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Feasibility to convert an advanced PWR from UO2 to a mixed (U,Th)O_2 core

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ABSTRACT

This work presents the neutronics and thermal hydraulics feasibility to convert the UO2 core of the Westinghouse AP1000 in a (U-Th)O2 core, rather than the traditional uranium dioxide, for the purpose of reducing long-lived actinides, especially plutonium, and generates a stock pile of ^{233}U, which could in the future be used in advanced fuel cycles, in a more sustainable process and taking advantage of the large stock of thorium available on the planet and especially in Brazil. The reactor chosen as reference was the AP1000, which is considered to be one of the most reliable and modern reactor of the current Generation III, and its similarity to the reactors already consolidated and used in Brazil for electric power generation. The results show the feasibility and potentiality of the concept, without the necessity of changes in the core of the AP1000, and even with advantages over this. The neutron calculations were made by the SERPENT code. The results provided a maximum linear power density lower than the AP1000, favoring safety. In addition, the delayed neutron fraction and the reactivity coefficients proved to be adequate to ensure the safety of the concept. The results show that a production of about 260 Kg of ^{233}U per cycle is possible, with a minimum production of fissile plutonium that favors the use of the concept in U-Th cycles.

1. INTRODUCTION

Currently, the nuclear industry employs the ^{235}U as fissile material in fuel production. Maintaining the current consumption rate, it is estimated that extractions costing less than US $ 80/kg uranium will last for the next 40 years, for costs of US $ 130/kg of uranium with a 60 years durability and for costs below $ 260/kg of uranium about 100 years [1]. The mentioned costs limit uranium as a primary source of energy for that century, if no recycling process is used and taking into consideration only the use of thermal reactors, without taking advantage of the remaining plutonium in the material used or from other sources [2]. In this way studies involving alternative nuclear fuels and production of other fissile materials have been carried out worldwide [3], and one of the most promising materials to be used as fuel would be ^{233}U, produced by the capture of a neutron by ^{232}Th.

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The thorium has as a great advantage to be more abundant in the Earth's crust than uranium, besides being found in nature in a isotopic abundance of 100% in ^{232}Th and having a higher melting point than uranium [4], being thermally more safe. In the context of this scenario, Brazil presents the largest global ore reserve [5], as shown in figure 1.

Reservas mundiais de tório: óxidos de tório, fosfatos e silicatos são encontrados em todo o mundo frequentemente como elementos de terras raras. O tório não é ainda minerado comercialmente, e suas abundâncias são apenas aproximadamente conhecidas em muitos países. Os números mostram as estimativas em milhares de toneladas.

São estimados no mundo cerca de 1781 milhares de toneladas

Figura 1: Reservas mundiais de Tório.

Still in this field, an increasing incentive has been set by the International Atomic Energy Agency for new technologies of thorium reactors and using ^{233}U to be developed [6]. In this way, a study was carried out aiming at using current technologies to start this fuel cycle. The reactor AP1000 [8] was used as a reference. The SERPENT code [7] was used to convert the reactor core to thorium. This new reactor was named AP-Th1000 and the parametric study for its determination was inclusive already published in an area journal [9]. Currently a new article is in the process of completion for submission in the same journal, with detailed calculations of the developed reactor. The results obtained in the parametric study [8] and the detailed calculations of the nucleus for the first cycle are presented in a succinct manner.

2. Methodology

A viable transition from the current UO_2 AP1000 core to one with mixed U/Th fuels should be such that minimum changes occur on its current core design and operational parameters. Thus one could consider the following requirements in this study: produce important amounts of ^{233}U for future ^{233}U/Th cores; keep the current fuel assembly geometry, i.e., fuel rod diameter and pitch and meet the current thermal-hydraulic limits such as maximum center line fuel rod temperature and maximum linear power density in order to avoid as much as possible changes in the current design; keep the current fuel cycle length of 18 months, and keep similar values of temperature coefficients of reactivity and kinetics parameters in order to maintain the current operation and economical parameters.

To do this it is necessary to search for a viable core configuration among many different alternatives bearing U/Th fuels. We do that through a parametric study in which we compare the different operational and design core parameters of the U/Th core configurations against a reference AP1000 core configuration chosen as benchmark. In this study we undertake the following steps:

1) Choose a AP1000 core configuration as the reference benchmark to compare the several U/Th fuel configurations;
2) Establish a set of criteria based on design and operational parameters of the AP1000 core. These criteria should ensure that minimum changes would occur with the new U/Th core configuration regarding plant operation, fuel assembly design variables, and sustainability. Thus this set of criteria will constitute requirements that the chosen U/Th configuration shall meet;
3) Identify possible configurations of mixed U/Th fuel to introduce in the AP1000 core. To do this we consider two possible assembly configurations: homogenous (U-Th)O_2 assemblies and heterogeneous seed-blanket approach with UO_2 in the seed region and (U-Th)O_2 in the blanket region.
4) Conduct core calculations at beginning of cycle (BOC) conditions and burnup calculations to verify how the several U/Th core configurations meet the requirements. Choose the best configuration to make the transition core from UO_2 to mixed U/Th core. This parametric study can be carried out with simplified core models due to the large amount of calculation to be performed;
5) Undertake detailed comparison of the chosen U/Th configuration with the AP1000 core in order to verify actual means of controlling the core excess reactivity along the fuel cycle.
6) Study the main safety parameters during the operation of the first cycle of operation.

