FEASIBILITY OF LONG-LIFE LWR CORES USING Th-BEARING FUEL IN TIGHT LATTICES

H. Matsumoto, E. Greenspan and J. Vujic
Department of Nuclear Engineering
University of California
Berkeley, CA 94720-1730
gehud@nuc.berkeley.edu, vujic@nuc.berkeley.edu

ABSTRACT

This work investigates the feasibility of designing a long-life (8-year) PWR core of homogeneous composition to have a small BOL excess reactivity along with negative void coefficient using thorium as the fertile fuel. It was found that the HM-to-water ratio has to be at least 50% higher than that considered practical to get a critical core having a nearly zero burnup reactivity swing. In order to achieve a negative void coefficient using a uniform core with p/d ratio smaller than 1.2, the complete removal of hydrogen from the core needs to be avoided. With p/d > 1.2, it is possible to achieve a negative void coefficient, but the attainable core life is not longer than 3 years.

1. INTRODUCTION

One of the design goals of the IRIS (International Reactor Innovative and Secure) [1] is to have a single batch long life core. The initially set target for the core life was 8 years. One way to achieve a long-life core is to design it to have a high conversion ratio so that k_{eff} will not vary much with burnup. In order to make the reactivity swing small and enhance core life, the core spectrum must be hard so that the η value of the fissile fuel will become large and so will become the conversion ratio. On the other hand, it is known that it is difficult to make the void coefficient negative in hard spectrum cores. A previous UCB study [2] concluded that it is difficult to realize both flat k_{eff} and negative void coefficient for tight lattice IRIS cores using Pu-U fuel.

The reactivity of a PWR core changes with voiding of the coolant due to the following phenomena: (1) Decrease of neutron loss to absorption in the coolant. (2) Increase in the fission probability of fertile material due to spectrum hardening. (3) Increase in the η value of fissile materials due to spectrum hardening, and (4) Enhanced neutron leakage due to coolant voiding. Among these mechanisms, (1 - 3) contribute to making the void coefficient positive, whereas (4) contributes to making it negative.

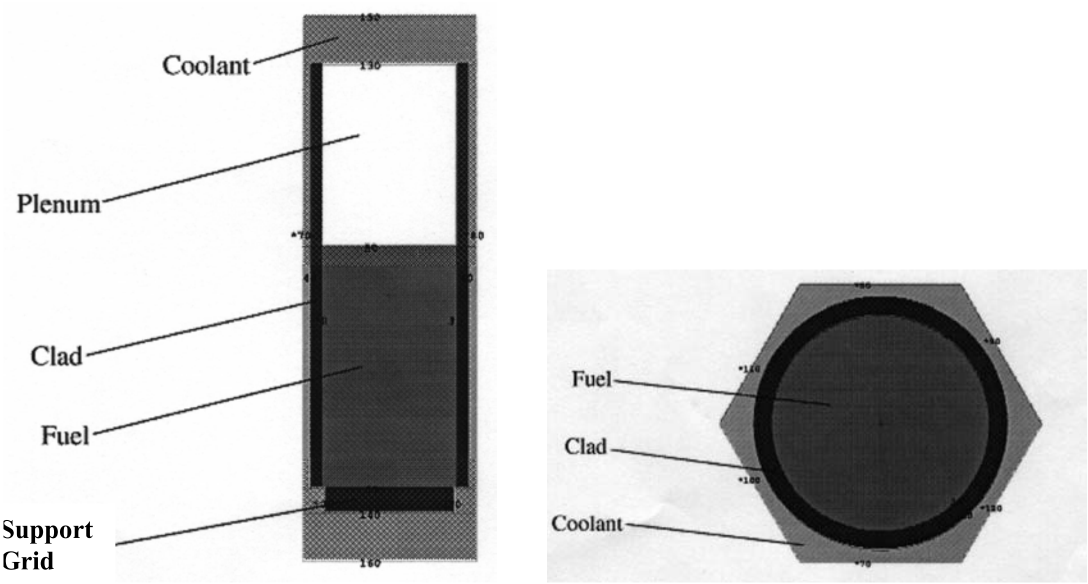
The purpose of the present work is to investigate the feasibility of achieving the stated goal of long life cores for IRIS using ^{232}Th instead of ^{238}U as the fertile fuel. Use of ^{232}Th instead of ^{238}U is expected to make the void coefficient less positive and, hopefully, negative due to a couple of reasons: (a) The threshold energy for ^{232}Th fission is higher and the fission cross-section is smaller than that of ^{238}U. (b) The increase in the η value with spectrum hardening due to voiding is smaller for ^{233}U than for ^{239}Pu. In addition to making the void coefficient less positive, use of ^{232}Th also has a potential to flatten the burnup reactivity swing. The conversion ratio of fuel with ^{232}Th is expected to be higher than that of fuel with ^{238}U, primarily due to the larger capture cross section of ^{232}Th.

