

A Review of Thorium Utilization as an option for Advanced Fuel Cycle- Potential Option for Brazil in the Future

José Rubens Maiorino* and Thiago Carluccio
Instituto de Pesquisas Energéticas e Nucleares(IPEN)
P.O. Box 11049(Pinheiros)
05422-970-São Paulo- SP -Brazil

Abstract

Since the beginning of Nuclear Energy Development, Thorium was considered as a potential fuel, mainly due to the potential to produce fissile ^{233}U . Several Th/U fuel cycles, using thermal and fast reactors were proposed, such as the Radkwocki once through fuel cycle for PWR and VVER, the thorium fuel cycles for CANDU Reactors, the utilization in Molten Salt Reactors, the utilization of thorium in thermal (AHWR), and fast reactors(FBTR) in India, and more recently in innovative reactors, mainly Accelerator Driven System, in a double strata fuel cycle. All these concepts besides the increase in natural nuclear resources are justified by non proliferation issues (plutonium constrain) and the waste radiological toxicity reduction. The paper intended to summarize these developments, with an emphasis in the Th/U double strata fuel cycle using ADS. Brazil has one of the biggest natural reserves of thorium, estimated in 1.2 millions of tons of ThO_2 , as will be reviewed in this paper, and therefore R&D programs would be of strategically national interest. In fact, in the past there was some projects to utilize Thorium in Reactors, as the “Instinto/Toruna” Project, in cooperation with France, to utilize Thorium in Pressurized Heavy Water Reactor, in the mid of sixties to mid of seventies, and the thorium utilization in PWR, in cooperation with German, from 1979-1988. The paper will review these initiatives in Brazil, and will propose to continue in Brazil activities related with Th/U fuel cycle

KEYWORDS: *Thorium, Advanced Fuel Cycle, non proliferation, waste radiological reduction, Brazilian experience, P&T,ADS,*

1. Introduction

Thorium (Th) is an actinide, metallic element, and it is named for “ Thor”, the Scandinavian god of war by his discover, Jöns Borzelius, a Sweden in 1829. Chemical properties of thorium may be found in [1]. 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 ($T_{1/2}= 1.4 \times 10^{10}$ 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

* Corresponding author, Tel. 55-11-3816-9111, Fax: 55-11-3816-9432, e-mail: maiorino@ipen.br

naturally thorium resources is in form of ThO_2 or 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 earth's crust than from combined uranium and fossil fuel sources.

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, $^{232}\text{Th}(n,\gamma)^{233}\text{Th}\rightarrow^{233}\text{Pa}\rightarrow^{233}\text{U}(\text{fissile})$, makes that Th could be used to produce $^{233}\text{U}(\text{fertile})$, and used as fuel or in blankets(breeder) of fast reactors. Figure 1, illustrate the Th cross sections, as function of energy with data given by ENDF-VI.

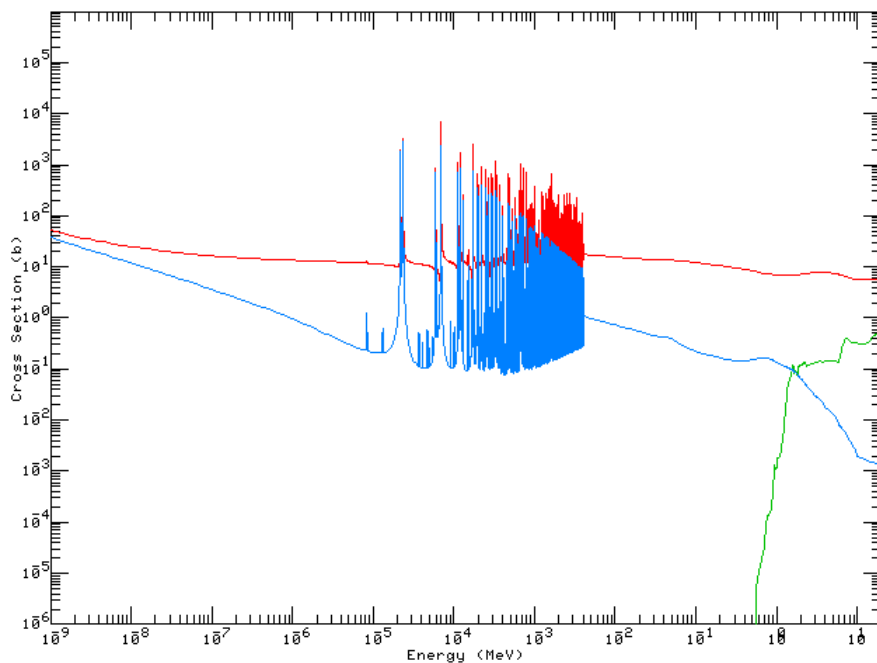


Figure 1: ^{232}Th cross sections from ENDF-B-VI. The red line is the total cross section, the blue line the absorption and the green line the fission.

This paper will review the utilization of thorium as fuel in several cycles and reactor types, which had been studied and proposed around the world, based mainly in technical documents published by the International Atomic Energy Agency (IAEA), mainly the TEC-DOC 1319[2], TEC-DOC-1349[3], which gave the options and trends in thorium utilization, as well as the potential of thorium based fuel cycles to constrain plutonium and reduce long lived waste toxicity. Finally, the past Brazilian experience in R&D on thorium utilization will be reviewed, and a proposal to continue such activities will be suggested.

