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SFR with once-through depleted uranium breed & burn blanket

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ABSTRACT

This paper assesses the feasibility of Sodium-cooled Fast Reactor (SFR) cores that have TRU recycled seeds and once-through depleted uranium blankets. The design objective of these Seed-and-Blanket (S&B) cores is to maximize the power generated by the blanket. As the blanket fuel cost is significantly lower than the cost of the seed fuel and does not need reprocessing, increasing the fraction of reactor power generated by the blanket will reduce the total fuel cycle cost and the fuel reprocessing capacity required per unit of electricity generated. The S&B core is designed to have a prolate ("cigar") shape seed ("driver") to maximize the fraction of neutrons that radially leak into the subcritical blanket and reduce neutron loss via axial leakage. Both seed and blanket contain multiple batches; the blanket batches are gradually shuffled inward, while one third of the fuel batches in the seed are recycled. The preliminary study found that it is possible to design the seed to accommodate a wide range of TRU conversion ratios (CR) without significantly penalizing the burnup reactivity swing. The relatively small burnup reactivity swing enables to design the S&B core to operate at longer cycles and discharge its fuel at a higher burnup relative to conventional TRU transmutation cores with identical CR. The S&B cores can generate 1000 MW_{th} and fit within the S-PRISM reactor vessel. The fraction of core power generated by the blanket is between 40% and 50% without exceeding the radiation damage constraint of 200 Displacements per Atom (DPA); this fraction increases when the seed is designed to have a smaller CR. These features are expected to improve the economics of SFR.

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1. Introduction

Sodium-cooled Breed-and-Burn (B&B) fast reactors are recently being proposed for utilizing the large stockpiles of depleted uranium using a once-through fuel cycle (Gilleland et al., 2008; Ahlfeld et al., 2011; Ellis et al., 2010; Greenspan and Heidet, 2009, 2011; Greenspan, 2012; Heidet et al., 2009; Heidet and Greenspan, 2010, 2012, 2013; Sekimoto et al., 2001; Takaki et al., 2012; Takaki and Sekimoto, 2008). Previous studies (Ellis et al., 2010; Greenspan and Heidet, 2009, 2011; Greenspan, 2012; Heidet et al., 2009; Heidet and Greenspan, 2010, 2012, 2013) found that the minimum average burnup required for sustaining the B&B mode of operation is close to 20% FIMA (Fissions per Initial Metal Atom). This corresponds to a peak burnup of approximately 35% FIMA in a B&B core and peak radiation damage to structural materials of ~550 DPA (Displacements Per Atom). The maximum radiation damage that cladding and structural materials have been exposed to so far is approximately 200 DPA. Hence, an extensive R&D effort would be required to develop and qualify cladding materials that could retain the fuel integrity up to at least 550 DPA. Such a program would have to include irradiation experiments in fast spectrum and post-irradiation analysis and would require a long time and resources.

Typical sodium-cooled fast reactor (SFR) cores are of a pancake shape and have an axial neutron leakage probability on the order of 20% (Kim et al., 2009; Fast reactor database, 2006; Hoffman et al., 2006). There is no beneficial use of these leaking neutrons. It has recently been proposed (Greenspan, 2012) to design a prolate seed to reduce axial neutron leakage and enhance radial neutron leakage. These radially leaking neutrons are utilized to "drive" a fertile-fueled radial blanket in the B&B mode without exceeding the 200 DPA radiation damage constraint of current cladding materials.

The primary design objective of this work is to maximize the fraction of the total power generated by the B&B blanket. Since the blanket feed fuel is made of inexpensive depleted uranium "waste" or thorium and the fuel discharged from the blankets does not require reprocessing, the overall fuel cycle cost of the seed-and-blanket core is expected to be significantly smaller, per unit of electricity generated, than the cost of conventional SFR that

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recycles all of its fuel (Zhang et al., 2013). Increasing the fraction of power generated in the blanket will reduce both the fuel cycle cost and the fuel reprocessing capacity required to support S&B core of a given power.

