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Thorium as A Nuclear Fuel

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ABSTRACT: Interest in nuclear power is rising while the world looks for non-deplcteable sources of energy that won't contribute to global warming. Thorium (Th) and its compounds are potential fuel sources for nuclear energy. Atomic fission in the ~-Th/~ "U fuel cycle or subatomic fuel using a particle accelerator to produce proton particles that interact with ""Th and " U to produce fast neutrons in an energy amplifier are gaining importance in the nuclear energy world. Both processes, will enhance the use of Th fuels in nuclear reactors more than uranium (U). Because it generates less radioactive wastes and cheaper energy. Presence and abundance of Th at the Moon crust and the new use of ThO; fuel seed in standard nuclear reactors enable Th to be very strategic for the next decade. This paper reviews the use of Th mainly in nuclear energy application and evaluates the importance of Turkish Th deposit. The Th fuel cycle, with its potential for breeding fuel without the need for fast-neutron reactors, holds considerable potential long-term. It is key factor in the sustainability of nuclear energy.

I INTRODUCTION

Nuclear power is the most probable solution for the world's energy needs in the short run. Since all other commercial power resources are depletable, nuclear energy will supply world's energy demand until a non-depletable resource is invented. There is a proven U reserve of 2.26 million tons (U.l0K) (Kaya, 2002) in the world. From this total, Turkey only has 9130 tons of U reserve. (DPT, 1996). It is clear that Turkey is dependent on the international U sources. On the other hand. Turkey has a proven reserve of 380.000 tons of ThO; at a grade of 0.21%. amounting about to l/3 of the total Th reserves in the world (1.4 million tons) (Kaya, 2002), Th, being a fertile element, can be "breeded" to a fissile element ^{11}U. A similar reaction can also occurs at every reactor fueled with U. Both of these elements, plutonium $^{:w}$Pu and $^{2\sim Vl}$U can be used as fuel in reactors. A mixture of Th-U may provide cheaper, cleaner and safer nuclear power.

2 GENERAL INFORMATION ABOUT Th

Over 40 stable Th bearing minerals have been identified in the environment. Th (Thor. Scandavian god of war) occurs in thorite (TI1SİO4), thorianite (ThO;+ $U0_2$) and monazite ((Ce, Lai Th, Nd. Y) PO4) which is the most common and commercially important Th bearing mineral containing 3 to 9% ThO;. with important deposits in India, Brazil, Sri Lanka, S. Africa, Russia, Scandinavia and Australia. Th, crustal abundance order is 39'\ is now thought to be about three times as abundant as U and as abundant as Pb or Mo. Th is an alternative source of nuclear power. There is probably more energy available from Th than from both U and fossil fuels. It can provide thousands of years of energy. Most of the internal heat of the earth has been attributed to radioactive Th and U.

2. / *Radioisotope Data of Thorium*

Twenty seven isotopes of Th are known with atomic masses ranging from 212 to 237. All are unstable. ^{21}-Th occurs naturally and has a half life of 1.4*10"" years. It is an a emitter. ""Th goes through six a and four ß decay steps before becoming the stable isotope $^{2(l<}$Pb. $^{2'}$ U decays with a reasonably long half life, therefore its quantity, once produced, does not reduce in a human's life span, making this fissile material possible to be used as a fissile fuel.

2.2 Thorium Compounds

Major Th compounds are Th (IV) oxide/dioxide (thoria) ThO,; Th (II) hydride. ThH_2; Th (III/IV) fluoride, ThF/ThF.,; Th (II/IV/II1) sulphide, ThS. ThS,, Th,S,; Th (III) nitride, TliN; Th diodide/ (III/

IV) iodide. Thh, ThI,, ThI_4.Th (IV) bromide. $ThBr_4$; Th (IV) chloride. $ThCl_4$: Th (IV) sclcnide. $ThSe_3$.