The methodology used for the study is described in Section 2. Section 3 summarizes findings from a number of parametric studies: Properties of beginning-of-life (BOL) Pu-ThO_2 lattices (Section 3.1);

burnup reactivity swing of Pu-ThO_2 lattices (Section 3.2); burnup reactivity swing of U-ThO_2 lattices (Section 3.3); and sensitivity of the tight lattice characteristics to the fuel density (Section 3.4).

2. DESCRIPTION OF GEOMETRY AND METHODOLOGY

Figure 1 shows geometry of the MCNP cell model (note that the scale of X-axis and Y-axis in Figure 1 is different). Fuel diameter is 0.825 cm, the clad thickness 0.0625 cm, and p/d (triangular) ranges from 1.05 to 1.20. The active fuel length in this study is 100 cm. The plenum height is 75% of the active fuel length (75 cm). A 20-cm thick stainless steel grid plate, which has a cross-sectional area equal to half of the unit cell, is placed under the fuel rod. The water reflector above and below the core is 40 cm thick.



(a) Unit Cell Vertical Cut-Through View (b) Unit Cell Horizontal Cut-Through View

Figure 1. Unit cell geometry

Since the reflective boundary condition is applied to all six sides of the cell, the model is infinite in the radial direction but finite in the axial direction. As for the burnup analysis, only uniform burnup was considered in this study, i.e., the fuel was represented as a single zone. Table I summarizes the core material composition.

Table I. Summary of material composition

Material	Components	Weight percent (w/o)
SS316L	Fe	69
	Cr	17
	Ni	12
	Mo	2
Thorium (natural)	Th232	100
Plutonium (CEA3)	Pu238	2.52
	Pu239	53.33
	Pu240	23.9
	Pu241	99
	Pu242	7.05
	Am241	1.21
Enriched Uranium	U235	20
	U238	80

Unless specified differently, the Pu constitutes 19.5 weight % of the heavy metal (HM). The fuel, cladding, coolant, and grid temperatures are, respectively, 900 C, 320 C, 290 C, and 290 C.

In this study, MOCUP [3] is used for neutronics calculations and depletion analysis. MOCUP is a coupled utility program that links MCNP [4] and ORIGEN2 [5], and allows a Monte Carlo based burnup analysis.

Analysis of the tight IRIS core requires much more than 26 zones allowed in MOCUP for space dependent burnup analysis. In addition to the modifications to MOCUP reported in [2], UCB extended from 26 to 50 the number of burnup zones that MOCUP can handle. Future modifications are expected to further increase the number of burnup zones, but it is impossible to have more than 100 burnup zones without modifying the MCNP code itself.

In order to have accurate results from MOCUP, the number of isotopes accounted for by MCNP must be large, in particular when lattices with hard spectrum are analyzed. However, the more isotopes are modeled in MCNP, the more CPU time is needed. The number of isotopes modeled is optimized in [2] so that MCNP accounts for more than 99.7% of the total absorption by the fission products (FPs).

In order to minimize statistical errors, it is necessary to follow as many neutron histories as possible, which requires large CPU time. In this study, 300,000 source neutrons are used per MCNP run. The first 50,000 neutron histories are discarded. By using this number of source neutron, the statistical error of one sigma for combined collision, absorption and track length estimates of k is 0.01–0.015%. Other parameters such as fluxes and reaction rates have somewhat larger statistical errors.

3. TIGHT LATTICE STUDY

3.1 BOC NEUTRONICS ANALYSIS FOR Pu-ThO_2 FUEL

The first effort was to characterize the beginning-of-cycle (BOC) core conditions for several p/d ratios. In order to investigate the void coefficient at BOC, k_{eff} values for 0% void and 100% void were calculated for p/d=1.05, 1.10, 1.15 and 1.20. The results are summarized in Figure 2. It was found that only in the case of p/d=1.20, k_{eff} of the voided core was smaller than that of the no-void core.

