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The AP-Th 1000 – An advanced concept to use MOX of thorium in a closed fuel cycle

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Summary

This work presents the feasibility studies to convert the UO_2 core of the Westinghouse AP1000 reactor to a U/Th core aiming at U/Th fuel recycling. The focus of the work is to establish a first core which allows normal operation of the AP1000 reactor and investigate a possible route for generating the ^{233}U for U/Th fuel recycling. The converted core named AP-Th1000 is divided in three homogenous zones with different UO_2/ThO_2 mass proportions. The reprocessing procedure envisioned is to separate fission products and Pu isotopes, retain Uranium, use this fuel material in subsequent fuel cycles and complement the required fissile material with U with enrichment below 20%. The goal was to gradually reduce the mass proportion of mined Uranium fuel and eventually attain a Th-^{233}U core with similar operation characteristics of current AP1000 core. We perform a detailed three-dimensional full core analysis with the SERPENT code examining core reactivity, power density distribution, and also a preliminary closed cycle study for the first 4 cycles where the production of ^{233}U are evaluated. The goal of converting the AP1000 reactor core to a U/ThO_2 fuel cycle was partially accomplished. While the first cycle was thoroughly examined and met all requirements we were not able to find a route to migrate it to a prevalent Th cycle. Basically, two of the set of criteria adopted in the study proved to be too restrictive to attain this goal with homogenous assembly, namely U enrichment below 20% and not recycling Pu. The results indicate that removing these two criteria the conversion factor in the ensuing fuel cycles can be increased and possibly attain a Th cycle without compromising the economics of power generation. The design changes were the elimination of IFBA burnable absorbers and replacement of gray control bundles by black control bundles.

KEYWORDS

AP1000, AP-Th1000, PWR, seed-blanket, thorium

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.[1] The program defined a

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U/Th core configurations for standard 1300 MW Siemens PWRs, defined technical specifications for fuel technology of (U-Th)O_2 and (Th-Pu)O_2, and studied fuel design and the behavior of irradiated fuel in experiments performed at the KFA. It conducted chemistry studies in laboratory for thorium reprocessing with non-irradiated elements emulating irradiated fuel elements aiming at closing the fuel cycle.[1,2] 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.[3-10]

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, heat transfer condition and 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.[3-6,11,12] In this line previous works studied the feasibility to convert an advanced PWR from UO_2 fuel cycle to a mixed U/ThO_2 fuel cycle.[3] It involved validation of the calculations and parametric studies including spectral analysis of unit cell and fuel assembly and full core calculations in which several alternatives for the concepts of heterogeneous seed-blanket assembly and homogenous assembly were tried to replace the first cycle of the AP1000 core.[3,13,14]

In these previous studies two types of fuel assemblies were considered 20 different mass proportions of U and Th for the mixed oxide fuel assemblies.[3,14] In the five homogenous fuel assemblies all fuel positions carried mixed oxide (U-Th)O_2 fuel rods. In the 15 heterogeneous fuel assemblies there were two regions: the first with a supercritical seed consisting of UO_2 fuel rods, and the second with a subcritical blanket with (U-Th)O_2 fuel rods. The heterogeneous seed-blanket alternatives presented better conversion factor but did not meet thermal hydraulic requirements keeping similar mass flow rate and coolant channel geometry due to higher peak power densities.[3,4,6,14] 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% UO_2-68% ThO_2), (24% UO_2-76% ThO_2, 16% UO_2-84% ThO_2). In all 3 zones the ^{235}U enrichment was 20% (fuel mass proportion and enrichment are all given in weight percent).[3,4,6,14] 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 (18 months) and producing ^{233}U to start a ^{233}U/Th fuel cycle. The best alternative for the concept of homogeneous assembly presented an enough flat power density distribution to meet thermal-hydraulic safety limits for similar reactor power level and sufficient initial core reactivity to provide an 18-month fuel cycle. But further work was necessary to verify other criteria.[3,14]

An important issue regarding homogenous U/Th fuels is that the ^{233}U produced is not purely recoverable, that is, it cannot be separated from other U isotopes including ^{232}U, ^{234}U, ^{236}U and ^{238}U. Therefore, in U/Th cycles one usually considers pure Th blankets and Pu/Th MOX fuel as a source for ^{233}U.[15] A recent study focused on the environmental impacts of long lived TRU storage considered the possibility of retaining actinides in Th based fuel cycles in PWRs aiming at TRU incineration[10] in PWRs. In this work we try to establish a first core which allows normal operation of the AP1000 reactor, and to attain a possible route for generating the ^{233}U for future U/Th fuel recycling and improving sustainability. The converted core named AP-Th1000 is divided in three homogenous zones with different UO_2/ThO_2 mass proportions. The reprocessing procedure envisioned is to separate fission products and Pu from the irradiated fuel and retain Uranium. This fuel material would then be used in subsequent fuel cycles aiming at gradually to reduce the mass proportion of the UO_2 feed in each cycle. Similar schemes of reprocessing have been used before in India and United States and appear possible to be adapted for this purpose.[16]

This work verifies with detail the feasibility to convert the AP1000 first cycle from UO_2 to a mixed U/ThO_2 cycle. To do that we verify how well the proposed core, named here AP-Th1000, meets the set of criteria presented in the previous paragraph. The core design parameters studied are the initial core reactivity, power density distribution, temperature coefficients of reactivity, kinetics parameters and the reactivity control system encompassing the control and safety banks, soluble boron concentration as a function of burnup and Pyrex burnable absorbers. In addition, we present a preliminary study for a closed fuel cycle analyzing four fuel cycles of the proposed recycling approach. We start in Section 2 presenting the methods and data used in this work, then Section 3 presents the verification results, Section 4 discusses the results and finally Section 5 presents the conclusions.

2 | THE AP-TH1000 AND METHODS

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.[3] The calculations are based on the SERPENT code, version 2.1.30, which is a three-dimensional Monte Carlo code with static and burnup neutronic capabilities.[17,18] It provides k_{eff}, power density distribution, allows for burnup calculations and its general validation for the AP1000 and other cores are reported elsewhere.[3,17-22] The following parameters were considered in the detailed verification of the AP-Th1000 configuration: power density distribution in the core, reactivity control system, burnup and ^{233}U production, kinetic parameters, DNBR and a study for the first 4 cycles of recharge of the reactor.

