NEUTRONIC STUDY OF AN INNOVATIVE BWR THORIUM-URANIUM FUEL

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ABSTRACT

This paper presents the neutronic design of an innovative fuel design proposed to be used in a Boiling Water Reactor (BWR). The study was carried out assuming different infinite lattice configurations calculated with HELIOS. The idea behind the lattice design is to use as much as possible the thorium conversion capability in a BWR spectrum, taking advantage of the U-233 build-up in a once-through cycle. Other of the main goals is to reduce the production of long-live actinides and of course to improve the fuel cycle economy searching to reduce de U-235 enrichment. The blanket-seed concept was used, and a triangular pitch lattice was designed including the blanket sub-lattice (ThO_2 rods) and the seed sub-lattice (U/Zr rods) in a heterogeneous arrangement. The blanket sub-lattice is first loaded in the core (one cycle) to produce its own fissile fuel. At this step a dummy zircaloy rod instead of the seed rod occupies the center of the triangular lattice. At the next cycle the blanket sub-lattice will be assembled with the fresh seed sub-lattice to form the blanket-seed lattice. A fuel lattice was designed with a U-235 enrichment of 5.5% in the seed rods, which produces a reactivity performance similar to typical UO_2 and MOX fuel used in BWR's. Regarding the reactivity void coefficient, the proposed blanket-seed lattice shows a negative value: -240 pcm at BOL and –54 pcm at 60,000 MWd/T.

1. INTRODUCTION

The use of thorium as a nuclear material in light and heavy water reactors has taken a new interest because of the potential advantages that can be obtained from this fuel cycle [1,2,3]. For instance, it can be first mentioned that the thorium cycle is an easy way to improve the fuel conversion in a once-through cycle in the thermal reactors. Second, the thorium cycle tend to reduce the proliferation of spent fuel, it is much more favorable in plutonium contents, decay heat amount and radioactivity level from spent fuels. Third, the thorium cycle improves the long-lived minor actinides production compared with the uranium and plutonium cycle; the radiotoxicity level of spent fuel is less in thorium cycle than the others, in case of once-through cycle application for LWR.

Nowadays three main research areas related with the thorium fuel cycle are in progress in different universities or laboratories around the world. The accelerator driven systems (ADS) in which the thorium breeding capability is achieved by the neutrons obtained by the spallation reaction from the particles obtained from the accelerator. The breeder reactors in which the burned fuel is reprocessed in order to recover the U-233 produced from the Th-232 conversion. The third research area deals with actual nuclear reactors, mainly PWR, BWR and CANDU, in which innovative thorium-uranium and thorium-plutonium fuel designs are in development trying to improve the fuel cycle performance, safety and economy.

We are interested in the third area and as part of a project to investigate energy systems based on the thorium fuel cycle, an innovative thorium-uranium fuel is been under investigation to be used in a BWR-type core (actual BWR, ABWR or SBWR). A lattice was designed to take advantage of the thorium conversion capability in a BWR spectrum, taking advantage of the U-233 build-up in a once-through cycle. Other of our main goals is to reduce the production of long-live actinides and to improve the fuel cycle economy searching to reduce de U-235 enrichment.

The study presented in this paper, was carried out with the HELIOS code [4]. This code was previously validated for thorium applications in LWR's [5] against a benchmark problem. The benchmark is based on a thorium fuel cell moderated with light water, proposed by X. Zhao, et al [6]. The burn-up depending eigenvalue and isotopes concentrations were successfully compared with those obtained with state-of-the-art codes as MOCUP and CASMO4.

