Design Study of Thorium Cycle Based Long Life Modular Boiling Water Reactors

Nuri Trianti¹⁾, Zaki Su'ud¹⁾, and Eka Sapta Riyana²⁾

¹⁾Nuclear Physics and Biophysics Research Division
Faculty of Mathematics and Natural Sciences
Institut Teknologi Bandung, Indonesia

²⁾Nuclear Energy Regulatory Agency (BAPETEN), Jakarta
e-mail: szaki@fi.itb.ac.id, nuri.trianti@gmail.com

Received 6 July 2011, Revised 5 September 2011, Accepted 20 September 2011

Abstract

Design study of long life (cycle) Boiling Water Reactor, which can be operated for 20-30 years of operation time without the necessity of refuelling during that period, has been performed. In shown in the previous study Th232-U233 cycle based fuel has potential for longer operation time in the thermal reactor domain. To increase reactor operation time and minimize excess-reactivity burnable poison may be used. Protactinium (Pa-231), Np-238, or gadolinium has good properties for such purpose. Here based on the previous study we select Protactinium and Gadolinium poisons to be used in the present study. Optimizations the content of ²³¹Pa in the core enables the BWR core to sustain enough reactivity for long period of time with reasonable burn-up reactivity swing. Based on the optimization of fuel element composition (Th and Pa) in various moderation compositions can be achieved reactor core with longer operation time, 20 ~ 30 years operation without fuel shuffling or refuelling. Similarly Gadolinium has been successfully used to extend refuelling time and reduce excess reactivity during burnup period for both oxide fuel and nitride fuel.

Keywords: Th-232, U-233, Pa-231, BWR, gadolinium, tight lattice, long life core

1. Introduction

Long life modular reactors without onsite refuelling become important candidates for next generation nuclear power reactors suitable for remote area. Learning from Chernobyl and Fukushima nuclear accidents it is important to reduce excess reactivity during burn-up passively and also enhance natural circulation of the coolant or alternative system for decay heat removal system¹⁻³⁾.

Thorium cycle in general has larger conversion ratio in the thermal neutron spectrum domain than uranium cycle so that it has potential for long life operation and at the same time reducing maximum excess reactivity during reactor operation^{1,2,4)}. Reducing maximum excess reactivity during burnup may reduce the risk of severe accident such as in the case of Chernobyl accident.

In the long-life operation for modular reactors it is usually related to smaller average power density and higher natural circulation component during their operation. Therefore it can help avoiding severe accident due to decay heat removal failure during station blackout accident such as in the case of Fukushima nuclear accident.

2. Calculation Method

In this study multi groups diffusion calculation is performed using CITATION code FI-ITB CH1 code, while burn-up calculations are performed inside the fuel cell using PIJ modules in SRAC code system⁵⁾.

BWR design general specification in this study adopted from standard specification of BWR-6 as seen on Table 1.

Table 1. General specification of Reactor Design

Parameters	Specifications
Power (thermal)	100 MW – 600 MW
Refuelling period	over 29 years
Core geometry	Cylinder Balance
Core characteristic	Small-long life core
Fuel	Th-U oxide Th-Pa-U oxide
Cladding	Zircalloy (Zr)
Coolant	Light water (H ₂ O)
Smear density	90% T.D.
Fuel density	11.6 g/cm ³
Average density of H ₂ O	0.76 g/cm ³
Average density of H ₂ O vapour	0.0377 g/cm ³
Void composition	0 – 40%
Operational pressure	71.94 bar
Pin cell type	Square cell
Pin pitch	1.62 cm

Each neutron has different energy level, i.e. about 10 MeV to 10⁻⁵ eV. In this study, energy spectrum is divided into 5 energy groups such we can see on Table 2. Fast energy group is divided into 3 groups, while thermal energy region is divided into two energy groups. BWR used in this study is thermal

Table 4. General Specification of BWR Core Design

Parameters	Specifications
Power (thermal)	90 MW – 720 MWyr
Refuelling period	25 – 30 years
Fuel	Th-Pa-U oxide
Shielding material	Zircalloy (Zr)
Coolant	Light water (H ₂ O)
U-232 percentage	8.1% - 11%
Pa-231 percentage	6.7% - 12.5%
Fuel volume, cladding, and moderator fraction	60% - 20% - 20%
Moderation void range	0 – 40%
Power density	17.6 – 44 Watt/cc
Pin pitch	1.62 cm
Core geometry	Cylinder Balance
Cell geometry	Square cell

One mesh has 6.48 cm of size, inner fuel zones have 90.72 cm of radii, and outer fuel thickness 58.32 cm. Vertical zone about 15 mesh (97.2 cm) was zone with 0% void (water without bubbles), 3 mesh (19.44 cm) was zone with 5% void. Immediately with void interval 5% to 40%, 3 mesh (19.44 cm), respectively. Thickness of reflector was 30 cm for radial and axial directions.

The differences of U-233 enrichment between inner fuel and outer fuel employed due to power density for each region on radial direction relatively are the same so that power peaking from reactor could be reduced. Meanwhile, the enrichment on axial direction was not distinguished due to reactor safety still preserved though blockage on coolant flow occurred. Consequently, power distribution on axial direction will not flat.

Void was an important factor that gives an effect to k-eff values. Figure 2 showed up the effect of void to k-eff values. In this reactor design, we assumed that axial direction void composition in the core on 0 – 40% of range, both the range and the number of void composition was time-independent; this assumption was taken to simplify analysis.

