An Overview of Thorium Utilization in Nuclear Reactors and Fuel Cycles

Jose Rubens Maiorino [1,2], Francesco D'Auria[2], Reza Akbari-Jeyhouni[2,3]
[1]Federal University of ABC, CECS, Av. dos Estados, 5001, Santo André-SP-Brazil
[2]University of Pisa, GRNSPG-DESTEC, Largo L Lazzarini, Pisa, Italy.
[3] Amirkabir University of Technology, Department of Energy Engineering & Physics, Tehran, Iran
joserubens.maiorino@ufabc.edu.br ; f.dauria@ing.unipi.it ; reza_akbari@aut.ac.ir

ABSTRACT

The Nuclear Power Plants (NPP) constructed in the XX century, also called generation II reactors, are still in operation, most of them Light Water Reactors, but are being decommissioned. These reactors have a low burn up (~30 MWD/kg U) and utilize UO2 as nuclear fuel and are operating in a Once Through Cycle (OTC); they use a very low energy content of the natural resources (~0,5%). To overcome economic and political and partly safety issues, since the end of last century, and beginning of this century, the nuclear industry launched a new generation of evolutionary reactors, called Generation III, such as the Westinghouse AP 1000, and AREVA EPR. These reactors still use uranium as primary source but have an increased burn up (~60 MWD/Kg U), which although increasing the utilization of the natural resources (up to 1%), still are not significant to be considered sustainable: if only uranium is used in an OTC, uranium will be exhausted in this century. To increase the utilization of natural resources, recycling of uranium and plutonium is already in use in many countries and used as Mixed Oxide of U-Pu fuel (MOX) in the same thermal reactors. To turn nuclear energy sustainable, a long-term deployment of innovative reactors is underway. These reactors and their associated fuel cycle are old concepts with technological improvements and generically denominated as Generation IV, are in development and, in some cases, they are breeders, HLW burners, and efficient concepts. Another concept that although not new is constitute by the Small Modular Reactors (SMR), with power less than 300 MWe, which nowadays are deserving a lot of attention by the nuclear industry. Another option is to utilize thorium as a primary source of energy. Although not fissile at thermal energy, it produces ^{233}U, which is one of best fissile nuclide (number of neutrons produced per neutron absorbed). Also, it is three times more abundant than uranium in the earth crust and has thermal physics properties when used as (U-Th) O_2 better than UO_2. Several Th/U fuel cycles, using thermal and fast reactors were proposed and are still under investigation. Although, the first reactors to utilize thorium were PWR, using (U-Th)O_2, such as the Indian Point, and Shipping Port, thorium has been proposed as fuel for the molten salt reactor, the advanced heavy water reactor, High Temperature Reactors, Pebble Bed reactor, fast breeder reactors, and more recently, for the innovative accelerator driven system in a double strata fuel cycle and for the Generation IV, such as the LFTR - Liquid Fluoride Thorium Reactor, which is a self-sustainable Molten Salt Reactor, promising to turn nuclear energy by fission in a sustainable source, with a utilization of the natural resources of 100%. This paper, besides an introduction of the present time uranium fuel cycles, will give an over view of the thorium utilization in nuclear reactors and fuel cycles, with an emphasis in Advanced PWR.

Keywords: *Thorium, Reactors and Fuel Cycles, Advanced Big and Small PWR, Liquid Fluoride Thorium Reactor*

1 INTRODUCTION

Most of the commercial nuclear reactors in operation in the word (PWR; BWR; PHWR) were constructed in the XX century, and use uranium as primary source of energy, operating in a Once Through Cycle (OTC). These reactors have an extraction burn up (B) of ~30 MWD/kg U (for Light Water Reactors, PWR, BWR), or ~7-8 MWD/kg U (for Heavy Water Reactors, HWR which uses natural uranium as input feed), and are denominated Generation II reactors, to differentiate from the early prototypes reactors built in the beginning of nuclear age, denominated Generation I reactors. Figure 1, illustrates a typical mass balance for a typical 1000 MWe, PWR, with a B=30 MWD/kg U, and an average enrichment of 3 wt % in mass of the input UO_2, as calculated by the IAEA VISTA code [1]. As illustrated by this Figure 1, Generation II reactors has a very low utilization of natural resource, defined as the mass of fissionable material in the reactor by the mass of natural resource used (~0.5%) [2].

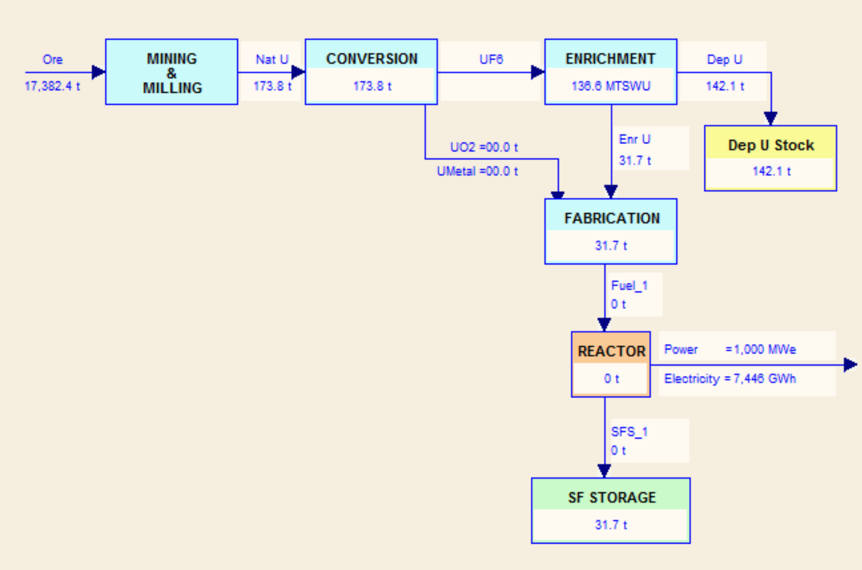


Figure 1: Mass Balance for a typical generation II PWR (3wt%; 30 MWD/kg U)[1]