2.1. AP1000 core.

The AP1000 advanced PWR reactor operates at a nominal power of 3400 MW thermal and contains 157 fuel elements with three different enrichment regions as shown in Figure 2. Region 1 has fuel with enrichment of 4.45 w/o, Region 2 with enrichment of 3.40 w/o and region 3 with enrichment of 2.35 w/o. The fuel element contains a 17x17 matrix with 264 fuel rods and 25 guide tubes. The guide tubes can be used to insert instrumentation, control rods and burnable poison rods. The project considers for the first nucleus two types of burnable poisons: the Integral Fuel Burnable Absorber (IFBA) and the Pyrex Burnable Absorber. The IFBA rods occupy the positions of the fuel rods while the Pyrex rods are inserted into the guide tubes. In Figure 1, the number of IFBA sticks present in a fuel element is indicated by the letter I and the number of Pyrex sticks is indicated by the letter P [8].

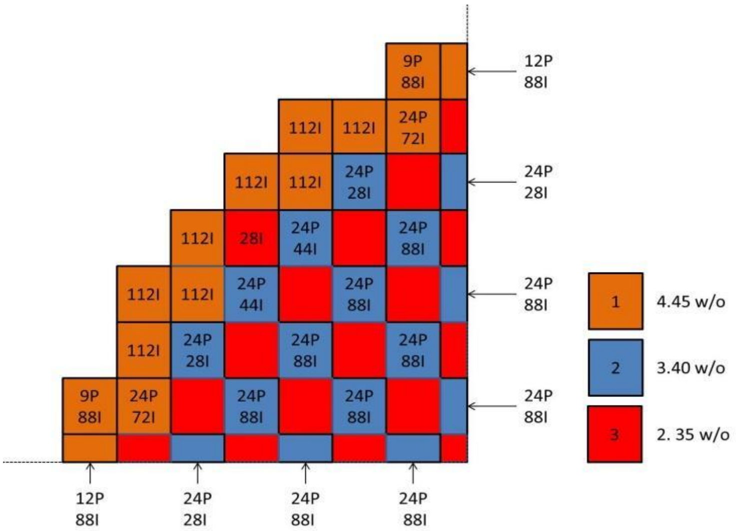

Figure 2: Distribution of the fuel elements in a core room showing the regions of different enrichments. The numbers indicate the amounts of burnable poison rods of the IFBA (I) and Pyrex (P) type on a given fuel element.

Figure 3 shows a cross section of the fuel rod used in the fuel element and shows the dimensions of the fuel pellet, gap, zirlo coating and the pitch between the rods. The distribution of fuel rods and guide tubes of a fuel element is shown in Figure 4. This figure also shows the axial enrichment distribution in the fuel rod which at the ends is lower. Table 1 shows the data describing the fuel rod.

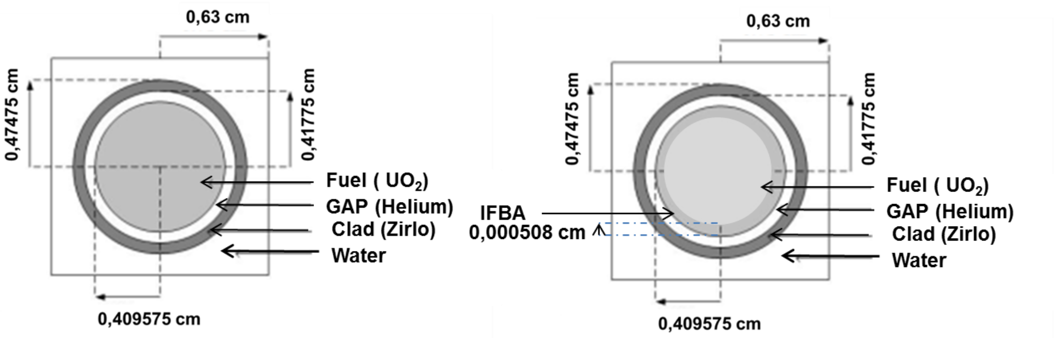

Figure 3: Cross section showing the dimensions of the fuel rod including, gap, zirlo coating, IFBA (when it exists) and pitch.