2. Review of the Thorium Utilization R&D- Reactors and Fuel Cycle

Several countries (Brazil, Canada, China, France, Germany, India, Japan, Nederland, Republic of Korea, Russia, United States etc) were, or still are, involved with R&D related with the Th utilization in different fuel cycles and reactor types(Light and Heavy Water, Fast Reactors, High Temperature Reactors , Molten Salt Reactors, and more recently Accelerator Driven System, ADS). The IAEA had also promoted several Technical Meetings(TM), Coordinate Research Projects (CRP), etc related with Th utilization, and is starting a new CRP based on recommendation of the International Technical Working Groups on Light Water, Heavy Water, and Fast Reactors, and had already realized a first Consultancy Technical Meeting[4], in December, 2003, to kick off such CRP. This paper will briefly review these R&D programs, by classifying the Th utilization by reactor type and fuel cycle.

Light Water Reactor:

Due to this type of Reactor is the most commercially utilized, mainly in a “once trough fuel cycle”, many R&D programs had focused in the Th utilization in it. In the USA, in the sixties the PWR Indian Point Reactor number 1(270 MW_e), was the first to utilize a core load with (Th_{0.9}/U_{1-0.1})O₂, with high enriched U (93w/0), achieving a maximum burn up of 32 MWD/kg HM[5]. Also the last core of the Shipping port PWR(shutdown in 1982) was ThO₂ and (Th/U)O₂, operating as a Light Water Breeder Reactor(Seed-Blanket Concept) during 1200 effective full power days of operation (60 MWd/kg HM)[6]. The experience on fabrication, post irradiation analysis of thorium fuel from these developments had been reported [7,8] demonstrating the technical feasibility of the utilization of Thorium as fuel. The seed-blanket concept proposed by Radwosky[9,10]offers an option for fuel thorium utilization in LWR, and a non proliferation fuel cycle.(Radwosky Thorium Fuel-RTF).. Basically, a typical fuel element of a Westinghouse PWR(3400 MW_{Th}, 193 fuel assemblies) , is divided into two regions, as illustrated in figure 2, with the core and fuel assembly parameters given in table 2. 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, and reduce the requirements in the spent fuel storage[11].

Table 2: Core and Fuel assembly RTF parameters (Th-U and Th-Pu Cycles)[9]

<i>Parameter</i>	<i>Th-U Cycle</i>	<i>Th-Pu Cycle</i>
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 % ²³⁵ U	Pu _{0.2} /Zr alloy
Blanket Fuel	(Th _{0.9} -U _{0.1})O ₂ , 20% ²³⁵ U	(Th _{0.9} -Pu _{0.1})O ₂
In core fuel management	3 batch seed scheme, 300 Full Power Days	same

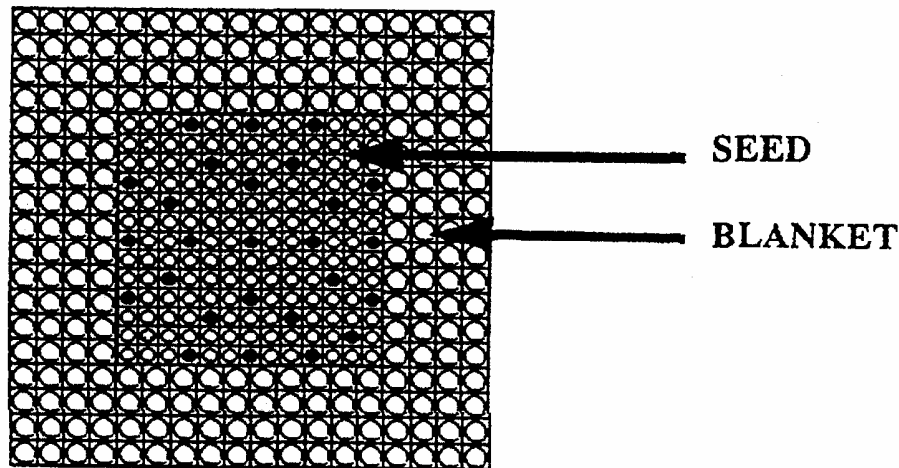


Figure 2: Seed-Blanket Unit (SBU) fuel assembly.

Also, the Radwosky Light Water Thorium Nuclear Reactor concept, are being considered for utilization in Russia's VVER with hexagonal RTF assemblies, and studies are being conducted by the Kurchatov Institute in Moscow, Brookhaven National Laboratory, and MIT in the USA[11]. Also the Institute of Physics and Engineering, Obninsk in Russia, also is conducting Research in the utilization of Thorium in a VVER-1000[12]

Moreover, the US DOE in its Nuclear Energy Research Initiative (NERI), supported the projects, a) The Advanced Proliferation Resistant, Lower Cost Dioxide Fuel for Light Water Reactors Project (INEEL); b) The Fuel for a Once-Through Cycle(Th, U)O₂ in a Metal Matrix Project(ANL), AND C) A Proliferation Resistant Hexagonal Tight Lattice BWR Fuel Core Design for Increased Burn up and Reduced Fuel Storage Requirements(BNL)[3].

In other countries, Japan some investigation were realized at JAERI and in Kyoto in Nuclear Data, critical experiments of polyethylene moderated core fuelled with thorium and highly enriched uranium, and a once trough burning process of plutonium has been studied for the disposal of excess Pu, using a stable fuel material of multi-phases which would geological stable and becomes high level waste (HLW) without reprocessing (PuO₂-ThO₂-Al₂O₃-MgO[13]. In France, CEA performed some neutronics studies of thorium utilization for a 900 MW_e PWR for 4 cases, a) Highly Enriched Uranium/²³²Th, b) First Generation Plutonium/²³²Th, c) Uranium with a high ²³³U content/²³²Th , d) Medium Enriched Uranium/²³²Th, and confirmed the advantage of thorium carrier which offer a better conversion factors than in the uranium cycle and low minor actinide production[14]. The Brazilian experience on thorium utilization in PWR is going to be presented in the next session. Finally, the last IAEA CRP(1995-2001)[3],with participation of Germany, Israel + USA, Japan, Netherlands, Russia, had as one of the benchmarks, the calculation of the isotopic composition, cross sections and fluxes for a typical PWR cell loaded with (Pu-Th)O₂ as function of burn up, including the residual amount of Pu Minor Actinides. A new

IAEA CRP, on thorium utilization had been recommended to start next year, involving Light and Heavy Water Reactor, Fast Reactors, and innovative Reactors (e.g. ADS)[4].