Given the loss of competitivity of the nuclear industry, the public opinion against nuclear generation, and safety issues, since the beginning of the century the industry launch new innovative designs to be competitive and safety improvement. These reactors denominated as Generation III, are already in advanced stage of projects, many of them in construction and operation [3]. They are big reactors, with powers in the range of 1000 MWe. These reactors are still using the same type of fuel, i.e., UO_2, and the main characteristics remain almost the same as the Generation II Reactor but with improvements related to safety, economy and operational performance, such as:

- Å Design Standardization to expedite licensing (pre-licensing), diminishing construction time implying in reducing the capital cost (economics criteria);
- Å Simplified Design to simplify the operation and reduce the operational faults;
- Å Greater availability, increase the time between refuelling, and increase the plant life time (60 year);
- Å Minimization of the possibility of Core Meltdown;
- Å Emergency coolant system, passive;
- Å Greater Burn up (60 MWD/ Kg U) and reduces the waste production;
- Å Utilization of advanced fixed burn up poison to increase the fuel lifetime.

Table 1 illustrates the main reactors already in operation, in construction or ready for deployment, restricting to Pressurized Water Reactor, (PWR or VVER), since this is the type of Reactor the one with most commercial interest.

Table 1: Commercial Advanced PWR in the World [3]

Developer	**Reactor**	**MWe**	**Stage of Development**
Advanced power reactors operational			
KHNP(Korea)	APR1400	1450	Shin Kori 4 in South Korea, operating since Jan 2016. Under construction: Shin Hanul 1&2 in South Korea, Barakah in UAE. Korean design certification 2003. US design certification application.
Gidropress (Russia)	VVER-1200	1200	Novovoronezh II, from mid-2016, as AES-2006. Under construction at Leningrad. Planned for Akkuyu in Turkey and elsewhere
Advanced power reactors under construction			
Westinghouse(USA)	AP 1000	1170	Under construction in China and USA, many units planned in China (as CAP1000). US design certification 2005, UK generic design approval 2017. Canadian design certification in progress.
AREVA (France)	EPR	1630	Was to be future French standard, French design approval. Being built in Finland, France & China.
CNNC & CGN (China)	Hualong	1170	Main Chinese export design, under construction at Fangchenggang and Fuqing, also Pakistan;
Advanced power reactors ready for deployment			
Mitsubishi(Japan)	APWR	1400	Planned for Tsuruga in Japan. US design certification application for US but delayed. EU design approval for EU-APWR Oct 2014.
AREVA & Mitsubishi	Atmea1	1150	Planned for Sinop in Turkey. French design approval Feb 2012. Canadian design certification in progress.
Gidropress	VVER-TOI	1300	Planned for Kursk II, Nizhny Novgorod and many more in Russia.

Presently the Generation II reactors are being decommissioned and substituted by Generation III reactors. Although related with operational performance, economy, and safety issues they are a great improvement compared with generation II reactors, still there are a small improvement n the natural resource utilization (~factor of 2), as illustrated in the mass balance, Figure 2, for a typical Advanced PWR (1000 MWe), with a burnup of 60 MWD/kg U, and an average enrichment of ~4% in mass of ^{235}U operating in a OTC, also calculated by VISTA [1]

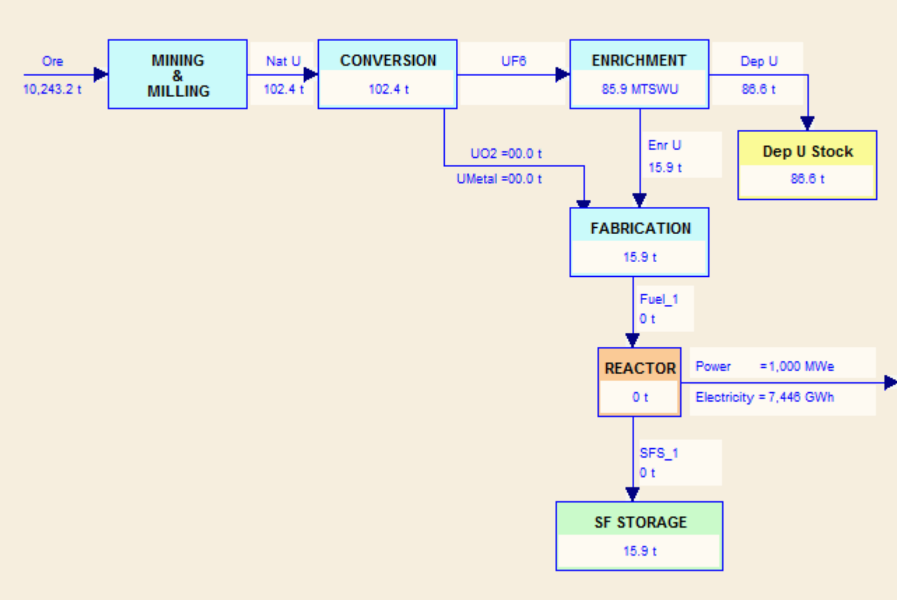


Figure 2: Mass Balance for a typical generation III PWR (~4wt%; 60 MWD/kg U) [1]

To increase the utilization of the energy content of the natural resources, many countries, are already reprocessing the spent fuel, from the present time thermal reactors, to extract the uranium and plutonium and reutilize in the same reactor as mixed oxide of U-Pu, MOX fuel, in a closed fuel cycled. This option increases the utilization of the natural resources by a factor of ~10[2].

To turn nuclear energy sustainable, a long-term deployment of innovative reactors is underway. These reactors and their associated fuel cycle are old concepts with technological improvements and generically denominated as Generation IV, are in development and, in some cases, they are breeders, HLW burner, and efficient concepts, such as the High Temperature Reactors (Thermal and Fast), Sodium or Lead Fast Breeder Reactors, Molten Salt Reactors, and the water super critical reactor [4].

In this work a review of thorium and its utilization in nuclear reactors and fuel cycles is going to be made, with an emphasis in Advanced PWR reactors.