The S&B cores were designed to have the same outer diameter and the nominal power – 1000 MW_{th}, as of the core of the Super Power Reactor Innovative Small Module (S-PRISM) developed by General Electric (Dubberley et al., 2000), which was used as the reference core.

The study methodology, including design variables and constraints, are briefly described in Section 2. Parametric studies of the driver fuel with a wide range of CR are described in Section 3.1, and comparisons with conventional SFR are discussed in Section 3.2. Conclusions are given in Section 4.

2. Methodology

The core configuration considered in this study is shown in Fig. 1. The active core height is 250 cm – typical for B&B reactors (Greenspan, 2012; Heidet and Greenspan, 2010, 2013; Zhang et al., 2013), and the diameter of interface between seed and blanket is initially set at 102.5 cm in order to have around 20% of the fission neutrons generated in the seed leak into the blanket. All other geometry and composition specifications are derived from S-PRISM (Dubberley et al., 2000). The core is divided into 3 radial seed batches and a variable number of blanket batches. Each batch is divided for burnup calculations into 6 axial nodes. The seed fuel is the ternary metallic alloy U-TRU-10wt%Zr that has a theoretical density of 15.7 g/cm^3 and a smear density of 75%. The smear density of the U-10wt%Zr blanket fuel is 85% and the theoretical density is 15.7 g/cm^3. The low-swelling ferritic martensitic steel HT9 is selected as the structural and cladding material. The assembly pitch, inter-duct gap and duct thickness are the same as in S-PRISM: 161.42 mm, 4.32 mm, and 3.94 mm, respectively. Grid spacers are accounted for; the distance between them is assumed to be 25 times the fuel outer diameter D. The fuel rod outer diameter and lattice pitch are design variables. The ratio of cladding thickness and fuel diameter D is kept constant at 0.075, same as that of the driver fuel in S-PRISM.

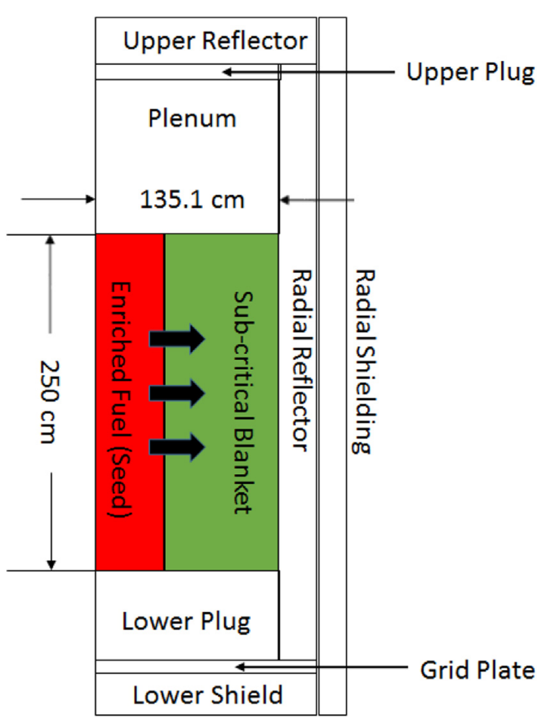

Fig. 1. Core configurations of S&B design.

MCNP6 (Goorley & et al., 2013) is used with the ENDF/B-VII.0 cross section library (Chadwick & et al., 2006) for the neutronics calculations with 1200 neutron histories per cycle and 200 active cycles to obtain a target statistical error in k_{eff} of ~100 pcm. ORIGEN2.2 (Croff, 1980) is applied for the burnup calculations using effective one group cross sections generated by MCNP6 for major actinides and fission products. Fission reaction rates and neutron fluxes calculated by MCNP6 are normalized by the core power before used in ORIGEN2.2 for burnup calculations. Burnup dependent compositions calculated by ORIGEN2.2 are transferred back to MCNP6 after each burnup step. MCNP6 and ORIGEN2.2 are coupled via a two-tiered solver – MocDown – that automates an efficient iterative search for the equilibrium composition of multi-fuel-batch cores depending on a prescribed fuel management scheme (Seifried et al., 2013); this iterative process is schematically illustrated in Fig. 2a. The number of fuel pins per assembly, the fuel pin outer diameter and pitch-to-diameter (P/D) ratio are optimized by the ADOPT code (Qvist and Greenspan, 2014) to accommodate the peak power and meet constraints on fuel, cladding peak temperature, maximum permissible coolant speed, and core pressure drop. The overall computation flow is shown in Fig. 2b.

