Use of Thorium in the Nuclear Fuel Cycle

How should Thorium be considered in the GIF?

Prepared by the GIF Experts' Group

12/23/2010

Use of Thorium in the Nuclear Fuel Cycle

How should Thorium be considered in the GIF?
Position paper prepared by the GIF Experts' Group

1 – Introduction

Thorium is a naturally occurring radioactive element with potential application in the nuclear fuel cycle. Thorium has no fissile isotopes, meaning that unlike uranium it cannot be enriched to produce a viable nuclear fuel. Natural thorium is almost entirely comprised of the isotope ^{232}Th. A microscopic amount of ^{228}Th that is created in the radioactive decay of ^{232}Th. Small amounts of other thorium isotopes can be detected from decaying uranium atoms that often occur with thorium elements in nature.

^{232}Th would play a role equivalent to ^{238}U for use in a nuclear reactor. Both elements are fertile and can absorb a neutron to transmute into a fissile isotope capable of sustaining a chain reaction. In the case of ^{238}U the fissile isotope produced is ^{239}Pu and ^{232}Th produces the less well known fissile isotope ^{233}U. Both the thorium base material and ^{233}U have potential applications in the nuclear fuel cycle[i].

.

2 – Resources and Physical Properties of Thorium

The average concentration of thorium in the Earth's crust is reported to be three to four times higher than the one of uranium. More relevant, though, are the number and the significance of large scale and rich deposits. Although there is no significant commercial market for thorium today, past exploration of deposits, such as carbonatites and alkaline igneous bodies, for uranium, rare earth elements, niobium, phosphate, and titanium, demonstrated that thorium is abundant and widely dispersed. Resources have been identified in several countries, amounting to a global total of roughly 4 to 6 million tonnes, with estimates varying somewhat due to differing methods used[ii]. Countries with significant thorium resources (>100 000 t Th) include Turkey, Brazil, India, United States, Australia, Venezuela and Norway. Resources have also been documented in Canada, Greenland, the Russian Federation and South Africa. Today, thorium is recovered mainly from the mineral monazite as a by-product of processing heavy-mineral sand deposits for titanium-, zirconium-, or tin-bearing minerals[iii]. Given its relative abundance and the current absence of a significant market, no specific efforts have been made in recent decades to improve the knowledge of thorium resources. Undoubtedly, the development of demand for thorium would lead to the identification of significant additional resources.

Thorium dioxide (ThO_2) has a melting point of 3370°C well above that of UO_2 (2840°C) and a slightly better thermal conductivity. However, these assets do not result in more robust thorium-based fuels as thorium fuels blended with uranium or plutonium have thermal properties somewhat less favorable than thorium oxide. Thorium dioxide is the highest oxidation state of thorium which means the material will not oxidize further while in long term storage.[iv]

3 – Fertile ^{232}Th and Fissile ^{233}U

As shown on Figure 1, the single dominant isotope of thorium does not fission when it absorbs a neutron at thermal energy, which is the spectrum of all commercially operating reactors today. However, ^{232}Th is a fertile isotope, transmuting to ^{233}U upon neutron absorption.

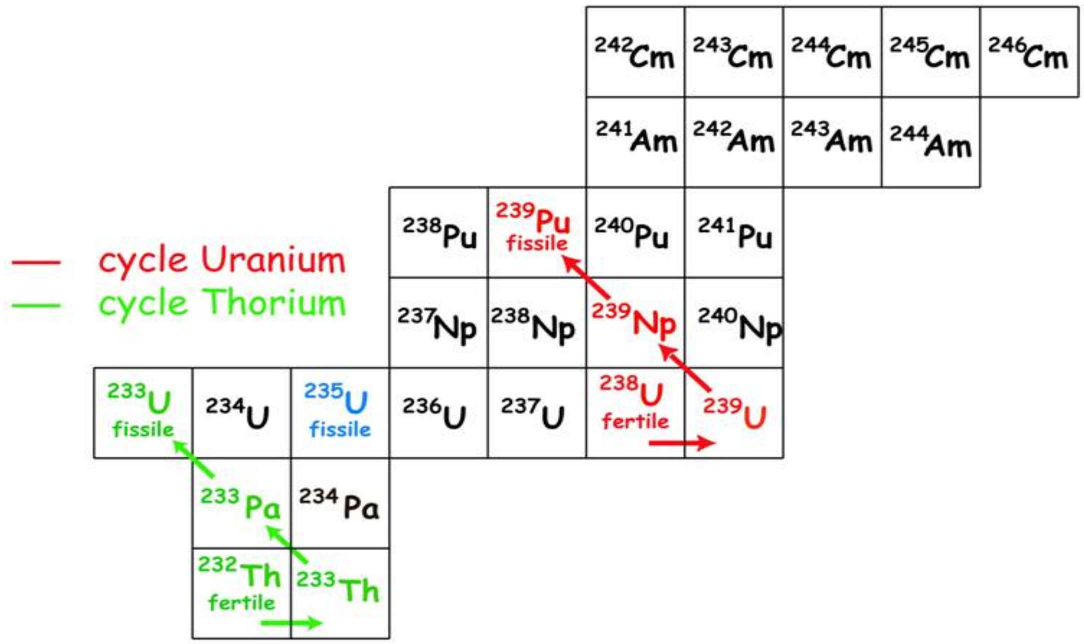


Figure 1: Comparison of thorium and uranium cycles

^{233}U is an excellent fissile isotope in a thermal spectrum, superior to ^{235}U and ^{239}Pu that are used today because of its higher neutron yield per neutron absorbed (η factor). A self sustaining chain reaction requires less ^{233}U than ^{235}U. This is evidenced by Table 1 that compares the nuclear properties of the three above fissile nuclei in thermal and fast neutron spectra.

