Study on SMART Reactor Design Using ThO\textsubscript{2}-UO\textsubscript{2} Fuel

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Abstract. There are two heterogenous core design options for thorium based fuel cycle in PWRs. One of them is Whole Assembly Seed and Blanket (WASB) design. In WASB design, seed units and blanket units separately occupy one full-size PWR assembly each, and the assemblies are arranged in the core in a modified checkerboard array. In this study, the seed units was loaded with UO\textsubscript{2} fuel rods and the blanket units was loaded with ThO\textsubscript{2}-UO\textsubscript{2}. The configuration for each assemblies in both seed and blanket units were based on 17x17 KOFA (Korean Standard Fuel Assembly). Neutronics calculation was performed by using PIJ and CITATION modules of SRAC 2006 code with JENDL 3.3 as nuclear data library. The calculation showed that for the same fuel material configuration in each asssem bly uints the WASB-I core loading pattern produce a better power distribution than WASB-II core loading pattern. The criticality condition for both core loading patterns can be achieved by loading 4.95 wt.% of enriched-U in seed fuel assemblies while blanket fuel assemblies were loaded by 20 % UO\textsubscript{2} (15 wt.% of enriched-U ) and 80% ThO\textsubscript{2}.

1. Introduction
One of the main issues that concerns the world is the increasing need of energy. Some studies predict that by 2020 the energy consumption worldwide will be about 48% higher than in 2011 [1]. Population growth has always been and will remain one of the key drivers of energy demand, along with economic and social development. The challenges of energy consumption growth make nuclear power a prominent major energy source for the next several decades according to the projections made by the International Atomic Energy Agency (IAEA). The IAEA predicts two scenarios concerning the growth of nuclear power, a low and a high. The low projection assumes that all nuclear capacity which is currently under construction or firmly in the development pipeline, gets completed and attached to the grid, but no other capacity is added. It states that, there would be growth in capacity from 370 GWe at the end of 2006 to 447 GWe by 2030. This means a growth in the nuclear capacity of 20.8% [2].

On the other hand the growth in the nuclear consumption also arises some questions about the viability to accomplish the expectations with the current fuel reserves, to respect the non-proliferation treaty, to reduce the radiotoxicity of the waste and to maintain and enhance the safe and reliable operation. One of the solutions to face these issues is the use of thorium as a fuel.

Korea Atomic Energy Research Institute (KAERI) has been developing a small-sized integral reactor called SMART (System integrated Modular Advanced ReacTor) for a dual purpose: seawater desalination and electricity generation [3,4]. SMART has been developed as a small-sized integral
reactor, hence most of its major components is housed within the reactor vessel. Major components including 4 main coolant pumps, 12 steam generator cassettes, a self-pressurizer as well as active core are placed in a single reactor vessel as shown in Fig.1.

**Figure 1. Vertical cross section of SMART reactor vessel [5]**

SMART’s core consists of 57 FAs with a 17 x 17 fuel rod array. The fuel assembly is based on the design of KOFA (Korean Standard Fuel Assembly) that was designed by KAERI/Siemens-KWU [6]. In this study, the SMART’s core configuration was developed based on Whole Assembly Seed and Blanket Concept. The nuclear calculation for this core configuration was performed by using CITATION and JENDL3.3 as its nuclear data library.

2. Nuclear Core Design
The goal of this study is the search for an advanced heterogenous core design for thorium based fuel cycle in SMART reactor. There are two major heterogenous PWR core design: 1) the Seed-Blanket Unit (SBU)/Radkowsky Thorium Fuel (RTF) which employs a seed-blanket unit that is a one-for-one replacement for a conventional PWR fuel assembly; and 2) the whole assembly seed and blanket (WASB) where the seed units and blanket units separately occupy one full-size PWR assembly each, and the assemblies are arranged in the core in a modified checkerboard array [7].

In this study, the SMART’s core design was developed based on WASB concept. The WASB concept was developed as an answer to the drawback from SBU concept[8]. In SBU concept, the fuel assembly has two different regions which makes design, fabrication and refuelling process more complex. Therefore, the WASB concept was developed to simplify refuelling and manufacture process because the core is loaded with separate seed and blanket fuel assembly.

The fuel assembly for the seed units was loaded with UO$_2$ fuel rods and the blanket units was loaded with ThO$_2$-UO$_2$. Other than normal fuel rods, each FAs also consist of shim rods as its burnable absorber rods. Burnable absorber material in shim rods are B$_4$C in Al$_2$O$_3$.

