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HETEROGENEOUS CORES FOR IMPLEMENTATION OF THORIUM-BASED FUELS IN HEAVY WATER REACTORS

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ABSTRACT

New reactor concepts to implement thorium-based fuel cycles have been explored to achieve maximum resource utilization. Pressure tube heavy water reactors (PT-HWR) are highly advantageous for implementing thorium-based fuels because of their high neutron economy and on-line re-fuelling capability. The use of heterogeneous seed-blanket core concepts in a PT-HWR where higher-fissile-content seed fuel bundles are physically separate from lower-fissile-content blanket bundles allows more flexibility and control in fuel management to maximize the fissile utilization and conversion of fertile fuel. The lattice concept chosen was a 35-element bundle made with a homogeneous mixture of reactor grade PuO_2 (~67 wt% fissile) and ThO_2, with a central zirconia rod to reduce coolant void reactivity. Several annular and checkerboard-type heterogeneous seed-blanket core concepts with plutonium-thorium-based fuels in a 700-MWe-class PT-HWR were analyzed, using a once-through thorium (OTT) cycle. Different combinations of seed and blanket fuel were tested to determine the impact on core-average burnup, fissile utilization, power distributions, and other performance parameters. WIMS-AECL 3.1 was used to perform lattice physics calculations using 2-D, 89-group integral neutron transport theory, while RFSP 3.5.1 was used to perform the core physics and fuel management calculations using 3-D two-group diffusion theory. It was found that the various core concepts can achieve a fissile utilization that is up to 30% higher than is currently achieved in a PT-HWR using natural uranium (NU) fuel bundles. Up to 67% of the Pu is consumed; up to 43% of the energy is produced from thorium, and up to 363 kg/year of U-233 is produced in the discharged fuel.

I. INTRODUCTION

Improved sustainability of nuclear power is possible through the use of thorium fuels in a heterogeneous core configuration in which the fissile-containing seed fuels and the fertile-containing blanket fuels are located in separate regions of the reactor core.

Thorium is an attractive fuel option to improve the sustainability of the nuclear fuel cycle [1], given the limited and unevenly distributed uranium reserves. Natural thorium does not contain a fissile isotope; thus, thorium fuels in a reactor must involve a fissile component, using plutonium and/or uranium. The physical separation of low-fissile (blanket fuels) and high-fissile (seed fuels) components into separate regions in the reactor offers the potential to further improve the fissile utilization and increase the sustainability of the thorium fuel cycle [2, 3] over homogenous core concepts [4-9].

Heavy water moderated pressure tube reactors (PT-HWR) [6,7] have very high neutron economy due to the minimization of absorbing materials in the core, and online re-fuelling, which offers precise control of excess reactivity with minimal need for control absorbers. In addition, the small, simple fuel bundle eases fabrication of radioactive fuels. The pressure tube design of the PT-HWR offers the ability to separate the seed and blanket fuels in different channels, which can be re-fuelled at different rates, and thus optimized for sustainability metrics. For these reasons, the PT-HWR has great flexibility in terms of the potential materials that can be used as fuel, and it is an attractive reactor concept to implement thorium-based fuel cycles.

This work investigates several heterogeneous annular and checkerboard-type seed-blanket cores. In the annular concepts, the core is divided into varying numbers and sizes of concentric circles, which are loaded with either seed or blanket fuel bundles. In the checkerboard concepts, the core has a repeating, alternating pattern of clusters of four fuel channels containing either seed or blanket fuel bundles. Two different checkerboard concepts, with a 3-to-1 and a 1-to-1 ratio of seed to blanket fuel, are investigated. The outer region of fuel channels adjacent to the radial reflector are filled with blanket fuel, to capture as many of the leaking and reflected neutrons as possible.

The use of heterogeneous core concepts in heavy water reactors (HWR) with thorium-based fuels has been proposed by various researchers in the past [3, 10], while checkerboard-type seed-in-blanket configurations have been used for various light water breeder reactor (LWBR) concepts [2, 3].

Lattice and core concepts and associated computational models for lattice/core physics were modified versions based on earlier studies of PT-HWRs [8, 9] developed for using Pu/Th in an once-through-thorium (OTT) cycle. The reactor concept is based on a 700-MWe-class PT-HWR [6, 7, 11], with 380 fuel channels, with 12 fuel bundles (~50 cm long each) per channel, moderated and cooled with heavy water.

The core and fuel bundle / lattice (see also Section IV.A) specifications are shown in Table I and related details can be found in earlier publications [7-13]. The lattice was selected on the basis of a range of lattice physics scoping studies, with the objectives of achieving burnups ≥ 20 MWd/kg, and also reducing the coolant void reactivity (CVR) to lower levels (≤ +11 mk), (1 mk = 100 pcm = 0.001 Δk/k) than what may be found using NU bundles in PT-HWRs [6, 7, 14].

It is anticipated that these concepts, based on modest modifications to PT-HWR technology, will have higher probabilities of technological and economic feasibility and nearer-term implementation by vendors and utilities, than by using a completely different and untested reactor concept.

An OTT cycle [4, 5] was chosen for this study because it was presumed to be more economical and practical in the intermediate future, prior to the availability of commercial technology to recycle spent thorium-based fuels. For fuel manufacturing and operations, it is also simpler to use one type of fissile fuel at a fixed isotopic composition. The spent fuel from the OTT cycle will become a valuable future mine for U-233 to support a future generation of reactors [1, 7, 12, 15].

The goals of the analyses were the following:

1. Using a simplified PT-HWR (no reactivity devices), test a variety of different annular and checkerboard-type heterogeneous seed/blanket core concepts with a core-average fuel discharge burnup ≥ 20 MWd/kg (of initial heavy elements).
2. Improve sustainability performance parameters (metrics) over current technology. For example, achieve high fissile utilization (≥1,056 MWd/kg-fiss), high fissile inventory ratios (FIR) in the discharged fuel, high cumulative mass conversion ratios (CMCR), and a substantial energy generation from Th-232/U-233, while meeting operational constraints of maximum channel power, bundle power and linear element ratings. These metrics will be discussed and defined further in Section IV.B.3.

II. CODES AND LIBRARIES

Simulations of seed/blanket cores first involved performing lattice physics calculations of seed and blanket fuels using detailed multi-group neutron transport and burnup calculations. Data from lattice physics calculations were homogenized and collapsed to two-group diffusion data, which were then used in 3-D core physics calculations.

Lattice physics calculations for the 35-element plutonium/thorium fuel bundle (referred as "35-Pu/Th-ZrO_2-Rod") were performed using WIMS-AECL Version 3.1 [16], in combination with an 89-group nuclear data library, based on ENDF/B-VII.0 [17]. WIMS-AECL was used to perform the detailed 89-group, 2-D collision-probability neutron transport analysis of individual, single-cell lattice cells with burnup in a critical spectrum (k_{eff}=1.000). Transport calculations were performed with reflecting boundary conditions imposed on the surface of the square lattice cell. WIMS-AECL was also used to evaluate the properties of the heavy water reflector, using a cylindrical single-cell model with an additional annulus of heavy water.

WIMS Utilities Version 2.0 [18] was used for processing binary output data produced by WIMS-AECL to generate subsequent two-group homogenized diffusion data (macroscopic cross sections for various reactions) as a function of burnup/irradiation, and also the homogenized properties of the reflector. These data were used later in the core analyses with RFSP.

Core physics calculations were performed using RFSP Version 3.5.1 [19]. RFSP 3.5.1 was used to perform the steady-state 3-D, two-group neutron diffusion calculations for the PT-HWR core analysis. Key predictions are the 3-D, two-group neutron flux and power distributions (channel and bundle), along with the core reactivity, and re-fuelling rates. Using a given set of specified fuel types for each fuel channel, a pre-specified re-fuelling scheme, and a target exit burnup/irradiation for each fuel channel, and a total core power, RFSP was used to determine the "Time-Average" power distributions and channel re-fuelling rates, using the *TIME-AVER module in RFSP [20].

III. MODELING APPROXIMATIONS

The various lattice and core physics model approximations and numerical discretizations used were similar to those of previous studies [8, 9], with a few differences. Reactivity devices were not modeled in this study, although it is expected that future studies for a specific core concept will include devices. The number of axial lattice meshes were increased (from 12 up to 24 or 48) to improve convergence in the axial flux/power distributions and also the irradiation/burnup distributions in the time-average core model within RFSP. Modifications were also made to convergence and iteration criteria to account for the slower convergence rate in highly heterogeneous cores with steep flux gradients and spatial power oscillations.

Core analyses with RFSP involved two fuel types: seed, and blanket, designated by SEED-XX and BLNK-YY, where XX and YY are 2 × Pu wt% in the fuel. For example, SEED-06 is seed fuel containing 3 wt% PuO_2 and 97 wt% ThO_2, whereas BLNK-02 is blanket fuel containing 1 wt% PuO_2 and 99 wt% ThO_2. Only one fuel type was used per channel. The basis for the lattice is the 35-Pu/Th-ZrO_2-Rod concept (See Section IV.A), and seed and blanket fuel differ only in the Pu content.

The reactor was divided into multiple fuel regions, each region containing seed or blanket fuel, in either annular regions, or in a repeating checkerboard-type pattern. Different regions of channels in the core were defined with different levels of irradiation/burnup, which were then adjusted to achieve a desired core power distribution and reactivity level. In most analyses, a bi-directional 2-bundle shift re-fuelling pattern was used, with alternating fuelling directions for each channel. In a couple of cases, a 1-bundle shift or a 4-bundle shift re-fuelling pattern was tested.

All calculations were done with the simultaneous calculation of the equilibrium Xe-135 concentration distributions, which depends on the power level and the fuel type. A single set of cross sections were used for the reflector for all core models as a simplifying approximation.

IV. DESCRIPTION OF PROBLEM MODELED

IV.A. Lattice Specifications

The reactor lattice cell was based on a concept described in a previous study [9], with modifications. One concept, the 35-Pu/Th-ZrO_2-Rod lattice, was selected from scoping studies for further analyses, and for subsequent use in core analyses. The bundle is illustrated in Fig. 1, and it is based on a 43-element bundle with the central 8 pins removed and replaced with a central Zr-4 displacement tube filled with ZrO_2.

The fuel is homogeneous $(Pu,Th)O_2$, using reactor-grade plutonium (2.75 wt% Pu-238 / 51.96 wt% Pu-239 / 22.96 wt% Pu-240 / 15.23 wt% Pu-241 / 7.1 wt% Pu-242), which is expected to be obtained from high-burnup light water reactor fuel. Pu could be obtained from other sources, such as spent Magnox and AGR reactor fuel, or from fast reactors operating on the Pu/U fuel cycle.

Lattice and bundle specifications are shown in Table I. The bundle has a heavy metal mass of ~13 kg. The mass fractions of various isotopes as a function of burnup (as computed by WIMS-AECL) were curve fitted, to be used in conjunction with core calculations of re-fuelling rates and discharge burnups for different core irradiation regions to evaluate various core-average performance parameters.

The maximum relative pin power ($P_{pin\text{-}max}/P_{pin\text{-}ave}$), which usually occurs in the outer fuel element at or near zero burnup was extracted (see Table II) for use in determining the maximum linear element rating (LER) using the maximum bundle power, to be determined from the core analysis.