2. METHODOLOGY

The proposed lattice design use the blanket-seed concept [7,8] in a triangular lattice pitch, which includes the blanket and the seed rods (figure 1) in a heterogeneous loading fashion. The blanket rods has only thorium in the form of ThO_2 and the seed rods contain metal fuel in the form of uranium-zirconium alloy (U/Zr), as it is proposed in reference 7 and 8. The so defined triangular blanket-seed lattice is composed by the blanket sub-lattice and the seed sub-lattice. The fresh blanket sub-lattice will be first loaded in the core (one cycle) to produce its own fissile fuel (mainly U-233). At this step a dummy zircaloy rod instead of the seed rod occupies the center of the triangular lattice. At the next cycle the blanket sub-lattice will be assembled with the fresh seed sub-lattice to form the blanket-seed lattice (the zircaloy sub-lattice is retired at this time). The advantage to have the blanket-seed rods in the same fuel assembly is to reduce the power mismatch between blanket assemblies and seed assemblies presented in other designs. A mismatch between blanket and seed rods is expected to occur in the lattice, nevertheless we can take advantage of the higher thermal conductivity of the U/Zr seed rods (0.18 W/cm-ºC [9]) compare with the ThO_2 blanket rods (0.04 W/cm-ºK [10]) to produce more power in the seed rods. A neutronic – thermalhydraulic analysis must be done to determine the coolant flow and the fuel temperature in the proposed lattice.

The design process was carried out in different steps. In the first step, the pitch was selected in the triangular blanket-seed lattice. In the second step, the blanket composition was determined in order to improve the U-233 build-up from Th-232 conversion. In the third step the diameter of the dummy zircaloy rod was found that improve the conversion capability of the blanket sub-lattice by changing the dummy rod diameter (the pitch was fixed from step one). In the fourth step, the uranium to zirconium ratio and the U-235 enrichment in the U/Zr seed rods were determined in order to have the "better" neutronic performance, K_{inf} vs burn-up and void reactivity coefficient for a typical BWR.

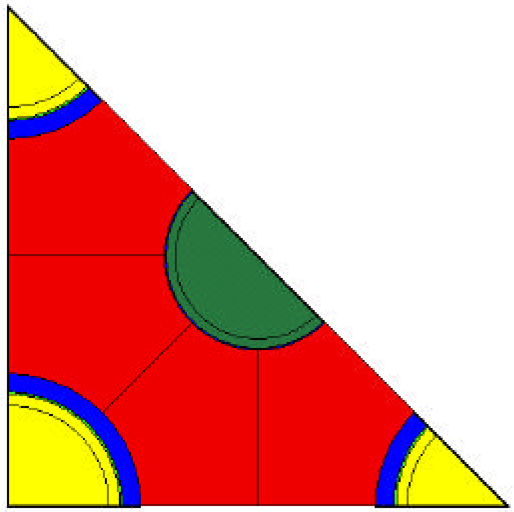

Figure 1. Blanket (yellow edge rods) – seed (central green rod) lattice.
Helios representation, reflective boundary condition (Orion view).

3. RESULTS

3.1 PITCH SELECTION IN THE BLANKET-SEED LATTICE

In this step, several calculations were done with different pitch sizes. The pitch in the blanket-seed lattice is defined as the distance between blanket rods (center to center). The dimensions of a standard BWR assembly must be taken into account in the final pitch selection, since a regular array of blanket-seed cells must be fixed in the assembly. Figure 2 shows the k-infinite values obtained for different pitch sizes and for different void percentage.

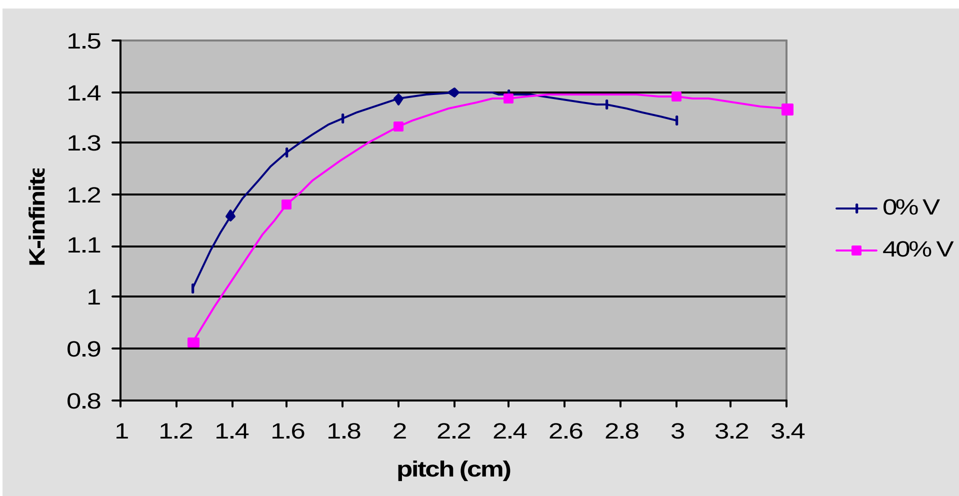

Figure 2. Pitch sensitivity calculations.

