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Advanced Burner Reactors with Breed-and-Burn Thorium Blankets for Improved Economics and Resource Utilization

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Abstract — *This paper assesses the feasibility of designing seed-and-blanket (S&B) sodium-cooled fast reactor (SFR) cores to generate a significant fraction of the core power from radial thorium-fueled blankets that operate in the breed-and-burn (B&B) mode. The radiation damage on the cladding material in both seed and blanket does not exceed the presently acceptable constraint of 200 displacements per atom (dpa). The S&B core is designed to have an elongated seed (or driver) to maximize the fraction of neutrons that radially leak into the subcritical B&B blanket and reduce the neutron loss via axial leakage. A specific objective of this study is to maximize the fraction of core power generated by the B&B blanket that is proportional to the neutron leakage rate from the seed to the blanket. Since the blanket feed fuel is very inexpensive and requires no reprocessing and remote fuel fabrication, a larger fraction of power from the blanket will result in a lower fuel cycle cost per unit of electricity generated by the SFR core. It is found possible to design the seed of the S&B core to have a lower transuranics (TRU) conversion ratio (CR) than a conventional advanced burner reactor (ABR) core without deteriorating core safety. This is due to the unique synergism between a low CR seed and the B&B thorium blanket. The benefits of the synergism are maximized when using an annular seed surrounded by inner and outer thorium blankets. Two high-performance S&B cores are designed to benefit from the annular seed concept: (1) an ultra-long-cycle core having a CR = 0.5 seed and a cycle length of ~7 effective full-power years (EFPYs) and (2) a high-transmutation core having a TRU CR of 0.0. The TRU transmutation rate of the latter core is comparable to that of the reference ABR with a CR of 0.5, and the thorium blanket can generate close to 60% of the core power. Because of the high blanket power fraction along with the high discharge burnup of the CR = 0 seed, the reprocessing capacity per unit of core power required by this S&B core is only approximately 1/6th that of the reference ABR core with a TRU CR of 0.5. Although the seed fuel CR is nearly zero, the burnup reactivity swing is low enough to enable a cycle length of more than 4 EFPYs. This is attributed to a combination of reactivity gain in the thorium blankets over the cycle and the relatively high heavy metal inventory. Moreover, despite the very low leakage, the S&B cores feature a less positive coolant reactivity coefficient and large enough negative Doppler coefficient even when using nonfertile fuel for the seed, because of the unique physics properties of the ^{233}U and Th in the thorium blankets. With the long cycles, the S&B SFR is expected to have a higher capacity factor, and therefore a lower cost of electricity, than conventional ABRs. The discharge burnup of the thorium blanket fuel is typically 70 MWd/kg such that the thorium fuel utilization is approximately 12 times that of natural uranium in light water reactors. A sensitivity study is subsequently undertaken to quantify the trade-off between the core performances and several design variables: amount of zirconium in the inert matrix seed fuel, active core height, coolant pressure drop, and radiation damage constraint. The effect of the criterion used for quantifying acceptable radiation damage is evaluated as well. It is concluded that a viable S&B core can be designed without significant deviation from typical SFR core design practices.*

Keywords — *Fast reactor, seed-and-blanket core, thorium blanket.*

Note — *Some figures may be in color only in the electronic version.*

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I. INTRODUCTION

Breed-and-burn (B&B) reactors are fed with fertile uranium (depleted, natural, or recovered uranium) and breed plutonium and then fission a significant fraction of the bred plutonium in situ. B&B sodium-cooled fast reactors (SFRs) have been proposed in the past as an alternative mode of operation of fast breeder reactors,[1,2] and TerraPower™ is presently pursuing the development of commercial B&B cores.[3–5] It is expected that B&B reactors can improve the economics of fast reactors and the uranium utilization relative to that of present light water reactors (LWRs) as they require no fuel reprocessing and the feed fuel is easy to fabricate.[6] However, in order to sustain the B&B mode of operation, it is necessary to fission at least ~20% of the initial depleted uranium feed.[7] An average burnup of 20% fissions per initial metal atom (FIMA) corresponds to a peak discharge burnup of up to 30% FIMA and the peak radiation damage on the cladding material in the vicinity of 500 displacements per atom[8,9] (dpa). The maximum neutron-induced radiation damage to which cladding and structural materials have been exposed at the Fast Flux Test Facility (FFTF) so far is approximately 200 dpa (Ref. 10). Hence, an extensive research and development (R&D) effort is required to develop and certify cladding materials that can retain the fuel integrity up to approximately 500 dpa. Such a program will have to include irradiation experiments in the fast spectrum together with postirradiation analysis and may take a long time and large resources. If thorium is to be used as fertile feed rather than depleted uranium, it is practically impossible to design a critical core with a self-sustaining B&B mode of operation.[11]

The seed-and-blanket (S&B) core concept has been recently proposed[12] as an approach to start benefiting from the B&B mode of operation without waiting for the development of cladding materials that can be licensed for 500 dpa. S&B SFR cores consist of a seed (or driver) that is radially surrounded by a fertile-fueled subcritical blanket. The excess seed neutrons leaking in the radial direction drive the blanket that is operated in the B&B mode without exceeding the presently acceptable radiation damage. When the cladding in the blanket reaches the radiation damage level proven at the FFTF (i.e., ~200 dpa), the blanket fuel is discharged and replaced with fresh fertile fuel.

Typical SFR cores, such as advanced burner reactors (ABRs) and advanced recycling reactors[13–15] (ARRs), are designed to have a pancake shape (short height and large diameter) with an axial neutron leakage probability on the order of 20%. The large neutron leakage enables passive safety by reducing the positive coolant reactivity feedback and increasing the negative reactivity feedback due to the radial core expansion and fuel axial expansion. Besides the safety reason, there is no beneficial use of these leaking neutrons except in certain breeding cores that feature axial depleted uranium blankets. The S&B concept, instead, features a seed with an elongated shape that makes use of the radially leaking neutrons to drive a subcritical blanket in the B&B mode that is without reprocessing the blanket fuel. As the blanket fuel cost is relatively low compared with the seed fuel and requires no reprocessing, it is expected that the overall fuel cycle cost of such S&B reactors will be lower than that of SFRs using conventional cores and the cost benefit will be proportional to the power fraction generated by the blanket.

The overall objective of this work is to study the feasibility of the S&B core design that consists of a burner seed fed with transuranics (TRU) from LWR used nuclear fuel (UNF) and a B&B blanket. Significant effort is devoted to understanding the unique synergism found between a TRU burner seed and a thorium B&B blanket. A specific objective is to identify a S&B core design that maximizes the fraction of the total power generated by the blanket while meeting major neutronics, thermal-hydraulic, and radiation damage design constraints.

This paper is organized as follows. Section II describes the methodology of this study, including the core configurations, computational tool kits, design constraints applied, and optimization strategy. Section III summarizes parametric studies of the simplified S&B cores that feature a central cigar-shaped seed and also compares depleted uranium versus thorium as the blanket feed fuel. Section IV focuses on the improved variants of the S&B core concept in which the driver is annular in order to enhance the radial neutron leakage and thus the power fraction from the blankets while improving reactor safety. Section V describes the sensitivity of the S&B core performance to a number of core design variables. Section VI explains the unique synergism found between a low conversion ratio (CR) seed and a thorium blanket. Section VII presents conclusions.

II. MODELS AND METHODOLOGY

II.A. Core Model and Fuel Management Scheme

Figure 1 shows the simplified S&B core configuration considered for the initial part of this study. All the

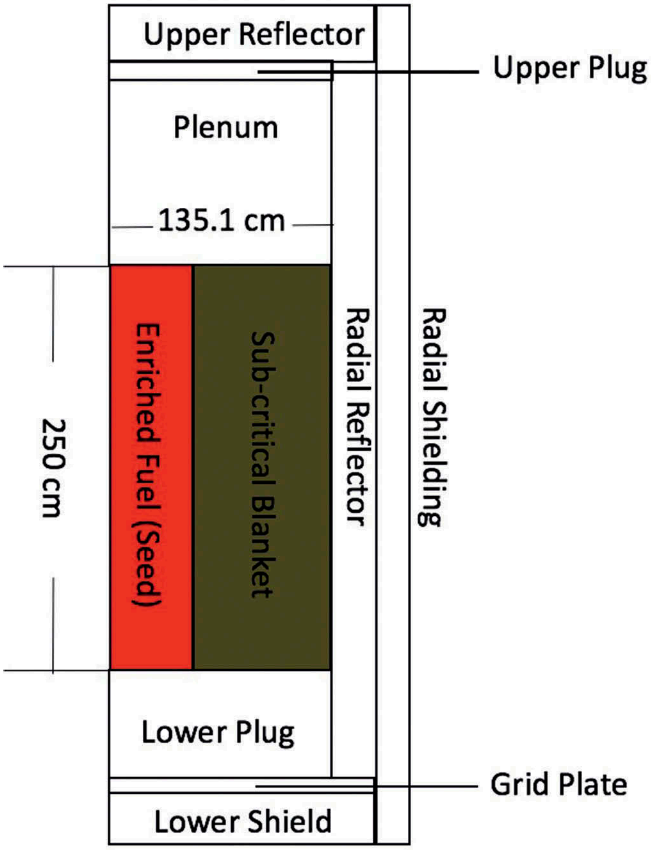

Fig. 1. Layout of the simplified computational model of the S&B core and surrounding regions.

regions are approximated by concentric cylinders. The radial dimensions of the active core (seed and blanket), reflector, and shielding are those of the metallic fuel version of the Super Power Reactor Innovative Small Module (S-PRISM) core developed by General Electric[16] (GE) such that the core could fit within the S-PRISM reactor vessel. The active core height is 250 cm, which is a typical value of B&B reactor cores[9] but is about 2.5 times that of compact cores, like the ABR designed by Argonne National Laboratory[13,15] (ANL) and S-PRISM. The fission gas plenum length is assumed to be 1.9 m although a longer fission gas plenum may be required for the higher-burnup cases unless a vented fuel design will be used. The effective diameter of the seed is initially set at 102.5 cm in order to have about 20% of its fission neutrons leak radially into the blanket.[17] All other geometry and composition specifications are derived from the S-PRISM design[16] and are summarized in Table I. The S&B cores examined in this study are designed to operate at the nominal thermal power of 1000 MW such as that of S-PRISM. The seed fuel is initially ternary metallic alloy (U-TRU-10wt%Zr) that has a theoretical density of 15.7 g/cm^3. A smear density of 75% is assumed to accommodate the fuel swelling with burnup. The blanket fuel is natural thorium in metallic form with a theoretical density of 11.7 g/cm^3. A smear density of 85% is assumed for the metallic thorium fuel due to the lower swelling of thorium relative to uranium and to the lower burnup of the blanket versus seed fuel. The low-swelling ferritic martensitic steel HT9 is selected as the structural and cladding material; its density is 7.874 g/cm^3. A uniform sodium density of 0.849 g/cm^3 is set throughout; it corresponds to an average coolant temperature of 700 K. Grid spacers are applied with a

TABLE I

Dimensions and Composition of the Components in S&B Cores*

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]
	Lower end plug	111.7	22% HT9–78% Na
	Grid plate	5.2	50% HT9–50% Na
	Lower shielding	30.0	47% B_4C–21% HT9–32% Na
Radial dimension[b]	Active core o.d.	270.3	Design variable[c]
	Reflector o.d.	326.2	50% HT9–50% Na
	Shielding o.d.	354.1	47% B_4C–21% HT9–32% Na
Assembly geometry	Assembly pitch	16.124	—
	Duct gap	0.432	—
	Duct wall thickness	0.394	—

*Reference 16.

[a] Same volume fractions for cladding and coolant are applied as those in active core region.

[b] Approximate value for R-Z model.

[c] The fractions of fuel/cladding/coolant depend on the P/D ratio of fuel assemblies.

spacing of 25 times the fuel outer diameter (o.d.). The ratio of cladding thickness and fuel diameter is kept constant at 0.075, such as that of the S-PRISM driver fuel.

The seed can be designed to have a low CR as an ABR or a TRU self-sustaining ARR (Refs. 13 and 15). Figure 2 shows the fuel management scheme of the S&B core. The fraction $1/N_s$ of the seed fuel, where N_s is the number of seed batches, is discharged at the end of each cycle and sent to the reprocessing facility. The fuel assemblies that remain in the seed are not shuffled. It is assumed that the heavy metals (HMs) are fully recovered and recycled into fresh seed fuel assemblies after being mixed with the makeup fuel, i.e., depleted uranium and TRU from LWR UNF, with 50 MWd/kg burnup followed by 10-year cooling time.[13] Table II provides the composition of the TRU used for the makeup feed fuel.

The blanket operates in a multibatch once-through B&B mode. At the end of equilibrium cycle (EOEC), the innermost blanket batch is discharged and stored whereas the other blanket batches are shuffled inward. The blanket feed fuel is loaded into the outermost blanket batch. This study utilizes natural metallic thorium as the blanket feed fuel because of the unique synergism found between a low CR seed and a B&B thorium blanket. The performance of the S&B core with a thorium blanket is compared against that of a similar core that uses depleted uranium for the blanket feed fuel (See Sec. III.B for details).

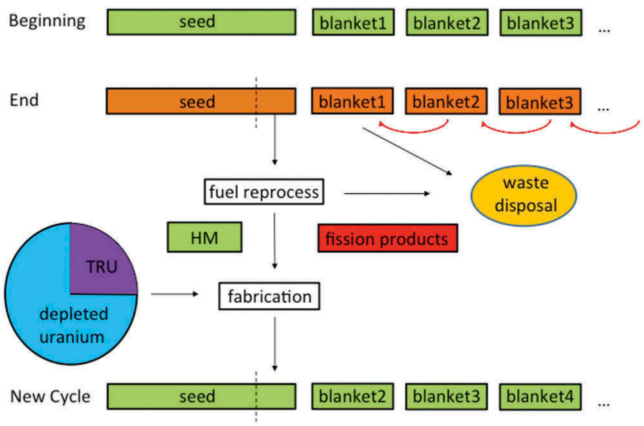

Fig. 2. Fuel management scheme of S&B cores.

TABLE II

Composition of the TRU from LWR UNF at Discharge Burnup of 50 MWd/kg and 10-year Cooling*

Isotope	Weight Percent
^{237}Np	4.7
^{238}Pu	2.2
^{239}Pu	47.3
^{240}Pu	22.8
^{241}Pu	8.4
^{242}Pu	6.8
^{241}Am	5.6
^{243}Am	1.6
^{244}Cm	0.5

*Reference 13.

The major design variables in this study include number and location of the S&B fuel assemblies; fraction of seed fuel recycled each cycle (i.e., number of seed batches), which is typically between 1/3 and 1; TRU-to-HM ratio in the seed makeup fuel; number of blanket batches; cycle length; fuel pin diameter; and pitch-to-diameter (P/D) ratio.

As the neutron mean free path in fast reactors is larger than the lattice pitch, each burnup node for neutronic analysis is homogenized[18]; the fuel, cladding-structural material, and coolant in the core are mixed preserving their volume fractions. For this feasibility study, the core is represented by a simplified radial-symmetric *R-Z* model. The results from the *R-Z* model are in good agreement with those obtained when the core is modeled as a collection of hexagonal fuel assemblies.[9,18] Because of the limitation of the *R-Z* model, control assemblies are not included in this study; this is expected to somewhat overestimate the core performance. The core is radially divided into three equal-volume concentric burnup zones for the seed and one burnup zone for each blanket batch; each radial zone is further divided into six axial burnup nodes. The coolant and structural components in the gas plenum region, axial support structures, reflectors, and shielding are also homogenized preserving the volume fractions defined in Table I. Vacuum boundary conditions are applied in the axial and radial directions.