isotopes	^{235}U		^{239}Pu		^{233}U	
spectrum	Thermal	Fast	Thermal	Fast	Thermal	Fast
σ_f (barn)	582	1.81	743	1.76	531	2.79
σ_c (barn)	101	0.52	270	0.46	46	0.33
$\alpha=\sigma_c/\sigma_f$	0.17	0.29	0.36	0.26	0.09	0.12
ν	2.42	2.43	2.87	2.94	2.49	2.53
$\eta=\nu\sigma_f/\sigma_a$	2.07	1.88	2.11	2.33	2.29	2.27
β_{eff} (pcm)	650		210		276	

Table 1: Comparison of nuclear properties of fissile isotopes ^{235}U, ^{239}Pu and ^{233}U: average cross sections of fission and neutron capture (σ_f, σ_c) in typical thermal and fast reactor neutron spectra, number of neutrons per fission (ν), delayed neutron fraction (β_{eff})

Effective breeding with uranium-thorium fuel cycle calls for both:

- Minimizing neutron parasitic absorption owing to the moderate margin of the η factor above the threshold of 2
- Peculiar provisions for managing ^{233}U's mother nucleus, ^{233}Pa, that has a half life of 27 days and may be converted into ^{234}Pu by neutron capture before decaying into ^{233}U.

$$^{232}\text{Th} + \text{n} \rightarrow {}^{233}\text{Th (22 min)} \rightarrow {}^{233}\text{Pa (27 days)} \rightarrow {}^{233}\text{U } (1.5\ 10^5 \text{ years})$$

As a lighter nucleus than uranium and plutonium, thorium fuel produces less transuranics than uranium fuel. This may somewhat alleviate the long term burden associated with the disposal of ultimate high level waste (whether it is spent fuel or packages of vitrified fission products and transuranics) in terms of decay heat and radiotoxic inventory. As regards the latter, though, daughter products of ^{232}Th and ^{233}U (such as ^{231}Pa and ^{229}Th respectively) cause excess radiotoxic inventory compared with uranium fuel used for producing the same amount of energy during the time period of 20 000 to 1000 000 years after use.[v,vi,vii] Furthermore, taking full benefit from the lesser production of transuranics requires recycling highly enriched ^{233}U fuel which may not be acceptable for non-proliferation (cf. §7).

Thorium fuel has been proposed for almost every type of reactor conceivable. The first ^{233}U reactor was built in 1961 to study advanced thorium reactor concept. The first commercial application of thorium-uranium fuel occurred in August 1962 at the Indian Point-1 Nuclear Power Plant. The first reactor fueled with fissile ^{233}U was the Oak Ridge National Laboratory molten-Salt Reactor in October 1968[viii]. Thorium and uranium fuel were efficient enough to demonstrate conceptual fissile fuel breeding with a water cooled reactor at the Shippingport Light Water Breeder test Reactor from 1977 to 1982.[ix] The Thorium High Temperature Reactor (THTR), a prototype of gas cooled pebble bed reactor of 300 MWe that operated in Germany from 1983 to 1989, contributed to demonstrate a fuel cycle with thorium and highly enriched uranium (HEU> 90% ^{235}U). This fuel cycle with a ratio of HEU/Th of 1/10 cannot be considered anymore for its lack of proliferation resistance.

4 – Thorium Fuel in Current Reactors

The application of thorium fuel directly into a current reactor faces multiple practical issues. The first is that commercial supplies and manufacturing infrastructures do not currently exist. The base technology exists but the infrastructure has not been created. The licensing process and the testing data base required to create the license have not been performed. Multiple scientific tests related to safety, fuel performance and evaluation of the radioactive source term would need to be created, submitted, evaluated and approved. Details related to the reduced number of delayed neutrons emitted by ^{233}U (270.10^{-5}) compared to ^{235}U (650.10^{-5}) may require fuel design or reactor design changes to address reactor transient behavior to maintain safety margins. This however raises little concern as plutonium fueled reactors have been operated, even though the delayed neutron fraction of ^{239}Pu is ~210.10^{-5} only and the effective value for plutonium fuel is about that for ^{233}U.

