 90 cm. A compact S&B core with 120 cm active height and less than half the reference core pressure drop is comparable in core volume, HM mass, and specific power to the S-PRISM core (Dubberley et al., 2000). 43% of this core power is generated from the once-through thorium blankets, and the reprocessing capacity per unit of electricity generated by this compact S&B core is approximately one-fifth that of a comparable ABR – only slightly larger than that of the reference 250 cm tall S&B core. Likewise, the TRU transmutation rate and the average discharge burnup of the thorium blanket of the compact S&B core are similar to those of the reference S&B core. The cycle length of the compact S&B core is reduced to 350 EFPD – still longer than that of the reference ABR design.

In summary, the reference S&B core considered in this study is the one used for getting upper bound estimates. It features 250 cm tall active core containing TRU-10wt% Zr fuel and 0.9 MPa pressure drop. Moreover, the radiation damage constraint of 200 DPA imposed on the S&B core design enables the seed and blanket fuel of this core to reach higher burnup, compared with the constraint imposed on the ABR design (Zhang et al., 2017a) – a fast neutron fluence of 4×10^{23} n/cm^2. Nevertheless, the conclusions of this paper are expected to reasonably represent those of a realistic S&B core design.

2.2. Reference ABR

The ANL's ABR was designed to consume transuranic elements generated from the present PWR fleet. The reference ABR core (Hoffman et al., 2006) features TRU-DU-10Zr fuel arranged in three TRU enrichment zones and operates in a multi-batch fuel management scheme. At the end of the equilibrium cycle, a certain number of fuel assemblies are discharged from each enrichment zone and reprocessed; TRU and DU are added as the makeup fuel; 98.8% of the heavy metals are recycled, and the remaining 1.2% are assumed lost[2] and eventually are disposed of in a geological repository. The ANL's studies demonstrated that the ABR concept could accommodate a wide range of TRU CR (Hoffman et al., 2006). The reference ABR compared against in this paper features a TRU CR of 0.5, which has a similar TRU transmutation rate as the reference S&B core of an identical power level. This avoids the bias on the power sharing of the two-stage systems considered in this study. It is possible to design the ABR core to have a CR lower than 0.5, but this implies undesirably short cycles when imposing the commonly used burnup reactivity swing constraint of 3.5%Δk/k. In fact, ANL recommends not to use CR of less than 0.73 for near-term applications (Kim et al., 2009).

2.3. Reference PWR

The stand-alone PWR core used as a reference in this study is fueled with 4.5 wt% enriched uranium dioxide (UOX) that is discharged at an average burnup of 50 MWd/kg. It uses a three-batch once-through fuel management scheme. The discharged fuel is sent to the geological repository after 10-year interim storage on site.

2.4. Two-stage systems

Fig. 2 shows a schematic view of the fuel cycle for a 2-stage PWR-SFR system in which either the S&B core or the ABR core is used in stage 2. The first stage consists of a typical PWR described in Section 2.3. The TRU recovered from the PWR in stage-1 is mixed with DU and fed to stage 2 cores – either to the seed of the S&B core or the ABR core. As the ABR and the seed in S&B cores are designed to incinerate TRU recovered from PWR's Used Nuclear Fuel (UNF), they operate on a closed fuel cycle. The blanket of the S&B core is a once-through thorium cycle. The fuel mass loaded into stage i reactor per unit of electricity generated is obtained from

$$M_i = \frac{P^i_{th}}{BU_i \times P^i_{el}} \times \frac{365d}{1yr} \tag{1}$$

where

M_i is the fuel mass charged per GWe-EFPY to stage i,
P^i_{th} is the thermal power of stage i
P^i_{el} is the electrical power of stage i
BU_i is the discharge burnup from stage i.

At the equilibrium state, the TRU discharge rate from stage 1 is equal to the TRU incineration rate in stage 2. That is,

$$F^1_{el} \times TRU^1_P = F^2_{el} \times TRU^2_D \tag{2}$$

F^i_{el} is the fraction of electricity generated from stage i reactors such that

$$F^1_{el} + F^2_{el} = 1.0 \tag{3}$$

TRU^1_P is the amount of TRU produced by stage 1 reactors per unit of electricity (kg/GWe-EFPY); the typical TRU production rate of PWR with discharge burnup of 50 MWd/kg is 251.3 kg/GWe-EFPY

[2] The 1.0% recycling losses and 0.2% fabrication losses were considered for the fuel cycle analysis results of which are presented in this paper. This is consistent with the FCE&S campaign (Wigeland et al., 2014).

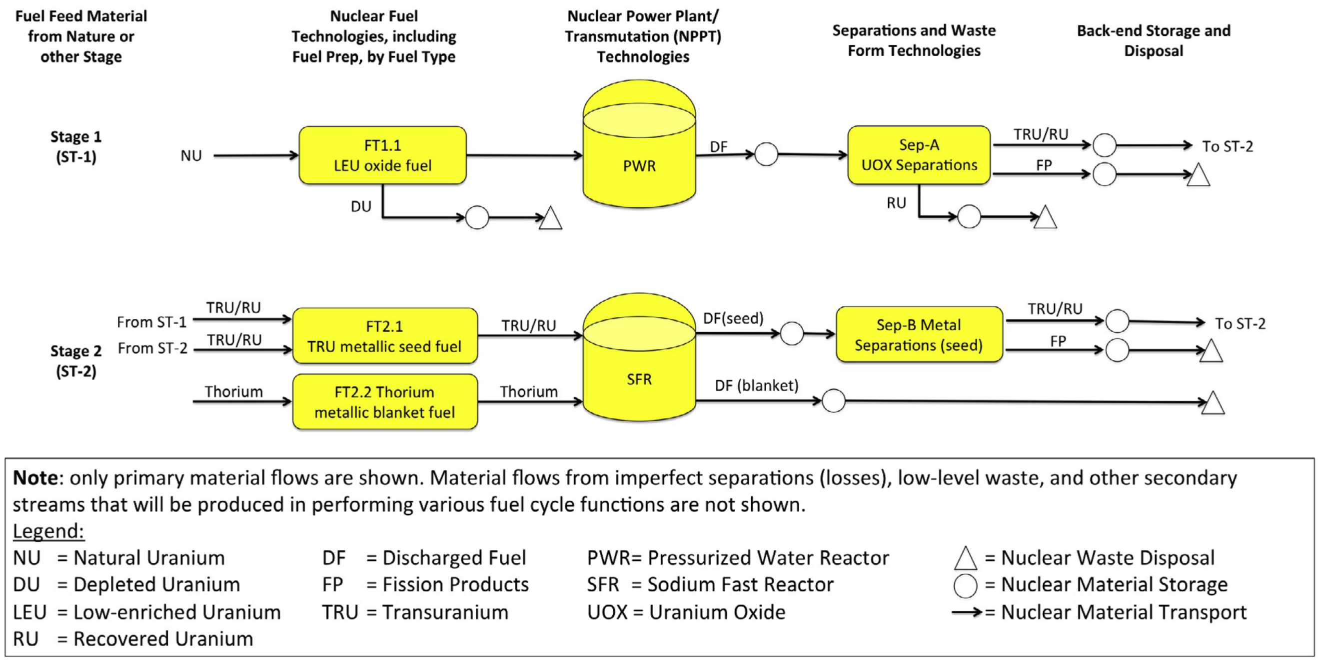

Fig. 2. Schematic view of the S&B fuel cycle. (This scheme was designed following the template of the Fuel Cycle Evaluation and Screening study (Wigeland et al., 2014).)

