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Published: *February 2008*

THORIUM-BASED NUCLEAR POWER: AN ALTERNATIVE?

It is said that the global reserves of thorium are considerably larger than natural uranium. Therefore the call for thorium-based nuclear energy is rising. In the past 50 years basic research and development on the use of thorium-based fuel cycles has been conducted in Germany, India, Japan, Russia, the UK and the USA. Test reactor irradiation of thorium fuel to high burn-ups has also been conducted and several test reactors have either been partially or completely loaded with thorium-based fuel.

In 2007, a lobby for nuclear power based on the thorium cycle, forced the Norwegian government to consider the option and establish a Thorium Report Committee. In February 2008 the report of the Committee, entitled *Thorium as an Energy Source – Opportunities for Norway*, was released. The Committee notes "[that] Norway has one of the major thorium resources in the world, a potential energy content which is about 100 times larger than all the oil extracted to date by Norway, including the remaining reserves." This sounds almost like the 1950s claim that 1 gram of 'concentrated' uranium, delivers the same amount of electricity as 100.000 kilos of coal. However, the authors also conclude that: "Due to a lack of data, it seems impractical to develop meaningful cost projections for any nuclear energy system using thorium. […] The main economical challenges to the development of a thorium based energy production will be the acquisition of funding necessary to carry out the required research and development." On receiving the report, Norway's minister of petroleum and energy, Åslaug Haga, said: "I register that the report neither provides grounds for a complete rejection of thorium as a fuel source for energy production, nor does it offer enough reason for embracing it as such. The government's viewpoint has not changed, meaning that there exist no plans to allow construction of nuclear power plants in Norway." Apparently financial and technical uncertainties in developing a thorium fuel cycle infrastructure have made the Norwegian government very careful to make a clear decision.

Just as uranium thorium is a naturally occurring radioactive trace element found in most rocks and soils. It was discovered in 1828 by the Swedish chemist Jons Jakob Berzelius, who named it after Thor, the Norse god of thunder. Australia and India each have around one quarter of the world's reserves, while both Norway and the United States have 15%. An international lobby is labeling thorium as a 'safe' alternative for uranium-based nuclear energy. The promoting experts point to a list of arguments that has to prove the advantages of thorium above uranium. However, can the supposed benefits of thorium pass the critical test?

Relying on the most frequently used claim of the lobby on the abundance of thorium there are reasons enough for a thorough analysis of their arguments. The lobby always starts with an argument like this: "Thorium is about three times more abundant than uranium. Unlike natural uranium, containing 0.7% 'fissile' uranium-235, natural thorium does not contain any 'fissile' material and is made up of 'fertile' thorium-232 only." This presentation is quite misleading, because it omits a comparison with the possible uses of uranium fuels and particular uranium-238, just like thorium-232 'fertile', for Fast Breeder Reactors (FBRs). When the large scale development of FBRs was envisaged, the possibilities of using the 'fertile' uranium-238 were emphasized and were also believed to lead to infinite sources of energy. However, it is well-known that countless technical, political and economical problems have undermined the FBR development.

Just like the non-fissionable uranium-238 isotope, thorium-232 can't be split. Comparable to the uranium based fuel cycle in which uranium-238 is used to breed fissionable plutonium-239, the thorium based fuel cycle uses thorium-232 to breed fissionable uranium-233. Three stages can be distinguished (see: Thorium Cycle Scheme). In the first stage uranium-238 is converted into plutonium-239 in Indian CANDU reactors (PHWR), fed with natural uranium. In the second stage uranium-233 (and plutonium) is produced in a Fast Breeder Reactor (FBR) in which plutonium is the raw material and uranium and thorium are used as the blanket.

India: Thorium Cycle Scheme

	reactor(s)	**fuel / blanket**	**product(s)**
Stage 1	PHWR (CANDU)	natural uranium	plutonium
Stage 2	Fast Breeder Reactor (FBR)	plutonium / thorium and uranium	uranium-233 and plutonium-239
Stage 3	Advanced Heavy Water Reactors (AHWR)	thorium-232 uranium-233 plutonium	uranium-233 thorium-232 plutonium

Though not yet achieved the first stage, forerunner India has almost reached the second stage of this three-staged fuel cycle. Last November the Indian minister of state Prithviraj Chavan declared that India has extracted 30,000 tons of thorium concentrate to prepare for the third stage of the nuclear power program. Nuclear scientists expect the thorium-based third stage (see box) to begin only around 2030. One of the reasons why the more than fifty year old Indian indigenous nuclear power program is making a slow progress is the lack of uranium technology and fuel, needed to speed up the utilization of thorium. The Indo-U.S. deal has to solve these problems.