23 Thorium Metal

When pure, Th is a silvery-white metal which is air-siable and retains its luster for several months. When contaminated with oxide. Th slowly tarnishes in air becoming gray and finally black. The physical properties of Th are greatly influenced by degree of contamination with the oxide. Pure Th is soft, very ductile and can be cold-rolled, swaged, and drawn. Th is slowly attacked by water, but does not often pyrophoric and should be carefully handled. When heated in air, Th ignites and burns brilliantly with white ligth. Several methods are available for producing Th metal; it can be obtained by reducing ThCh with Ca, by electrolysis of anhydrous $ThCl_4$ in the fused mixture of Na/KCls by Ca reduction of $ThCl_4$ mixed with anhydrous ZnCI;, and by reduction of Cl_4 with an alkali metal.

2.3 Thorium Oxide ($Th()_2$)

Formula weight is 264.037 g/mole. color is white, appereance is crystalline solid, boiling point is 4400 °C, and density is 10000 kg/nr. ThO: has a melting point of 3300"C, which is the highest of all oxides. Only tungsten and tantalum carbide have higher melting points. Powdered, peletized and wafer ThOi fuels can be used to produce " ' U in reactors.

2.4 Analysis of Thorium

Th and U analysis can be performed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) which require complete sample digest. Radiochemical techniques such as a and y spectroscopy can also be used. The technique of a spectrometry is used to detect a particles and to determine their energy. In this way, quantitative (i.e. activity) and qualitative information (the identity) for a emitting Th can be accurately assessed (Holmes, 2001). Routine detection limit is 1 ppm.

2.5 Use oj Thorium

Th is generally used in non-fuel and fuel applications. In non-fuel applications, the principle use of Th has been in the preparation of the Welsbach mantle, used for portable gas lights. These mantles, consisting of ThO: with about \% Ce-oxide and other ingrediants. glow with dazzling light when healed in a gas flame. Th is an important alloying element in Mg, imparting high strenth and creep resistance at elevated temperatures. Because Th has a low work-function and high electron emmission, it is used to coat tungsten wire used in electronic equipment (i.e. magnetron tubes). The oxide is also used to control the grain size of tungsten used for electric lamps; it is also used for high-temperature laboratory crucibles. Glasses containing ThO: have high reductive index and low dispersion. Consequently, they find application in high quality lenses for cameras and scintille instruments. TI1O2 has also used as catalyst in the conversion of ammonia to HNOj, in petroleum cracking, and in producing H:SO_i. Table I shows Th consumption patterns..

Tabic I. Tliorium consumption patterns in the USA according totheUSGSin 19X4 and 1987

Application Area	1984 (%)	1987 C/r)
Energy	11.8	
Refractory Applications	52.9	57
Lamp Mamies	15.0	18
Aero Space Alloys	7.1	15
Welding R<xls	2.6	5
Ceramics and lighting	10.6	
Others		5

3 THORIUM IN TURKEY AND METHODS OF CONCENTRATION TECHNOLOGIES

Unlike the common knowledge, Th and U are not rare elements. U exists at an average of 2.7 and Th 9.6 ppm in the earth crust. The research of MTA Institute revealed that there is a Th reserve of 380.000 tons of TI1O2 around Eskisehir-Sivrihisar-Kizilcabrcn which is one of the largest Th reserves (Kaya, 2002). Like U mining and refining, Th can be refined with various methods. When mined, both U and Th exist in very small concentrations. Th can be recovered as a by-product from minerals mined for the extraction of Ti, Sn, Zr, and rear earth elements/ oxides (REE/REO).

REO is concentrated from bastnacsite ores at Mountain Pass by a hot flotation. This produces a 60% REO concentrate that may be upgraded to a 70% concentrate by leaching or to a 90% concentrate by calcining (Harben&Kuzvart, 1996). The Ce-rich concentrate yields Ce-oxides and salts, and a Ce-poor lanthanides-rich concentrate used as a feedstock for further processing, either at the mine or in specialised plants around the world. Monozite is separeted from other heavy minerals, usually by wet gravity concentration and then electrostatic and magnetic separation to produce a concentrate with 55-66% REO. Both monazile and xenotime are usually cracked by heating the concentrate in an autoclave at I50"C with a 70% NaOH solution (Gschncidner. 1989). After cooling, the addition of H2O removes the soluable $Na?P0_4$, leaving the REE as REO and Th as $Th(OH)_4$. The REO are dissolved in HCl to form an anhydrous mixed rare-earth chloride, which is reduced electrolytically to make miscbmetal or processed further to yield individual

REE. There are a number ol methods for extracting and separating the individual REE, including liquid-liquid solvent extraction that is based on differences in affinity of the individual rare earths for a chelating agent in an organic. When the REE in water are mixed with chelating agent solution, the REE with the highest affinity becomes enriched in the solvent; if repeated sufficiently the concentration builds up to produce a 99.999% pure product.