The fuel management scheme is shown schematically in Fig. 3. At the end of a cycle, 1/3 of the fuel in each of the three seed batches is discharged. The discharged fuel is reprocessed to remove fission products and all the actinides are recycled. A mixture of depleted uranium and TRU from LWR's spent nuclear fuel (50 MWd/kg burnup and 10-year cooling time (Kim et al., 2009)) is added as makeup fuel. The innermost blanket batch is discharged and stored while each of the other blanket batches is shuffled inward and fresh depleted uranium fuel assemblies are charged into the outermost batch.

The coolant pressure drop across the core, including the pressure drop at the core inlet and outlet and along the 1.9 m long fission gas plenum, is constrained to 0.9 MPa (Fast reactor database, 2006; Qvist and Greenspan, 2014). The coolant temperature rise across the active core is constrained to 155 °C with an inlet temperature of 355 °C (Kim et al., 2009; Fast reactor database, 2006; Qvist and Greenspan, 2014). The constraint on the sodium coolant velocity is 12 m/s (Qvist and Greenspan, 2014; IAEA, 2002). The inner cladding temperature is required to be lower than 650 °C – the melting temperature of the HT-9 and Pu at eutectic point (Qvist and Greenspan, 2014; Hofman et al., 1997) and the fuel centerline temperature is conservatively constrained to 800 °C (Hoffman et al., 2006). The cycle length and number of blanket batches are searched such that the peak clad damage of both seed and blanket will be close to 200 DPA – the presently acceptable constraint based on the irradiation data obtained in FFTF (Leggett and Walters, 1993). The DPA value is calculated by a module built in MCNP6 assuming a collision efficiency of 80% (MacFarlane, 1996). It is desirable to limit the burnup reactivity swing over one cycle to ~3.5% $\Delta k/k$ (Kim et al., 2009; Hoffman et al., 2006).

3. Results

3.1. S&B core performance

A parametric study was conducted to assess the maximum fraction of core power that could be generated from the depleted uranium fueled blanket, the impact of the CR that the driver is designed to have on this fraction and other core performance metrics. The TRU CR is defined as the ratio of the neutron capture rate by ^{238}U in the driver to the fission rate of all the TRU isotopes in

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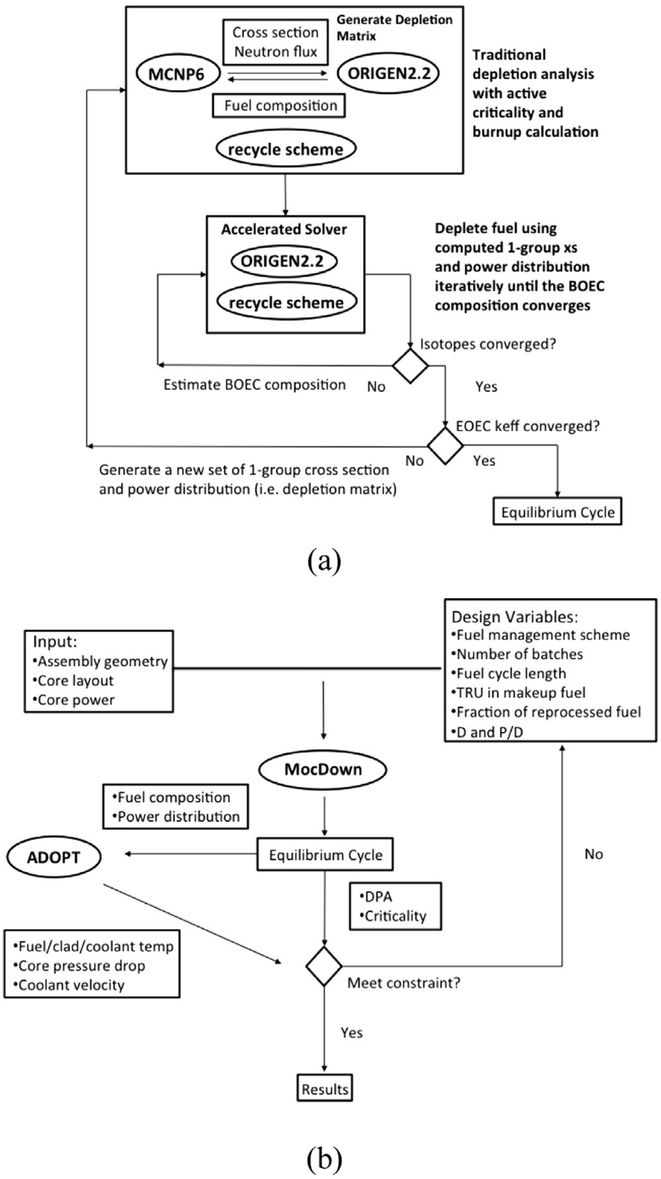

