# THE AP-Th 1000 AN ADVANCED CONCEPT TO USE MOX OF THORIUM IN A CLOSED FUEL CYCLE

**Giovanni Laranjo de Stefani[1] and José Rubens Maiorino[2]**

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)

Av. Professor Lineu Prestes 2242

05508-000 São Paulo, SP, Brazil

laranjogiovanni@gmail.com

[2]Universidade Federal do ABC

CECS - Centro de Engenharia, Modelagem e Ciências Sociais Aplicadas

Av. dos Estados, 5001

09210-580 Santo André- SP, Brazil

joserubens.maiorino@ufabc.edu.br

## ABSTRACT

This work presents a study for the firsts 4 cycles of recharge of the reactor AP-Th1000, a ve rsion of the reactor AP1000 using mixed uranium and thorium oxides as fuel, which the fea sibility studies had been already demonstrated in previous study for a first cycle. The APTh 1000 study is a proposal to start the thorium fuel cycle using the most common reactor tech nology in the nuclear industry, the Pressurized Water Reactors (PWR). A preliminary close d cycle study is carried out for the first 4 cycles where the production of $^{233}U$ are evaluated. In cycles 2, 3 and 4, new assemblies with a fuel of the remaining uranium from the previou s cycle are used instead of assemblies removed from the core, thus being a mixture of differ ent uranium's ($^{232}U$, $^{233}U$, $^{234}U$, $^{235}U$, $^{236}U$ and $^{238}U$) , where the additional fissile material i nserted into the fuel to ensure the 18-month operation of the reactor comes from uranium o xides enriched at 20 w / o.. The results demonstrate the viability of the proposal and a gain using closed fuel cycle.

## 1. INTRODUCTION

The feasibility to convert PWRs from $UO_2$ to mixed $U/ThO_2$ fuel cycle has been studied previously basically seeking to utilize the large existing Th reserves. With that aim, the Centro para o Desenvolvimento da Tecnologia Nuclear (CDTN) in Brazil and the former Kernforschungsanlage Juelich (KFA) in Germany conducted studies aiming at analyzing and demonstrating the option of thorium utilization in PWRs (NUCLEBRAS/KFA, 1988). The program defined a U/Th core configuration for standard 1300 MW Siemens PWRs, defined technical specifications for fuel technology of $(U\text{-}Th)O_2$ and $(Th\text{-}Pu)O_2$, and studied fuel design and the behavior of irradiated fuel in experiments performed at the KFA. It was conducted studies for closed fuel cycles with irradiated fuels including laboratory investigation on reprocessing spent thorium fuels with non-irradiated elements (NUCLEBRAS/KFA, 1988; Pinheiro, 2002). The original intent was to introduce eventually such fuels in PWRs. More recently $^{233}U/^{232}Th$ cycles gained renewed interest due to sustainability reasons such as its potential regarding better fuel utilization, reduction of transuranic high-level waste and possible incineration of Pu and the minor actinides Am and Cm inside PWRs (Maiorino et al, 2017; Baldova et al., 2014; Lindley et al., 2014; Zainuddin et al., 2017; Martin and Girieud, 2016, Ganda and Greenspan, 2010; Galperin et al., 2000; Lindley and Parks, 2012).