In the milling operation, the Th is extracted from the ore by a process called leaching. The dissolved ThO; are then recovered by solvent extraction (SX) or by ion exchange (IE). The product is then calcined to remove excess water. The result is a concentrate of TIlO2. First, Th ore is solved by HNO, or H2SO4 . In order to have a complete solution of Th ore, an acidity of pH 1.2 is needed. The solution is filtered and large particles are separated from the solution. After this process, some chemicals are added to the solution to precipitate some further impurities. Later, the solution is separated from the remaining impurities by the SX. As a product, Th-nitroxyde. Th(NO,)4.nH:0 is obtained. Later, the ThiNChh is heated and excess water is vaporised for 20 hours in 105"C. The product is heated upto 575"C and the Th (NO,(4 is oxidized to TIlO2.

The ThOi is a dust material. This material can be manufactured into small pellets using simple powder metalurgy methods. These pellets would be loaded into luel claddings and lowered into the reactor core. There is a commercially available Torex process (Thorium Oxide Recovery by Extraction). This is a procedure to produce fuel from the burned fuel elements of a reactor. The ~'U/Th fuel is dissolved in very highly concentrated 13M HNO,, 0.05 M HF and 0.1 M Al-ni träte held at boiling temperature. The residual solids are removed from the solution by centrifuging. The solution with Th(NO,h and UO2 (NO,): then enters the first extraction column and is moved in a counlercurrent flow against TBP dissolved in a hydrocarbon solvent. TBP selectively dissolves ThN and U-nitratc while moving upward in the column. The fission products, protactinium and Ai-nitrate leave the column at the bottom together with the scrub solution, which is added at the top of the column. Careful adjustment of these chemical proccses is necessary to separate fission products, especially Zr-95 Irom Th. In the letravalent slate, Th is chemically very similar to Zr. ~ Pa with a half life of 27.0 d is the precursor of " U and must be chemically recovered from the high level waste. Alternatively, the fertile fuel can be cooled until ^{21}Pa has decayed into ^{2}U. In the second column, Th(NO.<)$_4$ is recovered from the TBP by being moved in a counlercurrent flow against diluted HNO,. Th(NO,)$_4$ and HNO, leave the second column at the bottom. The organic solution together with UOi(NOi)i flows into the third column, where U is recxtracled. U is then purified in additional SX separation steps. Small traces of Pu and Np may be separated by additional extraction chromatography. In case more Pu is built up, e.g., in medium enriched "'^{5}U/^{11s}U/Th fuel, the separation from Pu and Np by extraction chromalrography is not sufficient. In these cases the Pu must be co-extracted with U and Th. This may also be achieved by SX in contact with TBP. However, this process is more complicated than the thorex process (Sıkık et.al. 2001).

Ipekoğlu (1983) conducted gravity, magnetic, flotation and acid leaching tests for Eskişehir Th ore. He found that acid leach was necessary for this ore. 99% Th extraction recovery was obtained with a 200 kg/t HCl within 3 hours.

4 PERSPECTIVES OF THORIUM FUEL CYCLES

Th is a source of nuclear power. Three development periods in the past nuclear energy history in the USA can be considered (Lung, 1996). 1945-1958: The follow-ups of the Manattan Project, at leading US Laboratories (Brookhaven. Oak Ridge and Los Alamos).'" U bred from Th is considered as a potential weapon of gun-type model, easier to manufacture than Pu weapons. About 55 kg $^{i\cdot}$U were available in 1958. 1958-1975: Energy applications increased after INFCE's prediction in 1980. About 1.5 tons " U were seperated in the USA during the period from 900 tonnes Th. Many reactor prototypes were built and operated. Th extraction plants were built in US, Germany and France. 6000 tonnes of Th were separeted. 1985-Today: President Ford and Carter did not support the water reactors and nuclear energy well. Disinterest for Th crops up and this line is progresively abandoned. Today. India is still very interested in nuclear energy as principle source for 1 billion inhabitants for energy self indépendance. India has the largest Th reserves (360.000 t monozile) in the world.