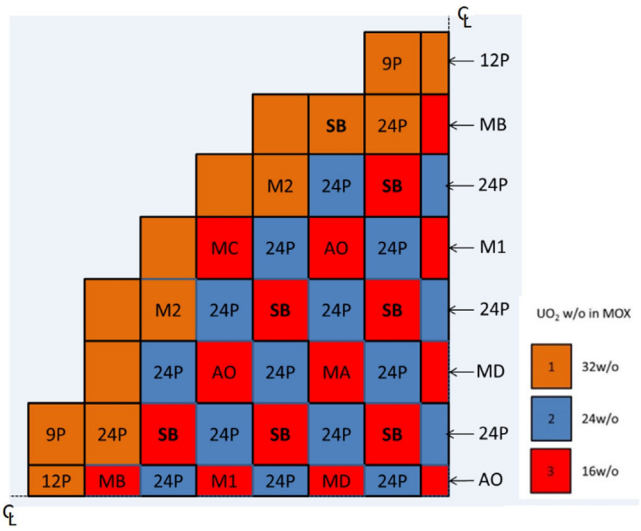

FIGURE 1 AP-Th1000 reactor core showing the three regions of different UO2 proportions in MOX, control and safety bank positions and burnable absorbers. The numbers indicate the number of burnable absorber rods of Pyrex (P) present in the fuel assembly [Colour figure can be viewed at wileyonlinelibrary.com]

2.1 | The AP-Th1000 core and the SERPENT model

The AP-Th1000 core is a proposal for the first cycle of a mixed U/Th core adapted to the AP1000 advanced PWR[23] for commencing the production of ^{233}U. This core was defined through parametric studies performed previously (Maiorino et al[3]). It contains 157 fuel assemblies based on a mixture of uranium and thorium oxides with 20% ^{235}U enrichment. The nominal thermal power is 3400 MWt. The reactor has three regions composed of mixed $(U\text{-}Th)O_2$ as shown in Figure 1. The proportions of UO_2 in the mixed oxide $(U\text{-}Th)O_2$ fuel for regions 1, 2 and 3 are respectively, 32%, 24% and 16%. 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.[3,23] 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 (IBFA) rods are removed, retaining 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 Figure 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.[3]

The AP-Th1000 core configuration is modeled after the AP1000 data (Westinghouse[23]). Table 1 presents relevant data describing the three core states considered in this work: cold zero-power (CZP), hot zero-power (HZP) and hot full-power (HFP). It presents for each reactor state the fuel, structure (including clad) and moderator temperatures, the moderator density, temperature for S (α,β) treatment for binding effects on the moderator cross-sections, and temperatures considered in the SERPENT code cross-section library. The temperatures considered for the $S(\alpha,\beta)$ treatment and cross-section data are the closest available in the SERPENT code cross-section library to those of the actual AP1000 reactor states.[17,18]

The local power density in the SERPENT Monte Carlo code is calculated from the local and total fission rates and the core total or nominal power level.[24] The minimum DNBR is estimated for hottest channel using the STH-MOX-Th code thermal-hydraulic.[25]

The reactivity of control banks, soluble boron and due to temperature changes are calculated using perturbation theory between different reactor core states.[26] Calculating the effective multiplication factor of two states, k_1 and k_2, the reactivity is given by $\Delta\rho = \frac{k_2 - k_1}{k_1 k_2}$. We calculate the soluble boron coefficient of reactivity, α_B, the critical boron concentration,[23] the reactivity control system with control banks, soluble boron and burnable absorbers, xenon worth, conversion factor, temperature

TABLE 1 Description of the three core states considered in the SERPENT model of this work

Reactor state	Fuel temperature (K)	Moderator and structure temperature (K)	Moderator density (g/cm^3)[a]	Temperature for S(α,β)[b] (K)	Temperature in the cross-section library (K)
CZP – cold zero-power	293.6	293.6	0.995	293.6	300
HZP – hot zero-power	565	565	0.744	550	565
HFP – Hot full-power[c]	900	565	0.744	550	900 (fuel) and 565 (moderator and structures)

[a]Considering pressure of 1 atm for CZP and of 153 atm for HZP and HFP.
[b]Closest temperatures available in the SERPENT code default nuclear library.
[c]Full power: 3400 MWt.

coefficients of reactivity, and kinetic parameters.[27,28] The calculations are performed with the SERPENT code based on a ¼ model of the core making use of symmetry considerations.

2.2 | Approach for the incore fuel cycle management

The reprocessing scheme adopted in this study is simplified because its goal is to verify the feasibility of introducing homogenous U-Th fuel cycles in an advanced PWR with recycled materials originated in its own energy generation process. Thus, it does not consider details such as time for refabricating, natural decay of nuclides during these periods, and other technical issues. It is assumed that the U and Th available in the spent fuel can be separated from fission products and other actinides and utilized in subsequent cycles, that is, it is assumed that these fuel materials are available.

Two constraints are considered in the recycling approach: all external uranium fed in all fuel cycles has enrichment equal or lower than 20% to meet proliferation requirements and facilitate commercial implementation; not recycling Pu isotopes to reduce generation of actinide waste. Thus fission products and Pu isotopes are not carried forward to ensuing fuel cycles. The recycled Uranium has thus the following isotope content: ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{236}U and ^{238}U being the ^{239}Pu removed prior to each fuel cycle. In all inventory calculations of fissile material we assume a 100 days cooling time to allow most of the ^{233}Pa to decay to ^{233}U.

The approach for the incore fuel management is thus as follows:

1 After a first cycle (450 days) the depleted 53 fuel elements from zone 3 are removed from the core;
2 The 52 fuel elements positioned in zone 2 are moved to zone 3 and the 52 fuel elements positioned in zone 1 are moved to zone 2. To the central position of zone 3 we load a fresh fuel identical to those of zone 3 first fuel cycle.
3 In the zone 1 positions we load new (U,Th)O_2 MOX fuels with uranium presenting the AP-Th1000 discharge characteristics and 20% enrichment in ^{235}U.
4 This shuffling scheme is repeated in the following cycles.