Some limiting constraints and desirable conditions may constitute a set of criteria to introduce U/Th fuel cycles in current generation PWRs. The relevant ones may include making minimum modifications in current fuel rod and assembly designs, geometry and materials, producing $^{233}U$ to start the U/Th cycle, maintaining current fuel cycle lengths, reactor power level, and current safety levels for temperature coefficients of reactivity, kinetics parameters and reactivity control systems, and reducing radioactive waste generation, requirements of high-level waste storage and use of natural resources (Baldova et al., 2014; Lindley et al., 2014, Maiorino et al., 2017). In this line the first part of this work studied the feasibility to convert an advanced PWR from $UO_2$ fuel cycle to a mixed $U/ThO_2$ fuel cycle (Maiorino et al., 2017). It was based on a parametric study in which several alternatives for the concepts of heterogenous seed-blanket assembly and homogenous assembly were tried to replace the first cycle of the AP1000 core. The best result was a homogenous alternative in which the core was divided in three zones of fuel assemblies with different mass proportions of mixed $UO_2$ and $ThO_2$: (32 wt % $UO_2$ – 68 wt % $ThO_2$), (24 wt% $UO_2$ – 76 wt % $ThO_2$) and (16 % wt $UO_2$ – 84 % wt$ThO_2$). In all 3 zones the $^{235}U$ enrichment was 20 wt%. It was possible in this study to show that this proposed first cycle met some of the criteria presented above such as keeping unchanged fuel rod and assembly dimensions, maintaining the reactor power level and the fuel cycle length (Effective Full Power Days-EFPD of 450 days) and producing $^{233}U$ to start a $^{233}U/Th$ fuel cycle. The best alternative for the concept of homogeneous assembly presented a enough flat power density distribution to meet thermal-hydraulic safety limits for similar reactor power level and sufficient initial core reactivity provide an 450 EFPD fuel cycle. But further work was necessary to verify other criteria.

This work complements the previous work (Maiorino et al., 2017) for analyzing detailed calculation for the first cycle of AP-Th 1000, and proposes a preliminary study for the firsts 4 cycles of recharge of the reactor AP-Th1000 by using ($^{232}U$, $^{233}U$, $^{234}U$, $^{235}U$, $^{236}U$ and $^{238}U$) from the previous cycle mixed with additional fissile material inserted into the fuel to ensure the 450 EFPD operation of the reactor.

## 2. **The AP-Th1000**

We start presenting a brief description of the AP-Th1000 core configuration proposed as a first cycle core with U/Th fuel for the AP1000 reactor. The AP-Th1000 core has been described in detailed elsewhere (Maiorino et al., 2017). The calculations are based on the SERPENT code which is a 3-dimensional Monte Carlo code with static and burnup neutronic capabilities (Leppanen et al., 2015; Leppanen, 2015). It provides keff, power density distribution, allows for burnup calculations and its validation for the AP1000 core is reported elsewhere (Stefani et al., 2019).

The AP-Th1000 core is a proposal for the first cycle of a mixed U/Th core adapted to the AP1000 advanced PWR (Westinghouse, 2011) for commencing the production of $^{233}U$. This core was defined through parametric studies performed previously (Maiorino et al., 2017). It contains 157 fuel assemblies based on a mixture of uranium and thorium oxides with 20 w/o $^{235}U$ enrichment. The nominal thermal power is 3400 MWt. The reactor has three regions composed of mixed (U-Th)$O_2$ as shown in Fig. 1. The proportions of UO2 in the mixed oxide (U-Th)$O_2$ fuel for regions 1, 2 and 3 are respectively, 32 w/o, 24 w/o and 16 w/o. The original geometric characteristics of the AP1000 core such as pitch, diameter of the fuel, thickness of the gap and clad were maintained in the AP-Th1000 core.

The AP-Th1000 reactivity control system consists of soluble boron, Pyrex burnable absorber rods, and control and safety banks (Maiorino et al., 2017; Stefani et al., 2018). Two changes occurred in the AP-Th1000 core proposal: the weakly neutron absorbing gray control bundles with 12 SS-304 and 12 Ag-In-Cd rods are replaced by black control bundles with 24 Ag-In-Cd rods; the Integral Fuel Burnable Absorber (IFBA) rods are removed remaining only the Pyrex burnable absorbers in the AP-Th1000 core. The distribution of control and safety banks in the AP-Th1000 core is also shown in Fig. 1. In this figure, the control banks are named MA, MB, MC, MD, M1, M2 and AO while all the safety bundles form one safety bank named as SB. The detailed geometrical and material data describing the mixed U/Th fuel elements, control and safety banks and burnable absorbers based on the Pyrex technology are found elsewhere (Maiorino et al., 2017).