Experts from the thorium lobby now say that all aspects of the thorium-based nuclear energy program can be technically achieved. The most important advantages according to the lobby are on the level of efficiency, proliferation, harmfulness and half-lifes of radioactive waste, and reactor safety. A Norwegian expert claims that thorium produces 250 times more energy per unit of weight than uranium in the present reactors. In addition the thorium lobby stresses that thorium fuel in contrast with uranium fuel doesn't produce any plutonium and that the spent thorium fuel would be much less radioactive than 'conventional' nuclear waste. Also they claim that the half-lifes of the radioactive waste products are in the range of hundreds of years instead of thousands of years in the case of 'conventional' spent nuclear fuel. Another often-used argument is that thorium reactors will not be based on moderated chain reactions like in 'conventional' nuclear reactors, but on accelerator-driven systems (ADS). ADS could be the third stage of the three-staged thorium based fuel cycle. However, India considers the Advanced Heavy Water Reactor (AHWR) as the first option.
ADS consist of three main units: the accelerator, the target/blanket unit and the separation unit. The accelerator generates high energy charged particles which strike a heavy material target. This bombardment leads to the production of a neutron source, a process called 'spallation'. The produced neutrons enter a subcritical core - often called a blanket - where they can be multiplied.
Indeed, all of these claims sound attractive, but in fact these 'advantages' don't pass the critical test. Criticasters states: in reality not 250 but some 40 times the amount of energy per unit mass – compared with uranium - might *theoretically* be available from thorium. Though less than claimed by the thorium-lobby, this still seems to be a high efficiency. However, the problem remains if this would be technically feasible. And, in theory the energy per unit mass is maybe even comparable in the case FBRs are used to breed fuel in the uranium based fuel cycle.

On proliferation: though it is important to note that a thorium reactor doesn't produce any weapons-grade plutonium, one needs to mention at the same time that the reactor does produce weapons-grade uranium-233. In fact uranium-233 is even a more effective fissile material than uranium-235. It has the same significant quantity (SQ) as plutonium-239: an amount of 8 kg is sufficient to make a nuclear bomb. Therefore the waste from thorium reactors is still a security risk. There is only one remark: compared to plutonium-239 uranium-233 is somewhat more difficult to separate from the spent fuel.

The main reason for that however, brings another disadvantage in the thorium-uranium fuel cycle to the surface: the high gamma radioactivity due to contaminants in recovered uranium-233, namely uranium-232 and thorium-228, both of which are neutron-emitters, reducing its effectiveness as a fuel and which is partly responsible for the high costs of fuel fabrication. Brian Johnson, a researcher from the Oregon State University, states more specifically on uranium-232 in a 2006 study sponsored by the American Nuclear Society: "Unfortunately if one assumes a closed fuel cycle, thorium has a disadvantage in that there are some highly penetrating radioactive materials, thallium-208 and bismuth-212, that are unavoidably created in the spent fuel. They occur as part of the decay of uranium-232 which cannot be separated chemically from the uranium-233 in the spent fuel." These disadvantages make clear the difficulties in handling thorium based spent fuel and the purification of uranium-233 for re-use in the three-staged cycle. Except the handling of the material, these problems don't play any role in the military use of uranium-233. The fissile power of uranium-233 is not influenced by the contaminants. Finally, it is worth to note that because of these disadvantages the spent fuel of a thorium reactor is much more dangerous when used in dirty bombs. As noted above thorium reactors must breed their own nuclear fuel from uranium-233. The point is, however, that there is almost no separated uranium-233 anywhere in the world. In order to get it one has to start with for example plutonium-239 to get one reactor in operation. After 40 years this will have bred enough