The reprocessed uranium mentioned in item III has the characteristics of the discharge AP-Th1000 fuel from zone 3. The mixture of external and reprocessed uranium must be such that the fuel loaded in the core provides sufficient amount of fissile material to allow 450 days of full power operation.

3 | RESULTS

3.1 | Core reactivity and power density distribution

Table 2 presents the k_{eff} for different states and conditions of the AP-Th1000 core at BOC obtained with the SERPENT code as described in Section 2.1. The conditions of each state are described in Table 1. Table 2 presents too the temperature and power defects and the core excess reactivity for CZP, HZP and HFP conditions as described in Section 2.1.

The calculations for the power density distribution were performed with the SERPENT code as described in Section 2.1. Each fuel rod was subdivided into 100 equal parts (z-axis). The x-y power density distribution is shown in Figure 2 at BOC depicting its checkerboard pattern. The maximum power density occurs at the mid height. The total power peak factor for the AP-Th1000 core configuration at BOC was 2.75, 6% higher than that from the AP1000 first core.

The thermal-hydraulic safety verifications for minimum DNBR (departure from nucleate boiling ratio) were

performed with the STH-MOX-Th code.[25] The minimum DNBR obtained for the hottest channel at BOC, MOC and EOC burnup levels were 2.28, 1.87 and 1.78, respectively.

Figure 3 presents spectrum information at the core center of the AP-Th1000 and AP1000 and compares the effects of Th and the IFBA burnable absorbers through the normalized neutron flux for four energy groups (E > 1 MeV; 5.53 keV < E ≤ 1 MeV; 0.625 eV < E ≤ 5.53 keV; E ≤ 0.625 eV). The neutron flux spectrum for the AP1000 at this location is harder though the ^{232}Th in the AP-Th1000 has an almost three times higher capture cross-section at thermal energy ranges. This occurs because the AP1000 has IFBA ^{10}B burnable absorber rods in the four fuel elements around the one located in the central position. These burnable absorbers with very high thermal neutron absorption cross section (3837 b) depress the thermal neutron flux around them making the spectrum in the central element of the AP1000 core harder.

TABLE 2 k_{eff} and core reactivity results for different core states and conditions at BOC and zero soluble boron concentration

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	18 210 pcm
Excess reactivity at HZP	12 395 pcm
Excess reactivity at HFP	11 263 pcm

This pattern is reproduced throughout the core due to the checkerboard fuel load pattern adopted in the AP1000 reactor so that, as shown in Figure 3, the AP-Th1000 core is more moderated than the AP1000 core. This fact has impact on their temperature coefficients of reactivity as we show below.

3.2 | Soluble boron reactivity results at BOC and as function of burnup

Table 3 presents the k_{eff} for different AP-Th1000 core states at BOC for determining the soluble boron reactivity coefficient, and Table 4 presents the results for α_B at BOC

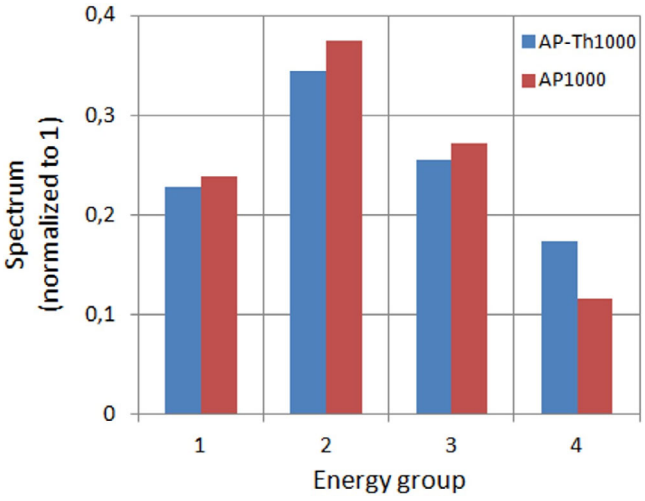

FIGURE 3 Normalized neutron flux spectrum at the core center for the AP-Th1000 and AP1000 configurations. The AP-Th1000 state is HFP-UW. The results for the AP1000 were taken from Westinghouse[23] [Colour figure can be viewed at wileyonlinelibrary.com]

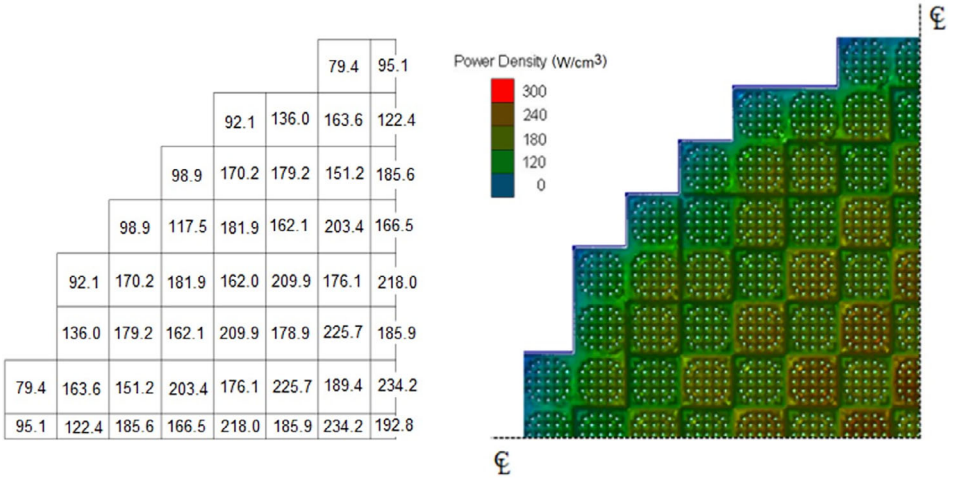

FIGURE 2 Power density distribution at HFP conditions at mid height. The average core power density is 111 W/cm^3 and the power peak factor is 2.75 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 k_{eff} results for the AP-Th1000 core in different states at BOC with different boron concentrations