TRU_D^2 is the amount of TRU incinerated by stage 2 reactors per unit of electricity of these reactors (kg/GWe-EFPY).

Two different support ratios are defined based on energy sharing and installed capacity. The energy support ratio S_e is defined as the ratio of the electricity generated by stage 1 reactors to the electricity generated by stage 2 reactors:

$$S_e = \frac{F_{el}^1}{F_{el}^2} = \frac{TRU_D^2}{TRU_P^1} \tag{4}$$

This is the same support ratio as defined by Department of Energy (DOE) Nuclear Fuel Cycle Evaluation and Screening (FCE&S) campaign (Wigeland et al., 2014). It is chosen to be technology neutral and is suitable for comparison of fuel cycle metrics such as waste mass, radiotoxicity, etc. The transmuting reactors designed to have a smaller conversion ratio will feature a higher energy support ratio so that a smaller fraction of the system energy needs to be generated by the transmuting reactors. It requires approximately 1 GWe of CR = 0.5 ABR or S&B per 2 GWe of PWRs.

A second support ratio (S_c in Eq. (5)) is defined as the ratio between installed capacity in each stage:

$$S_c = \frac{TRU_D^2}{TRU_P^1} \times \frac{f_2}{f_1} \tag{5}$$

where f_i is the capacity factor of the stage-i reactor. This definition of the support ratio is more suitable for economic consideration.

3. Methodology

3.1. Metrics

The metrics used in this study to compare different nuclear energy systems are divided into six categories: (1) fuel cycle parameters pertaining to the equilibrium cycle, including fuel loading, specific power, average discharge burnup, cycle length, and reprocessing capacity; (2) fuel cycle cost accounting for the front-end and back-end activities; (3) waste characteristics including radioactivity, inhalation radiotoxicity, and ingestion radiotoxicity of the UNF at short-term (10 years) and long-term (100,000 years) after fuel discharge; (4) proliferation resistance related characteristics such as plutonium throughput, fissile plutonium fraction, ^{238}Pu fraction in plutonium, specific plutonium decay heat, spontaneous fission rate, and material attractiveness; (5) fuel utilization – the fraction of the natural uranium or thorium mined that is burned; (6) comprehensive fuel cycle evaluation metrics developed by the FCE&S campaign (Wigeland et al., 2014).

3.2. Assumptions

The assumptions used for this fuel cycle analysis are: the thermal efficiency is 40% for the fast reactors (i.e., ABR and S&B) and 33% for PWR; the discharged fuel from the ABR and the seed in the S&B core is cooled for five years before recycling. The waste (Section 4.3) and fuel utilization (Section 4.4) studies assume 1.2% heavy metal loss via the waste stream during fuel reprocessing and fabrication.

Based on the cycle length – 493 Effective Full Power Days (EFPD) for the PWR and 221 EFPD for the ABR (See Table 2), the capacity factors of PWR and ABR are assumed to be 90% and 85%, respectively, although advanced ABR cores could most likely be designed to have longer cycles and nearly 90% capacity factor. With a cycle length of 1550 EFPD (Table 2) and an assumed shutdown time of three months, the capacity factor of the S&B design is estimated to be about 95%. Most of the performance characteristics reported in this paper are independent of the capacity factors including those normalized per unit energy generated or given in units of effective full power days (years).

3.3. Computation methods

The reactor physics analysis (Zhang et al., 2017a) of the S&B core design is based on a simplified "R-Z" model which is radially divided into three equal-volume concentric burnup zones for the seed fuel and one burnup zone for each of the blanket batches. MCNP6 is used with ENDF/B-VII.0 cross-section libraries for the neutronic calculation, and ORIGEN2.2 is applied for the burnup

Table 2
Fuel cycle parameters of ABR, S&B, and PWR.

Parameter	ABR	S&B (seed/ blanket)	PWR
Capacity factor, %	85	95	90
Average discharge burnup, GWd/t	131.9	312.2/70.2	50.0
Specific power, MWth/t	105.8	100.7/9.1	33.8
Number of batches	6/6/7[a]	2/5	3
HM inventory in core, t	9.5	4.2/63.4	116.1
HM mass per batch, t	1.7	2.1/12.7	38.7
Fuel residence time, EFPD	1326/1326/1547	3100/7750	1478
Cycle length, EFPD	221	1550	493
Burnup reactivity swing, %Δk/k	−2.9	−3.6	–
TRU transmutation rate, kg/GWe-EFPY	458.7	383.3[b]	–
TRU conversion ratio of stage-2 reactor	0.50	0.01	–
Power Fraction,%			
Stage 1 (PWR)	64.6	60.4	100.0
Stage 2 (S&B or ABR)	35.4	39.6	–
Energy support ratio	1.825	1.520	–
Installed-capacity support ratio	1.723	1.610	–
Reprocessing throughput, kg/GWe-EFPY			
PWR UNF from stage-1	14154.8	13233.9	–
SFR UNF from stage-2	2446.7	487.7	–
Pu from stage-2	580.5	266.2	–
TRU from stage-2	651.6	322.9	–
Charge mass fraction, %			
Th-232	–	–/100.0	
TransTh[c]	–	–/–	4.5
U-238	66.7	2.8/–	95.5
TRU	33.3	97.2/–	
Discharge mass fraction, %			
Th-232	–	–/84.9	
TransTh	–	1.1/7.9	1.3
U-238	59.02	0.3/–	92.4
TRU	26.63	66.4/–	1.1
FPs	14.36	32.2/7.2	5.2
Fuel mass at time of recycle, %			
Th-232	–	–/–[d]	
TransTh	–	1.3/–	1.3
U-238	59.02	0.3/–	92.4
TRU	26.63	66.2/–	1.1
FPs	14.36	32.2/–	5.2

[a] The batch numbers of the inner/middle/outer cores are 6/6/7, respectively
[b] The TRU transmutation rate is normalized by the total core power.
[c] TransTh includes the actinides bred from thorium, like ^{233}U, ^{234}U, ^{235}U, but not ^{238}U and TRU.
[d] The discharged thorium fuel is not recycled so the composition is not given.

calculations. The neutron flux calculated by MCNP6 is normalized by the total core power before used in ORIGEN2.2. One-group cross-sections generated by MCNP6 for major actinides and fission products are transferred to ORIGEN2.2. The burnup-dependent compositions generated by ORIGEN2.2 are sent back to MCNP6. MCNP6 and ORIGEN2.2 are coupled via a two-tiered solver (MocDown) that automates an efficient iterative search for the equilibrium composition of multi-batch cores based on a prescribed fuel management scheme (Seifried et al., 2013).

The ABR was designed by ANL using the fast reactor suit DIF3D/REBUS-3 supplemented by the ETOE-2/MC2-2/SDX multi-group cross-section generation codes (Hoffman et al., 2006). A 3-D hexagonal-Z model was used to represent the core, and enrichment zoning strategy was applied to flatten the radial power distribution. The cycle length was estimated to make the burnup reactivity swing less than 3.5%Δk/k. The radiation damage constraint applied for the ABR core design was a peak fast neutron (E > 0.1 MeV) fluence of 4.0×10^{23} n/cm^2 whereas the S&B design was constrained by 200 DPA. The performance differences introduced by these two constraints are discussed in Zhang et al. (2017a). The bottom line is that using a peak fast neutron (E > 0.1 MeV) fluence constraint of 4.0×10^{23} n/cm^2 the performance of the S&B core is not as good as the reference design that is based on a 200 DPA. The design parameters used in this paper for the ABR fuel cycle analysis were taken from an ANL technical report (Hoffman et al., 2006).