The performance characteristics of the S&B cores are compared against those of the reference ABR core design (TRU CR of 0.5). It should be noted that the ABR design might not necessarily be the best reference for the purpose of comparison. This reference ABR was designed to have the smallest possible core with 144 fuel assemblies whereas the S&B cores have 271 fuel assemblies. Additionally, the reference ABR core design was constrained by a peak fast neutron fluence of 4.0 × 10^{23} neutrons (>0.1 MeV)/cm^2 whereas this study set the radiation damage constraint to 200 dpa. The sensitivity of core performance to the radiation damage constraint is discussed in Sec. V.E.

II.B. Computational Tool Kits and Scheme

The MCNP6 code[19] is used with the ENDF/B-VII.0 cross-section library[20] for the neutronic calculations with 1200 neutron histories per cycle and 200 active cycles to obtain a target statistical error in k_{eff} of ~100 pcm. All the cross sections are calculated at 900 K. This temperature is close to the fuel temperature at the nominal operating condition. ORIGEN 2.2 (Ref. 21) is applied for burnup calculations using effective one-group cross sections generated by MCNP6. Burnup-dependent compositions calculated by ORIGEN2.2 are sent back to MCNP6 after each burnup step. MCNP6 and ORIGEN2.2 are coupled via a two-tier solver named MocDown (Fig. 3) that automates an efficient iterative search for the equilibrium composition of multibatch cores depending on a prescribed fuel management scheme.[22] The iterative search strategy is illustrated in Fig. 3; it consists of an outer loop and an inner loop. The outer loop is being repeated with updated transmutation constants from the transport calculation until the EOEC multiplication factors of two successive cycles fall within a prescribed tolerance. Within each outer loop cycle, an accelerated solver module initiates an inner loop in which the fuel depletion and management schemes are performed continuously until the beginning of equilibrium cycle (BOEC) fuel compositions between two successive cycles fall below a prescribed tolerance. In the inner loop, the transmutation constants are preserved, and the computational cost is significantly reduced. All the core designs presented in this paper are at the equilibrium state calculated by MocDown.

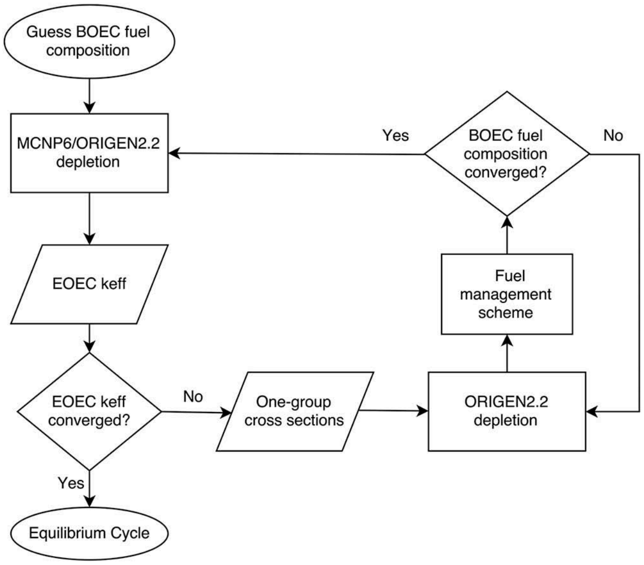

Fig. 3. Flowchart for equilibrium cycle search by MocDown.

II.C. Design Constraints

The following engineering design constraints (Table III) are applied throughout the analysis: (1) the coolant pressure drop through the core including the 1.9-m-long fission gas plenum together with the pressure drop at the core inlet and outlet orifices is initially limited to 0.9 MPa (Refs. 23, 24, and 25); (2) the coolant inlet temperature is 355°C, and the temperature rise across the core is 155°C (Ref. 13); (3) the maximum sodium coolant velocity is 12 m/s (Ref. 25); (4) the inner cladding temperature is required to be lower than 650°C, which is the eutectic point of HT-9 and plutonium mixture, and the fuel centerline temperature is conservatively constrained to 800°C (Ref. 26); (5) the peak radiation damage on cladding for both seed and blanket is limited to 200 dpa, which is the presently acceptable constraint based on the irradiation data obtained in the FFTF (Ref. 10) (in this study all equilibrium calculations apply a 10-dpa tolerance around such limit); (6) there is no hard limit for the burnup reactivity swing, but it is desirable to limit it to ~3.5% $\Delta k/k$ (Ref. 15), where k is the core multiplication factor and Δk is the difference between its maximum and minimum value during an equilibrium cycle. A larger burnup reactivity swing increases the number of control assemblies because the reactivity worth of a single control assembly should be lower than 1 $ for safety reasons.

II.D. Methodology for Radiation Damage Calculations

In order to estimate the neutron-induced radiation damage accumulated in structural materials, this study calculates the cumulative dpa values rather than the fast fluence (i.e., fluence of neutrons with energy >0.1 MeV). This choice is made to take into account the actual shape of the neutron spectra in the thorium B&B blanket. As shown in Fig. 4, the

TABLE III

Major Design Constraints

Design Constraints	Constraint
Minimum k_{eff} over cycle	1.000
Maximum burnup reactivity swing per cycle ($\Delta k/k$)	<3.5%
Coolant temperature rise (°C)	<155
Maximum coolant velocity (m/s)	12
Maximum cladding temperature (°C)	650
Maximum fuel temperature (°C)	800
Core pressure drop (MPa)	0.9
Peak radiation damage at discharge (dpa)	200

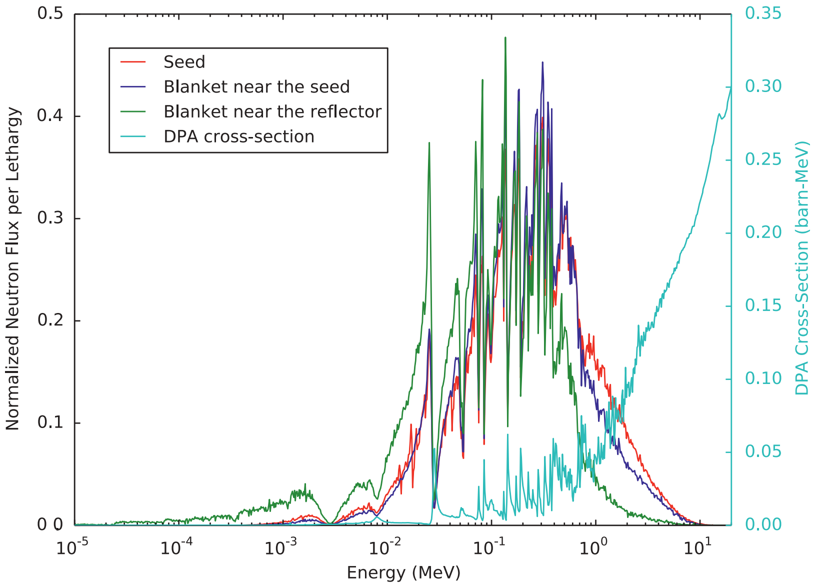

Fig. 4. Comparison of neutron spectra in different regions of the S&B cores.

average neutron energy increases significantly from the periphery to the center of the S&B cores, and the dpa cross section rises steeply with energy in the range above 0.1 MeV (Ref. 27).

The Kinchin and Pease (K&P) model is widely used for the atom displacement when a moving neutron strikes a stationary atom. Details of the K&P model are discussed in Ref. 28, and the number of displaced atoms resulting from a collision is given by

$$V_{\mathrm{K\&P}}(E) = \begin{cases} 0 & \text{for } E < E_d \\ 1 & \text{for } E_d < E < 2E_d \\ \dfrac{E}{2E_d} & \text{for } 2E_d < E < E_c \\ \dfrac{E_c}{2E_d} & \text{for } E_c < E \end{cases} ,$$

where E_d is the minimum energy that a neutron must transfer to a target atom in order to produce a displacement and E_c is the energy at which neutron-electron collisions compete with neutron-nuclei collisions for energy loss.

Lindhard further developed a detailed theory for energy partitioning. The model is applied to compute the fraction of the neutron energy that is dissipated in the system through elastic collisions with the system nuclei and energy losses to the electrons. Instead of a sharp cutoff between nuclear collisions and electronic collisions (in the K&P model), the Lindhard model considers the neutron-electron collisions below E_c and neutron-nuclei collisions above E_c. This work was further developed by Norgett, Robinson, and Torrens (NRT) to provide a displacement model that is being applied as a standard in the nuclear industry to compute the atomic displacement rate[29]:

$$DPA_{\mathrm{NRT}} = \eta \times \frac{\sigma_d}{2E_d} \int dt\phi \, ,$$

where

σ_d = regionwise effective (spectrum weighted) one-group dpa cross section that in this study is calculated using MCNP (barn·MeV)

η = collision efficiency assumed to be 80% in the NRT model[29]

E_d = the displacement energy, which is suggested to be 40 eV for Fe, Cr, and steels.[30]

A zero-dimensional (0-D) MCNP model of the FFTF is used to validate the dpa values computed for this study. The model is based on the fuel/cladding/coolant volume fractions and oxide fuel composition (Table IV) from Ref. 24. Fast neutron fractions above 1 MeV and above 0.1 MeV are estimated to be 10.6% and 60.0%, respectively, versus 12.0% and 62.0% reported in Ref. 31. It is therefore concluded that the spectrum obtained by the 0-D FFTF model can reasonably represent the spectrum of the FFTF.

Using the calculated one-group dpa cross section (about 0.024 barn·MeV) and assuming the displacement energy to be 40 eV, it is found that 4.0 dpa should be accumulated in the FFTF for every 10^{22} neutrons (>0.1 MeV)/cm^2. This is only slightly lower

TABLE IV

Parameters of 0-D FFTF Simulation*

Parameters	Value
Driver fuel	PuO_2-UO_2
Theoretical density for the fuel (g/cm^3)	11.1
Smear density (%)	85.5
Fissile Pu/(Pu+U)	0.2243
Fissile Pu/Pu (%)	88
Volume fraction	
Fuel	0.31
Coolant	0.39
Steel	0.26
Void	0.04
Cladding material	Type 316 stainless steel (20% cold work)

*Reference 24.

than the range between 4.1 and 4.5 dpa per 10^{22} neutrons (>0.1 MeV)/cm^2 estimated for the material open test assemblies in the FFTF core.[32] Therefore, the approach of using dpa to assess radiation damage is consistent with the value reported for the FFTF. Nevertheless, the SFR community is widely using a fast neutron fluence of 4 × 10^{23} neutrons (>0.1 MeV)/cm^2 as the radiation damage constraint[10]; all the ANL SFR and GE S-PRISM core designs are based on this constraint. Therefore, a sensitivity analysis is conducted to quantify the impacts of different radiation damage measures on the S&B core performance (Sec. V.E).

II.E. Design Optimization

The search for the optimal equilibrium core design involves a trade-off between core design variables. A combination of design variables satisfying all the design constraints is searched by the process schematically shown in Fig. 5. The TRU concentration in the driver fuel is determined almost exclusively by the desirable CR. Since the effective microscopic cross sections in SFR change moderately with most core design variations, the required BOEC TRU loading in the seed can be readily estimated. The approximate average enrichments (TRU-to-HM ratio) at BOEC required for CRs of 1.00, 0.75, 0.50, 0.25, and 0.00 are 14%, 21%, 33%, 56%, and 100%, respectively.[15]

In order to maximize the neutron leakage into the subcritical blanket, the number of seed fuel assemblies is minimized, and the P/D ratio is maximized as long as criticality is maintained throughout the cycle. Among these two design variables, the number of seed assemblies is the most effective parameter for leakage enhancement. The number of blanket assemblies and their intra-assembly parameters are varied for minimizing the net neutron leakage from the active core. These optimizations aim to maximize the fissile contents bred in the blanket and thus the fraction of core power generated from the blanket. The blanket is designed to have the smallest P/D ratio (i.e., the largest thorium fuel volume fraction) that enables one to safely accommodate the peak blanket assembly power. The cycle length is determined such that the core is critical and the burnup reactivity swing is less than ~3.5%$\Delta k/k$. The number of batches in the seed and blanket are determined to have a peak radiation damage of ~200 dpa at discharge in both seed and blanket cladding.

The core radial power peaking factor and fuel composition obtained from the neutronic calculations are passed to ADOPT, a code for thermal-hydraulic and structural analyses.[23] The intra-assembly parameters, like the number of fuel pins per assembly and the fuel pin o.d., are determined by ADOPT aiming to accommodate the peak power of the S&B fuel assemblies at the nominal core power of 1000 MW(thermal).

III. SCOPING STUDIES OF SIMPLIFIED S&B CORES

Scoping studies of S&B SFR cores with subcritical B&B blankets are conducted with the TRU CRs of 0.5 and 1.0 and two types of blanket fuel, i.e., depleted uranium and thorium. The performance characteristic of particular interest is the maximum fraction of core power that can be generated from the blanket. The S&B cores at the equilibrium cycle are optimized using the strategy described in Sec. II.

III.A. TRU CR of the Seed

The TRU CR is defined as the ratio of the neutron capture rate by ^{238}U in the seed to the fission rate of all the TRU isotopes, and its value is reported for BOEC. The present study is performed for a fuel self-sustaining seed (CR = 1.0) and for a TRU transmuting seed having a CR = 0.5. The blanket in both cases is fed with thorium. The resulting core performance is summarized in Table V. Because of the depletion of TRU in the seed and the buildup of fissile fuel in the blanket, the power shifts from the seed to the blanket over the cycle; therefore,

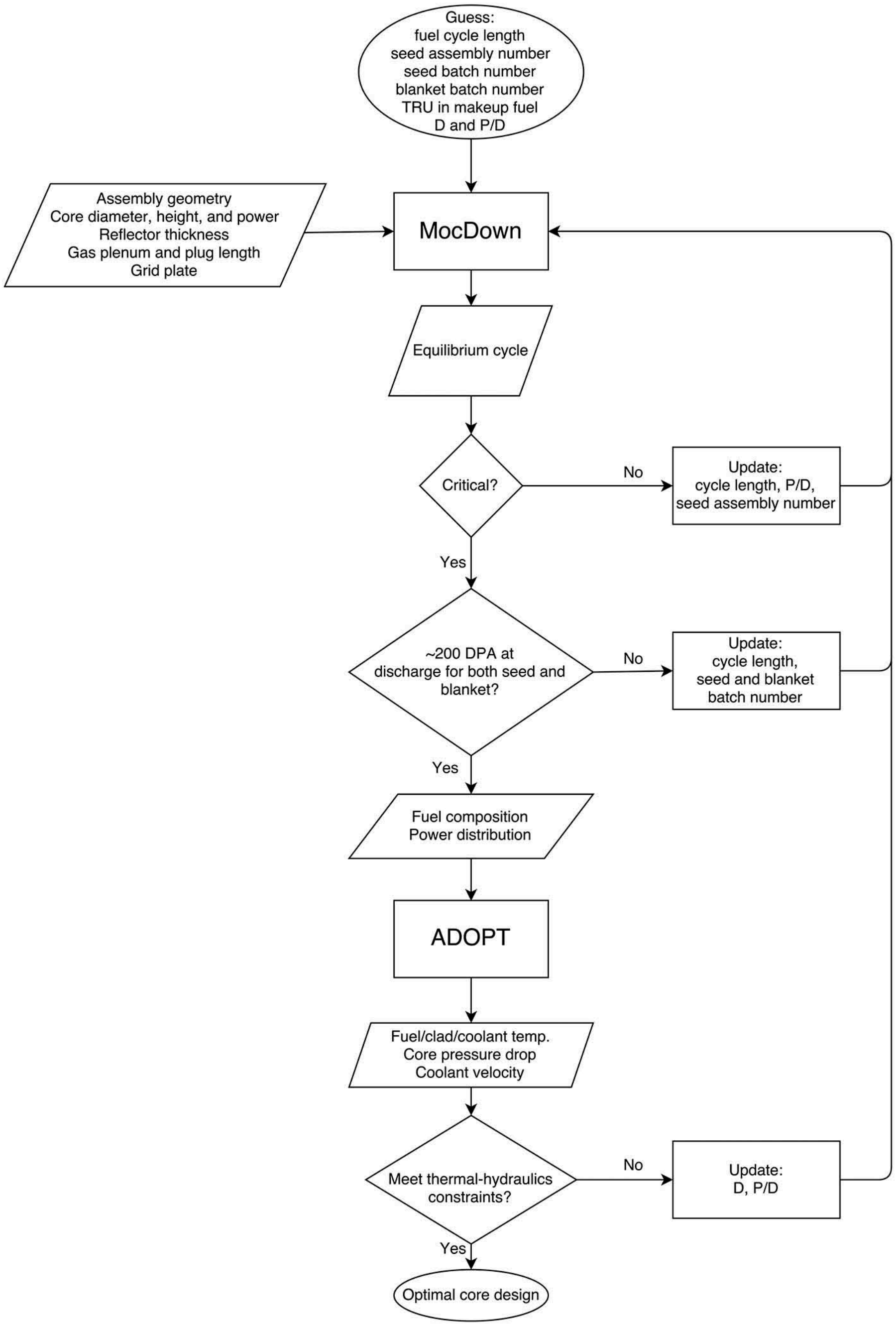

Fig. 5. Flowchart illustrating the search for a combination of design variables that lead to the optimal S&B core design.

the peak assembly power in the seed and in the blanket occurs at BOEC and EOEC, respectively.

