The Use of Thorium within the Nuclear Power Industry – 13472

Keith Miller
The UK's National Nuclear Laboratory, Chadwick House, Birchwood Park, Warrington
WA3 6AE, UK

ABSTRACT

Thorium is 3 to 4 times more abundant than uranium and is widely distributed in nature as an easily exploitable resource in many countries. Unlike natural uranium, which contains ~0.7% fissile ^{235}U isotope, natural thorium does not contain any fissile material and is made up of the fertile ^{232}Th isotope only. Therefore thorium and thorium-based fuel as metal, oxide or carbide, has been utilized in combination with fissile ^{235}U or ^{239}Pu in nuclear research and power reactors for conversion to fissile ^{233}U, thereby enlarging fissile material resources. During the pioneering years of nuclear energy, from the mid 1950s to mid 1970s, there was considerable interest worldwide to develop thorium fuels and fuel cycles in order to supplement uranium reserves. Thorium fuels and fuel cycles are particularly relevant to countries having large thorium deposits but very limited uranium reserves for their long term nuclear power programme. The feasibility of thorium utilization in high temperature gas cooled reactors (HTGR), light water reactors (LWR), pressurized heavy water reactors (PHWRs), liquid metal cooled fast breeder reactors (LMFBR) and molten salt breeder reactors (MSBR) were demonstrated. The initial enthusiasm for thorium fuels and fuel cycles was not sustained among the developing countries later, due to new discovery of uranium deposits and their improved availability. However, in recent times, the need for proliferation-resistance, longer fuel cycles, higher burnup, and improved waste form characteristics, reduction of plutonium inventories and in situ use of bred-in fissile material has led to renewed interest in thorium-based fuels and fuel cycles.

THE THORIUM FUEL CYCLE:

So far, thorium fuels have not been introduced commercially because the estimated uranium resources turned out to be sufficient. In recent years, the renewed and additional interest in thorium has been on the following basis:

Advantages:

- Thorium is 3 to 4 times more abundant than uranium, widely distributed in nature as an easily exploitable resource in many countries and has not been exploited commercially so far. Thorium fuels, therefore, complement uranium fuels and ensure long term sustainability of nuclear power.
- The Thorium fuel cycle is an attractive way to produce long term nuclear energy with low radiotoxicity waste. In addition, the transition to thorium could be done through the incineration of weapons grade plutonium (WPu) or civilian plutonium.

- For the fissile ^{233}U nuclei, the number of neutrons liberated per neutron absorbed is greater than 2.0 over a wide range of thermal neutron spectrum, unlike ^{235}U and ^{239}Pu. Thus, contrary to ^{238}U–^{239}Pu cycle in which breeding can be obtained only with fast neutron spectra, the ^{232}Th–^{233}U fuel cycle can operate with fast, epithermal or thermal spectra. Thus, thorium is a better fertile material than ^{238}U in thermal reactors but thorium is inferior to depleted uranium as a fertile material in fast reactors.

- Thorium dioxide is chemically more stable and has higher radiation resistance than uranium dioxide. ThO_2 has favorable thermo-physical properties because of the higher thermal conductivity and lower co-efficient of thermal expansion compared to UO_2. Thus, ThO_2–based fuels are expected to have better in–pile performance than that of UO_2 and UO_2–based mixed oxide.

- ThO_2 is relatively inert and does not oxidize unlike UO_2, which oxidizes easily to U_3O_8 and UO_3. Hence, long term interim storage and permanent disposal in repository of spent ThO_2–based fuel is simpler without the problem of oxidation.

- Th–based fuels and fuel cycles have intrinsic proliferation-resistance due to the formation of ^{232}U via (n, 2n) reactions with ^{232}Th, ^{233}Pa and ^{233}U. The half-life of ^{232}U is only 73.6 years and the daughter products have very short half-life and some like ^{212}Bi and ^{208}Tl emit strong gamma radiations. From the same consideration, ^{232}U could be utilized as an attractive carrier of highly enriched uranium (HEU) and weapons grade plutonium (WPu) to avoid their proliferation for non-peaceful purpose. The proliferation resistance however only extends to the prevention of countries gaining weapons grade material – due to the difficulties in handling the high gamma waste. Whilst the high levels of ^{232}U would make it more difficult to handle, this would not be a significant concern to terrorist organisations. Such organisations are not concerned with worker dose and thus the thorium fuel cycle (high levels of ^{233}U) still represents a significant risk of proliferation via terrorist groups.