To obtain detailed isotopic mass flow rates that are required for the fuel cycle analysis, the fresh fuel of the equilibrium cycle from MocDown is depleted by ORIGEN2.2 up to the average discharge burnup to track the isotopes that are not included in the neutronic model of MCNP or DIF3D. The one-group cross-sections used for the ORIGEN2.2 calculations are generated by MCNP with the representative neutron spectrum at the middle of equilibrium cycle. The one-group fast spectrum cross-section library distributed within the ORIGEN2.2 package is used for those isotopes that are not tracked in MCNP calculation. The waste characteristics of the discharged fuel are calculated by ORIGEN2.2, accounting for 128 actinides and 879 fission products. The PWR discharged fuel composition and waste characteristics are calculated with ORIGEN2.2 using the default ORIGEN2.2 PWR cross-section library (i.e., PWRU library).

4. Fuel cycle analysis

4.1. Fuel cycle parameters

Table 2 compares the equilibrium fuel cycle parameters of the three cores considered in this study. The capacity factor of the S&B reactor is estimated to be 95% assuming a 3-month downtime after each cycle. Due to the slightly higher TRU transmutation rate of the ABR per unit of electricity generated, a smaller fraction of the system energy is generated from the second stage in the PWR-ABR system than in the PWR-S&B system. Therefore, the support ratio of the ABR is slightly larger than that of the S&B reactor in the PWR-SFR two-stage energy system. However, if the uranium bred in the thorium blanket of the S&B core is recovered and recycled in a stage-3 PWR the support ratio of this three-stage energy system is 3.2 (Zhang et al., 2017b) – significantly higher than that of the PWR-ABR energy system. The seed fuel of the S&B core is designed to have nearly 100% TRU, and its discharge burnup is over twice that of the ABR. The high discharge burnup along with the nearly 60% of core power generated from the once-through B&B blanket significantly reduce the reprocessing capacity required per unit of electricity – 487.7 kg/GWe-EFPY for the PWR-S&B versus 2446.7 kg/GWe-EFPY for the PWR-ABR system.

4.2. Fuel cycle cost

The total cost of electricity is usually measured by the levelized electricity cost, which is composed of capital, operation-and-maintenance (O&M), and fuel cycle costs. This study evaluates the fuel cycle costs of the three nuclear energy systems, including the costs for the front-end and back-end activities. A detailed flow chart of the fuel cycles considered is shown in Fig. 3. The nominal costs of major fuel cycle activities (Table 3) reported in Shropshire et al. (2009) are used for this fuel cycle cost analysis. Due to the lack of commercial experience, there are large uncertainties in the cost components involving fuel recycling and waste disposal. Nevertheless, uncertainty quantification analysis is beyond the scope of this preliminary study.

Although extra shielding may be required to fabricate the driver fuel for the S&B core due to the higher TRU/HM ratio, this study assumes that the costs of fuel reprocessing and remote fabrication are independent of the TRU concentration in the SFR fuel. The blanket thorium fuel in the S&B core is assumed to cost 60% more than natural uranium and its fabrication cost as that of UOX fuel fabrication (Table 3). The thorium UNF disposal cost is assumed same

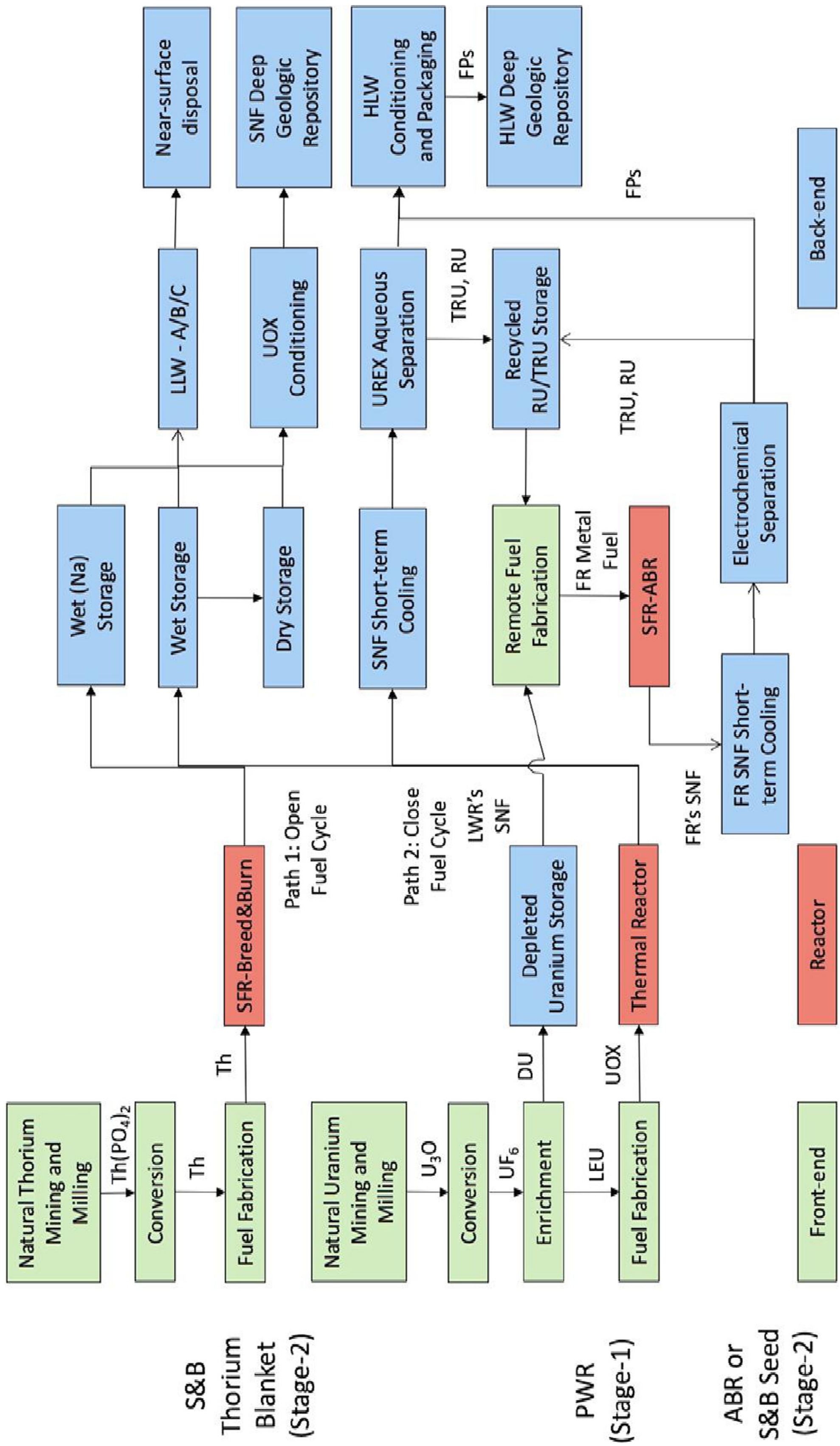

Fig. 3. Fuel cycle chart of the ABR and the S&B reactors.

Table 3
Costs of major fuel cycle activities (Shropshire et al., 2009).