Taking into account the results of figure 2 and the criteria of the BWR assembly dimensions, a pitch of 1.91 cm was selected, which allows to accommodate a 7x7 array of blanket rods and a 6x6 embedded array of seed rods (see figure 3). On the other hand the selected pitch is in the under-moderated region of the k-infinite vs pitch curve ensuring a safe behavior of the moderator reactivity coefficient.

3.2 BLANKET SELECTION

One of the goals of the blanket-seed design presented in this work is to improve the U-233 production of the blanket sub-lattice, which will be loaded in the core (in the periphery when they are fresh) during one operating cycle. Therefore we tried to find the better blanket composition that will improve the conversion. Figure 4 shows the main fissile isotopes evolution in the blanket sub-lattice. Three different cases are presented: U233_Unat represents a blanket with 90% ThO_2 and 10% natural uranium. U233_10%U25 is a blanket with 90% ThO_2 and 10% uranium enriched at 10% in U-235 and U233_ThO2 is the blanket with 100% ThO_2. It can be seen how the last case has the higher rate conversion of Th-232 to U-233 and reduce the plutonium production. Therefore this last blanket composition was chosen.

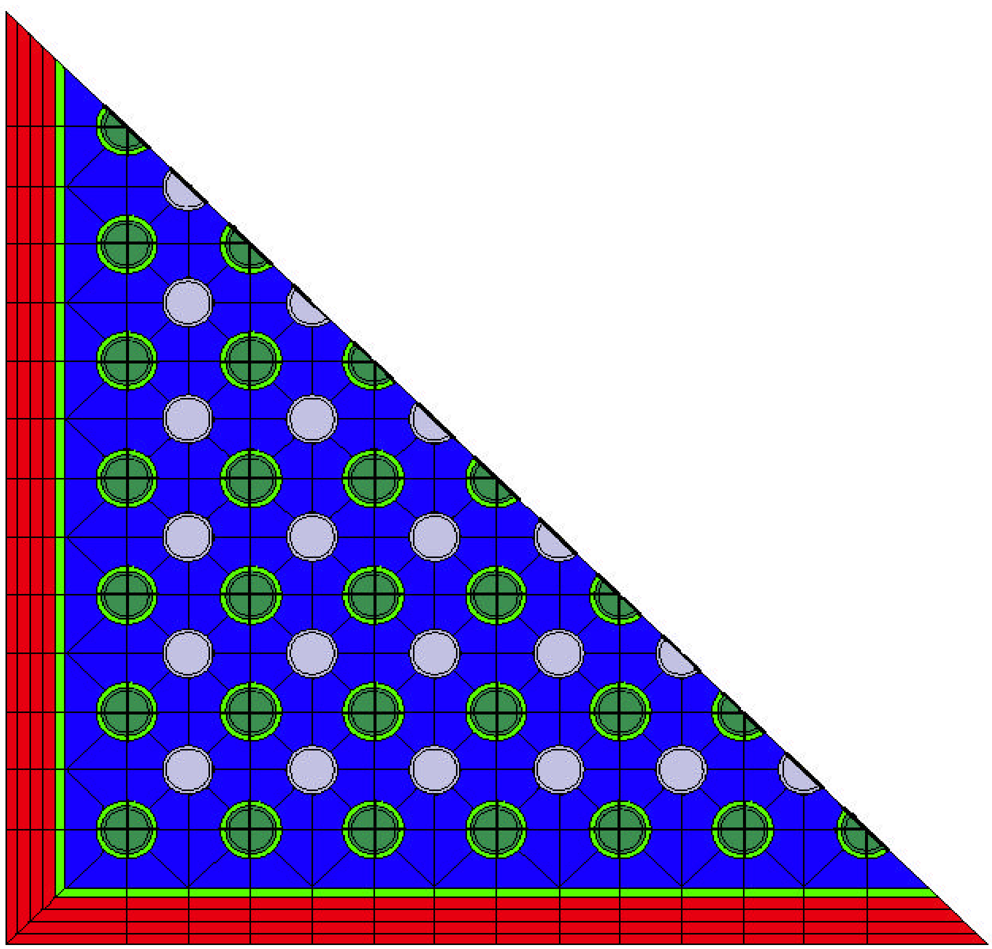

Figure 3. Blanket-seed lattice (diagonal symmetry).