It is observed that the power fraction generated by the thorium blanket driven by the low-CR seed is significantly higher than that driven by the high-CR seed. This is because the low-CR seed requires higher TRU enrichment and thus can spare a larger fraction of the fission neutrons for leakage. Moreover, the higher k_∞ of the seed enables one to maintain the core criticality using a smaller number of seed fuel assemblies and a larger P/D ratio. These two facts enhance the neutron leakage probability from the seed into the blanket and increase the fraction of core power generated by the blanket. The fuel assemblies with a larger P/D ratio have a larger coolant flow area and can safely accommodate higher assembly power for a given coolant velocity and pressure drop constraint. It is also found that the CR = 0.5 seed discharges its fuel at higher average burnup for the same peak radiation damage of ~200 dpa. The higher

TABLE V

Comparison of Performance Characteristics of the S&B Cores Driven by TRU Transmutation Seed and Fuel Self-Sustaining Seed

Property	CR = 0.5		CR = 1.0	
	Seed	Blanket	Seed	Blanket
Fuel form	U-TRU-10Zr	Th	U-TRU-10Zr	Th
TRU CR of seed	0.51		1.03	
Number of batches	4	26	3	14
P/D ratio	1.368	1.187	1.210	1.115
Fuel volume fraction (%)	22.29	37.62	28.49	42.63
Permissible assembly power [MW(thermal)]	16.8	9.0	10.0	5.6
Peak-to-permissible power ratio	0.97	0.98	0.86	0.88
Seed diameter (cm)	102.5		158.4	
Cycle length (EFPD)[a]	405		940	
k_{eff} at BOEC	1.041 ± 0.001		1.004 ± 0.001	
k_{eff} at EOEC	1.007 ± 0.001		1.009 ± 0.001	
Burnup reactivity swing (%$\Delta k/k$)	−3.26		+0.46	
Burnup reactivity swing rate (%$\Delta k/k$/EFPY)	−2.94		+0.18	
Radial leakage probability from seed	25.1%		15.4%	
Average blanket power fraction	42.7%		27.7%	
Average discharge burnup (MWd/kg)	161.6	83.0	110.2	77.5
Peak radiation damage (dpa)	194	196	201	201
TRU/HM at BOEC (wt%)	30.4	—	15.2	—
HM at BOEC (ton)	5.7	53.5	18.5	46.4
Specific power [MW(thermal)/ton HM]	99.8	8.0	39.1	6.0
TRU feed rate (kg/EFPY)	92.3	—	0.0	—
Depleted uranium feed rate (kg/EFPY)	116.3	—	259.3	—
Thorium feed rate (kg/EFPY)	0.0	1876.4	0.0	1304.6
Trans-Th discharge rate (kg/EFPY)	0.0	152.5	0.0	102.3
Reprocessing capacity [kg/GW(thermal)·EFPY]	1295.0		2392.5	

[a] EFPD = effective full-power day.

burnup per dpa is mainly attributed to the smaller flux amplitude required by the high TRU content to achieve a given fission rate. Because of the high burnup combined with the large fraction of core power generated by the blanket, the reprocessing capacity required to recycle the seed fuel per unit of electricity generated by the S&B core [1295.0 kg/GWt·effective full-power years (EFPY)] is significantly smaller than that required for the CR = 1.0 core [2392.5 kg/GW(thermal)·EFPY]. These values are about half of those required for the ANL reference SFR designs[15] with identical CRs [2767.2 kg/GW(thermal)·EFPY for the CR = 0.5 ABR and 5000.0 kg/GW(thermal)·EFPY for the CR = 1.0 ARR].

There is another synergy between a low-CR seed and the S&B core concept: As the blanket fissile contents build up over the cycle, the blanket k_∞ increases and partially compensates for the reactivity loss due to the TRU consumption in the seed (illustrated in Fig. 6). The net effect is that the burnup reactivity swing of the CR = 0.5 S&B core is −2.9%/EFPY whereas that of the CR = 0.5 reference ABR is −4.8%/EFPY (Ref. 15). The cycle length of the CR = 0.5 ABR is limited by the burnup reactivity swing constraint (i.e., 3.5%) to 7 months, whereas it is 13.5 months in the CR = 0.5 S&B core. The longer cycle is expected to improve the S&B reactor capacity factor. The blanket fuel adjacent to

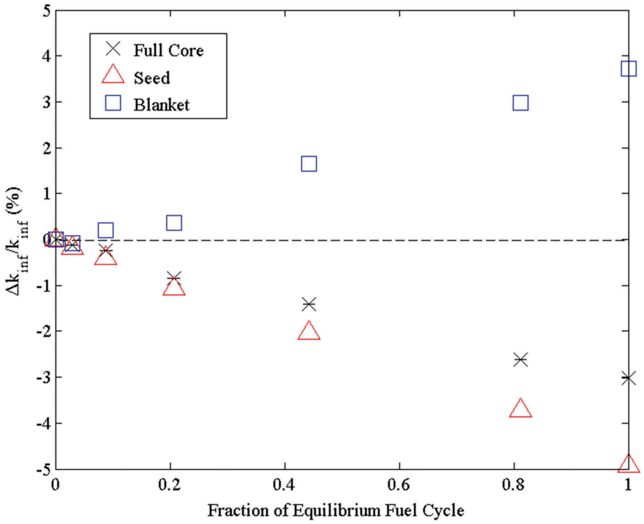

Fig. 6. Reactivity gain and loss of seed, blanket, and full core for CR = 0.5 design.

the seed has a pretty high fissile content at BOEC making its k_∞ close to 1.0 (Fig. 7). This contributes to the relatively small fractional change of the power density in the blanket batches over the equilibrium cycle. Section IV illustrates the radial power profile of S&B cores and its variation over the cycle.

III.B. Comparison of Thorium Versus Uranium Blankets

Previous studies concluded that a sustainable B&B mode of operation cannot be established using metallic thorium as the feed.[7,11,33] This is attributed to a couple of reasons: (1) at high energy, the number of fission neutrons per absorption (η value) in ^{233}U is smaller than that from ^{239}Pu (Fig. 8); (2) the fast fission cross section of ^{232}Th has a higher threshold energy and smaller magnitude than that of ^{238}U. Hence, it is expected that the neutron balance of a depleted uranium blanket is better than that of a thorium blanket in the S&B core.

Table VI compares the S&B core performance when using depleted uranium versus thorium blankets. The seed of both cores is designed to have a CR of 0.5. It is found that the cycle average power fraction that can be generated by the depleted uranium blanket, i.e., 51.1%, is larger than that generated by the thorium blanket, i.e., 42.7%. As less power is generated from the seed, the reprocessing capacity required per unit of electricity generated is lower in the core with the uranium blanket, i.e., 1026.2 kg/GW(thermal)·EFPY versus 1295.0 kg/GW(thermal)·EFPY for the thorium blanket core. Based on this observation, it is expected that a S&B core with a depleted uranium blanket has a lower fuel cycle cost and, hence, better economics than a S&B core with a thorium blanket.

The TRU consumption rate in the seed is not sensitive to the fertile fuel used for the blanket. The depleted uranium blanket produces TRU at a rate that far exceeds the TRU destruction rate in the seed (Table VI). When the primary objective of the SFR is to reduce the total TRU inventory, a thorium blanket is the preferable approach to the S&B concept.

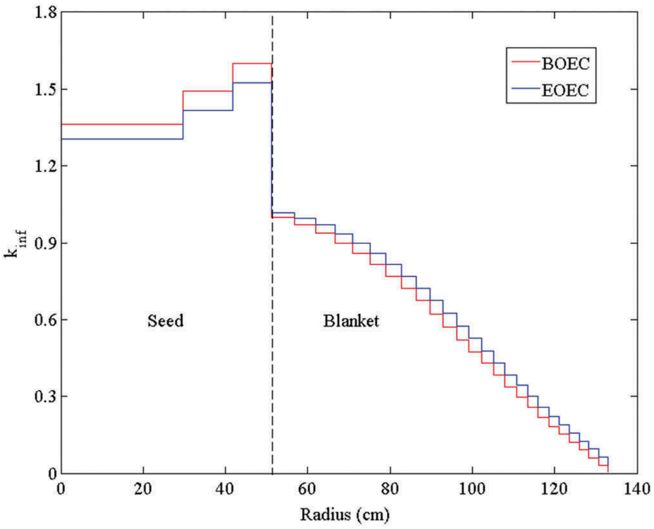

Fig. 7. Radial distribution of infinite multiplication factor for CR = 0.5 design.

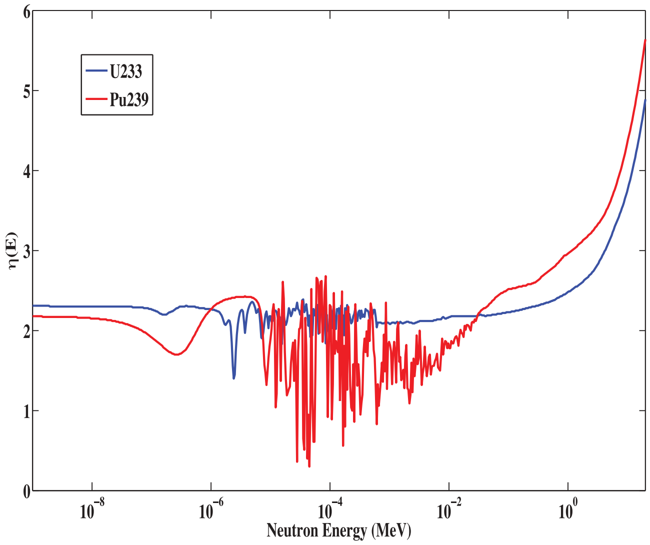

Fig. 8. Fission neutrons per absorption (η value) in ^{233}U and ^{239}Pu.

TABLE VI

Performance Characteristics of S&B Cores with Thorium and Depleted Uranium Blankets

Property	Thorium Blanket		Uranium Blanket	
	Seed	Blanket	Seed	Blanket
Fuel form	U-TRU-10Zr	Th	U-TRU-10Zr	U-10Zr
TRU CR of seed	0.51		0.51	
Number of batches	4	26	3	17
P/D ratio	1.368	1.187	1.510	1.220
Fuel volume fraction	22.29%	37.62%	18.29%	35.61%
Permissible assembly power [MW(thermal)]	16.8	9.0	21.0	10.5
Peak-to-permissible power ratio	0.97	0.98	0.69	0.98
Seed diameter (cm)	102.5		102.5	
Cycle length (EFPD)[a]	405		560	
k_{eff} at BOEC	1.041 ± 0. 0.001		1.036 ± 0.001	
k_{eff} at EOEC	1.007 ± 0. 0.001		1.001 ± 0.001	
Burnup reactivity swing (%$\Delta k/k$)	−3.26		−3.41	
Burnup reactivity swing rate (%$\Delta k/k$/EFPY)	−2.94		−2.22	
Radial leakage probability from seed	25.1%		23.7%	
Average blanket power fraction	42.7%		51.1%	
Average discharge burnup (MWd/kg)	161.6	83.0	174.0	77.1
Peak radiation damage (dpa)	194	196	198	203
TRU/HM at BOEC (wt%)	30.4	—	31.7	—
HM at BOEC (ton)	5.7	53.5	4.7	62.4
Specific power [MW(thermal)/ton HM]	99.8	8.0	103.6	8.2
TRU feed rate (kg/EFPY)	92.3	0.0	77.3	−201.7
Depleted uranium feed rate (kg/EFPY)	116.3	0.0	97.3	2416.4
Thorium feed rate (kg/EFPY)	0.0	1876.4	0.0	0.0
Trans-Th discharge rate (kg/EFPY)	0.0	152.5	0.0	0.0
Reprocessing capacity [kg/GW(thermal)·EFPY]	1295.0		1026.2	

[a] EFPD = effective full-power day.

III.C. Reactivity Coefficients and Kinetic Parameters

In the fast spectrum range, the number of fission neutrons per absorption in ^{239}Pu rises more rapidly with the fission neutron energy than in ^{233}U (Fig. 8). Therefore, the uranium-fueled blankets contribute more positive reactivity feedback to sodium voiding due to spectrum hardening compared with those fueled by thorium. Safety-related parameters of the S&B cores at BOEC are summarized in Table VII. The coolant densities in the seed and blanket are perturbed separately to calculate the reactivity response to sodium voiding. The sodium void worth of the full core is obtained by removing the coolant in the active core. A large positive coolant density coefficient and sodium void worth are observed for all the three cases because the S&B cores are designed to minimize the leakage in the axial direction. Another reason is that the bred ^{233}U is concentrated in the blanket region closer to the seed, and this high-reactivity blanket region reduces the effective radial leakage during coolant voiding. The overall negative feedback from enhanced neutron leakage induced by coolant voiding is of small magnitude. The void reactivity worth of these S&B cores is between 10 $ to 12 $ and close to that of a

TABLE VII

Comparisons of Safety-Related Characteristics of S&B Cores with Thorium and Uranium Blanket Driven by Self-Sustaining Seed and TRU Transmutation Seed

Blanket Fuel	Thorium	Thorium	Uranium
Target TRU CR of seed	0.5	1.0	0.5
Effective delayed neutron fraction	0.0028 ± 0.0002	0.0033 ± 0.0002	0.0038 ± 0.0002
Sodium void worth ($\Delta k/k$)			
Seed only	0.034 ± 0.001	0.043 ± 0.001	0.041 ± 0.001
Blanket only	−0.003 ± 0.001	−0.001 ± 0.001	0.008 ± 0.001
Full core	0.029 ± 0.001	0.042 ± 0.001	0.048 ± 0.001
Sodium temperature coefficient (¢/°C)			
Seed only	0.37 ± 0.02	0.31 ± 0.02	0.26 ± 0.02
Blanket only	0.00 ± 0.02	0.01 ± 0.02	0.03 ± 0.02
Full core	0.32 ± 0.02	0.31 ± 0.02	0.32 ± 0.02
Doppler coefficient (¢/°C)	−0.05 ± 0.03	−0.09 ± 0.02	−0.07 ± 0.02
Axial expansion coefficient (¢/°C)	−0.33 ± 0.04	−0.29 ± 0.03	−0.34 ± 0.03
Radial expansion coefficient (¢/°C)	−0.19 ± 0.03	−0.14 ± 0.02	−0.15 ± 0.02

large 3000 MW(thermal) SFR (Ref. 34). These values are significantly larger than that of a self-sustaining compact shape ARR core (coolant void worth ~7 $) (Ref. 35) as well as the reference CR = 0.5 ABR core (coolant void worth of ~9 $) (Ref. 15). The core with a thorium blanket has less positive coolant void worth than the core with a depleted uranium blanket. As more power is generated from the thorium blanket, the S&B core tends to have a less positive coolant void worth.

