Thorium

(*Updated October 2009*)

- **Thorium is much more abundant in nature than uranium.**
- **Thorium can also be used as a nuclear fuel through breeding to uranium-233.**

Thorium continues to be a tanatalising possibility for use in nuclear power reactors, though for many years India has been the only sponsor of major research efforts to use it, though other endeavours by Thorium Power (now Lightbridge Corporation) were focusing on Russian reactors.

In mid-2009, Atomic Energy of Canada Ltd (AECL) signed agreements with three Chinese entities to develop and demonstrate the use of thorium fuel in its CANDU reactors at Qinshan in China. This carries forward an earlier programme to utilise recycled PWR fuel in the Qinshan reactors. Another mid-2009 agreement, between Areva and Thorium Power, is to assess the use of thorium fuel in Areva's EPR, drawing upon earlier research.

Nature and sources of thorium

Thorium is a naturally-occurring, slightly radioactive metal discovered in 1828 by the Swedish chemist Jons Jakob Berzelius, who named it after Thor, the Norse god of thunder. It is found in small amounts in most rocks and soils, where it is about three times more abundant than uranium. Soil commonly contains an average of around 6 parts per million (ppm) of thorium.

Thorium-232 (Th-232) decays very slowly (its half-life is about three times the age of the Earth) but other thorium isotopes occur in its and in uranium's decay chains. Most of these are short-lived and hence much more radioactive than Th-232, though on a mass basis they are negligible.

When pure, thorium is a silvery white metal that retains its lustre for several months. However, when it is contaminated with the oxide, thorium slowly tarnishes in air, becoming grey and eventually black. Thorium oxide (ThO_2), also called thoria, has one of the highest melting points of all oxides (3300°C). When heated in air, thorium metal turnings ignite and burn brilliantly with a white light. Because of these properties, thorium has found applications in light bulb elements, lantern mantles, arc-light lamps, welding electrodes and heat-resistant ceramics. Glass containing thorium oxide has a high refractive index and dispersion and is used in high quality lenses for cameras and scientific instruments.

The most common source of thorium is the rare earth phosphate mineral, monazite, which contains up to about 12% thorium phosphate, but 6-7% on average. Monazite is found in igneous and other rocks but the richest concentrations are in placer deposits, concentrated by wave and current action with other heavy minerals. World monazite resources are estimated to be about 12 million tonnes, two-thirds of which are in heavy mineral sands deposits on the south and east coasts of India. There are substantial deposits in several other countries (see Table below). Thorium recovery from monazite usually involves leaching with sodium hydroxide at 140°C followed by a complex process to precipitate pure ThO_2.

Thorite ($ThSiO_4$) is another common mineral. A large vein deposit of thorium and rare earth metals is in Idaho.

The 2007 IAEA-NEA publication *Uranium 2007: Resources, Production and Demand* (often referred to as the 'Red Book') gives a figure of 4.4 million tonnes of total known and estimated resources, but this excludes data from much of the world. Data for reasonably assured and inferred resources recoverable at a cost of $80/kg Th or less are given in the table below. Some of the figures are based on assumptions and surrogate data for mineral sands, not direct geological data in the same way as most mineral resources.

Estimated world thorium resources[1]

(Reasonably assured and inferred resources recoverable at up to $80/kg Th)

Country	Tonnes	% of total
Australia	489,000	19
USA	400,000	15
Turkey	344,000	13
India	319,000	12
Venezuela	300,000	12
Brazil	302,000	12
Norway	132,000	5
Egypt	100,000	4
Russia	75,000	3
Greenland	54,000	2
Canada	44,000	2
South Africa	18,000	1
Other countries	33,000	1
World total	**2,610,000**	

Thorium as a nuclear fuel

Thorium, as well as uranium, can be used as a nuclear fuel. Although not fissile itself, Th-232 will absorb slow neutrons to produce uranium-233 (U-233)[a], which is fissile (and long-lived). The irradiated fuel can then be unloaded from the reactor, the U-233 separated from the thorium, and fed back into another reactor as part of a closed fuel cycle.

In one significant respect U-233 is better than uranium-235 and plutonium-239, because of its higher neutron yield per neutron absorbed. Given a start with some other fissile material (U-233, U-235 or Pu-239) as a driver, a breeding cycle similar to but more efficient than that with U-238 and plutonium (in normal, slow neutron reactors) can be set up. (The driver fuels provide all the neutrons initially, but are progressively supplemented by U-233 as it forms from the thorium.) However, there are also features of the neutron economy which counter this advantage. In particular the intermediate product protactinium-233 (Pa-233)a is a neutron absorber which diminishes U-233 yield.

