

## Rethinking the Thorium Fuel Cycle: An Industrial Point of View

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*Abstract - The use of thorium as a “fertile” material in combination with a fissile material (either U233, U235 or plutonium) as an alternative to the uranium fuel cycle received a great deal of attention in many venues from the 1950s to the mid 70s. More recently, new studies have been carried out on this cycle for transmutation purposes and several countries such as India still continue to consider the thorium cycle as an attractive option within the framework of their national nuclear programs.*

*The purpose of this paper is to provide an updated overview of the potential of the thorium cycle, taking into account the renewed interest in the development of nuclear energy as currently under consideration for future energy systems.*

*In this paper many of the issues related to the use of thorium at each stage of the nuclear fuel cycle are reviewed from the standpoint of industrial feasibility and economy.*

*First, past experience with using thorium as a fuel for prototype or commercial nuclear reactors, particularly in high temperature reactors, is examined. The neutronic and physic aspects of the thorium in various reactors will be overviewed. Second, updated data on world-wide thorium resources and supplies is presented. Then, the sustainability issues of nuclear energy development with regard to the future availability of natural resources (uranium and thorium) are addressed. After that follows a discussion of the pros and cons of radiological/ nuclear/chemical characteristics of thorium as it relates to the implementation of fuel cycle industrial processes and impacts on the wastes. In particular, the technical aspects of back end fuel cycle issues are examined for both open and closed fuel cycles including reprocessing and recycling technical issues. Also examined are proliferation issues related to the use of the thorium cycle. Accompanying this examination is a comprehensive analysis of the technical features of various thorium fuel cycle options from the standpoint of proliferation resistance. Finally, economical aspects of the thorium fuel cycle are addressed.*

*In summary, these analyses permit the reader to draw some general conclusions regarding the use of the thorium cycle for the development of a sustainable nuclear energy system.*

### I. THORIUM FUEL AS AN ALTERNATIVE TO URANIUM FUELS

Almost all of the world's nuclear reactors in operation today use **U235** to sustain the neutron chain reaction because this isotope is the **only naturally occurring, thermally fissile isotope** (the fuel is then either natural uranium or, in most cases, uranium enriched in U235). In this fuel, neutron captures by the fertile material U238 produce plutonium, and in particular its two thermally fissile isotopes Pu239 and Pu241, which are burned partly in situ (typically half part or so in a standard light water reactor). The remaining part of plutonium contained in the discharged fuel may be recycled in reactors in the so called MOX fuel cycle, which leads to natural uranium saving (about 12% for single plutonium recycling).

As uranium, **thorium** is also a natural occurring material but it **does not contain a thermally fissile isotope**, and only a fertile isotope, Th232. This fertile isotope can breed **U233**, which is **the best fissile isotope** in the thermal neutron spectrum. Therefore a neutron chain reaction can only be sustained with thorium if fissile materials are available (U235, U233, Plutonium) and mixed with thorium. Then, it becomes possible to operate a nuclear reactor with thorium in which U233 is produced. As with plutonium, U233 is partly burnt in reactors and the remaining part contained in the discharged fuel can be recycled.

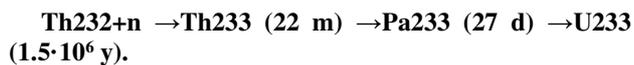
Thus, thorium provides an alternative to a uranium cycle if enough fissile isotopes are available from other sources to initiate the “thorium fuel cycle”.

### II. RADIOLOGICAL/NUCLEAR/CHEMICAL CHARACTERISTICS.

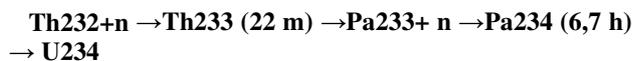
## II.A. Radiological/Nuclear properties.

Twenty five isotopes of thorium are known all of which are unstable with atomic masses ranging from 212 to 236. The most stable is thorium-232 (Th232) which is an alpha emitter and has a very long half life of approximately  $1.41 \times 10^{10}$  years. Th232 is the sole component of naturally occurring thorium<sup>1</sup>, which has atomic weight of 232.038. It undergoes natural disintegration and eventually is converted through a 10-step chain of isotopes to lead-208, a stable isotope; alpha and beta particles are emitted during this decay. One intermediate product is the gas Radon-220 also called Thoron.

In a reactor core, Th232 absorbs a neutron to first produce Th-233 which decays very rapidly (with a radioactive decay period of 22 min) into Protactinium-233 (Pa233) which itself decays (with a radioactive period of 27 days) to produce U233:



One had to know that this reaction is in competition with another, depending on the average flux level:



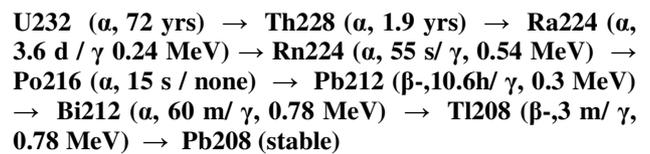
**U233 has a higher neutron yield per neutron absorbed than uranium-235 and plutonium-239 for thermal neutrons.** The average number of fission neutrons produced per thermal neutron absorption (called “eta” factor) is typically **2.27** for U233 in a standard PWR compared to 2.06 for U235 and 1.84 for Pu239). **This is one of the principal advantages of a thorium cycle: the generated fissile isotope, U233, is the best fissile isotope of all existing fissile isotopes for thermal neutrons.**

A breeding cycle, similar to that with U238 and plutonium is initially required to generate U233<sup>2</sup>, but to initiate this breeding process, enriched uranium or plutonium is required. Following removal from the reactor, the enriched uranium/thorium can be reprocessed to recover the U233 (and residual U235 or plutonium), and the residual fertile Th232. The separated U233 as well as other fissile isotopes and thorium can be re-fabricated into new fuel assemblies and fed back into another reactor as part of a closed fuel cycle.

<sup>1</sup> Thorium was discovered in 1828 by the Swedish chemist Jons Jacob Berzelius, who named it after the Norse God of Thunder and weather, Thor.

<sup>2</sup> The amount of fissile isotopes produced in the reactor divided by the amount of fissile isotopes consumed in the reactor is called the “conversion factor”

However, one of the principle drawbacks of the thorium cycle is the presence of U232, which is formed in the core through various nuclear reactions on Th232 and U233<sup>3</sup>. U232 is an alpha emitter with a 72 year half-life and is always present along with U233 at concentrations ranging from tenths to hundreds of parts per million. The U232 decay chain is as follow:



It can be seen that **this chain includes hard gamma emitters such as Thallium-208 (up to 2.6 MeV).** Therefore, the presence of U232 requires that the manufacture of U233 based fuels be performed remotely in a gamma-shielded environment and entails significant additional expenses (reference 1).

If uranium is chemically purified and its decay products are removed, freshly separated U233 with significant concentrations of U232 can be processed and converted into desired forms in lightly shielded enclosures without significant radiation exposure to workers. Depending on the U232 concentration, it takes days or weeks for the U232 radioactive decay products that emit gamma rays to build up to sufficient concentrations such as to require heavy shielding to protect the workers.