- For incineration of WPu or civilian Pu in ‘once-through’ cycle, (Th, Pu)O_2 fuel is more attractive, as compared to (U, Pu)O_2, since plutonium is not bred in the former and the ^{232}U formed after the ‘once-through’ cycle in the spent fuel ensures proliferation resistance.

- In ^{232}Th–^{233}U fuel cycle, much lesser quantities of plutonium and long-lived Minor Actinides (MA: Np, Am and Cm) are formed as compared to the ^{238}U–^{239}Pu fuel cycle, thereby minimizing the radiotoxicity associated in spent fuel. However, in the back end of ^{232}Th–^{233}U fuel cycle, there are other radionuclides such as ^{231}Pa, ^{229}Th and ^{230}U, which may have long term radiological impact.

Disadvantages:

- The melting point of ThO_2 ($3,350^0C$) is much higher compared to that of UO_2 ($2,800^0C$). Hence, a much higher sintering temperature ($>2,000^0C$) is required to produce high density ThO2 and ThO2–based mixed oxide fuels. Admixing of ‘sintering aid’ (CaO, MgO, ^{2O5}Nb, etc) is required for achieving the desired pellet density at lower temperature.

- ThO2 based mixed oxide fuels are relatively inert and, unlike UO_2 and (U, Pu) O_2 fuels, do not dissolve easily in concentrated nitric acid. Addition of small quantities of HF in concentrated HNO_3 is essential which causes the corrosion of stainless steel equipment and pipe works in reprocessing plants. The corrosion problem is mitigated with addition of aluminium nitrate.

- The irradiated Th or Th–based fuels contain significant amount of ^{232}U, which has a half-life of only 73.6 years and is associated with strong gamma emitting daughter products, ^{212}Bi and ^{208}Tl with very short half-life. As a result, there is significant build-up of radiation dose with storage of spent Th–based fuel or separated ^{233}U. This necessitates remote and automated reprocessing and refabrication in heavily shielded hot cells and increases the cost of fuel cycle activities.
- The three stream process of separation of uranium, plutonium and thorium from spent (Th, Pu) O_2 fuel, though viable, is yet to be developed.
- The database and experience of thorium fuels and thorium fuel cycles is very limited, as compared to UO_2 and (U, Pu) O_2 fuels, and need to be augmented before large investments are made for commercial utilization of thorium fuels and fuel cycles.

ECONOMICS OF THORIUM FUEL:

When implemented on a large-scale, the thorium fuel cycle can potentially offer an economic advantage over the current uranium-based open fuel cycle, despite the expectation that the fabrication cost of thorium fuel may be higher than uranium fuel.

The expected possibility of a higher cost is based on the more difficult handling of ^{233}U and the associated highly radioactive ^{232}U. Other factors, however, may mitigate the higher fabrication cost, for example; there is no enrichment required in the thorium fuel cycle. There are also fewer (than in the case of uranium) conversion process steps required to manufacture natural thorium oxide into fuel forms ready for first irradiation.

Furthermore, the ‘recycling’ capability of thorium fuel and the possibility of higher temperature operation will likely provide some additional economic benefit. The conversion from fertile ^{232}Th to ^{233}U is done during fission. The resulting fissile ^{233}U can continue to undergo fission and produce energy for a long time (a higher burn-up), up to the limit imposed by the behavior of the fuel cladding material and supporting structures. Higher temperature operation of future thorium-based reactor designs should increase the nuclear energy systems’ thermal efficiency from the current best of 34% to as high as 50% or even higher, directly contributing to a reduction of the fuel cost per unit of energy generation.

SO WHY AREN’T WE USING IT?

The utilization of thorium could start today, in the current generation of nuclear energy systems with some redesign and relicensing. However, in a once-through fuel cycle (i.e. no recycling to recover the remaining ^{233}U after discharge); the use of thorium fuel is not very economical.

The biggest challenge facing the introduction of the thorium fuel cycle for commercial power generation is the lack of fuel-fabrication-related infrastructure.

The nuclear industry has benefitted from the availability of similar infrastructure for the uranium fuel, which was made possible by investment in the past for non-civil applications. However, the fuel-fabrication infrastructure for the thorium fuel cycle will have to be developed for commercial considerations.

