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# THORIUM – FUEL FOR A BETTER NUCLEAR TECHNOLOGY?

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**Thorium is currently described by several nuclear proponents as a better alternative to uranium fuel. Thorium itself is, however, not a fissile material. It can only be transformed into fissile uranium-233 using breeder and reprocessing technology. It is 3 to 4 times more abundant than uranium; concerning safety and waste disposal there are no convincing arguments recognisable in comparison to uranium fuel. A severe disadvantage is that uranium-233 bred from thorium can be used by terror organisations for the construction of simple but high impact nuclear explosives. Thus development of a thorium fuel cycle without effective denaturation of bred fissile materials is irresponsible.**

## Introduction

Thorium (Th) is a heavy metal of atomic number 90 (uranium has 92). It belongs to the group of actinides, is around 3 to 4 times more abundant than uranium and is radioactive (half-life of Th-232 as starter of the thorium decay-chain is 14 Billion years with alpha-decay). There are currently hardly any technical applications. Distinctive is the highly penetrating gamma radiation from its decay-chain (thallium-208 (Tl-208): 2.6 MeV; compared to gamma radiation from Cs-137: 0.66 MeV). Over the last decade, a group of globally active nuclear proponents is recommending thorium as fuel for a safe and affordable nuclear power technology without larger waste and proliferation problems. These claims should be submitted to a scientific fact check. For that reason, we examine here successively the claims of thorium proponents.

## Claim 1: The use of thorium expands the availability of nuclear fuel by a factor 400

Thorium itself is not a fissile material. It can, however, be transformed in breeder reactors[1] into fissile uranium-233 (U-233), just like non-fissile U-238 (99.3% of natural uranium) can be transformed in a breeder reactor to fissile plutonium. For that reason, the use of thorium presupposes the use of breeder and reprocessing technology. Because these technologies have almost globally fallen into disrepute, it cannot be excludes that the more neutral term thorium is currently also used to disguise an intended reintroduction of these problematic techniques.

The claimed factor 400: A factor of 100 is due to the breeder technology. It is achievable as well in the uranium-plutonium cycle. Only a factor of 3 to 4 is specific to thorium, just because it is more abundant than uranium by this factor.

## Claim 2: Thorium did not get a chance in the nuclear energy development because it is not usable for military purposes

In the early stages of nuclear technology in the USA (between 1944 and the start of the 1950s), reprocessing technology was not yet well developed. Better developed were graphite moderated reactors that used natural uranium and bred plutonium. For the use of thorium (which, other than uranium, does not contain fissile components), enriched uranium or possibly plutonium would have been indispensable. Initially, neither pathway for thorium development was chosen because it would have automatically reduced the still limited capacity for military fissile materials

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[1] A breeder reactor is a reactor in which more fissile material can be harvested from spent nuclear fuel than present in the original fresh fuel elements. It may be sometimes confusing that in the nuclear vocabulary every conventional reactor breeds, but less than it uses (and therefore it is not called a breeder reactor).

production.[2] Only when the US enrichment capacity at about 1950 delivered sufficient enriched uranium, the military and later civil entry into thorium technology started: in 1955 a bomb with U-233 from thorium was brought to explosion, and a strategic U-233 reserve of around 2 metric tons was created. The large head start of the plutonium bomb could not be overtaken any more, and plutonium remained globally the leading military fission material (although, according to unconfirmed sources Indian nuclear weapons contain U-233). The US military research concluded in 1966 that U-233 is a very potent nuclear weapon material, but that it offers hardly any advantages over the already established plutonium [6]. Because light water reactors with LEU[3] were already too far developed, thorium use remained marginal also in civil nuclear engineering: for instance in the short time operating German "thorium reactor" THTR-300 in Hamm, which in reality was a uranium reactor (fuel: 10% weapon grade 93% enriched U-235 and 90% thorium) because the amount of energy produced by thorium did not exceed 25 percent.