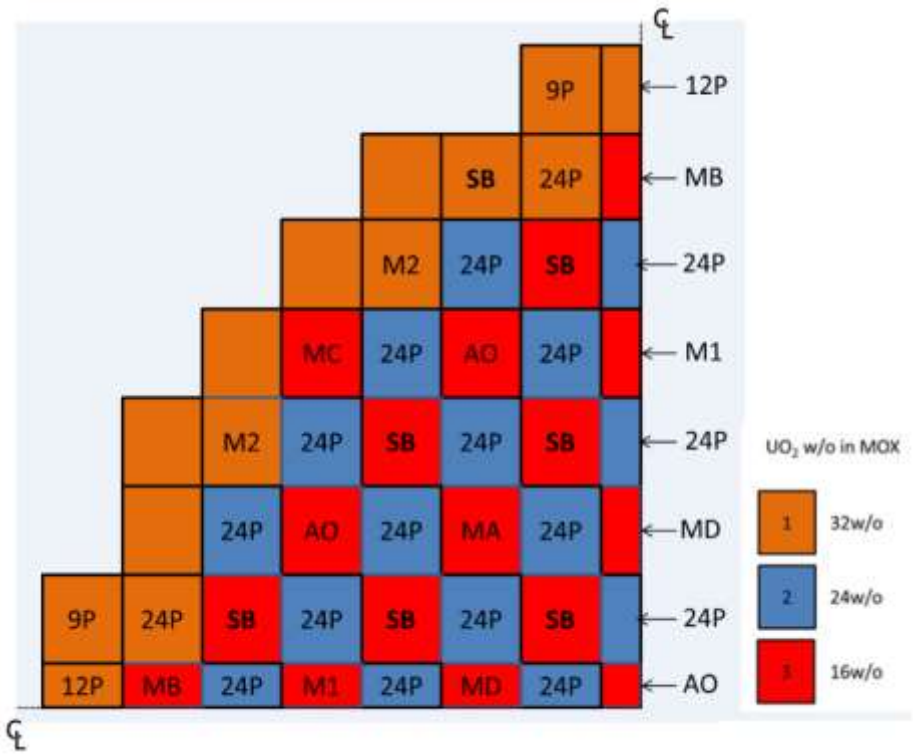


Figure 1. AP-Th1000 reactor core showing the 3 regions of different UO2 proportions in MOX, control and safety bank positions and burnable absorbers. The numbers indicate the number of burnable absorber rods of Pyrex (P) present in the fuel assembly

Detailed calculations of AP Th 1000 were performed in a detailed 3-dimensional full core analysis of the proposed AP-Th1000 core with the SERPENT code and examined if it could function as the initial Th/U fuel cycle in that reactor. The core was adapted with only two modifications: elimination of the IFBA burnable absorbers and replacement of all gray control bundles by black control bundles. The converted core was divided in 3 zones with different $UO_2/ThO_2$ mass proportions: 32 %, 24 % and 16 % of $UO_2$ and the remainders of $ThO_2$. The total thermal power is 3400 MW and average power density is 111 $W/cm^3$. The following parameters remained unchanged with respect to the AP1000 design: core thermal hydraulic conditions, fuel cycle length and average power density. The design variables examined were core reactivity, power density distribution, thermal hydraulic safety limits, temperature coefficients of reactivity, kinetic parameters and reactivity control system (Stefani, G.L., 2017; Maiorino et al, 2017), showing the technical feasibility of the concept. As an illustration of these results, Fig.2 shows the Boron curve of AP-Th 1000, compared with that of AP-1000, and Table 1 the $k_{eff}$ at BOC for different operational conditions (Cold Zero Power-CZP; Hot Zero Power-HZP, and Hot Full Power-HFP).