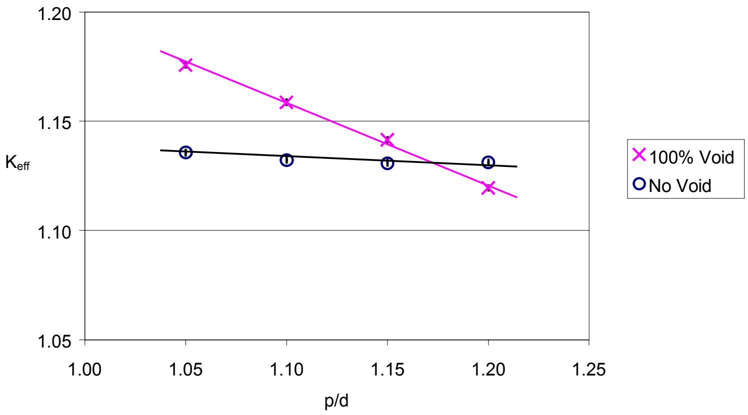


Figure 2. Effect of p/d on k_{eff} with 0% and 100% void (Pu-ThO_2, BOC)

In order to clarify why the void coefficient is negative if p/d=1.20, the leakage probability and the effect of spectrum hardening were investigated. Figure 3 shows: (a) the leakage probability, and, (b) the fuel fission-to-absorption cross section ratio. The leakage probability of the voided cores increases with p/d, resulting in a more negative void coefficient. On the other hand, the ratio of the fission-to-absorption cross sections for fuel slightly decreases with p/d, making the void coefficient more positive for larger p/d. At the cross over point of p/d=~1.17 (Fig. 2) the two effects are of a similar magnitude. The effect of leakage outweighs that of spectrum hardening for p/d>1.17. This can be verified by calculating for the 0% and 100% void cases the product {1-(a)}x(b), which is closely proportional to k_{eff}. The resulting curves are plotted in Figure 3, showing a similar trend as in Figure 2, i.e., the cross over occurs at p/d=~1.15. The effect of p/d and of voiding on the cumulative fission probability is shown in Figure 4.

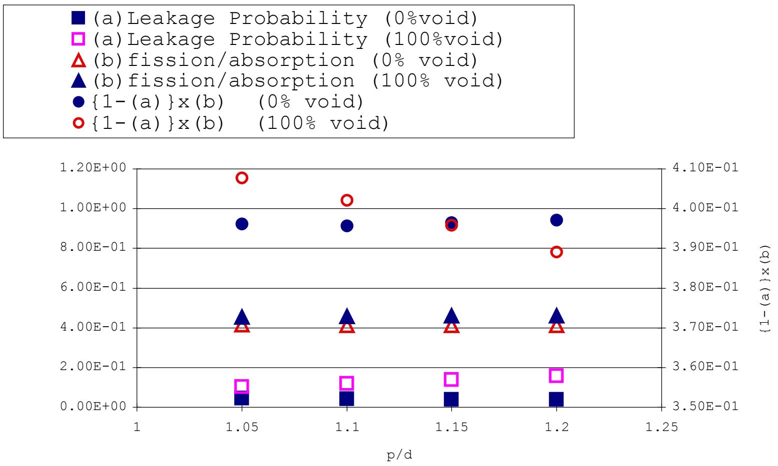


Figure 3. Leakage probability and fission/absorption cross section ratio vs. p/d (Pu-ThO$_2$, BOC)

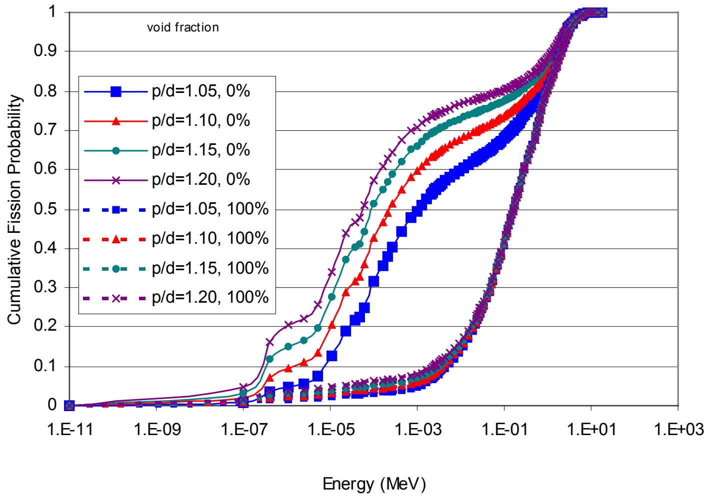


Figure 4. Cumulative fission probability vs. p/d and voiding (Pu-ThO$_2$, BOC)

Based on the above analysis, it is concluded that a negative void coefficient could be obtained by using Th-PuO$_2$ fuel, but the p/d ratio needs to be greater than ~1.2.