2 THORIUM

Thorium is an actinide, metallic element, and it is named for ñThorò, the Scandinavian god of war by his discover, Jöns Borzelius, a Sweden in 1829. The abundance of Th in the earth is 6,000 ppb, three times that of uranium, and it is found naturally in its isotope ^{232}Th (100%), being radioactive ($T_{1/2}$= 1.4x10^{10} years), and in its natural chain decay produces isotopes like ^{228}Ra; ^{228}Ac; ^{228}Th, ^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{208}Tl to a stable ^{208}Pb. Much of the internal heat the earth has been attributed to Thorium and Uranium natural decay. Most of naturally thorium resources is in form of ThO_2: Thorianite and thorite as in New England(USA) (melting point of 3300 C, the highest of all oxides), or in monazite sand(a mixture of calcium, cerium, thorium, and other rare earth elements), in the Brazilian coast. It is important to notice that there is probably more energy available for use from thorium in the minerals of the earthôs crust than from combined uranium and fossil fuel sources [5,6].

The International Thorium Energy Organization, gives for Brazil, Turkey and India the biggest reserves of thorium in the world, as illustrate in Table 2[7].

Table 2 - Estimated thorium reserves in the word (higher estimation) [7]

Country	Th reserves (kt)	Country	Th reserves (kt)
Brazil	1300	Canada	172
Turkey	880	Russia	155
India	846	South Africa	148
Australia	521	China	100
US	434	Greenland	93
Europe(Norway)	430	Kazakhstan	50
Egypt	380	Rest of the world	1781
Venezuela	300	World	7590

2.1 Nuclear Properties of Th

Although the cross section for fission at thermal energy is zero (non-fissile material), and only fast fission would be possible by using thorium, given the high capture thermal cross section for the reaction, ^{232}Th(n,ɔ)^{233}ThŸ ^{233}PaŸ ^{233}U(fissile), makes that Th could be used to produce ^{233}U(fertile isotope), and used as fuel or in blankets(breeder) of fast reactors. Figure 3, illustrate the Th cross sections, as function of energy with data given by ENDF-VI [5].

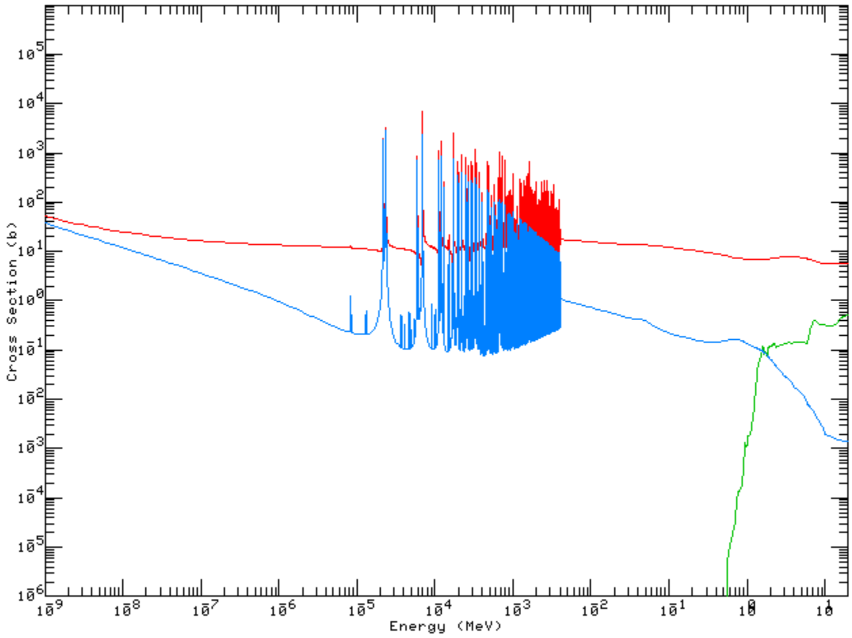
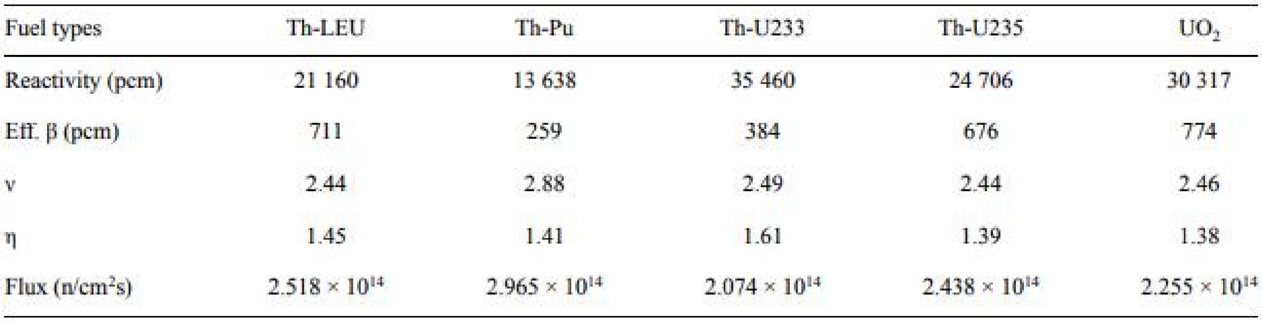


Figure 3: ^{232}Th cross sections from ENDF-B-VI. The red line is the total cross section, the blue line the absorption and the green line the fission