The nuclear characteristics of U233 are significantly different from those of weapons grade plutonium (WGP) or high enriched uranium (HEU). The minimum critical mass of U233, in a uniform fluoride aqueous solution, is 0.54 kg (American National Standards Institute [ANSI] 1983). This is somewhat less than that of WGP or HEU; thus, facilities designed for WGP or HEU might not be suitable for storage or processing of U233 unless more restrictive criticality precautions are instituted (reference 2) although it is likely fabrication of reprocessed U233/thorium based fuel will be performed in a sole purpose facility whose criticality safety will be designed for U233.

## II.B. Chemical characteristics.

Uranium-233 is chemically identical to natural, depleted, and enriched uranium. Consequently, the same chemical

<sup>3</sup> First : Th232 (n,2n) Th-231 (β-) Pa-231 (n,γ) Pa-232(β-) **U232** ; Second : Th232 (n,γ) Th-233 (β-) Pa233 (n,2n) Pa-232(β-) **U232** ; Third : U233 (n,2n) **U232**

processes used for natural, depleted, and enriched uranium are applicable to U233. The U233 isotope, however, has a higher specific radioactivity than the naturally occurring isotopes of uranium (i.e., U234, U235 and U238). Thus, certain radiation-induced chemical reactions are faster in uranium containing significant quantities of U233. This knowledge is of some importance in situations such as long-term storage where the higher-radiation levels of U233 require that storage containers and U233 storage forms neither contain organics (plastics etc.) or water that react radiolytically (unless they can somehow be vented) to form potentially explosive concentrations of hydrogen gases. (reference 2).

### III. HISTORICAL CONTEXT: PAST AND CURRENT DEVELOPMENTS OF THORIUM FUEL CYCLES.

#### III.A. Past experience of the use of thorium in experimental and power reactors.

During the pioneering years of nuclear energy, 1950-1970, with great enthusiasm and regardless of the costs, a large number of possible avenues for energy production with thorium was investigated, not only in the USA and USSR, but also in Europe and, to some extent, in Asia. For example, it is remarkable that the thorium-based Elk River (1963) and Peach Bottom (1967) reactors were started only a few years after the "founding fathers" of the two main reactor families of today, based on uranium fuel, PWR Shippingport (1957) and BWR Dresden (1960). It must be emphasized that **breeder demonstration was performed at Shippingport in the late 1970s and early 1980s using a U233/thorium cycle** (reference 3). This was the only U.S. demonstration program using U233 as the fissile seed material. Although this demonstration was successful from the standpoint that slightly more U233 was bred than consumed, success was only achieved at the high cost of a sophisticated core design, and by sacrificing reactor performance.

Since that time, a significant amount of experience on thorium-based fuel in experimental or power reactors was accumulated. An exhaustive list of these reactors is provided table 2 (however, this table does not include experimental reactors in which thorium fuels have been also tested, such as CIRUS in India, KUCA in Japan, MARIUS in France, etc).

TABLE I

Nuclear reactors using (or having used) thorium fuels (partially or completely)

| Country | Name                   | Type           | Power (MW)       | Startup date | Fuel                               | Note |
|---------|------------------------|----------------|------------------|--------------|------------------------------------|------|
| USA     | Indian point 1         | PWR            | 265 <sub>e</sub> | 1962         | ThO <sub>2</sub> - UO <sub>2</sub> | 1    |
|         | Elk River              | BWR            | 22 <sub>e</sub>  | 1964         | ThO <sub>2</sub> - UO <sub>2</sub> | 2    |
|         | Shippingport           | PWR            | 60 <sub>e</sub>  | 1957         | ThO <sub>2</sub> - UO <sub>2</sub> | 3    |
|         | Peach Bottom           | HTR            | 40 <sub>e</sub>  | 1967         | ThC <sub>2</sub> - UC <sub>2</sub> | 4    |
|         | Fort St. Vrain         | HTR            | 330 <sub>e</sub> | 1976         | Same                               | 5    |
|         | MSRE                   | MSR            | 10 <sub>th</sub> | 1965         | ThF <sub>4</sub> - UF <sub>4</sub> | 6    |
| UK      | Dragon                 | HTR            | 20 <sub>th</sub> | 1964         | ThC <sub>2</sub> - UC <sub>2</sub> | 7    |
| Germ.   | AVR                    | HTR            | 15 <sub>e</sub>  | 1967         | (Th,U) O <sub>2</sub>              | 8    |
|         | THTR                   | HTR            | 300 <sub>e</sub> | 1985         | Same                               |      |
|         | Lingen                 | BWR            | 60 <sub>e</sub>  | 1968         | Th/Pu                              | 10   |
| India   | Kakrapar (KAPS) 1 - 2  | PHWR           | 200 <sub>e</sub> | 1993/95      | UO <sub>2</sub> -ThO <sub>2</sub>  | 11   |
|         | Kaiga 1 - 2            | PHWR           | 200 <sub>e</sub> | 2000/03      | UO <sub>2</sub> -ThO <sub>3</sub>  | 12   |
|         | Rajasthan (RAPS) 3 - 4 | PHWR           | 200 <sub>e</sub> | 2000         | UO <sub>2</sub> -ThO <sub>4</sub>  | 13   |
|         | KAMINI                 | Neutron Source | 30 Kwe           | -            | U233                               | 14   |

Notes:

- 1 - Power includes 104 Mwe from oil-fired superheater
- 2 - Power includes 5 Mwe from coal-fired superheater. Th loaded in the first core only
- 3 - Used both U235 and Pu as the initial fissile material. Successfully demonstrated thermal breeding using the "seed/blanket" concept (TH/U233)
- 4 - Coated particle fuel in prismatic graphite blocs - TH/HEU
- 5 - Coated particle fuel in prismatic graphite blocs - TH/HEU
- 6 - Did operate with U233 fuel since October 1968 - No electricity production
- 7 - Coated particle fuel - No electricity production Many types of fuel irradiated
- 8 - Coated particle fuel in pebbles - Maximum burnup achieved : 150 GWd/t - TH/HEU
- 9 - Coated particle fuel in pebbles - Maximum burnup achieved : 150 GWd/t - Th/HEU
- 10 - Th/Pu was only loaded in some fuel test elements
- 11 - Fuel : 19-element bundles. - 500 kg of Th loaded
- 12 - Fuel : 19-element bundles. Th is used only for power flattening
- 13 - Fuel : 19-element bundles. Th is used only for power flattening
- 14 - Experimental reactor used for neutron radiography

Within the framework of this paper, it is not possible to provide details on each one of these reactors. The reader is directed to references 3 to 6. This paper will just focus on High Temperature Gas-cooled reactors (HTRs) since, as it

is seen on table 1, thorium fuel was mainly developed for this type of reactor (apart from those carried out for light water reactors in the U.S., already mentioned above).