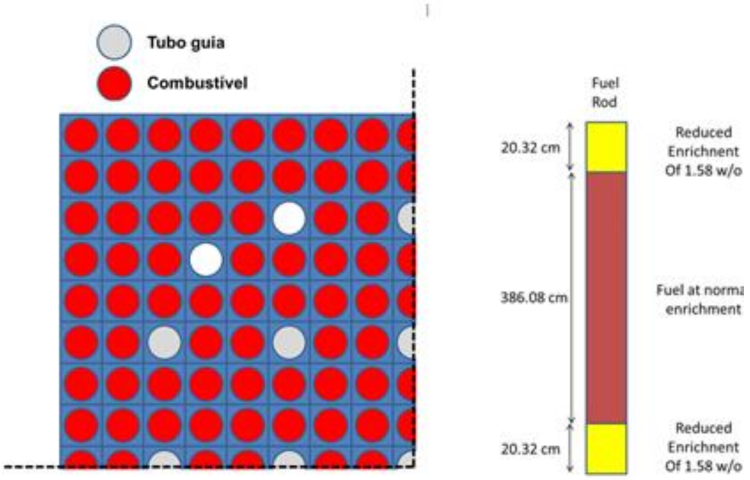

Figure 4: Distribution of the fuel rods and guide tubes to ¼ of the AP1000's typical fuel assembly (17x17).

Table 1 - Geometric data and materials of the fuel rod and assembly [8].

Parameter	Value
Fuel Diameter	0.81915 cm
Outside diameter	0.94996 cm
Diameter gap	0.01651 cm
Clad thickness	0.05715 cm
Clad specific mass	6.56 g/cm^3
Fuel specific mass	10.28 g/cm^3
GAP specific mass	0.000176 g/cm^3
Length	426.72 cm
Rod Pitch	1.26 cm
Rod Array	17x17
Fuel Rods per assembly	264
Clad material	Zirlo
Fuel Material	UO_2
GAP material	Helium

2.2. Parametric studies.

To carry out the parametric study we utilized a simplified configuration of the AP1000 core as the reference configuration. This UO_2 core configuration, is similar to the original configuration presented in Figure 2 but without any type of burnable poison.

To determine the most appropriate U/Th core configuration, we considered two types of fuel assemblies, a homogeneous and an heterogeneous (seed-blanket) assemblies, as shown in Figure 5. In the homogenous assembly all fuel positions carry mixed oxide $(U\text{-}Th)O_2$ fuel rods. In the heterogeneous assembly there are two fuel regions: the first with a supercritical seed consisting of UO_2 fuel rods, and the second with a subcritical blanket with $(U\text{-}Th)O_2$ fuel rods. The ^{235}U enrichments for both assembly types are always kept below 20 $^{w}/_{o}$.

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We consider 20 different mass proportions of U and Th for the mixed oxide fuel in the parametric study: 15 heterogeneous and 5 homogenous [9]. The U/Th core is also divided in three different regions with increasing assembly reactivity resembling the AP1000 configuration shown in Figure 5. In this way a similar fuel load pattern can be utilized for the mixed oxide U/Th cores. The reactivity of the U/Th assemblies is defined through ^{235}U enrichment, and U and Th mass proportions. These configurations, similarly to original configuration, bear no burnable poison.

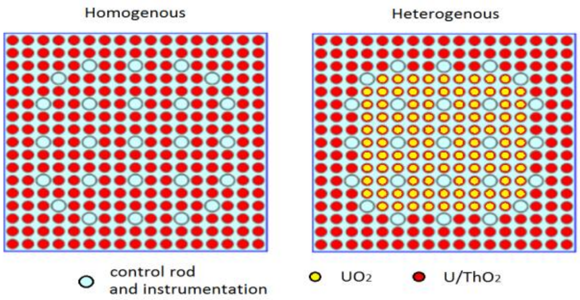

Figure 5. Homogenous and heterogeneous assembly types considered in the parametric study.

2.3. AP-Th1000 core.

The AP-Th1000’s core retains the same characteristics of the AP1000, but its fuel pellets are composed of a mixture of uranium and thorium oxides whose uranium dioxide has 20 w/o enrichment. The reactor has three regions composed of different proportions UO_2 for ThO_2, as shown in Figure 6, for a quarter of the nucleus. Region 1 is composed of 32 w/o UO_2, the 2 region by 24 w/o UO_2 and the 3 region by 16 w/o UO 2. The proportions of the figure are in percentage mass for the UO_2 contained in the MOX of ThO2-UO2.

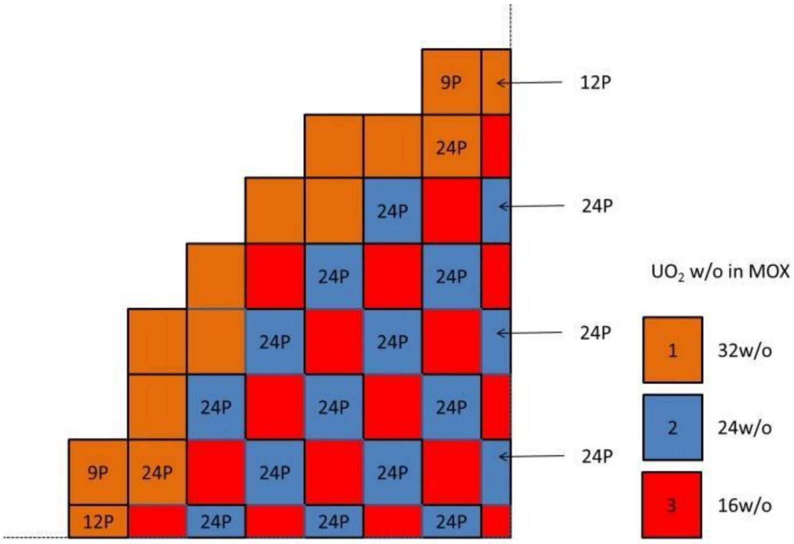

Figura 6. The APTH1000 core with 3 regions and PYREX rods (P).