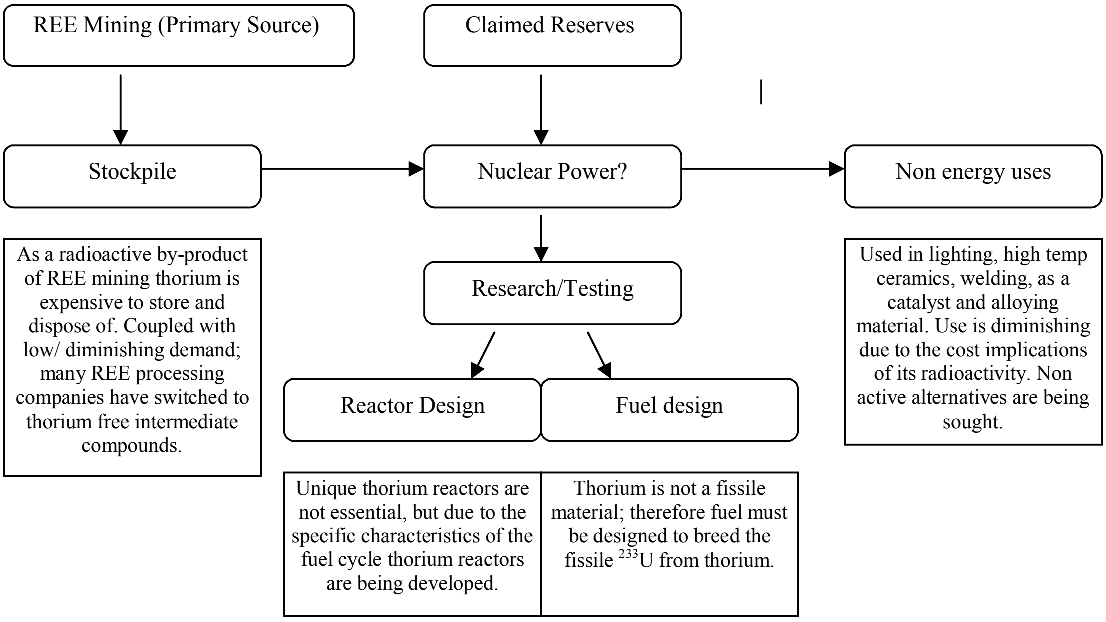
It is important to note that for all of the potential advantages of Thorium as a fuel, they are in practice not yet proven. With current levels of experience it is not possible to say whether Thorium will deliver as a fuel. A great deal more knowledge and research is required before there is enough confidence to make the necessary large investments required.

THORIUM MARKET CHARACTERISTICS:

Due to its physical properties (producing bright white light when burned), thorium is used in the manufacturing of light bulbs, camera flashes and welding equipment. However, due to the immature nature of Thorium as a fuel, there is currently little demand for it within the commercial nuclear industry.

Thorium consumption worldwide is relatively small compared with that of most other mineral commodities. Thorium and its compounds are produced mainly from the mineral monazite as a recovered by-product of mining activities for REE's (Rare Earth Elements), only a small fraction of which is used. The limited demand for Thorium continues to create a global oversupply of Thorium compounds and residues.

The diagram below shows the different segments of the thorium market:



As a radioactive by-product of REE mining thorium is expensive to store and dispose of. Coupled with low/ diminishing demand; many REE processing companies have switched to thorium free intermediate compounds.

Used in lighting, high temp ceramics, welding, as a catalyst and alloying material. Use is diminishing due to the cost implications of its radioactivity. Non active alternatives are being sought.

Unique thorium reactors are not essential, but due to the specific characteristics of the fuel cycle thorium reactors are being developed.

Thorium is not a fissile material; therefore fuel must be designed to breed the fissile ^{233}U from thorium.

WHO'S DOING WHAT?

