Self-Sustaining Thorium-Fueled BWR

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Abstract

This study assesses the feasibility of a thorium-based fuel-self-sustaining Reduced moderation BWR (RBWR-Th) core. This core features a hexagonal tight-lattice fuel, high exit coolant quality, axial segregation of seed and blanket regions, and compatibility with the ABWR reactor vessel inherited from the high void U-Pu fuel cycle RBWR-AC proposed by Hitachi. The RBWR-Th departs from the RBWR-AC by eliminating the internal blanket, eliminating absorbers from the axial reflectors, replacing depleted urania with thoria as the primary fertile fuel, elongating the fissile region, and axially varying the concentration of transthoria loaded into the fissile region. When the same modeling assumptions and correlations are used, the RBWR-Th obtains an average discharge burnup of 61 $GWd \div t$ versus 45 $GWd \div t$ for the RBWR-AC. However, when more conservative assumptions are made, the average discharge burnup drops to 25 $GWd \div t$. The RBWR-Th maintains negative coolant void coefficients of reactivity throughout each cycle–between -155 and -131 $pcm \div \%$–but currently does not have sufficient margin for shutdown.

Keywords: thorium, reduced moderation, BWR, breeder, multi-recycling, equilibrium

1. Introduction

The RBWR-Th core design is based upon the Hitachi designed RBWR-AC[1], a reduced-moderation BWR which employs axial seed and blanket segregation for fuel-self-sustaining operation within an ABWR pressure vessel. The RBWR-Th replaces depleted urania with thoria as the primary makeup, eliminates the internal blanket and elongates the seed region, and eliminates absorbers within the upper axial reflectors. In order to accommodate newly imposed constraints for coolant dryout and two-phase flow stability, the design underwent a number of parametric studies. Section 2 lists the constraints, section 3 lists the design variables and describes the design process undertaken and the selected configuration, section 4 tabulates the core and fuel-cycle performance metrics of the reference design and compares it with a previous design variant, section 5 demonstrates the performance sensitivity to several uncertain modeling assumptions, and section 6 shares some results of an assembly physics study.

2. RBWR-Th core design constraints

The RBWR-Th core design is guided by several mission constraints:

1. Charge only natural thoria
2. Recycle all transthoria
3. Maintain a fissile inventory ratio (FIR) of 1 at equilibrium
4. Fit within an ABWR pressure vessel
5. Provide the full ABWR thermal power

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6. Operate for at least 12 month cycles
7. Discharge fuel at $> 20GWd \div t$
8. Use light water as coolant

The core must meet additional physical and operational constraints:

9. Have a reasonable coolant pressure drop
10. Possess negative coefficients of reactivity for fuel temperature, coolant void, and power
11. Maintain criticality
12. Avoid coolant dryout: $MCPR \geq 1.5$
13. Suppress density wave oscillations: $DR < 0.7$
14. Have sufficient shutdown margins

Here, $MCPR$ is the minimum critical power ratio, and DR is the decay ratio of the core response to two-phase density wave oscillation (DWO) perturbations. Constraints 12 and 13 were not considered during the 2011 design effort [2], but are met (depending upon uncertain modeling assumptions) by the reference design described in Sections 3 and 4. Failure to meet constraint 14 is discussed in Section 6 and will be reported in future work, as it is being addressed in current design studies.

3. Parametric study of the RBWR-Th core design

The RBWR-Th core design underwent parametric studies which sought to accommodate the two recently imposed constraints while maximizing discharge burnup. For these studies, a hierarchical approach was taken towards adjusting design variables. Coolant flow-rate and cycle length were chosen as the two primary design variables because for fixed power (constraint 5), constraint 12 is most sensitive to the former and constraint 11 is most sensitive to the latter. The effects of changes to the seed and blanket region axial lengths, axial isotopic charge distribution, inlet sub-cooling, fuel pin outer diameter, and fuel pin pitch-to-diameter ratio are multi-faceted, so these variables were selected as secondary design variables.