2.4. AP1000 and AP-Th1000 standard configurations

The core was modeled considering the fuel assemblies, the moderator, the control rods and burnable poison of Pyrex and IFBA. For the cold reactor, the moderator is at a temperature of 293 K and the specific mass of water is 0.995 g/cm³ and for a hot reactor the temperature is 565 K and the specific mass of water is 0.7441292 g/cm³. The calculations are also divided into zero power, taken here as 100 W thermal, hot and at full power of 3400 MW thermal. For these three states, the average fuel temperature is 300 K, 600 K and 900 K, respectively [10].

The Doppler temperature coefficient was evaluated for fuel temperature variations between 600 K and 1800 K, with 300 K intervals, using the C7 configuration setting the temperature of the other components to 600K. The heat treatment of light water was considered in 550 K.

The moderator reactivity coefficient was calculated by setting material temperatures to 600K and varying the moderator's heat treatment between 293K and 600K in 50K intervals. The value of the specific mass adopted was considered using tabulated values in relation to temperature and pressure [11] for the C7 configuration.

Note that SERPENT does not present in its standard nuclear libraries for intermediate temperatures between 293 K and 600 K, this factor is limiting in some cases and will be discussed in the results section. The details of the studied configurations for the complete core are described in table 2.

Table 2: AP1000 core configurations used in this paper.

Configuration	Description
C1	Complete core, zero power, cold (T = 293 K), BOL, water not bored and control bars removed.
C2	Complete core, zero power, cold (T = 293 K), BOL, water with soluble boron (1574 ppm) and control bars removed.
C3	Complete core, zero power, hot (T = 565 K), BOL, water with soluble boron (1502 ppm) and control bars removed.
C4	Full core, total power (Fuel temperature T = 900 K and moderator temperature T = 565 K), BOL, without xenon, water with soluble boron (1184 ppm) and control rods removed.
C5	Full core, total power (Fuel temperature T = 900 K and moderator temperature T = 565 K), BOL, xenon equilibrium, water with soluble boron (827 ppm) and control rods removed.
C6	Complete core, zero power, hot (T = 565 K), BOL, water with soluble boron (1382 ppm) and control rods removed.
C7	Complete core, zero power, hot (T = 600 K), BOL, water not bored and control bars removed.

3. RESULTS AND DISCUSSIONS

3.1. Parametric Studies

The study of the feasibility of converting the reactor core AP1000 from UO_2 to a $(U/Th)O_2$ fuel must be such that minimal changes occur in its design and operational parameters. Thus the following requirements were considered in this study:

I) produce significant amounts of 233U for use in future 233U / Th cores;
II) in order to avoid changing the original design of the fuel element with respect to geometry, ie the rod diameter and pitch length, so that the thermo-hydraulic limits are still satisfied;
III) Maintain the current fuel cycle of 18 months;;
IV) M aintain the values of the negative temperature reactivity coefficients;
V) Ensure that the fraction of delayed neutrons is not drastically reduced.

To perform the parametric study and determine which core configuration will reproduce better the AP1000 core one needs the set of values representative of the AP1000 core. We calculated the core parameters with the SERPENT code for a simplified configuration of the AP1000, configuration C7: full power condition without burnable poison, without soluble boron and without control rods. Table 3 presents the reference parameters. The maximum fuel centerline temperature was obtained with the STH-MOX-Th code [12[[13]. Notice that the q'_{max} is larger than that of Standard configuration presented in Reference [8] due to no burnable poison is present in configuration C7.

Table 3. Reference parameters for the parametric study. The AP1000 parameters were obtained with the SERPENT code for configuration A2 at full power.

Parameter	Value
BOC* k_{eff}	1.31954
EOC** k_{eff}	1.05753
Conversion ratio at BOC, C	0.67
β_{eff}	0.00694
q'_{max} (W/cm)	559
Maximum fuel centerline temperature, T_{CL} (ºC)	1926
BOC* ^{235}U mass (kg)	2866
EOC** ^{235}U mass (kg)	1503
EOC ^{239}Pu mass (kg)	370
EOC ^{241}Pu mass (kg)	48
EOC ^{233}U mass (kg)	0.0

* BOC: beginning of cycle
** EOC: end of cycle

The configurations considered for the parametric study were presented in sect. 2. The desired parameters for the analyses are those presented in Tables 3. For all 20 configurations we used the SERPENT code to perform three-dimensional full core neutronic and burnup calculations. The maximum fuel centerline temperature was calculated with the STH-MOX-Th code. The results obtained for core reactivity parameters and thermal-hydraulic limits are given in Table 4, and those for mass results, in Table 5.