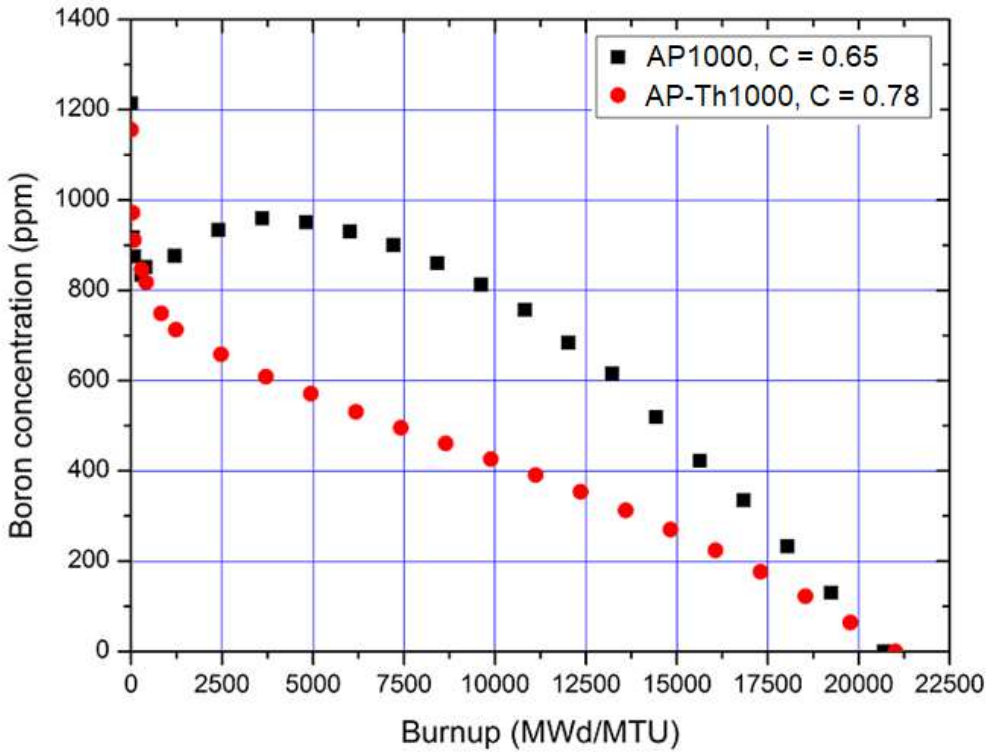


Fig. 2. Boron curve for the AP1000 and AP-Th1000 reactor core configurations. The legend presents the conversion factor for each core (first cycle)

Table 1. $k_{eff}$ and core reactivity results for different core states and conditions at BOC.

| **Core state or condition** | **$k_{eff}$** |
|---|---|
| CZP | 1.22264 ± 0.00003 |
| HZP | 1.14149 ± 0.00003 |
| HFP | 1.12693 ± 0.00003 |
| HFP-Xe Eq | 1.09539 ± 0.00003 |
| | **Reactivity** |
| Temperature defect | 5815 pcm |
| Power defect | 1132 pcm |
| Equilibrium Xenon reactivity | 2555 pcm |
| Excess reactivity at CZP | 18210 pcm |
| Excess reactivity at HZP | 12395 pcm |
| Excess reactivity at HFP | 11263 pcm |

From these results, we may conclude that it is feasibly to convert the AP 1000, to use U/Th oxide without any change in the plant, only changing the fuel pellets, with advantages such as a lower maximum linear heat density, eliminating the IFBA, reducing the soluble boron concentration, and even the possibility of an extended discharge burnup (>60,000

MWD/MTHM). Although regarding the natural uranium resource consume is a disadvantage, in OTC fuel cycle, since AP-Th 1000 consumes more uranium, we note that by optimizing the production of $^{233}U$, we expected that the concept could be used as producer of $^{233}U$, and therefore the first step in a closed U/Th fuel cycle, by recycling the uranium($^{233}U$; $^{235}U$; $^{238}U$) and use in the same reactor, in such way that the requirement of $^{235}U$ is reduced and substitute by $^{233}U$; $^{235}U$ recycled. In this paper, although not using any optimization technique, we will present a preliminary study for the firsts 4 cycles of recharge of the reactor AP-Th1000.

## 3. PRELIMINARY STUDY FOR A CLOSED FUEL CYCLE

If the first cycle is the one described previously, the inventory of uranium in BOC and EOC, where EOC is assumed 100 days of cooling time to allow most of the $^{233}Pa$ to decay in $^{233}U$, is like the one illustrated in Table 2, we notice that are produced 531. 76 kg of $^{233}U$ in the full core at the EOC, being 124.01 kg in zone 1; 170.81 kg in zone 2, and 236.94 kg in Zone 3.