Stakeholder	Current activities
BARC India	(Bhabha Atomic Research Centre) The main research facility in India, carrying out research into thorium fuel cycle. Currently operating a small research thorium fuelled uranium breeding fast reactor.
China'	Atomic Energy of Canada Limited (AECL) has signed an agreement with China's Third Qinshan Nuclear Power Company (TQNPC), China North Nuclear Fuel Corporation (CNNFC) and Nuclear Power Institute of China (NPIC) to cooperate in assessing the use of thorium fuel in CANDU reactors.
Dauvergne Brothers Inc. US	Designing a completely 'closed' thorium reactor in which fissile material is burnt and spent fuel is vitrified. No prototype as yet.
Thor Energy Norway	Early stages of developing ceramic oxide TOP (thorium and plutonium) fuel for LWRs. Designs are to work with existing MOX infrastructure.
Thorium Energy Inc. US	Holds rights to thorium reserves in the US, intend to mine thorium as primary product once a market/demand has developed.
Lightbridge Corporation. US	Carrying out research/tests of well developed thorium fuel assembly designs with Red Star at the Kurchatov institute, Moscow. International interest from Areva, UAE and India.

CLAIMED RESERVES:

Although thorium is readily available as a by-product from REE mining processes, some reserves have been claimed with the view of extracting thorium as the primary product. Thorium Energy Inc (www.thoriumenergy.com), a privately owned US company have laid claims on "…one of the largest documented high-grade thorium properties in the world-approximately 80% of the U.S. known and estimated reserves". They hold the mineral rights to the Lemhi Pass in Idaho and Montana. The reserves are claimed on the following basis:

1. The pass is rich in thorium containing minerals. It is hoped that in the not so distant future there will be a large demand; based on the commercialisation of thorium as a nuclear fuel.
2. The reserves are also rich in REE's, which are being used increasingly in high tech innovation (such as hybrid cars). The majority of the worlds REE's are currently exported from China (up to 95%). With the US's growing requirement for such resources and China's tactical stand on REE exports, Thorium Energy hope that they will control one of the largest sources outside China.

The reserves are not being mined yet, due to the lack of demand and the expense of storage, processing and transportation.

FUEL DESIGN:

The designs for thorium fuel assemblies are largely based upon a fissile seed (Uranium or Plutonium) and blanket (thorium) design.

The company that appears to be ahead with its fuel design is Lightbridge Corp (formerly Thorium Power (www.ltbridge.com)); a US company that has recently gone public on the NASDAQ exchange. The company is currently in the process of designing and testing plutonium-thorium seed and blanket fuel rod assemblies for the Russian VVER-1000. The designs are based upon those of Alvin Radkowsky, the 'father' of the commercial nuclear plant. The work has been carried in a partnership between Lightbridge Corp. and the Russian government owned Red Star (a nuclear reactor design company) at the Kurchatov Institute, Moscow. The fuel is currently in the testing phase within full scale VVER-1000 reactors and going through post irradiation examinations. The fuel, if successful will be able to be utilized with small adaptations, in the world's LWR's.

The company has also entered into two five year agreements with the UAE to provide strategic advice for the planning and implementation of nuclear power. They have also recently this year entered "…an initial collaborative agreement with Areva relating to thorium-based fuel designs." Perhaps most importantly; the designs and technology have been acknowledged and approved by major nuclear authorities such as the WNA and the IAEA. It is also alleged that India is interested in purchasing Lightbridge technology to exploit its thorium reserves.

A new thorium-based fuel is being developed by the Norwegian company Thor Energy (part of Scatec www.scatec.no) that will target the commercial LWR market. The ceramic oxide fuel will incorporate recovered LWR plutonium – homogeneously distributed in a fertile thorium oxide matrix. The fuel material is denoted as TOP- Thorium Og Plutonium, Og being Norwegian for "and".

Thor Energy is working within a staged approach for deploying thorium fuels – a first phase will build on today's MOX fuel infrastructure. A second phase will see industrialization of technologies for extracting bred-in ^{233}U and reusing this in current-generation reactors. The third phase will see thorium fuels designed for breeding in advanced LWR's, and subsequent recycling of bred-in ^{233}U. Thor Energy has started detailed planning for an experimental campaign comprising pellet fabrication trials and a test irradiation in the Halden research reactor, in which the performance of $(Th,Pu)O_2$ fuel pellets will be investigated in conditions valid for licensing in LWRs.

Thorium is currently being used as fuel in PHWR research reactors in India, and has in the past been used in MSR's (Oak Ridge) and HTGR's.

Should MSR's ever become a commercially used reactor type then they would be an ideal reactor for the use of thorium fuel. This is mainly due to the physical properties of thorium that make fuel fabrication expensive; such as high melting/sintering temperatures. In an MSR the thorium could be put straight into the coolant of molten salt (with a fissile material) as a liquid fuel; removing the necessity of fuel fabrication.