4.1 – Open Thorium Fuel Cycle

Near term thorium fuel design proposals are based on thorium fuel being used only once in the reactor without recovering the created ^{233}U. This is mainly considered by countries that currently operate their generating fleet with uranium fuel in the open cycle mode; uranium (LEU) and thorium fuels may then be used either mixed together or separately in the core. Thorium may also be considered by countries concerned by excess plutonium burning as, unlike uranium, thorium breeds very little plutonium; plutonium and thorium may then be used most likely as mixed fuel. Core design studies investigate conditions under which thorium fuel operating for many cycles in the reactor may build up enough ^{233}U eventually to offset the additional enrichment in ^{235}U of uranium fuel. CANDU heavy water reactors (HWRs) that feature a high neutron economy, as having primarily been designed around the ability to use natural uranium, may be particularly well suited to achieve high conversion of thorium into ^{233}U (as they do for ^{238}U into plutonium)[x].

Figure 2 shows two possible uses of thorium fuel with once-through fuel cycle in light or heavy water reactors (LWRs or HWRs).

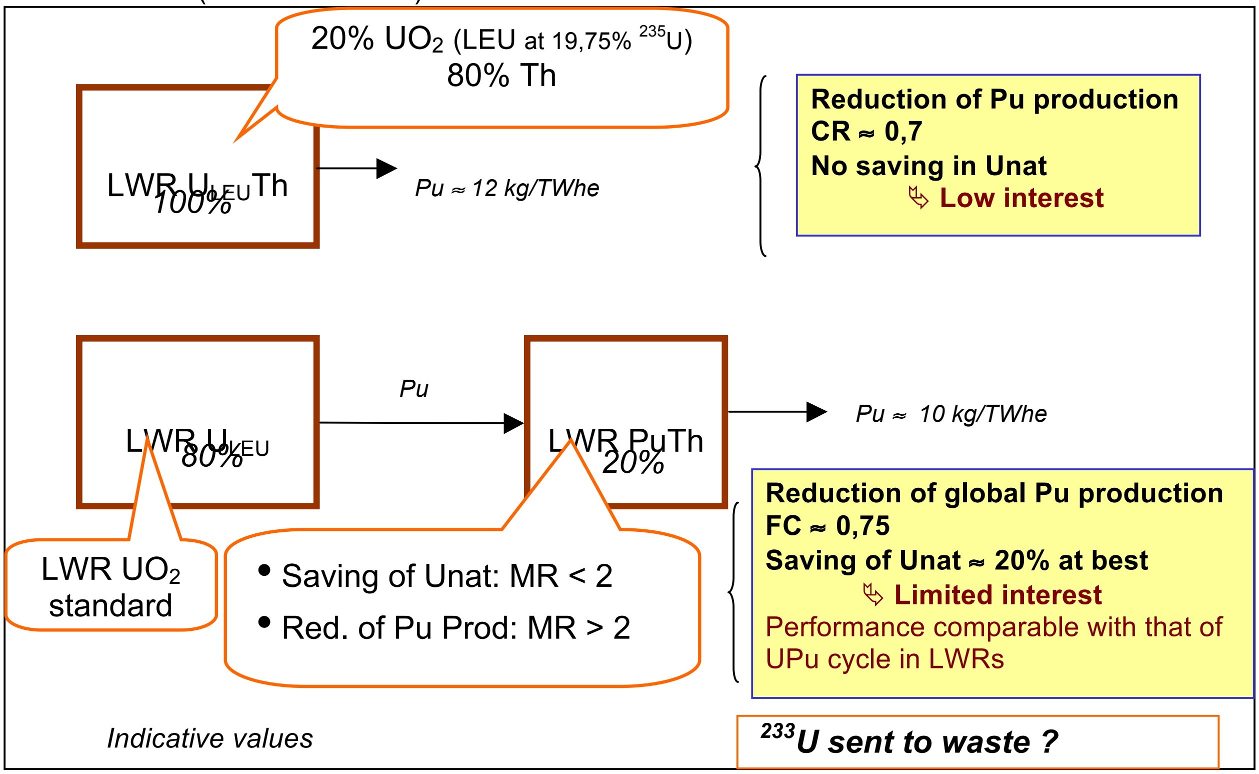


Figure 2: Use of thorium-based fuels in LWRs with an open fuel cycle. Comparable use can be made in HWRs fueled with ~5% UO2 (LEU at 19.75% 235U) and ~95% thorium.

The first consists of using U_{LEU}Th fuel with uranium enriched at 19.75% ^{235}U in place of ~4-5% ^{235}U in LWRs or ~1% in HWRs. Either type of reactor may use a mixed U_{LEU}Th fuel or mixed fuel bundles made of separate U_{LEU} and thorium fuel pins arranged in such a way as to optimize the conversion factor[xi]. Even though slightly improving the conversion factor this option is of limited interest to really improve the use of natural resources in LWRs. U_{LEU}Th fuel effectively breeds ^{233}U that is burned in situ but it produces less plutonium than standard uranium fuel which overall results in little saving of uranium for a given supply of energy. Regarding HWRs, India is currently studying a variant of advanced HWR (AHWR) that uses thorium and LEU-based fuels, with plans for further optimizing this reactor type for operation with uranium-thorium fuel cycle and maximum conversion factor.