3.3 DUMMY ROD DIAMETER SELECTION.

At this step, a sensitivity study was performed changing the dimension of the zircaloy dummy rod. Figure 5 shows that the U-233 build-up is almost the same for different dummy rod radius, therefore the final dummy rod dimension is chosen as the same as the seed rod, in order to avoid mechanical troubles when the dummy rods will be changed by the seed rods. It can be concluded that the zircaloy rods does not help to change the neutron spectra when the moderator to fuel volume is changed. Another material, more transparent to neutrons, could be better to increase the U-233 build-up at this step.

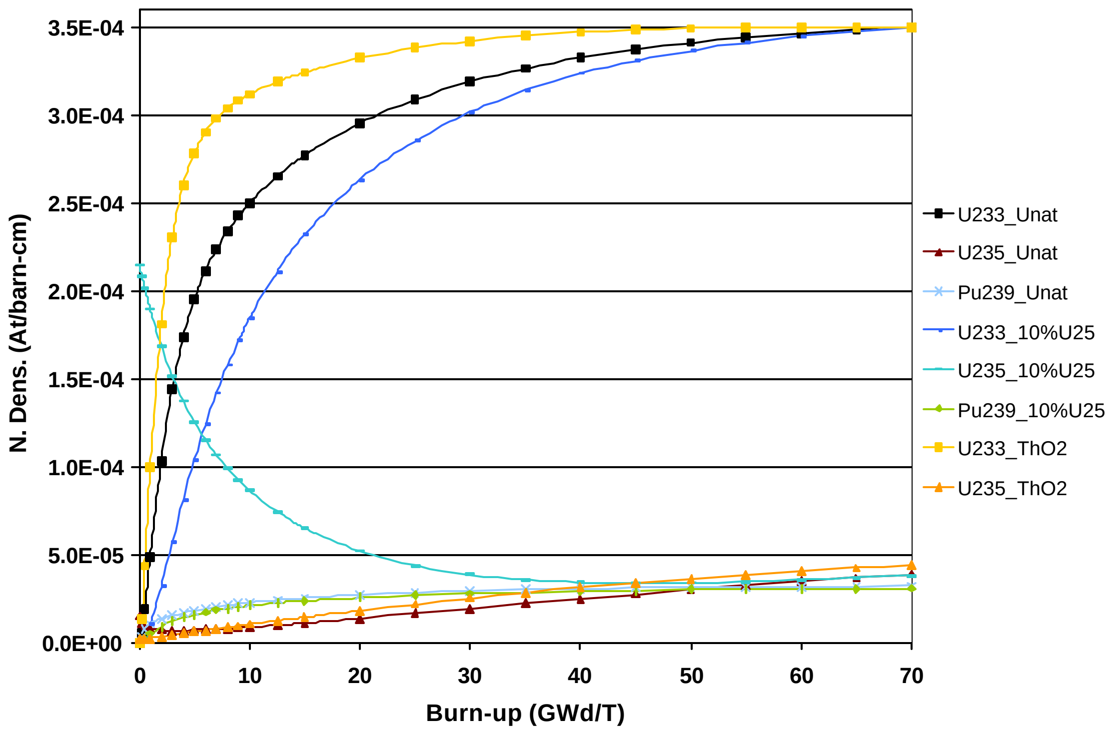

Figure 4. Main fissile isotopes evolution in the blanket sub-lattice

3.4 BLANKET-SEED LATTICE RESULTS.

At this step, the blanket-seed lattice was defined from the neutronic point of view. The selected U/Zr alloy is composed by 80% uranium and 20% zirconium. This proportion provides a high alloy density (16.5 g/cc), which permits a reduction in the seed U-235 enrichment and a small rod diameter (0.8 cm). This seed rod diameter gives a good reactivity performance, as can be seen in figure 6. Rods with higher dimension could provide better reactivity performance; nevertheless they would have a higher power production that could produce thermal limits problems. The final seed rod dimensions will be fixed with the thermal-hydraulic calculations.