**Figure 2. SMART core loading pattern based on WASB concept a) WASB-1, b) WASB-II**
In Fig. 2, SMART core loading pattern based on WASB concept is presented. The WASB core loading pattern is based on the general rule that more energy is extracted from the fuel if the ratio of peak-to-average power in the core is as low as possible [7]. In this study we designed two different core loading pattern with 1:2 seed and blanket units ratio. This arrangements were made to analyzed the effect of seed-blanket units ratio and their location in core performance.

### Table 1. SMART major parameters

| Parameter               | Value           |
|-------------------------|-----------------|
| Thermal Output          | 330 MWt         |
| Electric Output         | 100 Mwe         |
| Refueling Cycle         | 3 years         |
| Active Length           | 200 cm          |
| Cladding Material       | Zircaloy-4      |
| Cladding Thickness      | 0.57 mm         |
| Pellet Diameter         | 8.05±0.01 mm    |
| Pin Pitch               | 1.26 cm         |
| Fuel rod to fuel rod    | 21.10 x 21.10   |

3. Results and Discussion

The neutronic behaviour of the two core design was studied on different fuel optimization. As seen from Table 2, there were seven different fuel optimization. The seed unit were loaded with UO₂ fuel with 4.95 wt% enrichment, while the blanket unit were loaded with ThO₂-UO₂ with different fuel fraction and UO₂ enrichment that varied from 10 wt% to 15wt%.

### Table 2. Fuel material composition for seed and blanket units

| Fuel material composition | Seed | Blanket |
|---------------------------|------|---------|
| I                         | 80% ThO₂ + 20% UO₂ (10 wt%) |         |
| II                        | 80% ThO₂ + 20% UO₂ (12 wt%) |         |
| III                       | 80% ThO₂ + 20% UO₂ (13 wt%) |         |
| IV (UO₂ (4.95 wt%))       | 80% ThO₂ + 20% UO₂ (15 wt%) |         |
| V                         | 75% ThO₂ + 25% UO₂ (10 wt%) |         |
| VI                        | 75% ThO₂ + 25% UO₂ (12 wt%) |         |
| VII                       | 75% ThO₂ + 25% UO₂ (15 wt%) |         |

The multiplication factor of WASB-II core design is smaller than in WASB-I for the same fuel material configuration. For example when blanket units were loaded with 80% of ThO₂-UO₂ and 20% UO₂ (10 wt% of U-235) and seed units were loaded with 4.95 wt% UO₂, the k-eff of WASB-I core was 1.078875 but the k-eff of WASB-II was 1.073251.
Figure 3. Effective multiplication factors ($k_{\text{eff}}$) of WASB-I core design

Fig. 5, 6, 7 and 8 show the power distribution at the beginning of life in X and Y direction for each core design. For WASB-I core loading pattern, the fuel material composition that gave us the lowest peak-to-average power distribution was the 7th optimization. The seed units were loaded with UO$_2$ fuel rods (4.95 wt% of U-235), while the blanket units were loaded with 75% ThO$_2$ and 25% UO$_2$ (15 wt% of U-235). In WASB-II core loading pattern the fuel material composition that gave us the lowest peak-to-average power distribution was when the blanket units were loaded with 75% ThO$_2$ and 25% UO$_2$ (12 wt% of U-235). Therefore if we compare the power distribution in these two core loading pattern, the WASB-I core loading pattern gave us the better power distribution with smaller peak-to-average power distribution than in WASB-II core loading pattern.

Figure 5. Power distribution in X direction at BOL (Beginning of Life) in WASB-I core design

Figure 6. Power distribution in X direction at BOL (Beginning of Life) in WASB-II core design
4. Conclusion
The study of SMART core design using ThO$_2$-UO$_2$ fuel with Whole Assembly Seed and Blanket (WASB) concept are presented. We develop two SMART core loading patterns based on WASB concept with the same seed-blanket units ratio but different configuration. For the same fuel material compositions, the multiplication factor of WASB-II core design was smaller than WASB-I. In WASB-I core loading pattern, the fuel material composition that gave us the lowest peak-to-average power distribution was when the seed units were loaded with UO$_2$ fuel rods with 4.95 wt.% of enriched-U, while the blanket units were loaded with 75% ThO$_2$ and 25% UO$_2$ (with 15 wt% of enriched-U). But in WASB-II core loading pattern, the fuel material composition that gave us the lowest peak-to-average power distribution was when the blanket units were loaded with 75% ThO$_2$ and 25% UO$_2$ (12 wt% of enriched-U). Therefore if we compare the power distribution in these two core loading pattern, the WASB-I core loading pattern gave us the better power distribution with smaller peak-to-average power distribution than in WASB-II core loading pattern.

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