These results were compared with the reference AP1000 configuration shown in Table 3 in order to identify possible configurations to convert UO_2 AP1000 cores to mixed U/ThO_2 cores. To facilitate the data analysis the results presented in Table 7 are ordered according to EOC k_{eff} (largest to smallest), q’$_{max}$ (smallest to largest) and BOC k_{eff} (smallest to largest); and those of Table 5 are ordered according to BOC ^{235}U (smallest to largest), EOC ^{233}U (largest to smallest) and EOC ^{239}Pu (smallest to largest).

Table 4. Neutronics and thermal-hydraulics results for the several configurations.

Configuration	**BOC* k_{eff}**	**EOC** k_{eff}**	**C**	**β_{eff}**	**q’$_{max}$ (W/cm)**	**Fuel T_{CL} (^oC)**
THET-1	1.28696	1.17155	0.87	0.00683	868	3169
THET-2	1.27596	1.13116	0.83	0.00682	934	3454
THET-14	1.25263	1.12293	0.84	0.00679	879	2703
THET-9	1.25958	1.1221	0.83	0.0068	809	2432
THET-15	1.2435	1.11734	0.83	0.00679	804	2481
THET-4	1.26282	1.11119	0.81	0.00683	862	3139
THET-10	1.23899	1.10102	0.83	0.00681	806	2418
THET-6	1.23898	1.10072	0.83	0.0068	813	2445
THET-8	1.2323	1.10032	0.83	0.00678	781	2325
THOM-3	1.25712	1.08906	0.80	0.00681	526	1457
THOM-5	1.25808	1.08449	0.80	0.00678	533	1479
THET-11	1.21853	1.07925	0.82	0.00681	794	2370
THOM-1	1.22064	1.05957	0.82	0.00679	537	1490
THET-5	1.24808	1.08949	0.80	0.00681	790	2925
THET-3	1.22475	1.05729	0.78	0.00685	728	2578
THOM-2	1.21581	1.0502	0.79	0.0068	538	1494
THET-12	1.16951	1.02495	0.80	0.0068	713	2071
THOM-4	1.16319	1.00498	0.81	0.00683	589	1651
THET-13	1.13681	0.99744	0.81	0.0068	613	1729
THET-7	1.23232	0.98116	0.76	0.00675	840	2539

* BOC: beginning of cycle
** EOC: end of cycle

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Table 5. Uranium and Plutonium mass results for the several configurations.

Configuration	**BOC*** **^{235}U mass (kg)**	**EOC*** **^{239}Pu mass (kg)**	**EOC** **^{241}Pu mass (kg)**	**EOC** **^{235}U mass (kg)**	**EOC** **^{233}U mass (kg)**
THET-7	2784	99	21	1394	515
THET-13	3062	126	21	1649	587
THOM-4	3154	136	21	2239	538
THET-12	3353	138	21	1893	543
THET-3	3583	208	26	2118	381
THOM-2	3785	156	21	1687	476
THET-5	4073	205	22	2657	371
THOM-1	3964	132	17	2382	505
THOM-5	4283	210	24	2812	378
THOM-3	4416	175	20	2709	425
THET-11	4626	171	19	3077	469
THET-4	4887	210	21	3321	363
THET-15	5116	154	16	3521	484
THET-6	5148	184	19	3568	436
THET-10	5148	184	19	3569	435
THET-8	5284	155	16	3686	485
THET-2	5539	210	19	3937	357
THET-9	5669	196	18	4064	400
THET-14	5807	167	16	4180	451
THET-1	7895	229	14	6238	348

* BOC: beginning of cycle
** EOC: end of cycle

Analyzing the results given in Table 4, we notice that the heterogeneous configurations, with seed-blanket fuel elements, satisfy the neutronic constraints but do not satisfy the thermal-hydraulic limits. 17 of them have EOC k_{eff} greater than 1.05000, which indicate that they can potentially meet the end of cycle core reactivity requirement. However, the maximum linear heat generation rates of all heterogeneous configurations are greater than the reference result, and consequently the fuel centerline temperature.

For the homogeneous case, the situation is completely different. All configurations satisfy neutronics and thermal-hydraulic limits with exception of THOM-4, which does not have enough reactivity at the end of life. We choose THOM-1 as the preferred configuration to carry out the study because it has the closest EOC k_{eff} to the reference AP1000. We notice that all configurations present conversion ratio greater than that of the AP1000 reference core and the effective delayed neutron fraction similar to it.

Once THOM-1 was selected as the feasible configuration, we modeled the AP-Th1000 core to compare its behavior with the actual AP1000 18 month cycle. The purpose here is to define possible means of core reactivity control throughout the cycle, namely the boron concentration and burnable poison options, and verify results of temperature coefficients of reactivity and kinetics parameters. The AP1000 configuration is A1.