Figure 5 shows the effect of partial voiding on k_{eff}. It is seen that for p/d=1.20, k_{eff} becomes the smallest when the void fraction is ~90%. The result for the core with p/d=1.10 shows a similar trend although k_{eff} becomes the smallest at ~70% void. This behavior can be explained by the void effect on the leakage probability and fission probability.

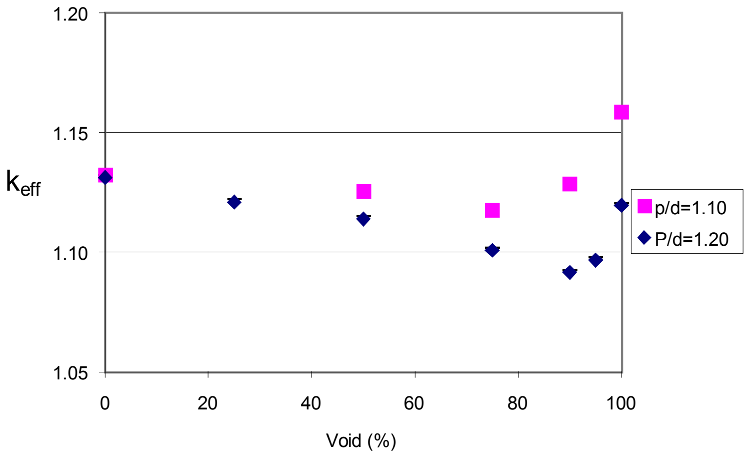


Figure 5. k_{eff} vs. void fraction (Pu-ThO$_2$, BOC)

The leakage and coolant absorption probability for the core with different void fraction is plotted in Figure 6. As the void fraction increases, the leakage probability increases. The absorption probability in the coolant is negligible compared with the leakage probability.

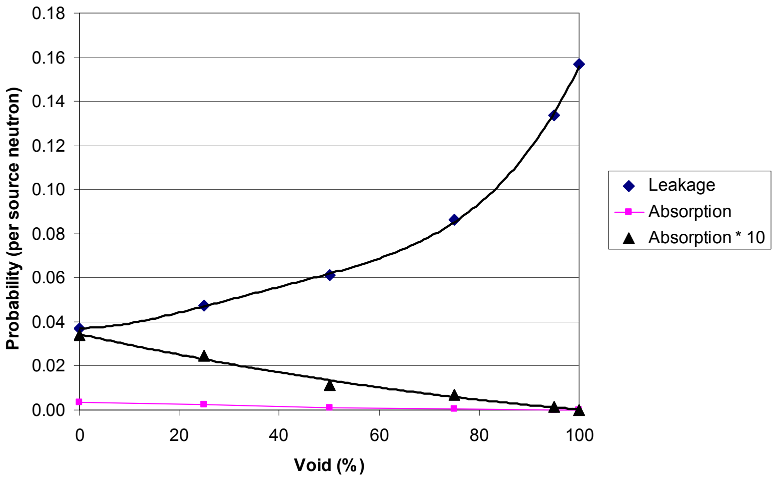


Figure 6. Leakage and coolant absorption probability vs. void
fraction (Pu-ThO$_2$, p/d=1.20, BOC)

Figure 7 shows the energy-dependent cumulative fission probability for different void fractions; the larger the void fraction, the more fissions occur by high energy neutrons. The spectrum with voided core is significantly harder than that with no void. As explained in introduction, the increase of leakage has a negative effect on the void coefficient while spectrum hardening has a positive effect. Therefore, the trend shown in Figure 5 can be explained by considering that leakage is dominant when the void fraction is less than 90%, while spectrum hardening is dominant at higher void fractions.

The k_{eff} behavior in Figure 5 shows that for p/d=1.10 the void coefficient is negative up to 70% void fraction, thus if total voiding can be averted, we can achieve a negative void coefficient. For example, if certain amount of the solid moderator ZrH$_{1.6}$ were to be included in the lattice, one would avert the total loss of moderator (H) from the core even in the event of total coolant loss. As a result the void coefficient could be negative over the entire range of coolant voiding.