Fig. 2. MocDown scheme (a) and computation flow (b).

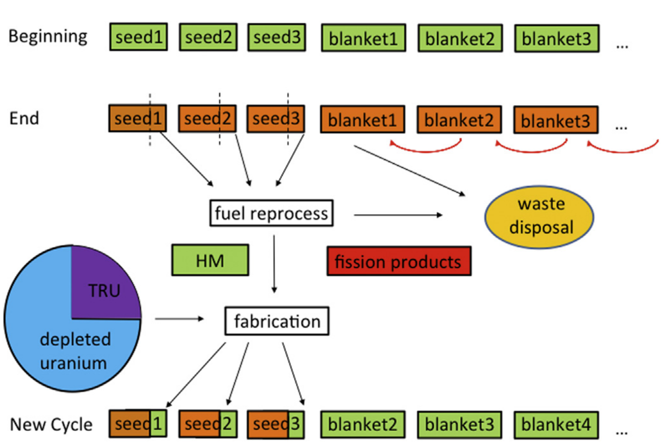

Fig. 3. Fuel management scheme.

Table 1
Performance characteristics of S&B core designs with different seed CR.

	Seed	Blanket	Seed	Blanket	Seed	Blanket
Target TRU CR of seed	CR = 0.5		CR = 0.75		CR = 1.0	
Number of batches	3	17	3	17	3	14
Fuel rod outer diameter (cm)	0.649	0.919	0.852	0.935	0.922	0.979
P/D ratio	1.51	1.22	1.31	1.20	1.215	1.15
Fuel volume fraction	18.29%	35.61%	24.31%	36.81%	28.26%	40.08%
Diameter of seed (cm)	102.5		102.5		130.4	
Core power (MW_{th})	1000		1000		1000	
Fuel cycle length (EFPD)	560		570		750	
k_{eff} at BOEC	1.036 ± 0.00093		1.016 ± 0.00085		1.002 ± 0.00085	
k_{eff} at EOEC	1.001 ± 0.00090		1.001 ± 0.00080		1.008 ± 0.00078	
Burnup reactivity swing (%$\Delta k/k$)	−3.41% ± 0.12%		−1.49% ± 0.11%		0.64% ± 0.11% (gain)	
Radial leakage probability from seed	23.7%% ± 0.09%		20.7% ± 0.08%		15.9%% ± 0.07%	
Blanket power fraction, BOEC/EOEC	46.9%/55.3%		46.3%/52.6%		37.1%/41.6%	
TRU CR in seed at BOEC	0.51		0.76		1.03	
Average discharge burnup (GWd/tHM)	17.4	7.1	13.2	6.8	11.1	6.5
Peak radiation damage (DPA)	198	203	196	207	189	193
TRU/HM at BOEC (wt%)	31.7	N/A	21.5	N/A	15.2	N/A
TRU feed rate (kg/GWt-yr)	157.9	−394.9	78.7	−398.8	0.2	−430.8
Specific power (MW_{th}/tHM)	103.6	8.2	77.4	7.7	48.9	6.2
Reprocessing rate (kg/GWt-yr)	1026.2		1384.6		2017.0	
Permissible assembly power (MW_{th})	21.0	10.5	14.5	9.6	10.3	7.2
Fraction of maximum permissible	0.69	0.98	1.00	1.01	1.01	1.08
Maximum fuel T (°C)	730.3	622.6	684.2	609.4	619.6	576.0
Maximum inner clad T (°C)	549.5	522.8	531.6	521.4	522.5	518.1
Core pressure drop (MPa)	0.892		0.892		0.892	