Activities of fuel cycle	Cost
Natural uranium mining and milling, $/kg U	60
Natural thorium mining and milling, $/kg Th	100
Conversion processes, $/kg U	10
Enrichment, $/SWU	105
UOX fuel fabrication, $/kg U	240
UREX aqueous separation, $/kg HM	1000
Electro-chemical reprocessing & remote fuel fabrication, $/kg HM	5000
Aqueous HLW conditioning (FPs + Ln), $/kg FPs	2000
Recycled Uranium conditioning, $/kg RU	93
UOX fuel conditioning, $/kg HM	100
Geological repository (UNF), $/kg HM	1000
Geological repository (HLW FPs + Ln + Tc), $/kg FPs	10000

as that of the PWR UNF disposal although in reality it may be somewhat higher due to the higher discharge burnup – about 70 MWd/kg for the thorium blanket fuel versus 50 MWd/kg for the UOX fuel in PWR, and the different isotopic compositions. If the cost of disposing thorium UNF is 50% higher than that of LWR UNF, the fuel cycle cost of the PWR-S&B system is estimated to increase by 0.019 cents per electric kWh or 3.2% (Fig. 4). This will not change the overall conclusions of this work. For a PWR that uses uranium enriched to 4.5 wt% ^{235}U and a tailing stream containing 0.2 wt% ^{235}U, the required total separation work is 7.6 SWU per kg of enriched uranium. Thus, the cost of UOX enrichment is approximately 800 $/kg LEU.

Fig. 4 compares the fuel cycle costs of the PWR-ABR, PWR-S&B, and PWR systems. As the fuel reprocessing capacity of the S&B core is only about one-fifth that of the equal power ABR, the cost of reprocessing and remote fuel fabrication for the S&B reactor is about one-fifth that of the ABR. All the other cost components of the two 2-stage energy systems fuel cycles are similar. The net result is that the fuel cycle cost of the PWR-S&B system is about 0.60 cents/kWh versus 0.73 cents/kWh for the PWR-ABR system; it is even lower than that of present PWRs – 0.68 cents/kWh.

Due to the significantly longer fuel cycle, the capacity factor of the S&B reactor is expected to be about 10% higher than that of the reference ABR. The higher capacity factor is expected to result in lower O&M and capital cost components of the S&B reactor cost of electricity.

As noted in Section 2.1, the reference S&B core was designed to have unconventionally tall core of 250 cm to minimize the axial leakage while maximizing the radial leakage from the seed into

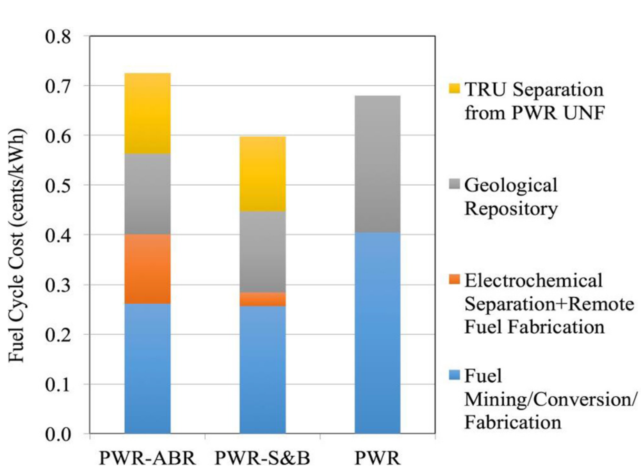

Fig. 4. Fuel cycle cost of PWR-ABR, PWR-S&B, and PWR.

the subcritical radial blanket (Zhang and Greenspan, 2014; Zhang et al., 2013, 2015). Conventional SFR cores, like ANL's ABR (Hoffman et al., 2006) and GE's S—PRISM (Dubberley et al., 2000), feature a core height of about 100 cm. Compared with these compact SFR cores, the taller S&B core is expected to somewhat increase the capital cost as it would require a larger reactor vessel and a more challenging seismic design. Nevertheless, the higher capacity factor of the S&B core is expected to compensate for the higher cost of the reactor vessel and associated systems. Moreover, a recent trade-off study (Zhang et al., 2017a) found that it is possible to design a 120 cm S&B cores with the blanket power fraction of 43.1% and approximately one-fifth the reprocessing capacity of the ABR core. This shorter S&B core would fit within the S-PRISM reactor vessel (Dubberley et al., 2000). The capital cost penalty of the S&B reactors having such a compact core is expected to be very small. Overall, the S&B core is expected to improve the economic benefit of the SFR technology.

4.3. Waste characteristics

Waste characteristics of the used nuclear fuel are quantified at short-term (10 years) and long-term (100,000 years) after the fuel is discharged from the core. The fresh fuel loaded into the equilibrium cycle of each core is depleted using ORIGEN2.2 up to the average discharge burnup (Table 2) to get an estimate of the concentrations of those isotopes that are not included in the neutronic model used for the full core analysis. Then, the waste characteristics, like isotopic inventories, radioactivity, and decay heat of the discharged fuel are computed by ORIGEN2.2 accounting for 879 fission products and 128 actinides. It is assumed that 1.0% of the recycled heavy metals are lost in the reprocessing, and 0.2% are lost during fuel fabrication. The heavy metal loss along with all the fission products and the blanket fuel discharged from the S&B reactor end up in the waste stream.

Fig. 5 displays the radioactivity of the UNF at 10 and 100,000 years after discharge. In the short-term, fission products contribute most of the activity. The higher radioactivity of the FPs from the PWR is mainly attributed to the lower thermal efficiency compared with that of the fast reactors. Also, ^{235}U fissions yield fission products of slightly higher radioactivity than those from ^{239}Pu fissions, but this makes a small difference (Stauff et al., 2015; Ault et al., 2017; Heidet et al., 2016). The ^{233}U fission products are slightly higher radioactive than the ^{235}U fission products making the short-term radioactivity of the S&B reactor waste slightly higher than that of the ABR (shown in Fig. 5a). The disposal of ^{233}U discharged from the thorium blanket in the S&B core has no significant impact on the short-term radioactivity because ^{233}U has a very long half-life of 159,200 years. In the case of the reference PWR that operates on the once-through fuel cycle, the disposal of plutonium (mainly ^{241}Pu) contributes notably to the short-term radioactivity of the waste repository.

In the long-term, the ^{233}U discharged from the thorium blanket is the predominant contributor to the higher radioactivity relative to the reference PWR and ABR. The long-life ^{233}U decays into highly radioactive nuclides such as ^{209}Pb, ^{213}Bi, ^{217}At, ^{221}Fr, ^{225}Ra, ^{225}Ac, and ^{229}Th. The discharged plutonium and minor actinides from the PWR-ABR and the PWR systems as well as the S&B seed undergo substantial decay by 100,000 years, and their decay daughters are less radioactive.