It is concluded that from the viewpoint of BOC void coefficient, the core with p/d=1.20 is the most favorable candidate for IRIS. If partial voiding is acceptable, smaller p/d cores could be acceptable as well. It ought be realized that the unit cell model used for the analysis does not account for radial leakage. Radial leakage is expected to reduce the p/d value above which 100% voiding will result in negative voids coefficient. The effect of radial leakage will be quantified later.

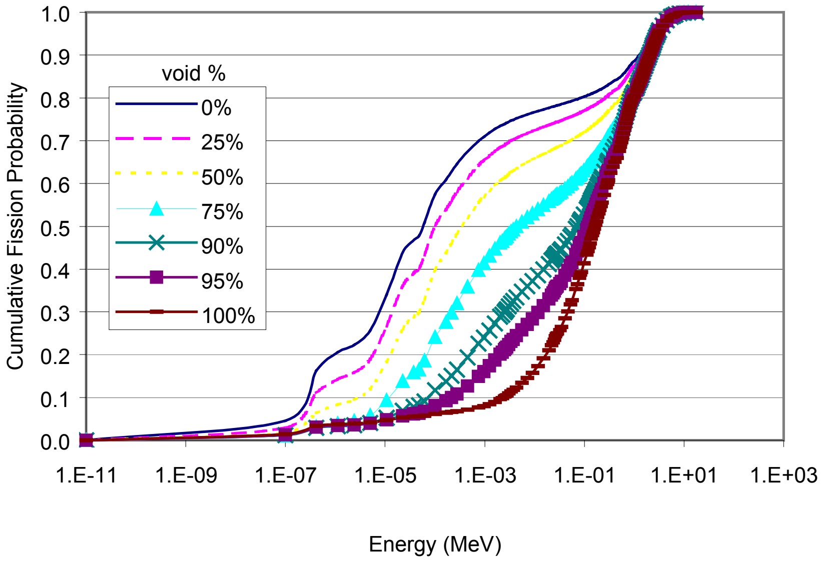


Figure 7. Cumulative fission probability vs. void fraction (Pu-ThO_2, p/d=1.20, BOC)

3.2 BURNUP ANALYSIS FOR Pu-ThO_2 FUEL

The results of burnup analysis for Pu-ThO_2 fuel in different p/d lattices are summarized in Figure 8. Since our calculational model does not account for leakage in the radial direction, k_{eff} must be greater or equal to approximately 1.05 throughout 8 years of operation for the core to meet our design objective. However, the results show that such a long life core is not achievable. The larger p/d is, the shorter is the core life. This is because the conversion ratio becomes smaller as p/d becomes larger, causing the spectrum to soften. In case of p/d=1.20, k_{eff} drops below 1.05 within 3 years.

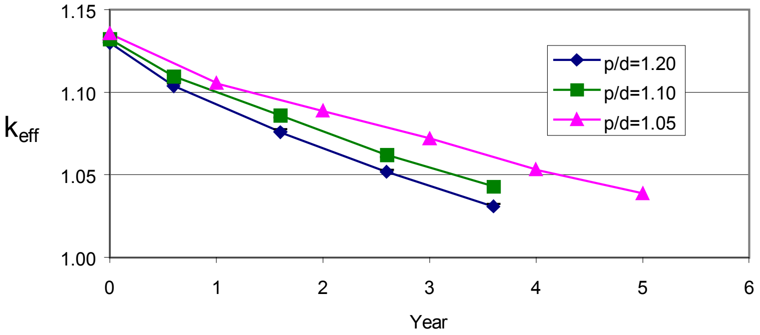


Figure 8. k_{eff} evolution with burnup (Pu-ThO_2)

In order to find an upper bound on the achievable core life, the p/d was set at 1.05, which is close to the minimum p/d from heat-removal considerations, despite the fact that it will make the void coefficient positive. The fuel pins were assumed to be infinitely long. The Pu concentration is reduced in order to increase the conversion ratio. The results are shown in Figure 9. Even though k_{eff} becomes flatter as the Pu concentration decreases, the BOC k_{eff} becomes smaller than 1.05 before an acceptable core life is achieved.