the driver at the beginning of the equilibrium cycle (BOEC). Since the effective microscopic cross section ratios in SFR cores change only moderately with core design variations, the conversion ratio depends primarily on the TRU-to-^{238}U atom ratio and can be readily estimated. The approximate average enrichments (TRU/HM) at BOEC required for CR of 1.0, 0.75 and 0.5 are, respectively, 14%, 21%, and 33% (Hoffman et al., 2006). Due to the higher required TRU enrichment, a smaller CR seed can be designed to have a larger P/D ratio and, hence, a larger coolant mass flow rate for a given pressure drop constraint and thereby, a larger assembly power. Additionally, driver fuel with larger TRU/U ratio can provide a higher neutron leakage probability and, therefore, a higher fraction of power generation by the blanket. The parametric study searched for the largest P/D ratio along with the TRU enrichment that give the desired CR with sufficient excess reactivity to enable a cycle length that will result in ~200 DPA for both seed and blanket at discharge. The P/D ratio that the blanket is designed to have is the smallest required for safely accommodating the peak blanket assembly power. Additional variables of the parametric study are the seed diameter, cycle length and number of blanket batches.

The permissible assembly power, along with assembly design details, were calculated using the ADOPT code (Qvist and Greenspan, 2014). Due to depletion of TRU in the seed and buildup of TRU in the blanket, the power shifts from the seed to the blanket over the cycle. Hence, the peak assembly power occurs at EOEC in the blanket and at BOEC in the seed. Table 1 summarizes the results of this parametric study.

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The parametric study demonstrates that the cycle average power fraction generated from the blanket decreases from ~51% to ~39% when the CR that the seed is designed to have varies from 0.5 to 1.0. As explained above, to achieve higher CR, the TRU-to-^{238}U ratio needs be reduced and more fuel has to be loaded per unit core volume to compensate for the loss of reactivity due to the lower enrichment. As a result, the seed needs be designed to have a smaller P/D ratio and a larger diameter. These changes reduce the radial neutron leakage probability from the seed and, therefore, the power generated from the blanket (Table 1).

As expected, a lower CR design increases the net TRU consumption rate per unit of electricity generated in the seed. The amount of fuel reprocessing required per GWt-yr also decreases for lower CR designs since the seed fuel can achieve higher burnup by the time the cladding material reaches the 200 DPA constraint. The higher burnup per DPA is primarily due to the higher TRU concentration of the low CR seed that results in a lower flux amplitude for a given fission rate. The larger fraction of power generated by the blankets also contributes to the lower specific reprocessing rate of the low CR seeds. In conclusion, there is a good synergism between a low CR seed and the proposed S&B core concept.

The TRU production rate in the depleted uranium blanket far exceeds the TRU destruction rate in the seed. The S&B reactors that use depleted uranium blanket are not intended for TRU transmutation but for providing less expensive electricity than conventional fast reactors that recycle all their fuel. S&B cores that use thorium for their blanket feed fuel will achieve effective TRU transmutation along with reduced fuel cycle cost. Preliminary results indicate that the thorium blanket will be able to generate approximately 40% of the core power when the seed is designed to have a CR of 0.5 (Zhang et al., 2014). This is about 20% smaller blanket power than the attainable with a depleted uranium blanket driven by a CR = 0.5 seed but comparable to that of a depleted uranium blanket driven by a CR = 1 seed.