The inhalation and ingestion radiotoxicity of the waste are computed by weighting the radiation imparted to different parts of the human body with the inhalation and ingestion conversion factors taken from Reference (Eckerman et al., 2012) for 207 fission products and 91 actinides. The effective inhalation/ingestion coefficients are applied for a typical adult member of the public assuming median aerodynamic (diameter = 1 μm) radionuclides

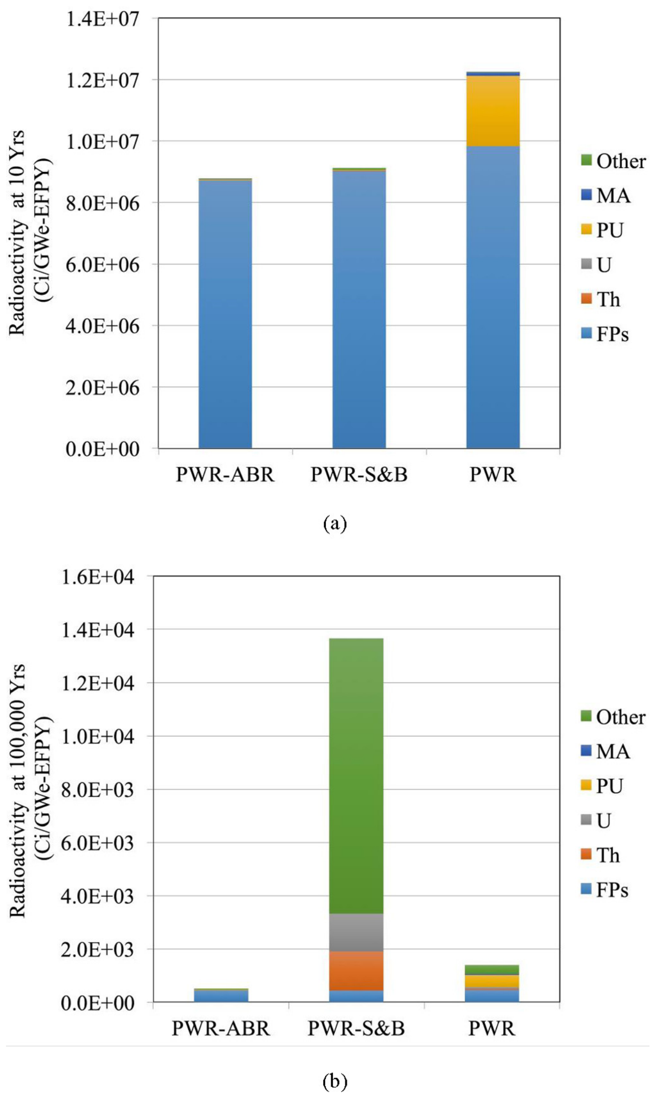

Fig. 5. Radioactivity of UNF + HLW at 10 years (a) and 100,000 (b) years.

Table 4
Range of inhalation and ingestion dose conversion factors (Sv/Bq) Eckerman et al., 2012.

Isotope	Inhalation	Ingestion
Actinides	10^{-5}–10^{-4}	10^{-7}–10^{-6}
FPs	10^{-10}–10^{-8}	10^{-10}–10^{-8}

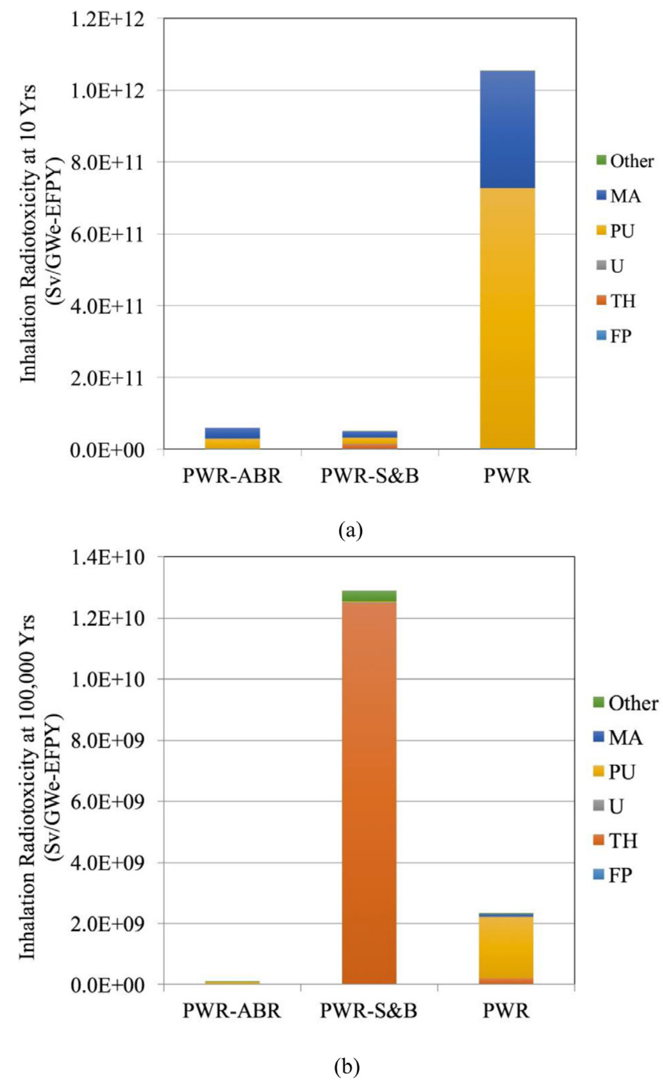

Fig. 6. Inhalation radiotoxicity of UNF + HLW at 10 years (a) and 100,000 years (b).

being inhaled via the lungs and getting into the blood stream. Typical ranges of inhalation/ingestion conversion factors (Eckerman et al., 2012) are shown in Table 4. In general, the alpha-emitting heavy metals tend to induce higher radiation damage than most of the low atomic mass isotopes (like FPs) that are beta-emitters. The actinides inhaled through the lungs are far more hazardous than those ingested via stomach (Stauff et al., 2015).

Fig. 6 compares the inhalation radiotoxicity of the UNF at 10 and 100,000 years. ^{238}Pu, ^{244}Cm, ^{241}Pu, and ^{241}Am are the dominant contributors to the inhalation radiotoxicity at ten years. As the PWR disposes of all of its plutonium and minor actinides, its short-term inhalation radiotoxicity is the highest. As 98.8% of the fuel discharged from the seed in the S&B core and the ABR core is recycled, the total inhalation radiotoxicity of the PWR-S&B and the PWR-ABR systems are similarly low. Since the discharge burnup of the seed in the S&B core is more than twice that of ABR, the waste stream of the PWR-S&B system contains less TRU (Fig. 6a). ^{233}U from the thorium blanket of the S&B core contributes a very small amount to the short-term inhalation radiotoxicity.

However, by 100,000 years, ^{238}Pu, ^{244}Cm, ^{240}Pu, and ^{241}Am have mostly decayed whereas ^{229}Th – a decay daughter of ^{233}U that is a strong alpha-emitter with a half-life of 7340 years – becomes the major contributor to the inhalation radiotoxicity of the PWR-S&B system. The PWR-ABR system exhibits the lowest long-term inhalation radiotoxicity due to its closed fuel cycle and absence of ^{233}U.