The second consists of burning in thorium-based fuel the plutonium produced in standard uranium fueled light or heavy water reactors in a two tiered generating fleet. For LWRs, this approach is believed to achieve approximately 20% saving in uranium compared to uranium-fueled standard reactors operating with an open fuel cycle. Savings at this level are no more than those achieved in standard LWRs with a single recycle of plutonium as MOX fuel and reprocessed uranium (saving of ~10% each) which makes this use of thorium moderately attractive unless the spent plutonium-thorium fuel is reprocessed for retrieving and recycling ^{233}U in reactors operated with a uranium-thorium fuel cycle. This recycle mode would then allow for a transition from a uranium-plutonium fuel cycle into a thorium-uranium fuel cycle.

4.2 – Closed Thorium Fuel Cycle in thermal neutron reactors

The use of recycling opens up many more fuel cycle options. Most nuclear countries that currently reprocess the spent nuclear fuel or acknowledge recycle as an essential feature of sustainable nuclear power, consider closed thorium fuel cycles as the most efficient path to make use of thorium (through its conversion into ^{233}U). Indeed, as for uranium, open fuel cycles lead to use less that 1% of the overall thorium energy content whereas more than 80% can be burned as ^{233}U with multiple recycle. Figure 3 shows examples of symbiotic fuel cycles in a two-tiered generating fleet of LWRs or HWRs with recycle of ^{233}U and plutonium respectively from spent thorium and low enriched uranium fuels.

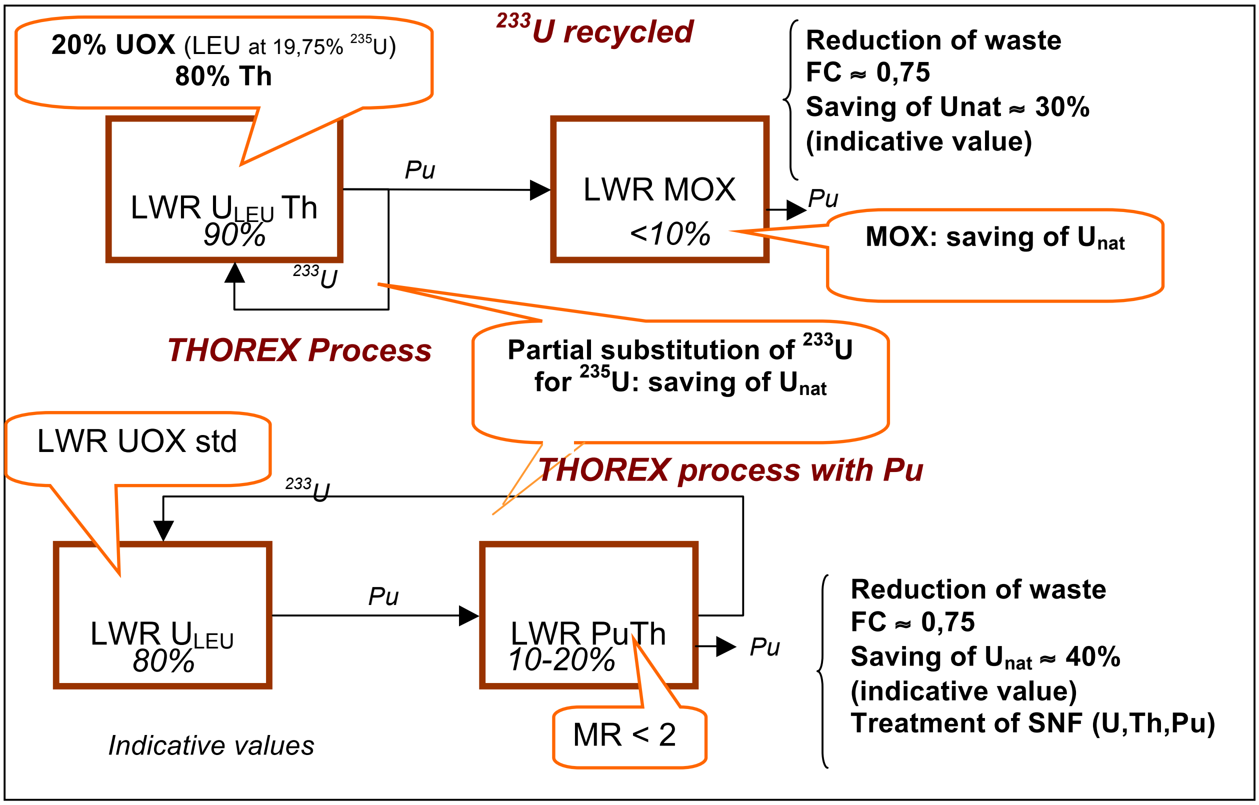


Figure 3: Use of thorium-based fuels in LWRs with a closed fuel cycle. Comparable fuel cycles may also be considered with HWRs.

Separating ^{233}U allows fuel to then be manufactured with an inherent fissile content analogous to enriched uranium. Separating the thorium also allows it to be recycled back to the reactor. However, the reprocessing of thorium-based fuel cannot be achieved with processes that are currently used for uranium fuel. It calls for a specific process (Thorex) that requires a mixture of hydrofluoric and nitric acids in place of the second only for uranium and plutonium fuels. Therefore the implementation of the Thorex process at industrial scale can only be envisaged in the medium term after demonstrations at pre-industrial scale have been made.