In the U.S., during the 1960s and 1970s, the use of a HEU (high enriched uranium)-thorium fuel cycle was demonstrated at the Peach-Bottom and subsequently, Fort Saint Vrain HTRs. Both reactors used prismatic block type fuel elements containing thorium fertile coated particles on one hand and smaller HEU fissile coated particles on the other hand.

In the U.K., the first demonstration HTR known as Dragon operated between 1966 and 1975. It used various types of fuel elements including thorium with a 10:1 Th/U (HEU) ratio.

In Germany, two pebble bed type HTGRs were operated. The first one, AVR, was a prototype pebble bed reactor that mainly used a HEU/thorium cycle. The fuel consisted of billiard ball-sized fuel elements. A commercial version, the THTR-300, a 300 MWe thorium/HEU fueled HTGR commenced operations in 1985. It was permanently shut down in 1989 largely for political reasons although high operational costs and an operational incident in 1986 that resulted in the release of radioactive materials are generally cited as the grounds for shutdown.

### *III.B. An analysis of the stimulants and brakes in the historical development of the thorium cycle.*

The initial driver for thorium was to provide an alternative fuel cycle in anticipation of a projected rapid growth in nuclear power and possible shortage of natural uranium. An added stimulus was thorium's supposed abundance in nature, based on the fact that the average concentration in the earth crust is approximately 3-times that of uranium (one will come back on this point later on in this paper : see section 4.1-a). Further, by the mid-1970s, the price for uranium reached \$40.00/pound U<sub>3</sub>O<sub>8</sub> and this resulted from a perceived low price uranium shortfall based in part on one large nuclear power plant vendor being unable to meet uranium supply commitments to its customers. Along with the abundance of thorium in nature and breeding U<sub>233</sub>, there were a number of other reasons at that time for the interest in thorium fuel cycles. They included:

- the absence of uranium resources but large amounts of identified thorium resources in some countries having an ambitious civil nuclear program, such as India
- a good in-core neutronic and physical behavior of thorium fuel; and
- a lower initial excess reactivity requirement (higher thermal conversion factor) of thorium-based cores using particular configurations.

Thus, as it is illustrated on table 1, **the feasibility of different types of reactors based on Th/U<sub>233</sub> fuels has been successfully demonstrated and significant experience has been accumulated so far**, theoretical as well as practical and engineering-wise.

However, the picture changed by the early 1980s, first because interest in the nuclear option waned significantly, especially in the U.S where public support for nuclear power dramatically declined following the TMI event. Moreover, the general overall anti-nuclear environment intensified and was further exacerbated in Europe by Chernobyl, 7-years later. Therefore, in this general context, matters such as alternative fuel cycles seemed to command much less attention.

In another hand, with the availability of low priced uranium starting in the early 1980s that lasted for over two decades, there was less interest in developing alternative fuel cycles. Further contributing to the availability of low priced uranium was the introduction to the market of down-blended uranium obtained from nuclear weapon disarmament programs (e.g., the US's collaboration with Russian in the Megatons to Megawatts program). Also, the absence of reprocessing capability in the U.S to permit recovery and recycle of fissile U<sub>233</sub> was a detriment to the development of alternative fuel cycles. In addition to that, there were proliferation concerns with a HEU thorium cycle, which was at that time the reference option to implement the thorium cycle. Not only is HEU chemically separable from thorium assuming seed and fertile material are combined, but some fuel designs completely separated the HEU driver fuel from the fertile thorium.

Thus the infrastructure needed for large scale commercialization of thorium fuels never came about. Further, in the U.S., by the end of the 1970s, the Ford and Carter Administrations put an end to reprocessing in their country and the U.S. no longer had the capability to recover the fissile U<sub>233</sub> that is generated from the irradiated thorium fuel.

However, in the last decade there has been a revival of interest in thorium-based fuels. This revival seems to have been initially motivated by an interest in the development of a LWR proliferation-resistant fuel cycle (i.e. Radkowsky Concept.)<sup>4</sup> It was also stimulated by some of the same factors that were the drivers for the initial interest in

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<sup>4</sup> Use of a seed/blanket concept in PWR fuel assemblies with LEU as the seed material and Th with slightly enriched U in the blanket. The U seed section is separable and about 1/3 is replaced annually. The blanket is irradiated for 10 yrs resulting in a substantial decrease in the fissile Pu and the high in-situ fissioning of U<sub>233</sub> that is bred into the blanket. The U<sub>238</sub> in the blanket acts to denature the remaining U<sub>233</sub>. Neither the seed nor the blanket are attractive options for diversion. They are highly radioactive and contain limited fissile material. Also, no reprocessing is assumed; the residual fissile material is of marginal value.

thorium cycles in the 1950s and 1960s. Depending on countries, some additional factors for the renewed interest include:

- the potential for the low production of Pu and minor actinides in thorium based-fuel cycles;
- The capability of destroying plutonium by fissioning it in a plutonium/thorium cycle in thermal reactors. These investigations include advanced reactor concepts based on thorium fuel cycles for future nuclear applications such as LWRs, HTRs, MSR, ADS and even fusion blanket systems (see reference 2);
- the transmutation of minor actinides;
- the possibility to reach breeding of fissile isotopes (that is a conversion factor greater than one) with a thorium cycle in some reactors such as MSRs which is one of the concepts retained for Generation IV systems;
- more recently, the dramatic increase in the price of uranium that is tied to the perceived shortage of this material.

In this paper we will come back in more details on some of these points.

For these reasons, thorium continues to generate interest in specialised circles, but more at an academic level, for long term prospects, especially in Japan where the HTTR could well be used in the future with thorium (as well as HTR-10 in China). Furthermore, India is still considering thorium to be an industrial fuel for use in the not too distant future, and since this is the only country in the world today which is implementing this option at a large scale, it deserves some comments.

### *III.C. Current developments in India*

India has limited indigenous uranium resources and almost no possibility to import uranium (presently) because of political reasons, but it has large reserves of thorium to support its ambitious nuclear power program and has therefore decided to proceed with the development of thorium fuels and fuel cycles. A closed self sustaining Th232/U233 fuel cycle is being pursued to utilize that country's thorium resources. India intends to use thorium fuel and/or thorium blanket assemblies in an integrated system of reactors to generate U233 (and possibly plutonium with depleted U/U233 fuel cycles) for recovery and use as the fissile component in its various types of reactors. Thorium oxide pellets have been irradiated in its research reactors and reprocessed via a simplified THOREX process to recover U233 (see section 4.4). Recovered U233 has also been utilized in research reactor programs. India has manufactured THO2 pellets that are being used in its fast breeder test reactor as stainless steel

clad blanket assemblies and in pressurized heavy water reactors as Zircaloy clad pin assemblies for neutron flux flattening of the initial core during start-up. The Kakrapar-1 and -2 units are loaded with 500 kg of thorium fuel in order to improve their operation when newly-started. Kakrapar-1 was the first reactor in the world to use thorium, rather than depleted uranium, to achieve power flattening across the reactor core. In 1995, Kakrapar-1 achieved about 300 days of full power operation and Kakrapar-2 about 100 days using thorium fuel. The use of thorium-based fuel is planned in Kaiga-1 and -2 and Rajasthan-3 and -4 reactors, which are now in commercial operation. India plans to build a 500 MWe fast breeder sodium-cooled reactors which will use thorium in part of the blanket. Engineering loops are under demonstration. (references 1 and 8).