As the ingestion conversion factors of actinides are smaller than the inhalation ones by two orders of magnitude, fission products dominate the short-term ingestion radiotoxicity shown in Fig. 7. At ten years, the ingestion radiotoxicity per unit of electricity generated by the PWR system is much higher than those for the PWR-ABR and PWR-S&B systems. This is consistent with the observations of the short-term radioactivity in Fig. 5a. As most fission products decay with relatively short half-life, heavy metals in the waste stream become the main contributors at 100,000 years. The disposed thorium blanket fuel contains highly radio-toxic nuclides such as ^{229}Th (the decay daughter of ^{233}U) so that the total

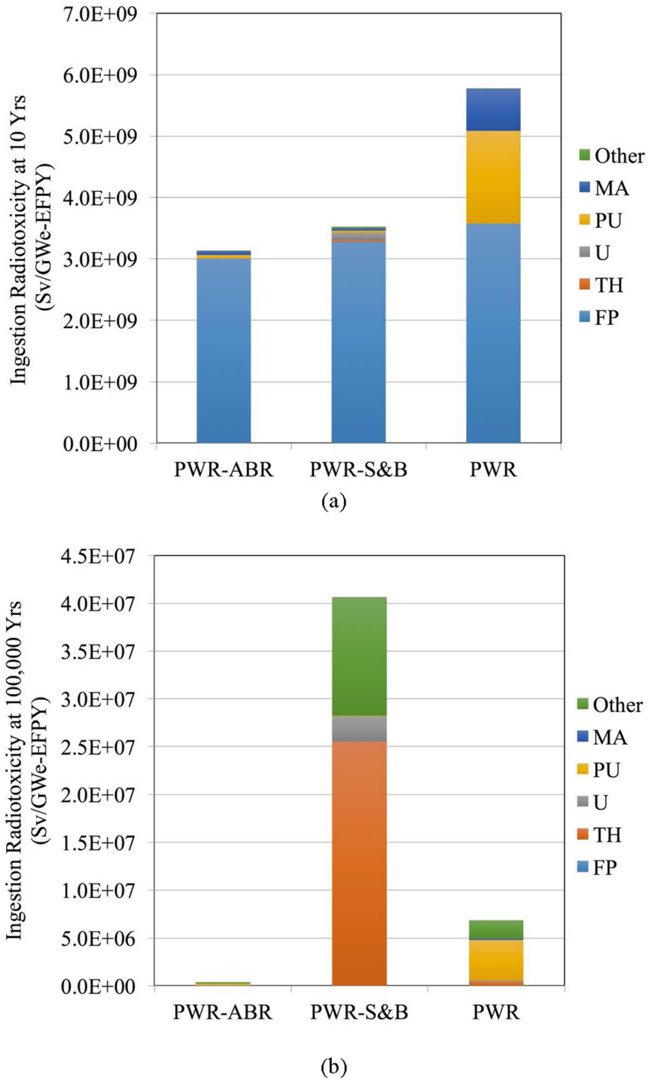

Fig. 7. Ingestion radiotoxicity of UNF + HLW at 10 years (a) and 100,000 years (b).

long-term ingestion radiotoxicity of the PWR-S&B system is much higher than of the other two systems.

4.4. Proliferation resistance

The proliferation resistance is evaluated based on the plutonium inventory, fissile plutonium fraction, specific decay heat and spontaneous fission neutrons emission rate of the recovered plutonium, ^{238}Pu/Pu ratio, and ^{232}U/^{233}U ratio. ^{238}Pu, ^{240}Pu, and ^{242}Pu have high spontaneous fission rate which can significantly reduce a weapon's yield; ^{238}Pu also has a large specific decay heat that further complicates the design of an explosive device (Xu et al., 2005; Pellaud, 2002). Material Attractiveness (MA) is applied in this study as an additional measure to quantify the proliferation resistance of the recovered plutonium. The procedure for calculating the material attractiveness value is described in Bathke et al. (2012). Material for which MA < 0.0 is considered as unattractive for making weapons; 0.0 < MA<1.0 is unattractive, but theoretically applicable for weapons; 1.0 < MA<2.0 is attractive; and material for which MA > 2.0 is highly attractive.

Table 5 compares the proliferation resistance metrics of the spent fuel from the three energy systems. The seed fuel in the S&B core is designed to have a TRU CR ratio of ~0.0, so its plutonium loading is much higher than the other two cores, but its discharge burnup is the highest. Due to the higher burnup, the fuel discharged from the seed has the lowest fissile plutonium fraction and the highest ^{238}Pu/Pu ratio of 6.1%: much higher than that of the ABR (4.1%) and PWR (3.0%). Of the three cores, the plutonium recovered from the S&B core is the least attractive for making weapons. Nevertheless, the makeup fuel for the seed of the S&B core is TRU separated from LWR UNF and is of proliferation concern. However, the makeup fuel the ABR core also requires separation of TRU from LWR UNF even though it can be mixed with depleted uranium. In principle it is also possible to add some depleted uranium to the makeup fuel for the S&B seed fuel – we have designs with seeds that feature a conversion ratio of 0.25, 0.5, and even 1.0 (Zhang et al., 2017a) but this will impair the S&B core performance.

Table 5
Proliferation resistance metrics of ABR, S&B and PWR after 5-year cooling time.

Property	ABR	S&B (seed/blanket)	PWR
Total plutonium reprocessed, tons/GWe-EFPY	1.67	1.59/0.00	0.21
Fissile plutonium fraction, %	46	29/4	63
^{238}Pu/Pu ratio, %	4.1	6.1/95.6	3.0
Specific decay heat of plutonium, W/kg	26.94	38.47/542.74	20.54
Spontaneous fission neutrons per kg Pu, n/s-kg	6.49E+05	9.00E+5/2.49E+6	4.41E+05
Material Attractiveness of plutonium	1.92	1.69/–	2.09
^{232}U/^{233}U ratio, ppm	–	–/2233	–
Fissile U/U ratio, %	0.0	7.6/91.1	0.7
Fissile U/Th ratio, %	–	–/8	–
(Pu + fissile U)/(^{238}U + Th) ratio, %	41	17271/8	2

The thorium fuel cycle seems not to be more proliferation resistant than the uranium fuel cycle (Greneche, 2006). ^{233}U is applicable for weapon use because the critical mass of ^{233}U is close to that of ^{239}Pu whereas its spontaneous fission rate is much lower (Kang and Hippel, 2001). Nevertheless, the decay chain of the co-product ^{232}U includes ^{208}Tl which generates penetrating 2.6 MeV gamma rays; therefore, a contamination of ^{232}U makes ^{233}U a less desirable weapon material as it is very difficult to separate ^{232}U from ^{233}U due to their close atomic mass. ^{232}U decays with a half-life of 68.9 years to ^{228}Th. The ^{228}Th decays into ^{208}Tl immediately as the decay daughters of ^{228}Th have very short half-lives. After the in-growth of ^{208}Tl, the dose rate from ^{233}U containing 1 ppm ^{232}U is about the same as that from reactor-grade plutonium (Kang and Hippel, 2001). The thorium fuel discharged from the blanket has a ^{232}U/^{233}U ratio of 2233 ppm, well above the contamination level that requires remote operations to extract ^{233}U on a large scale without incurring large occupational dose (Kang and Hippel, 2001). The Material Attractiveness of ^{233}U with an initial concentration of 3200 ppm ^{232}U is similar to that of reactor-grade plutonium after 10-year cooling (Bathke et al., 2012). To achieve the IAEA criterion for self-protection of 100-rem per hour at 1 m, the level of ^{232}U needs to be 2.4% (Kang and Hippel, 2001; IAEA, 1999). The ^{232}U level of the discharged blanket fuel is an order of magnitude below the IAEA criterion for self-protection; therefore, the uranium in the fuel discharged from a blanket in the S&B core will need to be safeguarded to prevent proliferation, similar to the situation for the PWR reactor-grade plutonium. However, the breed-and-burn thorium blanket has an intrinsic proliferation resistance as the discharged fuel is not required to be reprocessed, and the ^{233}U concentration in the thorium blanket discharged fuel is 8%. A recent study (Bathke et al., 2014) by Los Alamos National Laboratory concluded that dilution with ^{238}U or ^{232}Th reduces the attractiveness of the material to a sub-state actor; with >80% ^{238}U or 70% ^{232}Th, the material is unattractive (Bathke et al., 2014). Moreover, the fissile uranium (mainly ^{233}U) in the blanket discharged fuel can be converted to a non-weapon-usable material by diluting it with DU (Forsberg and Hopper, 1998). It is also possible to increase the $^{232}U/^{233}U$ ratio in the discharged fuel by softening the spectrum in the blanket and thereby increasing the blanket fuel proliferation resistance. The spectrum softening can be achieved by using thorium oxide or possibly thorium hydride rather than metallic thorium (Zhang et al., 2017b).