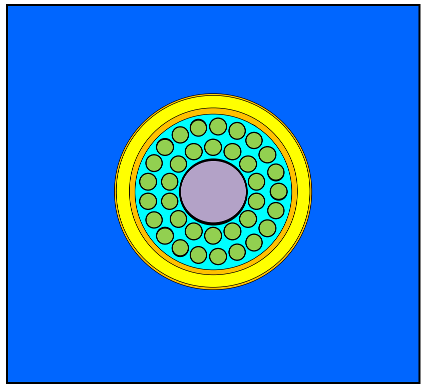

Fig. 1. 35-Pu/Th with Central Zr-4 Tube Filled with ZrO_2

TABLE I
PT-HWR and Bundle Specifications

Quantity	Value, Units
Reactor Power	2,061 MW_{th}
# of fuel channels	380
# bundles per channel	12
Lattice pitch (square)	28.575 cm
Length of fuel channel	~594 cm
Reflector thickness	~66 cm
Moderator Temp.	~69°C
Moderator D_2O purity	99.8 wt%D_2O
Pressure Tube (PT)	Zr-2.5Nb
Calandria Tube (CT)	Zr-2
Average D_2O Coolant	99 at%D_2O, ~288°C
Fuel	$(Th,Pu)O_2$
Number of Fuel Pins	35
Average Fuel Temp.	~586°C
Density of Fuel	~9.7 g/cm^3
Cladding Material	Zr-4
Central Zr-4 tube filler	ZrO_2,~4.3 g/cm^3
Length of Bundle	49.5 cm
Fuel Element Radius	0.57 cm
Bundle HM mass	13.058 kg

TABLE II
Maximum Relative Pin Power for Different Fuel Types

Fuel Type	PuO_2 Fraction	ThO_2 Fraction	Maximum Relative Pin Power
BLNK-02	0.010	0.990	1.1138
BLNK-04	0.020	0.980	1.1509
SEED-06	0.030	0.970	1.1931
SEED-08	0.040	0.960	1.2289
SEED-10	0.050	0.950	1.2592
SEED-12	0.060	0.940	1.2850
SEED-14	0.070	0.930	1.3069

IV.B. Core Specifications

A 700-MWe-class PT-HWR reactor (728 MW_e, 2,061 MW_{th}) was used as the reference concept [6, 7, 11] for testing various heterogeneous seed/blanket cores, using the 35-Pu/Th-ZrO_2 lattice. General specifications are shown Table I. Several different annular and checkerboard-type heterogeneous seed/blanket cores were tested, using different types of seed and blanket fuel.

For each core concept, the core power level and irradiation distributions were adjusted iteratively to achieve the following goals:

1. Core reactivity (k_{eff}) was between ~1.002 and 1.003. It is assumed that the reactor will be critical with an excess reactivity allowance of 2 mk to 3 mk. This neglects reactivity allowances that would be needed if reactivity devices such as shut off rods, adjusters or zone controllers were incorporated into the concept [6, 9].
2. Blanket fuel has nominal discharge burnup of ~20 MWd/kg (or ~40 MWd/kg).
3. Seed fuel has a nominal discharge burnup of ~20 MWd/kg, or higher, depending on Pu content.
4. Radial power distribution in the core (at least in the seed region) is made as flat as possible.

5. Core power is made as high as possible (up to ~2,061 MW_{th}), although it is expected that it may need to be de-rated to meet other criteria.
6. Maximum channel power ≤ 6,500 kW_{th}.
7. Maximum bundle power ≤ 750 kW_{th}, in the time-average calculation (with a few exceptions). This limit will ensure that most of the bundles will have a maximum LER ≤ 57 kW/m, to ensure fuel integrity, as may be found with NU-type fuel. However, thorium-based fuels may be able to tolerate somewhat higher levels.

IV.B.1. Description of Core Concepts - Annular

Three different annular heterogeneous seed/blanket core concepts were tested, and for each core concept two to four different combinations of seed and blanket fuels were tested. The initial set of combinations of seed fuel and blanket fuel for each given core were intended to give a core-average burnup of ~20 MWd/kg, with similar burnup levels in both the seed and blanket fuel. Additional cases were devised to achieve high blanket burnup (~40 MWd/kg) using the low-reactivity BLNK-02 fuel (1 wt% PuO_2 / 99 wt% ThO_2). Two of the core concepts are essentially homogeneous cores, using one fuel type (using either SEED-06 or SEED-08 fuel), and are used for comparison with the heterogeneous cores. There will be radial variations in the target exit irradiations, which are adjusted to flatten the power distribution.

Core concept 1S-1B (see Fig. 2) has 1 inner seed region (188 channels) and 1 outer blanket region (192 channels). Three of the 1S-1B cores used SEED-06 fuel, and one with SEED-08 fuel. This annular core concept is motivated by its simplicity, and its ability to achieve the maximum reactivity for the seed fuel region. One of the cores involved a 4-bundle shift (with SEED-08 fuel) to help reduce axial power peaking.

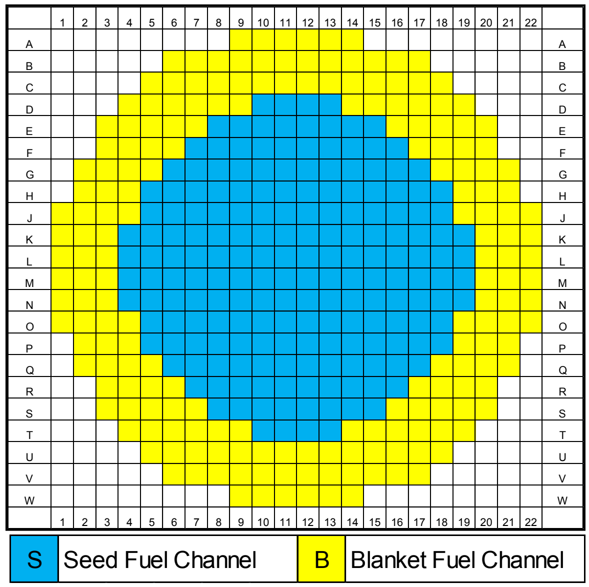

Fig. 2. Core Layout – 1S-1B – Annular, 1 Seed Region, 1 Blanket Region

Core concept 4S-4B (see Fig. 3) has 4 seed regions (4+40+60+84=188 channels) and 4 blanket regions (8+36+60+88= 192 channels). One of the 4S-4B cores is planned for low burnup with (SEED-06/BLNK-04), while the other is planned for higher burnup with (SEED-08/BLNK-02) fuel. This highly heterogeneous core is motivated by an attempt to maximize the conversion ratio and the fraction of the energy obtained from U-233/Th-232.

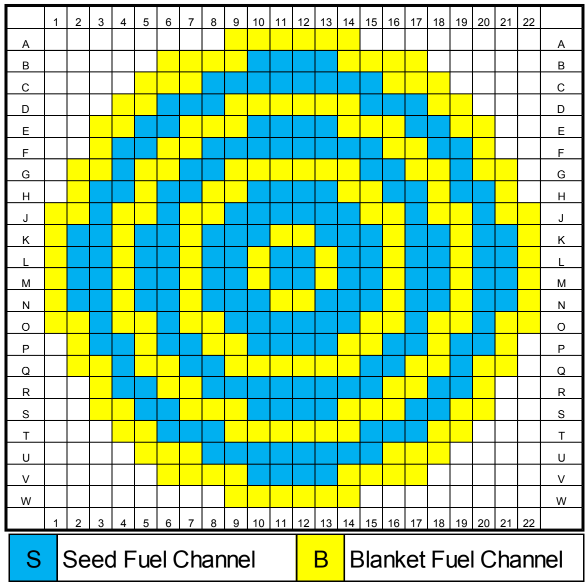

Fig. 3. Core Layout – 4S-4B – Annular, 4 Seed Regions, 4 Blanket Regions

Core concept 84%-Seed/16%-Blanket (see Fig. 4) is similar to 1S-1B, but the blanket region is much smaller. It is considered a very modest change from a homogeneous core, with blanket fuel channels being placed in the periphery of the core, adjacent to the reflector, in the low flux region. The inner seed region has 320 channels, and the outer blanket region has 60 channels. A low-burnup and a high-burnup core were tested, along with a homogeneous core. This concept is motivated by an attempt to maximize the core power, while still achieving some improvement in the fissile utilization and conversion of fertile to fissile fuel. One of the cores (SEED-08/BNLK-08 – a homogeneous core) involved the use of 1-bundle shift (with a finer axial lattice mesh), as a test to reduce the power peaking during re-fuelling.

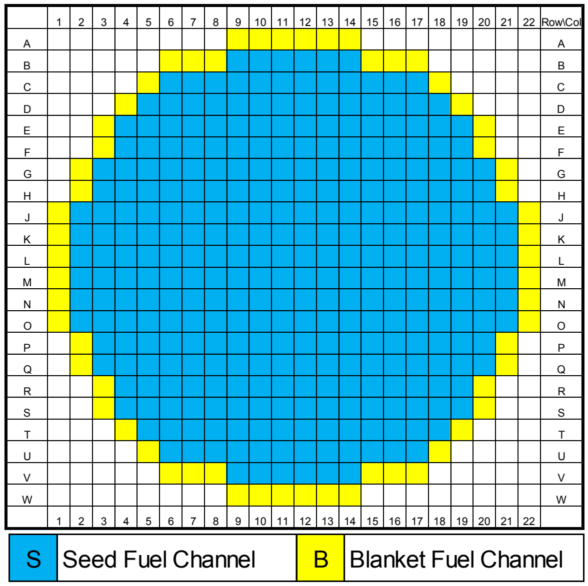

Fig. 4. Core Layout – 84%S/16%B – Annular, 320 Channels of Seed Fuel, 60 Channels of Blanket Fuel

IV.B.2. Description of Core Concepts - Checkerboard

Two different checkerboard-type heterogeneous seed/blanket core concepts were tested, and for each core concept three or four different combinations of seed and blanket fuels were tested. The initial set of combinations of seed fuel and blanket fuel for each given core were intended to give a core-average burnup of ~20 MWd/kg, with similar burnup levels in both the seed and blanket fuel. Additional cases were run to achieve high blanket burnup (~40 MWd/kg) using the low-reactivity BLNK-02 fuel (1 wt% PuO_2 / 99 wt% ThO_2). There were radial variations in the target exit irradiations, which were adjusted to flatten the power distribution.

Core concept 3-to-1-S/B (Fig. 5) has a central region of 192 seed channels with nine 4-channel groups of blanket fuel. For the 36 channels of blanket fuel inserted in the seed region, the ratio of seed to blanket fuel is 3:1. Four channels of blanket fuel are surrounded by 12 channels of seed fuel. There is an outer blanket region, roughly consisting of the two rings of channels around the periphery of the core, with 152 channels. This checkerboard core concept is motivated by an attempt to flatten the power distribution, to achieve higher power, and to generate more power in the blanket fuel.