The axial expansion coefficient accounts for the reactivity change due to the fuel/cladding expansion and the corresponding reduction of their density. The value is calculated conservatively without considering an effective insertion of control rods that remain stationary during core expansion.[18] The radial expansion coefficient represents the reactivity change due to the expansion of the reactor supporting structure, which is induced by the grid temperature change when the inlet coolant temperature increases. The assembly pitch increases with temperature according to the thermal expansion coefficient of the structural material whereas the fuel and structure densities decrease to preserve the initial mass. The thermal expansion coefficients are more negative in a core with a lower-CR seed because the radial leakage probability from the lower-CR seed is enhanced. The Doppler coefficient is calculated by applying a fuel temperature increase of 300°C. Because of the smaller ^{238}U-to-TRU ratio, the CR = 0.5 cores feature less negative Doppler feedback.

The effective delayed neutron fraction β_{eff} is smaller for the core with a thorium blanket. Although the delayed neutron yields of ^{238}U and ^{232}Th are significantly larger than those of ^{239}Pu and ^{233}U, the fission probability of ^{232}Th is much smaller than that of ^{238}U.

IV. S&B CORES WITH INTERNAL/EXTERNAL THORIUM BLANKET

The preliminary study of the simplified S&B cores described in Sec. III indicates that it is beneficial to maximize the neutron radial leakage probability from the seed. A larger neutron leakage probability increases the fraction of core power generated by the blanket and reduces the positive coolant expansion reactivity feedback along with the sodium void worth.

In order to enhance the radial neutron leakage probability and reduce the radial peaking power in the blanket,[36] the feasibility of S&B cores with an annular seed is evaluated. The seed is located between an inner blanket placed at the center of the core and an outer blanket on the core periphery (Fig. 9). At the end of each cycle, the innermost

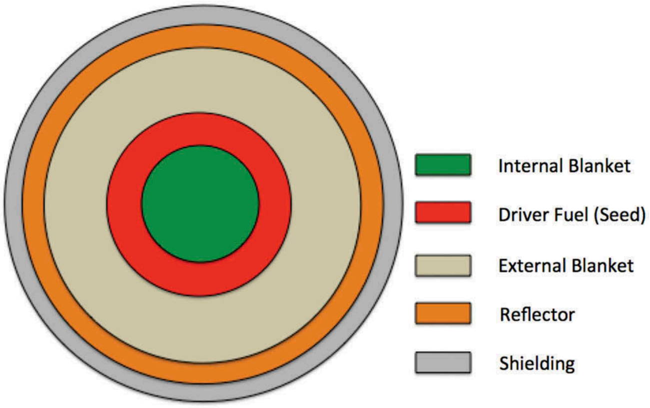

Fig. 9. Schematic core configuration of annular S&B design.

blanket batch is discharged, and the blanket fuel of the other batches is shuffled inward. Fresh thorium fuel is fed to the outermost blanket batch. Near the seed region, the blanket fuel is shuffled from the innermost batch of the outer blanket to the outermost batch of the inner blanket. The annular seed features a larger surface-to-volume ratio than a cylindrical seed, and thus, a larger neutron leakage probability into the blanket is expected. The S&B cores with an annular seed have an additional design variable, i.e., the radius of the internal blanket, and this will be the first parameter to be investigated.

IV.A. Annular Seed Design

A parametric study is performed to understand the effect of the internal blanket radius on the performance characteristics of the annular seed design. The numbers of fuel assemblies and batches in the internal blanket are design variables whereas the number of seed batches is kept at four. As more thorium assemblies are loaded in the internal blanket, the number of fuel assemblies in the seed needs to increase in order to assure criticality throughout the cycle. The total number of S&B fuel assemblies is fixed.

Table VIII compares selected design and performance characteristics of three annular seed cores along with the reference cigar-shaped seed core design described in Sec. III. All the cores are designed to have a seed CR of 0.5. It is found in Fig. 10 that loading more thorium assemblies in the internal blanket (1) increases the leakage probability from the seed to the blanket and, therefore, the fraction of power generated by the blanket from 42.7% to 46.4% (the "Small-Size" case is an exception), (2) reduces the blanket radial power peaking factor from 5.08 to 2.51, (3) decreases the peak seed assembly power by about 40% (Fig. 11), (4) reduces the power jump between the seed and blanket (orifices will be applied to adjust the inlet coolant flow to avoid thermal stripping caused by the power jump), (5) reduces the positive void reactivity worth, (6) decreases the burnup reactivity swing to almost zero for the "Large-Size" case, and (7) extends the cycle length to more than double the reference S&B core and about four times that of the ABR with the CR of 0.5 (Ref. 15).

The sodium void worth of the annular seeds is lower, by more than 50%, compared to the reference central cigar-shaped seed design. This is due to the enhanced neutron leakage from the annular seed. On the contrary, the sodium void worth of the blanket increases with the inner blanket size because coolant voiding enhances neutron leakage from the inner blanket into the high-reactivity seed. The net result of these two competing effects is a reduction in the total coolant void worth with the larger inner blanket.

The smaller burnup reactivity swing of the S&B designs is more pronounced in the annular seed cases because a larger fraction of the core power is generated by the internal blanket. A large amount of fissile contents is bred in the internal blanket, which is nearly critical and located in a relatively high neutron importance region. The nearly zero burnup reactivity swing of the "Large-Size" case (Fig. 12) suggests that it is possible to achieve higher-performance S&B cores with the annular seed while having the burnup reactivity swing within the maximum acceptable (~3.5%). In Secs. IV.B and IV.C, a couple of annular seed designs with improved performance are explored: (1) an extended cycle length for an enhanced capacity factor (ultra-long-cycle case) and (2) a lower CR for a higher TRU transmutation rate (high-transmutation case).

IV.B. Ultra-Long-Cycle S&B Core

The approach used to maximize the cycle length is to reduce the number of S&B batches as long as the burnup reactivity swing does not exceed 3.5%$\Delta k/k$. The ultra-long-cycle S&B core design is obtained by operating the annular seed in a single batch mode while featuring the same TRU CR of 0.5 as the reference ABR. That is, at EOEC, all the seed fuel is discharged rather than 25% of the fuel in the "Large-Size" case. The number of blanket batches is reduced as well from 3 to 1 for the internal blanket and from 7 to 2 for the external blanket. Performance characteristics of the ultra-long-cycle S&B core arrived at are compared in Table IX against those of the reference ABR core design.

The neutronic study finds that it is possible to design a S&B core to have a cycle length of 88 months or 7 EFPY, which is 12 times that of the reference ABR (Ref. 15) with the same TRU CR and similar burnup reactivity swing. The significant increase in the cycle length of this S&B core is due to a couple of reasons: the higher HM inventory (nearly a factor of 7) and much smaller rate of burnup reactivity swing, i.e., nearly 1/10 of that of the ABR. The large burnup reactivity swing forces the ABR to have six batches. A large amount of fissile contents is bred where the internal blanket fuel is nearly critical in a relatively high neutron importance region. As shown in Fig. 12, the reactivity of the internal blanket increases significantly through the fuel cycle. The longer cycle could significantly increase the capacity factor of the SFR.

The fraction of power generated by the blanket is 42.5%, and as a result, the reprocessing capacity required

TABLE VIII

Comparison of Performance Characteristics and Safety Parameters of S&B Cores with Annular Seed as a Function of Inner Blanket Radius

Property	Reference	Small Size	Medium Size	Large Size
Fuel form	U-TRU-10Zr/Th			
TRU CR of seed	0.51	0.51	0.50	0.50
Number of assemblies				
Inner blanket	0	13	35	62
Seed	37	61	61	65
Outer blanket	234	197	175	144
Number of batches				
Inner blanket	0	1	2	3
Seed	4	4	4	4
Outer blanket	26	15	10	7
P/D ratio	1.368/1.187	1.392/1.222	1.265/1.166	1.190/1.124
Permissible assembly power [MW(thermal)]	16.8/9.0	17.8/10.6	12.5/8.0	9.1/6.0
Peak-to-permissible power ratio	0.97/0.98	0.58/0.89	0.80/0.93	0.98/0.96
Cycle length (EFPD)[a]	405	635	760	865
Total residence time (EFPD)	1620/10530	2540/10160	3040/9120	3460/8650
k_{eff} at BOEC	1.041 ± 0.001	1.036 ± 0.001	1.020 ± 0.001	1.001 ± 0.001
k_{eff} at EOEC	1.007 ± 0.001	1.007 ± 0.001	1.006 ± 0.001	1.001 ± 0.001
Burnup reactivity swing (%$\Delta k/k$)	−3.30	−2.80	−1.30	−0.01
Burnup reactivity swing rate (%$\Delta k/k$ /EFPY)	−2.97	−1.61	−0.62	0.00
Radial leakage probability from seed at BOEC				
To external blanket	25.1%	23.3%	25.1%	26.4%
To internal blanket	0.0%	1.4%	3.7%	6.1%
Combined	25.1%	24.7%	28.8%	32.5%
Core leakage at BOEC				
Axial	3.4%	3.6%	3.1%	2.8%
Radial	1.7%	2.8%	2.8%	3.6%
Combined	5.1%	6.4%	5.9%	6.4%
Average blanket power fraction	42.7%	41.0%	44.4%	46.4%
Radial peaking factor at BOEC	1.01/5.08	1.03/5.10	1.04/3.74	1.05/2.51
Average discharge burnup (MWd/kg)	161.6/83.0	167.4/91.0	154.7/80.5	139.7/75.7
Peak radiation damage (dpa)	194/196	197/205	195/201	186/208
TRU/HM at BOEC (wt%)	30.4	30.7	29.7	29.0
HM at BOEC (ton)	5.7/53.5	9.0/45.1	10.9/49.7	13.3/52.3
Specific power [MW(thermal)/ton HM]	99.8/8.0	65.9/9.1	50.9/8.9	40.4/8.9
TRU feed rate (kg/EFPY)	92.3/0.0	94.9/0.0	90.2/0.0	87.0/0.0
Depleted uranium feed rate (kg/EFPY)	116.3/0.0	119.8/0.0	112.7/0.0	108.9/0.0
Thorium feed rate (kg/EFPY)	0.0/1876.4	0.0/1643.8	0.0/2011.4	0.0/2238.1
Trans-Th discharge rate (kg/EFPY)	0.0/152.5	0.0/138.1	0.0/160.6	0.0/171.3
Reprocessing capacity [kg/GW(thermal)·EFPY]	1295.0	1286.6	1312.4	1399.7
Safety Parameters at BOEC				
Effective delayed neutron fraction	0.0028 ± 0.0002	0.0031 ± 0.0002	0.0034 ± 0.0002	0.0032 ± 0.0002
Sodium void worth ($\Delta k/k$)				
Seed only	0.034 ± 0.001	0.034 ± 0.001	0.024 ± 0.001	0.017 ± 0.001
Blanket only	−0.003 ± 0.001	0.003 ± 0.001	0.008 ± 0.001	0.010 ± 0.001
Full core	0.029 ± 0.001	0.036 ± 0.001	0.031 ± 0.001	0.028 ± 0.001
Doppler coefficient (¢/°C)	−0.05 ± 0.03	−0.10 ± 0.02	−0.05 ± 0.02	−0.12 ± 0.02
Axial expansion coefficient (¢/°C)	−0.33 ± 0.04	−0.33 ± 0.03	−0.25 ± 0.03	−0.36 ± 0.03
Radial expansion coefficient (¢/°C)	−0.19 ± 0.03	−0.18 ± 0.02	−0.15 ± 0.02	−0.19 ± 0.02

[a] EFPD = effective full-power day.

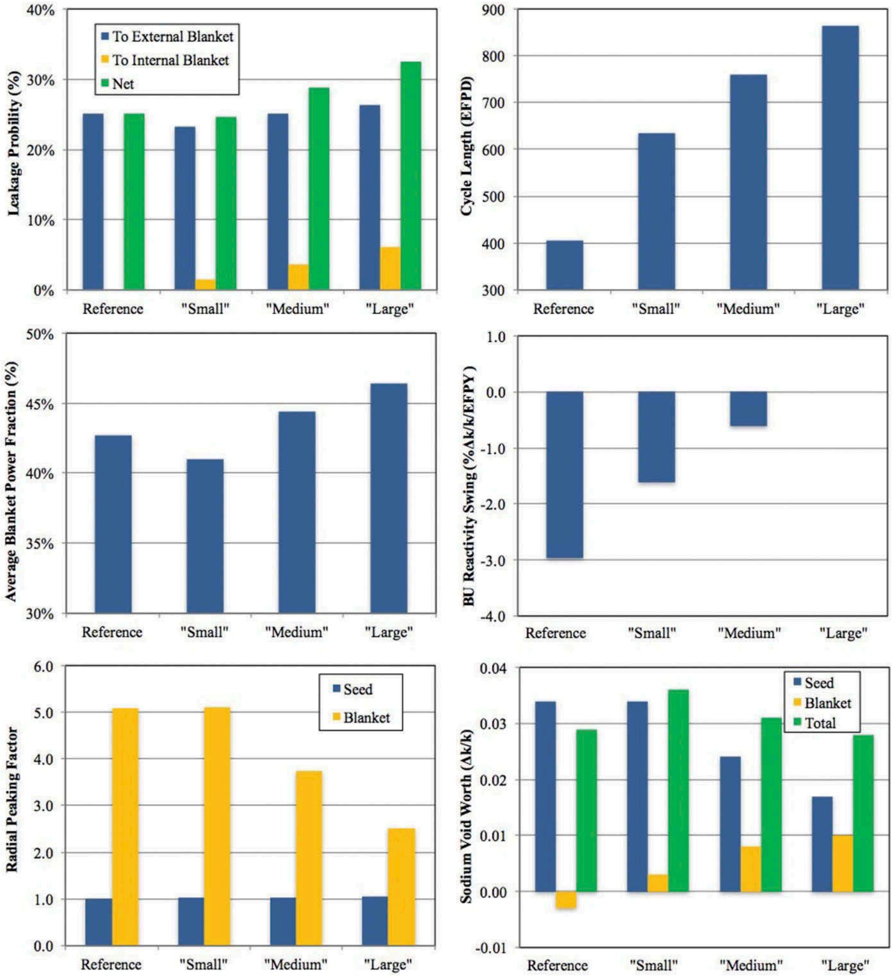

Fig. 10. Performance characteristics of the S&B cores with annular seed as a function of inner blanket radius.

for the S&B core is about 62% that of the ABR. The TRU transmutation rate of the S&B core is only 54% that of the reference ABR. The sodium void worth is +7.6 $, which is smaller than that of the pancake-shaped reference ABR core (+9.2 $) (Table IX).