**Claim 3: Thorium use has hardly any proliferation risk**

The proliferation problem of Th / U-233 needs a differentiated analysis, general answers are easily misleading. First of all one has to assess the weapon capability of U-233. Criteria for good suitability are a low critical mass and a low rate of spontaneous fission. The critical mass of U-233 is only 40% of that of U-235, the critical mass of plutonium-239 is around 15% smaller than for U-233. A relatively easy to construct nuclear explosive needs around 20 to 25 kg U-233. The spontaneous fission rate is important, because the neutrons from spontaneous fission act as a starter of the chain reaction; for an efficient nuclear explosion, the fissile material needs to have a super-criticality[4] of at least 2.5. When, because of spontaneous fissions, a noticeable chain reaction already starts during the initial conventional explosion trigger mechanism in the criticality phase between 1 and 2.5, undesired weak nuclear explosions would end the super-criticality before a significant part of the fissile material has reacted. This is largely depending on how fast the criticality phase of 1 to 2.5 is passed. Weapon plutonium (largely Pu-239) and moreover reactor plutonium have – different from the mentioned uranium fission materials U-235 and U-233 – a high spontaneous fission rate, which excludes their use in easy to build bombs. More specifically, plutonium cannot be caused to explode in a so called gun-type fission weapon, but both uranium isotopes can. Plutonium needs the far more complex implosion bomb design, which we will not go into further here. A gun-type fission weapon was used in Hiroshima – a cannon barrel set-up, in which a fission projectile is shot into a fission block of a suitable form so that they together form a highly super-critical arrangement – see the picture in sheet 7 in [1]. Here, the criticality phase from 1 to 2.5 is in the order of magnitude of milliseconds – a relatively long time, in which a plutonium explosive would destroy itself with weak nuclear explosions caused by spontaneous fission. One cannot find such uranium gun-type fission weapons in modern weapon arsenals any longer:[5] their efficiency is with maximal a few percent rather low, they are bulky (the Hiroshima bomb: 3.6 metric tons, 3.2 meter long), inflexible and not really suitable for carriers like intercontinental rockets. On the other hand, gun-type designs are highly reliable and relatively easy to build. Also the International Atomic Energy Agency (IAEA) reckons that larger terror groups would be capable

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[2] Thorium has a higher capture cross section for (thermal, that means slow) neutrons than U-238. For that reason, it needs as fertile material in reactors a higher fissile density than U-238.

[3] LEU = low-enriched uranium

[4] Criticality: the amount of new fissions produced by the neutrons of each fission.

[5] Between 1977 and 1990, the apartheid regime in South Africa built 7 gun-type fission weapons on the basis of uranium-235 (from an enrichment plant in Pelindaba); they shied away from the high development effort needed for modern implosion bombs. In spite of an embargo, the nuclear research centre in Jülich, Germany, delivered 1988 HTR technology to the apartheid regime intended for use as propulsion of submarines (safekeeping of nuclear bombs). The nuclear explosives were dismantled in 1993.

of constructing a nuclear explosive on the basis of the gun-type fission design provided they got hold of a sufficient amount of suitable fissile material [1]. Bombs with a force of at maximum double to 2.5 times that of the Hiroshima bomb (13 kt TNT) are conceivable. For that reason, USA and Russia try intensively already for decades to repatriate their world-wide delivered highly enriched U-235 (HEU).