4.1 Thorium as a Nuclear Fuel

There is a strikiim parallel between natural U containing 99.3% ^{2S}U and Th almost exclusively composed of ^{2,2}Th. It can he seen that the fertile isotopes are $^{2,I\cdot}$U and ^{2,2}Th. and that the fissile isotopes are 0.7% ^{2i}*U* and the artificial fissile isotopes comparable to ^{2U}U for Th (Lung, 1996). A new fuel increase the time nuclear reactors can run between shutdowns. Longer runs mean cheaper electricity, which should help nuclear power plants compete with coal and natural gas powered plants. The new fuel should also generate less waste than all-U fuel (www.eurekalcrt.org).

Advantages of the Th Cycle: ''U bred (rom Tlı is, seen from a neutronic standpoint at least, the best of the 3 nuclear fuels ^{2}"U. $^{2,'J}$Pu and ^{2,}"U. As a matter of fact, the eta ratio of neutron yield per fission, to neutrons absorbed is higher to that of $^{2,<}$U/$^{2'W}$Pu. This means that "U will be a good fuel in any reactor type. Th comes out of the ground as a I 00% pure, usable isotope, which does not require enrichment, whereas natural U contains only 0.7% fissionable "U. So some 40 times the amount of energy per unit mass might be available for Th (www.world-nuclear.org). Moreover, from the perspective position of U and Th in the periodic table, the long-lived minor actinides resulting from fission are in much lower quantity with the Th cycle, especially compared with the Pu cycle. This ecological advantage is an important argument brought forward these days. Th produces l0 to UKXX) times less long-lived radioactive waste than U or Pu. The radioactive waste from Th reactor contains vastly less long-lived material than that from conventional reactors. In particular, Pu is completely absent from the Th reactor's waste. Finally, quadrivalent Th and its compounds are very stable and among the highest known refractories. ThO melts around 3300"C (UO: 2700-2800"C). This stability authorizes high burnups and high temperaiures. It does complicate somewhat, however, the chemical treatments for the preparation of Th compounds or their dissolution for reprocessing. Moreover, ^{2,,}U also keeps its good neutronic properties with high temperatures, better than either ^{2}'U or ^{2W}Pu. These properties have led naturally to recommend the Th cycle for high temperature reactors. Because Th docs not sustain chain reaction, fission stops by default if we stop priming it. and a runaway chain reaction accident is improbable (www.cavendish science.org).

Disadvantages- of the Th Cycle: The first remark is that a reactor fulled with Th only will not diverge. Th needs a "match" which, today could only he ~'U or Pu. Here is indeed an excellent way to use up the excess Pu stocks on the market these days. It appears from what proceeds that sooner or later "U formed should be separated to be incorparated in efficient nuclear fuel elements. This means that reprocessing is an integral part of a sustainable Th fuel cycle. In a reactor, "•"Th by neutron absorption produces first $^{:1,}$Th and ^{2}"Pa which has a 27-day half-life to produce$^{:}$"Pa (Fig. 1):

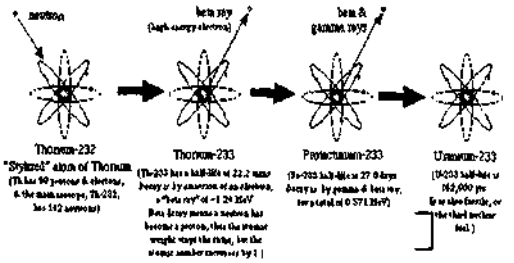

Figure1 Production of ^{233}U from ^{232}Th.