A 300 MWe advanced heavy water reactor (AHWR 300) is now undergoing design and development. The driver fuel will be thorium/plutonium oxide and thorium/U233. The AHWRs will be essentially getting about 75% of their power from thorium (reference 8).

The spent fuel will then be reprocessed to recover fissile materials for recycling.

Another option for a third stage, while continuing with the PHWR and FBR programs, is a sub-critical Accelerator-Driven System (ADS).

Based on this overview of past and present developments of the thorium fuel cycle, we now summarise their main findings and give an industrial view of the advantages and weaknesses of the thorium as a fertile material for nuclear (fission) energy.

## IV. TECHNOLOGICAL AND INDUSTRIAL ISSUES RELATED TO THORIUM FUEL CYCLE IMPLEMENTATION.

### *IV.A. Extension of natural resources for nuclear energy.*

#### **a) Thorium abundance and reserves**

As it was said above, natural thorium (which is essentially 100 % Th232 isotope) is a relatively abundant element with an average concentration of 7.2 ppm in the earth's crust, compared to uranium which is only between 2.5 and 3 ppm, reflecting the differences in the half-lives of Th232 ( $1.4 \cdot 10^{10}$  years) and U238 ( $4.5 \cdot 10^9$  years). Nevertheless, this does not mean at all that the exploitable reserves of thorium are two or three times larger than uranium, as many asserts. In fact, because of its limited uses so far, extensive prospecting of thorium has not been conducted. Therefore, a reliable estimation of the world-wide reserves of thorium is not currently available. Besides, the IAEA renounced to publish of such estimations for many years in

its famous periodic “red book” (only devoted to uranium reserves).

The knowledge that one has today of these reserves can be summarized as follow (see table 1). The largest source of thorium is the mineral monazite (phosphate), also a primary source of rare earth elements. It is also found in the mineral thorianite (thorium dioxide) and some has been recovered from igneous veins and igneous carbonate deposits called carbonatites. Significant deposits of thorium are found in Australia, Brazil, Canada, Greenland, India, South Africa, and the United States. The United States Geological Survey (USGS) published the following data at the beginning of 2005. USGS world thorium reserve estimates going back as far as 1999 remain unchanged.

TABLE II

World Thorium Resources (Economically extractable)

| Country            | Reserves (tonnes) |
|--------------------|-------------------|
| Australia          | 300 000           |
| India              | 290 000           |
| Norway             | 170 000           |
| USA                | 160 000           |
| Canada             | 100 000           |
| South Africa       | 35 000            |
| Brazil             | 16 000            |
| Other countries    | 95 000            |
| <b>World total</b> | <b>1 200 000</b>  |

Source: US Geological Survey, Mineral Commodity Summaries, January 2005

More generally, beyond these data, the world's reasonably assured reserves (RAR) are known to be at least as large as those of uranium, and quite probably higher.

Anyhow, should a thorium cycle be deployed on a large industrial scale with thorium recycle, it must be underscored here that **thorium reserves are not a real issue** since, once again it is only a fertile isotope as is U238 (which available quantities are largely sufficient to sustain nuclear energy development for a very long time, with the help of the plutonium breeding process). To provide an explanation of what we mean, if it is supposed for example that thorium reserves are only those which are identified today (let say between 1 and 2 million tons), and one transforms all these reserves into U233 in nuclear reactors, the complete fission of this uranium 233 would be enough to produce an energy equivalent to that which is produced annually by all the nuclear power plants which exist to day for several thousands of years . Therefore, the problem is not that of the amount of available thorium reserves but that of the quantities of fissile materials necessary to initiate and then sustain a cycle with thorium

(this is exactly the same problem with U238 and plutonium or U235 availability).

### b) Mining and milling

Since no thorium-based fuel is being used in the world today, there is almost no international market for thorium, and consequently, a supporting mining industry will not develop until the demand for thorium fuel develops. Nevertheless, thorium is still being used today for various specific applications (see footnote 5), and is generally obtained as a by-product of uranium or rare earth mining. The corresponding available mining experience, even if it is weak, allows one to make some of the the following observations.

Mining of monazite deposits is easier than that of uranium bearing ores because there is very little overburden to remove as monazite is being produced from beach sands or placer deposits. However, it must be emphasized that the preparation of thorium, similar to that of the rare-earths, entails its separation from many other (valuable) compounds, hence the chemical separation is not straightforward and necessitates many manipulations and chemical steps (with the possibility of corrosion by highly aggressive chemicals). The high melting points of thorium (1750 °C) and thorium oxide (3300 °C) give them remarkably resilient properties (stability, refractory and radiation resisting characteristics) which are balanced by added difficulties for preparation compared with uranium.

Monazite is pulverized and leached in a 50-70 % solution of hot sodium hydroxide and undergoes solvent extraction, stripping operations and ion exchange to obtain thorium nitrate which is ultimately converted to thorium oxide powder. Like uranium, thorium is naturally radioactive but the “radon impact” from processing thorium ores is easier to handle because its radioactive daughter thoron (Rn220) is shorter lived (its half live is 56 sec) than its radon counterpart from uranium milling operations (Rn222 with a half live of 3.8 days).

### IV.B. Fuel manufacture.

There has been more than 40 years of experience with the manufacture of thorium-based fuels, thanks to the past operation of several thorium fuel based reactors described above. This is particularly the case for HTRs, which are reactors considered as well suited to accommodate thorium fuels. In this regard, the fuel fabrication processes developed for the Fort St. Vrain and the MHTGR/GT-MHR reactor designs could be the starting basis for defining a new manufacturing plant for other reactor types.

On another hand, it must be underlined that India has recently manufactured thorium fuel on a scale that is

beyond the R & D/developmental phase (see section 3.3). They have manufactured fuel for their thorium fuels programs that includes 7 tons of pellets at their Nuclear Fuel Complex – NFC, Hyderabad and at BARC for their PHWR 220 Units and 5 tons for their LMFBR program.

In conclusion, one can say that, although development of a thorium-based fuel cycle would require significant additional work, **there are no major technical obstacles for the manufacture of thorium based fuels** and experience gained with LEU fuel would provide a base line for the development of this fuel fabrication process.

#### *IV.C.Thorium use in nuclear reactors.*

##### **a) General properties of thorium based fuels in reactors.**

The high fission efficiency of U233 ("eta" value) has results in swings of the fissile content and reactivity of thorium fuels over the fuel lifetimes being much smaller than in uranium cycles. Thus, over the lifetime of a core, variation in reactivity and power distribution (power peaking) are less than in a uranium core which makes thorium reactor cores more manageable. The in-situ breeding is better than for U cycle, especially for low average flux level and low burn-up. This property gives significantly greater flexibility to programs based on thorium use from a reactor operation standpoint.