Each set of secondary design variables uniquely determined the values of the coolant flow-rate and cycle length required for attaining constraints 12 and 11 at the beginning and end of the cycle. Upon each choice of primary design variables, a new equilibrium core composition was calculated and the primary design variables were once again updated. A few iterations were required before constrained primary design variables were found. While this approach guaranteed satisfaction of constraints 12 and 11, the remainder of the constraints were satisfied by the adjustment of secondary design variables.

These adjustments of the secondary design variables were guided by a sensitivity study, which estimated the effects of one-at-a-time variable adjustments upon $MCPR$, DR, and achievable burnup (BU). These sensitivities are tabulated in Table 1.

Modification	MCPR	DR	BU
Increase of the coolant flow-rate	+	+	−
Increase of the cycle length			+
Elongation of the seed	+	−	+
Contraction of the blankets		+	+
Axial variation of the transthoria charge	+	++	+
Reduction of the inlet sub-cooling		++	
Decrease in fuel pin outer diameter	+	− −	
Increase of the fuel pin P÷D	+		− −

Table 1: Effects of primary and secondary design variable changes upon coolant dryout, two-phase stability, and achievable burnup. Here, +'s indicate improvement, –'s indicate deterioration, double symbols indicate large effects, and blanks indicate no or ambiguous effects.

Elongation of the seed was found to improve $MCPR$ due to a decreased linear heat generation rate (LHGR), to worsen DR due to increased two-phase pressure drop, and to improve BU due to a decreased blanket volume fraction. Contraction of the blanket regions improved DR due to decreased two-phase pressure drop and improved BU due to a reduced blanket volume fraction with only small penalties in breeding. Charging transthoria in axial grades with concentration increasing towards the top of the core improved $MCPR$ by shifting the LHGR upwards, improved DR by reducing the two-phase pressure drop, and improved BU by reducing fluence peaking[3]. Reduction of the inlet sub-cooling improved DR. Reduction of the fuel pin outer diameter improved $MCPR$ by reducing LHGR, but at the cost of worsening DR due to a shortened heat transfer time-constant. An increase of the fuel pin pitch-to-diameter ratio improved $MCPR$ performance by allowing for fuel wetting, but significantly penalized BU.

Based upon this sensitivity study, several design variable changes were made to the 2011 design[2], creating a 2013 reference: the coolant flow-rate and cycle length were increased by 30%; the seed region was elongated by 170%; the total blanket length was contracted by a third; transthoria became charged into the seed, graded at three concentrations–75% of the average for the lower third, the average for the middle third, and 125% of the average for the upper third; and the inlet subcooling was reduced by 4.06°C. The fuel pin outer diameter and pitch and assembly thermal power remained unchanged. Table 2 provides the main design specifications which incorporate the changes established by the parametric studies.

Design variable	Units	Value
Thermal power	MW	3926
Coolant flow-rate	kg/s	8795
Cycle length	$EFPD$	2300
Axial height (LB/S/UB)	cm	40/300/40
Seed >Th loading (L/M/U)	$^a/_o$ of average	75/100/125
Fuel pin (OD/pitch)	cm	1.005/1.135
Coolant inlet temperature	$^\circ C$	282.56
Coolant inlet pressure	MPa	7.25

Table 2: Main design specifications of the 2013 reference RBWR-Th core design. Here, LB/S/UB refers to the lower blanket, seed, and upper blanket axial regions, >Th denotes transthoria, and L/M/U are the lower, middle, and upper axial third of the seed region.

4. Performance of the 2013 reference RBWR-Th core design

The MocDown thermal/hydraulics-coupled depletion and core equilibrium search tool was used to simulate a single-pin unit cell of the 2013 reference RBWR-Th core design[4]. Using MCNP6.1 for neutron transport and ORIGEN2.2 for transmutation, 55 axial fuel zones were depleted–10 lower blanket, 30 seed, and 15 upper blanket–in 14 constant-power depletion steps. Online coupling of a single-channel heat balance and void fraction correlation ensured self-consistent neutronics (power distribution) and thermal/hydraulics (coolant density distribution) solutions to within 5%. Fuel passed through the system over 50 times before reaching an asymptotic equilibrium. Fuel was assumed to be at 90% of its nominal density. The void fraction was estimated with an MIT-modified LPG correlation[5]. An MIT-modified CISE-4 correlation was used to estimate the critical power ratio, while assuming a 25% inter-assembly power peaking and a 5% coolant flow-rate depression[5]. The core radial leakage probability was assumed to be 2.5% and the density wave oscillation decay ratio was estimated using the STAB frequency domain stability code[6].