4.5. Resource utilization

Table 6 compares the natural resources required for the PWR-ABR, PWR-S&B and PWR systems per unit of electricity. The present PWRs fission only about 0.6% of the natural uranium mined. It requires the largest amount of natural uranium per unit of electricity generated. The stage 2 reactor in a 2-stage system fissions most of the TRU discharged from the PWR and effectively increases the natural uranium utilization of the 2-stage system to ~1%. The natural uranium required per energy generated by the PWR-S&B system is lower than that of the PWR-ABR system because more than half of the S&B core power is generated from natural thorium.

The utilization of thorium in the S&B core is about 7% when using metallic thorium with no reprocessing; this is a factor of ~12 higher than natural uranium utilization in current PWRs. As improved cladding materials capable of withstanding higher radiation damage become available, the thorium utilization of S&B reactors can increase. For example, if the blanket fuel cladding could withstand 400 DPA, the thorium utilization could be close to 17% (Zhang et al., 2017a). Alternatively, if the blanket is designed to have a softer spectrum by using thoria or thorium hydride, the thorium utilization of S&B reactors is estimated to increase to 11% and 19%, respectively (Zhang et al., 2017b).

4.6. Overall fuel cycle evaluation

In late 2011, the U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) chartered a study on the evaluation and screening of nuclear fuel cycle options. The study considered the entire fuel cycle of 40 energy systems (referred to as “Evaluation Groups” – EG) to identify a relatively small number of promising fuel cycle options with the potential for achieving substantial improvements compared to the current nuclear fuel cycle prevailing in the United States. The results of this study are intended to strengthen the basis for prioritization of the research and development activities undertaken by the DOE (Wigeland et al., 2014).

The comprehensive fuel cycle evaluation methodology developed by the Department of Energy’s Nuclear Fuel Cycle Evaluation and Screening (FCE&S) campaign (Wigeland et al., 2014) is applied to further evaluate the S&B-based fuel cycle. The evaluation criteria include nuclear waste management, safety, environmental impact, and resource utilization. Each evaluation criterion is composed of several evaluation metrics defined in Appendix A of the FCE&S report (Wigeland et al., 2014). The detailed impact factors (e.g., the water use for uranium enrichment, the radiological dose for fuel reprocessing) are summarized in Appendix C of the report (Wigeland et al., 2014). To account for uncertainties in the calculation approach, each calculated metric is assigned a letter score based on a binned approach defined in Appendix D of the report (Wigeland et al., 2014) such that two systems exhibit the same performance for a given metric if their calculated metric values fall within the range of the same bin. This method enables to evaluate the overall fuel cycle performance of the S&B cores in comparison with the forty evaluation groups (EGs) established by the FCE&S campaign (Wigeland et al., 2014).

Table 6
Natural resources utilization of PWR-ABR, PWR-S&B, and PWR.

Property	PWR-ABR	PWR-S&B	PWR
Natural uranium required per energy generated, t/GWe-EFPY	117.2	109.6	181.1
Natural thorium required per energy generated, t/GWe-EFPY	0.0	3.0	0.0
Natural uranium + thorium required per energy generated t/GWe-EFPY	117.2	112.6	181.1

To take into account the different thermal efficiencies of nuclear energy systems, the FCE&S campaign renormalized the mass flow rates in the fuel cycle and power-sharing of a multi-stage system to a uniform thermal efficiency of 33%. Analytical formulas were developed for this re-normalization in Appendix D of the report (Wigeland et al., 2014):

$$F_k^n = \frac{\omega_k}{\sum_i \omega_i F_i^0} F_k^0 \tag{6}$$

$$M_k^n = \frac{1}{\sum_i \omega_i F_i^0} M_k^0 \tag{7}$$

where the superscripts of n and o indicate that the parameter pertains to the new and original thermal efficiencies, respectively, and the subscript k and i denote the stage number

F_k^n = Power-sharing fraction of k-th stage reactor with new thermal efficiency
F_k^o = Power-sharing fraction of k-th stage reactor with original thermal efficiency
M_k^n = Mass flow data of k-th stage reactor using the new thermal efficiency
M_k^o = Mass flow data of k-th stage reactor using the original thermal efficiency
ω_k = New-to-original thermal efficiency ratio of k-th stage reactor (η_k^n/η_k^0), and
η_k = Thermal efficiency of k-th stage reactor.

The original power fraction of the stage 1 PWR (Table 2) is multiplied by the mass normalization factor (Table 6) so that the thermal efficiency of stage-2 S&B cores is adjusted to 33%; the rest is generated from the S&B core. Similar adjustments are done for the ABR-PWR energy system. The mass flow is adjusted according to the new power-sharing.

The PWR-ABR system is selected in the FCE&S report as one of the best performance options; it is defined as EG32: “continuous recycle of TRU/U from PWR in SFR burner”. This evaluation group is selected to maintain current PWR technology while reducing the amount of nuclear waste from the first stage. It also improves the uranium resource utilization as the ABR uses the PWR generated TRU along with depleted uranium for the makeup fuel and operates on a closed fuel cycle. The PWR system is defined in the FCE&S report as EG01: “Once-through using enriched-U fuel in thermal critical reactors” and served as the “Basis of Comparison”. It represents the prevailing fuel cycle in the U.S. (Wigeland et al., 2014).

Table 7 summarizes the detailed evaluation results for PWR-ABR, PWR-S&B, and PWR systems. The metrics of EG32 and EG01 are reproduced from the FCE&S report (Wigeland et al., 2014). Both PWR-ABR and PWR-S&B systems recycle the TRU in the spent fuel and therefore feature lower high-level TRU containing waste per unit of electricity generated than that of the PWR. As observed in Section 4.3, the long-term waste metrics of the PWR-S&B design are worse than those of PWR-ABR and PWR systems. This is

Table 7
Evaluation of EG32 (PWR-ABR), PWR-S&B, and EG01 (PWR) fuel cycles.