REACTOR DESIGN:

Although specific reactors are not required to utilise thorium as a fuel, the US company Dauvergne Brothers Inc (www.dauvergne.com) has designed a reactor that eliminates the problems created by a traditional once through reactor cycle. The traditional reactors simply use Th as a blanket to help increase the breeding of fissile material ^{233}U, which in turn is used in a traditional uranium fuel cycle.

DBI proposes a new reactor design, based upon a self contained closed cycle. The DBI Thorium Reactors are designed to breed the artificial ^{233}U from thorium, burn most of that fuel as soon as it is bred, and store the minor amount of unburned fuel—all in situ. “Taking advantage of the benefits of thorium, a DBI Thorium Reactor can produce electricity for a cost of only $0.04-$0.07 per kilowatt-hour”. while its breed-and-burn fuel cycle could over time reduce long-term radiotoxic waste by more than 90% without the need for fuel reprocessing (due to more efficient fuel utilization, the elimination of packaging waste, and significant reduction of long-lived radioactive isotopes).

In addition, no waste would be produced for 30 - 60 years, until plant decommissioning, when waste will remain in the reactor encapsulated in glass. No external storage (geological repository) will be necessary.

DBI hope to receive funding to enable them to manufacture a test/demonstration reactor in order to bolster their claims with gathered data.

The entire assets of DBI were sold (April 2012) to a Canadian entity, Thorium Power Canada, Inc. (“TPC”).

The agreement calls for TPC to finance the reactor (10 MWe) for northern Chile and potentially a reactor for NASA to produce cryogenic hydrogen and oxygen from seawater at a short distance to launch site(s).

Part of the agreement calls for rights (in the form of a license), to be given to “DBI Ceramics” in California. Using an export license, “DBI Ceramics” will produce hardware for DBI Chile (under Chilean laws) and will build and operate a 10MWe plant for the desalination of seawater.

INTERNATIONAL SUPPORT FOR THORIUM AS A FUEL:

In addition to the afore mentioned companies and institutions, several governments are reaffirming their interest in thorium as a fuel after over five decades of marginalizing the topic. Initial interest during the beginning of the nuclear age in the 50’s dissipated after the discovery of new uranium reserves and the subsequent low prices. With uranium prices on the rise and the nuclear non-proliferation and international energy security issues prevalent in 21st century politics, governments are once again looking to thorium as an alternate means of energy.

India has always had interest in the thorium fuel cycle due to its thorium endowment, and consequently has perhaps the most advanced thorium industry at present. One of the major aims of the ambitious and expanding nuclear power programme in India is thorium utilization in all the three stages of the indigenous nuclear power programme with a ‘closed’ fuel cycle linking pressurised heavy water reactors, liquid metal cooled fast breeder reactor and ^{232}Th–^{233}U fuelled self sustaining advanced reactors. India is already running a very small research reactor on ^{233}U fuel extracted from thorium which has been irradiated and bred in another reactor. When this started in 1996 it was hailed as a first step towards the thorium cycle utilising "near breeder" reactors. India is actively researching ADS as an alternative to its main fission program focused on thorium. Having said this, the international view on thorium ADS systems is sceptical as to whether this technology will be viable in the near future. This view is backed by a 2008 Norwegian study into such technology, which stated “such a system was not likely to operate in the next 30 years”.

Other countries that are particularly prevalent in the current thorium for energy industry are detailed below.

China:	the government has voiced its commitment to developing thorium fuel technology.
Australia:	little to do with current research and development, but strong supporters due to the large thorium reserves in the northern territory.
France:	the nuclear industry is heavily supported and funded by the French government, thus Areva’s interest in thorium fuel is one of the same. Energy security is also high on the government’s agenda inline with their foreign policy.
Canada:	is involved in research using thorium fuel within its CANDU reactors.
Czech: Republic	the national research lab UJV is carrying out research, with particular attention to the back end of the thorium fuel cycle.
Russia:	the collaborations with Thorium Power ltd mean that Russian VVER reactors will almost certainly be the first to utilise thorium fuel.
Norway:	the fuel research is backed by the government, to enable the nation (with diminishing oil reserves) to maintain its position as a net energy exporter.