This rather long half-lite of$^{:,:,}$Pa results in a reactivity surge after reactor shutdown due to "^{13}U production, and this must be taken into account. ThO: dissolution is not as easy that of UCK But this problem can be overcome with a buffered floride addition in the dissolver solution. Finally, one of the principal drawbacks of the Th cycle today is the presence of hard Y emitters (2 to 2.6 MeV) among the descendents of the ~"Th isotope, and especially of$^{2\,2}$U, an a emitter of 72 years half-life which is always present along "U at concentrations ranging from some tenths to some hundreds ppm. This obliges to manufacture $^{:1}$'U based fuels completely remotely in y-shield environment, a very expensive technique which only starts to be mastered with MOx UOi-PuOi fuel elements fabrication.

5 THORIUM-FUELED REACTORS

A typical reactor which consume fissionable fuel and produces only energy is called a burner. A reactor which creates energy and fuel which produces fuel less than it consumed in the process is called a converter. A reactor, which creates more fuel than it consumes, is called a breeder. Global warming caused by fossil fuels and a boost from International Atomic Energy Agency regarding the use of Th in nuclear reactors will increase the importance of nuclear energy. Almost all of the world's active 440 power reactors (357.000 MWc) are conventional and rely on U-fuel rather than Th. Natural U is 99.3% ^{2,S}U which can not sustain a chain reaction. But it also contains 0.7% "U, a fissile isotope that can sustain a chain reaction. Most power reactors operate with slightly enriched U, typically about 4% "^{5}U. In contrast to natural U, Th lacks a fissile isotope. But it is "fertile". When bombarded with neutrons, a portion of the Th is converted to ""U, a fissile isotope. The source or "seed" fuel would breed ^{2,,}U. The ^{2,1}U then could unloaded from the reactor, separated from the Th fuel, and fed back into the reactor in a closed-fuel-cycle. Alternatively, the ^{23,}U could remain in the reactor, eventually becoming a key component in the chain reaction.

Over the decades, several nations (Germany, India, Japan, Russia, the UK and the USA) experimented with Th-U fuel, but the economics of it never seemed to work, in part because the physiscs of Th and U differed greatly. Most Th-cycle schemes relied on reprocessing/recycling of nuclear fuel. Today. India remains a strong proponent of the Th fuel cycle. Test reactor irradiation of Th fuel to high burnups has also been conducted and several test reactors have either been partially or completely loaded with Th-based fuel.

5.1 Radkowsky Light Water Reactor (LWR)

A joint US-Russian project still in the research and development phase, would produce little weapons-useable material. Because of its Th-fuel design, the amount of Pu produced by a Radkowsky reactor would be about 20% of the Pu produced by a more conventional U-fuel reactor (Friedman, 1997). Radkowsky did some experiments with Th-U fuel in 1977 at Shippingport, Pensilvania for about five years. Radkowsky Thorium Power Corp. was established in 1992. Its reactor core are less expensive by up to 20%' and additional savings occur because its design would use less fuel than would a comparable U-fuel reactor. The Th-U blanket would be left in place for about 10 years to maximize "'l) burnup. In contrast, the seed elements would be placed every 18 mounths or so. The net result; over its operation life time, the Radkowsky design would use less fuel than would a comperable U-fuel reactor. The ligth water breeder reactor uses U-Th fuel. It is possible to produce fissile isotope of $^{;'1,}$U from " "Th. " U produces more neutrons if fissioned by a low energy (thermal) neutron than does ^{215}U. This characteristic means that more excess neutrons are available to convert fertile material. In a carefully designed and constructed reactor, U-Th reactors have enough excess fission neutrons to overcome the parasitic neutron absorptions inherent in a water cooled and moderated reactor. In fast breeder reactor, the designers chose a seed and blanket core configuration. The fissile material is concentrated in the central core region while the fertile material surrounds the central core region including the top and bottom. Most of the neutrons produced in the central core are used to sustain the chain reaction, while most of the those than leak out at boundary are either reflected back into the fissile material or absorbed by fertile material.