The chosen AP-Th1000 core configuration resembles typical cores with three enrichment zones but substituting enrichment for mass proportion of Th and U. The ^{235}U enrichment is 20 $^{w}/_{o}$, and the three mass proportion zones contain the following mixtures: (32 $^{w}/_{o}$ UO_2 – 68 $^{w}/_{o}$ ThO_2), (24 $^{w}/_{o}$ UO_2 – 76 $^{w}/_{o}$ ThO_2), and (20 $^{w}/_{o}$ UO_2 – 80 $^{w}/_{o}$ ThO_2). In Tables 9 and 10 we compare these results at BOC for the AP1000 and AP-Th1000 obtained with the SERPENT code model. In this way we can observe what differences in the core parameters the mixed Th/U fuel introduces without any modeling interference.

The maximum centerline fuel temperature and DNBR was calculated with STH-MOX-Th code yielding T_{CL}=1615°C and minimum DNBR of 2.85 [13].

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Table 6. Comparison of the neutronic core parameters between AP1000 configuration A1 and AP-Th1000 at BOC.

Parameter	AP1000	AP-Th1000
Doppler reactivity coefficient, α_F (pcm/°F)	-2.87±0.14 to -0.91±0.14	-1.91±0.15 to -1.45±0.15
Moderator reactivity coefficient, α_M (pcm/°F)	-3.72±0.47 to -25.1±0.53	-3.52±0.49 to -28.38±0.56
Maximum linear power density for configuration at full power (W/cm)	519±30	406±23
Prompt neutron mean generation time (μs)	25.7±3.8	19.1±4.3
Effective delayed neutron fraction	0.00694±0.00124	0.00683±0.00125
k_{eff} (zero power, BOC, cold and control rods removed)	1.20421±0.00051	1.14420±0.00005

Table 7. Boron concentration at BOC for the AP1000 configuration A1 and AP-Th1000.

Operational Condition	Boron concentration (ppm)	
	AP1000*	AP-Th1000
Zero power, BOC, hot, without Xe, and control rods removed	1502	1200
Full power, BOC, hot, without Xe, and control rods removed	1184	1000
Full power, BOC, hot, equilibrium Xe, and control rods removed	827	650
Zero power, hot, and control rods removed	1574	1400

* From WESTINGHOUSE [8].

Fig. 5 presents the behavior for the k_{eff} as a function of burnup (in days) for the AP1000 and AP-Th1000. Since the Thorium core has a lower initial k_{eff} it does not require as much burnable poison as the AP1000 core. Thus we kept the same positions for the IFBA burnable poison in the core but considered three different ^{10}B concentrations in the ZrB_2: 50 $^w/_o$, 20 $^w/_o$ and 0 $^w/_o$, i.e., without IFBA. One can observe that the AP-Th1000 core requires less burnable poison to control the core reactivity throughout the cycle. It is even possible to remove all IFBA burnable poison from the core.

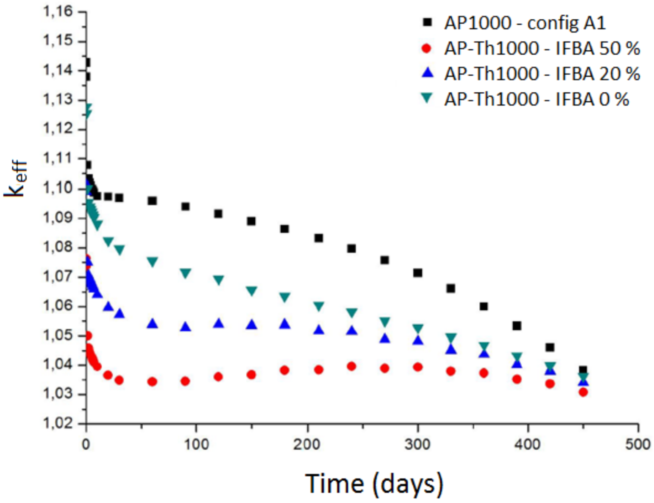

Fig. 5. k_{eff} versus burnup for the AP1000 and AP-Th1000 for several ^{10}B concentrations in the IFBA burnable poison.

3.2 Detailed Calculations

The study of the detailed calculations of the AP-Th1000 reactor, studied in section 3.1, must meet some minimum design criteria, already mentioned in 3.1 (items I to V). Within these criteria there will be an evaluation of each one of them in Begin of Life (BOL), Medium of Life (MOL) and End of Life (EOL).

In section 3.1 the AP-Th1000 reactor was defined through a parametric study. It was defined that the AP-Th1000 reactor would not use burnable poison by coating the fuel (IFBA), thus simplifying the design of the fuel rods. In this section of results this reactor will be evaluated in detail regarding operation and safety.

The definition of the amount of soluble poison in Begin of life is an important parameter for a PWR. This data will provide the required maximum values of boron dilution in the moderator to allow the control of the reactor with the control banks in different states of operation.

In the design of AP-Th1000, as mentioned previously, the burnable poisons of IFBA, which coated the fuels, were removed. Thus, the concentration of boron to be used in each of the main reactor states at the beginning of life should be re-evaluated. Due to this structural change in the core of the reactor it is expected that the values of boron dissolved in the moderator are higher than those calculated in table 7, for the data states.