Heavy Water Reactors:

Thorium in heavy water reactor is of strategic interest in heavy water reactors in countries like Canada and India, since the natural resources in these countries are significant. For the Canadian Deuterium Reactor (CANDU), AECL is conducting programs on thorium fuel cycles, including fuel-cycle studies, reactor physics measurement, and development of reactor physics methods, fabrication of thorium fuels, fuel irradiation in the NRU reactor at Chalk River, post-irradiation examination, and assessments of fuel performance and waste management. The cycles studied by AECL include the recycling, the once-through thorium cycle (OTT), the utilization of thorium as a carrier for plutonium annihilation, and even in the DUPIC fuel cycle. The simulations were made for a CANDU-6 reactor using a CANFLEX fuel bundle with 1.8 % slight enriched UO_2 , in the outer 35 elements and natural ThO_2 in the inner elements. Also gadolinium-doped bundles were used in the inner core regions in an OTT cycle. The main conclusion was that the reactor performs within the existing enveloping design parameters without major design modification, and the uranium utilization is better than that of the natural-uranium fuel cycle. Measurements were performed at the Zero Power ZED-2. critical facility and provided data for reactor physics calculation qualification(WIMS-AECL). Fabrication process were investigated at AECL to fabricate ThO_2 and $(\text{Th/Pu})\text{O}_2$, dry-powder blending, wet-powder blending, , and co-precipitation. Irradiation experience, as reported in WR-1 reactor (1970-1980), and in NPD reactor [15,16].

In India, the utilization of thorium is a priority given the natural resources in the country (India has a relatively modest U resources, but is one of biggest deposits of Th in the world, ~300,000 ton), and generation of nuclear power is the ultimate goal of the India Nuclear Power Strategy. BARC (Bhabha Atomic Research Center), is actively involved in R&D, fabrication, characterization and irradiation testing of ThO_2 , $(\text{Th-Pu})\text{O}_2$, $(\text{Th-U})\text{O}_2$ fuels in power and test reactors. Use of ThO_2 for flux flattening in PHWR, the proposed utilization of $(\text{Th-Pu})\text{O}_2$, ThO_2 , $^{233}\text{UO}_2$ in the Advanced Heavy Water Reactor are some steps towards utilization of Thorium in India. Also the Test Reactor, KAMINI is the first to utilize ^{233}U -Al alloy fuel. Fuel cycles studies in PHWR (SSET- Self Sustaining Equilibrium Thorium, and OTT), had been also conducted by India [17, 18].

High Temperature Reactors:

The High Temperature Gas Cooled Reactor (HTGR), considered in its design coated micro spheres of thorium and high enriched uranium. In fact, the only US commercial Th/U fuelled HTGR in operation was the Fort St. Vrain (330 MW_e). The Gas Cooled Fast Breeder Reactor, also propose to utilize Th as blanket.

In Germany and Nederland there were studies for utilization of thorium as coated particles embedded in the fuel elements in the Pebble bed HTR[3] Also, Germany and China in the IAEA CRP, performed some studies in the Th fuel cycles to burn Pu in the 200 MW- Module Pebble bed reactors[3].India also reported a study of a compact High Temperature Reactor(CHTR), based on thorium cycle for high temperature applications, using fuel in the form of micro spheres of $(\text{Th-}^{233}\text{U})\text{C}_2$ kernel coated with 3 layers of soft pyrolytic carbon, ZrC and a hard outer carbon layer[3].

Now days, with the proposal of HTR's as innovative reactors in GIF, and INPRO, the utilization of Th, could again be re born as an attractive fuel to meet the criteria for these initiatives.(non proliferation, sustainability, radio toxicity reduction).

Fast Reactors:

Although, thorium is a fertile material (^{233}U producer), and quite adequate to be used in fast reactors, as fuel or blanket, in a closed fuel cycle (reprocessing- THOREX), mainly with breeding purposes, it has not been considered in the liquid metal(Na) fast reactors in operation(French Reactors, the Japanese, MONJU, Russia's BN-600) or in construction(the Chinese , Experimental Fast Reactor, CEFR, or in the India, Prototype Fast Breeder Reactor) which still relying on the use the U/Pu fuel cycle. The only initiative which deserves some attention is the possibility of ThO_2 as axial and radial blanket in the Na cooled Fast Breeder Test Reactor, at Kalpakkam, India[3], indicating that India may consider in the future Th/U fuel cycle in Fast Reactors. However since the Fast Gas Cooled Reactor is one of reactor types in GIF, helium cooled reactor and closed fuel cycle, it could bring again the interest of Th/U fuel cycle in fast reactors.