Examples of figure 3 are symbiotic fuel cycles in a two-tiered generating fleet of LWRs or HWRs with recycle of ^{233}U and plutonium respectively from spent thorium and low enriched uranium fuels. Both examples require an industrial use of the Thorex process. The first example consists in $U_{LEU}Th$ and 100% UPu MOX fueled reactors. ^{233}U from spent $U_{LEU}Th$ is recycled in the former while plutonium in recycled in the latter. This overall recycle scheme achieves uranium savings of the order of ~30% compared with standard LWRs operating with an open uranium fuel cycle. The second example consists in U_{LEU} and PuTh fueled reactors. Plutonium from spent uranium fuel is recycled as PuTh fuel whereas ^{233}U from the latter is recycled as a component of U_{LEU} fuel. This overall recycle scheme achieves uranium savings of the order of ~40% compared with standard LWRs operating with an open uranium fuel cycle.

Besides, ^{233}UTh fuel also has a significant radioactive field generated by isotopes intrinsic to the creation of ^{233}U (namely ^{229}Th, ^{231}Pa, ^{232}U and daughter products). These isotopes require remote fuel manufacturing, but also provide some deterrent to nuclear proliferation.

Technical and economic studies are needed to assess the commercial viability of such uses of thorium as a function of the price of uranium, the cost of recycle of ^{233}U and plutonium (investment and operating cost for fuel reprocessing and re-fabrication…) and costs of associated fuel cycle back-end. Non-proliferation issues also need to be thoroughly addressed.

5 – Thorium Fuel in Symbiotic Generating Fleets *(LWRs/CANDUs & Fast Reactors)*

Symbiotic fuel cycles in two-tiered generating fleets made of ^{233}U fueled light or heavy water reactors and fast neutron reactors breeding plutonium for their own needs and ^{233}U from thorium blankets may achieve a sustainable nuclear production if both types of reactors feature a high conversion or breeding ratio. Figure 4 shows examples of such symbiotic generating fleets with flows of nuclear materials between various reactor types. Both examples require an industrial use of the Thorex process.

In the first example, the thermal reactor is a high conversion LWR using uranium fuel made of recycled ^{233}U and depleted uranium. In principle, this fleet only needs depleted uranium and thorium as make-up fuel, thus achieving an efficient use of both resources. The number of LWRs supported by a fast neutron reactor depends on the breeding ratio of the latter and the conversion factor of the former, which also depends on the fuel discharge burn-up. Increasing the conversion factor indeed calls for reducing the discharge burn-up as parasitic neutron absorptions in fission products tend to reduce this factor.

In the second example, the thermal reactor is a high conversion heavy water moderated reactor operated with a uranium-thorium fuel cycle thus recycling ^{233}U bred in blankets of fast neutron reactors. The latter needs to achieve break even breeding in plutonium in the core alone (without the blankets). As in the previous fleet, only depleted uranium and thorium are needed as make-up fuel, thus allowing this fleet to also achieve an efficient use of both resources. The number of HWRs supported by a fast neutron reactor depends on the breeding ratio of the latter and the conversion factor of the former, which also depends on the fuel discharge burn-up. India's nuclear program has focused on such synergies between advanced HWRs (AHWRs) and fast neutron reactors with advanced fuel cycles based on uranium, MOX and thorium as an important component of a self-sufficient energy system. Encouraging results of $(Th\text{-}Pu)O_2$ fuel tests have been obtained with 1-4%Pu. Other reactor types such as HTRs and SCWRs may supplement LWRs and HWRs in such symbiotic generating fleets and be supported in the same way by fast neutron breeder reactors.