Table 3 tabulates the core and fuel cycle performance metrics for the design and compares them with those of the 2011 design[2]. The 2013 design offers a smaller core average cycle burnup over the 2011 reference. Compared to the 2011 reference, the 2013 design features an elongated and flattened LHGR, both of which are depicted in Figure 1. Whereas the 2011 variant peaks at 280 $W \div cm$ in the lower seed at BOEC, the 2013 variant peaks only at 100 $W \div cm$ in the upper seed at EOEC. Also seen is the larger amount of breeding within the blankets of the 2011 design due to a shorter core with a higher probability of leakage from the seed into the blanket. Figure 2 shows the axial distributions of ^{232}Th and ^{233}U over a cycle. Clearly seen are the graded seed transthoria charge concentration, the higher rate of gross breeding within the seed (proportional

Performance metric	Units	2011	2013
Fissile inventory ratio	-	1	1
Cycle length	$EFPD$	1780	2300
Average discharge burnup	$GWd \div t$	32	25
Minimum CPR	-	1.1	1.5
DWO decay ratio	-	1.23	1.08
Power density	$MW_{th} \div m^3$	70	42
Maximum LHGR	$W_{th} \div cm$	300	100
Specific power	$MW_e \div t$	6	4
Transthorium abundance	$^w/_o$	12.7	11.6
Transthorium loading	$t \div GW_e$	20.5	30.9
Heavy-metal reprocessing	$t \div GW_e \cdot y$	33	42
Transthorium discharge	$t \div GW_e \cdot y$	4.2	4.9
FTCR (B/E)	$pcm \div K$	-4.2/-4.2	-5.1/-4.6
VCR (B/E)	$pcm \div \%$	-95/-75	-155/-131
Cycle reactivity swing	$\%\Delta k$	1.9	0.85
Void collapse worth (B/E)	$\%\Delta k$	21/15	24/17
Outlet void fraction	%	82	75

Table 3: Core and fuel cycle performance metrics of the 2011 and 2013 reference RBWR-Th core designs. Here, FTCR and VCR are the fuel temperature and coolant void coefficients of reactivity, CZP denotes cold-zero-power conditions, and B/E denote conditions at the BOEC and EOEC states. A 34.5% thermodynamic efficiency is assumed for both variants.

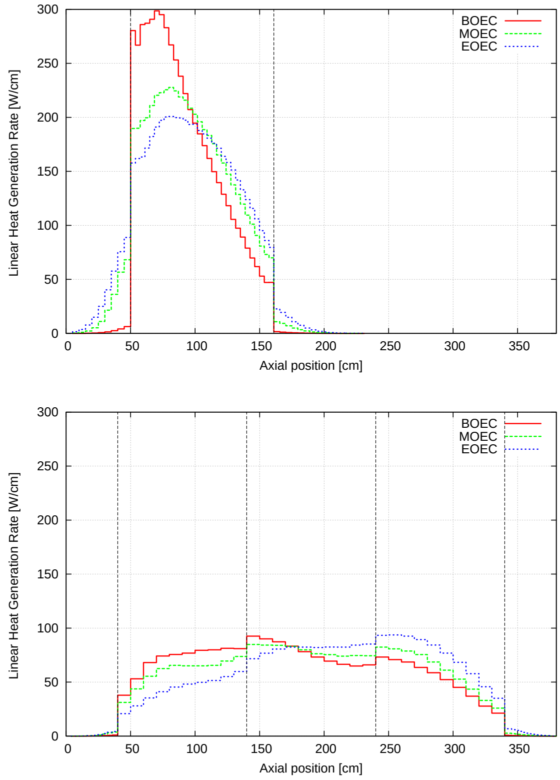

Figure 1: Linear heat generation rate of the (top) 2011 and (bottom) 2013 reference RBWR-Th core designs. The elongated active region and graded transthoria concentration of the 2013 variant significantly lowers and flattens its power distribution.

to the depression in thoria across the cycle), and the higher net rate of breeding within the blankets (due to a lower fissile content).

