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

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ABSTRACT

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.

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.

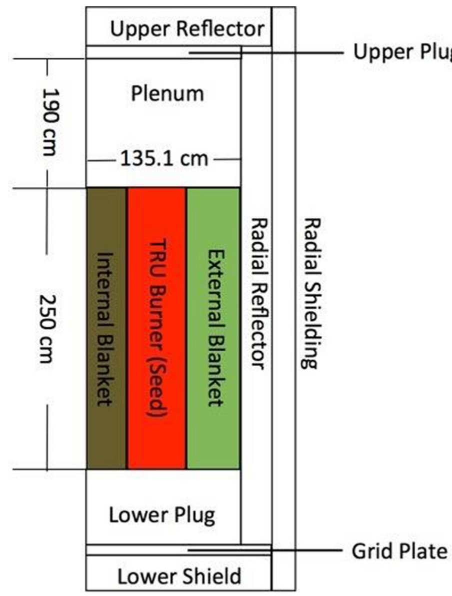

Fig. 1. Schematic configuration of the S&B core.

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.