IV.C. High-Transmutation S&B Core

Two design variants are investigated for the high TRU transmutation S&B core: One has a TRU CR of 0.25 seed, and the other features a TRU CR of 0.0 seed. The CR is reduced by increasing the TRU contents in the seed. Design and performance characteristics of the two S&B core designs arrived at are summarized in Table X in comparison against the reference ABR. The TRU transmutation rate of the CR = 0 design is 373.5 kg/GW(thermal)·EFPY per unit of electricity generated by the seed, which is more than two times that of the ABR. However, when normalized by the total core power, the TRU consumption rate is 158.1 kg/EFPY, which is almost 10% smaller than that of the ABR, i.e., 173.8 kg/EFPY. The high fissile contents in the CR = 0.0 seed increase the seed k_∞ and, hence, the seed excess neutrons. This enables one to reduce the number of driver assemblies and increase the P/D ratio that the seed fuel assembly can be designed to have. As a result, the neutron leakage into the blanket is enhanced, which leads to a higher blanket power fraction, i.e., 57.7%, the highest of all S&B design options arrived at so far when using thorium blankets. The higher TRU concentration in the seed also results in a lower flux magnitude for a given fission density such that the seed fuel could be discharged at an average burnup of 312.4 MWd/kg without exceeding the cladding radiation damage limit of 200 dpa. This is more than twice the average discharge burnup of the reference ABR. The high discharge burnup along with the high fraction of core power generated by the blanket reduces the reprocessing capacity to 494.5 kg/GW(thermal)·EFPY, which is only about 1/6 of that required for the reference ABR core. The smaller capacity for reprocessing and remote fuel fabrication are expected to

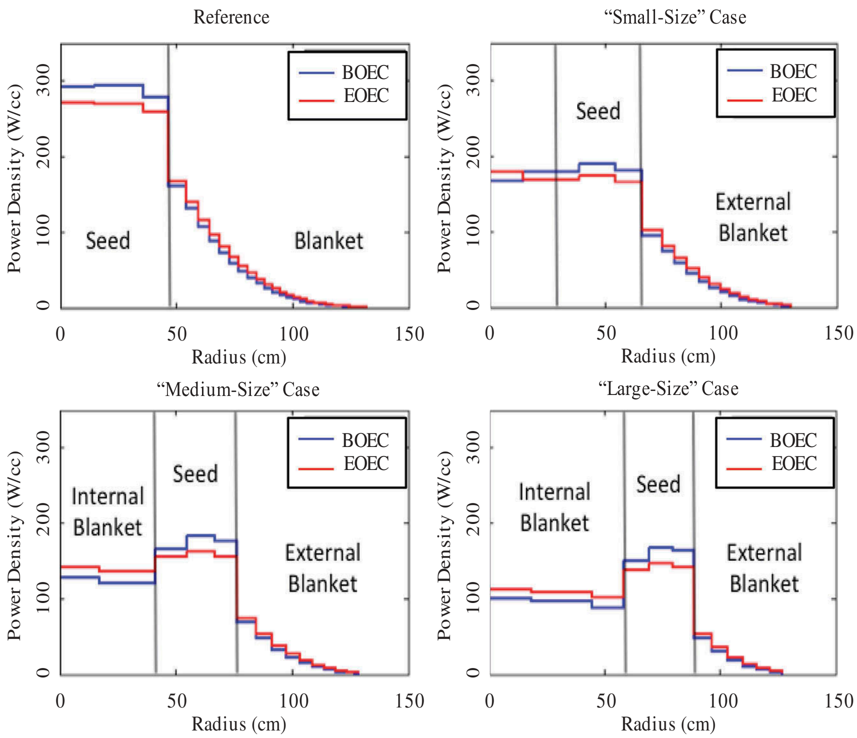

Fig. 11. Comparison of radial power distribution in S&B cores as a function of inner blanket radius.

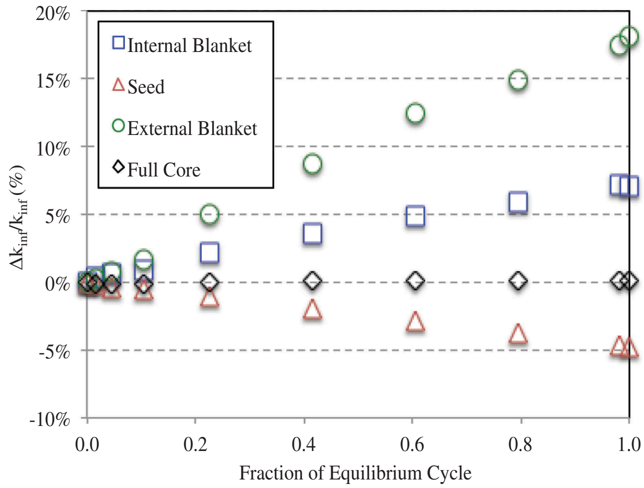

Fig. 12. Reactivity changes of seed, internal blanket, external blanket, and full core in "Large-Size" case.

reduce the fuel cycle cost.[37] The low burnup reactivity swing rate enables one to design the CR = 0 S&B core to have a long cycle of over 4 EFPYs. Therefore, the capacity factor of this S&B reactor is expected to be larger than that of the reference ABR, which also contributes to a lower electricity cost. A thorough comparison of the fuel cycle characteristics between the CR = 0 S&B and the reference ABR cores is presented in Ref. 38.

The high leakage probability from the seed to the blanket also contributes to a relatively small sodium void worth for the seed (+4.2 \$). The internal blanket contributes a sodium void worth of +3.8 \$ while the external blanket has a negative sodium void worth. As a result, the overall sodium void worth of the blankets is +2.3 \$, and the full core coolant void worth is +6.6 \$, which is smaller than that of the ABR (+9.2 \$) (Ref. 15). As the seed fuel in the CR = 0.0 high-transmutation core contains no fertile fuel, its Doppler coefficient is only slightly negative: −0.02 ¢/°C. Nevertheless, the large thorium inventory in the blankets and large fraction of core power that they generate contribute additional negative feedback to the fuel temperature rise. The Doppler coefficient of the full core is −0.07 ¢/°C, which is similar to that of the reference ABR.

V. SENSITIVITY ANALYSIS OF S&B CORES

In order to have a higher fraction of core power generated by the blanket, the S&B cores studied in Secs. III and IV feature elongated cores (the active core height of 2.5 m is more than twice that of conventional SFR core designs) to minimize the axial neutron leakage and maximize the fraction of excess neutrons that leak radially from the seed. The performance

TABLE IX

Comparison of Performance Characteristics of Ultra-Long-Cycle S&B Core and Reference ABR Core

Property	Ultra-Long-Cycle S&B Core	ABR Core
Fuel form	U-TRU-10Zr/Th	U-TRU-10Zr
TRU CR of seed	0.46	0.5
Number of assemblies		
Inner blanket	42	-
Seed	61	144
Outer blanket	168	—
Number of batches		
Inner blanket	1	—
Seed	1	6/6/7
Outer blanket	2	—
P/D ratio	1.261/1.151	1.293
Permissible assembly power [MW(thermal)]	12.3/7.3	—
Peak-to-permissible power ratio	0.96/0.99	—
Cycle length (EFPD)[a]	2630	221
Tot. residence time (EFPD)	2630/7890	1326/1326/1547
k_{eff} at BOEC	1.039 ± 0.001	—
k_{eff} at EOEC	1.004 ± 0.001	—
Burnup reactivity swing (%$\Delta k/k$)	−3.39	−2.90
Burnup reactivity swing rate (%$\Delta k/k$/EFPY)	−0.47	−4.79
Average blanket power fraction	42.5%	0.0%
Average discharge burnup (MWd/kg)	123.2/65.0	131.9
Peak radiation damage (dpa)	175/204	[b]
TRU/HM at BOEC (wt%)	29.9	33.3
HM at BOEC (ton)	12.3/51.4	9.4
Specific power [MW(thermal)/ton HM]	46.8/8.3	106.4
TRU feed rate (kg/EFPY)	93.2/0.0	173.8
Depleted uranium feed rate (kg/EFPY)	117.0/0.0	217.5
Thorium feed rate (kg/EFPY)	0.0/2386.0	0.0
Trans-Th discharge rate (kg/EFPY)	0.0/174.5	0.0
Reprocessing capacity [kg/GW(thermal)·EFPY]	1703.6	2767.2
Safety Parameters at BOEC		
Effective delayed neutron fraction	0.0032 ± 0.0002	0.003
Sodium void worth ($\Delta k/k$)		
Seed only	0.019 ± 0.001	—
Blanket only	0.003 ± 0.001	—
Full core	0.024 ± 0.001	0.028
Doppler coefficient (¢/°C)	−0.03 ± 0.02	−0.08
Axial expansion coefficient (¢/°C)	−0.34 ± 0.03	−0.52
Radial expansion coefficient (¢/°C)	−0.19 ± 0.02	−0.41

[a] EFPD = effective full-power day.

[b] The peak radiation damage on the cladding of the ABR design is constrained by peak fast fluence of 4×10^{23} neutrons (>0.1 MeV)/cm^2.

characteristics of the S&B core reported in Sec. IV.C set an upper bound on the improvements that can be provided by this core concept. Another core design parameter that deviates from design practices followed by the SFR design community is the pressure drop; the value used in the S&B cores examined before are more than twice the commonly used values. The application of nonfertile fuel for a zero CR seed is an additional deviation from common practice; there is very limited experience with such fuel. Typical ABR cores targeting early licensing are designed to have a TRU-to-HM ratio that does not exceed ~30% (Ref. 15).

Sensitivity studies are therefore undertaken to design S&B cores with more acceptable design practices and

TABLE X

Comparison of Performance Characteristics of the High-Transmutation S&B Core and ABR Core

Property	High-Transmutation S&B Core		ABR Core
Fuel form	U-TRU-10Zr/Th		U-TRU-10Zr
TRU CR of seed	0.25	0.01	0.5
TRU/HM at BOEC (wt%)	45.9	99.5	33.3
Number of assemblies			
Inner blanket	39	96	—
Seed	40	30	144
Outer blanket	192	145	—
Number of batches			
Inner blanket	2	2	—
Seed	4	2	6/6/7
Outer blanket	10	3	—
P/D ratio	1.316/1.164	1.406/1.104	1.293
Permissible assembly power [MW(thermal)]	14.7/7.9	18.3/5.1	—
Peak-to-permissible power ratio	0.93/0.99	0.97/0.99	—
Cycle length (EFPD)[a]	685	1550	221
Total residence time (EFPD)	2740/8220	3100/7750	1326/1326/1547
k_{eff} at BOEC	1.026 ± 0.001	1.041 ± 0.001	—
k_{eff} at EOEC	1.004 ± 0.001	1.003 ± 0.001	—
Burnup reactivity swing (%$\Delta k/k$)	−2.11	−3.60	−2.90
Burnup reactivity swing rate (%$\Delta k/k$/EFPY)	−1.12	−0.85	−4.79
Average blanket power fraction	50.0%	57.7%	—
Average discharge burnup (MWd/kg)	213.5/74.0	312.4/70.2	131.9
Peak radiation damage (dpa)	206/193	185/207	[b]
HM at BOEC (ton)	6.4/55.0	4.2/63.7	9.4
Specific power [MW(thermal)/ton HM]	77.9/9.1	100.8/9.1	106.4
TRU feed rate (kg/EFPY)	127.5/0.0	158.1/0.0	173.8
Depleted uranium feed rate (kg/EFPY)	56.8/0.0	0.2/0.0	217.5
Thorium feed rate (kg/EFPY)	0.0/2467.0	0.0/3024.2	0.0
Trans-Th discharge rate (kg/EFPY)	0.0/191.2	0.0/223.3	0.0
Reprocessing capacity [kg/GW(thermal)·EFPY]	854.8	494.5	2767.2
Safety Parameters at BOEC			
Effective delayed neutron fraction	0.0035 ± 0.0002	0.0031 ± 0.0002	0.003
Sodium void worth ($\Delta k/k$)			
Seed only	0.018 ± 0.001	0.013 ± 0.001	—
Blanket only	0.008 ± 0.001	0.007 ± 0.001	—
Full core	0.026 ± 0.001	0.020 ± 0.001	0.028
Doppler coefficient (¢/°C)	−0.11 ± 0.02	−0.07 ± 0.02	−0.08
Axial expansion coefficient (¢/°C)	−0.35 ± 0.03	−0.34 ± 0.03	−0.52
Radial expansion coefficient (¢/°C)	−0.18 ± 0.02	−0.23 ± 0.02	−0.41

[a] EFPD = effective full-power day.

[b] The peak radiation damage on the cladding of the ABR design is constrained by peak fast fluence of 4×10^{23} neutrons (>0.1 MeV)/cm^2.

improved cladding materials if successfully developed in the future. Section V.A reports the effect of 40 wt% instead of 10 wt% Zr in the nonfertile seed fuel TRU alloy. Sections V.B, V.C, and V.D quantify the sensitivity of the S&B core performance to the active core height, pressure drop, and radiation damage constraint, respectively. Section V.E investigates the impact of different radiation damage measures on the S&B core performance.

V.A. Zirconium Fraction in Nonfertile Seed Fuel

The S&B core used as the reference for the following sensitivity analyses is derived from the high-transmutation core described in Sec. IV.C with one exception: The seed fuel is TRU-40Zr rather than TRU-10Zr alloy. TRU-40Zr is assumed for the seed fuel because it is supported by existing irradiation experiments. The U.S. Department of Energy

(DOE) Fuel Cycle Research and Development program in the early 2000s successfully irradiated fuel rods made of Pu-40Zr and Pu-10Am-10Np-40Zr up to a burnup of 22.6% FIMA and 17.7% FIMA, respectively.[39] These fuels could possibly retain their integrity up to even higher burnups. As the TRU content of a metallic transmutation fuel alloy increases, the fuel melting temperature decreases. A zirconium concentration of 40 wt% is suggested in order to have an acceptable melting temperature.[39]

Table XI compares selected design and performance characteristics of the new reference S&B core with the high-transmutation core in Sec. IV.C along with the standard ABR core that features a TRU CR of 0.5. Because of the higher Zr concentration in the seed fuel, the number of the seed assemblies is doubled compared with that of the original high-transmutation core in order to maintain the criticality throughout the equilibrium cycle. The cycle length is cut to meet the burnup reactivity swing constraint, and the number of batches in the seed is increased from two to four. The increase of fuel assemblies in the seed reduces the neutron leakage probability from the seed to the blanket. As a result, the fraction of core power generated from the blanket decreases from 57.7% to 50.7%. However, because of 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. As a result, the reprocessing capacity required per unit of electricity generated is slightly lower in the new reference core than in the original high-transmutation core. Compared with the ABR core[15] that features approximately the same TRU transmutation rate, the new reference core requires about 1/6 the reprocessing capacity and is therefore expected to have a significantly lower fuel cycle cost. The new reference S&B core features a four-times-longer cycle and is expected to have a higher capacity factor and, possibly, better economics. The safety parameters of the new reference S&B core (e.g., delayed neutron fraction, sodium void worth, and Doppler coefficients) are comparable to those of the ABR.