Thorium fuel cycle in India

In the early 1950s India started research and development efforts on the thorium / uranium fuel cycle and thorium-fuelled reactor programs. India can be considered as the main pioneer in developing the thorium fuel cycle and has several advanced facilities to this. The Indian authorities consider a closed nuclear fuel cycle of crucial importance for its three-stage nuclear power program with its long-term objective of tapping India's vast thorium resources. In the front end of the cycle, the program is providing inputs to the indigenous Pressurized Heavy Water Reactor (PHWR) phase. This type of reactor is elsewhere known as CANDU, the Canadian heavy-water reactors fuelled by natural uranium. Though the long-term goal of India's nuclear program is to develop a heavy-water thorium cycle, their PHWRs and light-water reactors are currently used to produce plutonium. Hence, 'fertile' thorium and thorium-based fuel has to be utilized in combination with 'fissile' material (for now plutonium-239 or uranium-235) in order to breed 'fissile' uranium-233. Besides a breeding product this uranium-233 has to become also the feeding 'fissile' material in the future for the just described first stage of the aimed thorium-based nuclear fuel cycle in order to close this fuel cycle. The second stage in the fuel cycle uses fast breeder reactors (FBRs) burning the plutonium to breed uranium-233 from thorium. The blanket around the core will have uranium as well as thorium, so that further plutonium is produced as well as the uranium-233. Finally, in the third stage or the back end of the fuel cycle Advanced Heavy Water Reactors (AHWRs) are supposed to burn the uranium-233 and the plutonium with thorium, getting about two thirds of their power from the thorium, according to the lobby. Up to a few years ago the lobby mentioned a figure of 75 per cent.

Despite the glorifying stories from Indian officials even the first stage of their indigenous nuclear energy program is not yet fully achieved. The two PHWR-units in Kakrapar were the first reactors

(continued on page 4)

uranium-233 from thorium-232. Thus, if the Indians succeed in their ambitions somewhere in 2048 the first thorium reactor of the closed thorium fuel cycle could be in operation. But only if India succeeds to develop a proper method to reprocess the thorium-based spent fuel and to isolate the uranium-233 for re-use. As described above this is not an easy job and much more difficult than isolating plutonium-239 from uranium-based fuel. The technology is still in a experimental stage and hasn't even reach the developmental stage.

Though thorium – compared with uranium – has the advantage that smaller quantities of long-lived minor actinides and transuranic elements are formed when this fuel is used, the fact remains that these long-lived and highly radioactive elements are still present in the spent nuclear fuel. The chemical separation appears to be much more complicated than in the reprocessing of spent fuel in the uranium-based fuel cycle. This means that the half-lifes of the high-level radioactive elements can't be reduced from thousands to hundreds of years in the partitioning and transmutation process. That has to be rejected as wishful thinking. Thorium produces its own set of actinides which also pose problems for their management.

(Continued from page 3)

in the world that have tested thorium. In 1995, Kakrapar-1 achieved only about 300 days of full power operation and Kakrapar-2 about 100 days utilizing thorium fuel. More details are not available. In fact the first stage has not passed the laboratory scale. Irradiation of thorium fuel bundles takes place in a research reactor at Trombay. The use of thorium-based fuel on a 'commercial' scale is planned in Kaiga-1 and -2 and Rajasthan-3 and -4 reactors, which are currently under construction. Finally these thorium-based PHWRs can only become 'commercial' when India has sufficient resources of natural uranium to feed these PHWRs in order to get plutonium as the fissile material to start the thorium based nuclear fuel cycle.

After operating a fast breeder test reactor (FBTR) for two decades India is now on the brink of launching a commercial fast breeder program to take India's ambitious thorium program to the second stage. India has vast reserves of thorium but modest amounts of uranium. Scientists at the Indira Gandhi Centre for Atomic Research, Kalpakkam, have said the conversion of thorium into uranium-233 fuel would depend on the rate of growth of the second-stage, fast-breeder reactors. Currently a 500 MW prototype FBR at Kalpakkam is under construction and is expected to become operational in about four years. It will have a blanket with thorium and uranium to breed fissile uranium-233 and plutonium respectively. Three more of such FBRs have been announced for construction by 2020.

Other steps the Indian government has taken to develop appropriate technologies for the utilization of thorium are the setting up of the research reactor Kamini at Kalpakkam, operating since 1997, using uranium-233 fuel obtained from irradiated thorium, and the development of technologies to reprocess irradiated thorium fuel and in fabricating uranium-233 based fuel.

According to Indian scientists the planned FBRs can use about 30 tons of thorium for conversion. The actual amount of thorium available for conversion from the 30,000 tons of thorium concentrate would depend on the level of concentration. A one per cent concentration would mean 300 tons while a 10 per cent concentration would mean 3,000 tons of thorium available for conversion. Thorium in India is mainly recovered from monazite, a naturally occurring mineral. Monazite is produced as a co-product along with substances such as ilmenite, zircon and rutile.