There is another synergism between a low CR seed and the S&B core concept – the relatively steep decline of the seed k_∞ with burnup is partially compensated by an increase of the blanket k_∞. This phenomenon is illustrated in Fig. 4. A large burnup reactivity swing (−9.9% $\Delta k/k$) is observed (Fig. 4 left) for the seed designed with a CR of 0.5. This reactivity swing is similar to that of the CR = 0.5 Advanced Burner Reactor (ABR) (Kim et al., 2009; Hoffman et al., 2006). The gain of reactivity (5.3% $\Delta k/k$) in the blanket (Fig. 4, right) due to the fissile fuel buildup over the cycle compensates for much of the seed $\Delta k/k$ loss. The net effect is that the burnup reactivity swing of CR = 0.5 S&B core is −2.2% $\Delta k/k$ per EFPY while that of the CR = 0.5 ABR is −4.8% $\Delta k/k$ per EFPY. Thus, whereas the fuel cycle length is 7 months for the CR = 0.5 ABR, it can be extended to 18 months in the S&B core without increasing the core excess reactivity that needs to be compensated by the control assemblies (See following section for more details). The larger fuel cycle length will improve the reactor capacity factor and the higher discharge burnup will reduce the fuel reprocessing capacity per unit of electricity generated – both improve the economics of the S&B reactor.

Table 2
Comparisons of selected fuel cycle characteristics of S&B core with the references by ANL (Hoffman et al., 2006) and S-PRISM (Dubberley et al., 2000) designs.

	ANL ABR	S&B	ANL ARR	S&B	S-PRISM
TRU CR	0.50	0.51	1.00	1.03	1.05
P/D ratio, seed/blanket	1.293	1.51/1.22	1.10	1.215/1.15	1.213/1.098
HM in driver fuel (tons)	9.4	4.7	16.7	12.4	12.5
Fuel cycle length (EFPD)	221	560	370	750	595
# of cycles	6/6/7	3	3/3/4.5	3	3
Burnup reactivity swing (%/cycle)	−2.90	−3.41	0.06 (gain)	0.64 (gain)	−0.12
Specific power in driver (MW_{th}/tHM)	106.0	103.6	60.0	48.9	59.4
Ave. discharge BU (% FIMA)	13.2	17.4/7.1	7.3	11.1/6.5	10.6 (driver)
Reprocessing rate (kg/GWt-yr)	2508.1	1026.2	4705.1	2017.0	5335.3
TRU transmutation rate (kg/GWt/yr)	173.8	157.9	−4.7 (gain)	0.2	−33.6 (gain)

3.2. Comparison with conventional SFR

Selected performance characteristics of the S&B core designs are compared with those of the reference ANL designs and S-PRISM in Table 2. The fuel of all these cores is a metallic alloy. As discussed in the previous section, due to, primarily, its significantly smaller reactivity drop with burnup, the CR = 0.5 S&B core cycle length can be more than double that of the reference ABR with the TRU CR of 0.5. The TRU incineration rate per unit of electricity generated by the driver of S&B core is approximately 9% smaller than that of the ABR core. This difference is not generic; it is probably due to a difference in the thermal energy recovered per fission event assumed by the ANL code and MocDown; the latter accounts for the decay heat and thereby underestimated the number of fissions per thermal energy by ~9%.

As the seed generates only ~50% of the total core power and has somewhat higher discharge burnup, the CR = 0.5 S&B core requires only ~40% of the reprocessing capacity of the reference ABR core per unit of electricity generated.

The more than double cycle length of the CR = 1 S&B core relative to the reference ARR (Advanced Recycling Reactor; CR of 1.0) (Hoffman et al., 2006) is primarily due to its ~50% higher discharge burnup and, to a lesser extent, to its ~20% lower specific power relative to the ARR core. The higher burnup is enabled by the