In fact just about any nation with a nuclear industry is beginning to show increasing interest in thorium as an alternative fuel source for the future. There is growing unilateral cooperation between nations, including intergovernmental organisations such as INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) under the IAEA, MICANET (Michelangelo Network Competitiveness and Sustainability of Nuclear Energy in EU) and the US led GIF (Generation IV international forum). Such cooperation has lead to talks of future plans to provide nuclear (thorium based) power to developing countries, previously impossible due to the risk of proliferation of weapons.

MARKET VALUE:

Although there is an astounding level of interest and research at present, it remains remarkably hard, if not impossible to place any quantitative figures on the industry. As discussed the technology can work, but it is the lack of infrastructure at the front and back-end of the cycle that is preventing commercialisation. Since no thorium-based fuel is being used in the world today, there is almost no international market for thorium. Consequently the necessary supporting mining, fuel fabrication and reprocessing industries will not develop until the demand for thorium fuel develops.

Despite this catch 22, it is possible to nonetheless quote some ball-part figures from Thorium Power Ltd, as to what they estimate the market to be for there solid fuel designs. In a presentation presented to prospective investors; Thorium Power Ltd estimated that the annual international thorium fuel market could currently be between US$390-780 million. This figure is based on the worlds current PWR reactors (either in operation, or under construction), and thorium holding a 5-10% market share of their annual fuel expenditure (assumes an average spend of US$40Million per reactor per year). The figures go on to make predictions for the future planned and proposed PWR reactors, including an increased market share as thorium fuel is proliferated. These figures bring the total market estimated value to between US$708M-2.0B.

There is always the current cost of thorium, which currently stands at approximately $150-250/kg (99.9% purity). However, this figure is largely useless in terms of establishing a market value for thorium as a fuel. As previously discussed, thorium is traded in small quantities (diminishing) for use in lighting, welding and other uses. This figure is not representative of a price for the 1000's of tonnes required should it be used as a fuel (nor is the purity). There is much debate as to whether once a demand for thorium fuel is established the price will go up or down. The former is supported by the fact that the required infrastructure will require significant costs to be recovered from sales. Also, the price is argued to be likely to increase due to the economics of demand, and the countries holding the largest reserves (similar to the oil price dictated by OPEC).

The latter argues that the price will drop due to the implementation of the necessary market infrastructure, and a subsequent drop in the cost of production, economies of scale etc.

FUTURE PROSPECTS:

The future prospects of thorium fuels and fuel cycles in different nuclear energy systems are summarized as follows:

(a) LWRs:

(i) ThO_2 and (Th, ^{235}U) O_2 (LEU) 'pellet-pin' fuel assemblies, the 'Radkowski seed blanket thorium fuel' of high burnup and in 'once-through' cycle.

(ii) Cermet fuel consisting of fuel microspheres of (Th, ^{235}U) O_2 (LEU) in zirconium matrix.

(iii) (Th, Pu) 'pellet-pin' fuel assemblies for burning civilian and weapons plutonium in 'once-through' high burnup fuel cycle.

(b) HTGR:

Multilayer coated fuel particles (in some cases using ZrC coating in place of SiC) of Th–based mixed oxide or dicarbide in graphite matrix for very high temperature gas cooled reactors of the Pebble–Bed or Prismatic Block type, primarily with the objective of delivering high temperature (800 – 1,000^{o}C) process heat for generation of hydrogen based on thermo chemical iodine sulphur process.

(c) Heavy water moderated reactor:

(i) High burnup 43–element CANFLEX (9 inner elements of ThO_2) pin assemblies in combination with slightly enriched uranium oxide pins (34 outer elements) in advanced CANDU reactor (ACR) on ‘once-through’ basis.

(ii) High burnup 54–elements fuel assemblies containing thirty (Th, ^{233}U) O_2 fuel pins in two inner circles and twenty four (Th, Pu) O_2 pins in outer most circle for AHWR working on self-sustaining mode.

(d) Fast reactors:

(Th, Pu) O_2 ‘pellet-pin’ fuel assemblies operating on ‘once-through’ open cycle mode for burning weapons or civilian plutonium and simultaneously making the spent fuel proliferation-resistant because of the formation of ^{232}U by (n, 2n) reaction of ^{232}Th.