Molten Salt Reactors:

Several countries are presently involved in the development of Molten Salt Reactor, such as Japan, Russia (MOSART), Hungary, Czech Republic(SPHINX- Closed fuel cycle)[19,20,21, 2, 3]. Also this kind of Reactor, had been considered as an innovative reactor in the USA GIF and IAEA INPRO R&D initiatives, and thorium may be an option for these reactors and it's on line fuel cycle. In fact the THORIS-NES (Thorium Molten Salt Reactor Nuclear Energy Synergetic System, [2,19]), which is composed of simple thermal power fission station (FUJI) and a AMSB based in a single fluid, as $^7\text{Li}_2\text{F}-\text{BeF}_2$, Molten Salt target-blanket concept(ADS) was proposed as a global nuclear energy system[x]. This concept (MSR) was proposed to be studied by Japan in the framework of the last IAEA-CRP on "Potential of Thorium-based Fuel Cycles to constrain Plutonium and to reduce long-term Waste toxicity, using as Pu vector the same as the IAEA benchmark problem and as MSR a fuel salt, $\text{Li}_2\text{F}-\text{BeF}_2-\text{ThF}_4-\text{PuF}_3$, flowing into a hexagonal graphite column.[3]

Accelerator Driven System(ADS)

ADS are an innovative reactor, in which a sub critical fuel mixture (U, Th, Pu, and TRU) is bombarded with ultra fast neutrons coming from a spallation source induced by an accelerator. Given the hard fast spectrum this concept is being considered as a dedicated burner of High Level Waste (HLW, Minor Actinides, and Long Lived Fission Products) preferable in a Double Strata Fuel Cycle, using the concept of Partition& Transmutation[x,y]. Thorium and Th/U fuel cycle are being considered to be used in such concept. In fact, C.D. Bowman from LANL, proposed in 1991, a conceptual molten salt thermal energy amplifier and transmutation system using Th/U fuel cycle[22]. Later on, a group from CERN, led by Carlos Rubbia's[23],presented the basic concept of the Fast Energy Amplifier a sub critical nuclear system based in the utilization of $^{233}\text{U}_{0.1}-^{232}\text{Th}_{0.9}$ as BOL fuel imbibed in melted lead as coolant with an external source of neutrons coming from spallation in Pb induced by protons from a 3 stage cyclotron(1 GeV,12.5 MeV), which raised the international interest in ADS. Further, with slight FEA modifications Rubbia proposed a dedicated ADS incinerator[24]using as equilibrium fuel mixture a total of 9.2 ton of $^{232}\text{Th}+30\%$ TRU with an overall performance to burn ~400 Kg/year of TRU

and producing 175 Kg/ year of ^{233}U . Figure 3 illustrates the flow diagram of the LWR HLW for incineration in the Rubbia's concept, and table 3, the main characteristics of the EA incinerator ADS. The Rubbia concept was applied for the case of Spain[24], where 9 large PWR are in operation, and concluded that a cluster of 5 EA's would be an effective solution to the elimination in 37 years to the present and foreseen(2029) PWR waste stockpile of Spain with a major improvement over Geological repository.

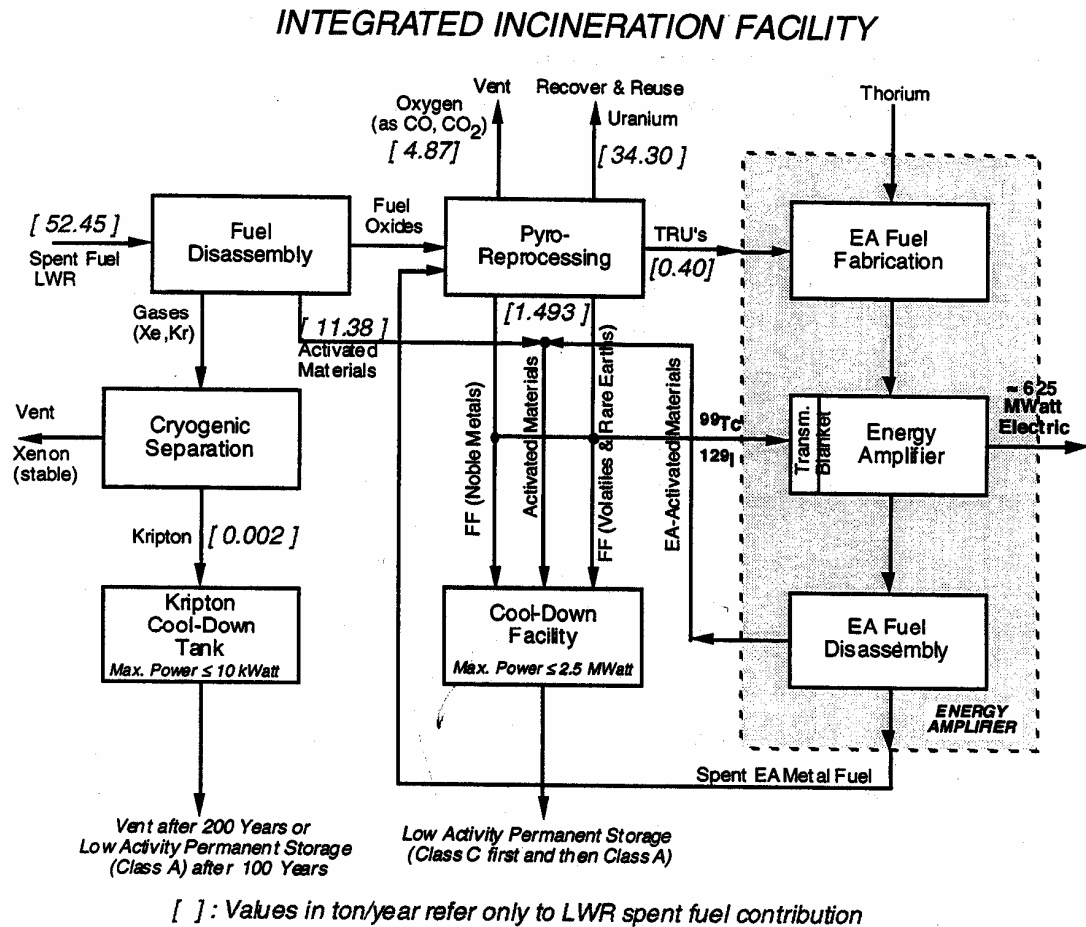


Figure 3: Flow diagram of the LWR waste fuel incinerated into an ADS[24]