	Metric	EG32 (PWR-ABR)	PWR-S&B	EG01 (PWR)
	Mass Renormalization Factor	1.07	1.074	1.00
Nuclear Waste Management	Mass of UNF + HLW disposed, t/GWe-yr	1.32/A	3.86/C	21.92/E
	Activity of UNF + HLW (@100 years), MCi/GWe-yr	1.08/C	1.06/C	1.34/C
	Activity of UNF + HLW (@100,000 years), 10^{-4} MCi/GWe-Yr	5.2/B	121.7/F	16.5/C
	Mass of DU + RU + RTh disposed, t/GWe-yr	127.2/E	116.7/D	166.7/E
	Volume of LLW, m^3/GWe-yr	579.3C	564.7/C	398.8/C
Safety	Challenges of addressing safety hazards	C	C	C
	Safety of the deployed system	Can be deployed safely		
Environmental Impact	Land use per energy generated, km^2/GWe-yr	0.130/B	0.14/B	0.175/B
	Water use per energy generated, ML/GWe-yr	23838/B	23823/B	23891/B
	Radiological exposure, Sv/GWe-yr	1.13/B	0.95/B	1.10/B
	Carbon emission - CO_2 released per energy generated, kt CO_2/GWe-yr	41.6/B	40.7/B	44.1/B
Resource Utilization	Natural Uranium required per energy generated, t/GWe-yr	128.5/C	117.7/C	188.6/D
	Natural Thorium required per energy generated, t/GWe-yr	0.0/A	2.6/A	0.0/A

attributed to the use of thorium fuel in the once-through B&B blanket. If the blanket is designed to have thoria or thorium hydride fuel, its spectrum will be softer enabling to significantly increase the average discharge burnup of the once-through thorium fuel (discussed in Section 4.5). As a result, the amount of trans-thorium elements discharged from the S&B cores per unit of generated electricity will decrease, and the long-term waste metrics will be improved.

The challenges of addressing safety hazards were considered based on a set of fuel cycle hazard categories defined in the FCE&S campaign. The hazard categories associated with each fuel cycle process were identified, and the mapping of the fuel cycle hazard categories to the fuel cycle process list is taken from Appendix C of the report (Wigeland et al., 2014). The operation of the seed in the S&B core and the ABR cores pose similar safety hazards. The thorium blanket involves thorium fuel mining, fabrication of fresh thorium fuel, and disposal of discharged thorium fuel. These activities are mapped with similar fuel cycle hazard categories as the corresponding uranium-based activities (Wigeland et al., 2014). Since the thorium blanket requires no fuel enrichment and reprocessing, the PWR-S&B system is believed to generate similar hazards as EG32 and EG01.

The PWR-S&B system has a similar environmental impact as the other two energy systems. Both EG32 and PWR-S&B improve the natural uranium resource utilization of present PWRs by about 60%. The PWR-S&B requires slightly less natural uranium per unit of electricity compared with the PWR-ABR system and utilizes at least 7% of the thorium resource energy worth without requiring irradiated thorium fuel reprocessing.

The FCE&S campaign aims to identify the most promising fuel cycles out of 40 evaluation groups (Wigeland et al., 2014) with a combination of a couple of major considerations: benefit they offer versus technological challenge for their implementation. EG32 scores a benefit of 0.6 (1.0 is the highest possible benefit) and a challenge of 0.38 (1.0 is the least challenging). For comparison, the contemporary once-through PWRs (EG01) scores a benefit of 0.45 and a challenge of 1.0. Thorium-based systems feature, in general, a somewhat lower challenge score (meaning more challenging) than uranium-based systems (Wigeland et al., 2014). This is primarily attributed to the lack of experience in reprocessing and recycling of irradiated thorium fuel (Wigeland et al., 2014). However, since the thorium fueled blanket in the S&B core operates on a once-through fuel cycle, this conclusion is not applicable to the S&B core concept. Taking into account the lower expected cost per unit of electricity generated (Section 4.2) and the much smaller SFR fuel reprocessing capacity (Section 4.1), the PWR-S&B system potentially have a higher benefit score than EG32 even though it is not as good as the SFR-PWR energy system in terms of mass of radioactive waste – primarily the thorium fuel discharged from the blanket, that needs to be disposed of and the higher activity at 100,000 years that is also due to the thorium UNF. The use of inert matrix fuel to very high discharge burnup may require experimental verification leading to some reduction in the challenge scale. Nevertheless, it is possible to start using and benefiting from the S&B core concept with a conventional seed fuel such as a CR of 0.5 fuel. In such case, there will be no challenge penalty.

5. Conclusions

The fuel cycle cost of the PWR-S&B system is found to be lower than that of the PWR-ABR system due to (1) the large fraction of power generated from the low-cost natural thorium fueled blanket that operates in the breed-and-burn mode and, therefore, does not require recycling; (2) the higher discharge burnup of the TRU inert matrix seed. Both features contribute to a significantly smaller fuel reprocessing capacity per unit of electricity generated by the S&B core. The fuel cycle cost of the PWR-S&B system is even lower than that of present PWRs. Moreover, due to the longer cycles, the capacity factor of the S&B reactor could be higher than that of the reference ABR. Although the cost of the S&B reactor vessel may be somewhat higher than that of the reference ABR, the higher capacity factor is expected to compensate for the higher cost of the reactor vessel and support structure so that the overall economics of the S&B SFR is likely to be superior to that of the ABR.

Relative to the ABR, the S&B core has comparable short-term radioactivity and radiotoxicity, but much higher long-term values. There is a significant amount of ^{233}U in the discharged blanket fuel, and the higher long-term radioactivity and radiotoxicity values are attributed to the long-lived decay daughters of ^{233}U. The high long-term radiotoxicity of the discharged thorium fuel from the S&B could be reduced if the average discharge burnup of the blanket increases by either a successful development of improved cladding material or spectrum softening. The spent fuel from the seed in S&B cores has lower fissile Pu contents, higher $^{238}Pu/Pu$ ratio, higher specific plutonium decay heat, and higher spontaneous fission rate. Overall, the reprocessed S&B plutonium has lower material attractiveness for weapons application. The fuel discharged from the S&B core blanket has a $^{232}U/^{233}U$ ratio of 2233 ppm, well above the contamination level that requires remote operations to extract ^{233}U on a large scale without incurring large occupational dose. Since the breed-and-burn thorium fueled blanket requires no fuel reprocessing, the ^{233}U contained in the discharged fuel from the blanket is unattractive for weapons application.

Compared with PWR, the PWR-S&B system has much lower short-term radioactivity, and radiotoxicity as the hazardous TRUs are recycled, but higher long-term values due to the ^{233}U in the fuel discharged from the blanket. The S&B core features higher proliferation resistance of the recovered plutonium and approximately 60% higher natural uranium utilization. With presently proven cladding materials, the S&B cores can utilize 7% of the thorium resource without a need to develop an irradiated thorium reprocessing technology. This is ~12 times the amount of energy that PWRs extract per unit of natural uranium mined. As improved cladding materials become available or the blanket is designed to have a softer spectrum, the thorium utilization of S&B reactors could be more than doubled.

A comprehensive fuel cycle evaluation using the methodology developed by the recent DOE Nuclear Fuel Cycle Evaluation and Screening campaign concludes that the PWR-S&B system has similar fuel cycle performance characteristics as the PWR-ABR system except for a larger mass of discharged fuel (the blanket fuel) to be disposed of and a higher long-term radioactivity and radiotoxicity. Nevertheless, taking into account of the lower expected cost per unit of electricity generated the PWR-S&B system may feature a higher benefit score than EG32.

Nevertheless, the comparison of the performance characteristics of the S&B core against the ABR may be biased in favor of the S&B core due to the following assumptions: (1) the seed fuel used for the S&B core design is TRU-10wt% Zr whereas experiments suggest 40wt%Zr for the inert matrix fuel; (2) the radiation damage constraint imposed on the S&B core design (i.e., 200 DPA) enables irradiating both seed and blanket fuel to higher burnup than possible if using the constraint imposed on the ABR design (i.e., a fast neutron fluence of 4×10^{23} n/cm^2). However, the conclusions regarding the much smaller recycling capacity and lower fuel cycle cost offered by the S&B core concept compared with the ABR are still valid.

Acknowledgments

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