5. Sensitivity of performance to modeling assumptions

RBWR-Th performance is highly sensitive to the void fraction, critical power, and core radial leakage probability. The first two are estimated by correlations with large experimental uncertainties [5] and the third requires a full-core model. The impact of these uncertain modeling assumptions upon performance is quantified by relaxing the assumptions in turn and re-optimizing the design variables. These results are summarized in Table 4.

The MIT-modified LPG correlation [5] offers a best-estimate of the RBWR-Th coolant void fraction which is conservatively lower than that predicted by the RELAP correlation, used by Hitachi to model the RBWR-AC. Upon switching to the RELAP correlation, the estimated coolant void fraction increases, system slowing-down power decreases, flux spectra harden, fissile breeding improves, equilibrium fissile content increases, and longer cycle lengths can be achieved [7]. The result is an increase in the achievable burnup from 25 to 38 $GWd \div t$. Additionally, the higher void fractions and increased fissile contents make the void coefficients of reactivity less negative, so the DWO decay ratio drops from 1.08 to 1.00.

The MIT-modified CISE-4 correlation [5] offers a best-estimate of the RBWR-Th critical power and recommends a conservative limit of 1.5. Hitachi uses their own modified CISE-4 correlation and a 1.3 limit, which permits less wetting of the fuel before dryout. Upon switching to the Hitachi-modified correlation and limit, a reduced coolant flow and shortened active fuel length can be accommodated, which, when combined, improves both burnup and stability. The former does so by increasing coolant void

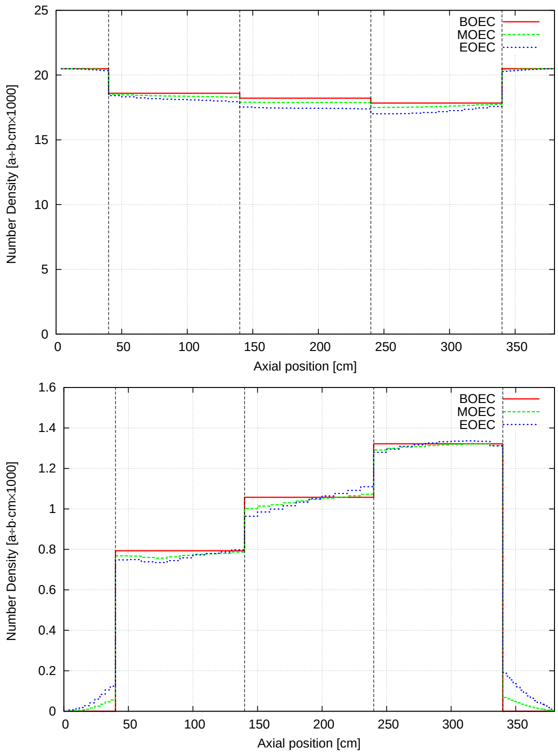

Figure 2: Axial concentration of (top) ^{232}Th and (bottom) ^{233}U along a cycle of the 2013 design. Transthoria is charged in graded enrichments within the seed.

fraction and the latter does so by reducing the heavy metal loading and reducing the two-phase pressure drop. This switch, in addition to the usage of the RELAP void fraction correlation, more than doubles the achievable burnup 25 to 61 $GWd \div t$ and drops the DWO decay ratio from 1.08 to 0.48.