The LWR. WERT-1000. designed by Radkowsky for Russia can achieve powers up to 1000 MWe OOOOMWth) and has a power density of 106 W/cnr' (Radkowsky&Galperin. 1998). The seed and blanket lattice parameters is optimised such that ~'U produced is burned at the same time. Radkowsky Th fuel provides a practical and attractive solution to the utilisation of Th since there is no reprocessing plant is necessary. Th-fueled nuclear reactors are important for Russia and Asia. Russian Pu can be used as core fissile material neutron source at the Radkowski's advanced LWR. Japon. Indonesia, Vietnam, Malasia and China are also posibblc users of the Radkowsky design.

Further development of nuclear power depends on improving its performance with regard to economics, safety, waste production, and proliferation resistance. The use of Th in a once-through fuel cycle has the potential to improve all four areas. It is likely to reduce the need for control materials in a fresh core while enhancing the production of fissile materials during fuel residence, both of which will reduce the fuel cost. While the above potential benefits will need to be evaluated in specific-designs, one benefit is almost design independent, and that is the benefit of added proliferation resistance (Kazimi et.nl.. 1999).

5.2High Temperature Gas-Cooled Reactors (HTGR)

The high enriched (HE) Th and U (93% ^{2J5}U) and the low-enriched (LE) U (8-12% ^{23,}U) fuel cycles concept are considered for utilization in HTGRs. For both fuel compositions suitable reprocessing procedures are required which are capable to separate the actinides Th, U and Pu from fission products and from each other. In any case, the processes under consideration utilize tri-n-butylphosphate (TBP) together with a straight-chain paraffinic diluent (Cs-Cu, to day usually dodecane) as extradant in an aqueous nitrate system. Most commonly, the related processes are known by the acronyms Purex and Thorex, which will be explained later. Kloosterman et al. (1997) has performed burnup calculations on a PWR fueled with three fuel types: ordinary UO: fuel (LEU), 20W% enriched UOi in ThO$_:$ (medium enriched U: MEU) and 93W% enriched UO$_:$ (HEU) mixed in ThO?. From the radiotoxicity point of view, the use of HEU fuel has preference. Up to 20.000 years of storage, the radiotoxicity per unit electricity generated is lower by a factor of 5-10 compared to ordinary LEU fuel. For MEU fuel, this factor is 2.

5.3 Fast Breeder Reactors (FBR)

In the USA, FBRs were cancelled quite early in their history. In 1980, congress rejected the Carter administration's request to back the project and since no advancement had been achieved in USA in the FBR field. This cancellation resulted in a delay which would move the operation date of the first commercial FBR to after 2000. Furthermore, in 1984 U.S. Congress terminated all funding for the development of a breeder reactor. (Archie, 1991). Although the tendency to reduce research in this project was in effect in early 1980s, after the Chernobyll

accident, in many of the countries the accident resulted in a avalanche of support loss. For example, in Japan, the commercial breeder plans were scrapped because of the fallen nuclear energy support. Although in this country, more than 300 billion yens were invested, the possibility to build a FBR in the Japan before 2030 is diminished.

On the other hand, some countries need the breeded energy to continue with their nuclear weapon and power programs. India and Pakistan recently demonstrated their nuclear capability with test explosions of nuclear bombs. Neither Pakistan nor India has U reserves, like Turkey. But still, they have a number of commercial power plants. India has its own designs and recently Indian FBR went critical and also in 1998 their Th reactor was commissioned. In India, Kakrapar-1 was the first reactor in the world to use Th rather than depleted U, to achieve power flattering across the reactor core. Both Kakrapar-1 and 2 units were loaded with 500 kg Th fuel and operated about 300 and J 00 days full power operation, respectively. Rasjasthan-3 and 4 reactors are under construction (www.world-nuclear.org/info).

5.4 Heavy Weiter Reactors

Heavy water moderated reactors have better neutron economy and a harder neutron spectrum with respect to other kinds of reactors. This ability makes them one of the most economically suitable converter reactor when utilization of Th is considered. The most popular type Candu (Canadian Deuterium-Uranium) heavy water reactors use Th fuels. No apparent change must be made but some considerations must be taken for the shutdown conditions and initial fuel loading (Sikik. 2001). Candu is fueled by natural U generate Pu. FBRs use this Pu-based fuel to breed $^{:""}$u from Th and then advanced nuclear power systems will use the " "U. The spent fuel will then be reprocessed to recover fissile materials for recycling.