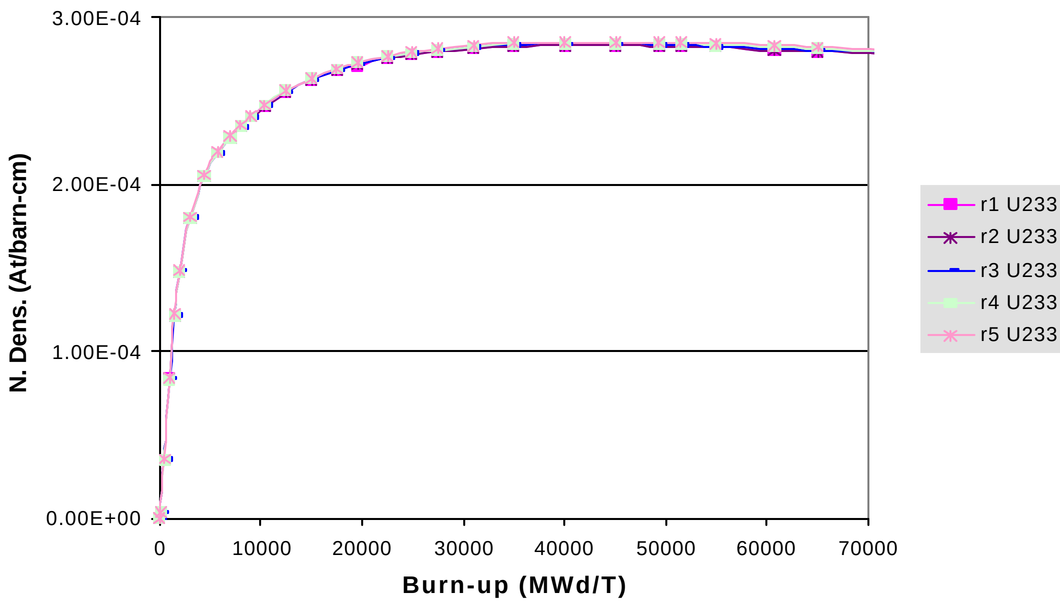

Figure 5. U-233 build-up for different dummy rod dimensions.
(r1=0.33cm, r2=0.4cm, r3=0.45cm, r4=0.5cm, r5=0.55cm)

The reactivity performance of the blanket-seed lattice is shown in figure 7, where the k-infinite vs burn-up is shown at hot full power conditions and 40% voids, for the following equivalent BWR lattice types:

- Lat3 = triangular blanket-seed lattice where the blanket is first burned one cycle and the seed is loaded afterwards. The seed U-235 enrichment is 5.5%. The blanket sub-lattice was burned up to 9,000 MWd/T before being assembled with the fresh seed sub-lattice.
- Lat4 = triangular blanket-seed lattice where the blanket and the seed are both loaded fresh together since beginning of life. The seed U-235 enrichment is 5.5%.
- UO2_3.37 = regular rectangular lattice of uranium oxide fuel. The U-235 enrichment is 3.37 %.
- MOX_3.93 = regular rectangular lattice of a mixed oxide fuel of plutonium and uranium. The Pu fissile enrichment is 3.93 %.

As can be seen in figure 7, the proposed design (Lat3) has a good reactivity performance with a relative low U-235 enrichment (5.5%), even more if we take into account that the seed represents only 42% of the lattice volume. The Lat4 case does not reaches the required reactivity.

Regarding the reactivity void coefficient, the proposed blanket-seed lattice has always a negative value: -240 pcm at BOL and –54 pcm at 60,000 MWd/T.