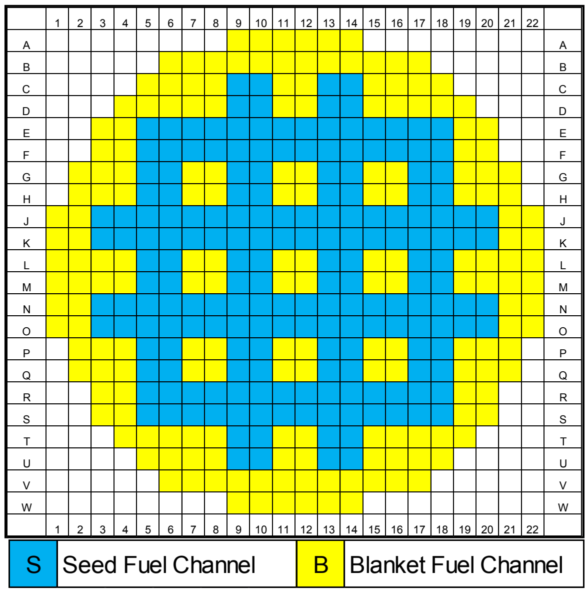

Fig. 5. Core Layout – 3-to-1-S/B – Checkerboard, 36 Inner Channels of Blanket Fuel, 192 Channels of Seed Fuel, 152 Outer Channels of Blanket Fuel

Core concept 1-to-1-S/B (see Fig. 6) contains fuel in the central region with a nearly 1:1 ratio of seed and blanket channels, which are grouped together in 4-channel regions. Only blanket channels are allowed to be adjacent to the reflector. There are 188 seed channels and 192 blanket channels. This core concept is motivated by an attempt to drive blanket fuel channels to high powers to maximize the production rate of fissile uranium, and to achieve higher core power levels.

It is recognized that by setting up groups of four channels (either 4 seed channels, or 4 blanket channels), one can avoid a problematic postulated accident scenario where checkerboard voiding during a loss-of-coolant-accident (LOCA) might lead to all blanket channels being voided while seed channels remain cooled, or vice versa.

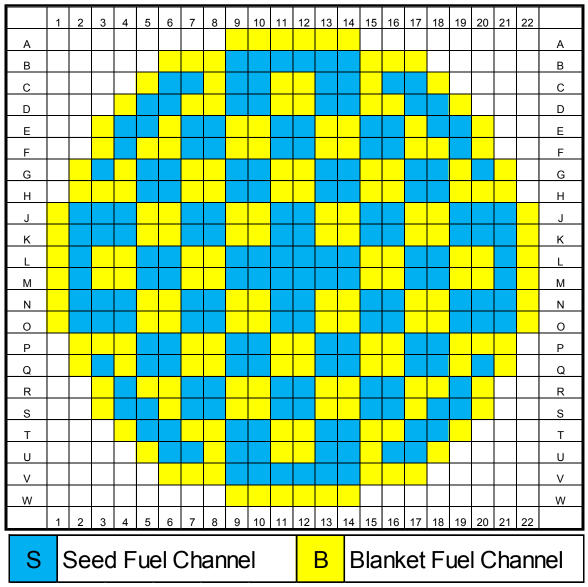

Fig. 6. Core Layout – 1-to-1-S/B – Checkerboard, 188 Channels of Seed Fuel, 192 Channels of Blanket Fuel

IV.B.3. Core Calculations, and Post-Processing Analyses

For each of the core concepts, time-average RFSP core calculations were performed. Output data were extracted and processed to obtain the following key results: radial power distributions, channel powers, axial power distributions in channels with peak bundle power, k_{eff}, peak channel and bundle powers, re-fuelling rates and burnups for different irradiation zones of seed and blanket fuel channels.

The re-fuelling rates and burnups from the RFSP calculations were used in conjunction with the detailed bundle specification data and WIMS-AECL lattice physics calculations for isotopic composition changes with burnup (for both seed and blanket fuels) to compute various performance parameters. Such parameters included maximum

LER (based on the maximum bundle power), core-average burnup, fissile utilization (FU - energy produced per mass of initial fissile isotopes in fuel), power fraction in seed/blanket, # bundles consumed per year, fissile inventory ratio (FIR = ratio of fissile mass to initial fissile mass in discharged fuel) and the cumulative mass conversion ratio (CMCR) as given by:

$$CMCR = \frac{\Delta M\left({}^{233}_{91}Pa + {}^{233}_{92}U + {}^{235}_{92}U\right)(t)}{\Delta M\left({}^{239}_{94}Pu + {}^{241}_{94}Pu\right)(t)} \quad (1)$$

The CMCR is the ratio of the net mass production of (Pa-233 + U-233 + U-235) to net mass consumption of (Pu-239 + Pu-241) in the discharged fuel. Pa-233 is included because it decays to U-233 after it is removed from core.

Other computed parameters include the cumulative fraction of energy generated from U-233 fission (and other isotopes in the thorium chain), the annual production rate of fissile uranium (which includes Pa-233, U-233 and U-235), the consumption rate of Pu, and other parameters to be discussed below.

V. LATTICE PHYSICS RESULTS

V.A. Reactivity and Burnup

The lattice reactivity and burnup characteristics for various compositions of PuO_2 mixed with ThO_2 are illustrated in Fig. 7 and Table III. For both seed and blanket fuels, the nearly asymptotic value of k_{inf} ~0.900 is observed. Fuel with ≤ 2 wt% of PuO_2 is best suited for blanket fuel, whereas fuel with ≥ 3 wt% of PuO_2 is suitable as seed fuel. According to infinite lattice calculations, an idealized uniform core of SEED-06 fuel (3 wt% PuO_2, 97 wt% ThO_2) can achieve a burnup of ~23 MWd/kg, assuming 3% core leakage. The fissile utilization (FU) is ~1,149 MWd/kg-fiss. An idealized core with SEED-08 fuel (4 wt% PuO_2, 96 wt% ThO_2) can achieve a burnup of ~39 MWd/kg, with FU~1,461 MWd/kg-fiss. By comparison, a PT-HWR using a 37-element bundle with NU fuel [6, 7] can achieve a burnup of 7.5 MWd/kg, and a FU of 1,056 MWd/kg. Thus, idealized homogeneous cores in PT-HWRs with ≥ 3 wt% Pu mixed with Th could achieve FU's that are ≥10% than that achieved with NU.

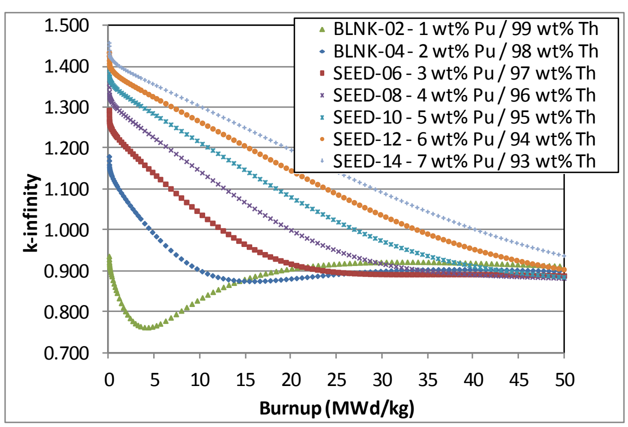

Fig. 7. Lattice Reactivity vs. Burnup

TABLE III
Lattice Maximum Burnup and Fissile Utilization

Fuel	PuO_2 (%wt)	k_{inf} (t=0)	BU	FU MWd/kg	FU Rel.
B02	1.0	0.94	N/A	N/A	N/A
B04	2.0	1.18	7.44	555.6	0.53
S06	3.0	1.30	23.11	1,149.5	1.09
S08	4.0	1.36	39.15	1,460.8	1.38
S10	5.0	1.41	53.88	1,608.4	1.52
S12	6.0	1.44	68.25	1,697.7	1.61
S14	7.0	1.46	81.98	1,748.0	1.65

BU= Burnup (MWd/kg); integrated k_{inf}=1.03 (exit burnup)
FU = Fissile Utilization (MWd/kg-fiss)
FU Rel. = Relative to FU of PT-HWR with NU (1,056 MWd/kg-fiss).

V.B. Coolant Void Reactivity

The infinite lattice coolant void reactivity, the change in reactivity with 100% voiding of the coolant, $CVR_{inf} = (k_{inf\text{-}void} - k_{inf\text{-}cool})/(k_{inf\text{-}void} \times k_{inf\text{-}cool})$, and its variation with burnup was determined for each fuel type and is shown in Fig. 8. Values of burnup-averaged CVR at different levels of discharge burnup are shown in Table IV. The CVR increases with burnup, as Pu in the outer pins is depleted more quickly, and typically ranges between +6 mk and +12 mk. A given PT-HWR core will contain seed and blanket fuels at various levels of burnup, thus, the core-average CVR will be somewhere between these bounding values. For fuels to be used in the core analyses and at the expected burnup levels, the burnup-averaged CVR is expected to range between +7.6 mk and +9.7 mk. Leakage effects may reduce the CVR by ~1 mk [21].

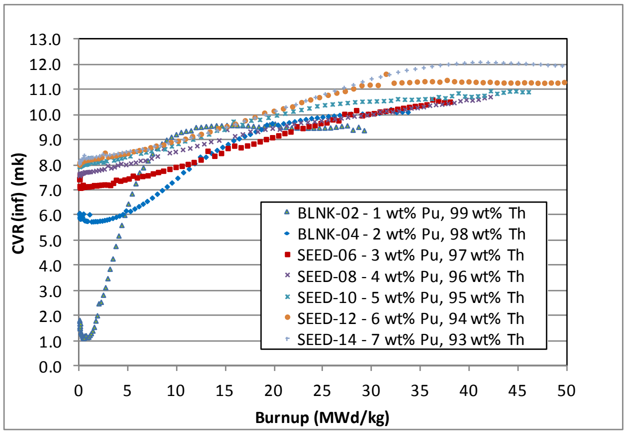

Fig. 8. Coolant Void Reactivity vs. Burnup

TABLE IV
Burnup-Averaged Coolant Void Reactivity (in mk) for Different Fuel Compositions

Burnup (MWd/kg)	20	30	40
Volume Fraction PuO_2	Burnup-Averaged CVR (mk) at Discharge Burnup		
0.010	7.63	8.20	8.90
0.020	7.51	8.32	9.10
0.030	8.00	8.58	9.20
0.040	8.58	8.99	9.32
0.050	8.94	9.38	9.70
0.060	9.05	9.59	10.02
0.070	9.07	9.64	10.19

V.C. Maximum Relative Pin Power

The maximum relative pin powers ($P_{pin\text{-}max}/P_{pin\text{-}ave}$) for the different fuel types are shown in Table II, while the variation of relative pin power with burnup for the outer fuel pins for the different fuel types is shown in Fig. 9. The maximum relative pin power usually occurs in fresh fuel. As the Pu (and fissile content) is increased, so does the maximum relative pin power, which will increase the LER. For example, if the maximum bundle power is 750 kW, then SEED-06 fuel (3 wt% PuO_2) will have a maximum LER~ 51.6 kW/m (1.1931× 750 kW / 35 pins / 0.4953 m). If an upper limit for LER~57 kW/m was imposed, then the maximum bundle power permitted for SEED-06 fuel would be ~828 kW, and for SEED-08 fuel it would be ~804 kW.