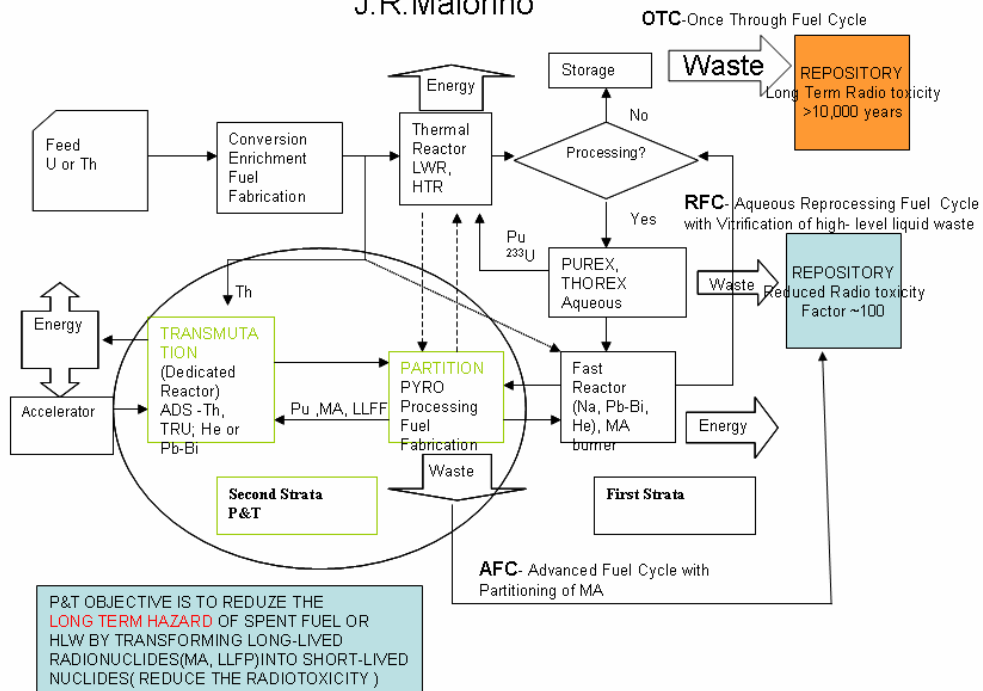
After Rubbia's concept proposal, the European Community created a coordinated group to establish a common base for design and R&D need, synergies, cooperation, cooperation etc.. This group produces the "European Road Map"[25], which has as the objective the construction of an experimental ADS(XADS), lead Bismuth or Helium cooled, and established several cooperative research, including with the participation of non European countries(USA, Japan,Korea) in R&D in almost all technical aspects of ADS(Target, fuel, design, reactor physics, nuclear data, termohydraulics, etc.). Also the ADOPT (the Advanced Option for Partitioning and Transmutation Thematic Network), is a cooperative research network on P&T[29]. Most of these programs are funded within the

European Frame Work Programs(FWP).. Among several of these programs, or Work Packages(WP) the FUTURE- FUel for Transmutation of Trans Uranium Elements, has as objective to study the feasibility of oxide actinide compounds to be irradiated as homogeneous or composite fuel(diluted in an inert matrix), for ADS including, (Th,Pu, Am)O₂. Other WP's include the study of thorium cycle calculations, Nuclear Data of ²³²Th, and PYROREP (PYROMetallurgical processing Research Program).

The IAEA has promoted a series of coordinate research programs, technical meetings and published a series of technical documents related to P&T and ADS[26,27]. An IAEA Technical Working Group(TWG-FR), in which the main author is a member, provides a forum for scientific and technical information, international cooperation and advises the IAEA on the status and achievements on Fast Reactors, Accelerator Driven Systems, as well as associated advanced fuel cycles for transmutation and thorium utilization. The Technical Working Material presented at the TWG-FR meeting annual meeting reports the national programs of the participating countries. Several documents may be down loaded from the IAEA website "Technology Advances in Fast Reactors and Accelerator Driven System for Actinide and long lived fission product transmutation [28]. Some country programs related with ADS and thorium utilization are being conducted in Belarus(YALINA, Nuclear Data), Brazil(see 4), China, India, Republic of Korea (HYPER project), Russia(Molten Salt ADS) etc.

Finally, the scheme bellow, illustrates a general fuel cycle scheme presented by the author in the IAEA Scientific Forum 2004- Nuclear Fuel Cycle Issues and Challenges, mainly those in which thorium could be used.

IAEA Scientific Forum 2004
 P&T: An option for Spent Fuel and Waste Management using a Double Strata Fuel Cycle with a dedicated waste burner reactor (ADS)
 J.R. Maiorino



4. Brazilian Experience on Thorium Utilization

The role of Nuclear Energy in Brazil is complementary to others sources of Energy. Presently two PWR NPP are in operation (ANGRA I and II) with a total of 2007 MW_e installed power (3.6%) and in 2002 it contributes with 14 TWh of the total electrical energy generated in the country (345TWh), and a third unity is under construction. Even though with such relatively small nuclear park in international standards, Brazil has one of the biggest world nuclear resources (uranium and thorium), being the sixth natural uranium resource in the world (309,000 t U₃O₈), one of the first world thorium natural resource (estimated as 1.2 millions of ThO₂), and has a fuel cycle industry (INB) capable to provide fuel elements for the National NPP, including the enrichment. Besides Energy Generation, Brazil is conducting R&D through the Research Institutes of the Brazilian Nuclear Energy Commission (CNEN) and in Universities. Also a National Development Program for Nuclear Propulsion, conducted by the Brazilian Navy is underway, and Brazil is participating in the International initiatives such as Generation IV and INPRO, although without a clearly defined type of reactor and associated fuel cycle program. Thorium fuelled Reactors (LWR, ADS) and associated fuel cycle (OTC, Double Strata) is a good recommendation to the Brazilian authorities to participate in such forums.