Tables 8 show the k-eff and boron concentration for some of the main reactor states. The states are described in Table 2.

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Table 8. K-eff of the AP1000 and AP-Th1000 in the core in different states in BOL.

	Ref. [8] – AP1000	SERPENT – AP1000	SERPENT – AP-Th1000	Boron Concentration (PPM)	
				AP1000 [8]	AP-Th1000
C1	1,205	1,20385 ± 0,00004	1,22567 ± 0,00003	-	-
C2	0,99	0,99208 ± 0,00004	0,99023 ± 0,00003	1502	2389
C3	0,99	0,98987± 0,00004	0,99001 ± 0,00004	1574	2068
C4	1,0	0,99983 ± 0,00003	0,99993 ± 0,00004	1382	1904
C5	1,0	1,00945 ± 0,00003	0,99948 ± 0,00003	1184	1699
C6	1,0	0,99983 ± 0,00003	1,00013 ± 0,00003	827	1290

The boron curve was also calculated for the AP-Th1000 reactor and compared to the boron curve of AP1000 in Figure 6. A curva de boro calculada com base em vários steps de tempo. In each of these steps was diluted 100 pcm of boron, and in comparison, to the same step without boron was determined the coefficient of dilution of boron at each instant of time. The desired reactivity at each time point was that available at the end of the cycle (EOL).

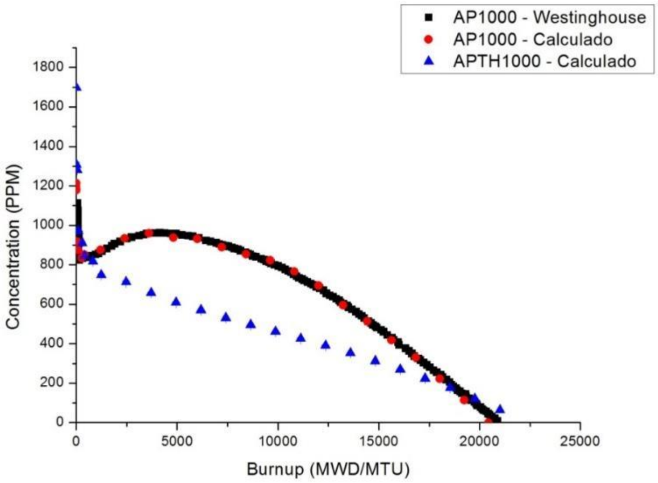

Figure 6: Boron curve for the AP1000 and AP-Th1000.

The safety parameters inherent in this reactor were investigated: its maximum linear power density, its coefficient of temperature reactivity for the moderator and fuel, and its delayed neutron fraction. All the mentioned factors were evaluated at the beginning of cycle (BOL), cycle mean (MOL) and end of cycle (EOL), thus guaranteeing its safety throughout its operation, in the period of 18 months. The values obtained are presented in table 9.

Table 9. Core main Security parameters.

Parameter	BOL	MOL	EOL
Coefficient of fuel reactivity, α_F (pcm/ºF)	-0.91 ± 0.15 à -2.45 ± 0.15	-0.89 ± 0.16 à -1.73 ± 0.16	-0.98 ± 0,16 à -1.60 ± 0,16
Moderator reactivity coefficient, α_M (pcm/ºF)	-3.52 ± 0.13 à -28.38 ± 0.13	-3.33 ± 0.14 à -28.03 ± 0.15	-3.04 ± 0,16 à -29.83 ± 0,16
Effective fraction of delayed neutrons, β_{eff}	0.00683±0.00010	0.00599±0.00011	0.00539±0.00012
Maximum linear power density, Q_L (W/cm)	454±23	560±18	532±21
Maximum temperature in the center of hot channel fuel, T_{CL} (°C)	1789	2188	2081

The values shown in Table 9 show that the temperature reactivity coefficient for the moderator remained negative throughout the reactor operating time. In addition, the moderator temperature reactivity coefficient (α_M) maintains its value always close to the value of early life, showing little variation.

The value of the β_{eff} demonstrates a variation of the order of 100 pcm, over time, and a maximum insertion of 500 pcm of reactivity is recommended to guarantee the integrity of the reactor.

The maximum linear power density is the parameter that guarantees the integrity of the fuel, since it relates to the maximum temperature in the center of the fuel. The linear power density Q_L demonstrates complete preservation of the material's physical integrity over time through its maximum temperature in the center of the fuel. The temperature remains well away from the temperature of 2800 ° C, which would imply in the melting of the fuel, for the UO_2, it is worth to emphasize that this parameter is overestimated, since in the case of the mixture of oxides of uranium and thorium its value of fusion has A considerable increase.

Table 10 shows the mass of the main fissile isotopes present in the irradiated fuel after 240 days of cooling.

Table 10. Mass of fissile isotopes present in the irradiated fuel in AP1000 and AP-Th1000. The values demonstrate a considerable reduction of plutonium compared to AP1000.