State	k_{eff}
CZP with 2700 ppm	0.96549 ± 0.00003
HZP with 2700 ppm	0.95135 ± 0.00003
HFP with 2700 ppm	0.93907 ± 0.00003
CZP with 400 ppm	1.17687 ± 0.00003
HZP with 400 ppm	1.10710 ± 0.00003
HFP 400 ppm	1.09260 ± 0.00003

TABLE 4 Soluble boron coefficient of reactivity for the AP-Th1000 and AP1000 at different conditions

Core	α_B (pcm/ppm)
AP-Th1000 at CZP and BOC	−8.1
AP-Th1000 at HZP and BOC	−6.4
AP-Th1000 at HFP and BOC	−6.5
AP-Th1000 at different burnup conditions	−14.1 to −5.9
AP1000 at different burnup conditions[a]	−10.5 to −6.9

Note: The Monte Carlo uncertainties are ~±0.15 pcm. ppm B - ppm of soluble boron in the reactor coolant.
[a]Westinghouse.[23]

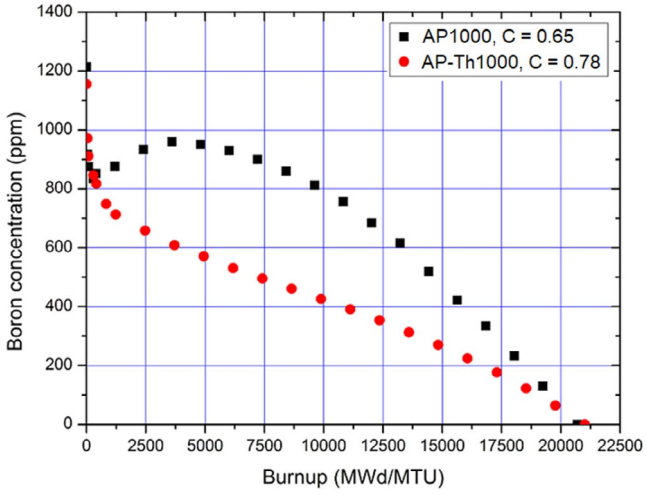

FIGURE 4 Boron curve for the AP1000 and AP-Th1000 reactor core configurations. The legend presents the conversion factor for each core [Colour figure can be viewed at wileyonlinelibrary.com]

and as function o burnup and for the AP1000 first core for comparison.

The critical boron concentration curve as a function of the burnup is presented in Figure 4 for the AP-Th1000 and AP1000 reactors as described in Section 2.1. The conversion factors, defined as the ratio of the number of fissile nuclei at EOC divided by number of fissile nuclei at BOC, are presented in the figure for both cores. The minimum k_{eff} required for power maneuvers from BOC to EOC was taken as 1.052 for the AP-Th1000 core and 1.036 for the AP1000 core. These are the EOC k_{eff} for both cores and the difference is due to the fact that the AP1000 and the AP-Th1000 have the same cycle length but different fuel materials and control means. Thus the differences are due to different power/temperature defect, use of IFBA rods and the presence of Th in the AP-Th1000.

TABLE 5 Temperature coefficients of reactivity for the AP-Th1000

Coefficient of reactivity	AP-Th1000	AP1000[a]
α_F (pcm/°F) interval for different burnup levels	−2.45 ± 0.15 to −0.91 ± 0.15	−2.1 to −1.3
α_M (pcm/ °F) interval for different burnup levels	−28.38 ± 0.13 to −3.52 ± 0.13	−35 to 0

[a]Westinghouse.[23]

3.3 | Temperature coefficients of reactivity and kinetic parameters

The fuel and moderator temperature coefficients of reactivity, α_F and α_M, are presented in Table 5 in which we see that the results are similar and cover similar ranges. The small differences are explained by the fact that the AP-Th1000 core is more moderated than the AP1000 core as shown in Figure 3 and further discussed in Section 4.3. These results show that the introduction of this Th/U cycle in the AP1000 core does not affect its operational and safety parameters related to α_F and α_M.

The values for the effective delayed neutron fraction and mean generation time are presented in Table 6 for the AP-Th1000 at different burnup levels. Table 6 also presents the mean generation time for different reactor core conditions of neutron absorption. For comparisons, we show the kinetic parameters of the AP1000 first core calculated with the SERPENT code and reported by Westinghouse.[23]

3.4 | Reactivity worth of control banks

Table 7 shows the reactivity worth for the control and safety banks at HZP and BOC condition determined as described in Section 2.1, using full core calculations with the Monte Carlo SERPENT code. The calculation was based on ¼ of the core relying on symmetry considerations. These results

TABLE 6 Kinetic parameters for the AP-Th1000 and AP1000 core configurations calculated with the SERPENT code

Configuration	β_{eff}	Λ (μs)
AP-Th1000 at BOC	0.00683 ± 0.00010	16.5[b]
AP-Th1000 EOC	0.00539 ± 0.00012	17.7[b]
AP-Th1000 at BOC with all control banks inserted	-	14.4[b]
AP-Th1000 at BOC with 2360 ppm of soluble boron	-	13.8[b]
AP1000 at BOC	0.00701 ± 0.00011 0.0075[a]	19.8[a]
AP1000 at EOC	0.00538 ± 0.00010 0.0044[a]	-

BOC and EOC mean beginning and end of cycle.
[a]Westinghouse.[23]
[b]The Monte Carlo calculation uncertainty is negligible.

TABLE 7 Reactivity worth of control and safety banks for the AP-Th1000 at HZP, zero boron concentration, no bank overlap and BOC conditions

Inserted bank	Bank reactivity (pcm)
MA – HZP (4 bundles)	315 ± 3
MB – HZP (4 bundles)	359 ± 3
MC – HZP (4 bundles)	629 ± 3
MD – HZP (4 bundles)	223 ± 3
M1 – HZP (4 bundles)	397 ± 3
M2 – HZP (8 bundles)	1406 ± 3
AO – HZP (9 bundles)	1314 ± 3
SB – HZP (32 bundles)	3774 ± 3

indicate that the most reactive control bank is M2. The uncertainties presented in Table 7 are derived from the Monte Carlo standard deviations furnished by the k_{eff} calculations with the SERPENT code.