5.5 Pressurized Water Reactors (PWR)

Th-based fuel for PWRs was investigated at the Shippingport reactor in the USA using both ~"U and Pu as the initial fissile material. It was concluded that Th would not significantly affect operating strategies or core margincs. The ligth water breeder reactor (LWBR) concept was also sucessfully tested here from 1977 to 1982 with Th and $^{:1}$ U fuel clad with zircaloy using seed/blanket concept (www.world-nuclear.org/info). The 60 MWe Lingen PWR in Germany utilised Th/Pu-based fuel test elements. Temkin (1985) clearly reveals that a pressurised heavy water reactor (PHWR) is more advantegous with respect to LWRs. First of all, PHWR gives more energy output with respect to PLWR therefore more effective in power generation, secondly a PHWR has a much higher design life compared to the PLWR, and lastly, the criticality control necessity is smaller in comparison with that for PLWRs. India is working on Advanced Heavy Water Reactors and like the Canadian Candu-NG.

5.6 *Accelerator Driven Systems (ADS)*

Powerful accelerators can produce neutrons by spallation. This process may be linked to conventional nuclear reactor technology in ADS to transmute heavy isotopes in spent nuclear fuel into shorter-lived fission products. There is also increasing interest in the application of ADS to Th fueled reactors. The ADS is a coupled system of a subcritical reactor and an external accelerator. Extra neutrons are generated by a spallation process in the target and the external source neutrons initiate a significant multiplication in the reactor core allowing for an efficient transmutation and incineration potential. The proton beam enters the center of the reactor core through an evacuated tube and hits the Pb target where neutrons are emitted. The pool type reactor is cooled by liquid Pb/Pb-Bi. In the design given a bubble lift pump supports natural convection and transports thermal energy to the heat exchangers. Besides transmutation the system additionally serves as a power generator (www.iket.fzk.de). There are some problems in Th-based fuel cycle (i.e. high cost of fuel fabrication due to " "U contamination and $"^{K}$Th contamination in recycling) (IAEA, 2000).

5.*7 Pebble Bed Modular Reactors (PBMR)*

Arising from German work, the PBMR was conceived in S. Africa is now being developed by a multinational consortium. It can potentially use Th in its fuel pebbles. Between 1967 and 1988, the experimental pebble bed reactor at Jülich, Germany operated for over 750 weeks at 15 MWe, about 95% of the time with Th-based fuel. The fuel used consisted of about 100.000 billard ball-sized fuel elements. Overall a total of 1360 kg of Th was used. Maximum burnups of 150.000 MWd/t were achieved. Th fuel elements with a 10:1 Th/U (HEU) ratio were irradiated in the 20 MWth Dragon reactor (OECD/ Euratom project worked between 1964 and 1973 at Winfrith, UK. Th and Pu utilization in PBMR was investigated with aim to predict the economical value of vast Th reserves of Turkey by Sikik et al.(2001). Neutronics and thermal-hydraulics analysis of the reactor core were performed for various mixtures of U, Pu and ThO: fuel pebbles. Various U enrichments. Pu concentrations and Th with certain impurities were considered. Burnup calculations for equilibrium cores were performed and the amount of U and Th consumption was calculated.

5.X Energy Amplifiers (EA)

1984 Nobel Physic prize winner Prof. Carlo Rubbia devised EA at the CERN for Th-fucl. The cross-section of EA is given in Fig. 2. In the EA, a proton beam impinges on Pb, the high energy protons splitting Pb nuclei, leading to release of neutrons. In Rubbia's design, the molten Pb doubles also as primary coolant. Most of the EA is below ground level. High energy protons emerge through a window in the tip of the proton beam tube inside the core. Proton split Pb nuclei, with neutrons emitted into the core. The molten Pb carries nuclear heat upward by convection. The Pb vessel is nearly 30 in long and 6 m in diameter and contains 10.000 tons of Pb. Fission rate is determined by the proton accelerator. If the accelerator stops sending protons, fission stops almost instantly. Thus shutdown is easy and also accidents can be prevented. The radioactive waste from the Th reactor contains vastly less long-lived radioactive material than that from conventional reactors, (www.cavendishscience.org).