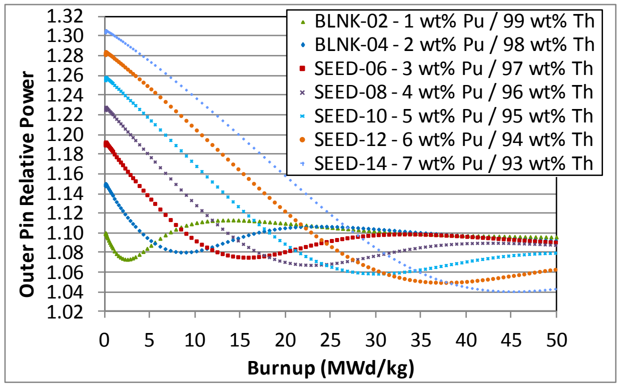

Fig. 9. Outer Pin Relative Power vs. Burnup

V.D. Inventories of Isotopes with Burnup

The fissile Pu (Pu-239, Pu-241) and fissile U (Pa-233, U-233, U-235) contents as a function of burnup are shown in Fig. 10 and Fig. 11 respectively, while the total fissile content is shown in Fig. 12. For both seed and blanket fuels, the total fissile content approaches a nearly asymptotic fissile content of ~ 1.4 wt%.

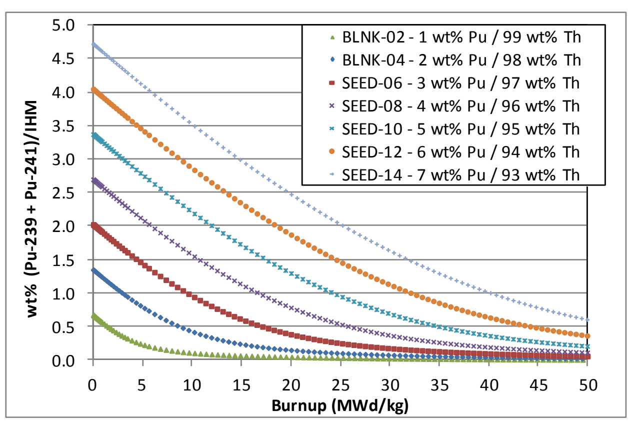

Fig. 10. Pu-Fissile Content vs. Burnup

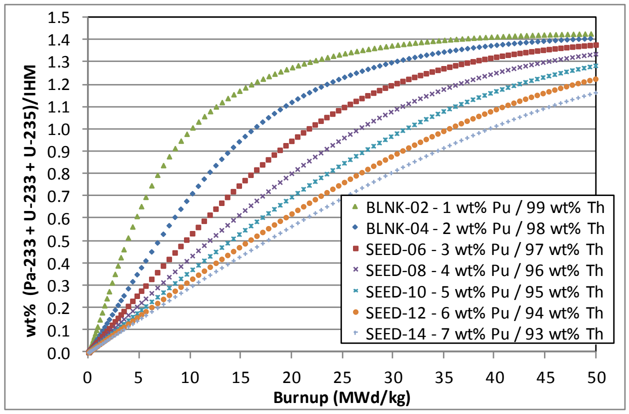

Fig. 11. U-Fissile Content vs. Burnup

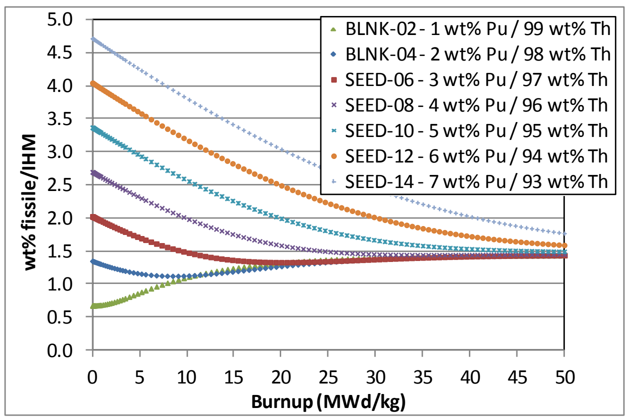

Fig. 12. Fissile Content vs. Burnup

Using the inventories of the various fissile isotopes and Th-232, an approximate estimate of the conversion ratio (CR) for the various fuels was determined and is shown at different burnups in Fig. 13. The CR is defined as the ratio of the thermal neutron (Maxwellian-averaged) capture rate in Th-232 to the sum of the thermal neutron absorption (capture + fission) rates in Pa-233, U-233, U-235, Pu-239, and Pu-241. This simplified evaluation neglects the effects of fast neutrons and resonance absorption. The conversion ratio (CR) is not the same as the cumulative mass conversion ratio (CMCR), which will be computed for the average discharged fuel in the various heterogeneous cores, to be discussed in Section VI. Because of the high absorption cross sections of Pu isotopes and the low neutron reproduction factor ($\eta = \nu\Sigma_f/\Sigma_a$) for Pu in a thermal spectrum ($\eta \leq 2.0$), the conversion ratio is less than unity, except for the blanket-type fuels with ≤ 1 wt% PuO_2.

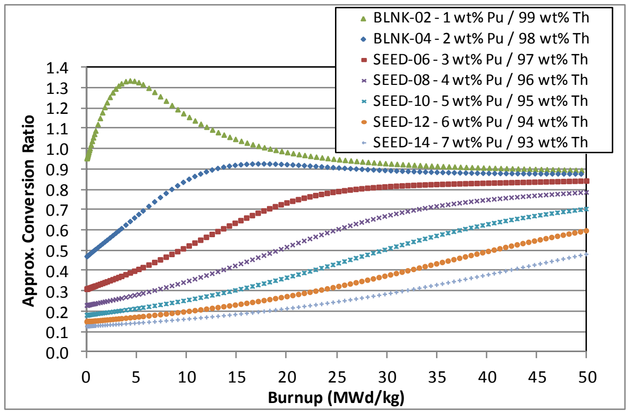

Fig. 13. Approximate Thermal CR vs. Burnup

Using the mass inventories of the various isotopes, an estimate of the cumulative (not instantaneous) fraction of the energy that is generated by the conversion and fission of isotopes in the Th-U chain was made and is shown in Fig. 14. By ~40 MWd/kg, ~80% of the energy generated in the BLNK-02 blanket fuel has come from U/Th. In contrast, in SEED-08 seed fuel, ~35% of the energy comes from U/Th at 40 MW/kg and ~65% comes from Pu.

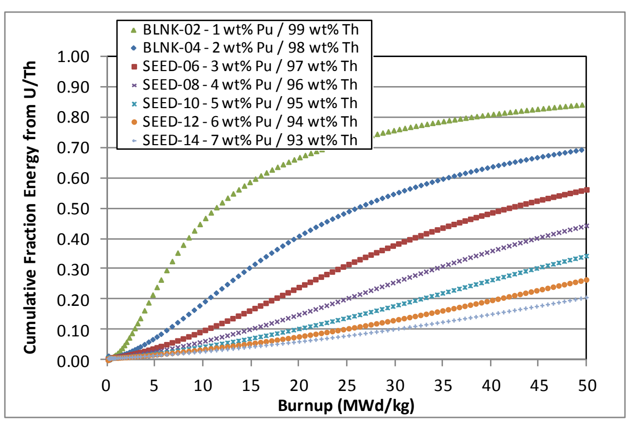

Fig. 14. Cumulative Energy from U/Th vs. Burnup

VI. CORE PHYSICS RESULTS

VI.A.1. Power Distributions – Annular Cores

Radial power distributions for the annular cores are shown in Fig. 15 to Fig. 17. The radial power distributions are the total channel powers in Row L, which is near the middle of the core. Axial power distributions for the annular cores are shown in Fig. 18 to Fig. 20. The axial power distributions show the bundle powers in the channels containing the bundle with the maximum power in the core. As shown later in Table V, the channel with the maximum total power is not necessarily the same as that with the maximum bundle power.

With the exception of the homogeneous SEED-06 core, the 1S-1B and 4S-4B cores must be de-rated in power to ~58% to 65% of full power (100% → 2,061 MW_{th}) while the 84%S/16%B core can be operated at 90%, in order to stay below the maximum allowed LER (57 kW/m, see Section IV.B). Most of the cores have peak channel powers less than 6,500 kW, although the 4S-4B cores are slightly above.

As shown in Fig. 15 and Fig. 17, both the 1S-1B and 84%S/16%B cores have relatively flat radial power profiles across the seed region, due to the adjustment of the exit burnup distributions, with seed at higher burnups in the interior of the core. The power drops off dramatically in the outer radial blanket, to values as low as ~500 kW. In the homogeneous cores with SEED-06 and SEED-08 fuel operating at 100% power, the outer channels adjacent to the radial reflector are at ~3,500 kW. The 4S-4B core experiences dramatic spatial oscillations in the radial power distribution, with the blanket channels being nearly 2,000 kW lower in power.

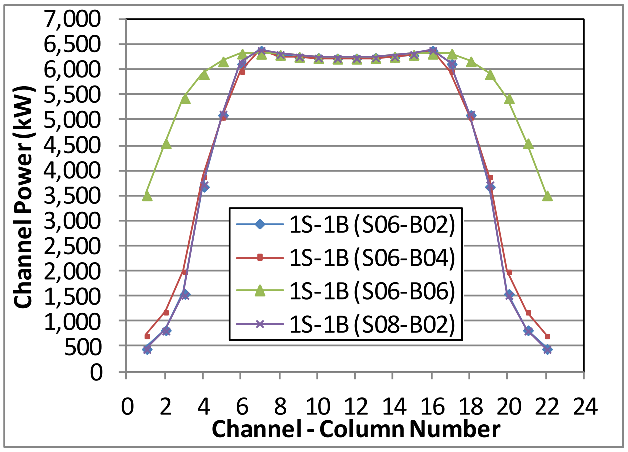

Fig. 15. Channel Powers in Row L in Core 1S-1B

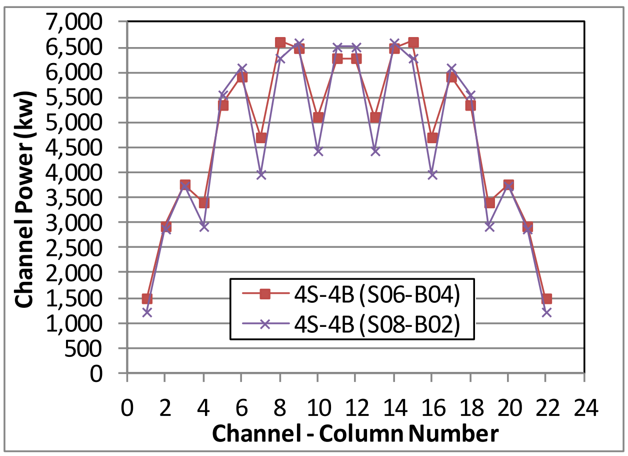

Fig. 16. Channel Powers in Row L, Core 4S-4B

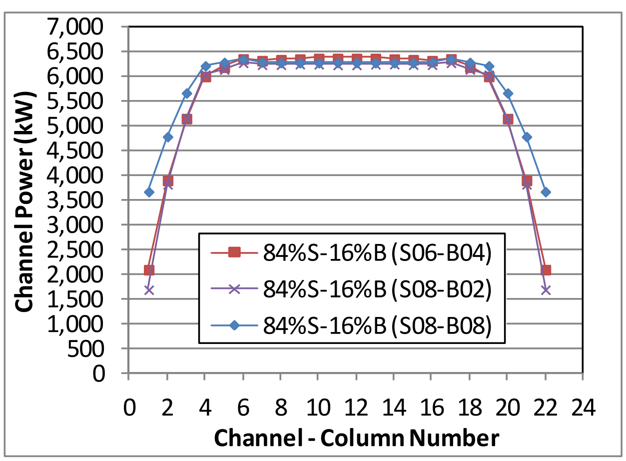

Fig. 17. Channel Powers in Row L, Core 84%S-16%B

The highest bundle powers are found in the cores with SEED-08 fuel, reaching nearly 900 kW in the homogeneous SEED-08 core. Further de-rating of the 84%S/16%B cores with SEED-08 fuel may be necessary, to perhaps to 80%, to keep the peak bundle power below 750 kW. The maximum bundle power usually occurs in axial position 3 or 4 (between z~100 cm and z~200 cm) or in axial position 9 or 10 (between z~400 cm and z~500 cm). With SEED-08 fuel in the 2-bundle shift, the maximum bundle power can occur in axial position 2 (or 11).