Another positive consequence is that **thorium-U233 cycles increase the conversion factor in current thermal reactors compared to U-Pu cycles** (the increase is usually between 20 to 30 %).

The nuclear properties of U233 allow a much more flexible use in thermal reactors than the use of plutonium because the 3 main isotopes of plutonium have great resonances at a very low energy, which complicate the neutronic behaviour of plutonium fuels.

Globally, one can say that Th-U233 is more flexible in many dimensions for use in various types of reactors than the U-Pu cycle.

Other specific features of thorium fuel are as follow:

- Thorium and its oxide (ThO<sub>2</sub>) have better behaviour under irradiation than uranium and its oxide (UO<sub>2</sub>), allowing higher burnups from this stand point
- A significant weaker power and temperature dependence of the U233 nuclear parameters is favourable for reactor safety and operation, especially when changing the LWR's from "cold" to "hot" conditions (and conversely)

- The yield of fission products affecting reactor poisoning during operation (such as Xe, Sm, etc.) is significantly lower for U233, compared to that of U235 and plutonium. This results in decreasing average cross section values of neutron absorption by U233 fission products (by 25-30 %) and hence, lowering reactivity loss and increasing the lifetime of the core
- The higher melting point of metallic thorium compared to uranium (1750 °C instead of 1130 °C) allows higher margins for the design and for operation of reactors using metallic fuels. This is the same for reactors using oxide fuels since the ThO<sub>2</sub> melting point (3300 °C) is higher than UO<sub>2</sub> (2800 °C)
- Metallic thorium interaction with water and steam is less intense than for metallic uranium.

Conversely, one of **the main drawbacks to the use of the thorium fuel in reactor cores is due to the rather high concentration of Pa233**. This results from the relatively long decay period of Pa233 (27 days), compared to Np239 (forming Pu239) in a uranium cycle which is 2.3 days only. This entails a "delayed reactivity" increase after reactor shutdown, which must be carefully investigated. Furthermore, this also results in a rather high concentration of Pa233, which can become particularly penalizing for high thermal neutron flux reactors. As a matter of fact, when a Pa233 nucleus disappears by a neutron capture (which is proportional to the number of neutrons, thus to the neutron flux, and proportional to the capture cross section of Pa233 which is high for thermal neutrons), this is equivalent to the loss of a U233 nucleus which would have been formed in the other case by normal radioactive decay of Pa233. This phenomenon can then lead to a significant reduction of the conversion factor in reactor cores and this reduction is all the more significant as the thermal neutron flux increases. Besides, this resulted in studying in the past reactor cores having low thermal neutron flux, therefore with low power density, which in another respect is economically penalizing.

Another drawback revealed by German studies on thorium use in HTR's was that this fuel entails a higher decay heat production than U-Pu fuels.

##### **b) Thorium fuels and nuclear material management**

A once through cycle would require fissile component seed material (e.g. U235 or plutonium) each time the reactor was refueled. To take advantage of the fertile thorium and its capability to generate fissile U233 in a once through cycle, extended cycles would be required to permit continued generation of U233 and its fissioning to sustain reactor operations. In this regard, thorium with its high

melting point and excellent refractory properties is a good candidate for extended burnup.

However, from a sustainability and resource utilization perspective, there is still a dependency on uranium with a once-through cycle (even if plutonium is used as the fissile material). As a matter of fact, if thorium is used in classical thermal reactors, the conversion factor is generally less than one, but generally superior to the conversion factor achieved in a standard U-Pu cycle. For example, with thorium, the conversion factor is 0.7 in a LWR (instead of 0.6 for U-Pu fuels) and may reach easily 0.8 or even 0.9 in some other types of reactors such as HWRs or HTRs. **A self-sufficient equilibrium thorium cycle, that is a conversion factor equal or greater than 1, can even be reached in some thermal reactors**, such as LWRs (as it has been demonstrated the Shippingport reactor: see section 3.1) but also in CANDU-Type reactors (SSET) and especially in molten salt reactors (because in that case, the breeding of U233 can be increased by the continuous removal of Pa233 from the core), keeping the burn-up and specific power low enough (which entails an economical penalty). This is not possible with a U-Pu cycle and this constitutes a **true advantage of the thorium cycle**, since thermal reactors present certain characteristics more favourable than those of the fast neutron reactor, in particular a lower fissile inventory in the core and may be a lower investment cost.

Many studies have investigated the use of thorium in thermal reactors, since many combinations of fuel cycles are possible with a mix of various types of reactors, operating in the frame of symbiotic systems. To summarize simply, the results of these studies show that **thorium use in non-breeder thermal reactors allows a global uranium savings from a few tens of percent to a maximum of roughly 80 %**, when equilibrium of the reactor fleet is reached.

With regard to the use of **thorium in fast neutron reactors (FNRs)**, number of studies (performed particularly in Russia for the BN-800 reactor, but also in France: reference 3 or in Europe, reference 7) demonstrated the possibility of achieving self sufficiency in a Th232/U233 fuel cycle; i.e. achieving a conversion factor greater than one. However, this kind of thorium fuel in FNRs does not allow the attainment of breeding performances as good as that obtained with the standard U-Pu cycle. For example, thorium based FNRs need very large material inventories in the blankets to achieve a conversion factor greater than 1. The main reason is that plutonium has an eta factor slightly better (1.33) than that of U233 (1.27) for fissions by fast neutrons (contrary to what occurs for fissions by thermal neutrons). Another reason is that fission cross section of thorium in the fast

range is much lower than that of U238. In summary, **the use of a thorium cycle in FNRs is not very attractive.**

Globally, **if thorium was intensively used in non-breeder thermal reactors with closed cycle (i.e., the U233 recycling) the world's fissile resources would be increased by around a factor 2** in the very long term (provided that enough natural uranium is available to sustain such thorium cycle). If **breeder reactors** are intensively used (with a conversion factor at least equal to 1), the **energy potential** of natural resources of **uranium** would be **multiplied by a factor of 50 to 100** and in that case the **thorium** breeding would multiply again this already huge energy potential by an additional **factor 2 or so** (depending on thorium resources).

### c) Plutonium consumption.

Even if the objective of "the burning" of plutonium does not constitute a sustainable option for the deployment of uranium-based nuclear energy in the long term, certain strategies considered today aim at reducing to the maximum the plutonium inventory in nuclear reactors as well as in spent fuels (often because of proliferation threats). In this frame, the use of thorium offers interesting possibilities insofar as it can be used as fertile material without producing plutonium (but it produces instead another fissile material, U233, which can also raise proliferation concern; see section 4.7). As a matter of fact, if thorium is used with Medium Enriched Uranium (< 20 %), called a MEU cycle, the reactor will still produce plutonium but in lesser amounts than standard U-Pu cycle. If it is used with High Enriched Uranium called HEU cycle (which would raise proliferation concerns as well), the production of plutonium would be very low. If only pure U233 is used as a fissile material in combination with thorium, then the plutonium production is essentially zero. Thus, we can say that **an extensive use of a thorium cycle would provide a significant reduction in the rate of plutonium accumulation**. In this regard, it must be stressed however that other solutions such as 100 % Pu HTR cores or even 100 % MOX-LWR cores, would make it possible to also reach high levels of plutonium consumption. Consequently, if maximum plutonium consumption were sought, the use of a thorium cycle does not appear to be much more effective than what can be achieved with other fuel cycles.