Given the huge thorium reserves in the country, as illustrated in tables 4, since the beginning of nuclear activities in the country some projects were developed having with the objective to utilize thorium. This session will review these indicatives.

Table 2 . Thorium Potential Resources in Brazil [30]

Occurrence	Associated Mineral	Average Content(%)	Measured, t ThO ₂	<i>Estimated, t ThO₂</i>
Coastal deposits	Monazite	5	2,250	-
Morro do Ferro(MG)	Thorite and others	1 to 2	35,000	-
Barreiro, Araxa(MG)	Pyrochlore	0.09	-	1,200 000
Area Zero, Araxa(MG)	Pyrochlore	0.09	30,000	-
Aluvial and Pegmatite	Monazite	5	3,000	2,500
Total			73,500 ^a	1,202,500

^a Including 3,500 t of Monazite sand of INB

note: The IAEA gives(1992) 606,000 t as indicated reserves and 700,000 t of inferred reserves

Pinheiros[31], in a IAEA technical meeting in 1997, published at TECDOC 1319, made an excellent review on thorium utilization in Brazil, so here we will summarize this paper, and just add the recent R&D initiatives on thorium utilization in Brazil.

Since the beginning of Nuclear Energy Development in Brazil in the sixties, it was recognized the strategicity of the thorium utilization for the country. In fact the first project was conducted by a research group from a Brazilian State, Minas Gerais, very rich in mineral resources, including thorium. This research group was called the “Thorium Group”, and in the framework of a cooperation agreement with the French CEA aimed at the development of a thorium fueled PHWR with a concept of a pre stressed concrete reactor vessel. This project was officially nominated “ Instituto/ Toruna”, and realized several progresses in the conceptual design(fuel technology, reactor physics, thermal hydraulics, reactor vessel, materials and component test and fuel cycle economics). These studies resulted in some reports, most of them in Portuguese [32, 33, 34]. With the decision of the Brazilian Government to build a Westinghouse PWR (ANGRA I) in a turn key bases, in the late sixties, beginning of seventies, discontinued the activities of the” Thorium Group”, however the human power and knowledge developed under the frame work of this initiative were very useful for the future Brazilian Nuclear Programs (staff highly qualified in different aspects of the analysis and design of NPP).

Also, in the beginning of the seventies, in the frame work of a cooperation agreement of IPEN, in São Paulo, with the USA General Atomic (GA), several activities, theoretical and experimental, were developed on thorium technology and utilization mainly for the HTGR concept. Many of these studies resulted in thesis presented at São Paulo University,[35,36,37], papers[38], and internal reports on thorium utilization in HTGR, Gas Cooled Fast Reactors, and even the possibility of utilization of thorium in PWR, in ANGRA I[39]. With the signature of the ambitious program of technology transfer signed between Brazil and Germany(1975), for the construction of 8 PWR, and the complete light water reactor fuel cycle industry(enrichment, reprocessing, heavy equipment’s etc), also this program was discontinued.

However, it was in the framework of the Brazilian German agreement that the biggest R&D program on thorium utilization was developed with the incentive of “ International Nuclear Fuel Cycle Evaluation”. This program was conducted by the Brazilian Center for Development of Nuclear Technology(CDTN), in that time the R&D branch of the former holding, NUCLEBRAS, and the Germans KFA- Jülich, Siemens A.G-KWU, and NUKEN. The general objectives of the program were, a) to analyze and prove thorium utilization in PWR, b) to design PWR fuel elements and core for the Th-fuel cycle, c) to manufacture, test and qualify Th-U and Th-Pu fuel elements under operating conditions, d) to study spent fuel treatment and to close the thorium fuel cycle by reprocessing spent Th-containing PWR fuel assemblies. The program starts in 1979, and was interrupted in 1988, when there was a complete reformulation of the Brazilian Nuclear Structure, with extinguish of NUCLEBRAS, and CDTN transferred to the CNEN. A final report[40] contains detailed technical results obtained by this program, in i)Nuclear core design and strategy for a standard 1,300 MW Siemens PWR, ii) Fuel Technology, for (Th-U)O₂ and (Th-Pu)O₂ , iii) Fuel design and modeling, including the fuel behavior in irradiation experiment(FRJ-2 at KFA, Jülich), and a test fuel assembly for the ANGRA I reactor , and iii) Spent Fuel treatment, including laboratory investigation on reprocessing spent fuel thorium with non irradiated elements. As main conclusions of this Brazilian-German joint program were that the utilization of thorium in PWR presents a long term option providing in some interesting results. The most attractive application of Th-based

fuels is the use of recycle plutonium in an extend ended burn up once-through fuel cycle. Also the fabrication utilized by merging of the standard LWR palletizing process with the chemical ex-gel process developed for the HTR fuel can be used successfully.