Table 8 presents k_{eff} for different control rods configuration in order to verify the shutdown margin at BOC. Due to non-symmetric situation when considering stuck rod conditions these calculations are based on complete geometric representation of the three-dimensional core. The boron concentration is around 2000 ppm for HZP and CZP conditions. The HZP core configurations are: core without all control and safety banks (69 control rods); core with all 69 control and safety banks inserted; core with all but the most reactive control rod inserted (the one from the M2 bank) to represent stuck rod condition; and the core with all but the most reactive control bank inserted (M2) also to represent stuck rod condition.

Table 8 also presents the CZP core shutdown k_{eff} with 2150 ppm of boron, the estimated worth of all control

TABLE 8 k_{eff} for several configurations of control banks inserted into the AP-Th1000 core

Core state	k_{eff}
HZP with 2000 ppm of boron and all 69 control rods out of the core	0.99290 ± 0.00003
HZP with 2000 ppm of boron and all 69 control and safety rods inserted	0.91726 ± 0.00004
HZP with 2000 ppm of boron and 68 control and safety rods inserted	0.92292 ± 0.00003
HZP with 2000 ppm of boron and 61 control and safety rods inserted	0.93136 ± 0.00003
CZP with 2150 ppm of boron and all 69 control and safety rods inserted	0.93569 ± 0.00004
Estimated total worth of all 69 control rods	8305 pcm
Estimated total worth of 68 control rods (all but one control rod of the M2 bank)	7637 pcm
Estimated total worth of 61 control rods (all but the M2 bank)	6655 pcm
Estimated worth of the most reactive control rod (from the M2 bank)	669 pcm
Estimated worth of the most reactive bank (M2)	1650 pcm

Note: The control bank stuck out are those of the M2 bank.

and safety banks at HZP condition considering the stuck bank condition, and the estimated worth of the most reactive control rod and control bank.

Table 9 presents the verification of the reactor shutdown margin criterion presented in two situations: (a) one of the M2 control rods stuck out with all other 68 control rods inserted (most reactive control rod stuck out); (b) the complete M2 bank (with eight control rods) stuck out with all other 61 control rods inserted. For both verifications we performed explicit full core Monte Carlo calculations. The soluble boron concentration taken in this evaluation was 2000 ppm occurring at BOC condition which is less than the 2700 ppm allowed limit. The margin with all M2 bank out of the core resulted in 2107 pcm which can accommodate different uncertainties, since the above margin is calculated with reference k_{eff} of 0.95.

3.5 | Preliminary study for a closed fuel cycle

To start a closed fuel cycle we adopt the incore fuel management described in Section 2.2. The fuel elements in zone (or region) 3 are discharged, and the fuel elements

TABLE 9 Reactivity control and shutdown margin at BOC for two stuck rod conditions at HZP condition (stuck bundle and stuck bank)

Requirement considering two situations	Reactivity control system
a $k_{eff} < 0.95$ at HZP absorb excess reactivity with the most reactive bundle stuck out of the core	The soluble boron (2000 ppm) and the available 68 control and safety bundles absorb all excess reactivity and provide $k_{eff} = 0.92292 \pm 0.00003$ (see Table 8).
b $k_{eff} < 0.95$ at HZP absorb excess reactivity with the most reactive bank stuck out of the core	The soluble boron (2000 ppm) and the available control and safety banks (61 control bundles) absorb all excess reactivity and provide $k_{eff} = 0.93136 \pm 0.00003$ (see Table 8).
Shutdown margin available for HZP condition	Situation (a) 3089 ppm Situation (b) 2107 pcm

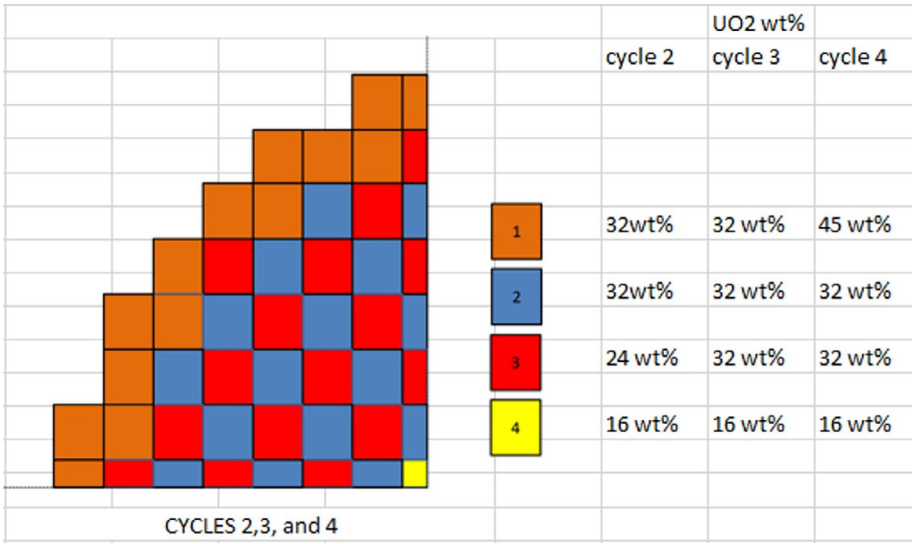

FIGURE 5 Cycles 2, 3 and 4 of AP Th 1000 closed fuel cycle [Colour figure can be viewed at wileyonlinelibrary.com]

of zones 1 and 2 after the first cycle move to the positions of zones 2 and 3, respectively in the second cycle. The vacant zone 1 is occupied with fresh MOX (Th-U)O_2 fuel elements with the UO_2 mass proportion presented in Figure 5 for cycle 2. The same procedure is repeated for the subsequent cycles 3 and 4 with the UO_2 mass proportions shown in Figure 5 too. The central zone is occupied with a fuel element with 16% UO_2 mass proportion. Note that the fourth cycle required a UO_2 mass proportion of 45% to obtain the necessary excess reactivity to operate for a cycle length of 450 EFPD.

The fuel inventory for the first cycle at BOC and EOC, for each zone and for the full core, is presented in Table 10. Table 11 presents the fuel mass inventory for the second, third and fourth cycles at BOC and EOC and Table 12 consolidates these mass data to facilitate discussing the results. In the calculation we assumed that ^{233}Pa has decayed to ^{233}U, U isotopes are carried forward and Pu isotopes are removed in subsequent cycles as described in Section 2.2.