The axial power distributions in Fig. 18 to Fig. 20 show what is known as the "double-hump" effect, due to fresh fuel being inserted at either end in alternating channels. This is effect is a result of using a bi-directional, 2-bundle shift re-fuelling scheme with very reactive fuel that is pushed progressively through the core from zero burnup to a high discharge burnup. As seed fuel becomes more enriched and is pushed to higher burnups, the effect becomes more pronounced. As shown in Fig. 20 for the homogeneous SEED-08 core, the lowest fuel bundle power (~300 kW to 400 kW) is found near the middle of the reactor (at positions 6 or 7), while the highest bundle power (~892 kW) is found near the channel inlet at position 2. Such a core may need to be further de-rated, or may require adjuster rods near positions 2 and 11 to help flatten the axial distribution.

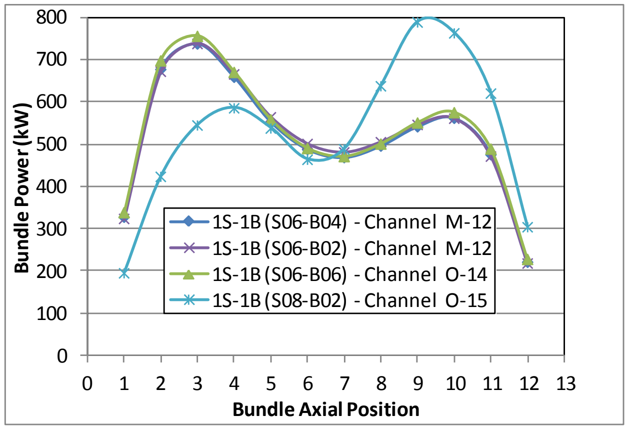

Fig. 18. Peak Bundle Powers in Core 1S-1B

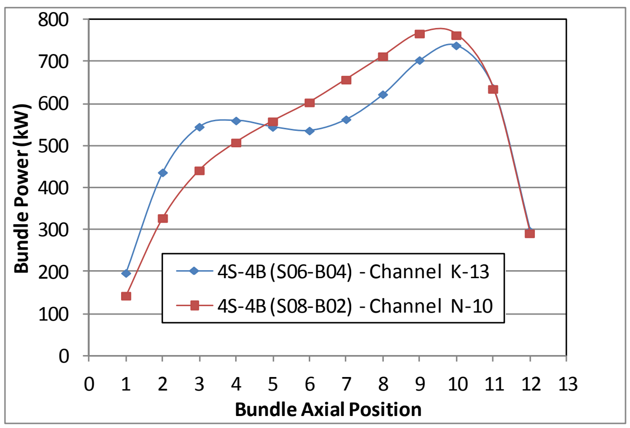

Fig. 19. Peak Bundle Powers in Core 4S-4B

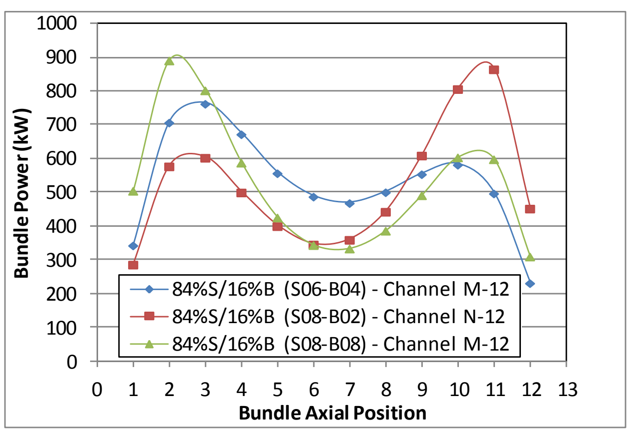

Fig. 20. Peak Bundle Powers in Core 84%S-16%B

VI.A.2. Power Distributions – Checkerboard Cores

Radial power distributions for the checkerboard cores are shown in Fig. 21 to Fig. 24. The radial power distributions are the total channel powers in Rows L and K, which are near the middle of the core. Axial power distributions are shown in Fig. 25 and Fig. 26. Axial power distributions show the bundle powers in the channels containing the bundle with the maximum bundle power in the core.

The checkerboard cores must be de-rated in power to ~65% to 74% of full power (100% → 2,061 MW_{th}) in order to operate below the maximum allowed LER; the 1-to-1-S/B cores can be operated at somewhat higher powers due the highly driven internal blanket assemblies. Peak channel powers range from ~6,300 kW to 6,500 kW. The maximum bundle power ranges from ~702 kW to 773 kW. The maximum bundle power usually occurs in position 3 or 4 (between z~100 cm and z~200 cm) or in position 9 or 10 (between z~400 cm and z~500 cm). If BLNK-02 fuel is used in combination with seed fuel that undergoes a modest burnup relative to its maximum capability, then the peak bundle power position will shift to position 4 (or 9) in Core 3-to-1-S/B, or positions 5 or 6 (or 7 or 8) in Core 1-to-1-S/B.

The checkerboard-type cores experience a number of dips in the radial power distribution, which become more pronounced when the differences in reactivity between the seed and blanket fuel become more significant. Hence, there are more drastic power variations for the SEED-08/BLNK-02 combinations than the SEED-06/ BLNK-04 combinations. Channel powers may change by as much as 2,400 kW between adjacent seed and blanket channels. These large variations may be challenging for the reactor regulating system, and will be the topic of further study.

In a sense, there is a bi-modal radial power distribution: one for the seed, and one for the blanket fuel. The seed power radial power distribution across the checkerboard core is relatively flat, as is the blanket power distribution. The power drops off significantly only at the outer radial boundary near the reflector. The lowest channel powers, found in the outer blanket region, typically range from 600 kW to 2,000 kW.

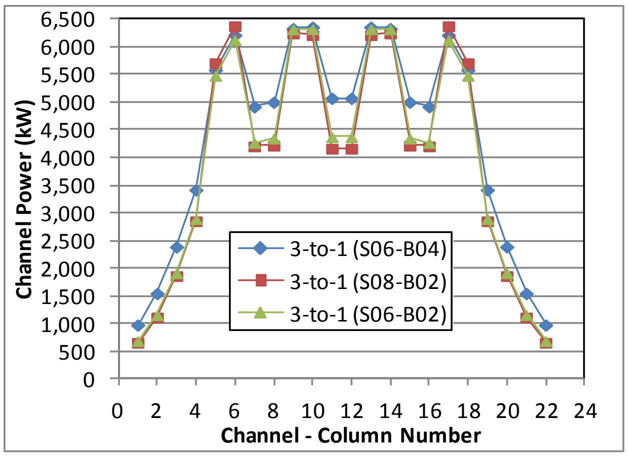

Fig. 21. Channel Powers, Row L, Core 3-to-1-S/B

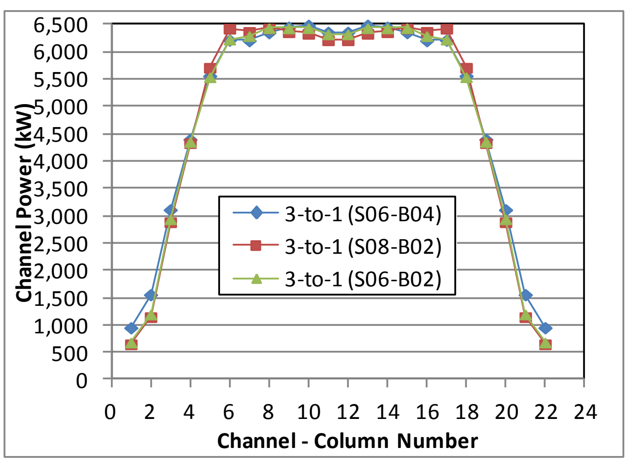

Fig. 22. Channel Powers, Row K, Core 3-to-1-S/B

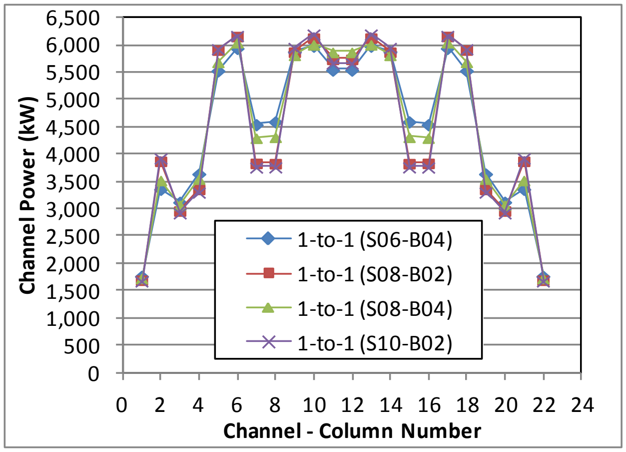

Fig. 23. Channel Powers, Row L, Core 1-to-1-S/B

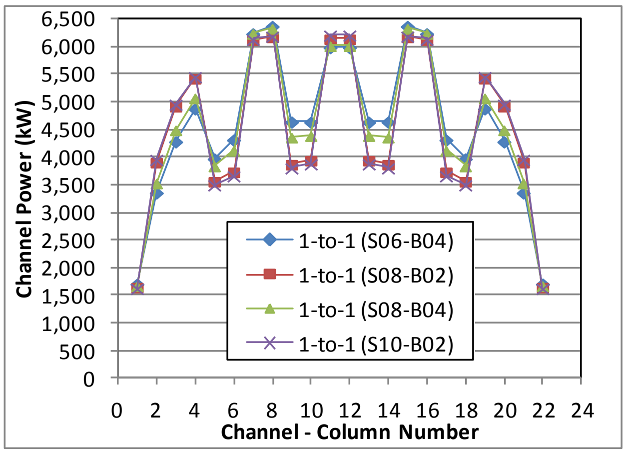

Fig. 24. Channel Powers, Row K, Core 1-to-1-S/B

The axial power distributions for channels with the peak bundle power are shown in Fig. 25 for the 3-to-1-S/B core, and in Fig. 26 for the 1-to-1-S/B core. The core power level and exit irradiations have been adjusted to ensure that the peak bundle power remains below ~750 kW for the lower burnup (~20 MWd/kg) cores.