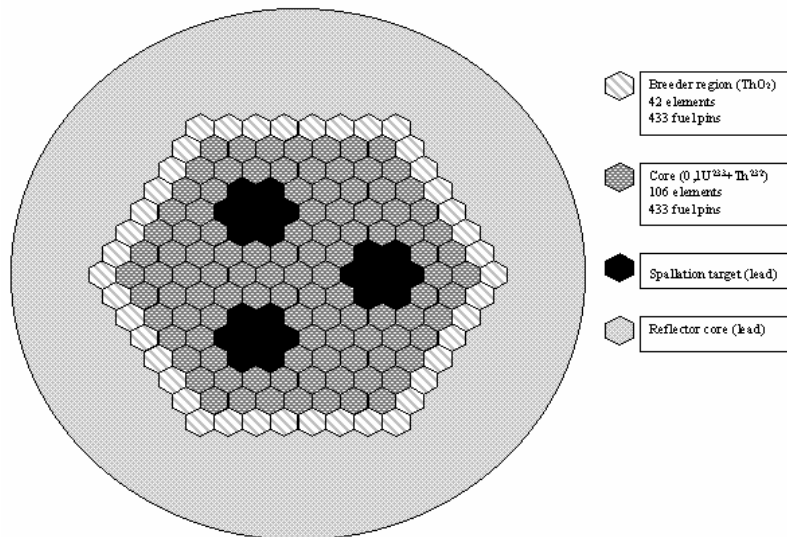
Other initiatives took place at IEAv(Institute for Advanced Studies), in São Jose dos Campos in the eighties, studying thorium-fuelled both gas-cooled and sodium fast reactors[41].. Also energy scenarios for thorium-fueled in Molten Salt Reactors were studied at Federal University of Minas Gerais. Material studies, such as diffusion properties of ceramics/ ThO₂, (Th,U)O₂, and (Th,Ce)O₂ are studied at CDTN and Federal University of Ouro Preto . Recently a proposal involving IPEN. CDTN and CTM-SP (Navy Center of Technology) to conduct Thorium a fuelled lattice experiment in a water critical facility(IPEN-MB-01)was proposed and are still under way.

Finally, with a recent interest of IPEN to study ADS, with a thorium utilization motivation, some academic work have been reported, mainly by the author in the annual meetings of the IAEA TWG-FR, national and international conferences, and a Ph.D thesis was presented at USP [42,43,44], proposing a modified conceptual fast energy amplifier ADS, cooled by helium, and using ²³²Th and ²³³U as fuel. Benchmark studies of Th experimental critical assemblies (THOR and JEZEBEL), were performed to qualifying nuclear data and codes and the results obtained are illustrated in table 3. Figure 4 illustrates the modified concept, and some preliminary results These studies are on going and the main objective will be to utilize thorium in a double strata fuel cycle(LWR-ADS), as an attractive option for HLW management. Although calculation capability for ADS(MCNPX, transmutation and burn up) are under way, some preliminary results were recently presented at the Brazilian Meeting on Nuclear Physics[45], ADOPT 2003[46], and PHYSOR 2004[47] ..

Table 4. Comparison between experimental versus calculated results for the THOR experimental benchmark

	Experimental	Calculated
K_{eff}	1,000 ± 0,001	0.9960 +/- 0.0030
$\frac{\sigma_f(Th232)}{\sigma_f(U238)}$	0,26 ± 0,01	0.2500 +/- 0.0040
$\frac{\sigma_{n,\gamma}(Th232)}{\sigma_{n,\gamma}(U238)}$	1,20 ± 0,06	1.2900 +/- 0.0004
$\frac{\sigma_{n,2n}(Th232)}{\sigma_{n,2n}(U238)}$	1,04 ± 0,03	1.0900 +/- 0.0040

Figure 4: Modified Energy Amplifier ADS. Helium Cooled, 3 points of spallation[44]



Power	105 MW _{th}
Accelerator	Cyclotron, E _p =500MeV, I _p =3 Ma
Multiplicity(n/p)	10.06
Source Criticality Factor, (M-1)/M	0.98
Target	Liquid Lead(windowless)
Multiplication Factor	0.97
Gain	70(E _p =500 MeV); 110(1GeV)
Radial Peak Factor	1.854
Specific Power(W/g)	2.58
Power Density(W/cm ²)	25.82
N ₂₃₃ /N ₂₃₂	0.107
Fuel	0.1 ²³³ UO ₂ + ²³² ThO ₂

Acknowledgements

The partial financial support of the post graduate school of Nuclear Technology-IPEN/USP, and the travel assistance provided by the U.S. Department of Energy, Office of Nuclear, Science & Technology is recognized by the author.

References

1. <http://www.webelements.com>
2. IAEA, "Thorium fuel utilization: Options and Trends", TECDOC-1319, (2003).
3. IAEA, "Potential of thorium based fuel cycles to constrain plutonium and reduce long lived waste toxicity", TECDOC-1349 (2003).
4. IAEA, "Consultancy Meeting on Implementing thorium in Nuclear Reactor Fuel Cycles: Potential Benefits and Challenges", IAEA-03CT13095,TWG-FR/115 (2004).
5. KERR, J.M. et al., "Performance of ThO₂-UO₂ fuel in Indian Point 1, American Ceramic Society Bulletin 59(6), 606-610 (1980).
6. WEINREICH, W.A. et al., "Fabrication of high-density, high-integrity thorium based fuel pellets", transactions of American Nuclear Society, 27, 305-307 (1977).
7. CONNORS, D.R. et al., " Design of the Shipping port Light Water Breeder Reactor", Bettis Atomic Power Laboratory Report, WAPD_TM_1208 (1979).
8. GOLDBERG,I. et al., "Fission gas released from ThO₂ and ThO₂-UO₂ fuels", Transaction of the American Nuclear Society 27, 308-310 (1977).
9. GALPERIN, A. et al., "Thorium fuel cycle for light water reactors-reducing proliferation potential of nuclear power cycle" Science & Global Security, 6, 267-292 (1997) –also in [2].
10. GALPERIN, A. et al., "A pressurized water reactor design for plutonium incineration: fuel cycle options", Nuclear Technology, 117, 125-132 (1997).
11. HIGATSBERGER, "The non-proliferate commercial Radkowsky. Thorium-fuel concept", IAEA TECDOC-1319, 321-342 (2003).
12. DEKOUSSAR,V. ,"The use of thorium for plutonium utilization in reactors", IN [2]
13. HIRAKAWA, "Studies of thorium fuel cycle in Japan", IN [2]
14. PORTA, J. et al. ," Thorium fuel for LWR and innovative concepts" IN [2]
15. BOCZAR, P.G. et al. ,"Thorium fuel cycle studies for CANDU reactors", IN [2]
16. BOCZAR, P.G. et al. ," Recent advances in thorium fuel cycles for CANDU reactor", IN [2]
17. MAJUMDAR, S. et al." Experience of thorium fuel development in India", IN [2]
18. KUMAR, A. et al., "Physics Design of Advanced Heavy Water Reactor", IN [2]
19. FURUKAWA, K. et al., "Thorium molten salt nuclear energy synergetic", Nuclear Science and Engineering, 27, 1157(1990), also IN [2]
20. IGNATIEV, V., "Neutronic, Fuel and material properties of a molten salt transmute", IN Technical Meeting on Review of Solid and Mobile Fuels for Partitioning and Transmutation system, CIEMAT, Spain, IAEA-TM-26241, TWG-FR(2004)
21. LELEK, V., "Closed Fuel Cycle and contemporary tendencies of the nuclear