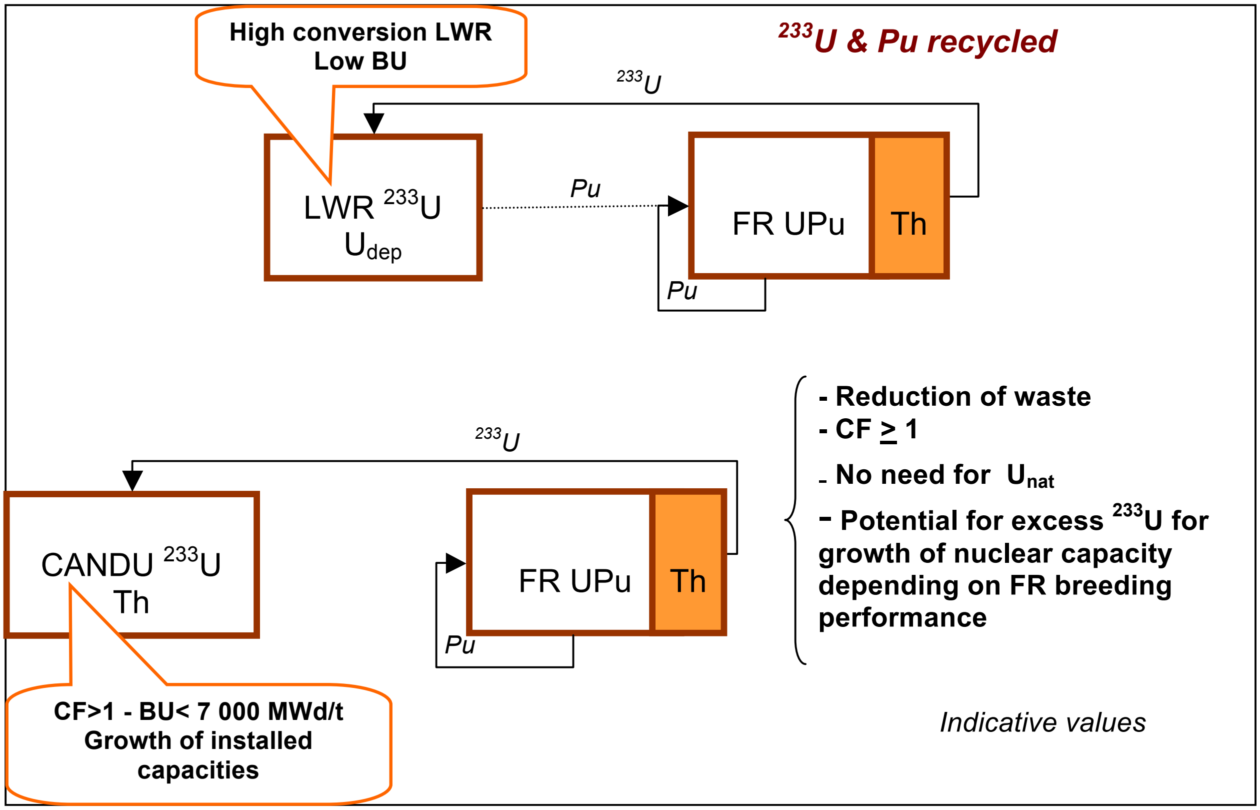


Figure 4: Use of thorium-based fuels in symbiotic nuclear fuel cycles with LWRs, HWRs and Fast Reactors

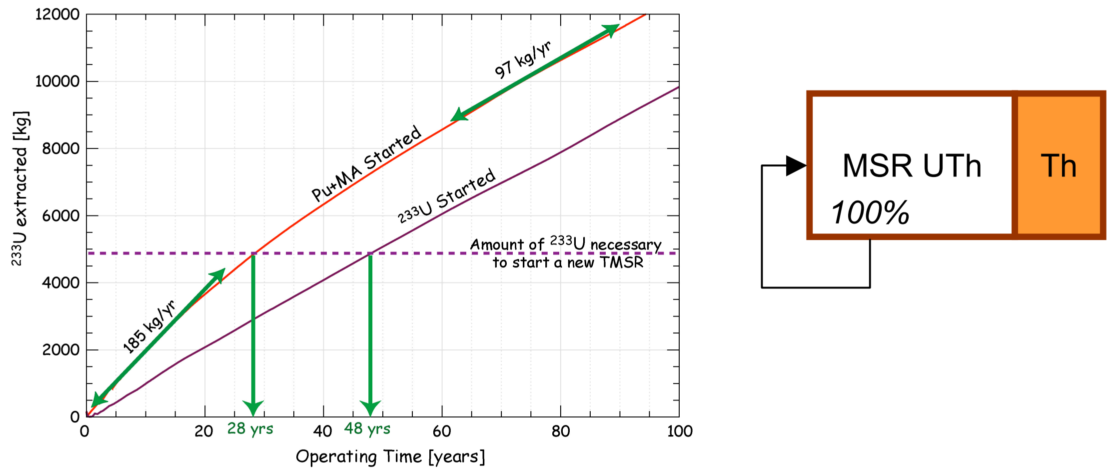
Technical and economic studies are needed to assess the commercial viability of using thorium in comparison with fuel cycles using uranium and plutonium only in both considered symbiotic generating fleets. This commercial viability indeed depends on the price of uranium, on the breeding and conversion performances achievable in either type of reactor, on the cost of recycle of ^{233}U and plutonium (investment and operating cost for fuel reprocessing and re-fabrication…), as well as on costs associated with the fuel cycle back-end. Non-proliferation issues also need to be thoroughly assessed.

6 – Thorium Fuel in Molten Salt Reactors *(TMSR)*

Molten salt reactors that minimize parasitic neutron captures in reactor core structures and allow for a fast treatment of spent fuel and recycle of nuclear fuel offer attractive features for achieving effective breeding with a uranium-thorium fuel cycle. If found technically and commercially viable, they may be considered as a possible alternative to uranium-plutonium fueled fast neutron reactors as an avenue to sustainable nuclear power, if ever fast reactors were facing technical or political difficulties. Among the molten salt reactors considered in the Generation IV International Forum, the non-moderated Thorium Molten Salt Reactor (TMSR)[xii] is offering attractive perspectives in this direction and has potential for further improvement.

Figure 5 shows some of the characteristics of a 1000 MWe TMSR.