The axial power distribution is usually a skewed and depressed cosine for cores with SEED-06 fuel and with low relative burnup. With the 2-bundle-shift, bi-directional fuelling scheme, a slight "double hump" effect occurs, similar to that for the annular cores. Because there is significant neutron absorption by the surrounding blanket channel, especially in the 1-to-1-S/B core with BLNK-02 blanket fuel, the seed burnup must be reduced significantly to maintain reactivity. Thus, the relative change in reactivity in the seed fuel between the fuel channel inlet and exit is not large enough to cause a more severe double-hump effect, as has been seen in annular heterogeneous cores. Because the "double-hump" effect is only modest in the checkerboard cores, it may not be necessary to use adjusters to help flatten the axial power distribution, unless much higher burnup seed fuel is used.

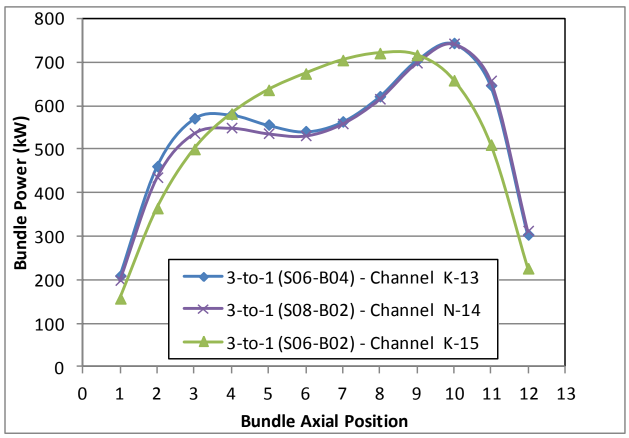

Fig. 25. Bundle Powers in Core 3-to-1-S/B

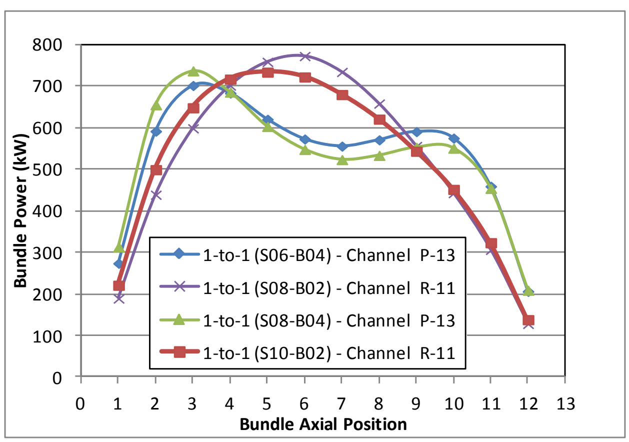

Fig. 26. Bundle Powers in Core 1-to-1-S/B

VI.B.1. Performance – Annular Cores

Performance characteristics for the various annular heterogeneous cores are shown in Table V and Table VI. The core average burnup using SEED-06 seed fuel ranges from ~16.6 MWd/kg to 22 MWd/kg, and is highest for the homogeneous 1S-1B core, and lowest for the 4S-4B core. The B02 blanket fuel is burned to ~40 MWd/kg, to take advantage of its increase in reactivity with burnup. The burnup in the seed fuel must be reduced to compensate for the loss of reactivity due to absorption of neutrons in the blanket fuel, in order to maintain core reactivity ($1.002 \leq k_{eff} \leq 1.003$). This situation is most severe in the 4S-4B core. With SEED-08 fuel, the core-average burnup ranges from ~27.9 MWd/kg (4S-4B) to ~36.2 MWd/kg (84%S/16%B). Given the same volumes of seed and blanket fuel, the 1S-1B core is superior to the 4S-4B core for maximizing core-average burnup.

Taking into account the different consumption rates of seed and blanket fuel bundles, the core-average fissile utilization (FU) in the discharged fuel was evaluated. These range from ~904 MWd/kg-fiss to 1,375 MWd/kg-fiss. For comparison purposes, a PT-HWR using NU fuel in a 37-element bundle (PT-HWR-NU) can achieve a burnup of ~7.5 MWd/kg [6, 7], and this gives an FU ~ 1,056 MWd/kg-fiss. Thus, the relative FU (relative to PT-HWR-NU) ranges from ~0.86 to 1.30, and is highest in the 1S-1B core with the SEED-08/BLNK-02 combination. Thus, the seed / blanket cores with Pu/Th fuels can achieve a fissile utilization that is comparable, or up to 30% higher than what is achieved with NU fuel.

The 1S-1B and 4S-4B cores both contain ~50% blanket fuel. Less than 20% of the power is generated in the low-flux outer blanket for the 1S-1B core. The blanket power production increases to ~37% in the 4S-4B core, where the blanket fuel is highly driven. Less than 7% of the power is generated in the blanket fuel in the 84%S/16%B core.

Between 1,000 and 2,800 bundles are consumed per year (3 to 8 bundles per day), requiring between 1 and 5 re-fuelling shifts per day. By comparison, a PT-HWR operating with NU fuel typically consumes ~15 bundles per day with ~2 re-fuelling shifts per day. Although it was tested, the 1-bundle shift used for the homogeneous core of SEED-08 fuel does not appear to offer a significant advantage in reducing power peaking. The 4-bundle shift used for the SEED-08/BLNK-02 1S-1B core does help reduce axial power peaking, but the reactivity insertion with 4 fresh SEED-08 bundles during re-fuelling may be too high for the reactor regulating system to handle. This will need to be assessed in future studies.

The core-average FIR ranges between 0.53 and 0.74, and is highest for the 4S-4B core with SEED-06 fuel. This is a bit misleading because of the low seed burnup. A better indicator of conversion performance is the CMCR, which ranges from 0.49 to 0.64. Cores with ≥ 4 wt% Pu seed fuel have lower values of CMCR. The Pu competes with Th-232 and U-233 for the absorption of neutrons, and Pu-239 has a lower neutron reproduction factor ($\eta \leq 2.0$) than U-233 ($\eta \geq 2.2$) in a thermal spectrum at elevated fuel temperatures (e.g., 600°C). The cumulative fraction of the energy that is generated by the fission of U-233 (and other isotopes of Pa and Th) ranges from ~28% to 43%, higher for cores using the SEED-08/BLNK-02 combination, and highest for the 4S-4B core.

By comparison, a PT-HWR using NU fuel will have an FIR~0.7, a CMCR~0.56 (kg of Pu-fiss produced / kg of U-235 consumed), and approximately 48% of the energy will be produced from the fission of Pu bred from U-238 and from fast fission of U-238, versus the other 52% produced from U-235 fission. Thus, the PT-HWR seed-blanket cores with 35-Pu/Th-ZrO_2-Rod fuel can achieve comparable or higher values of CMCR than homogeneous cores with NU fuel. To extract more energy from thorium, the blanket fuel must be highly driven and pushed to high burnups (>40 MWd/kg).

The amount of fissile uranium produced per year in the discharged fuel ranges from ~158 kg/year to 363 kg/year. Less U-233 is produced in the SEED-08. Approximately 500 to 1,100 kg of Pu must be fed into the reactors per year, depending on burnup and power level. Of the original Pu, ~48% to 67% of it is consumed in the OTT cycle.

Of the nine different annular core concepts shown, the optimum concept depends on what performance parameter is considered most important. To compare the concepts across several metrics, an integral performance parameter (IPP) has been defined:

$$IPP = CMCR \times FU \times Th/U_{PowerFraction} \times BU_{Core} \times \%Power \qquad (2)$$

The parameter $Th/U_{PowerFraction}$ is the fraction of the energy that is generated by the fission of the isotopes of Th, Pa, and U. BU_{Core} is the core-average burnup. As shown in Table V, the IPP ranges from ~1,700 to 7,500, with the highest being achieved for a homogeneous core of SEED-08 fuel. However, if additional de-rating was applied to cores with SEED-08 fuel, then the 84%S/16%B core with SEED-08 / BLNK-02 fuel would have the highest IPP. By comparison, a PT-HWR operating with NU fuel would have an IPP ~ 2,016, which is low due to the low burnup of NU fuel. Thus, the various annular core concepts have relative IPPs that range from ~0.84 to 3.7.

In comparing cores with ~50% seed / 50% blanket, the 1S-1B core gives higher values for IPP than the 4S-4B cores. The key advantage of the 1S-1B cores with

BLNK-02 blanket fuel is that they can achieve both a high FU and CMCR, which are important for resource conservation.

TABLE V
Performance Characteristics of 1S-1B Annular Cores

Core Model	**1S-1B**	**1S-1B**	**1S-1B**	**1S-1B**
Seed Fuel	SEED-06	SEED-06	SEED-06	SEED-08
Blanket Fuel	BLNK-04	BLNK-06	BLNK-02	BLNK-02
wt% Pu in Seed Fuel	3	3	3	4
wt% Pu in Blanket Fuel	2	3	1	1
Bundles per shift	2	2	2	4
% of Full Power	62.0	100.0	58.3	58.3
Reactor Power (MWth)	1,278.4	2,061.4	1,202.4	1,202.4
Max. Chan. Pow. (kW)	6,386.64	6,389.88	6,399.57	6,404.51
Max. Bun. Pow. (kW)	737.5	755.6	737.7	788.4
Max. LER (kW/m)	50.94	52.19	50.96	56.09
Max. Power Channel	O-15	Q-16	M-16	M-16
Max. Power Bundle	M-12 Bundle 3	O-14 Bundle 3	M-12 Bundle 3	O-15 Bundle 9
k-effective	1.00253	1.00198	1.00243	1.00257
Core BU(MWd/kg)	19.78	21.58	20.94	33.77
FU (MWd/kg-fiss)	1,044	1,067	1,090	1,376
Relative FU (1)	0.988	1.01	1.032	1.302
Blanket BU (MWd/kg)	20.18	19.84	40.94	40.95
Seed BU (MWd/kg)	19.69	23.11	19.30	32.78
Blanket Bundles/Year	359.20	1306.04	127.60	125.34
Seed Bundles/Year	1532.20	1489.53	1552.82	916.92
Power Fraction Blanket	0.19	0.43	0.15	0.15
Power Fraction Seed	0.81	0.57	0.85	0.85
Bundles per Day	5.2	7.7	4.6	2.9
FIR (discharged fuel)	0.70	0.66	0.70	0.59
CMCR	0.63	0.59	0.62	0.54
Energy from Th/U (2)	0.29	0.28	0.34	0.38
Th-232 consumed (kg/year)	394.28	605.43	379.97	352.83
Pu-in (kg/year)	696.693	1099.332	627.359	497.170
Pu-out (kg/year)	316.082	476.793	292.960	181.027
Pu consumed (kg/year)	380.61	622.54	334.40	316.14
% Pu Consumed	54.6	56.6	53.3	63.6
U-fissile (kg/year) (3)	238.592	363.097	208.812	158.415
IPP (arbitrary units) (4)	2,215	3,597	2,666	5,234
Relative IPP (5)	1.099	1.784	1.322	2.596