The basic parameter viewed to define the (Th-U)O_2 external feed in each cycle was the initial fissile material content in each cycle required to be similar to that of the first cycle in order to warrant the desired cycle length. This approach caused the Th content to decrease from cycle to cycle and thus compromising the total core conversion rate in the ensuing cycles (see Table 12).

Figure 6 presents the k_{eff} vs time in equivalent full power days (EFPD). In general, a core critical boron curve presents a more pronounced decline along the cycle as the core conversion factor decreases. The results of Figure 6 show that the conversion factor of cycles 2, 3 and 4 decreased and consequently reduced their generation rate of ^{233}U.

4 | DISCUSSIONS

4.1 | Core reactivity and power density distribution

The AP-Th1000 core shown in Section 3.1 presents core excess reactivity at BOC similar to those of other PWRs. At cold zero power conditions its excess reactivity is

TABLE 10 Fuel mass inventory for cycle 1 (data in kg)

	Zone 1		Zone 2		Zone 3		Full core	
Cycle 1	**BOC**	**EOC**	**BOC**	**EOC**	**BOC**	**EOC**	**BOC**	**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	15 855.00	15 525.64
Th-232	18 615.48	18 414.27	20 764.29	20 481.93	23 345.13	22 990.04	62 725.0	61 886.30

TABLE 11 Fuel mass inventory for cycles 2, 3, and 4 (data in kg)

	Zone 1		Zone 2		Zone 3		Zone 4		Full core	
Cycle 2	**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	19 221.46	18 866.60
Th-232	18 615.51	18 422.47	18 414.29	18 167.69	20 484.21	20 205.90	440.33	434.20	57 954.80	57 230.70
Cycle 3	**Zone 1**		**Zone 2**		**Zone 3**		**Zone 4**		**Full core**	
	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	22 649.73	22 258.40
Th-232	16 701.75	16 504.30	18 422.91	18 186.26	18 168.24	17 973.57	440.33	435.15	53 733.60	53 064.70
Cycle 4	**Zone 1**		**Zone 2**		**Zone 3**		**Zone 4**		**Full core**	
	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	10 480.18	10 324.87	8673.90	8529.17	6861.54	6738.74	67.28	65.90	26 082.91	25 658.80
Th-232	17 957.77	15 014.97	16 504.75	16 293.95	18 186.78	14 831.67	440.33	435.33	50 147.20	49 519.10

about 2000 pcm greater than that of the AP1000 reactor and at hot zero power conditions, greater only about 500 pcm.[23] These results show that in principle the AP-Th1000 proposed core at BOC can be controlled with familiar schemes of control rods and soluble boron used in PWRs. However, the APTh-1000 core does not have the IFBA burnable absorbers present in the AP1000 core to reduce the initial excess reactivity. If one excludes both

TABLE 12 Summary of the fuel mass inventory (kg)

Cycle	(U-Th)O_2 proportion of the feed (%)	$^{235}U+^{233}U$		^{238}U		^{232}Th		$^{232}U+^{234}U+^{236}U$	
		BOC	EOC	BOC	EOC	BOC	EOC	BOC	EOC
1	32	3963.76	2958.47	15 855.0	15 525.6	62 725.0	61 886.3	0.0	325.3
2	32	3890.65	3019.58	19 221.5	18 866.6	57 954.8	57 230.7	325.3	580.7
3	32	3963.93	3033.79	22 649.7	22 258.4	53 733.6	53 064.7	580.7	806.2
4	45	3985.28	3047.43	26 082.9	25 658.8	50 147.2	49 519.1	806.2	1009.3

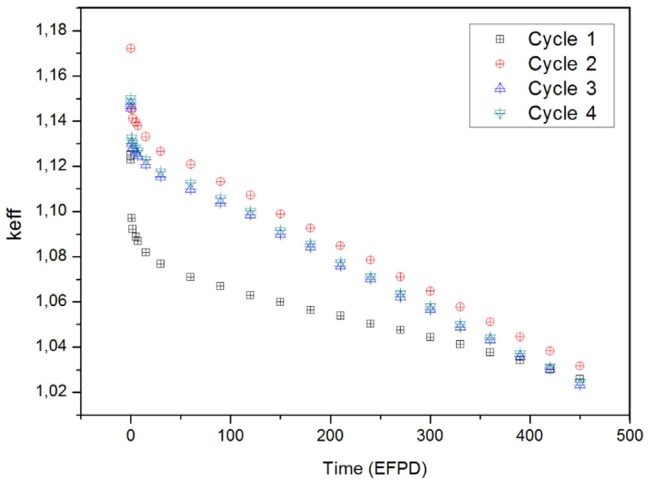

FIGURE 6 k_{eff} vs the time for the 4 cycles [Colour figure can be viewed at wileyonlinelibrary.com]

burnable absorbers (Pyrex in the APTh-1000 core and Pyrex and IFBA in the AP1000) the available initial excess reactivity of the AP-Th1000 is much smaller than that of the AP1000. In order to have a fuel cycle length similar to that of the AP1000 the AP-Th1000 core has to be a better converter and produce sufficient fissile ^{233}U to compensate for its initial smaller available excess reactivity.

The power density distribution shown in Figure 2 presents too the checkerboard pattern found in the AP1000 core but there are two main differences: the variation between neighboring fuel assemblies is smaller and the assembly positions with low and high power density values are inverted due to the removal of the IFBA burnable absorbers that were present in all fuel assemblies with medium and high enrichments in the AP1000 original core.[23]

The AP-Th1000 core presented a 6% higher power peak factor at BOC than that of the AP1000 and yet this result produced a comfortable minimum DNBR and met thermal-hydraulic safety limits (Section 3.1). This result was possible due to the homogenous assembly choice for introducing the mixed U/Th fuel in the AP1000 core and provided a thermal power of 3400 MW.[3] A similar attempt for introducing U/Th fuel in a PWR using heterogeneous seed-blank assemblies produced a higher peak power density and allowed a safe total thermal power of 1943 MW.[4] The high concentration of fissile materials in the seed region led to a large power peak at BOC and required reduction in the core power level to meet thermal-hydraulic safety limits.[4]

To reduce the 6% difference at BOC it would be necessary to improve the Pyrex burnable absorber design and distribution in the core and, additionally, design more carefully the monitoring system of the power density distribution during operation.[29,30] However, the actual power peak factor difference is not as great as it appears. This study with the SERPENT code considers uniform fuel and moderator temperatures throughout the core which tends to increase the power peak factor. A similar uniform temperature model applied to the AP1000 original core produces a power peak factor only 2% smaller than that from the AP-Th1000 configuration.[13]

Figure 3 shows the spectrum differences between the AP-Th1000 and AP1000 core configurations at the core center where both of them bear no burnable absorber rods. The more thermal neutron spectrum of the AP-Th1000 at the core center increases the power density in this assembly with lower fissile material content. Additionally, over the cycle it contributes to produce more ^{233}U and to reduce the power density mismatch among neighboring assemblies in the AP-Th1000 core configuration.