Using of Thorium base fuel option in nuclear reactor has many nuclear advantages: the ^{233}U has highest number of neutrons produced per neutron absorbed among all thermally fissile isotopes; neutron poison (Xenon and Samarium) production is 20% lower than other fissionable isotopes; by having a big absorption cross section and being fertile, it could reduce burn up poison in Advanced PWR reactors and extended the time life cycle; and reducing the radiotoxicity of the spent fuel. Also a recent report from IAEA[8], analyzed the PWR neutronics characteristics with mixed oxide

thorium fuel compared to UO_2 using 3-D calculation of a typical PWR assembly, OTC cycle; average burnup up to 45 MWD/kg HM, considering: i)Thorium with low enriched uranium (enrichment < 20% ^{235}U) (thoriumï LEU fuel); ii) Thorium with reactor grade plutonium (thoriumï plutonium fuel); iii) Thorium with ^{233}U (Th-^{233}U fuel); and iv) Thorium with ^{235}U (Th-^{235}U fuel).
Table 3 presents calculated neutronic parameters of the cores with the different thorium fuels and the standard UO_2 fuel. At the same level of fissile enrichment of 5 wt% in all fuels, the excess reactivity at the beginning of life (BOL) is the highest for the Th-^{233}U fuel, reflecting the ability of this fuel type for extended burnup operations. The UO_2 fuel achieves the next highest excess reactivity at BOL. At the assumed enrichment level, the excess reactivity of thorium-plutonium fuel core is not sufficient to achieve a realistic cycle length. It is well known that for this type of fuel, a higher enrichment level, in the range of 15 to 20 wt%, is required to achieve realistic cycle length. The effective delayed neutron fraction (eff. ϐ) in the thorium-LEU, Th-^{235}U and UO_2 fuels is at the same level due to the same major fissile nuclide, ^{235}U. The effective delayed neutron fraction of a fuel is determined by its fissile nuclides. The effective delayed neutron fraction of the Th-^{233}U and thorium-plutonium fuels is significantly lower than that of the other fuels. This is because the delayed neutron fraction of ^{233}U and ^{239}Pu is half the value.

Table 3: Neutronic characteristic of PWR cores with different fuels [8]



Fuel types	Th-LEU	Th-Pu	Th-U233	Th-U235	UO_2
Reactivity (pcm)	21 160	13 638	35 460	24 706	30 317
Eff. β (pcm)	711	259	384	676	774
ν	2.44	2.88	2.49	2.44	2.46
η	1.45	1.41	1.61	1.39	1.38
Flux (n/cm^{2}s)	2.518×10^{14}	2.965×10^{14}	2.074×10^{14}	2.438×10^{14}	2.255×10^{14}

Once irradiated in a reactor, the fuel of a thoriumï uranium cycle contains an admixture of ^{232}U (half-life 68.9 years), which appear by the reaction ^{233}U(n,2n)^{232}U(n,ɔ)^{233}U, whose radioactive decay chain includes emitters (particularly ^{208}Tl) of high energy gamma radiation (2.6 MeV). This makes spent thorium fuel treatment more difficult, requires remote handling/control during reprocessing, or shielding thickness and during further fuel fabrication, but on the other hand, may be considered as an additional non-proliferation barrier [9].

2.2 Thermal Physics and Irradiation Properties of Th based fuels

Thorium Oxide has good thermal physics properties which allows thermal hydraulics advantages to be used in PWR reactors. Thorium oxide (ThO_2) is relatively inert and does not oxidize further, unlike UO_2. It has higher thermal conductivity and lower thermal expansion coefficients compared to UO_2, as well as a much higher melting point (3300 °C). The work of Kutty et al [10] presents an excellent review of the Thermophysical Properties of Thorium-based Fuels, for the variation of densities, thermal expansion coefficients, and thermal conductivity with temperature, and here we will not repeat these correlations.

Also, properties of Thorium-based fuels under irradiation, early experiments showed great promise for ThO_2 based fuel, with fuel performance parameters superior to UO_2 under similar operating conditions. These results created an incentive for various experiments in the late 1970s and early 1980s. An important lesson learned during this period was the importance of uniform, non-granular structure to ensure superior performance from the thorium fuel. It is noted that even poorly fabricated (granular) thorium performed comparably with high quality UO_2 fuel. Throughout these experiments, numerous fuel performance parameters were investigated and correlated, including fuel power, fuel burnup, fission gas release, pellet microstructure, sheath strain, sheath corrosion.

Fission gas release (FGR) is primarily dependent on power density (fuel temperature), with fuel burnup as a secondary variable [8]. Figure 4 plots FGR versus linear power density and compares UO_2 to granular and non-granular thorium. Below ~40 kW/m fuel microstructure plays a minimal role in FGR due to the low fuel temperature. The lines drawn in the figure represent data trends and demonstrate comparable performance between UO_2 and granular thorium; non-granular thorium demonstrates superior performance [8].

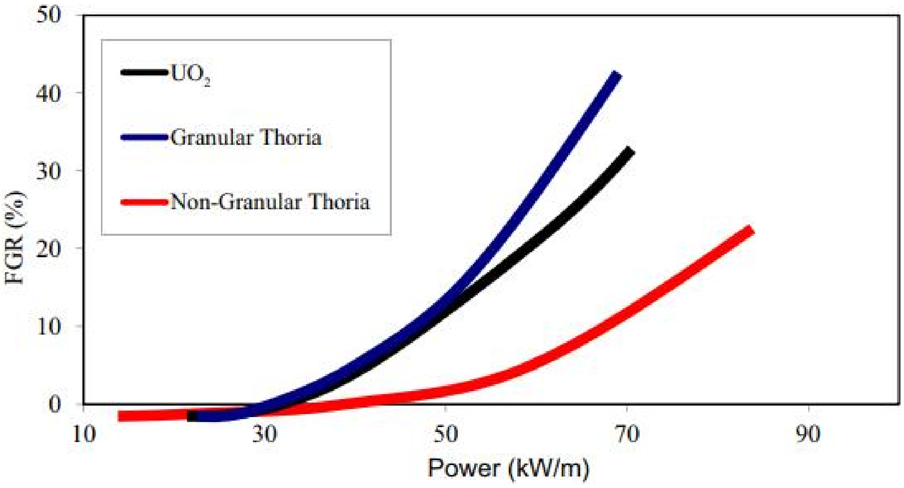


Figure 4: Fission gas release (%) of UO_2 and thorium fuel [8]

Finally, a sophisticated data collection programme has been designed in which several thorium-plutonium oxide fuel pins will be irradiated in simulated LWR conditions in the fuel-testing reactor in Halden, Norway. The fuel will be prototypical of what can be fabricated commercially as a variant of todayĝs uraniumï MOX fuel. The irradiation will be performed by the Institutt for Energiteknikk (IFE) operators of the Halden Reactor. Accordingly, with a recent note published at Nuclear News [11], the experiments were successfully conducted, and Th MOX fuel is ready to be certified to be used commercially.