Figure 2 showed up that this void parameter has strong effect on the fuel neutronics characteristics. This void effect looked bigger on the beginning of fuel operation (BOL) and smaller on the end of fuel burn-up period (EOL). The higher void fraction provides the smaller k-eff values on the BOL.

Optimized results of reactor core could be seen in Table 5. It is shown that U233 enrichment about eight and eleven percents are used in the inner and outer core regions. And high fuel volume fraction of 60% is used to improve criticality due to smaller size of the core than the conventional BWR cores. Much smaller coolant volume fraction of 20% than that of the conventional BWR is used due to smaller power density and to improve conversion ratio.

Figure 3. k-eff versus time graphic of 8.1% Th-U-O₂ and 6.7% ²³¹Pa

Table 5. Design specifications of BWR core

Parameters	Specifications
Power (thermal)	620 MWyr
Refuelling period	30 years
Fuel	Th-Pa-U oxide
Shielding material	Zircalloy (Zr)
Coolant	Light water (H ₂ O)
U-233 percentage	8.1% and 11%
Pa-231 percentage	6.7% and 12.5%
Fuel volume, cladding, and moderator fraction	60% - 20% - 20%
Moderation void range	0 – 40%
Reactivity excess	0.384%
Power density	17.6 – 44 Watt/cc
Active volume (litres)	17,635.8

Table 6. General design parameter for system using Gadolinium

Parameter	Value
Fuel volume fraction	60%
Coolant volume fraction(H ₂ O)	20%
Cladding volume fraction(Zircaloy)	20%
Axial void fraction	0 – 40%
Fuel type	(ThU)O ₂ dan ThN
Pitch	1,62 cm
Fuel to Fuel Distance	1 mm
Linear Power Level	40 watt/cm
Average Power Density	18 watt/cc
Cell	

Figure 4 show infinite multiplication change during burn-up of nitride fuels for various gadolinium addition with 8% U-233 enrichments. In general the addition of gadolinium reduce overall excess

reactivity during burn-up but also reduce the reactivity swing. Figure 5 shows the effect of void fraction in the k_{inf} change during burnup for 8%U233 and 10% Gd 157 nitride fuels. It is shown that the higher the void fraction the higher the k_{inf} values during burn-up. It is shown that the gadolinium absorption has strong effect and for higher void fraction the spectrum is shifted to the epithermal region and the effective cross section of Gd-157 is reduced.

Figure 4. Infinite multiplication factor changes for various gadolinium addition for the nitride fuel with 8% U233

Figure 5. The effect of void fraction to the infinite multiplication change during burnup for the nitride fuel based system with 8%U233 and 10% Gd-157

Finally Table 7 shows optimal design using U^{233} -Th-Gd nitride fuel system based long life BWR. It is shown that 12 years life time without refuelling can be reached with maximum excess reactivity of about 0.4%dk/k can be reached.

Table 7. Optimized Design specifications of BWR core with U233-Th232-Gd157 fuel

Parameter	Value
Power	620 MWth
Refueling interval	12 tahun
Shielding material	Zircalloy
Coolant	Light water (H2O)
Fuel	Th-Gd-U nitride
U-233 enrichment	8% dan 9%
Gd-157 percentage	7% dan 10%
Fuel, cladding and coolant volume fraction	60 %-20%-20%
Void fraction range	0 – 40%
Maximum excess reactivity (% dk/k)	0,384%
Power Density	34,2 watt/cc
Active volume (litter)	17.635,8

4. Conclusions

Design study of long life(cycle) Boiling Water Reactor which can be operated for 20-30 years of operation time without the necessity of refuelling during that period has been performed. To achieve 20 years operational life time, addition Protactinium-231 which has huge capture cross section as Burnable Poisons can decrease maximum reactivity excess of the reactor core to 0.56% dk/k and increase operational life time of reactor core to 25 – 30 years.

Core with 17,635.8 litter volume which has 620 MW of power, operational time 30, and maximum reactivity excess of 0.384% dk/k, could be reached

using the 8.1 – 11% U-233 compositions and adding the 6.16 – 11.13% Pa-231 as fuel.

Meanwhile, core with 5,193.034 litter volume which has 182 MW of power, operational time 28, and maximum reactivity excess of 0.56% dk/k, could be reached using the 10 – 13% composition of U-233 and adding the 9.36 – 16.01% composition of Pa-231 as fuel.

The use of gadolinium can also reduce maximum excess reactivity during burnup and the calculation results show that 12 years life time core without refuelling can be achieved with maximum excess reactivity of about 0.4% dk/k.

References

1. T. Imamura *et al.*, Preliminary of ^{231}Pa for Gas Cooled Long-Life Core, *Ann. Nucl. Energy*, **39**, 226, 2000.
2. E. S. Riyana and Z. Su'ud, Preliminary Design Study of Thorium Cycle Based Tight Lattice Long Life BWR, COE-INES Indonesia International Symposium, 2005.
3. K. Takase *et al.*, Behaviour in an Advanced Light-Water Reactor Core, JAERI, Japan, 2004
4. IAEA-TECDOC-1450, Thorium Fuel Cycle – Potential Benefits and Challenges, 2005
5. K. Okumura, T. Kugo, K. Kaneko, and KK. Tsuchihashi, SRAC (Ver. 2002); The Comprehensive Neutronics Calculation Code System, Department of Nuclear Energy System, Japan Atomic Energy Research Institute (JAERI), 2002.