V.B. Core Height

The reference S&B core is designed to have an unconventionally tall core of 250 cm in order to minimize the axial leakage out from the core while maximizing the radial leakage from the seed into the subcritical radial blanket.[17,36,40] Conventional SFR cores, like ANL's ABR (Ref. 15) and GE's S-PRISM (Ref. 16), feature a core height of about 100 cm. The o.d. of the active S&B cores is comparable to that of S-PRISM. Compared with these compact SFR cores, the large S&B core is expected to increase the SFR capital cost as it would require a higher reactor vessel and a more challenging seismic design. A parametric study is undertaken to quantify the effect of a shorter core on the S&B core performance.

Table XII compares the performance characteristics of the S&B cores optimized to have an active core height in a range from 250 to 90 cm. The P/D ratios for the S&B fuel assemblies of the shorter cores are approximately the same as of the reference core; therefore, the shorter cores also feature a lower pressure drop. As the core height decreases, the axial leakage probability significantly increases, and thus, more seed fuel assemblies are required to sustain critical. As a result, the radial leakage probability from the seed to the blanket decreases together with the fraction of core power generated by the blanket. Compared with the reference core (Fig. 13), the shorter S&B cores feature (1) higher neutron leakage out of the active core, (2) smaller blanket power fraction, (3) smaller HM inventory and higher specific power, (4) larger burnup reactivity swing per year and increased number of seed batches, (5) shorter cycles, (6) higher average discharge burnup of seed fuel due to the smaller axial power peaking factor, (7) slightly larger reprocessing capacity per unit of electricity but still about 1/5 that of the ABR (Ref. 15), (8) significantly less positive feedback to coolant voiding due to the enhanced leakage induced by coolant expansion, and (9) more negative feedback to core axial and radial expansion due to the larger core leakage.

This study indicates that it is possible to shorten the S&B core to ~120 cm with only a 15% reduction in the fraction of core power generated by the blanket (from 50.7% of the 250-cm-tall core to 43.1%) and only a 10% increase in the required reprocessing capacity. The fraction of fission neutrons that is lost via leakage in the axial direction increases in the compact cores. The discharge burnup of the seed fuel slightly increases due to the smaller axial peaking factor. The cycle length significantly decreases with core height reduction due to the larger burnup reactivity swing rate. The increase of the burnup reactivity swing rate is due to a combination of the smaller HM inventory and the smaller power fraction generated by the blanket to compensate for the seed reactivity drop. The increase in the burnup reactivity swing requires more batches for the seed fuel. For a core height of 120 cm, it is possible to design S&B cores to have 1-year-long cycles, and the total blanket fuel residence time is approximately 14 years, which is close to half that of the reference S&B core (Sec. V.A). The shorter cores feature a smaller pressure drop and a less positive coolant void worth.

V.C. Pressure Drop

The S&B cores studied so far have a coolant pressure drop of 0.9 MPa, which is higher than the value used for

TABLE XI

Performance Characteristics of the S&B Cores with TRU-10Zr and TRU-40Zr Seed Fuel

	High Transmutation	Reference	ABR
	Seed/Blanket	Seed/Blanket	
Fuel form	TRU-10Zr/Th	TRU-40Zr/Th	U-TRU-10Zr
TRU CR of seed	0.01	0.00	0.5
Number of assemblies			
Inner blanket	96	63	—
Seed	30	61	144
Outer blanket	145	147	—
Number of batches			
Inner blanket	2	3	-
Seed	2	4	6/6/7
Outer blanket	3	7	—
P/D ratio	1.406/1.104	1.216/1.132	1.293
Permissible assembly power [MW(thermal)]	18.3/5.1	10.3/6.4	—
Fraction of maximum permissible	0.97/0.99	0.92/0.99	—
Core height (cm)	250	250	101.6
Leakage probability			
Axial	2.8%	3.5%	—
Radial	4.2%	3.9%	—
Core pressure drop (MPa)	0.9	0.9	—
Cycle length (EFPD)[a]	1550	840	221
Total residence time (EFPD)	3100/7750	3360/8400	1326/1326/1547
k_{eff} at BOEC	1.041 ± 0.00095	1.042 ± 0.00093	—
k_{eff} at EOEC	1.003 ± 0.00085	1.007 ± 0.00085	—
Burnup reactivity swing ($\%\Delta k/k$)	−3.60	−3.33	−2.90
Burnup reactivity swing rate ($\%\Delta k/k$/EFPY)	−0.85	−1.45	−4.79
Average blanket power fraction	57.7%	50.7%	0.0%
Average discharge burnup (MWd/kg)	312.4/70.2	374.0/79.8	131.9
Peak radiation damage (dpa)	185/207	196/208	[b]
TRU/HM at BOEC (wt%)	99.5	99.3	33.3
HM at BOEC (ton)	4.2/63.7	4.4/52.6	9.4
Specific power [MW(thermal)/ton HM]	100.8/9.1	111.3/9.6	106.4
TRU feed rate (kg/EFPY)	158.1/0.0	182.4/0.0	173.8
Depleted uranium feed rate (kg/EFPY)	0.2/0.0	0.3/0.0	217.5
Thorium feed rate (kg/EFPY)	0.0/3024.2	0.0/2317.0	0.0
Trans-Th discharge rate (kg/EFPY)	0.0/223.3	0.0/182.1	0.0
Reprocessing capacity [kg/GW(thermal)·yr^{-1}]	494.5	481.3	2767.2
Safety Parameters at EOEC			
Effective delayed neutron fraction	0.0030 ± 0.0002	0.0029 ± 0.0002	0.003
Sodium void worth ($\Delta k/k$)			
Seed only	0.012 ± 0.001	0.017 ± 0.001	—
Blanket only	0.014 ± 0.001	0.013 ± 0.001	—
Full core	0.026 ± 0.001	0.029 ± 0.001	0.029
Doppler coefficient (¢/°C)	−0.08 ± 0.02	−0.06 ± 0.03	−0.09
Axial expansion coefficient (¢/°C)	−0.27 ± 0.03	−0.27 ± 0.04	−0.54
Radial expansion coefficient (¢/°C)	−0.16 ± 0.02	−0.10 ± 0.03	−0.43

[a] EFPD = effective full-power day.

[b] The peak radiation damage on the cladding of the ABR design is constrained by peak fast fluence of 4×10^{23} neutrons (>0.1 MeV)/cm^2.

TABLE XII

Sensitivity of the S&B Core Performance to Active Core Height

Property	Reference	180-cm Height	120-cm Height	90-cm Height
	Seed/Blanket			
Fuel form	TRU-40Zr/Th			
TRU CR of seed	0.00	0.00	0.00	0.00
Core height (cm)	250	180	120	90
Number of assemblies				
Inner blanket	63	57	57	37
Seed	61	61	71	79
Outer blanket	147	153	143	155
Number of batches				
Inner blanket	3	3	4	4
Seed	4	4	5	6
Outer blanket	7	8	10	17
P/D ratio	1.216/1.132	1.208/1.128	1.190/1.117	1.204/1.125
Permissible assembly power [MW(thermal)]	10.3/6.4	10.0/6.2	9.1/5.7	9.2/6.1
Fraction of maximum permissible	0.92/0.99	0.98/1.00	1.00/0.97	0.97/1.00
Leakage probability				
Axial	3.5%	5.9%	10.7%	15.0%
Radial	3.9%	3.5%	3.6%	2.8%
Core pressure drop (MPa)	0.9	0.8	0.7	0.66
Cycle length (EFPD)[a]	840	600	350	220
Total residence time (EFPD)	3360/8400	2400/6600	1750/4900	1320/4620
k_{eff} at BOEC	1.042 ± 0.001	1.046 ± 0.001	1.041 ± 0.001	1.056 ± 0.001
k_{eff} at EOEC	1.007 ± 0.001	1.004 ± 0.001	1.000 ± 0.001	1.007 ± 0.001
Burnup reactivity swing (%$\Delta k/k$)	−3.33	−4.03	−3.98	−4.64
Burnup reactivity swing rate (%$\Delta k/k$/EFPY)	−1.45	−2.45	−4.15	−7.70
Average blanket power fraction	50.7%	48.6%	43.1%	37.0%
Average discharge burnup (MWd/kg)	374.0/79.8	382.3/83.0	396.6/84.5	416.5/96.4
Peak radiation damage (dpa)	196/208	192/205	189/197	192/202
TRU/HM at BOEC (wt%)	99.3	99.4	99.4	99.4
HM at BOEC (ton)	4.4/52.6	3.2/38.1	2.5/24.6	2.0/17.4
Specific power [MW(thermal)/ton HM]	111.3/9.6	159.3/12.8	226.6/17.5	315.5/21.2
TRU feed rate (kg/EFPY)	182.4/0.0	189.9/0.0	210.0/0.0	231.9/0.0
Depleted uranium feed rate (kg/EFPY)	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0
Thorium feed rate (kg/EFPY)	0.0/2317.0	0.0/2138.3	0.0/1863.8	0.0/1402.5
Trans-Th discharge rate (kg/EFPY)	0.0/182.1	0.0/172.6	0.0/153.5	0.0/120.9
Reprocessing capacity [kg/GW(thermal)·yr^{-1}]	481.3	490.3	523.4	551.7
Safety Parameters at EOEC				
Effective delayed neutron fraction	0.0029 ± 0.0002	0.0030 ± 0.0002	0.0030 ± 0.0002	0.0023 ± 0.0002
Sodium void worth ($\Delta k/k$)				
Seed only	0.017 ± 0.001	0.015 ± 0.001	0.014 ± 0.001	0.014 ± 0.001
Blanket only	0.013 ± 0.001	0.010 ± 0.001	0.005 ± 0.001	0.002 ± 0.001
Full core	0.029 ± 0.001	0.025 ± 0.001	0.018 ± 0.001	0.016 ± 0.001
Doppler coefficient (¢/°C)	−0.06 ± 0.03	−0.10 ± 0.03	−0.07 ± 0.02	0.00 ± 0.03
Axial expansion coefficient (¢/°C)	−0.27 ± 0.04	−0.27 ± 0.03	−0.31 ± 0.03	−0.34 ± 0.04
Radial expansion coefficient (¢/°C)	−0.10 ± 0.03	−0.18 ± 0.03	−0.22 ± 0.02	−0.29 ± 0.03

[a] EFPD = effective full-power day.

most SFR core designs. The experimental SFR cores were designed with a pressure drop of 0.3 MPa whereas the demonstration SFR cores were constrained by a pressure drop of 0.5 to 0.7 MPa (Ref. 24). The lower pressure drop was preferable for decay heat removal by natural circulation. Besides the pumps in FFTF that were

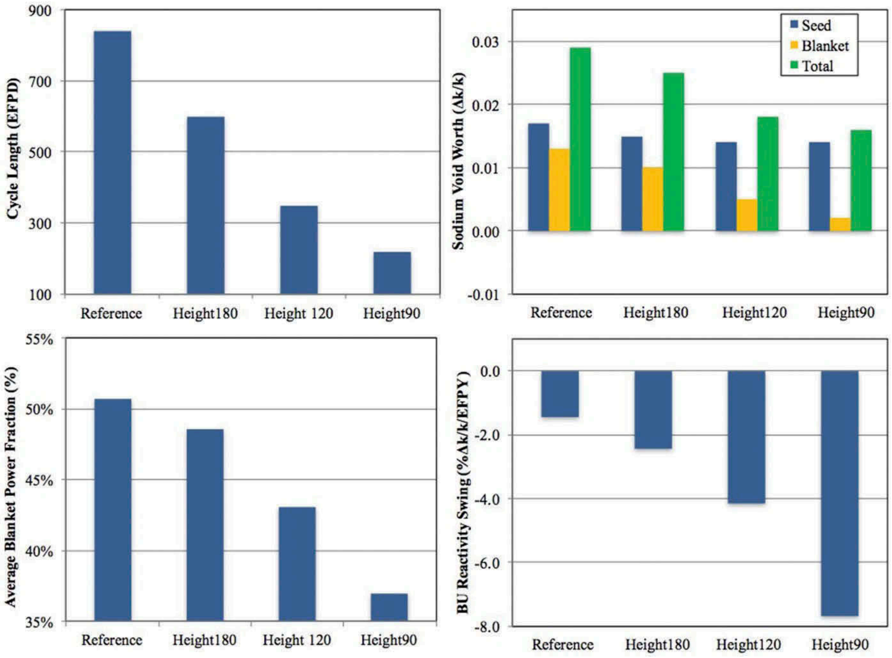

Fig. 13. Impacts of active core height on the S&B core performances.

designed to generate a head of up to 1 MPa (Ref. 24), the sodium pumps fabricated and tested so far were designed to generate a pump head smaller than 0.9 MPa. This section summarizes the findings of a study that investigates the effect of the coolant pressure drop on the S&B core performance. The pressure drop is adjusted by changing the distance between fuel pins while preserving the reference core height at 250 cm. Three cases with larger P/D ratios for both S&B fuel assemblies are optimized to achieve a coolant pressure drop of 0.7, 0.5, and 0.3 MPa, respectively. The P/D ratio is increased by reducing the fuel pin diameter while preserving the number of fuel pins per assembly. The assembly pitch and outer diameter of all cores are not changed, so the fuel inventory in the core decreases as the pressure drop is reduced.

Table XIII compares the performance characteristics of the S&B cores optimized to have different coolant pressure drops. Compared to the reference core (Fig. 14 and Table XIII), the 0.3-MPa pressure drop core has (1) larger net leakage probability, (2) more seed fuel assemblies and fewer internal blanket assemblies, (3) larger number of seed batches primarily due to the larger rate of burnup reactivity swing and shorter cycles, (4) smaller fraction of core power generated by the thorium blanket, (5) slightly higher fuel reprocessing capacity, (6) more positive feedback to coolant voiding due to the higher TRU fuel inventory loaded in the core, and (8) more negative reactivity feedback to core axial and radial expansion.

Nevertheless, the S&B core performance is relatively insensitive to the reduction of the pressure drop constraint. A pressure drop reduction from 0.9 MPa all the way to 0.3 MPa results in a decrease of the blanket power from 50.7% to 44.0% and a corresponding increase in the required reprocessing capacity from 481.3 to 515.0 kg/GW(thermal)·yr^{-1}. The latter is still less than 1/5 that of the reference ABR (TRU CR of 0.5). The cycle length decreases with a lower pressure drop due to a reduction in the HM inventory in the fixed volume core. However, even for the core with a pressure drop of 0.3 MPa, the cycle length is more than twice that of the ABR core (TRU CR of 0.5).