3 THORIUM UTLIZATION IN NUCLEAR REACTORS AND FUEL CYCLES

Although there are many review papers [5,6,12] as well as technical reports [8,13,14] discussing the thorium utilization in nuclear reactors and their associated fuel cycle, here we are going to shortly review this topic, with an emphasis in the PWR, since it is the reactor with a great chance to utilize thorium in a near term deployment.

3.1. Utilization of thorium in PWR.

The feasibility of thorium utilization in PWRs has been demonstrated in nuclear power plants such as the PWR Indian Point Reactor number 1 (270 MWe), which was the first to utilize a core loaded with (U-Th)O2, with high enriched U (93 w/o), and achieving a maximum burn up of 32 MWD/kg HM[15]. The last core of the Shippingport PWR was loaded with ThO_2 and $(U\text{-}Th)O_2$ fuel rods using the seed-blanket concept and operated as a light water breeder reactor during 1200 effective full power days and reached a final burnup of 60 MWD/kg HM[15]. The experience on fabrication, post-irradiation analysis of thorium fuel from these developments had demonstrated the technical feasibility of the utilization of Thorium as fuel in PWR [15]. The Radkowsky concept proposes a concept to be used in typical fuel elements of PWRs in which the seed is a U/Zr alloy, and the blanket an $(Th_{0.9}\text{-}U_{0.1})O_2$ oxide using low enriched uranium(RTF), as illustrated in figure 5, with the core and fuel assembly parameters given in table 4. Calculations showed that the utilization of the RTF, offers a solution to a problem of an efficient utilization in LWR of current technology with the two fuel cycle options: the non- proliferate thorium based, and the plutonium incineration thorium-based cycles, demonstrating a potential for an efficient and competitive thorium-based fuel, aimed to improve an overall proliferation resistance of the fuel cycle [16].

Table 4: Core and Fuel assembly RTF parameters (Th-U and Th-Pu Cycles) [16]

Parameter	*Th-U Cycle*	*Th-Pu Cycle*
Total Power(MW_{th})	3,400	3,400
Assemblies(SBU)	193	193
Seed/Blanket Vol. Fraction	0.4/0.6	0.5/0.5
Seed V_m/V_f	3.0	3.0
Blanket V_m/V_f	1.8	1.8
Seed Fuel	$U_{0.2}$/Zr alloy, 20 wt% ^{235}U	$Pu_{0.2}$/Zr alloy
Blanket Fuel	$(Th_{0.9}$-$U_{0.1})$ $O_{2,}$, 20wt% ^{235}U	$(Th_{0.9}$-$Pu_{0.1})O_2$
In core fuel management	3 batch seed schemes, 300 Full Power Days	same

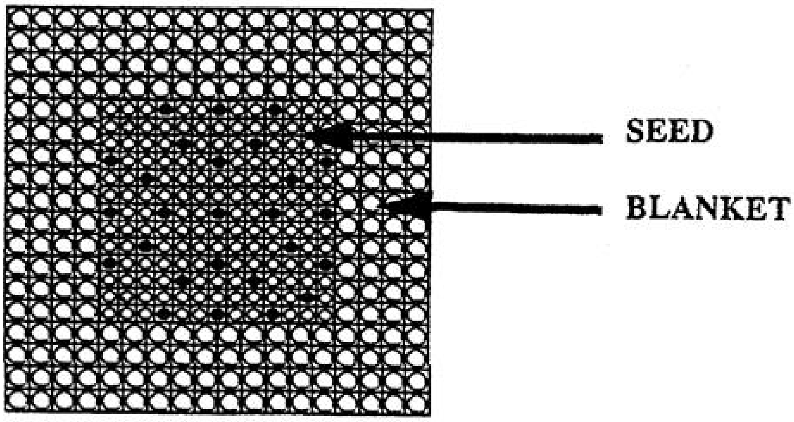


Figure 5: Seed-Blanket Unit (SBU) fuel assembly of RTF[16].

In Brazil, in the framework of the Brazilian German agreement that a comprehensive research program about Th utilization in PWRs was conducted by the CDTN/NUCLEBRAS (ñCentro para o Desenvolvimento da Tecnologia Nuclearò) in Brazil and the former KFA (Kernforschungsanlage Juelich) in Germany aiming at analysing and proving the option of thorium utilization in PWRs [17]. The program was conducted between 1979 and 1988, and defined core configurations of Th fuel cycles for standard 1300 MW Siemens PWRs; defined technical specifications for fuel technology of $(U\text{-}Th)O_2$ and $(Th\text{-}Pu)O_2$; studied fuel design and modelling, including the fuel behaviour in irradiation experiments at the FRJ-2 at KFA; studied the spent fuel treatment, including laboratory investigation on reprocessing spent thorium fuels with non-irradiated elements. The program was interrupted in 1988 when a complete reformulation of the Brazilian nuclear sector took place and the CDTN was transferred from NUCLEBRAS to the ñComissão Nacional de Energia Nuclearò (CNEN). A final report [18] contains detailed technical results obtained in this research program.

Recently in the open literature many researchers turned their attention to Th fuel cycles in PWRs aiming at reducing the generation of minor actinide waste, at improving the nuclear power sustainability, and at better fuel utilization and breeding. Herring et al.[19] studied the utilization of mixed thorium/uranium dioxide $(U\text{-}Th)O_2$ in a typical generation II PWR using a 17x17 type fuel assembly. The results showed that the (U-Th)O_2 cores could be burned to about 87MWD/ kg HM using 35 wt% UO_2 and 65 wt% ThO_2 with an initial enrichment of about 7 wt.% of the total heavy metal fissile material. Ashley et al.[20] discussed open cycles for thorium-fueled nuclear power systems, Baldova et al.[21,22,23]discussed the use of high conversion Th-^{233}U fuels in current generation PWRs in the assembly and full core three-dimensional levels, and Lindley et al. [24,25,26] studied thorium-fueled PWRs with reduced moderation and possible closed fuel cycles. Tucker et al. [27] have studied the using of a thoriumï plutonium mixed oxide fuel for a Westinghouse-type 17x17 PWR. These studies were interested in assessing the feasibility of using ^{233}U-Th fuels in PWR without worrying about how to obtain the initial ^{233}U fuel load or the transition from a uranium to a thorium core in the current nuclear power plants.