Another potentially use of thorium comes from its ability to burn existing stock piles of what is called "military" plutonium (that is weapons-grade plutonium now being declared excess-to-military-needs in the United States and Russia). This possibility is particularly attractive in high temperature reactors where plutonium can be burned in a very efficient manner but thorium matrix is not strictly required in this case. This solution has been

proposed by the US and is now under study in Russia, in cooperation with other countries.

#### *IV.D. Reprocessing.*

It must be reminded first that, although a once through cycle may be an alternative, the use of thorium-based fuels generally assumes reprocessing of used fuel to recover fissile U233 and provide seed material for continued use in thorium fuel cycles (thorium itself being recycled to save natural thorium resources), since, once again, thorium is only a fertile material. Therefore, it is clear that to take full advantage of the thorium fuel cycle, it is highly desirable to retrieve the fissile U233 recovered by reprocessing the spent thorium fuel, and to recycle, as much as possible.

Starting in the late 1940s, the U.S. reprocessed approximately 900 metric tons of irradiated thorium fuels to recover about 1500 kg U233. Other countries also recovered U233 from thorium based fuels. India has done so recently.

Experience with commercial reprocessing of thorium-based fuel was limited in the U.S. as was reprocessing in general at that time. The only U.S. reprocessing facility to ever operate on a commercial basis was the Nuclear Fuel Services (NFS), West Valley, N.Y. Plant which permanently shut down in 1972 after operating for 6 years. The initial core from Indian Point 1 was fabricated with HEU/thorium fuel. It was reprocessed at the NFS Plant in late 1968. The amount of heavy metal contained in the fuel as built was 16 MT. Approximately 1.1 MT of enriched uranium containing 7 wt% U233, 58 wt% U235 and other uranium isotopes was recovered, then shipped to Oak Ridge National Laboratory where it was stored for over 15 years in liquid form, and finally processed to produce a stable oxide form. This demonstrated a potential stabilization process for other U233 bearing materials (reference 9 and 10).

Reprocessing of thorium-based fuel is somewhat more challenging than that of uranium based fuels mainly because the dissolution of thorium metal and thorium oxide is not as straight forward as with uranium. The mechanical head-end steps are similar to those of the uranium based fuels, but the dissolution of irradiated thorium-based fuel is slow in nitric acid and hydrofluoric acid must be added as a catalyst to improve the dissolution process. The presence of fluoride ion causes corrosion of the stainless steel equipment (dissolver tanks etc.- fluorides are well known for aggressively attacking chemical equipment), needing appropriate buffering agents to prevent corrosion. Aluminum nitrate can be added to the aqueous dissolver solution to reduce this corrosion. A downside of adding aluminum nitrate is that it passes through the plant with the fission products and adds to the fission product waste. The

**THOREX** (for THORium-uranium EXtraction) process is described in reference 8.

The chemistry of the THOREX process is somewhat different than the PUREX process. If thorium is to be disposed because of its radioactivity, the presence of sulphates, phosphates, and fluorides in the reprocessing plant raffinates could result in considerable corrosion problems at the high temperatures required to vitrify the waste materials. Also, the THOREX process is expected to generate 50-70 % more glass than PUREX (See reference 8). It must be added that the protactinium remains mixed with the fission products because it is not extractable (studies were carried out in the sixties to develop a process of extraction of the protactinium from a nitric solution but no simple solution was found at the time).

One can mention that non-aqueous processes, alternative to THOREX, were also studied in the past, like processes of volatilization of fluorides, but they did not lead to any convincing result.

Another problem in the back-end of the thorium fuel cycle, already mentioned for reactor cores (see section 4.3.1), comes from the rather long half live of Pa233 (27 days), which produces U233. As a matter of fact, the surge of reactivity resulting from the transformation of Pa233 to U233 after reactor shutdown not only must be taken into account in the design and operation of the reactor but also in the design of facilities for handling and storage of used fuel that are needed prior to reprocessing. Practically, it is necessary to have a minimum cooling time of 9 months (10 Pa233 half lives) or more prior to reprocessing to complete the decay of Pa233 to U233 to avoid loss of any U233 (but anyhow, such cooling time may be needed for other reasons, such as decay heat). Any remaining Pa233 is passed into the fission product waste in the THOREX process and this could have a long-term radiological impact because of the formation of Pa-231 an alpha emitting isotope of protactinium in the thorium burnup chain with a relatively long half life of 30,000 years.

#### *IV.E. U233 (and thorium) recycling : handling Issues*

With recovery and recycle of U233 (and perhaps thorium) there are added handling issues beyond those associated with fabrication of fuels containing recycled plutonium, which is generally mixed with depleted uranium (MOX fuels). This is mainly due to the fact that U233, with the contaminant U232 (four decades compared to UOX), introduces an additional shielding problem, compared to the one already encountered with plutonium. As a matter of fact, and as it was said in section 2.1, U232 has a high specific activity because of its radioactive daughters. Hence, the high radiation exposure rates encountered in U233 handling and processing requires

biological shielding and usually necessitates the use of remote-handling techniques during fuel manufacturing and all other operations through reloading back into the reactor. **This considerably complicates U233 fuel fabrication and constitutes one of the major drawback of the Th/U233 fuel closed fuel cycle**, for it generates a significant cost penalty. It must be added that reprocessed thorium also contains Th228 and Th234 which prevent direct handling for many years.

It may be possible to reduce the shielding requirements by commencing fabrication of the recycled U233/thorium fuel promptly after reprocessing before buildup from U232 daughters occurs. However, there would appear to be some risk associated with this strategy unless there was a way to mitigate the consequences of U232 daughter products buildup caused by potential fabrication process delays. This has to be studied in details to assess the real impacts of the recycling strategies on handling issues.

#### *IV.F. Interim storage and Waste Disposal.*

The interim dry storage of thorium spent fuel shows characteristics a little less constraining than those of uranium based spent fuel because of the relative inertness of thorium. As a matter of fact, maximum acceptable temperatures for dry storage of spent UO<sub>2</sub> fuel are lower than thorium fuel because at higher temperatures, UO<sub>2</sub> fuel may oxidize to U<sub>3</sub>O<sub>8</sub> and cause rupture of the fuel cladding. Matrix oxidation is not an issue with thorium-based fuels. Also, the thorium structure can easily accommodate oxidation of minor solid-solution components such as U and Pu. Consequently, fuel oxidation is unlikely to be a concern during dry storage of thorium based fuels and the maximum storage temperature may be limited by other factor such as cladding degradation (See reference 11).