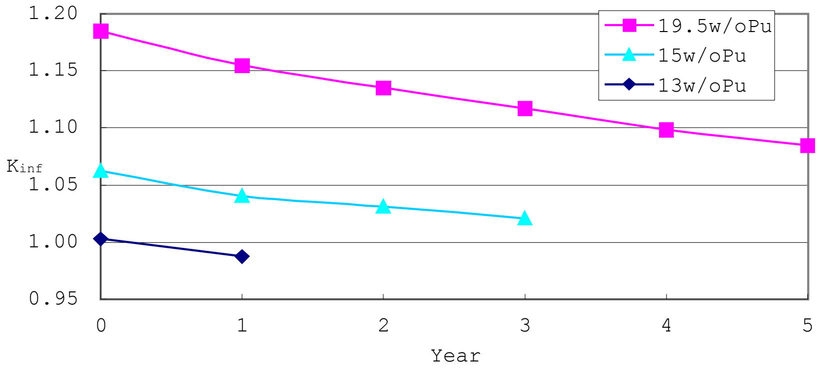


Figure 9. k_{eff} evolution with burnup for different Pu loadings ($Pu-ThO_2$, infinite pin length)

In an additional analysis, the $Pu-ThO_2$ fuel lattice was voided to different degrees, making the spectrum harder. Results are shown in Figure 10.

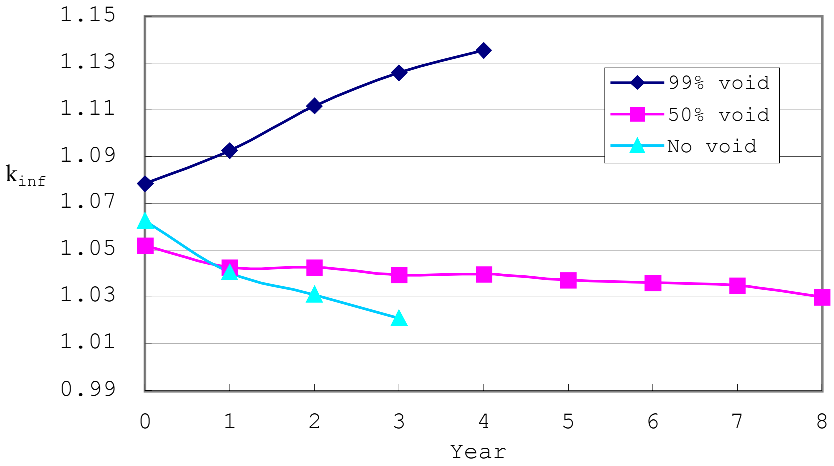


Figure 10. k_{inf} evolution with burnup vs. void fraction ($Pu-ThO_2$, p/d=1.05, infinite pin length)

It was found that k_{inf} becomes almost flat with 50% voided core. With 99% voided core, k_{inf} significantly increases with burnup. We can conclude that in order to get a long life core by increasing the conversion ratio to the point of nearly zero burnup reactivity swing, the amount of water need to be reduced to less than 50% of the amount of water in a p/d=1.05 lattice. Alternatively, for the same amount of water as in the p/d=1.05 lattice, it may be possible to flatten k_{inf} by doubling the fuel cross sectional area.

3.3 BURNUP ANALYSIS FOR $U-ThO_2$ FUEL

The $U-ThO_2$ fuel was also investigated. Since $^{235}\eta$ is closer to $^{233}\eta$ than to $^{239}\eta$, the reactivity swing with burnup might be smaller than with $Pu-ThO_2$. In the study of $U-ThO_2$ fuel the core life was investigated first. In order to estimate the upper limit of the core life, an infinite length pin model was adopted.

In this study, 20 % enriched uranium was assumed. The uranium concentration in the fuel was set to be 60 w/o and 70 w/o. Results of the burnup analysis for this case with p/d=1.05 are shown in Figure 10. The maximum core life of about 4 year was obtained with 70 w/o of uranium. In order to make the spectrum harder, the burnup analysis was also performed with p/d=1.03, but the core life was not much longer. Results of these analyses thus indicated that the use of thorium oxide fuel is not too promising, if the goal is an 8-year core.