Table 2: Uranium Mass (Kg)Inventory for cycle 1.

.

| **Cycle 1** | Zone-1 BOC | Zone-1 EOC | Zone-2 BOC | Zone-2 EOC | Zone-3 BOC | Zone-3 EOC | Full core BOC | Full core EOC |
|---|---|---|---|---|---|---|---|---|
| U-232 | 0.00 | 0.23 | 0.00 | 0.37 | 0.00 | 0.45 | 0.00 | 1.05 |
| U-233 | 0.00 | 124.01 | 0.00 | 170.81 | 0.00 | 236.94 | 0.00 | 531.76 |
| U-234 | 0,00 | 7,87 | 0,00 | 13,50 | 0,00 | 18,40 | 0.00 | 39.76 |
| U-235 | 1756.89 | 1203.97 | 1315.06 | 779.36 | 891.80 | 443.39 | 3963.76 | 2426.71 |
| U-236 | 0.00 | 106.12 | 0.00 | 99.95 | 0.00 | 78.41 | 0.00 | 284.48 |
| U-238 | 7027.58 | 6914.86 | 5260.22 | 5141.48 | 3567.21 | 3469.31 | 15855.00 | 15525.64 |

To start a closed fuel cycle we propose an empirical in core fuel management in which for the second cycle the Fuel Elements(FE) of zone 3 are withdraw, and an rearrange of zone 1 and 2 as illustrated in Figure 3, and blended with a feed of uranium 20 wt% enriched with uranium recycled from the first cycle as a mixed U-Th oxide and introduced into zone 1, in such way that now the zones are as illustrated in Figure 3, and we introduce in the central zone, a new FE with 16 wt% of $UO_2$. This scheme introduces only 915 kg of $^{235}U$ fissile feed which is a lot less that 1757 kg used in zone 1 in the first cycle, since now we have additional 234 kg of fissile $^{233}U$, and 1359 kg of fissile $^{235}U$ recycled in zone 1. With this pattern we burn using SERPENT code using HFP condition and achieved some cycle length (450 EFPD) as in the 1$^{st}$ cycle, although with a high value of $k_{eff}$ in the BOC, as showed in Figure 4, indicating clearly that the feed FEs would need some burnup poison to be inserted, which could be Pyrex or even $ThO_2$ pins.