We also have made a study to convert an Advanced PWR, to use Th-U fuel. [28,29]. As case study to demonstrate the feasibility to convert an Advanced Reactors, we use the AP 1000, as reference reactor. To perform the conversion study, we consider the AP 1000 core without any burnup poison and set of criteria were adopted in this study to ensure minimum changes due to the plant with the U/Th fuel as follows: (a) Produce the maximum amount of fissile ^{233}U at end of cycle (EOC). This can be done by maximizing the conversion ratio; (b) Generate minimum amount of fissile plutonium to reduce long lived waste generation (an important sustainability criterion for nuclear power). (c) Ensure that the maximum centre line fuel temperature and maximum linear power density do not exceed the values from the AP1000 reference core; (d) Ensure that kinetics parameters and temperature coefficient of reactivity do not change significantly to maintain similar current AP1000 safety and transient behavior; and (e) Ensure that the fuel cycle life is 18 months or longer.

To find a feasible core we considered 20 cases with different mass proportion of ^{232}Th, ^{235}U, and ^{238}U, keeping as constrain the maximum enrichment of ^{235}U as 20 w/0(LEU). From these cases, 15 were seed blanket Fuel Element concept (heterogenous), and 5 were homogeneous fuel elements distributed in the 3 different regions of the AP 1000. The fuel elements studied are illustrated in Figure 6, and reference 28 contains a detailed mass proportion in the different regions of the core. Thus, we performed neutronics burn up, using SERPENT code, calculation for the first cycle and check for each case the thermal limits using STH-MOX-Th [30]. The results obtained for these 20 cases for the k_{eff} at BOC and EOC, conversion factor, ɓ$_{eff}$, maximum linear power density, fuel centre line temperature, and mass of ^{233}U; ^{239}Pu, ^{241}Pu, can be found in [28]. These results showed that the configurations based on the heterogeneous concept presents the better reactor physics properties but the highest peak linear power densities. They were dismissed simply because of thermal hydraulic limits, i.e., high maximum centre line fuel temperature. Among the configurations with EOC keff greater than 1.05000 the q$\hat{q}_{max}$ was always larger than the reference AP1000 value by 30ï 67%. For the homogeneous configurations, most of them satisfied the criteriaôs, however the configuration with three different mass proportion zones, the first containing (32wt% UO_2-68wt%ThO_2); the second with (24wt% UO_2-76wt% ThO_2), and the third with (20wt% UO_2-wt80% ThO_2), using ^{235}U LEU (20 wt%), and corresponding with the 3 enrichment zones of the AP 1000 (4.45 wt%; 3.40 wt%; 2.35 wt%).was the one which produces more ^{233}U at EOC, as well as a lower linear power density, and therefore it was the one choose to be the converted core of AP 1000.

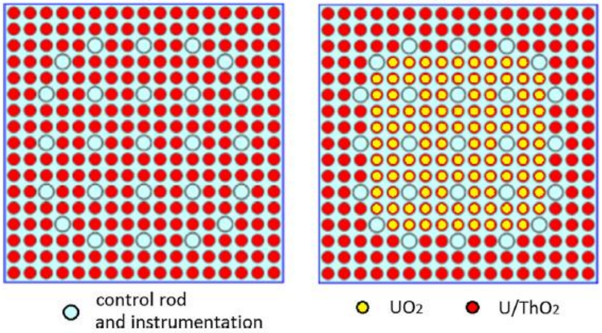


Figure 6: Homogenous and heterogeneous assembly types

Once a homogeneous configuration was selected as the feasible configuration, we modelled the AP-Th1000 core to compare its behaviour 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. Figure 7 shows the variation of the reactivity(k_{eff}) with full power operation time for several concentrations of Boron into the IFBA, and the Soluble Boron Concentration curve. 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).

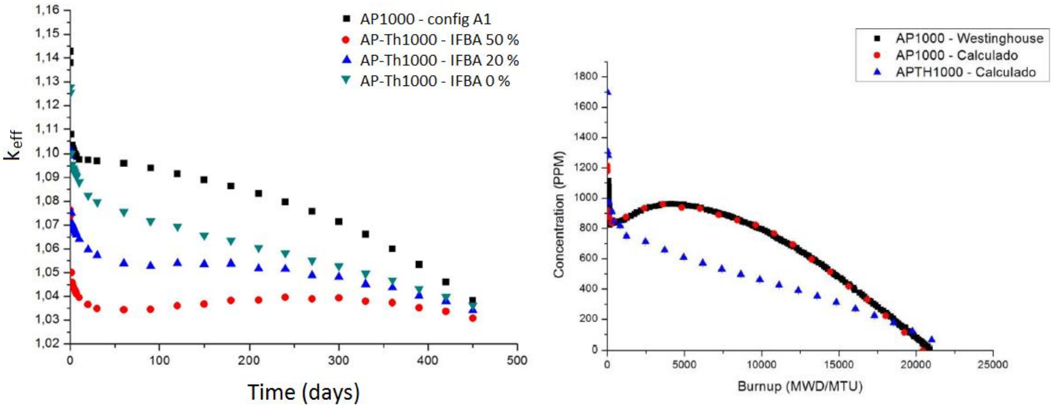


Figure 7: keff versus burnup for the AP1000 and AP-Th1000 for several ^{10}B concentrations in the IFBA burnable poison and the soluble boron concentration curve(first cycle)

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 the in-core fuel management is ongoing. 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, by reprocessing the uranium(^{233}U, ^{235}U, ^{238}U) and using in the same reactor, as a pure closed U-Th fuel cycle.