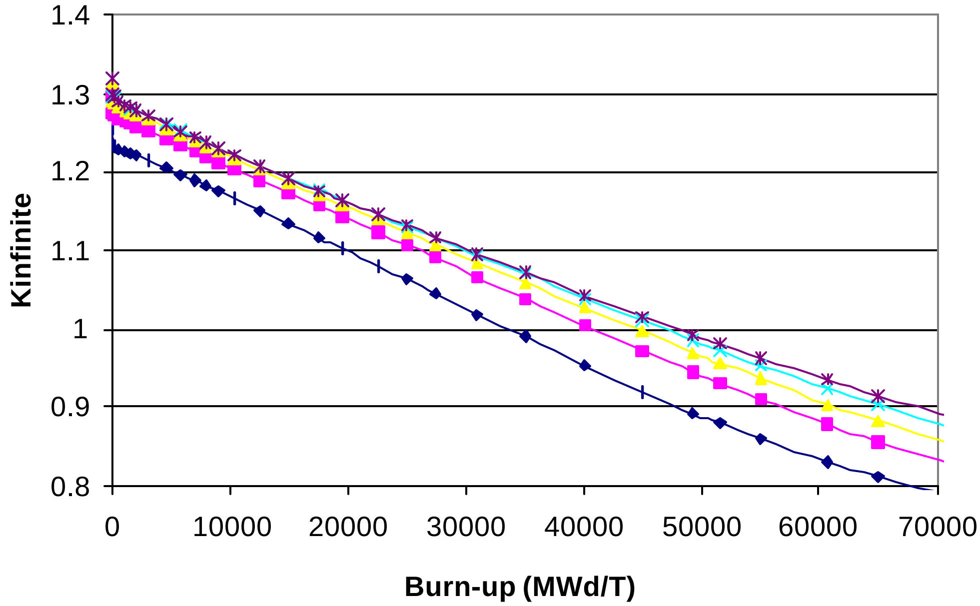

Figure 6. K-infinite vs burn-up for different seed rod dimensions.
(r1=0.33cm, r2=0.4cm, r3=0.45cm, r4=0.5cm, r5=0.55cm)