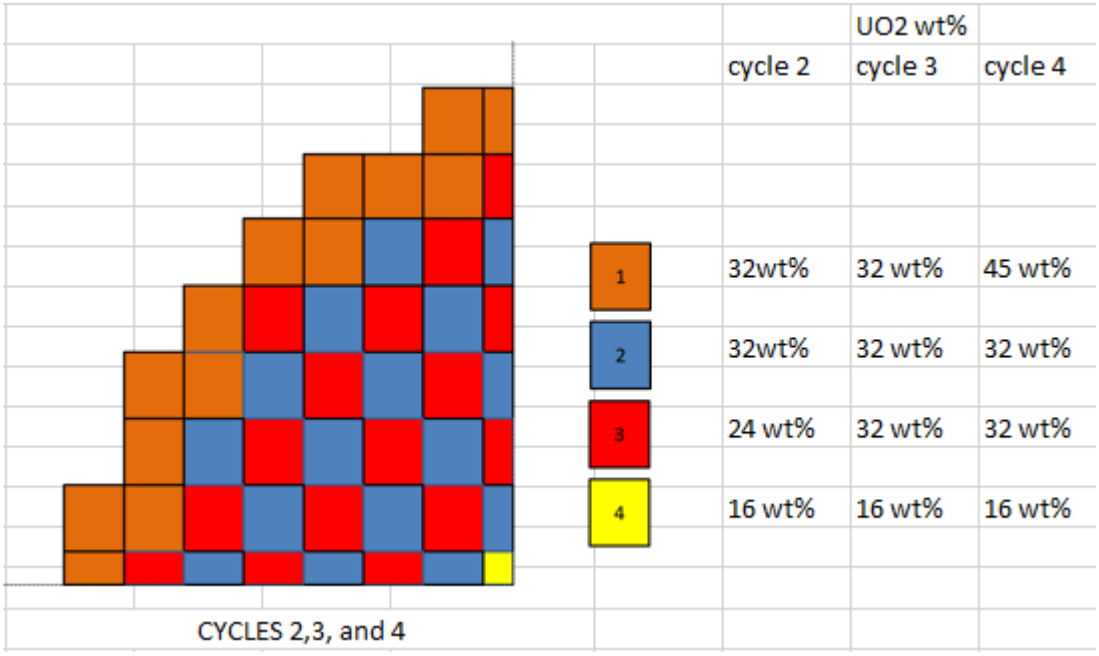


Figure 3: Cycles 2,3 and 4 of AP Th 1000 closed fuel cycle

The results obtained for cycle 2, give us some insight, and for cycle 3, we repeat the same scheme used for cycle 2, i.e., we withdraw FEs from zone 3 and made a rearrangement of zone 1 and 2, from cycle 2, and introduces a feed of $(U\text{-}Th)O_2$ with 20 wt% $^{235}U$ blended with recycled uranium from cycle 2. Also, we notice the feed of $^{235}U$ is 935 Kg, same order of magnitude needed in cycle 2. The mass inventory for these cycles (2 and 3) are showed in Table 4. With this pattern we burn using SERPENT code using HFP condition and achieved some cycle length (450 EFPD) as in the 2$^{nd}$ cycle, but now with a lower $k_{eff}$, at BOC, the same order of the one obtained in cycle 1. These results " a priori " turn us very optimist since it was looking that we are achieving an equilibrium cycle, however when we try to calculate cycle 4, using the same percentual content of $UO_2$(32 wt%) in the feed, unfortunately the calculation showed that to keep the same cycle length(450 EFPD), it was necessary to increase the $UO_2$ in the feed, even though the feed of $^{235}U$ remains almost the same, 944 kg. In table 4, the uranium mass inventory for the 4 cycles at BOC and EOC are showed, and in Figure 4, the $k_{eff}$ versus time (EFPD) are illustrated.