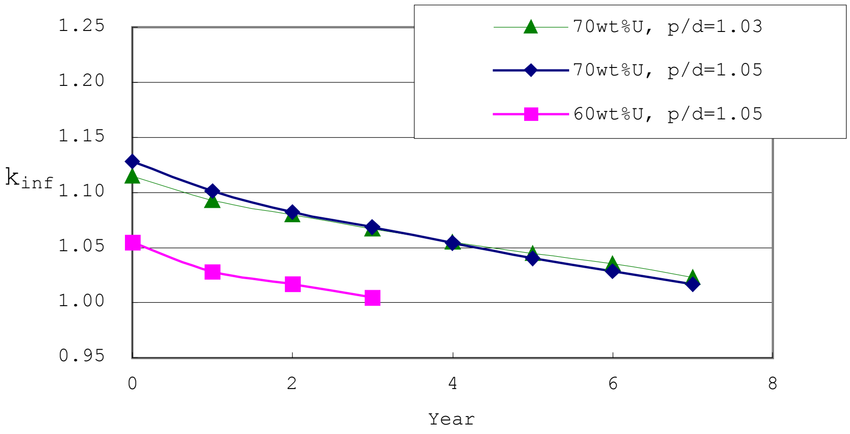


Figure 10. k_{inf} evolution with burnup (U-ThO$_2$)

3.4 OTHER SENSITIVITY ANALYSIS

An alternative way to increase the HM-to-water ratio is to increase the fuel density, rather than to reduce the amount of water. In this section, metallic fuel lattices were investigated, with p/d=1.05 and an active core length of 1 m. Note that we are not proposing the use of metallic fuel for IRIS core, since it is not chemically compatible with water, but this was a simple way of investigating the effect of fuel density. In this study, Pu-Th-Zr was selected as the metallic fuel material with following fuel properties: Pu composition – CEA3 (see Table I), 10 w/o of Zr, Th composition – 100% ^{232}Th, nominal density 15.85 g/cm^3, and smear factor 0.85. The results of the burnup analysis are shown in Figure 11.

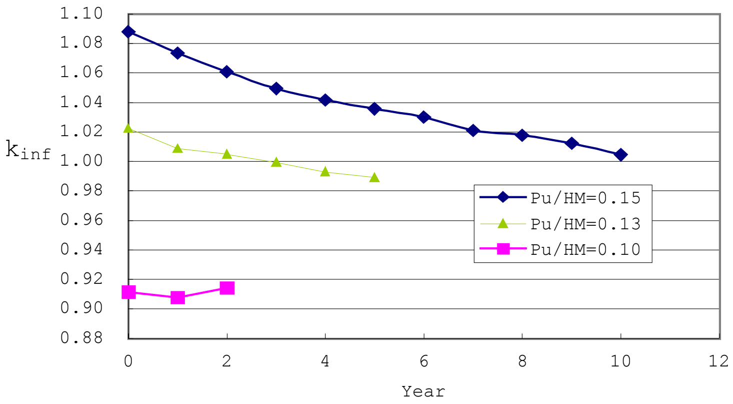


Figure 11. k_{inf} evolution with burnup in p/d=1.05 lattices (Pu-Th-Zr fuel).

Based on the above results, a core life longer than 8 years may be attained with high Pu concentration. However, the higher Pu concentration means higher BOC k and larger reactivity drop with burnup. Judging from the results, Pu/HM may be slightly higher than 0.15 to achieve core life longer than 8 years. In case of Pu/HM=0.15, k_{inf} drops ~7 % in 8 years. For Pu/HM=0.15, BOC k_{inf} was calculated for various void fractions. The results are shown in Figure 13. A similar trend to that of oxide fuel shown in Figure 5 is observed, but with metallic fuel the minimum k occurs around 50%. As there is no leakage from the infinite lattice, the calculated void reactivity effect is not realistic.

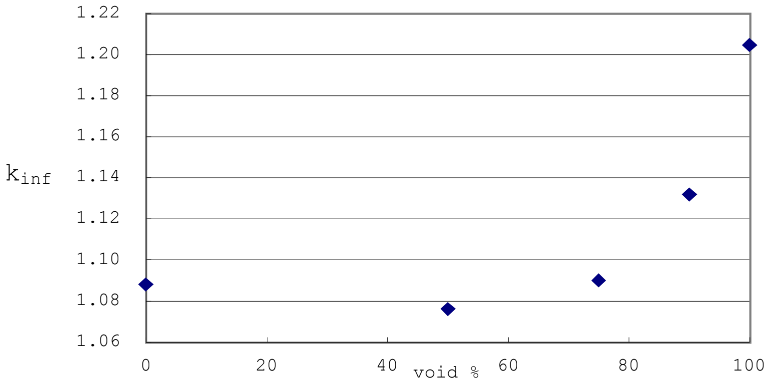


Figure 13. k_{inf} vs void ratio (Pu-Th-Zr, p/d=1.05, BOC)