In a recent interview the Indian minister of state Chavan said India needed to have international cooperation to acquire uranium technology and fuel, which was insufficient in the country. In a veiled reference to the Indo-U.S. deal he said: "The government is trying for international cooperation in this sector and also trying to convince the House to allow it to obtain uranium to speed up the process of atomic nuclear fuel." [..] "If the government is allowed to go for international cooperation, there will be enough uranium available that will speed up our nuclear program much faster."

The encountered problems can't be solved with the current reprocessing technology. Therefore new technologies and plants have to be developed.

Lately, thorium-based fuel is named as a promising alternative for MOX-fuel to burn weapons grade plutonium. Through a joint operation between the Kurchatov Institute and Thorium Power Inc. funded by the US, a plutonium incinerating thorium-based fuel design for current reactors is "about two or three years from implementation in a reactor", according to Thorium Power Inc. in 2006 in Brian Johnson's 2006 study.. The author continues: "Thorium-based fuels could reach the disposition goal more than twice as fast as MOX in the same reactor." This would mean that fewer reactors would be needed to burn the plutonium. At the same time he notes: "While MOX and thorium-based fuels have a great deal of data, it is difficult to get any hard data on how much plutonium can be disposed of per year using fast reactors." Therefore it isn't easy to make any conclusive statements on the value of thorium-based fuels for this purpose, when we restrict ourselves strictly to the available methods of burning plutonium. In fact there is not so much difference with the use of MOX and all the disadvantages connected to this as described in the past decades (reactor-safety, Pu-transports, Pu-fuelfabrication, proliferation-risks, etc)

Further there are some disadvantages of thorium - when compared with uranium - that were recognized from the beginning, but now appeared to be almost forgotten: thorium is more radioactive than uranium, making its handling in fabrication stage more beset with dangers. In addition there are potential difficulties in the back-end of the fuel cycle. The plutonium-238 content would be three to four times higher than with conventional uranium fuels. This highly radioactive isotope causes a much higher residual heat and therefore the time for spent fuel storage in water is much longer. To put it mildly, the technical problems regarding the reprocessing of spent fuel is not solved for this reason.

It would be a revolutionary step forward in nuclear safety if all nuclear reactors could be replaced by accelerator-driven systems (ADS) in the foreseeable future; there is no need to use a moderated chain reaction: a chain reaction that can get out of control, which could cause melt-downs. In addition the lobby claims that introducing ADS can reduce by at least 3 orders of magnitude the time needed for the geological disposal of nuclear wastes.

The recent Norwegian study summarizes the advantages of an ADS fuelled by thorium, relative to a conventional nuclear power reactor, as follows, and states that such a system is not likely to operate in the next 30 years: There is a much smaller production of long-lived actinides, there is a minimal probability of runaway reaction, an efficient burning of minor actinides and a low pressure system. The disadvantages are summarized as follows: more complex; less reliable power production due to accelerator downtime; the large production of volatile radioactive isotopes in the spallation target; and the beam tube may break containment barriers. This overview still gives a too optimistic view. One has to keep in mind that the ADS is in an early testing stage. Even when ADS will succeed there are still problems such as the production of radioactive waste, as noted above. Though the system was named as a promising instrument to transmuted long-lived highly radioactive transuranic elements, the results are poor.

Above this, there are other serious problems that could occur with thorium fuelled reactors. A well-known example is the thorium high-temperature reactor (THTR 300) in the German municipal Hamm/Uentrop. The reactor has been out of operation since 1986. Besides the reactor building, the nuclear power plant has been demolished. Hamm/Uentrop was closed, because the company in charge of the plant was unable to control it properly and covered up numerous technical problems, such as serious problems with replacing the thorium fuel spheres.

For those reasons one has to conclude that thorium is not a serious alternative for uranium. Even when India is able to solve the many hooks and eyes it would take many decades, if ever, before the full thorium cycle is large and reliable enough to be 'commercial', while the current problems with nuclear fission remain to exist. Just like ‘conventional’ nuclear power the technology can’t play any significant role in tackling the urgent problems connected with climate change.

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Published: *Nuclear Monitor*, 21 February,, 2008