The single-pin unit cell idealizes the core as an infinite hexagonal lattice of fuel pins and doesn't explicitly account for the leakage of neutrons through the radial extremities of the core. A 2.5% core radial leakage probability was chosen, but preliminary studies estimate it to be 2.2%. Upon switching the core radial leakage probability from 2.5% to 2.2%, a longer cycle length can be accommodated and the achievable burnup increases by roughly 16%.

Modelling change	Metric	Impact
LPG to RELAP	BU	25 to 38 $GWd \div t$
	VCR	less negative
	DR	1.08 to 1.00
LPG to RELAP & M-CISE to H-CISE	BU	25 to 61 $GWd \div t$
	DR	1.08 to 0.48
2.2% to 2.5% leakage	BU	25 to 29 $GWd \div t$

Table 4: Summary of performance sensitivity to modeling assumptions. LPG and RELAP are drift-flux correlations for void fraction and M-CISE and H-CISE are correlations for critical power.

6. Fuel assembly physics study

Although single-pin unit cell models are ideal for rapid parametric studies, only by simulating a fuel assembly can one address several important aspects of the core. These include, but are not limited to the control element worth, the degree of pin power peaking, and the effects of the flow bypass region, assembly can, and control blade followers. An assembly unit cell model depicted in Figure 3 was built and these effects were studied.

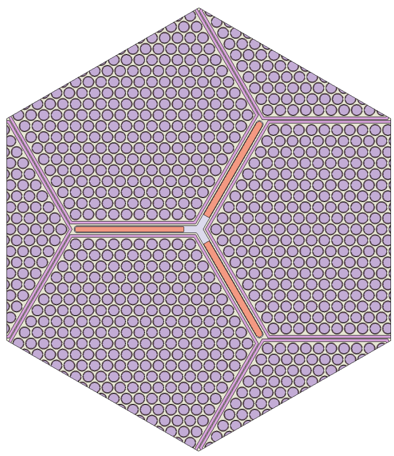

Figure 3: RBWR-Th multi-assembly unit cell.

The assembly can increased parasitic absorption slightly and the flow bypass region and control blade followers greatly increased moderating power at the assembly periphery. The enhanced local moderation was found to cause a power peaking of 1.4 in the corner pin at BOEC. Upon loading transthoria in four radial grades (increasing fissile content at the interior of the assembly and reducing it at the edges) the power peaking was reduced to 1.1 at

BOEC and 1.2 at EOEC. The reactivity worth of changing the core state from hot full-power to cold zero-power was calculated to be +15 $\%\Delta k$, whereas the reactivity worth of the control blades was calculated to be -10 $\%\Delta k$. This control worth deficit would increase if the highest-worth control element were not accounted for and ^{233}Pa as allowed to decay into ^{233}U.

Although the control worth deficit could be addressed by increasing the ratio of control to fuel elements (by either reducing the number of fuel pins per assembly or increasing the number of control blades per assembly) most approaches would increase the volume of assembly bypass and penalize achievable burnup through spectrum softening. Instead, the approach being pursued for attaining the desirable shutdown margin is to load an adequate amount of depleted uranium to the thorium feed fuel. The larger the fraction of depleted uranium, the less negative the void coefficient of reactivity is expected to be. A decrease in the magnitude of the void coefficient of reactivity would also improve two-phase flow stability.

7. Conclusions

The RBWR-Th core design was improved to accommodate coolant dryout and two-phase flow stability constraints. By elongating the seed and flattening the LHGR profile, shortening the blankets, axially varying the transthoria seed charge, and reducing the inlet subcooling, the constraints were met with only modest penalties on the fuel discharge burnup. The performance of both systems is highly sensitive to modeling assumptions. Using the assumptions and correlations Hitachi used for the design of their RBWR-AC, the RBWR-Th average discharge burnup is 61 $GWd \div t$ versus 45 $GWd \div t$ of the depleted uranium fueled RBWR-AC. All coefficients of reactivity are negative, but the void coefficient of reactivity is too negative to allow for safe shutdown at cold zero-power conditions. The partial replacement of thoria makeup with depleted urania is expected to provide adequate shutdown margin.

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