(1) Fissile Utilization relative to PT-HWR using NU fuel, where FU~1,056 MWd/kg
(2) Fraction of energy that is generated by fission of isotopes of Th, Pa, and U.
(2) Includes Pa-233, U-233 and U-235
(4) IPP = Integral Performance Parameter = CMCR × FU × Th/U-Power-Fraction × Core-Average Burnup × % Power
(5) Relative to PT-HWR with NU Fuel, IPP ~ 2,016

TABLE VI
Performance Characteristics of 4S-4B and 84%S-16%B Annular Cores

Core Model	**4S-4B**	**4S-4B**	**84%S-16%B**	**84%S-16%B**	**84%S-16%B**
Seed Fuel	SEED-06	SEED-08	SEED-06	SEED-08	SEED-08
Blanket Fuel	BLNK-04	BLNK-02	BLNK-04	BLNK-02	BLNK-08
wt% Pu in Seed Fuel	3	4	3	4	4
wt% Pu in Blanket Fuel	2	1	2	1	4
Bundles per shift	2	2	2	2	1
% of Full Power	65.0	60.0	93.0	90.0	100.0
Reactor Power (MWth)	1,340.4	1,237.4	1,917.4	1,855.4	2,061.4
Max. Chan. Pow. (kW)	6,613.16	6,595.83	6,457.85	6,356.19	6,380.94
Max. Bun. Pow. (kW)	739.5	767.8	763.8	866.0	892.1
Max. LER (kW/m)	51.08	54.63	52.76	61.61	63.47
Max. Power Channel	M-15	M-14	R-12	R-13	R-12
Max. Power Bundle	K-13 Bundle 10	N-10 Bundle 9	M-12 Bundle 3	N-12 Bundle 11	M-12 Bundle 2
k-effective	1.00217	1.00224	1.00245	1.00415	1.00257
Core BU(MWd/kg)	16.60	27.90	20.76	35.17	36.17
FU (MWd/kg-fiss)	904	1,243	1,052	1,352	1,341
Relative FU (1)	0.856	1.176	0.996	1.28	1.269
Blanket BU (MWd/kg)	22.36	41.23	19.72	40.70	32.53
Seed BU (MWd/kg)	14.40	24.06	20.84	34.90	36.66
Blanket Bundles/Year	653.06	290.47	197.3	74.1	195.1
Seed Bundles/Year	1709.92	1007.80	2505.7	1469.8	1472.7
Power Fraction Blanket	0.37	0.33	0.07	0.06	0.11
Power Fraction Seed	0.63	0.67	0.93	0.94	0.89
Bundles per Day	6.5	3.6	7.4	4.2	4.6
FIR (discharged fuel)	0.74	0.67	0.67	0.55	0.53
CMCR	0.64	0.58	0.60	0.50	0.49
Energy from Th/U (2)	0.28	0.43	0.28	0.35	0.34
Th-232 consumed (kg/yr)	422.44	404.57	572.59	515.76	553.64
Pu-in (kg/year)	843.621	566.468	1037.069	780.320	874.463
Pu-out (kg/year)	442.224	259.714	459.960	270.176	292.906
Pu consumed (kg/year)	401.40	306.75	577.11	510.14	581.56
% Pu Consumed	47.6	54.2	55.6	65.4	66.5
U-fissile (kg/year) (3)	262.745	175.499	345.456	238.301	260.241
IPP (arbitrary units) (4)	1,687	4,891	3,273	7,206	7,490
Relative IPP (5)	0.837	2.426	1.624	3.574	3.715

(1) Fissile Utilization relative to PT-HWR using NU fuel, where FU~1,056 MWd/kg
(2) Fraction of energy that is generated by fission of isotopes of Th, Pa, and U.
(2) Includes Pa-233, U-233 and U-235
(4) IPP = Integral Performance Parameter = CMCR × FU × Th/U-Power-Fraction × Core-Average Burnup × % Power
(5) Relative to PT-HWR with NU Fuel, IPP ~ 2,016

VI.B.2. Performance – Checkerboard Cores

Performance characteristics for the various annular heterogeneous cores are shown in Table VII and Table VIII. The core average burnup using SEED-06 fuel ranges from ~15.2 MWd/kg to 18.9 MWd/kg, and is higher for the 3-to-1-S/B core. The BLNK-02 fuel is burned to ~40 MWd/kg, to take advantage of the increase in reactivity with burnup (see Fig. 7). Burnup in the seed fuel must be reduced to compensate for the loss of reactivity due to absorption of neutrons in the blanket fuel, to main core reactivity. This situation is most severe in the 1-to-1-S/B core. With SEED-08 fuel, the core-average burnup ranges from ~25.6 MWd/kg (1-to-1-S/B) to ~30.8 MWd/kg (84%S/16%B). The 3-to-1-S/B core is superior to the 1-to-1-S/B core for maximizing the core-average burnup, although it is acknowledged that the former has slightly more seed channels (192) than the latter (188). Only one case with SEED-10 fuel was tested, and it is able to achieve a core-average burnup ~34 MWd/kg. The seed fuel burnup in the same core is ~31 MWd/kg, which is well below the maximum that would be expected for a homogeneous core with SEED-10 fuel (54 MWd/kg), as shown previously in Table III.

Taking into account the different consumption rates of seed and blanket fuel bundles, the core-average fissile utilization (FU) in the discharged fuel was evaluated, and ranges from ~832 MWd/kg-fiss to 1,329 MWd/kg-fiss. The relative FU (relative to PT-HWR-NU) ranges from ~0.79 to 1.26. For the same combination of fuel (SEED-08/BLNK-02), the 3-to-1-S/B core gives a higher burnup and FU than the 1-to-1-S/B core. The use of low-burnup fuels (e.g. SEED-06/ BLNK-04) gives an FU that is below what can be obtained in annular heterogeneous cores, or a PT-HWR running on NU fuel.

Both the 3-to-1-S/B and 1-to-1-S/B cores contain ~50% blanket fuel, and approximately 25% to 41% of the power is generated in blanket channels, particularly in the highly-driven inner blanket channels. Between 1,200 and 3,000 bundles are consumed per year (3 to 8 bundles per day), requiring between ~1.5 and 4 re-fuelling shifts per day.

The core-average FIR ranges between 0.62 and 0.75, and is highest for the 1-to-1-S/B core with SEED-06/BLNK-04 fuel. This is a bit misleading because of the very low seed burnup (~12.6 MWd/kg). A better indicator of conversion performance is the CMCR, which ranges from 0.54 to 0.64. The CMCR should not be confused with the CR, although they are related.

Cores with ≥4 wt% Pu content seed fuel have lower values of CMCR. As discussed previously, the Pu competes with Th-232 and U-233 for the absorption of neutrons, and Pu-239 has a lower neutron production factor ($\eta \leq 2.0$) than U-233 ($\eta \geq 2.2$) in a thermal spectrum. The choice of blanket fuel has little effect on the CMCR. Cores with BLNK-02 and BLNK-04 blanket fuels have comparable values of CMCR, using the same seed fuel. The cumulative fraction of the energy that is generated by the fission of U-233 (and other isotopes of Th, Pa, and U) ranges from ~28% to 43%, and is higher for the cores using BLNK-02 fuel, in combination with high burnup seed (such as SEED-10). The PT-HWR checkerboard seed-blanket cores with 35-Pu/Th-ZrO_2-Rod fuel can achieve comparable or higher values of CMCR than homogeneous cores with NU fuel. To extract more energy from thorium, the blanket fuel must be highly driven and pushed to high burnups (>40 MWd/kg), and the checkerboard cores are well suited for this purpose. The amount of fissile uranium produced per year in the discharged fuel ranges from ~185 kg/year to 303 kg/year. Approximately 580 kg to 1,100 kg of Pu must be fed into the reactors per year, depending on burnup and power. Of the initial Pu loading in the fuel, ~44% to 60% of it is consumed in the OTT cycle.

Of the seven different checkerboard core concepts shown, the optimum concept depends on what performance parameter is considered most important. To compare the concepts across several metrics, the integral performance parameter (IPP) is used again. As shown in Table VI, the IPP ranges from ~1,500 to 7,300, with the highest being achieved for the 1-to-1-S/B core with SEED-10/BLNK-02 fuel. For the same set of seed/blanket fuel, the 3-to-1-S/B core gives higher values for the IPP. Using the IPP metric as a guide, it is undesirable to use the SEED-06/BLNK-04 fuel combination, especially in the 1-to-1-S/B core, at least in comparison with using NU fuel in a PT-HWR. Overall, the 3-to-1-S/B core is the preferable checkerboard concept. The apparent advantages of the 1-to-1-S/B concept are that the fraction of the power generated by the blanket and the production rate of U-233 are higher, and the CMCR is slightly higher.

In comparison to annular heterogeneous cores, the checkerboard-type seed/blanket cores have a lower fissile utilization for the same combination of seed and blanket fuels. The checkerboard cores also have more dramatic variations in the core radial power distribution, which may be more challenging for reactor operations. The key advantages of checkerboard cores over the annular cores are that they can operate at slightly higher power, and can achieve a slightly higher CMCR. The latter may be more important for cores configured to use U-233/U-235 instead of Pu as the initial fissile fuel.

TABLE VII
Performance Characteristics of 3-to-1-S/B Checkerboard Cores

Core Model	**3-to-1-S/B**	**3-to-1-S/B**	**3-to-1-S/B**
Seed Fuel	SEED-06	SEED-08	SEED-06
Blanket Fuel	BLNK-04	BLNK-02	BLNK-02
wt% Pu in Seed Fuel	3	4	3
wt% Pu in Blanket Fuel	2	1	1
% of Full Power	68.0	65.0	65.0
Reactor Power (MWth)	1401.4	1340.4	1340.4
Max. Chan. Pow. (kW)	6495.71	6437.24	6442.39
Max. Bun. Pow. (kW)	743.2	742.3	720
Max. LER (kW/m)	51.34	52.81	49.73
Channel with Max. Power	N-13	N-15	N-13
Bundle of Max Power	K-13 Bundle 10	N-14 Bundle 10	K-15 Bundle 9
k-effective	1.00271	1.00237	1.00264
Core Burnup (MWd/kg)	18.0	30.8	18.9
FU (MWd/kg-fiss)	975	1,325	1,015
Relative FU (1)	0.923	1.255	0.961
Blanket Burnup (MWd/kg)	19.9	41.1	41.1
Seed Burnup (MWd/kg)	17.3	28.4	16.0
Blanket Bundles/Year	603.89	235.97	242.9
Seed Bundles/Year	1677.21	1038.35	1828.6
Power Fraction Blanket	0.29	0.25	0.25
Power Fraction Seed	0.71	0.75	0.75
Bundles per Day	6.2	3.5	5.7
FIR (discharged fuel)	0.72	0.63	0.74
CMCR (discharged fuel)	0.64	0.56	0.64
Energy from Th/U (2)	0.28	0.40	0.36
Th-232 consumed (kg/year)	437.237	411.205	437.991
Pu consumed (kg/year)	422.757	342.102	359.712
% Pu consumed	51.7	59.5	47.9
Pu-fiss consumed (kg/year)	426.798	328.173	367.927
U-fissile (kg/year) (3)	273.220	184.855	234.438
IPP (arbitrary units) (4)	2,018	5,633	2,726
Relative IPP (5)	1.001	2.794	1.352