Finally, a study to convert a Small Modular Reactor(SMR), to use U-Th)O_2 was successfully made[31], however since this work is going to be present at this conference[32], we are going to skip this work here in this paper, and just conclude that a Korean SMART Reactor[32] can use a mixed fuel core with 65wt% and 10wt% thorium respectively in the central and outer zone, with a longer cycle than reference SMART core. In the reference core 680 burnable absorber rods have been used while in the proposed thorium mixed oxide core 388 burnable absorber rods have been used that means a large reducing in the amount of poison material. Also, analysis of the soluble boron changes during the cycle shows that in the proposed core we can used less amount of soluble boron during the cycle.

3.2. Utilization of Thorium in other Reactors and Fuel Cycles

The utilization of thorium-based fuel has been investigating in several types of reactors, such as the PHWR, High Temperature Reactors(HTR), and more recently in Generation IV, reactors, mainly the Molten Salt Reactors(MSR), and Accelerator Driven Systems.

In India, the utilization of Thorium is a priority since it has relatively modest Uranium resources but very large Th resources. BARC (Brabha Atomic Research Center), is actively involved in R&D, fabrication, characterization and irradiation testing of ThO_2, $(Th\text{-}Pu)O_2$, $(Th\text{-}U)O_2$ fuels in power and test reactors. India designed AHWR 300 Mwe) using thorium-plutonium or thorium-^{233}U seed fuel in mixed oxide. Some steps towards utilization of Thorium in India include use of ThO_2 for flux flattening in PHWR, use of (Th-Pu) O_2 fuels, and use of ThO_2-$^{233}UO_2$ fuels in the Advanced Heavy Water Reactor [33]. In addition, the KAMINI Test Reactor was the first to utilize ^{233}U-Al alloy fuels. ThO_2 as axial and radial blanket in the Kalpakkam Fast Breeder Test Reactor in India is being considered [34,35].

Closed Thorium fuel cycles have been designed in which PHWRs play a key role due to their fueling flexibility. Thorium based HWR fuels can incorporate recycled U-233, residual plutonium and uranium from used LWR fuel, and minor actinide components in waste-reduction strategies. In the closed cycle, the driver fuel required for starting is progressively replaced with recycled U-233, so that an increasing energy share in the fuel comes from the Thorium component. AECL has a Thorium Roadmap R&D project [3]. Chinese R&D groups associated with Canadians study the possible Thorium fuel use in the China's Qinshan Phase III PHWR units.

For HTR, the experience in thorium-based fuel in the old concept of HTGR, and Pebble Bed German Reactor using TRISO type of fuel, are been used in Generation IV HTR, and in the Pebble Bed Modular Reactor. Also, the experience of the old Oak Ridge MSR Reactor, allied with the utilization of TRISO in a Liquid Fluoride Salt Coolant, the so-called Generation IV, LTR (Fluoride Salt-Cooled High-Temperature Reactors) are deserving an attention of several countries. Finally, the LFTR - Liquid Fluoride Thorium Reactor, which is a self-sustainable Molten Salt Reactor, promising to turn nuclear energy by fission in a sustainable source, with a utilization of the natural resources of 100%., is being pursued as a longer-term science focused science program, mainly by China, and the final goal of thorium utilization. Figure 8, illustrated schematically, the LFTR, with on line reprocessing of ^{233}U [4,36].

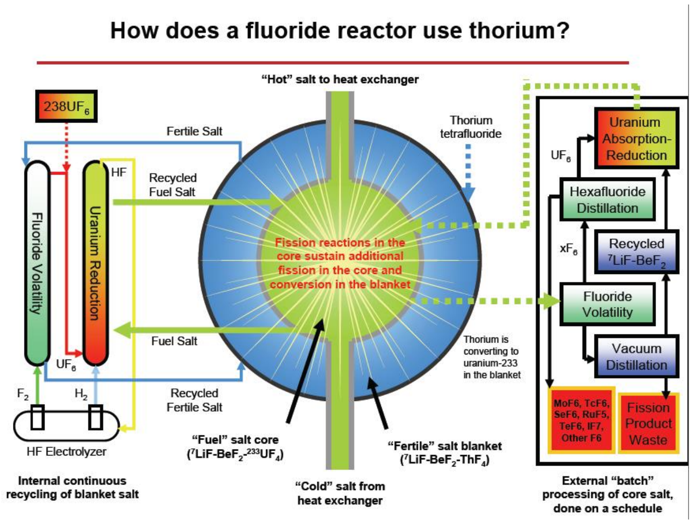


Figure 8: Schematic view of the LFTR ð Liquid Fluoride Thorium MSR(available at https://liquidfluoridethoriumreactor.glerner.com/)

Besides the utilization of thorium in Generation IV reactors, its utilization has been proposed in a subcritical reactors driven by an external neutron source(spallation), as the proposed by Carlo Rubbia[37], in which a fast subcritical reactors composed of thorium and transuranic(TRU), cooled by lead and having as external source of ultra-fast neutrons produced by protons from an accelerator, now days denominated Accelerator Driven System(ADS).These systems used in fuel cycles, such s the double strata fuel cycle, could reduce the radiotoxicity in time by a factor of a

100, being a good option for spent fuel management, to reduce the requirements in the final repository[38]. Figure 9 illustrate schematically the ADS, and Figure 10, a possibilities of closed fuel cycles using Fast Reactors and ADS.