A draw-back of U-233 in weapon technology is that – when it is produced only for energy generation purposes – it is contaminated with maximally 250 ppm[6] U-232 (half-life 70 years) [2]. That does not impair the nuclear explosion capability, but the uranium-232 turns in the thorium decay chain, which means - as mentioned above – emission of the highly penetrating radiation of Tl-208: A strongly radiating bomb is undesirable in a military environment – from the point of view of handling, and because the radiation intervenes with the bomb's electronics. In the USA, there exists a limit of 50 ppm U-232 above which U-233 is no longer considered suitable for weapons. Nevertheless, U-232 does not really diminish all proliferation problems around U-233. First of all, simple gun-type designs do not need any electronics; furthermore, radiation safety arguments during bomb construction will hardly play a role for terror organisations that use suicide bombers. Besides that, the hard radiator Tl-208 only appears in the end of the decay chain of U-232: freshly produced or purified U-233/U-232 will radiate little for weeks and is then more easy to handle [2]. It is also possible to suppress the build-up of uranium-232 to a large extent, when during the breeding process of U-233 fast neutrons with energies larger than 0.5 MeV are filtered out (for instance by arranging the thorium in the reactor behind a moderating layer) and thorium is used from ore that contains as little uranium as possible. A very elegant way to harvest highly pure U-233 is offered by the proposed molten salt reactors with integrated reprocessing (MSR): During the breeding of U-233 from thorium, the intermediate protactinium-233 (Pa-233) is produced, which has a half-life of around one month. When this intermediate is isolated – as is intended in some molten salt reactors – and let decay outside the reactor, pure U-233 is obtained that is optimally suited for nuclear weapons.

An advantage of U-233 in comparison with Pu-239 in military use is that under neutron irradiation during the production in the reactor, it tends to turn a lot less into nuclides that negatively influence the explosion capability. U-233 can (like U-235) be made unsuitable for use in weapons by adding U-238: When depleted uranium is already mixed with thorium during the feed-in into the reactor, the resulting mix of nuclides is virtually unusable for weapons. However, for MSRs with integrated reprocessing this is not a sufficient remedy. One would have to prevent separation of protactinium-233 [9].

The conclusion has to be that the use of thorium contains severe proliferation risks. These are less in the risk that highly developed states would find it easier to lay their hands on high-tech weapons, than that the bar for the construction of simple but highly effective nuclear explosives for terror organisations or unstable states will be a lot lower.

### Claim 4: Thorium reactors are safer than conventional uranium reactors

The fission of U-233 results in roughly the same amounts of the safety relevant nuclides iodine-131, caesium-137 and strontium-90 as that of U-235. Also the decay heat is virtually the same. The differences in produced actinides (see next claim) are of secondary importance for the risk during operation or in an accident. In this perspective, thorium use does not deliver any recognisable advantages. More safety relevance has the fact that uranium-233 fission produces 60% less of so called delayed neutrons than U-235 fission. Delayed neutrons are not directly created during the fission of uranium, but from some short-living decay products. Only due to the existence of delayed neutrons, a nuclear reactor can be controlled, and the bigger their share (for instance 0.6 % with U-

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[6] ppm = parts per million = $10^{-6}$

235), the larger is the criticality range in which controllability is given (this is called delayed criticality). Above this controllable area (prompt criticality) a nuclear power excursion can happen, like during the Chernobyl accident. The fact that the delayed super-critical range is with U-233 considerably smaller than with U-235, is from a safety point of view an important technical disadvantage of thorium use.

During the design of thermal molten salt reactors (breeders), the conclusion was that the use of thorium brings problems with criticality safety that do not appear with classical uranium use in this type of reactors. For that reason, it was necessary to turn the attention to fast reactors for the use of thorium in molten salt reactors. Although this conclusion cannot be generalised, it shows that the use of thorium can lead to increased safety problems.

As already mentioned before, a serious safety problem is the necessity to restart the breeder and reprocessing technology with thorium.

Thorium is often advertised in relation to the development of so called advanced reactors (generation IV). The safety advantages attributed to thorium in this context are mostly, however, not germane to thorium but due to the used reactor concept. Whether or not these advanced reactor concepts indeed bring over-all increased safety, falls outside the scope of this article, but that is certainly not a question with a clear “yes” as answer.