Over the last 40 years there has been interest in utilising thorium as a nuclear fuel since it is more abundant in the Earth's crust than uranium. Also, all of the mined thorium is potentially useable in a reactor, compared with the 0.7% of natural uranium, so some 40 times the amount of energy per unit mass might theoretically be available (without recourse to fast neutron reactors). But this relative advantage vanishes if fast neutron reactors are used for uranium.

The Light Water Breeder Reactor (LWBR) concept is a major potential application for conventional pressurised water reactors (PWRs) and was successfully demonstrated at the Shippingport reactor in the USA[2,3]. Shippingport commenced commercial operation in December 1957 as the first large-scale nuclear power reactor to be operated solely for electricity production. In 1965 the Atomic Energy Commission began designing a uranium-233/thorium core for the reactor and in 1976, the Energy Research and Development Administration (now the Department of Energy) established the Advanced Water Breeder Applications programme to evaluate the LWBR concept for commercial-scale applications. Shippingport operated as an LWBR between August 1977 and October 1982, when the station was finally shut down. During this period, the demonstration LWBR operated for over 29,000 effective full power hours with an availability factor of 76% and had a gross electrical output of over 2.1 billion kilowatt hours. Following operation, inspection of the core found that 1.39% more fissile fuel was present at the end of core life than at the beginning, proving that breeding had occurred.

The core of the Shippingport demonstration LWBR consisted of an array of seed and blanket modules surrounded by an outer reflector region. In the seed and blanket regions, the fuel pellets contained a mixture of thorium-232 oxide (ThO_2) and uranium oxide (UO_2) that was over 98% enriched in U-233. The proportion by weight of UO_2 was around 5-6% in the seed region, and about 1.5-3% in the blanket region. The reflector region contained only thorium oxide at the beginning of the core life. U-233 was used because at the time it was believed that U-235 would not release enough neutrons per fission and Pu-239 would parasitically capture too many neutrons to allow breeding in a PWR.

This work at Shippingport was developed by Alvin Radkowsky, who was the chief scientist of the United States Navy's nuclear propulsion programme from 1950 to 1972 and headed the team that built the Shippingport plant. The Radkowsky Thorium Reactor (RTR) addresses the aspects of the thorium fuel cycle that are considered sensitive from the point of view of weapons proliferation. In particular the RTR avoids the need to separate U-233.

Radkowsky proposed the use of a heterogenous seed-blanket fuel assembly geometry, which separates the uranium (or plutonium) part of the fuel (the seed) from the thorium part of the fuel (the blanket). In the blanket part, U-233 is generated and fissioned, while the seed part supplies neutrons to the blanket. Either uranium enriched to 20% U-235 or plutonium can be used in the seed region[4]. One method of increasing the proliferation resistance of the design is to include some U-238 in the thorium blanket. Any uranium chemically separated from it (for the U-233) would not be useable for weapons. Spent blanket fuel would also contain U-232, which decays rapidly and has very gamma-active daughters creating significant problems in handling the bred U-233 and hence conferring proliferation resistance. Plutonium produced in the seed will have a high proportion of Pu-238, generating a lot of heat and making it even more unsuitable for weapons than normal reactor-grade plutonium. Radkowsky's designs are currently being developed by Thorium Power (now Lightbridge Corp.)[b], based in McLean, Virginia.

Since 1994, Thorium Power Ltd has been involved in a Russian programme to develop a thorium-uranium fuel, which more recently has moved to have a particular emphasis on utilisation of weapons-grade plutonium in a thorium-plutonium fuel. The program is based at Moscow's Kurchatov Institute and receives US government funding to design fuel for Russian VVER-1000 reactors. The design has a demountable centre portion and blanket arrangement, with the plutonium in the centre and the thorium (with uranium) around it[c]. The blanket material remains in the reactor for nine years but the centre portion is burned for only three years (as in a normal VVER). Design of the seed fuel rods in the centre portion draws on extensive experience of Russian navy reactors.

The thorium-plutonium fuel claims four advantages over the use of mixed uranium-plutonium oxide (MOX) fuel: increased proliferation resistance; compatibility with existing reactors - which will need minimal modification to be able to burn it; the fuel can be made in existing plants in Russia; and a lot more plutonium can be put into a single fuel assembly than with MOX fuel, so that three times as much can be disposed of as when using MOX. The spent fuel amounts to about half the volume of MOX and is even less likely to allow recovery of weapons-useable material than spent MOX fuel, since less fissile plutonium remains in it. With an estimated 150 tonnes of surplus weapons plutonium in Russia, the thorium-plutonium project would not necessarily cut across existing plans to make MOX fuel.

Thorium R&D history

The use of thorium-based fuel cycles has been studied for about 30 years, but on a much smaller scale than uranium or uranium/plutonium cycles. Basic research and development has been conducted in Germany, India, Japan, Russia, the UK and the USA. Test reactor irradiation of thorium fuel to high burnups has also been conducted and several test reactors have either been partially or completely loaded with thorium-based fuel.