Non Moderated Thorium Molten Salt Reactor (CNRS)



Source CNRS

Indicative values

F.C. ≈ 1.02 (annual) – Td = 48 y
Core holdup in HM ~ 46 t/GWe
Core initial fissile holdup ~ 5,7 t/GWe (^{233}U)
Annual throughputs of HM (fab/rep) ~ 33 t/GWe/y

Significant R&D still required to demonstrate viability and performance

Figure 5: The non-moderated Thorium Molten Salt Reactor (TMSR)

TMSRs are fueled with ^{233}UTh fluoride salt at equilibrium: a conversion factor of 1.02, a core holdup of 46 tons of heavy metal including ~6 tons of ^{233}U. Such reactor may best be started with an initial load of ^{233}U (~5.3 tons) that should be supplied by an external source. Alternative options that would make use of transuranics fuels to start the reactor call for a transition towards the ultimate ^{233}UTh fuel cycle that may prove hardly feasible from both points of view of reactor salt chemistry and spent fuel reprocessing.

Non-proliferation issues associated with the initial load of ^{233}U and the operation of the TMSR need to be thoroughly assessed.

7 – Proliferation Potential of Thorium Fuels

A specific role thorium fuels can play in the non-proliferation area is as matrix fuel for burning excess fissile materials in an open fuel cycle mode. Because thorium blends well with other fuels, sturdy fuels made with highly enriched uranium or plutonium could be made with a thorium base matrix. These fuels could then be utilized in reactors where the fissile material would be consumed at the maximum rate. This would maximize the rate at which fissile material of concern is eliminated.[xiii]

Closed thorium-based fuel cycles however are very subject to proliferation risks as ^{233}U is a weapon grade material and its critical mass is only 1/3 of that of ^{235}U.

Recycled ^{233}U naturally benefits from some radiation protection as associated traces of ^{232}U decay into ^{228}Th and a series of daughter products including ^{208}Tl and ^{212}Bi that generate heat and high energy gamma rays (2.6 and 1.8 MeV respectively). It also benefits from some physical protection as manufacturing of ^{233}U-based fuels has to be performed remotely in a shielded production line. In addition, these high energy gamma rays constitute an excellent radiative signature of reprocessed ^{233}U that makes its detection easier and its potential diversion more difficult.

However, the proliferation potential of thorium fuel cycles with less than 20% fissile materials (as recycled ^{233}U, ^{235}U or plutonium) is believed to be comparable with that of the uranium fuel cycle with recycle of plutonium. Indeed, thorium fuel cycles require sizably higher uranium enrichment levels than uranium fuel cycles. Furthermore, separation work that is needed to produce pure ^{233}U from used UTh or PuTh fuel may be judged comparable to that required to produce separated plutonium from the uranium/plutonium fuel cycle[xiv], even though the chemical reprocessing of used thorium-based fuels remains a technical challenge today.

"Denaturing" the thorium with the addition of ^{238}U may somewhat mitigate risks of proliferation as the ^{238}U lowers the effective enrichment in ^{233}U of the reprocessed uranium (as the chemical reprocessing cannot separate the ^{238}U from the ^{233}U). This approach, however, generates transuranics, including plutonium, when the uranium in the fuel is irradiated.[xv]

For all above reasons, reaching an international agreement on banning the use of highly ^{233}U-enriched uranium cannot be excluded.

8 – Summary

The use of thorium fuels has the potential to be a positive addition to the nuclear fuel cycle when the time is right. The robust physical nature of thorium ceramics and natural abundance are potential assets for this perspective. The lesser amount of minor actinides formed in the used fuel may also be an asset for alleviating the long term burden of high level long-lived waste in terms of decay heat and radiotoxic inventory. However, daughter nuclei of ^{232}Th and ^{233}U (such as ^{231}Pa and ^{229}Th respectively) cause a higher radiotoxic inventory than uranium spent fuel in the time period between 20 000 and 1000 000 years for the same energy supply. Furthermore, reduction of transuranics calls for recycling highly ^{233}U enriched uranium which may cause risks of proliferation.

In the short term the industrial infrastructure, research, design and licensing data base do not exist to rapidly utilize thorium fuels in current reactors. However, there do not appear to be insuperable technical obstacles to the development of thorium fuel technology as past large scale reactor technology demonstration efforts were successful. Reprocessing and re-fabricating UTh-fuels, however, call for significant effort of research and development.

A first application for thorium fuels in countries concerned with excess plutonium may be as the matrix used to eliminate this plutonium. Here, when the plutonium-thorium fuel technology is available at industrial level the lesser generation of transuranics than in mixed uranium-plutonium fuel would allow the maximum destruction of included plutonium. If found of interest compared to recycle of excess plutonium in uranium-based fuel, a plutonium disposition program based on thorium-based fuels would allow necessary research, infrastructure development and design work to occur before commercial uses of thorium become viable.

In this respect, using thorium-based fuels in a once-through mode in light or heavy water reactors does not appear to allow for attractive uranium savings compared with the sole use of uranium and plutonium in similar fuel cycles (either once through or recycle of plutonium and reprocessed uranium once).