(1) Relative to PT-HWR with NU fuel, FU = 1,056 MWd/kg-fiss
(2) Fraction of energy that is generated by fission of isotopes of Pa, U, and Th.
(3) Includes Pa-233, U-233 and U-235
(4) IPP = Integral Performance Parameter = CMCR × FU × Th/U-Power-Fraction × Core-Average Burnup × % Power
(5) Relative PT-HWR with NU Fuel, IPP ~ 2,016

TABLE VIII
Performance Characteristics of 1-to-1-S/B Checkerboard Cores

Core Model	**1-to-1-S/B**	**1-to-1-S/B**	**1-to-1-S/B**	**1-to-1-S/B**
Seed Fuel	SEED-06	SEED-08	SEED-08	SEED-10
Blanket Fuel	BLNK-04	BLNK-02	BLNK-04	BLNK-02
wt% Pu in Seed Fuel	3	4	4	5
wt% Pu in Blanket Fuel	2	1	2	1
% of Full Power	74.0	74.0	74.0	74.0
Reactor Power (MWth)	1525.4	1525.4	1525.4	1525.4
Max. Chan. Pow. (kW)	6408.3	6291.3	6371.8	6304.55
Max. Bun. Pow. (kW)	702.1	772.9	737.3	734.2
Max. LER (kW/m)	48.50	54.99	52.46	53.52
Channel with Max. Power	P-13	R-12	P-13	R-12
Bundle of Max Power	P-13 Bundle 3	R-11 Bundle 6	P-13 Bundle 3	R-11 Bundle 5
k-effective	1.00248	1.00239	1.00287	1.00277
Core Burnup (MWd/kg)	15.2	25.6	27.3	34.1
FU (MWd/kg-fiss)	832	1,142	1,167	1,329
Relative FU (1)	0.788	1.081	1.105	1.258
Blanket Burnup (MWd/kg)	21.9	41.2	39.9	41.3
Seed Burnup (MWd/kg)	12.6	21.0	22.7	31.1
Blanket Bundles/Year	830.5	395.6	437.7	389.6
Seed Bundles/Year	2098.0	1350.3	1198.7	918.1
Power Fraction Blanket	0.41	0.37	0.39	0.36
Power Fraction Seed	0.59	0.63	0.61	0.64
Bundles per Day	8.0	4.8	4.5	3.6
FIR (discharged fuel)	0.75	0.69	0.64	0.62
CMCR (discharged fuel)	0.64	0.58	0.55	0.54
Energy from Th/U (2)	0.28	0.42	0.37	0.43
Th-232 consumed (kg/year)	479.547	487.812	458.360	470.156
Pu consumed (kg/year)	461.480	377.228	404.295	369.783
% Pu consumed	44.3	49.6	54.4	56.7
Pu-fiss consumed (kg/year)	476.153	380.119	394.177	356.366
U-fissile (kg/year) (3)	303.335	219.493	216.775	190.781
IPP (arbitrary units) (4)	1,564	4,910	4,590	7,325
Relative IPP (5)	0.776	2.436	2.277	3.633

(1) Relative to PT-HWR with NU fuel, FU = 1,056 MWd/kg-fiss
(2) Fraction of energy that is generated by fission of isotopes of Pa, U, and Th.
(3) Includes Pa-233, U-233 and U-235
(4) IPP = Integral Performance Parameter = CMCR × FU × Th/U-Power-Fraction × Core-Average Burnup × % Power
(5) Relative PT-HWR with NU Fuel, IPP ~ 2,016

VII. PERFORMANCE RELATIVE TO ALTERNATIVE REACTOR CONCEPTS

In considering the results from core physics calculations for the various heterogeneous seed/blanket cores in this study, a number of preliminary observations can be made with regards to their performance relative to a number of alternative reactor concepts which make use of thorium-based fuels. Two alternative reactor concepts are considered, including the LWBR-1000 (light water breeder reactor) concept that was investigated by Knolls Atomic Power Laboratory during the early 1980s [22] and the Advanced Heavy Water Reactor (AHWR) under development in India [23, 24].

VII.A Comparison with LBWR-1000

The LWBR-1000 (~1000 MW_e) concept [22] made use of the experience gained from the small-scale prototype LWBR (237 MW_{th}, 72 MW_e) reactor at Shippingport [1, 2]. The LWBR-1000 concept was fuelled with $(U,Th)O_2$ and ThO_2 fuels in heterogeneous seed-in-blanket core designs, with a light water coolant/moderator. Full recycling of the U, Th and bred U-233 was assumed. There were two types of blanket fuel which surrounded the axial-movable hexagonal seed sub-assemblies, and an outer reflector made of pure ThO_2 fuel pins to absorb leaking neutrons. With use of U-233 (~63 wt% U-233/U) as the main fissile fuel, a higher value of η (> 2.2) in the fuel was possible, enabling slight breeding. The outer blanket/reflector was made of pure ThO_2. To achieve net breeding, the discharge burnup in both the seed and blanket fuels had to be kept low to avoid excess *in situ* burning of the U-233 and neutron capture in Pa-233. Thus, in the LWBR-1000 concept, the equilibrium burnup in the seed was ≤ 14 MWd/kg, while the burnup in the blanket and reflector regions were ≤ 4 MWd/kg. With a core-average burnup of ≤ 11 MWd/kg, and a core-average initial fissile content of

~2.5 wt% fissile/IHE (IHE= initial heavy element of fuel), the fissile utilization was approximately 408 MWd/kg-fissile, approximately 39% of a PT-HWR running on NU fuel. In contrast, the various heterogeneous seed/blanket concepts considered in this study for a PT-HWR core have burnups ranging from approximately 15 MWd/kg to 36 MWd/kg, and fissile utilizations that range from 0.79 to 1.30 times that of a PT-HWR running on NU fuel. The main advantage of the LWBR-1000 concept is that it is a slight, net breeder, with an equilibrium core FIR of 1.01 at end-of-cycle (EOC). Presumably, one of these PT-HWR heterogeneous cores could be adapted to run using $(U,Th)O_2$ fuel, and could achieve higher burnup and fissile utilization, while breeding simultaneously.

VII.B Comparison with AHWR

The AHWR [23, 24] is a heavy-water-moderated, boiling light water-cooled reactor. It uses heterogeneous bundle designs, with two types of recycled fissile fuel (Pu and U-233). There are also AHWR designs that use enriched uranium mixed with Th in $(U,Th)O_2$, although these designs will not be discussed here. For the "Standard" AHWR fuel and core design, which recycles both the spent Pu and U-233, and adds some extra Pu (75 wt% fissile) and U-233, the fissile content is approximately 3.25 wt% fissile/IHM, and the core-average burnup is approximately 38 MWd/kg. This gives a fissile utilization of ~1,169 MWd/kg-fissile, which is approximately 11% higher than achieved with a PT-HWR with NU fuel. This is somewhat higher than the core concepts in this study which use SEED-06 (3 wt% PuO_2) fuel and achieve a burnup of ~20 MWd/kg. However, most of the core concepts in this study that used SEED-08 (4 wt% PuO_2) seed fuel can achieve fissile utilizations that are 11% to 30% higher than a PT-HWR with NU fuel, and this is also well above the AHWR. Although the Standard AHWR produces approximately 75% of its cumulative energy from Th/U (core-average burnup is ~19 MWd/kg, discharge burnup ~38 MWd/kg), this is due to the large initial content of U-233. At start-up, approximately 45% of the core power is already coming from U-233. Thus, relative to the initial start-up, the fraction of core power by Th/U has increased in absolute terms by 30%. In the heterogeneous seed/blanket PT-HWR cores considered in this study, approximately 28% to 43% of the cumulative power is generated by Th/U, starting from zero (clean thorium with no U-233), which is comparable or higher than the AHWR. The AHWR requires the recycling of two types of fuels (Pu and U-233), and the use of a heterogeneous bundle design. Both features will make the fuel cycle somewhat more complicated and potentially more expensive. In contrast, the lattices considered in this study use only one initial source of fissile fuel (Pu) with a relatively simple bundle concept.

VIII. CONCLUSIONS

Seven different annular and seven different checkerboard-type heterogeneous seed/blanket cores in a PT-HWR with a 35-element Pu/Th fuel bundle have been analysed, along with a low-burnup and a high-burnup homogeneous core for comparison. A once-through thorium cycle is chosen for simplicity.

The key result is that most or all of these cores are able to achieve core average burnups ranging from ~15.2 MWd/kg to 36.2 MWd/kg. The fissile utilization is comparable or higher (up to 30% higher) than what can be achieved with NU fuel. The highest fissile utilization is achieved in cores using seed fuels with 4 wt% to 5 wt% of Pu. Annual production of fissile uranium bred from thorium ranges from ~158 kg/yr to 363 kg/yr. A range of 44% to 67% of the plutonium is consumed. Based on lattice physics calculations, such cores are expected to have a coolant void reactivity ranging between +7.6 mk and +9.7 mk, which is below what is found in PT-HWRs with NU fuel [6].

To avoid severe power peaking in bundles and channels in cores with both seed and blanket fuel, the reactor power must be de-rated to ~58% to 74% of full power. Such de-ratings have also been found to be necessary in seed-blanket cores in various light water breeder reactor designs [1-3, 22]. The economic impact of this de-rating and options to mitigate it will be the subject of further studies.

If the highest priority is to maximize the core power, then a homogeneous core of seed fuel is preferred, followed by the use of the 1-to-1-S/B core. To maximize both the fissile utilization and the CMCR simultaneously, a simple two-region core with a central seed region and an outer blanket region is preferred over a core with multiple seed and blanket regions, or the checkerboard cores.

The various heterogeneous core concepts considered in this study are attractive for achieving high fissile utilization of thorium-based fuels, while maintaining simplicity in the fuel bundle, making them competitive with alternative reactors concepts for exploiting the use of thorium.

IX. FUTURE OPTIONS

Severe axial power peaking is a potential issue that must be addressed, if high-burnup (>40 MWd/kg) seed fuel bundles are to be used in a PT-HWR at high core power levels, with little de-rating. Future studies may investigate the possibility of the use of axial and radial shuffling of seed fuel to help flatten core power distributions, making use of the experience with batch re-fueling in LWRs and various shuffling schemes considered in the past for PT-HWRs [15, 25]. Alternative fuel bundle geometries and materials that further enhance heat transfer and permit operation at higher bundle powers may also be investigated.

Future studies may also consider the use of U/Th homogeneous fuels and other lattice and bundle concepts, to potentially increase the fissile utilization, the conversion ratio (enabling net breeding), and also to further reduce coolant void reactivity. It is expected that more detailed evaluations of various core reactivity coefficients and incorporation of reactivity devices for specific core concepts will be assessed.

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