	Mass (kg)			
	^{233}U	^{235}U	^{239}Pu	^{241}Pu
AP1000	-	211	136	26
AP-Th1000	260	397	37	8

4. CONCLUSION

The objective of this work was to evaluate the possibility of converting an advanced PWR reactor with UO2 fuel into a mixed oxide fuel of (Th, U) O2 to produce ^{233}U and reduction of the generated plutonium. These objectives were successfully achieved in accordance with the applied methodology, which demonstrated the advantages in its conversion, through minimum changes in the design of the reactor used as reference.

The results obtained by exchanging the constituent material of the fuel pellets with thorium mixed oxide (AP-Th1000 core) were to reduce the maximum power density by 22%, to reduce by 66% the produced fission plutonium, to produce 260 Kg of ^{233}U at the end of the first cycle on the removed fuel, and eliminate the need to use IFBA burnable venom to control core reactivity throughout the firing. In investigating the operation of the defined thorium reactor, it was noted that the combustible venom (IFBA) of the fuel could be removed because at the end of the cycle it led to an excess of reactivity lower than the reference reactor. The lower thermal limits of the developed reactor make it a safer option and allow an operational gain since it can be operated at a power above 3400 MW thermal.

Regarding safety, the fuel temperature and moderator reactivity coefficient was investigated during the entire reactor operation, the effective neutron fraction and the maximum power density in the hot channel (as well as the maximum temperature in the center of the fuel). The AP-Th1000 presented lower thermal limits than the reference reactor, AP1000. The effective fraction of delayed neutrons has always remained higher than 500 pcm and the temperature reactivity coefficients remain negative throughout the operating time. The evaluation of control rods was also verified [12], their details will be discussed in the article submitted to the journal Annals of Nuclear Energy, as the second part of the article already published together with an evaluation of the natural resource use in open and closed cycle and Cost to manufacture the fuel.

Future work involving the study of the AP-Th1000 should determine the recharge of the reactor in a new cycle through an artificial intelligence algorithm, and a more detailed hydraulic term investigation. The AP-Th1000 is not intended to be the reactor of the future but the present reactor, optimizing the fuel cycle in PWR reactors without the need to change the mechanical and operational specifications of its core.

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REFERENCES

1. J. Maiorino, J. M. L. Moreira, G. Laranjo, A. Busse e T. Santos, *“Thorium as a New Primary Source of Nuclear Energy”*, em IX Congresso Brasileiro de Planejamento Energético, Florianópolis, 2014.
2. International Agency Atomic Energy (IAEA), *“Technology Roadmap Update for Generation IV Nuclear Energy Systems”*, TEC-DOC, OECD, 2014.
3. INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), *“Analysis of Uranium Supply to 2050*”, TEC-DOC, Vienna, 2001.
4. WNA, “World Nuclear Association,” 15 April 2016. [Online]. Available: http://www.world-nuclear.org/. [Acesso em 22 Abril 2016].
5. IThEO, *“Thorium Resources*”, 2014. [Online]. Available: http://www.itheo.org/thoriumresources. [Acesso em 01 04 2016].
6. IAEA, *“Thorium fuel cycle — Potential benefits and challenges*”, IAEA-TECDOC-1450, Austria, 2005.
7. J . e. a. Leppänen, “*The Serpent Monte Carlo code: Status, development and applications in 2013*.”, **Annals of Nuclear Energy, vol. 82**, pp. 142-150, 2015.
8. WESTINGHOUSE, 2011, Westinghouse AP1000 Design Control Document Rev. 19. Westinghouse Electric Corporation. Available at http://pbadupws.nrc.gov/docs/ML1117/ML11171A500.html
9. J. R. Maiorino, G. L. Stefani, J. M. L. Moreira, P. C. R. Rossi, and T. A. Santos, *Feasibility to convert an advanced PWR from UO2 to a mixed U/ThO2 core – Part I: Parametric studies.”,* **Annals of Nuclear Energy, vol. 102**, 2017.
10. Godfrey, A. T., *“VERA core physics Benchmark Progression Problem Specifications”*, U. S. Departament of Energy & Oak Ridge National Laboratory, CASL-U-2014-0014-002, 2014.
11. Parry, W. T., et al., ASME International Steam Tables for Industrial Use, American Society of Mechanical Engineers 2000.
12. Stefani, L.G., Maiorino, J.R., Moreira, J.M.L., Rossi, P.C.R., Santos, T.A., The feasibility to convert the uranium dioxide core of an advanced PWR (AP 1000TM) in a thorium uranium mixed oxide core. Part II- Detailed Calculation, to be submitted for publication at Annals of Nuclear Energy.
13. Santos, T.A., Maiorino, J.R., Laranjo, S.G., 2016, On the thermal limits for PWR calculation in operational conditions using a mono channel, mono phasic model for mixed thorium-uranium oxide fuel, in 16th Brazilian Congress of Thermal Sciences and Engineering Proceedings of ENCIT 2016, ABCM, Vitoria, E.S. Brazil.