(e) MSBR:

Mixed fluoride molten salt fuel (and primary coolant) of composition 7LiF/BeF2/ThF4/UF4 for self sustaining ^{232}Th–^{233}U fuel cycle (the initial core would use LEU).

(f) ADS:

Thorium fuelled energy amplifier (EA) of completely thermalised EA (T–EA), partially thermalised Pressurized Water moderated EA (PW–EA) and Fast neutron lead cooled EA (F–EA).

INSIGHTS:

- In front end of fuel cycle, thorium resources identified, so far, are a factor of three lower than those reported for uranium, in spite of the fact that thorium is three times more abundant in nature than uranium. Activities on exploration and prospecting of thorium minerals need to be augmented all over the world.
- For most efficient use of thorium resources, self-sustaining, proliferation resistant and ‘closed’ ^{232}Th–^{233}U fuel cycle should be developed on an industrial scale for thermal neutron reactors like MSBR, HTGR and AHWR. Such fuel cycle will generate minimum quantity of low actinide waste, the radiotoxicity of which would be much lower than the existing reactors working on ^{238}U–^{235}U/^{239}Pu fuel cycle for the first 50,000 years of disposal.

- Civilian and weapons-grade plutonium could be burnt efficiently by introducing (Th, Pu) O_2 fuel in 'once-through' open cycle in either fast reactor, LWR or CANDU–PHWR. The spent fuel would be proliferation-resistant due to the presence of strong gamma emission from the daughter products of ^{232}U formed by (n, 2n) reaction with ^{232}Th.
- Utilizing (Th, LEU) O_2 fuel in 'once-through' open cycle in LWRs involving Radkowski seed blanket concept or as Cermet fuel in zirconium matrix. Alternatively, utilizing (Th, LEU) O_2 fuel in 'once-through' open cycle in Advanced CANDU Reactors involving 43–element CANFLEX bundle with 9 inner pins of ThO_2.
- Developing ADS with subcritical thorium assembly as a breeding fuel for minimizing transuranic actinide waste.
- For fabrication of highly radiotoxic plutonium and ^{233}U–bearing (with ^{232}U) thorium based ceramic fuels, the dust-free 'Sol-Gel-Vibratory-Compaction' or 'Sol-Gel-Microsphere Pelletisation' (SGMP) processes, amenable to remotisation and automation, should be developed on an industrial scale.
- For reprocessing of spent Th–based fuel, the thrust areas should be further modification of THOREX process in order to have two stream (U and Th) or three-stream (U, Pu and Th) routes for separation of ^{233}U, Pu and thorium. The proliferation-resistance of ^{233}U could be further improved by denaturing with the addition of ^{238}U.
- In the area of long interim storage and disposal of high active wastes, though ThO_2 and (Th, U) O_2 are known to be more stable than UO_2 or (U, Pu) O_2 in oxidizing environments such as ground water or hot air, further experimental data is needed to confirm this assumption.

CONCUSIONS:

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 ^{233}U). Nevertheless, thorium has always been considered as an attractive fuel cycle option for future development of nuclear energy for the reasons discussed.

Despite the benefits of thorium, its use, as discussed presents some challenges. 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 ^{233}U generated from the fertile thorium is intended. Fuel assembly fabrication using the recovered ^{233}U with its inseparable sister isotope ^{232}U, and the build up of ^{232}U's gamma emitting daughters will require a shielded facility. The fabricated fuel will need to be shielded as well from that point on.

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. More importantly, 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 regarding the technological hurdles linked to the implementation of the thorium cycle. This is true in particular with regard to the ^{233}U recycling, which is required in order take full advantage of thorium cycles.

To sum up, it is clear that thorium based fuels show 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 decades, thorium offers some interesting prospects in particular with regard to uranium saving and also with regard to the potential radio toxicity of final waste. The appearance of new constraints could modify the current context and lead to a development of thorium cycles. It is therefore considered desirable to continue upon the current direction of R&D into thorium cycles, in view of global commercialisation in the not so distant future. For this to succeed the amount of investment must be greatly increased. Whilst private investment is sufficient for the development of fuel designs, this amount is comparatively low when compared to the amount required to build an industrialized infrastructure. The motive of private investment being a timely return, the responsibility falls upon governments to make the large and long term investment needed. On this note, it is almost certain that the first nations to begin using thorium on an industrial basis will be those able to invest in the infrastructure….those in Asia.

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