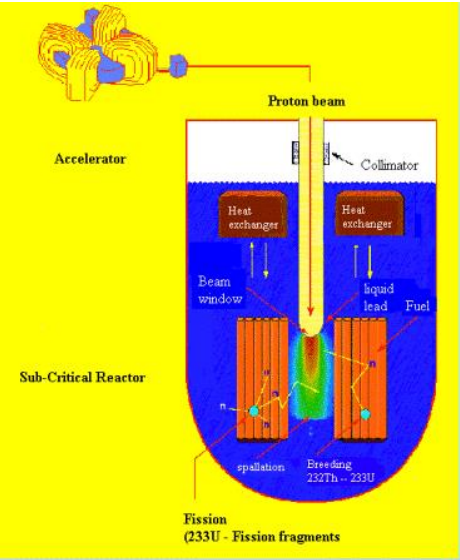


Figure 9: Schematic view of Thorium ADS

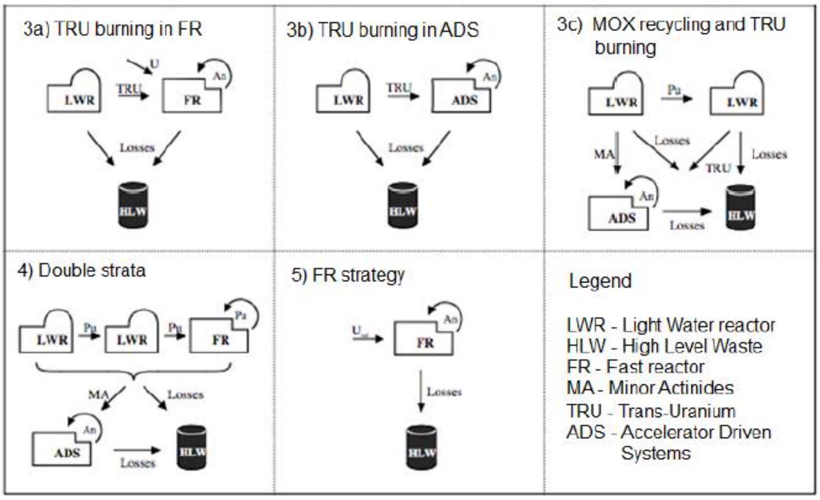
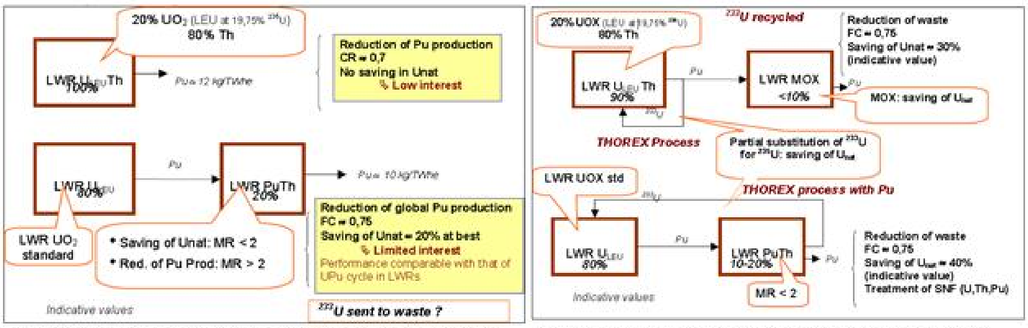


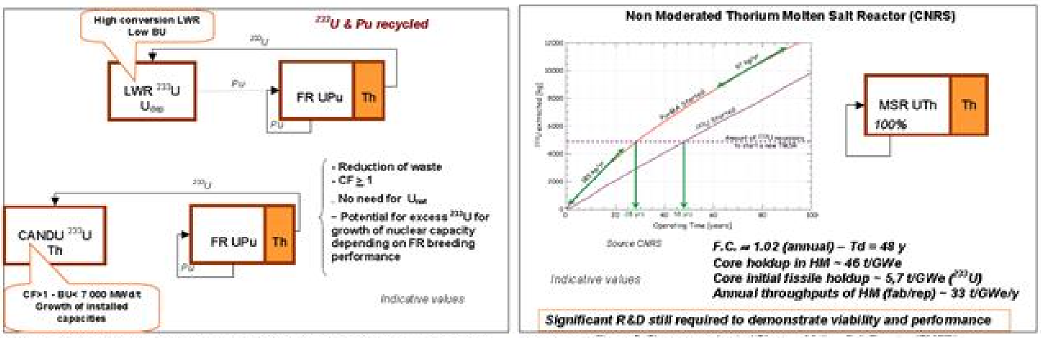
Figure 10: Possibilities of closed fuel cycles using Fast Reactors and ADS.

A study by Generation IV International Forum [39] suggested some thorium-based fuel cycles, as showed in Figure 11, in which the type of fuel cycle is self-explained. Although they conclude that the use of thorium in OTC for LWR is not attractive, as we have already mentioned, mainly due to no saving in natural resource, in our point of view they did not consider the option to use the uranium(233; 235;238) reprocessed in an PWR using LEU U-Th in the same reactor as is done in the closed U-Pu fuel cycle in thermal PWR, as illustrated in Figure , in which we are presently working, and is a pure U-Th fuel cycle using thermal Advanced PWR(AP-Th 1000).[29]. Also they did not consider the TANDEM fuel cycle proposed by Nuttin et al [40], for a PWR(UO_2)-CANDU(Th-Pu)-CANDU(^{233}U-Th).



(a)Use of thorium-based fuels in LWRs with an open fuel cycle. Comparable use can be made in HWRs fueled with ~5% UO2 (LEU at 19.75% 235U) and ~95% thorium

(b) Use of thorium-based fuel in closed LWRs fuel cycle.



(c)Use of thorium-based fuels symbiotic closed fuel cycles, FR and HWR.

(d) Thorium Molten Salt Reactors

Figure 11: Thorium-based fuel cycles.

4 CONCLUSION

This work has shown that there is a great interest in the Th utilization in power reactors and waste burners. Studies show that (Th-U) O_2 fueled reactors have an extended burnup compared to UO_2 fueled reactors and reduce significantly the amount of high level waste (Pu, minor actinides and long-lived fission products). Also, the technology for thorium utilization has a proved experience and not requires changes in the present time reactors**.**

Although the Liquid Fluoride Thorium Reactor, is the ideal for use Th, in a near term deployment it looks like the first reactors do utilize Th could be the Advanced PWR or PHWR reactors. For big reactors they could operate in closed fuel cycle U/Th, in the same way as the closed U/Pu and produces enough U-233 for the future Self Sustainable MSR. For SMR it is a suitable fuel to be used. Therefore, fission nuclear energy still has a long time as source of energy, clean, sustainable and renewable.

Finally, given the Brazilian large Thorium reserves, it appears important to follow the steps taken by India and other countries and promote R&D programs on Thorium in the country. In addition, energy planners should consider Thorium as a nuclear primary source of energy in their long-range planning.

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