### Claim 5: Thorium decreases the waste problem

Thorium use delivers virtually the same fission products as classical uranium use. That is also true for those isotopes that are important in issues around long term disposal [5]. Those mobile long-lived fission products (I-129, Tc-99…) determine the risk of a deep geological disposal when water intrusion is the main triggering event for accidents. Thorium therefore does not deliver an improvement for final disposal. Proponents of thorium argue that thorium use does not produce minor actinides (MA)[5], nor plutonium. They argue that these nuclides are highly toxic (which is correct) and they compare only the pure toxicity by intake into the body for thorium and uranium use, without taking into account that these actinides are hardly mobile in final disposal even in accidents. It may furthermore be true that thorium use does not deliver MA, but it does produce other actinides, especially protactinium-231 (Pa-231; half-life 33,000 years), with similar features as the MA. The advantage with thorium use is that the amount of the resulting long-lived actinides is smaller than that of MA in the case of uranium use by a factor of 5. On the other hand, the high level of U-233 in the waste is not without problems: This is in its toxicity comparable with plutonium and its long half-life (160,000 years) is aggravated by the fact that its decay product Th-229 (half-life 8000 years) is a strong gamma-radiator (besides alpha). The maximum concentration of Th-229 is reached after around 100,000 years.

Taken together, one could argue that concerning actinides, thorium use has a limited advantage in produced waste, but certainly not concerning the safety relevant long-lived fission products. For that reason, the claim that thorium use would considerably reduce the waste problem, cannot be upheld. It also needs deep geological final disposal.

### Conclusion

The arguments used by thorium proponents for a move from the use of uranium to thorium are at a closer look not sufficiently convincing. The use of technology based on thorium would not be able to solve any of the known problems of current nuclear techniques, but it would require an enormous development effort and wide introduction of breeder and reprocessing technology. For those reasons, thorium technology is a dead end.

In my opinion, the proliferation aspect is a vital issue: Here we would see a severe deterioration of the current situation, because the barriers to the construction of feasible nuclear explosives by, for instance, terror groups would be seriously lowered. This aspect deserves more attention. We can hope that the IAEA, the USA and Russia would oppose uncontrolled propagation of thorium technology, when they would see its introduction thwarting their decades long efforts to reduce the proliferation risk by repatriation of HEU. On the other hand, the current thorium hype, partially carried by a fanaticism based on limited knowledge, could lead in a populist environment to incalculable developments. For that reason, I think it important that the environment and peace movements should insist that thorium technology without sufficient proliferation control should be outlawed in the same way as currently is the case with the use of HEU. As a minimum requirement, thorium technology without U-233 denaturation with U-238, and on-line reprocessing in molten salt reactors should be banned.

## Epilogue: the scale of the international efforts supporting thorium technology

There exists still a large gap between the vocal propaganda of thorium proponents and real activities for the development of thorium technology – at least in western industrializsed countries. The brunt of the effort lies with smaller start-up firms. The large corporations remain passive and government support for thorium development remains small. Where full development of thorium technology would need investments of several Billions of euros or dollars, current EU-support is in the range of a few millions per year. This may well be taken as a clear sign of scepticism. This scepticism is fed by extensive studies, for instance by the governments of the UK and Norway, that were rather pessimistic about thorium [8, 10]. For that reason, I still think there are good grounds for hope that false developments towards the introduction of thorium technology may be countered with clear information. Take for example the Canadian company Terrestrial Energy, involved in the development of molten salt reactors, which in 2013 dropped thorium technology and on-line reprocessing for proliferation reasons, and now works on molten salt reactors based on classical uranium use (IMSR).

In Germany, work on thorium technology continues. The research centre in Jülich jumped on the thorium hype by evaluating its previous experiences with thorium fuels [7], and in Karlsruhe, the Joint Research Centre of the European Commission (JRC) and the Karlsruhe Institute of Technology (KIT) work at a EU-supported design for a fast molten salt reactor (MSFR) with thorium use. From the MSFR, annually 150 kg of U-233 would have to be extracted. Without denaturation that would be sufficient for several nuclear explosives. In Freiburg and Karlsruhe, new initiatives were founded against this development. They deserve support.

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