Table 3: Uranium Mass (Kg)Inventory for cycles 2,3, and 4

| **Cycle 2** | Zone-1 | Zone-1 | Zone-2 | Zone-2 | Zone-3 | Zone-3 | Zone-4 | Zone-4 | Full core | Full core |
|---|---|---|---|---|---|---|---|---|---|---|
| | BOC | EOC | BOC | EOC | BOC | EOC | BOC | EOC | BOC | EOC |
| U-232 | 0,45 | 0,57 | 0,23 | 0,85 | 0,37 | 1,07 | 0,00 | 0,01 | 1,05 | 2,49 |
| U-233 | 236,94 | 294,65 | 124,01 | 258,93 | 170,81 | 295,94 | 0,00 | 4,23 | 531,76 | 853,75 |
| U-234 | 18,40 | 31,33 | 7,87 | 24,92 | 13,50 | 33,43 | 0,00 | 0,29 | 39,76 | 89,98 |
| U-235 | 1358,75 | 935,53 | 1203,97 | 754,70 | 779,36 | 466,75 | 16,82 | 8,85 | 3358,89 | 2165,83 |
| U-236 | 78,41 | 153,25 | 106,12 | 183,28 | 99,95 | 150,27 | 0,00 | 1,40 | 284,48 | 488,21 |
| U-238 | 7097,84 | 6990,78 | 6914,86 | 6780,03 | 5141,48 | 5030,06 | 67,28 | 65,59 | 19221,46 | 18866,60 |
| **Cycle 3** | | | | | | | | | | |
| | BOC | EOC | BOC | EOC | BOC | EOC | BOC | EOC | BOC | EOC |
| U-232 | 1,08 | 1,09 | 0,57 | 1,06 | 0,85 | 1,48 | 0,00 | 0,01 | 2,49 | 3,64 |
| U-233 | 300,17 | 332,68 | 294,65 | 337,80 | 258,93 | 310,40 | 0,00 | 3,77 | 853,75 | 984,66 |
| U-234 | 33,72 | 48,53 | 31,33 | 49,27 | 24,92 | 42,18 | 0,00 | 0,22 | 89,98 | 140,20 |
| U-235 | 1403,14 | 945,02 | 935,53 | 597,65 | 754,70 | 496,73 | 16,82 | 9,72 | 3110,18 | 2049,13 |
| U-236 | 151,67 | 231,82 | 153,25 | 207,98 | 183,28 | 221,30 | 0,00 | 1,26 | 488,21 | 662,37 |
| U-238 | 8811,64 | 8673,90 | 6990,78 | 6861,54 | 6780,03 | 6656,99 | 67,28 | 65,85 | 22649,73 | 22258,40 |
| **Cycle 4** | | | | | | | | | | |
| | BOC | EOC | BOC | EOC | BOC | EOC | BOC | EOC | BOC | EOC |
| U-232 | 1,49 | 1,40 | 1,09 | 1,43 | 1,06 | 1,64 | 0,00 | 0,01 | 3,64 | 4,47 |
| U-233 | 314,18 | 331,36 | 332,68 | 349,08 | 337,80 | 358,09 | 0,00 | 3,68 | 984,66 | 1042,22 |
| U-234 | 42,40 | 56,00 | 48,53 | 63,83 | 49,27 | 65,69 | 0,00 | 0,21 | 140,20 | 185,73 |
| U-235 | 1441,14 | 977,20 | 945,02 | 623,20 | 597,65 | 394,86 | 16,82 | 9,93 | 3000,62 | 2005,21 |
| U-236 | 222,56 | 301,70 | 231,82 | 281,05 | 207,98 | 235,11 | 0,00 | 1,23 | 662,37 | 819,09 |
| U-238 | 10480,18 | 10324,87 | 8673,90 | 8529,17 | 6861,54 | 6738,74 | 67,28 | 65,90 | 26082,91 | 25658,80 |

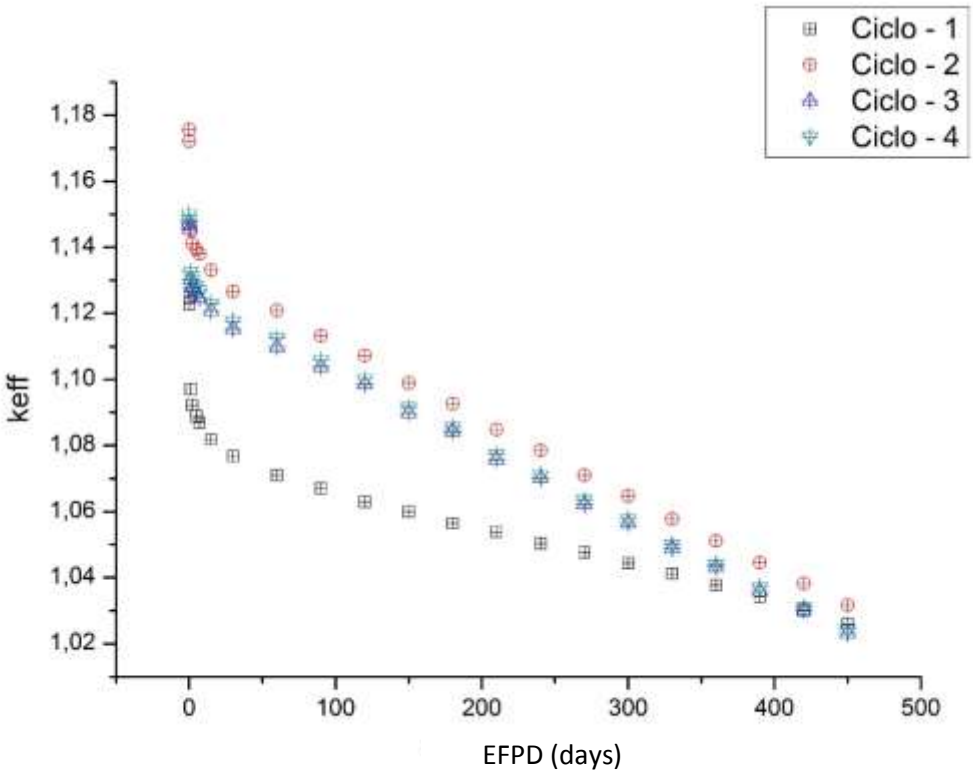


Figure 4: $k_{eff}$ versus the EFPD for the 4 cycles

.