The use of thorium-based fuels with a closed fuel cycle in light or heavy water reactors alone or in symbiotic generating fleets with thermal and fast neutron reactors are more appealing in terms of resource utilization. However, the commercial viability of such use of thorium depends on the price of uranium, the cost of recycle of ^{233}U and plutonium (investment and operating cost for fuel reprocessing and re-fabrication…) and costs associated with the fuel cycle back-end. Comprehensive feasibility and economic studies are needed to determine commercially viable strategies.

Besides, non-proliferation issues of thorium fuel cycles with less than 20% fissile materials (as recycled ^{233}U, ^{235}U or plutonium) are believed to be comparable with those of the uranium fuel cycle with recycle of plutonium. These issues need to be addressed on a case by case situation and appropriately resolved while accounting for the fact that recycling highly ^{233}U-enriched fuel may ultimately be precluded internationally.

The Generation IV international forum already considers molten salt reactors operating with a uranium-thorium fuel cycle as a potential long term alternative to uranium-plutonium fueled fast neutron reactors as an avenue to sustainable nuclear power provided they prove a sufficient technical and commercial viability. Owing to the potential merits of using thorium in symbiotic reactor fleets with fast neutron reactors, this option deserves to be considered in corresponding Generation IV nuclear systems.

All advanced applications of thorium as nuclear fuel will require significant research and development in thorium-based fuel technology, in processes associated with spent thorium fuel reprocessing and re-manufacturing fuels with ^{233}U with appropriate radiation protection and management of non-proliferation. Nuclear applications of thorium also call for design studies of cores likely to take full benefit from thorium fuel performance. Furthermore, technical and economic studies are needed to prove commercial viability. Ultimately, licensing basis and applications will need to be created and approved for commercial operation.

As regards thorium related GIF activities, the Experts Group suggests that scenarios of thorium utilization in symbiotic generating fleets be conducted on a national basis and be shared within existing international frameworks such as IAEA/INPRO and OECD/NEA, and that considering thorium fuel in the six GIF nuclear systems be left as an option to be decided by the relevant System Steering Committees.

---

[i] Griffith George, 2009, *Application of Thorium in Nuclear Fuel Cycle,* Idaho National Laboratory
[ii] Organization for Economic Co-operation and Development, *Uranium 2007: Resources, Production and Demand*, OECD, Paris 2008
[iii] Cochran, Robert and Nicholas Tsoulfanidis, 1999, *The Nuclear Fuel Cycle: Analysis and Management,* La Grange Park Illinois: American Nuclear Society
[iv] Benedict Manson and Pigford Tomas and Wolfgang Levi, 1981, *Nuclear Chemical Engineering,* New York: McGraw-Hill Series in Nuclear Engineering

[v] International Atomic Energy Agency, 2005, *Thorium fuel cycle – Potential benefits and challenges*, IAEA-TECDOC-1450, May 2005

[vi] International Atomic Energy Agency, 2005, *Potential of thorium-based fuel cycles to constrain plutonium and reduce long lived waste toxicity*, IAEA-TECDOC-1349, April 2003

[vii] Greneche Dominique, Szymczak William J., Buchheit John M., Delpech Marc, Vasile Alfredo and Golfier Herve, 2007, *Rethinking the Thorium Fuel Cycle: An Industrial Point of View,* Paper #7367 of Proceedings of ICAPP 2007 (Nice, France, May 13-18, 2007)

[viii] Dukert Joseph, 1970, *Thorium the Third Fuel*, United States Atomic Energy Commission Division of Technical Information, Washington, 1970, 74-606041

[ix] INEEL, 2002, *Fuel Summary Report: Shippingport Light Water Breeder Reactor,* INEEL/EXT-98-00799 Rev. 2, September 2002

[x] International Atomic Energy Agency, 2002, *Heavy Water Reactors: Status and Projected Development*, IAEA Technical reports series, ISSN 0074–1914; no. 407; STI/DOC/010/407, 2002

[xi] [3] P.G. Boczar, P.S.W. Chan, G.R. Dyck, R.J. Ellis, R.T. Jones, J.D. Sullivan and P. Taylor, *Thorium Fuel-Cycle Studies for CANDU Reactors, in Thorium fuel utilization: Options and trends*, Proceedings of three IAEA meetings held in Vienna in 1997, 1998 and 1999; IAEA TECDOC-1319, 2002 November

[xii] Delpech Sylvie, Heuer Daniel et al, *The non-moderated Thorium Molten Salt Reactor, TBD*

[xiii] Herring Stephen, MacDonald Philip E. and Kevan D. Weaver, 2003, "Thorium-Based Transmuter Fuels for Light Water Reactors," *Nuclear Technology,* Vol. 147, July 2004 pp. 84-101

[xiv] International Atomic Energy Agency, 1980, *International Nuclear Fuel Cycle Evaluation, INFCE Summary Volume 1980*

[xv] International Atomic Energy Agency, 2002, *Thorium fuel utilization: Options and trends*, IAEA-TECDOC-1319, November 2002