- facilities development”, same as [20]
22. BOWMAN, C.D. et al. ,”Nuclear energy generation and waste transmutation using an accelerator driven intense thermal neutral source”, Nucl. Instr. And Methods A,336-367(1992)
 23. C. Rubbia et al., "Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier", European Organization for Nuclear Research, CERN/AT/95-44-ET (1995).
 24. C. Rubbia et al, “Fast Neutron Incineration in the Energy Amplifier as Alternative to Geologic Storage: the Case of Spain”, CERN/LHC/97-01 (1997).
 25. A European Roadmap for Developing Accelerator Driven System (ADS) for Nuclear Waste Incineration, The European Technical Working Group on ADS, April 2001
 26. IAEA, Emerging nuclear energy and transmutation systems: Core Physics and engineering aspects”, IAEA TECDOC 1356(2003)
 27. IAEA, Review of National Accelerator Driven System Programs for Partitioning and Transmutation, IAEA TECDOC 1365, August 2003
 28. <http://www.iaea.org/linis/aws/fnss/>
 29. W. HAECK et al, Ed, International Workshop on P&T and ADS Development 2003, SCK CEN, Belgium, October 6-8 2003.
 30. GENTILE,E. et al.,” Radioactive Minerals Diagnosis”, Brazilian Association of Metallurgy and Materials(1996) in Portuguese
 31. PINHEIROS, R.D. ,” Brazilian Experience on thorium fuel cycle investigation” IN [2]
 32. BRITO, S. et al. ,” Instinto Project-Final Report for the period 1966/67”, IPR internal report(1967), in Portuguese
 33. PINHEIROS, R.D. et al. “PT-500 TORUNA Project: Preliminary Design of a Nuclear Power Plant with a 520 MW Natural Uranium Heavy Water Cooled Reactor with pre stressed concrete reactor vessel”, IPR-DR-38, internal report(1971), in Portuguese
 34. SOUZA, E.S.& PINHEIROS, R.D. ,” Notes on a pre stressed concrete pressure vessel for the Instituto de Pesquisas Radioativas”, SMIRT I, Berlin(1972)
 35. DIAZ, J.A. ,”Core Optimization of a 600 MW(e) HTGR Reactor”, thesis presented at São Paulo University(1971), in Portuguese
 36. KOSAKA,N. ,”Neutronic Feasibility of a thorium-fueled sub critical assembly”, thesis presented at São Paulo University(1976), in Portuguese
 37. TING, D.K,S. ,”Preliminary studies of neutronics and thermal hydraulics of a HTR utilizing Pu and Th fuel”, thesis presented at São Paulo University(1976), in Portuguese
 38. FAYA, A.J.G. ,”The use of a thorium metal blanket in fast reactors”, Annual meeting of the American Nuclear Society, Philadelphia (1974)
 39. CORREIA, F. ,” The use of thorium in PWR”, thesis presented at São Paulo University(1976), in Portuguese
 40. KFA, NUCLEBRAS, KWU&NUKEN, “Program of Research and Development on the Thorium utilization in PWR- Final Report”, JUL-SPEZ 488/NUCLEBRAS-CDTN 600-88/ Jülich-KFA(1988)

41. ISHIGURO, Y. ,” Sodium cooled thorium cycle breeder reactor with coated particles”, Winter Meeting of the American Nuclear Society(1981)
42. MAIORINO, J.R. et al., "Alternative Concept for a Fast Energy Amplifier Accelerator Driven Reactor", Research and Development Brazilian Journal, 3,1, p.13 (2001).
43. MAIORINO,J.R. et al., " A New Proposal for the Fast Energy Amplifier", Radiation Physics and Chemistry, 61,3-6, p. 789(2001).
44. ANEFALOS,S., An Alternative Concept of a Hybrid Reactor (A Sub Critical Assembly Coupled with an Accelerator), Ph.D. Thesis- IPEN-USP (in Portuguese) 2002.
45. MAIORINO,J.R. et al., " The Utilization of Accelerators in Sub Critical Systems for Energy Generation and Nuclear Waste Transmutation-The World Status and a Proposal of a National R&D Program ", Brazilian Journal of Physics, 33, 2, p.267 (2003).
46. W. Haeck et al, Ed, International Workshop on P&T and ADS Development 2003, SCK CEN, Belgium, October 6-8 2003.
47. MAIORINO ,J.R. & S. ANEFALOS, The utilization of a small accelerators to drive a zero power sub critical ADS, PHYSOR 2004, Chicago(2004)