Noteworthy experiments involving thorium fuel include the following, the first three being high-temperature gas-cooled reactors:

- Between 1967 and 1988, the AVR (Atom Versuchs Reaktor) experimental pebble bed reactor at Jülich, Germany, operated for over 750 weeks at 15 MWe, about 95% of the time with thorium-based fuel. The fuel used consisted of about 100,000 billiard ball-sized fuel elements. Overall a total of 1360 kg of thorium was used, mixed with high-enriched uranium (HEU). Burnups of 150,000 MWd/t were achieved.
- Thorium fuel elements with a 10:1 Th/U (HEU) ratio were irradiated in the 20 MWth Dragon reactor at Winfrith, UK, for 741 full power days. Dragon was run as an OECD/Euratom cooperation project, involving Austria, Denmark, Sweden, Norway and Switzerland in addition to the UK, from 1964 to 1973. The Th/U fuel was used to 'breed and feed', so that the U-233 formed replaced the U-235 at about the same rate, and fuel could be left in the reactor for about six years.
- General Atomics' Peach Bottom high-temperature, graphite-moderated, helium-cooled reactor in the USA operated between 1967 and 1974 at 110 MWth, using high-enriched uranium with thorium.
- In Canada, AECL has more than 50 years experience with thorium-based fuels, including burn-up to 47 GWd/t. Some 25 tests were performed to 1987 in three research reactors and one pre-commercial reactor (NPD), with fuels ranging from ThO_2 to that with 30% UO_2, though most were with 1-3% UO_2, the U being high-enriched.
- In India, the Kamini 30 kWth experimental neutron-source research reactor using U-233, recovered from ThO_2 fuel irradiated in another reactor, started up in 1996 near Kalpakkam. The reactor was built adjacent to the 40 MWt Fast Breeder Test Reactor, in which the ThO_2 is irradiated.
- In the Netherlands, an aqueous homogenous suspension reactor has operated at 1MWth for three years. The HEU/Th fuel is circulated in solution and reprocessing occurs continuously to remove fission products, resulting in a high conversion rate to U-233.

There have also been several experiments with fast neutron reactors.

Power reactors

Much experience has been gained in thorium-based fuel in power reactors around the world, some using high-enriched uranium (HEU) as the main fuel:

- The 300 MWe THTR (Thorium High Temperature Reactor) reactor in Germany was developed from the AVR and operated between 1983 and 1989 with 674,000 pebbles, over half containing Th/HEU fuel (the rest graphite moderator and some neutron absorbers). These were continuously recycled on load and on average the fuel passed six times through the core.
- TheFort St Vrain reactor was the only commercial thorium-fuelled nuclear plant in the USA, also developed from the AVR in Germany, and operated 1976-1989. It was a high-temperature (700°C), graphite-moderated, helium-cooled reactor with a Th/HEU fuel designed to operate at 842 MWth (330 MWe). The fuel was in microspheres of thorium carbide and Th/U-235 carbide coated with silicon oxide and pyrolytic carbon to retain fission products. It was arranged in hexagonal columns ('prisms') rather than as pebbles. Almost 25 tonnes of thorium was used in fuel for the reactor, and this achieved 170,000 MWd/t burn-up.
- Thorium-based fuel for PWRs was investigated at the Shippingport reactor in the USA (discussed earlier).
- In India, thorium has been used for power flattening in the initial cores of the two Kakrapar pressurised heavy water reactors (PHWRs).
- The 60 MWe Lingen Boiling Water Reactor (BWR) in Germany utilised Th/Pu-based fuel test elements.

Several advanced reactors concepts are currently being developed. These include light water reactors, in particular developments of the Radkowsky Thorium Reactor discussed earlier. Other advanced reactors under development include:

- High-temperature gas-cooled reactors (HTGRs) of two kinds: pebble bed and with prismatic fuel elements. The Gas Turbine-Modular Helium Reactor (GT-MHR) being developed by General Atomics uses a prismatic fuel and builds on US experience, particularly from the Fort St Vrain reactor. The GT-MHR core can accommodate a wide range of fuel options, including HEU/Th, U-233/Th and Pu/Th. Pebble bed reactor development builds on German work with the AVR and THTR and is under development in China and South Africa. A pebble bed reactor can potentially use thorium in its fuel pebbles.
- The molten salt reactor (MSR) is an advanced breeder concept, in which the coolant is a molten salt, usually a fluoride salt mixture. Much research has focused on lithium and beryllium additions to the salt mixture. The fuel can be dissolved enriched uranium, thorium or U-233 fluorides, and recent discussion has been on the Liquid Fluoride Thorium Reactor. The core consists of unclad graphite moderator arranged to allow the flow of salt at some 700°C and at low pressure. Heat is transferred to a secondary salt circuit and thence to steam. It is not a fast reactor, but with some moderation by the graphite is epithermal (intermediate neutron speed). The fission products dissolve in the salt and are removed continuously in an online reprocessing loop and replaced with Th-232 or U-238. Actinides remain in the reactor until they fission or are converted to higher actinides which do so. The MSR was studied in depth in the 1960s, but is now being revived because of the availability of advanced technology for the materials and components. There is now renewed interest in the MSR concept in Japan, Russia, France and the USA, and one of the six Generation IV designs selected for further development is the MSR (see also information page on Generation IV Nuclear Reactors).