V.D. Radiation Damage Constraint and Phased Development of B&B Reactors

The radiation damage constraint assumed for the cladding of all S&B cores examined so far is 200 dpa. Improved structural materials that are capable of withstanding a higher radiation dose are under development, and irradiation experiments to higher fast neutron fluence are being pursued.[41] A sensitivity study is conducted to quantify the improvement of the S&B core performance in response to successful development and certification of structural materials that will enable increasing the radiation damage limit from 200 to 300 dpa or 400 dpa. For this sensitivity analysis, the dpa value of the seed fuel is still kept at 200 dpa since

TABLE XIII

Sensitivity of the S&B Core Performance to Coolant Pressure Drop

	Reference	0.7-MPa Pressure	0.5-MPa Pressure	0.3-MPa Pressure
	Seed/Blanket	Seed/Blanket	Seed/Blanket	Seed/Blanket
Fuel form	TRU-40Zr/Th	TRU-40Zr/Th	TRU-40Zr/Th	TRU-40Zr/Th
TRU CR of seed	0.00	0.00	0.00	0.00
Core pressure drop (MPa)	0.9	0.7	0.5	0.3
Number of assemblies				
Inner blanket	63	62	60	43
Seed	61	64	71	84
Outer blanket	147	145	140	144
Number of batches				
Inner blanket	3	3	3	3
Seed	4	4	4	5
Outer blanket	7	7	7	10
P/D ratio	1.216/1.132	1.241/1.145	1.293/1.175	1.398/1.262
Permissible assembly power [MW(thermal)]	10.3/6.4	10.0/6.1	10.0/6.1	10.0/6.8
Fraction of maximum permissible	0.92/0.99	0.94/1.00	0.86/1.01	0.78/0.99
Core height (cm)	250	250	250	250
Leakage probability				
Axial	3.5%	3.6%	3.8%	4.6%
Radial	3.9%	4.1%	4.6%	5.2%
Cycle length (EFPD)[a]	840	780	780	630
Total residence time (EFPD)	3360/8400	3120/7800	3120/7800	3150/8190
k_{eff} at BOEC	1.042 ± 0.001	1.039 ± 0.001	1.041 ± 0.001	1.047 ± 0.001
k_{eff} at EOEC	1.007 ± 0.001	1.009 ± 0.001	1.006 ± 0.001	1.004 ± 0.001
Burnup reactivity swing ($\%\Delta k/k$)	−3.33	−2.89	−3.37	−4.04
Burnup reactivity swing rate ($\%\Delta k/k$/EFPY)	−1.45	−1.35	−1.58	−2.34
Average blanket power fraction	50.7%	48.7%	47.6%	44.0%
Average discharge burnup (MWd/kg)	374.0/79.8	355.0/74.0	356.3/78.8	397.2/94.3
Peak radiation damage (dpa)	196/208	182/192	179/195	191/202
TRU/HM at BOEC (wt%)	99.3	99.3	99.3	99.4
HM at BOEC (ton)	4.4/52.6	4.5/50.7	4.6/46.4	4.4/37.5
Specific power [MW(thermal)/ton HM]	111.3/9.6	113.8/9.6	114.2/10.2	126.1/11.7
TRU feed rate (kg/EFPY)	182.4/0.0	189.6/0.0	193.4/0.0	205.8/0.0
Depleted uranium feed rate (kg/EFPY)	0.3/0.0	0.3/0.0	0.3/0.0	0.4/0.0
Thorium feed rate (kg/EFPY)	0.0/2317.0	0.0/2403.6	0.0/2204.4	0.0/1700.5
Trans-Th discharge rate (kg/EFPY)	0.0/182.1	0.0/186.5	0.0/175.6	0.0/145.4
Reprocessing capacity [kg/GW(thermal)·yr^{-1}]	481.3	527.4	537.2	515.0
Safety Parameters at EOEC				
Effective delayed neutron fraction	0.0029 ± 0.0002	0.0027 ± 0.0002	0.0031 ± 0.0002	0.0027 ± 0.0002
Sodium void worth ($\Delta k/k$)				
Seed only	0.017 ± 0.001	0.018 ± 0.001	0.021 ± 0.001	0.029 ± 0.001
Blanket only	0.013 ± 0.001	0.013 ± 0.001	0.013 ± 0.001	0.011 ± 0.001
Full core	0.029 ± 0.001	0.031 ± 0.001	0.034 ± 0.001	0.040 ± 0.001
Doppler coefficient (¢/°C)	−0.06 ± 0.03	−0.03 ± 0.03	−0.10 ± 0.02	−0.10 ± 0.03
Axial expansion coefficient (¢/°C)	−0.27 ± 0.04	−0.32 ± 0.04	−0.34 ± 0.03	−0.36 ± 0.04
Radial expansion coefficient (¢/°C)	−0.10 ± 0.03	−0.18 ± 0.03	−0.20 ± 0.02	−0.18 ± 0.03

[a] EFPD = effective full-power day.

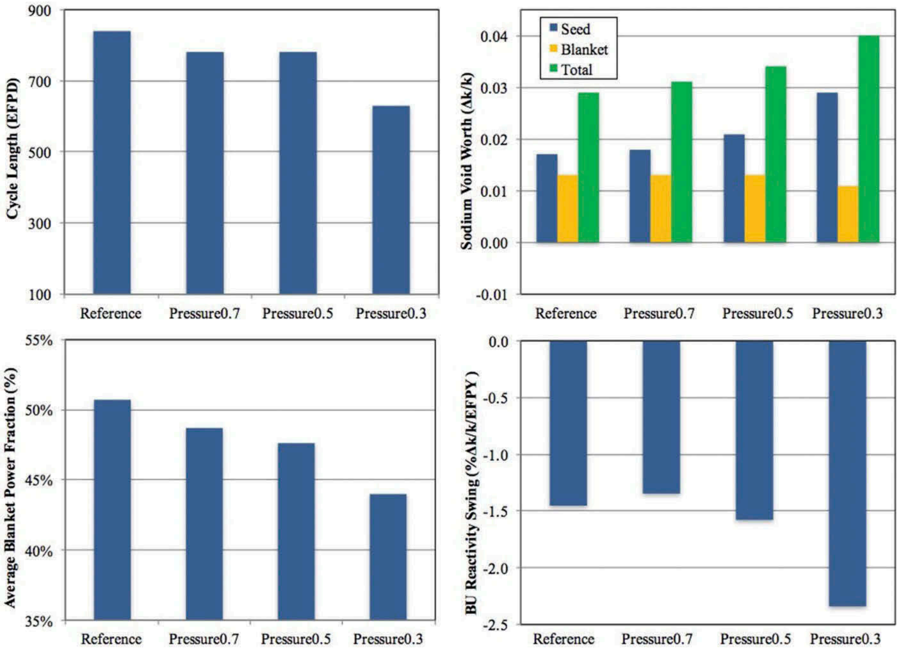

Fig. 14. Impacts of coolant pressure drop on the S&B core performances.

the discharge burnup of the nonfertile fuel (approaching 400 MWd/kg) is already higher than ~200 MWd/kg demonstrated so far.[39]

Table XIV summarizes the performance characteristics of the S&B cores optimized for the blanket peak radiation damage of 100, 200, 300, and 400 dpa. When the blanket fuel is discharged at a higher dpa value and higher burnup, the reactivity of the blanket fuel increases. As a result, (1) more blanket assemblies are loaded in the internal blanket region, (2) the cycle length is extended due to the smaller burnup reactivity swing, and (3) a larger fraction of the core power is generated by the blanket (Fig. 15). The positive feedback to coolant voiding also decreases due to a larger thorium blanket power. At 400 dpa, the B&B blanket can generate 64.2% of the core power despite the enhanced radial leakage out from the active core. The corresponding thorium energy value utilized in the blanket is about 17% FIMA without the need to reprocess irradiated thorium fuel; this is close to 30 times the natural uranium utilization in contemporary LWRs. The reprocessing capacity required to support this S&B core drops to 373.4 kg/GW(thermal)·yr^{-1}, which is only 13.5% the capacity required for the reference ABR core, which is 2767.2 kg/GW(thermal)·yr^{-1}. Because of the reduced power from the seed, it is able to design the seed assemblies with a slightly tighter lattice pitch, and therefore, the HM inventory in the seed increases with blanket discharge dpa.

V.E. Radiation Damage Measures

The neutron-induced radiation damage in this study is measured by the dpa. The dpa value is calculated using the model developed by NRT (Ref. 29) by assuming a displacement energy of 40 eV (Ref. 30). The dpa value is estimated by taking into account the specific shape of the fast neutron spectrum, which is different between the seed and the blanket (Fig. 4). A detailed benchmark calculation on a 0-D model of the FFTF core is performed by MCNP in Sec. II.D to justify the dpa values calculated so far in this study. However, a fast neutron fluence of 4 × 10^{23} neutrons (>0.1 MeV)/cm^2 for the radiation damage constraint is being widely used by the SFR design community. The objective of this section is to evaluate the impact of using the fast fluence rather than dpa on the S&B core performance.

Table XV summarizes the performance characteristics of two S&B cores designed with the different radiation damage constraints. The fast-fluence case has a comparable number of internal and external blanket assemblies as the reference case that uses the 200-dpa constraint. However, the residence times of the S&B fuel are much shorter when using the fast-fluence limit. Compared with the reference case, the fraction of core power generated by the blanket is reduced from 50.7% to 41.9%, and the achievable seed/blanket discharge burnup decreases from 374.0/79.8 to 311.2/46.5 MWd/kg. As a result, the reprocessing capacity of the fast-fluence case

TABLE XIV

Sensitivity of the S&B Core Performance to the Blanket Cladding Radiation Damage Constraint

	100 dpa	Reference	300 dpa	400 dpa
	Seed/Blanket	Seed/Blanket	Seed/Blanket	Seed/Blanket
Fuel form	TRU-40Zr/Th	TRU-40Zr/Th	TRU-40Zr/Th	TRU-40Zr/Th
TRU CR of seed	0.00	0.00	0.00	0.00
Number of assemblies				
Inner blanket	32	63	92	123
Seed	61	61	61	61
Outer blanket	178	147	118	87
Number of batches				
Inner blanket	2	3	4	7
Seed	6	4	3	4
Outer blanket	11	7	4	5
P/D ratio	1.280/1.155	1.216/1.132	1.184/1.132	1.154/1.119
Permissible assembly power [MW(thermal)]	13.2/7.5	10.3/6.4	8.8/6.4	7.4/5.8
Fraction of maximum permissible	0.90/0.92	0.92/0.99	0.96/0.92	0.94/0.90
Core height (cm)	250	250	250	250
Leakage probability				
Axial	4.1%	3.5%	3.3%	3.1%
Radial	2.7%	3.9%	5.2%	6.5%
Core pressure drop (MPa)	0.9	0.9	0.9	0.9
Cycle length (EFPD)[a]	380	840	1390	1215
Total residence time (EFPD)	2280/4940	3360/8400	4170/11120	3645/14580
k_{eff} at BOEC	1.034 ± 0.001	1.042 ± 0.001	1.043 ± 0.001	1.024 ± 0.001
k_{eff} at EOEC	1.002 ± 0.001	1.007 ± 0.001	1.008 ± 0.001	1.005 ± 0.001
Burnup reactivity swing (%$\Delta k/k$)	−3.01	−3.33	−3.30	−1.82
Burnup reactivity swing rate (%$\Delta k/k$/EFPY)	−2.89	−1.45	−0.87	−0.55
Average blanket power fraction	36.4%	50.7%	58.2%	64.2%
Average discharge burnup (MWd/kg)	368.2/35.1	374.0/79.8	362.8/121.3	349.6/171.6
Peak radiation damage (dpa)	184/106	196/208	195/306	190/405
TRU/HM at BOEC (wt%)	99.4	99.3	99.3	99.2
HM at BOEC (ton)	3.9/51.0	4.4/52.6	4.8/51.9	5.0/51.9
Specific power [MW(thermal)/ton HM]	161.5/7.1	111.3/9.6	87.0/11.2	71.9/12.4
TRU feed rate (kg/EFPY)	235.5/0.0	182.4/0.0	154.6/0.0	131.9/0.0
Depleted uranium feed rate (kg/EFPY)	0.4/0.0	0.3/0.0	0.3/0.0	0.2/0.0
Thorium feed rate (kg/EFPY)	0.0/3784.4	0.0/2317.0	0.0/1750.2	0.0/1366.1
Trans-Th discharge rate (kg/EFPY)	0.0/239.5	0.0/182.1	0.0/148.7	0.0/120.4
Reprocessing capacity [kg/GW(thermal)·yr^{-1}]	630.7	481.3	421.0	373.4
Safety Parameters at EOEC				
Effective delayed neutron fraction	0.0025 ± 0.0002	0.0029 ± 0.0002	0.0033 ± 0.0002	0.0027 ± 0.0002
Sodium void worth ($\Delta k/k$)				
Seed only	0.024 ± 0.001	0.017 ± 0.001	0.012 ± 0.001	0.009 ± 0.001
Blanket only	0.008 ± 0.001	0.013 ± 0.001	0.016 ± 0.001	0.019 ± 0.001
Full core	0.032 ± 0.001	0.029 ± 0.001	0.028 ± 0.001	0.027 ± 0.001
Doppler coefficient (¢/°C)	−0.07 ± 0.03	−0.06 ± 0.03	−0.12 ± 0.02	−0.10 ± 0.03
Axial expansion coefficient (¢/°C)	−0.44 ± 0.04	−0.27 ± 0.04	−0.28 ± 0.03	−0.28 ± 0.04
Radial expansion coefficient (¢/°C)	−0.33 ± 0.03	−0.10 ± 0.03	−0.17 ± 0.02	−0.12 ± 0.03

[a] EFPD = effective full-power day.

increases from 481.3 to 681.5 kg/GW(thermal)·yr. The latter is still far lower—only about 1/4—than the ABR required reprocessing capacity, 2767.2 kg/GW(thermal)·yr.

It is concluded that although the performance characteristics of the S&B cores are sensitive to the radiation damage measure applied, the S&B cores offer very

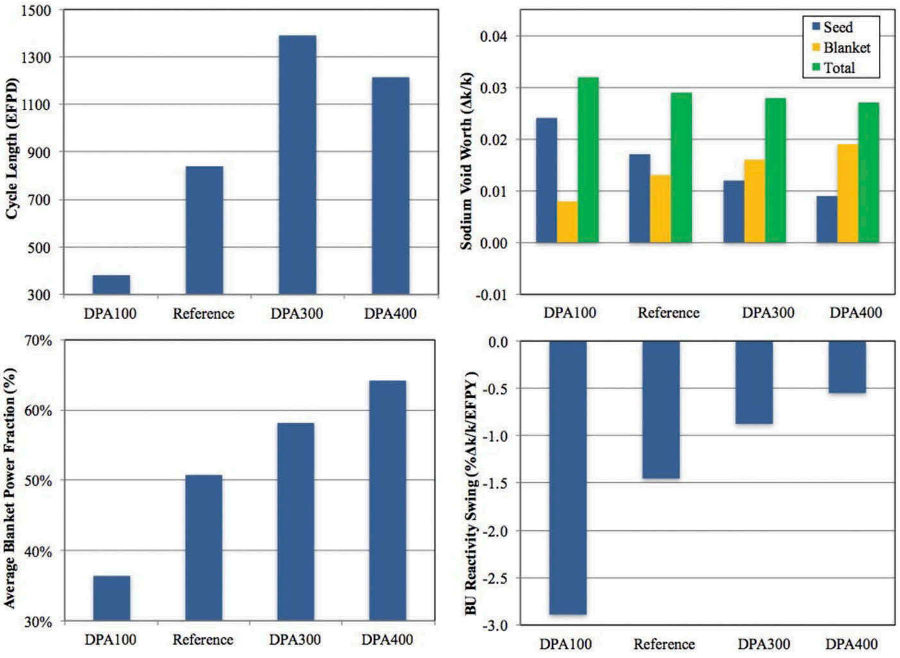

Fig. 15. Impacts of radiation damage constraint on the S&B core performances.

significant performance improvements relative to the conventional ABR core design even when using an identical radiation damage measure.