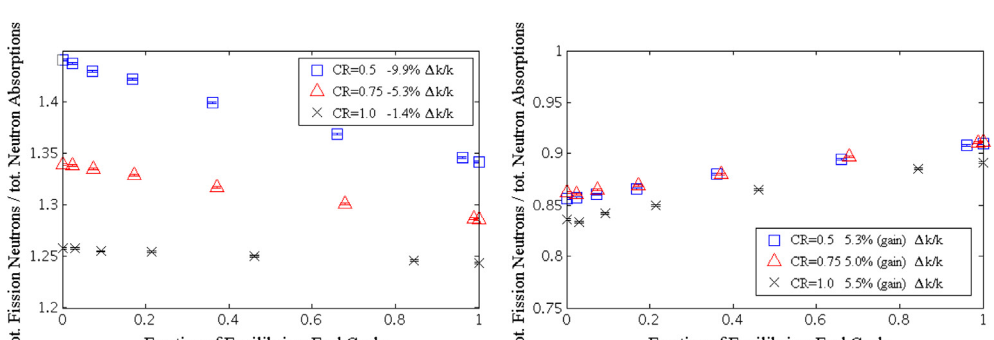

Fig. 4. Infinite multiplication factors of seed (left) and blanket (right).

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softer spectrum, i.e. – smaller DPA/burnup ratio that is due to the larger P/D of the seed in the S&B core. The effect of the difference in specific power is not generic.

The reprocessing capacity required to support the CR = 1.0 S&B core is only 43% that required for the ARR of the same total power - primarily because of the power generated by the blanket of the S&B core combined with the higher burnup of seed. Even though the S-PRISM has a comparable discharged burnup with the S&B, it is designed to recycle a significant amount of blanket fuel (Dubberley et al., 2000). The net effect is that the fuel reprocessing capacity of the S&B core is only 38% that of the S-PRISM.

Due to the large fraction of the core power generated from the blanket that is fed with inexpensive fuel, the fuel cycle cost of the S&B reactor is expected to be significantly smaller than that of a conventional SFR. As the S&B cores can be designed to have a longer fuel cycle, the capacity factor of the S&B reactors can be larger and this may also reduce the cost-of-electricity from S&B versus conventional fast reactors.

4. Conclusions

This preliminary study found that it is feasible to design a sodium-cooled fast reactor core to generate 40–50% of the total core power from a large radial blanket fueled by depleted uranium that operates on the breed-and-burn mode without reprocessing. Three S&B cores that can fit within the S-PRISM reactor vessel and generate the S-PRISM rated power of 1000 MW_{th} have been designed; one with a CR = 0.5 seed, another with a CR = 0.75 seed and a third with a fuel-self-sustaining (CR = 1) seed. The seed and blanket designs meet all the thermal-hydraulic and neutronic design constraints. The peak radiation damage on cladding materials of the seed and blanket does not exceed the presently acceptable level of 200 DPA.

There is a good synergism between a low CR seed and the S&B concept – Low CR enables designing the seed to have a large P/D ratio along with sufficient excess reactivity to operate both the seed and blanket to their radiation-damage limit while sparing more than 20% of the fission neutrons to leak into the blanket and drive it to generate a relatively large fraction of the core power. The smaller the seed CR is, the larger can be the fraction of power generated by the blanket. The blanket reactivity increases over the cycle, due to fissile fuel buildup, and compensates for a large fraction of the seed reactivity decline with burnup. As a result, the core reactivity drops with burnup significantly slower than in a conventional SFR core designed to have the same CR as the seed of S&B core. Therefore, the cycle length of the S&B core and discharge burnup of the seed fuel can be significantly higher than those of conventional SFR.

It is expected that the economics of the S&B reactor will be superior to that of a conventional SFR for the same power level due to the following findings and observations:

- Significantly low cost of the fuel charged to the blanket relative to the cost of the recycled seed fuel. The cost of a unit mass of driver (seed) fuel is comparable with conventional SFR
- The blanket fuel can generate 40%–50% of the S&B core power versus a very small fraction of conventional SFR core power.
- Higher discharge burnup and, hence, smaller capacity of fuel reprocessing and recycling required per unit of energy generated from the seed fuel
- Higher capacity factor due to longer cycle length.

A follow-up study will quantify reactivity coefficients and assess the feasibility of designing the S&B cores to be passively safe. The feasibility of S&B cores using thorium fueled blankets will be thoroughly explored. Thorium-fueled blankets are particularly of interest when a reduction of the total inventory of TRU is an important objective of the fast reactors.

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