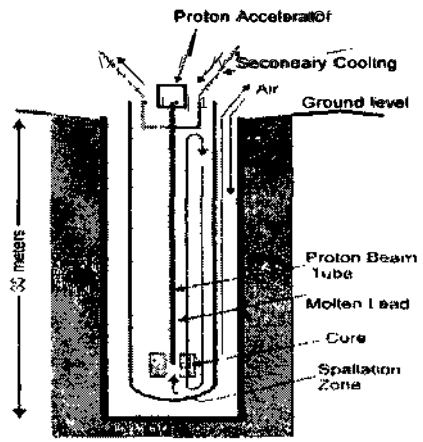

Figure 2 Energy amplifier

6 CLOSED FUEL CYCLE- THE Th/^{2}"U FUEL RECYCLING

Converter reactors operating on " U as a fissile fuel and ^{2,12}Th as a fertile material generate fissile ^{2,5}U which, after removal of the fuel from the reactor core, can be separated by chemical reprocessing. The fissile ^{2,,5}U obtained in this way can be recycled either in the same reactors or in reactor cores with pure ^{2,8}U/^{2,,2}Th fuel. However the generation of -^{M}U must be started with ^{1,5}U/^{2TM}U/ ^{232}Th fuel. Since this fuel also contains fertile ~^{K}U, Pu will be produced besides ^{2W}U. The production of Pu can be restricted by limiting the amount of ~~U contained in the fuel. This applies to highly HEU fuel with 93% ^{2,5}U enrichment.

7 BREEDER FUEL CYCLE-THE Th/""- U FUEL BREEDING

In principle, it is possible to design FBR's with ""U/Th fuel, which still attain breeding ratios above 1. Firstly, thermal and fast breeder reactors can be started with Pu/^{2,,}U available from chemical reprocessing of spent fuel from the thermal converter reactors. Later, when a FBR economy will have developed, sufficient $^{:}$"U would be generated also by the FBR's themselves to start additional FBR plants. However this is not the only way to start breeder reactors. If Pu/^U were not available in sufficient quantities from thermal reactor fuel reprocessing, breeders could also produce their own initial cores of Pu/^{2}"U fuel by starting with ^{2,5}U/$^{2,1(}$U or

8 CONCLUSIONS

All predictions today coincide to confirm for the next 30 years the world energy demand foreseen at the time of INFCE in 1980. We are also confronted with the problem of greenhouse effect. These challenges will foster nuclear energy again and in the longer term Th will have its place.

Th-fuel use reduces energy cost, due to longer runs and reduced U consumption. Separating ^{2} "U from Th is a relatively easy task compared to the enrichment of the U. As a result, such breeded fuel would be much cheaper than enriched fuel. Th-fuel also gives lower and less radiotoxic wastes than U fuel. Different types of reactors can be used with Th fuels, some with special designs, some with virtually no design change. As a result, especially PWR (Candu), LWR, HTR, PBMR and energy amplifier type of reactors show great promise in utilizing Th/U fuels. FBRs can produce the fissile fuel for these reactors. Especially India's experiments with these kinds of reactors and other similar experiments reveal that although the effectivenes is below of a HTR, the process is possible, feasible and preferrable

Turkey has very large Th resources in basnasite ore second to India's vast reserves. Even though there is no economical value of Th as nuclear fuel presently, the utilization of Th in some reactors can be feasible in the near future. If such a combined cycle is utilized, the best resource conservation is obtained. It must be noted that the earth is not the (wily source and place to utilize such reactors. For example, Nasa's Lunar Prospector satellite has found large amounts of Th on the surface of the moon. In the future, if a colony is founded on the surface of moon, it would be much cheaper and easier to use Th assisted reactors to obtain power (Lawrence et. al., 1999). It must be pointed that all of the research on Th is only a fragment of the FBR researches. Pu-

U cycle dominates the research and Th reactors/ technology has been researched very little. More research must be done on this technology.

Turkey must evaluate strategic Th reserves and use nuclear energy in order to became independent in energy production and provide sufficient, reliable and cheap energy for its developing industry.

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