An additional analysis was done to investigate the difference between two fertile materials: ^{238}U and ^{232}Th. The result of U-ThO$_2$ burnup analysis is plotted again in Figure 14 together with the results of enriched uranium burnup analysis. First of all, two cases with the same ^{235}U concentration (U-ThO$_2$ with 70 w/o U, and 14 w/o enriched UO$_2$) were compared. It was found that the U-ThO$_2$ fuel makes k_{inf} flatter although the k_{inf} value is lower. Next, two cases with almost the same BOC k_{inf} (~1.05) were compared (U-ThO$_2$ with 60 w/o U, and 8 w/o enriched UO$_2$). The results show again that the U-ThO$_2$ fuel makes k_{inf} flatter. The UO$_2$ fuel with 14 w/o enrichment could possibly provide 8 years of core life, but with a large BOC excess reactivity.

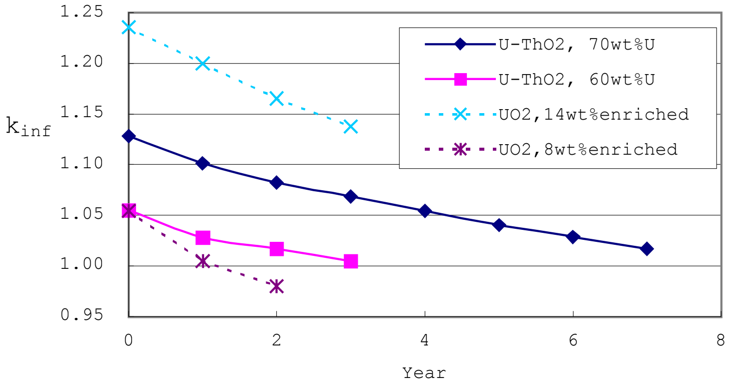


Figure 14. k_{inf} evolution with burnup, U-ThO$_2$ and UO$_2$ (p/d=1.05, H=infinite)

CONCLUSION

This study did not find a way to achieve an 8-year LWR core design with small BOL excess reactivity using ^{232}Th fertile fuel in tight lattices of uniform composition. It was found that the HM-to-water ratio has to be at least 50% higher than that of the p/d=1.05 lattices considered in this work to get a critical core having a nearly zero burnup reactivity swing. The 1.05 value was assumed to be the smallest practical p/d ratio from heat removal considerations. Another conclusion of this work is that in order to achieve a negative void coefficient using a uniform core with p/d ratio smaller than 1.2, the complete removal of hydrogen from the core needs to be avoided. With p/d > 1.2, it is possible to achieve a negative void coefficient, but the attainable core life is not longer than 3 years. Future work should examine the effect of radial leakage and thick fuel rods.

ACKNOWLEDGEMENT

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REFERENCES

1. M.D. Carelli, D.V. Paramonov, C.V. Lombardi, M.E. Ricotti, N.E. Todreas, E. Greenspan, J. Vujic, R. Yamazaki, K. Yamamoto, A. Nagano, G.L. Fiorini, P. Dumaz, T. Abram, H. Ninokata, "IRIS, International New Generation Reactor," *Proceedings of 8th International Conference on Nuclear Engineering, ICONE 8, Baltimore, MD USA, ICONE-8447*, April 2-6, 2000.
2. T.P. Lou, "Feasibility Study of Long Life cores for "IRIS" with Small Burnup Reactivity Swing," *Master Thesis*, Department of Nuclear Engineering, University of California Berkeley, May 2000.
3. R.L. Moore, B.G. Schnitzler, C.A Wemple, R.S. Babcock, D.E. Wessel, "MOCUP: MCNP-ORIGEN2 Coupled Utility Program," *INEL-95/0523, Idaho National Engineering Laboratory*, September 1995.
4. J.F. Briesmeister, Editor, "MCNP^{TM} – A General Monte Carlo N-Particle Transport Code, Version 4C," *LA–13709–M Report, Los Alamos National Laboratory*, April 2000.
5. A.G. Croff, "A User's Manual for the ORIGEN2.1 Computer Code," *ORNL/TM-7175, Oak Ridge National Laboratory*, July 1980.