## 4. CONCLUSION

This work and related works (Maiorino et al, 2017; Stefani, G.L, 2017) had demonstrated that it is technically feasible to convert the AP 1000, from an $UO_2$ to MOX of thorium, with minor modifications in the reactor.

The results obtained in this preliminary study indicates that is possible to close the cycle in the AP Th1000, although additional work needs to be done. Examples of these studies may include a modification even in cycle 1, through the introduction of burn up poison, or even pins of $ThO_2$ in some position of the FE, mainly in zone 1. Also, a study using modern techniques of optimization, as instance genetic algorithms, to find an optimized core and close the fuel cycle by recycling the uranium is needed.

## REFERENCES


Baldova, D., Fridman, E., Shwageraus, E., 2014. High conversion Th-U233 fuel for current generation of PWRs: Part II – 3D full core analysis. Ann. Nucl. Energy 73, 560-566.

Galperin, A., Segev, M., Todosow, M., 2000. A pressurized water reactor plutonium incinerator based on thorium fuel and seed-blanket assembly geometry. Nucl. Technol. 132, 214-226.

Galperin, A., Shwageraus, E., Todosow, M. 2002. Assessment of homogeneous thorium/uranium fuel for pressurized water reactors. Nucl. Technol. 138, 111-122.

Ganda, F. and Greenspan, E., 2010. Analysis of Reactivity Coefficients of Hydride-Fueled PWR Cores. Nucl. Sci. and Eng. 164, 1-32.

Leppanen, J., Pusa, M., Viitanen, T., Valtavirta, V., Kaltiaisenaho, T., 2015. The Serpent Monte Carlo code: Status, development and applications in 2013. Ann. Nucl. Energy 82, 142-150.

Leppanen, J., 2015. Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code - User's Manual. June 18. available at: <http://montecarlo.vtt.fi/>.

Lindley, B. A., Parks, G. T., 2012. Near complete transuranic waste incineration in a thorium fueled pressurized water reactor. Ann. Nucl. Energy 40, 106-115.

Lindley, B. A., Ahmad, A., Zainuddin, N. Z., Franceschini, F. and Parks, G. T., 2014. Steady state and transient core feasibility analysis for a thorium-fuelled reduced-moderation PWR performing full transuranic recycle. Ann. Nucl. Energy 72, 320-337.

Maiorino, J. R., Stefani, G. S., Moreira, J. M. L., Rossi, P. C. R. and Santos, T. A., 2017. Feasibility to convert an advanced PWR from UO2 to a mixed U/ThO2 core – Part I: Parametric studies. Ann. Nucl. Energy 102, 47-55.

NUCLEBRAS/KFA, 1988. Program of Research and Development on the Thorium Utilization in PWR – Final Report. JUL-SPEZ 488/NUCLEBRAS-CDTN 600-88/Jülich-KFA

Pinheiro, R.B., 2002. Brazilian experience on thorium fuel cycle investigations. In:IAEA Thorium Fuel Utilization: Options and Trends, TECDOC-1319.International Atomic Energy Agency (IAEA), Vienna, pp. 13–24.

Stefani. G. L., 2017, Feasibility to convert an advanced PWR from UO2 to a mixed U/ThO2 core, PhD Thesis, Federal University of ABC (UFABC), Santo André-SP-Brazil, 261 p (in Portuguese)

Stefani, G. L., Moreira, J. M. L., Maiorino, J. R., 2019. Detailed validation of the Neutronic Calculations of the AP1000 reactor. Prog. Nucl. Energy 116, 95-107.