4.2 | Soluble boron reactivity results at BOC and as function of burnup

The boron reactivity coefficients for both AP-Th1000 and AP1000 cores are similar ranging from −14 to −6 pcm/ppm throughout the whole first cycle.

The boron curves presented in Figure 4 show that the first cycle length of the proposed AP-Th1000 core is

similar to that of the AP1000 but with completely different behavior along the cycle. The different behavior is basically due to the greater conversion factor of the Th core, a parameter which takes into account fertile-capture-to-fissile-absorption ratio, fissile production/fertile destruction and spectral effects. The mixed Th/U core C value of 0.78, greater than that of the U core of 0.65, was sufficient to make the cycle length slightly longer than 20 000 MWD/MTU. The Th core with higher conversion factor produces more efficiently fissile material (^{233}U out of ^{232}Th).

The boron curve from the AP-Th1000 core decreases steadily as a function of burnup, while that from the AP1000 core presents the typical behavior of cores with strong burnable absorbers. In Figure 4, the increase-decrease trend shown by the AP1000 critical boron curve is due to the burnup of the burnable poisons along the cycle. After they have been consumed, around 15 000 MWD/MTU, the critical boron rapidly goes to zero indicating the EOC. The curve slope after 15 000 MWD/MTU is representative of the AP1000 core boron curve without burnable poisons.

Another important result is the smaller soluble boron concentration required by the AP-Th1000 core throughout the cycle which tends to generate less radioactive waste during operations.

4.3 | Temperature coefficients of reactivity and kinetics parameters

As was shown in Section 3.3, the fuel and moderator temperature coefficients of reactivity obtained for the AP-Th1000 are similar to and cover similar ranges as those from the AP1000 first core. This indicates that the change to a mixed Th/U core produces small influence on fuel and moderator coefficients of reactivity and negligible impact on the operation and safety of AP-Th1000 core when compared to the AP1000 core.

The differences on α_F and α_M of both cores are mostly explained by the spectral differences between them shown in Figure 3. The AP1000 core has a harder spectrum (higher values of the normalized flux spectrum for groups 1, 2 and 3, and smaller value for the fourth group [thermal]) when compared to that of the AP-Th1000 core. If one considers a plot of k_{eff} vs pitch obtained from a cell calculation, its slope is proportional to the negative of the moderator temperature coefficient of reactivity. For the same lattice pitch, the more moderated U/Th core produces a smaller moderator temperature coefficient of reactivity in absolute value, as is shown in Table 5, since it has a pitch closer to its correspondent optimal moderation condition and, consequently, a smaller slope. In addition, ^{238}U has a three times higher resonance integral than ^{232}Th, increases the neutron absorption, and further contributes to increase the absolute value of the moderator coefficient of reactivity in the AP1000 core. On the other hand, a change in the fuel temperature broadens the resonances of the fertile elements ^{232}Th and ^{238}U at the energies of few eV. These isotopes tend to absorb more neutrons in the more thermal lattice of the AP-Th1000 core causing it to present a higher fuel temperature coefficient of reactivity in absolute value.

The burnup causes also changes in the fuel and moderator coefficients of reactivity and can be explained by the total fuel capture along the fuel cycle. ^{239}Pu generation tends to increase α_M and α_F due to the neutron capture in its large resonance around 0.3 eV while in the U/Th cycles the ^{233}U generation contribution is less important.

The effective delayed neutron fraction results for the AP-Th1000 and AP1000 core configurations, calculated with the SERPENT code, present similar values as a function of burnup despite the appearance of ^{233}U in the fuel at EOC. The greatest difference occurred at BOC and was of 18 pcm (0.00683 for the AP-Th1000 against 0.00701 for the AP1000). The similarity of results as a function of burnup is due to the physical fractions of delayed neutrons for ^{233}U and ^{239}Pu are very similar.[31] The difference when compared with the value for the AP1000 reported by Westinghouse can be assigned to different physical fraction magnitude and delayed neutron spectra of different cross section libraries but it is not relevant regarding the reactor kinetics and control.[27,28]

The mean generation time results for the AP-Th1000 is similar to those of other PWRs. The presence of absorbing materials such as control rods or soluble boron decreased the mean generation time. This is expected since higher absorption removes neutrons more rapidly from the core and thus reduces its mean generation time.[27] At EOC the mean generation time increased about 7% mostly due to zero soluble boron concentration in the core.

These results of temperature reactivity coefficients and kinetic parameters indicate that the APTh-1000 and AP1000 cores present similar transient and stability behaviors.

4.4 | Reactivity worth of control and safety banks

The AP-Th1000 core has only black safety and control banks. Given the absence of IFBA burnable absorbers in it, it was necessary to replace all gray bundles by black bundles for the reactivity control system to be able to

shut down the reactor with the required margins. With the removal of the IFBA, its medium and high UO_2 proportion assemblies became more reactive. Since most control bundles in this core are in the lower UO_2 proportion assemblies they became less effective. But the reactivity worth of control and safety banks from the AP-Th1000 core presents approximately similar magnitudes to those from AP1000.[23]

The shutdown margin is accomplished in the first core without difficulties for cold and hot zero power conditions with soluble boron concentration much less than the 2700 ppm allowed limit.