Direct disposal of thorium based fuels is attractive from the standpoint of long term behaviour in geological repository, because thorium oxide is chemically stable and almost insoluble in ground water. The most important chemical difference between thorium and uranium oxides is that thorium is present in its maximum oxidation state whereas uranium is not. Under oxidizing conditions, uranium can be converted into soluble uranium cation UO<sub>2</sub> (2+) and its various derivatives and may release the actinides and fission products that are retained within. Conversely, actinide and fission product release from thorium is expected to be limited by the solubility of the ThO<sub>2</sub>. No credible aqueous or geochemical process has been identified that would greatly accelerate ThO<sub>2</sub> fuel-matrix dissolution under disposal conditions (reference 11).

Disposal of used thorium and attendant fission product waste after reprocessing of thorium-based fuel would require treatment similar to that of waste from reprocessed UO<sub>2</sub> fuels. Although, thorium-based fuel cycles may produce much less plutonium and associated minor actinides than uranium based fuels, they instead may generate other radionuclides such as Pa231, Th229 and U230 that will have a long-term radiological impact.

However, **global radiotoxic inventory (GRI)** of ultimate waste for a thorium cycle appears **significantly less** than for the standard U-Pu cycle, in the same conditions. This is a real asset for thorium based fuels, which has been confirmed in several studies, such a recent one, performed in the frame of an EC contract, published in reference 7. These findings are illustrated by figures 1 and figure 2.

Figure 1 compares the overall radiotoxic inventory (in Sv/TWhe) for U-Pu and Th-U cycles for a recycling case in a FNR-Na of all actinides (MAs) assuming 0.1 % losses at the reprocessing step. Figure 2 illustrates the same results for the recycling of major actinides only (that is U, Pu, and Th only). From these results we can draw the main following conclusions with regard to GRI:

- In the case of recycling of all minor actinides (assuming 0.1 % losses in the waste), there is a gain of almost a factor of 5 to 20 up to 10 000 years with thorium based fuels (compared to U-Pu fuels). After 20 – 30 000 years or so, GRI of thorium based fuels becomes greater than U-Pu fuels but it is then less a concern since in both cases the GRI is much lower than that of natural uranium itself (the comparison is based on equivalent amounts of natural uranium which is needed to feed an open uranium cycle).
- In the case of recycling of only major actinides (that is, assuming that all other actinides such as Np, Am, Cm, Pa, go to waste), the gain on GRI reaches a factor 10 until few thousands years then the gap decreases and Th waste radiotoxic inventory becomes a little greater than U/Pu after 10 000 y. However, once again, this is not a problem because in both cases the GRI becomes lower than for natural uranium beyond a few tens of thousands years.

**Figure 1**

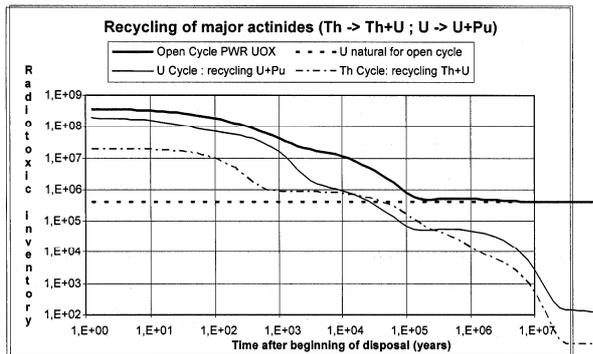
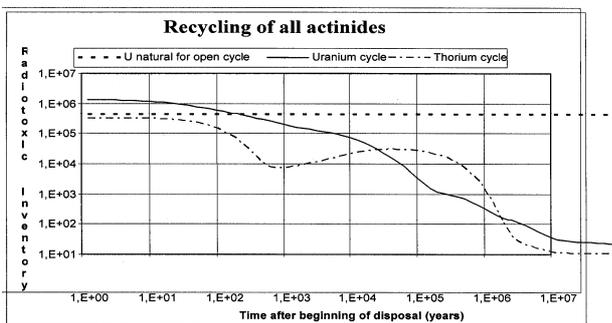


Figure 2



IV.G. Proliferation resistance.

The International Fuel Cycle Evaluation (INFCE) study (1978-1980) summarized thorium fuel activities worldwide and considered in particular issues related to the technical barriers to proliferation.

It was shown that the **technical characteristics that would inhibit proliferation for thorium cycles with up to 20 % of fissile material were similar to that of U-Pu cycles.**

Indeed, U233 can be used as a nuclear weapon material with only 5 kg to 15 Kg of it, depending on the design of the weapon, which is not very different from plutonium. As a matter of fact, U233 bare sphere critical mass is 16 Kg, compared to the 10 kg for Pu239 and 48 Kg for U235 (see table 2 of this report). Moreover, like for U235, a coarse bomb with U233 is simpler to fabricate than with plutonium, because there are very few spontaneous neutrons emitted (only 1 neutron / sec / Kg), and therefore it is possible to design and fabricate a “gun-type” weapon. This is not the case with plutonium, because neutrons emitted by its even mass number isotopes (Pu238, Pu240 and Pu242), always present in some quantities, require the manufacture of a more intricate implosion nuclear weapon. In this regard, it must be reminded that “civil” plutonium

which contains a large proportion of these isotopes would be very difficult to use to manufacture a nuclear weapon. Another important feature of U233 with regard to proliferation concerns is that it does not generate much heat compared to even mass number isotopes of plutonium, albeit higher than U235, and therefore this makes U233 potentially much less troublesome for making a nuclear weapon. In fact, according to some experts and unclassified documents, the US conducted a test of a U233 bomb core in 1957 (“Teapot test”) and has then conducted a number of other tests using this isotope.

Nevertheless, a specific technical hurdle does exist in the case of U233. This is due to the small quantities of U232 always mixed with U233 and its associated strong gamma emitters already mentioned. This creates a substantial problem for handling purified U233 during weapon fabrication process. As a matter of fact, after U233 containing U232 is processed, Th-228 builds up to a nearly constant level, balanced by its own decay. During this time the gamma emissions build up and then stabilize. Thus over a few years a fabricated mass of U233 can build up significant gamma emissions. A 10 kg sphere of weapons grade U233 (5 ppm U232) could be expected to reach 0.11 mSv/hr at 1 meter after 1 month, 1.1 mSv/hr after 1 year, and 2 mSv/hr after 2 years. Glove-box handling of such components, as is typical of weapons assembly and disassembly work, would quickly create worker safety problems. An annual 50 mSv exposure limit would be exceeded with less than 25 hours of assembly work if 2-year old U233 were used. Even 1 month old material would require limiting assembly duties to less than 10 hours per week

However, these radiation problems can be partly overcome by a “quick” processing of U233 after its separation and/or by the use of appropriate remote handling equipments. Furthermore, U232 build-up can be significantly reduced by specific provisions such as an irradiation of thorium in blankets of fast reactors (according to CEA calculations, a concentration of U232 as low as 5 ppm can be reached). This is because the (n,2n) nuclear reaction which produces U232 occurs only with very energetic neutrons ( $E > 6$  Mev), which number decreases rapidly while moving away from the reactor core in the surrounding blankets. Additionally, gamma emitter will build-up in U233 providing a radioactive “tag” attached to U233 which can help its detection and thus prevent covert proliferation attempts. It is to be noted that once a U233 weapon is fully assembled, radiation exposures would be reduced by absorption of the various materials surrounding the fissile core such as neutron reflectors. Nevertheless, the U232 highly penetrating gammas can provide a distinctive signature that can be used to detect and track the weapons from a distance.