VI. UNIQUE SYNERGISMS BETWEEN SEED AND BLANKET FOR THE S&B CONCEPT

The studies of the S&B SFR concept reported in the previous sections demonstrate remarkable differences in the performance of S&B cores relative to the conventional ABR core designs. These differences are attributed to the unique synergism that exists between a TRU transmuting seed and a B&B thorium blanket (Table XVI).

VI.A. Use of Inert Matrix TRU as Seed Fuel

The unique synergism between inert matrix seed fuel and thorium blankets includes the high seed discharge burnup for a given radiation damage level and the large fraction of core power generated from the thorium blankets (Sec. III.A). Inert matrix TRU fuel (CR = 0) is not practical for conventional SFR cores because such SFR cores feature a sharp drop of reactivity with burnup and therefore an impractically short cycle.[15] References 13, 15, and 42 conclude that the lowest practical CR that an ABR core can be designed to have is 0.6; this corresponds to a TRU/HM ratio of about 30% and a cycle length of 1 year. For this reason, application of inert matrix fuel was considered only for subcritical blankets that are driven by an intense source of either spallation neutrons in accelerator-driven systems or fusion neutrons in fusion-fission hybrid reactors[43] (FFHs). The S&B core concept enables one to design a critical fission reactor core to efficiently utilize inert matrix fuel such as TRU-40Zr in the seed region. In the S&B cores, the large reactivity gain in the blanket compensates for a significant fraction of the reactivity loss of the seed (Fig. 12).

Another difficulty in utilizing inert matrix TRU fuel is the large positive feedback to coolant voiding and the nearly zero Doppler reactivity coefficient.[15] Since a large fraction of core power is generated from the thorium blanket, the S&B cores with inert matrix TRU fuel have a relatively small positive void worth along with a sufficiently negative Doppler reactivity coefficient. The benefits are enhanced when using an annular seed.

VI.B. Small Fuel Reprocessing Capacity

The higher discharge burnup of the seed together with the large blanket power reduce the capacity required for fuel reprocessing and fabrication per unit of electricity generated by the core. For the S&B core with nonfertile fuel in the seed (Secs. IV.C and V.A), the required fuel recycling capacity is only about 1/6 that of the reference CR = 0.5 ABR. These facts are expected to reduce the fuel cycle cost.

TABLE XV

Effect of Radiation Damage Measure on the Performance of the S&B Cores

	Reference	Fast-Fluence
	Seed/Blanket	Seed/Blanket
Fuel form	TRU-40Zr/Th	TRU-40Zr/Th
TRU CR of seed	0.00	0.00
Number of assemblies		
Inner blanket	63	59
Seed	61	63
Outer blanket	147	149
Number of batches		
Inner blanket	3	2
Seed	4	3
Outer blanket	7	5
P/D ratio	1.216/1.132	1.229/1.124
Permissible assembly power [MW(thermal)]	10.3/6.4	10.9/6.0
Fraction of maximum permissible	0.92/0.99	1.00/0.94
Core height (cm)	250	250
Core pressure drop (MPa)	0.9	0.9
Cycle length (EFPD)[a]	840	850
Total residence time (EFPD)	3360/8400	2550/5950
k_{eff} at BOEC	1.042 ± 0.001	1.046 ± 0.001
k_{eff} at EOEC	1.007 ± 0.001	1.002 ± 0.001
Burnup reactivity swing (%$\Delta k/k$)	−3.33	−4.24
Burnup reactivity swing rate (%$\Delta k/k \cdot \text{EFPY}^{-1}$)	−1.45	−1.82
Average blanket power fraction	50.7%	41.9%
Average discharge burnup (MWd/kg)	374.0/79.8	311.2/46.5
Peak radiation damage with displacement energy of 40 eV (dpa)	196/208	162/139
Peak fast neutron fluence (10^{23} n/cm^2)	4.97/5.88	4.04/3.98
TRU/HM at BOEC (wt%)	99.3	99.3
HM at BOEC (ton)	4.4/52.6	4.8/53.2
Specific power [MW(thermal)/ton HM]	111.3/9.6	122.0/7.9
TRU feed rate (kg/EFPY)	182.4/0.0	215.5/0.0
Depleted uranium feed rate (kg/EFPY)	0.3/0.0	0.4/0.0
Thorium feed rate (kg/EFPY)	0.0/2317.0	0.0/3285.7
Trans-Th discharge rate (kg/EFPY)	0.0/182.1	0.0/222.6
Reprocessing capacity [kg/GW(thermal)·yr^{-1}]	481.3	681.5
Safety Parameters at EOEC		
Sodium void worth ($\Delta k/k$)	0.029 ± 0.001	0.029 ± 0.001
Doppler coefficient (¢/°C)	−0.06 ± 0.03	−0.14 ± 0.02
Axial expansion coefficient (¢/°C)	−0.27 ± 0.04	−0.36 ± 0.03
Radial expansion coefficient (¢/°C)	−0.10 ± 0.03	−0.19 ± 0.02

[a] EFPD = effective full-power day.

VI.C. Long Cycles

As explained above, the thorium blanket enables one to design S&B cores with a relatively small rate of reactivity drop and, therefore, much longer cycles than that of ABR cores (Sec. IV.B). The relatively small reactivity drop rate of S&B cores is due to a combination of a couple of phenomena: (1) the blanket reactivity increases with burnup and partially compensates for the reactivity loss in the seed over the cycle (Fig. 6) and (2) the low average specific power of the S&B core due to the high inventory of HM at the same core power level as the ABR core (Sec. IV.B).

TABLE XVI

Summary of the Unique Synergism Between Low-CR Seed and Thorium B&B Blanket

Cause	Effect
Low-CR seed	Higher TRU/HM and larger P/D ratio. Larger fraction (>20%) of fission neutrons leaking from the seed to the blanket. Larger fraction of core power generated by blanket. Lower fast neutron flux in the seed and higher discharge burnup of the seed fuel for 200 dpa. Lower fuel reprocessing and remote fabrication capacity.
Thorium B&B blanket	No thorium reprocessing technology required. Large reactivity gain in the blanket with burnup that significantly compensates for the reactivity loss in the seed; longer cycles and higher capacity factor. Less positive feedback to coolant voiding, comparable or smaller than that of high-leakage ABR cores. Negative Doppler reactivity coefficient even when nonfertile fuel is charged to the seed. Application of nonfertile fuel for the seed without need for a spallation or fusion neutron source. Significant thorium resource utilization without exceeding the proven radiation damage constraint.
Larger internal blanket	Larger leakage from seed and higher fraction of the core power generated in the blanket. Smaller burnup reactivity swing per year. Smaller void reactivity worth. Longer cycles; higher capacity factor. Smaller radial power peaking factor.

Even though the HM inventory of the reference S&B core is significantly higher than the conventional SFR cores, the HM loading in the seed is smaller than that of a typical SFR. The blanket fuel cost is only a very small fraction of the seed fuel cost. The longer cycles will enable one to operate the S&B cores with a higher capacity factor, which is expected to reduce the operation-and-maintenance cost.

VI.D. Small Radial Peaking Factor

The use of an internal blanket greatly flattens the radial power distribution in the S&B core and reduces the peak linear heat generation rate. The blanket fuel adjacent to the seed has pretty high fissile contents, and its k_∞ is close to 1.0 (Fig. 7). Unlike the blankets in conventional SFR designs, the large inventory of fissile contents in the blanket at BOEC contribute to a relatively small fractional change of the blanket power density over the equilibrium cycle (Fig. 11). There are no fundamental differences in this aspect between a thorium-fueled and a depleted uranium–fueled blanket.

VI.E. Less Positive Sodium Reactivity Coefficients

Even though the S&B cores examined above feature a much larger core volume and lower net leakage probability than the ABR cores, the positive reactivity feedback to coolant voiding in the S&B cores is comparable to or even smaller than that of a typical high-leakage ABR core design. This is attributed to the tight neutronic coupling between seed and blanket together with the unique physics characteristics of the thorium fuel. The thorium-fueled blankets feature less positive feedback to spectrum hardening than the seed due to the following two reasons: (1) the number of fission neutrons generated per neutron absorbed in ^{233}U (the η value) increases much more slowly with neutron energy than in ^{239}Pu and (2) the increase in the fast fission probability of ^{232}Th with neutron energy is significantly smaller than that of ^{238}U.

Consider, for example, the TRU CR = 0.0 S&B core design of Table X. The neutron leakage probability from the seed to the thorium blanket is 47.7% at nominal condition and increases to 47.9% when the coolant in the seed is fully voided. This small change of the leakage probability has a large impact on the void reactivity feedback. The reactivity gained due to the spectrum hardening in the seed (+5.5 \$) is partially compensated by the enhanced neutron leakage out from the seed (−3.0 \$). The leaking neutrons enter the blanket region where the reactivity is smaller than that of the seed. The net effect is that the sodium void worth of the CR = 0 seed fuel (+4.2 \$) is less than half the value (+9.2 \$) for the reference ABR. The coolant voiding in the internal blanket results in a positive coolant voiding reactivity worth due to the enhanced leakage of neutrons from the internal blanket into the higher-reactivity seed; the external blanket fuel contributes negative feedback to coolant voiding. The overall coolant void reactivity worth of the TRU CR = 0.0 S&B core (+6.5 $) is less positive than that of the reference TRU CR = 0.5 ABR core. With the depleted uranium–fueled blanket, the coolant reactivity coefficient of the S&B core would have been significantly more positive (Sec. III.C).

VI.F. Thorium Utilization

The S&B core concept enables significant thorium resource utilization in a critical fission reactor without a need for thorium reprocessing technology and for a new cladding material. In the metallic thorium–fueled S&B cores designed in this study, approximately 7% of the fed thorium is burned without recycling. This thorium utilization is about 12 times the natural uranium utilization in LWRs (Ref. 37). This high thorium utilization is due to the beneficial use of the excess neutrons from the seed that drive the blanket in a subcritical B&B mode. Significantly higher thorium utilization can be achieved by softening the blanket spectrum[44] and/or by the development of a cladding material capable of withstanding higher radiation damage (Sec. V.D).

VII. CONCLUSIONS

This study assesses the feasibility of designing S&B SFR cores to generate a significant fraction of the core power from thorium-fueled radial blankets that operate in a subcritical B&B mode without exceeding the radiation damage constraint of presently verified cladding materials. Since the blanket fuel requires no reprocessing and no remote fuel fabrication, a larger fraction of core power generated from the blanket will result in a smaller fuel recycling capacity and therefore lower fuel cycle cost per unit of electricity generated.

It is found that the seed in the S&B core can be designed to have a wide range of TRU CRs. There is a unique synergism between a low-CR seed and a thorium blanket: A lower-CR seed requires a higher TRU/HM ratio so that a larger fraction of fission neutrons in the seed is excess neutrons. These facts increase the fraction of core power generated by the blanket. As its fissile content builds up, the blanket reactivity increases over the cycle and partially compensates for the large reactivity loss of the low-CR seed. Because of this, the S&B core reactivity drops much more slowly than a conventional ABR with a comparable TRU transmutation rate. The smaller reactivity loss rate enables longer cycles and thus higher reactor capacity factors. In addition, the higher TRU/HM seed can achieve a higher average discharge burnup for a given radiation damage constraint due to the smaller magnitude of the neutron flux for a given fission density. The high seed discharge burnup also contributes to the lower capacity required for fuel reprocessing per unit of core power generated and to the longer cycles. The unique physics characteristics of the thorium blanket make it possible to use inert matrix fuel for the seed in S&B cores that feature a relatively small positive void reactivity worth and negative Doppler coefficient. In the equilibrium core, the blanket batches with relatively high power density are those adjacent to the seed and have pretty high fissile contents; their k_∞ at BOEC is close to 1.0. As a result, these blanket batches exhibit a relatively small fractional change in power density over the equilibrium cycle that simplifies the thermal-hydraulic design of the S&B cores. The power shifting between the seed and the blanket over the cycle is easily manageable.

The benefits of the synergism described above are maximized when using an annular rather than cylindrical seed. Loading thorium assemblies at the core center in addition to the periphery provides the following benefits: larger fraction of power generation by the blanket, smaller burnup reactivity swing and longer cycles, smaller radial peaking factor and lower peak heat generation rates, and less positive sodium void worth. Two high-performance cores are designed to benefit from this unique synergism: (1) the ultra-long-cycle core having a cycle length of 88 months or ~7 EFPY, which is about 12 times longer than that of the reference ABR with a comparable TRU CR of 0.5, and (2) the high-transmutation core, which features a TRU CR of 0.0. The latter core transmutes TRU at a comparable rate as the reference CR = 0.5 ABR but requires only about 1/6 the reprocessing capacity per unit of core power. The thorium blanket can generate close to 60% of the core power, and the cycle length of this S&B core is over 4 EFPY. The annular S&B cores have a smaller sodium void worth than the reference compact ABR core despite the low neutron leakage probability out of the S&B cores. This is due to an enhanced neutron leakage probability from the seed to the low-reactivity blanket upon coolant voiding. The application of a thorium blanket in the high-transmutation S&B core assures that the core has a negative Doppler coefficient even though its seed is charged with nonfertile fuel.

Nevertheless, these high-performance cores are designed to set upper bounds on the S&B core performance by using a larger height and pressure drop than those of the typical SFR design. Sensitivity analyses are subsequently undertaken to quantify the trade-off between S&B core design variables and the core performance. The design variables considered include the Zr contents in the TRU-Zr inert matrix fuel, the active core height, the pressure drop through the core, and the radiation damage constraint. The seed fuel in the high-transmutation core is changed from TRU-10Zr to TRU-40Zr that has been successfully irradiated in the past. The active core height is reduced in steps from 250 cm down to 90 cm. A compact S&B core with the active height of 120 cm will be comparable in core volume, HM mass, and specific power with the S-PRISM core. Of the core power, 43% is generated from the once-through thorium blankets, and the reprocessing capacity is approximately 1/5 that of a comparable ABR. The sodium void worth of this compact S&B core is significantly less positive than that of the reference ABR, and the Doppler coefficient is just about the same even though the seed utilizes a fertile-free fuel. An additional sensitivity analysis is conducted to remove the bias introduced by the use of different radiation damage constraints, i.e., the 200 dpa applied for the S&B core designs versus the fast fluence of 4×10^{23} neutrons (>0.1 MeV)/cm^2 applied by ANL and industry for SFR core designs. Although the performance characteristics of the S&B cores are noticeably sensitive to different radiation damage measures, the S&B cores still offer significant performance improvements relative to the conventional ABR core design when using fast fluence. This sensitivity study concludes that a viable S&B core can be designed without significant deviation from present SFR design practices.

In conclusion, a SFR based on the S&B core concept can be implemented using presently qualified cladding materials and can start benefiting from the B&B mode of operation without extensive R&D efforts. The expected benefits relative to the standard ABR offered by the S&B cores include a significantly smaller reprocessing capacity required per unit of electricity generated, lower fuel cycle cost, longer cycles for higher capacity factor, and significant utilization of the thorium resource. With proven cladding materials, the S&B cores can utilize approximately 7% of the thorium energy value without the need to reprocess the irradiated thorium fuel. This thorium utilization is ~12 times higher than the natural uranium utilization in LWRs. Significantly higher thorium utilization could be achieved by softening the blanket spectrum[a] and/or by successful development of improved cladding materials capable of withstanding higher radiation damage.

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[a] Details related to the effect of spectrum softening on the thorium utilization and S&B core performance will soon be published in Ref. 44. A thorough comparison of the fuel cycle characteristics among the S&B core, standard ABR, and present LWRs will soon be published in Ref. 38.

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