4.5 | Preliminary study for a closed fuel cycle

The first cycle with the (Th-U)O_2 mass proportion of 32%, 24% and 16% proved to be adequate for utilization in advanced PWRs but the subsequent cycles presented were only possible to be established with decreasing amounts of Th. This fact compromised the total conversion rate of fertile isotopes in fissile isotopes in the core.

The chosen incore fuel management strategy was to maintain in each cycle approximately the same amount of fissile materials ($^{235}U+^{233}U$) in the core as shown in Table 12 in order to warrant the 450 EFPD cycle length. Two criteria of the strategy established in Section 2.2 proved to be very restrictive namely not carrying forward the Pu content generated along the cycles and using only low enriched uranium (less than 20%) as external feed to complete the necessary fissile content in each cycle. Until the third cycle it was possible to meet all proposed criteria with external feed with 32% mass proportion of U, but the fourth cycle required an external feed with 45% mass proportion of U. Observing Table 12, one sees that this strategy required to augment the ^{238}U content in the beginning of each cycle compared to that of the previous one. The ^{238}U inventory varied from 15 855 kg at the beginning of the first cycle to 26 083 kg at the beginning of the fourth cycle and, consequently, the inventory of Th reduced from 62 725 to 50 147 kg. Thus, these results show that this fuel cycle strategy is gradually becoming an Uranium cycle. The main reason is the insufficient generation of converted fissile material along the cycles.

The reason for not carrying forward the Pu aimed at reducing generation of transuranic waste. But this decision meant also losing the reactivity potential of Pu odd isotopes. In addition the presence of high content of ^{240}Pu in the core could have helped in flattening burnup reactivity slope and control requirements.

In this recycling strategy, carrying forward to subsequent cycles the ^{233}U generated brings together ^{238}U and the other even isotopes ^{232}U, ^{234}U and ^{236}U. The ^{232}U and ^{234}U are fertile isotopes with neutron capture cross sections in thermal energy of 75 b and 100 b, respectively, and quickly become fissile elements. The ^{236}U, after a succession of neutron captures and beta decays, may eventually transmute to ^{239}Pu but due to its low neutron capture cross section in thermal energies, 5.3 b, the process is slow. Thus the ^{236}U content in the core builds up to 819 kg at the end of the fourth cycle as shown in Table 11; it functions in the core as a neutron absorber. The consequence of its presence is to effectively decrease the feeding enrichment, displace Th in the MOX fuel fed in the core and reduce the conversion rate of the fuel cycles.

The k_{eff} curves in Figure 6 describe the same difficulty of targeting the cycles toward a prevalent Th core. As shown in Figure 6 the slope of the k_{eff} curve as a function of burnup of cycles 2, 3 and 4 is more pronounced than that of cycle 1 indicating that they have a smaller generation rate of fissile material along their cycles. This reduction caused the necessity of increasing the mass proportion of Uranium in the fourth cycle. If such recycling strategy continued it would eventually become an U cycle.

There are some possibilities to overcome this difficulty: improve the design to increase the conversion factor in each cycle or do not consider the two criteria mentioned above, that is, allow U feeding with high enriched uranium (> 20%) and utilize the generated Pu along the cycles. These three actions increase the fissile content in the core along the cycles and may allow meeting the cycle length requirement. Another possibility is reducing the cycle length but this would damage the economics of the electricity generation.

5 | CONCLUSION

The objective of this work of converting the AP1000 reactor core to a U/ThO_2 fuel cycle was partially accomplished. While the first cycle was thoroughly examined and met all requirements we were not able to find a route to migrate it to a prevalent Th cycle. Basically, the set of criteria adopted in the study proved to be too restrictive to attain this goal. These criteria were: making minimum modifications in current fuel rod and assembly designs, geometry and materials; ruling out the heterogeneous seed-blanket alternative which presents better conversion factor but could not meet thermal hydraulic requirements keeping similar mass flow rate and coolant channel geometry due to higher peak power densities; and not recycling Pu to reduce generation of transuranic radioactive waste. Not making any significant changes in the

current fuel design and dropping the heterogeneous seed-blanket alternative due to its difficulties in thermal hydraulics design are reasons for not being able to meet the high converting thorium core and attain a prevalent Th cycle.

The results also indicated that removing some of these criteria it may be possible to attain a prevalent Th cycle with the homogenous assembly alternative. Removing the criteria of U enrichment below 20% and not recycling Pu, the results indicated that one may be able to increase the conversion factor in fuel cycles 2, 3 and 4 and attain a prevalent Th cycle.

The AP1000 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 three zones with different UO_2/ThO_2 mass proportions: 32%, 24% and 16% of UO_2 and the remainders of ThO_2. The following parameters remained unchanged with respect to the AP1000 design: thermal power (3400 MW), core thermal hydraulic conditions and fuel cycle length. The design variables examined were: core reactivity, power density distribution, thermal-hydraulic safety limits, temperature coefficients of reactivity, kinetic parameters and reactivity control system. A study of the first 4 cycles of recharge of the reactor was also performed.

The initial excess reactivity of the AP-Th1000 core is somewhat greater than that of the AP1000 core in order to have similar cycle length but it requires less burnable absorbers due to the larger Th thermal neutron absorption. The core has only Pyrex burnable absorbers in some fuel assemblies. The higher conversion factor 0.78 produces sufficient fissile ^{233}U along the cycle providing additional reactivity for the 18-month long cycle length. The power density distribution presents the checkerboard pattern found in the AP1000 core configuration. The power peak factor is similar and the thermal hydraulic hot channel verifications with the W-3 correlation yielded minimum DNBRs between 1.78 and 2.28. The thermal power output of the AP-Th1000 core was confirmed as the same of the AP1000 core: 3400 MW.

The temperature coefficients of reactivity and kinetic parameters are similar to those from the AP1000 core. The AP-Th1000 reactivity control system has only black bundles in order to meet shutdown margin requirements.

As future work we intend to conduct similar studies relaxing some of the mentioned restrictive criteria and include the heterogeneous assembly alternative in reactor physics and thermal-hydraulic studies. Other lines of investigation for the homogenous assembly alternative are retaining Pu, allow high enrichment U in the external feeds, altering the fuel pitch to increase the conversion factor and the production of ^{233}U, and improving safety parameters such as coefficients of reactivity.

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