Another deterrent to the use of U233 for making nuclear weapons, may be obtained by a dilution of U233 with U238, which may be easily done by mixing thorium with natural or depleted uranium in the fresh reactor fuel (this is the so called the “denatured thorium cycle”). However, this option would lead to plutonium production (through U238) and therefore would also raise proliferation concerns. Another option would be to dilute U233 with uranium (natural or depleted) in the course of the reprocessing of the thorium fuel (such isotopic dilution approach is not possible with Pu239 because unlike U238 all of the plutonium isotopes have sufficiently small bare-sphere critical masses to potentially permit use in nuclear explosives). In that case, the drawback would be that the U233 recycling (mixed with U238) would be much less attractive.

Another potential difficulty with use of U233 to make a nuclear weapon results from the high alpha activity of U232, which give rise to neutron emissions problems because of (alpha,n) nuclear reactions on light element contaminants in the fissile material. However, this process is a much less prolific generator of neutrons in uranium metal than the spontaneous fission of the Pu-240 contaminant in plutonium. Furthermore, a high degree of purification would allow the virtual elimination of this potential disturbing neutron source.

To sum up, **U233 is clearly a material that can be used to make a nuclear weapon but several routes can be implemented to “denature” this material easily enough**. Thus, should a uranium/thorium cycle be developed, this cycle would likely offer a degree of proliferation resistance equivalent to that of a LEU cycle, provided that uranium mixed with thorium is not used in the form of HEU (enrichment > 90 %, [reference 12]).

#### *IV.H. Thorium Fuel Cycle Cost.*

Attempting to develop a meaningful cost projection for a HTR-thorium cycle at this time is impractical. Although the cost of the raw materials itself (thorium) enters into the equation and there are published prices for these materials, the ultimate cost for a thorium cycle will depend on the costs associated with the seed material (U235 or plutonium first and U233 in the longer term), initial fabrication of fuel, the cost for recovery and recycle, i.e. fabrication of U233/thorium fuels and other variables that are difficult to predict at this time.

Further, today’s cost of thorium may be overstated (or some may argue “understated”). To begin with, the market for Thorium is diminishing as its uses for some commodities<sup>5</sup> are being replaced with non-radioactive

materials whenever possible. Since there is only limited production in the world at this time, the cost may be inflated. Some offer the opinion that an increase in production stimulated by its use for nuclear fuel could result in lower thorium prices. Counter to this opinion would be a situation where there is a significant demand brought about by the widespread use of thorium-based fuels resulting in an actual or perceived shortage bringing about higher prices.

In short, the only thing which one can say is that the total cost of a thorium cycle, once developed at an industrial scale, should not be a priori very different from that of a standard uranium cycle. However, in the case of a closed cycle (that is with the reprocessing of spent fuels and then the recycling of fissile materials), thorium cycles could be a little more expensive than U-Pu cycles because of the additional costs generated by the necessity to manufacture remotely U233 bearing and higher capacities required (larger inventories and lower burn-up).

#### V. CONCLUSION

Thorium is not a direct competitor to uranium since thorium does not contain fissile isotopes, and thus must be used in combination with fissile isotopes coming from another source (enriched uranium or plutonium or U233). Nevertheless, thorium has been always considered as an attractive fuel cycle option for future development of nuclear energy for the following main reasons, which have been discussed and assessed in this paper.

In the past, the main incentives for introducing thorium based fuel cycles have been:

- the enhancement of fuel resources by producing a new fissile isotope, U233, which is moreover the best fissile isotope for thermal neutrons,
- the existence of domestic thorium in some countries and conversely, shortages of natural uranium, knowing that thorium natural resources in the world are probably greater than those of natural uranium,
- the good in-core neutronic and physical behaviour of thorium fuel, allowing in particular, reaching high conversion factors and even breeding (i.e conversion factor superior to 1) in thermal reactors.

To day, in addition to this potential benefits, new priorities have stimulated renewed interest of thorium based fuels. Among them, two chief reasons are to be cited: (a) the fact that thorium cycles strongly reduces the buildup of long lived minor actinides (and thus the long term radiotoxic

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<sup>5</sup> Main applications are: special metal alloys with magnesium, coating tungsten wire filaments for some electronic equipments,

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ThO<sub>2</sub> for the manufacture of high refractive glasses, catalyst for chemical industry, etc.

inventory of final waste), (b) the fact that the use of thorium allows a very efficient burning of plutonium.

Another argument which is sometimes quoted in favor of thorium, is its ability to be more proliferation resistant. This argument is not very compelling because certain attractive physical properties of U233 make it a potential weapon usable material. Nevertheless, the discussion presented here on this particular point shows that several routes do exist to impede such utilisation.

Despite the benefits of thorium, its use presents some challenges that are touched on in this paper. A thorium infrastructure needs to develop on a large scale to support its industrial implementation, i.e. mining, milling, fuel fabrication, transport and reprocessing of thorium-based fuel. Reprocessing will be required if recovery and reuse of the U233 generated from the fertile thorium is intended. Fuel assembly fabrication using the recovered U233 with its inseparable sister isotope U232, and the build up of U232's gamma emitting daughters, will require a shielded facility. The fabricated fuel will need to be shielded as well from that point on.

Beyond these considerations, this review has shown that significant experience has been gained on thorium based fuel in both test reactors and power reactors, but not on an industrial scale. The feasibility of the front end fuel cycle technologies (mining, fuel fabrication) has been successfully demonstrated but for specific applications and with generally rather old technologies. Moreover, for the back-end of the cycle (treatment and recycling) the feed back experience is practically non-existent. Therefore, the use of thorium at an industrial scale would still entail quite significant R & D efforts and costs to master and optimize all the steps of the fuel cycle (including a better knowledge of thorium resources and extraction processes). Nonetheless, modern technological breakthroughs such as remote fuel fabrication techniques already applied to MOX fuels, should modify the visions which prevailed in the past on the technological hurdles linked to the implementation of thorium cycle, in particular with regard to the U233 recycling, which is required to take full advantage of thorium cycles.

To sum up, it is clear that thorium based fuels shows interesting characteristics but they do not appear sufficient to justify an industrial development of this cycle in the short-term, the more so as these potential advantages are compensated by some real drawbacks. On the other hand, in the term of a few tens of years, thorium offers some interesting prospects in particular with regard to uranium saving (if U-233 is recycled) and also with regard to the potential radiotoxicity of final waste. Then, the appearance of new constraints could modify the current context and lead to a development of thorium cycles. It is from this

point of view that it appears desirable to continue or to start a minimum of thoughts on this option to realistically assess its potential benefits under long term perspectives and anticipated technological developments, especially for the spent fuel treatment and scenarios studies.

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