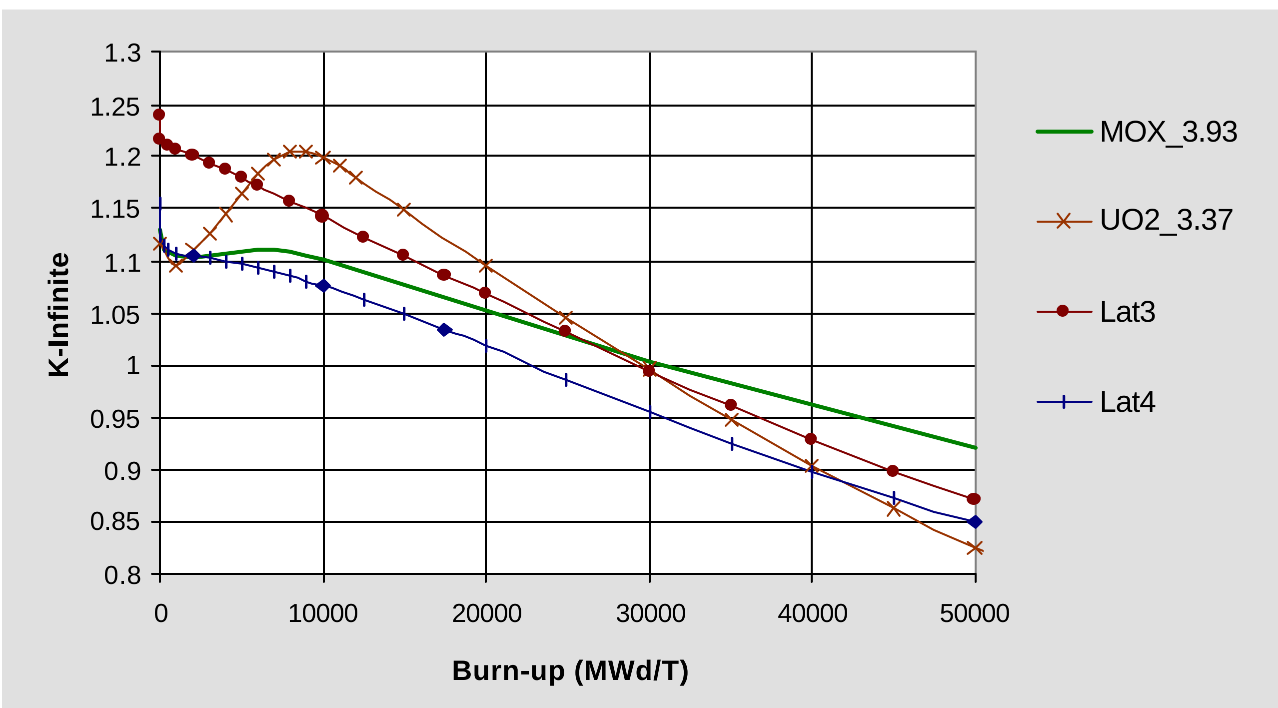

Figure 7. Blanket-seed lattice reactivity performance.

CONCLUSIONS

A blanket-seed thorium-uranium lattice for a BWR-type core was designed. The neutronic performance is very promising at this level. Several criteria and parameters must be taken into account during the design process, nevertheless the good reactivity performance obtained with a relative small U-235 enrichment in the seed rods, is a good signal for the utilization of this type of fuel cycle in current and future BWR cores. The feedback between the neutronic and the thermal-hydraulic calculations are now very important in order to optimize the moderator to fuel volume ratio and the seed rods diameter. This will permit to evaluate the coolant flow rate and the power distribution in the core.

Further work is in progress in order to design a BWR core loaded with the thorium-uranium fuel assembly designed in this work and evaluate the neutronic, thermal-hydraulic and economic performance.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the Mexican Science and Technology National Council (CONACyT) under agreement No. 34657-U, and was partly supported by the National University of Mexico (PAPIIT-UNAM) under project No. IN109400. One of the authors (A. N-C.) would like to thank the Nuclear Safety and Safeguards National Commission (Comisión Nacional de Seguridad Nuclear y Salvaguardias) for the support to perform this work.

REFERENCES

1. X. Zhao, M. J. Driscoll, M. S. Kazimi, P. Hejzlar, "An Innovative ThO2-UO2 Fuel for LWRs", *Trans. Am. Nucl. Soc*., Milwaukee, USA, June 17-21, 2001, **84**, 235-236 (2001).
2. T. K. Kim, T. J. Downar, "Thorium Fuel in Tight Pitch LWR Lattices", *Trans. Am. Nucl. Soc*., Milwaukee, USA, June 17-21, 2001, **84**, 236-238 (2001).
3. E. P. Lowen, K. D. Weaver, J. K. Hohorst, "Reactivity, Isotopics, and Thermal Steady-State Analysis of Homogeneous Thoria-Urania Fuels", *Nuclear Technology*, **137**, 97-110 (2002).
4. HELIOS Methods, *Studsvik Scandpower*, (1998).
5. J.L. François, A. Núñez-Carrera, "Validation of HELIOS Code with a PWR Thorium Pin Cell Burnup Benchmark", *Trans. Am. Nucl. Soc*., Hollywood, Fl, USA, June 7-13, 2002, **86,** (accepted for publication).
6. X. Zhao, E. E. Pilat, K.D. Weaver, P. Hejzlar, "A PWR Thorium Cell Burnup Benchmark". *Proceedings of the ANS Reactor Physics, Mathematics and Computation and Nuclear Criticality Safety, PHYSOR 2000 Topical Meeting*, Pittsburgh, USA, May 7-12, Proceedings on CD, (2000).
7. A. Galperin, P. Reichert, A. Radkowsky, "Thorium Fuel Cycle for Light Water Reactor - Reducing Proliferation Potential of Nuclear Power Fuel Cycle," *Science & Global Security*, (1997).
8. M-H. Kim, Il-T. Woo, "Once-Through Thorium Fuel Cycle Options for the Advanced PWR Core", *Proceedings of the ANS Reactor Physics, Mathematics and Computation*

and Nuclear Criticality Safety, *PHYSOR 2000 Topical Meeting*, Pittsburgh, USA, May 7-12, Proceedings on CD, (2000).
9. H. Etherington, *Nuclear Engineering Handbook*, *Mc. Graw Hill Book Company*, (1958).
10. J. Shackelford, W. Alexander, *The CRC Material Science and Engineering Handbook*, CRC Press, (1992).