- CANDU-type reactors - AECL is researching the thorium fuel cycle application to enhanced CANDU-6 and ACR-1000 reactors with 5% plutonium (reactor grade) plus thorium. In the closed fuel cycle, the driver fuel required to starting off is progressively replaced with recycled U-233, so that on reaching equilibrium 80% of the energy comes from thorium. Fissile drive fuel could be LEU, plutonium, or recycled uranium from LWR. AECL envisages fleets of CANDU reactors with near-self-sufficient equilibrium thorium (SSET) fuel cycles and a few fast breeder reactors to provide plutonium.
- Advanced heavy water reactor (AHWR) - India is working on this and, like the Canadian ACR design, the 300 MWe AHWR design is light water cooled. The main part of the core is subcritical with Th/U-233 oxide and Th/Pu-239 oxide, mixed so that the system is self-sustaining in U-233. The initial core will be entirely Th-Pu-239 oxide fuel assemblies, but as U-233 is available, 30 of the fuel pins in each assembly will be Th-U-233 oxide, arranged in concentric rings. It is designed for 100-year plant life and is expected to utilise 65% of the energy of the fuel. About 75% of the power will come from the thorium.
- Fast breeder reactor (FBRs), along with the AHWRs, play an essential role in India's three-stage nuclear power programme (see next section). A 500 MWe prototype FBR under construction in Kalpakkam is designed to breed U-233 from thorium.

India plans for thorium cycle

With about six times more thorium than uranium, India has made utilisation of thorium for large-scale energy production a major goal in its nuclear power programme, utilising a three-stage concept:

- Pressurised heavy water reactors (PHWRs) fuelled by natural uranium, plus light water reactors, producing plutonium.
- Fast breeder reactors (FBRs) using plutonium-based fuel to breed U-233 from thorium. The blanket around the core will have uranium as well as thorium, so that further plutonium (particularly Pu-239) is produced as well as the U-233.
- Advanced heavy water reactors burn the U-233 and this plutonium with thorium, getting about 75% of their power from the thorium. The used fuel will then be reprocessed to recover fissile materials for recycling.

This Indian programme has moved from aiming to be sustained simply with thorium to one 'driven' with the addition of further fissile uranium and plutonium, to give greater efficiency. In 2009, despite the relaxation of trade restrictions on uranium, India reaffirmed its intention to proceed with developing the thorium cycle.

Another option for the third stage, while continuing with the PHWR and FBR stages, is the use of subcritical accelerator driven systems.

Thorium and accelerator driven systems

In an accelerator driven system (ADS), high-energy neutrons are produced through the spallation[d] reaction of high-energy protons from an accelerator striking heavy target nuclei (lead, lead-bismuth or other material). These neutrons can be directed to a subcritical reactor containing thorium, where the neutrons breed U-233 and promote the fission of it. There is therefore the possibility of sustaining a fission reaction which can readily be turned off, and used either for power generation or destruction of actinides resulting from the U/Pu fuel cycle. The use of thorium instead of uranium reduces the quantity of actinides that are produced. (See also information page on Accelerator-Driven Nuclear Energy.)

Developing a thorium-based fuel cycle

Despite the thorium fuel cycle having a number of attractive features, development has always run into difficulties.

The main attractive features are:

- The possibility of utilising a very abundant resource which has hitherto been of so little interest that it has never been quantified properly.
- The production of power with few long-lived transuranic elements in the waste.
- Reduced radioactive wastes generally.

The problems include:

- The high cost of fuel fabrication, due partly to the high radioactivity of U-233 chemically separated from the irradiated thorium fuel. Separated U-233 is always contaminated with traces of U-232 (69 year half-life but whose daughter products such as thallium-208 are strong gamma emitters with very short half-lives). Although this confers proliferation resistance to the fuel cycle, it results in increased costs.
- The similar problems in recycling thorium itself due to highly radioactive Th-228 (an alpha emitter with two-year half life) present.
- Some concern over weapons proliferation risk of U-233 (if it could be separated on its own), although many designs such as the Radkowsky Thorium Reactor address this concern.
- The technical problems (not yet satisfactorily solved) in reprocessing solid fuels. However, with some designs, in particular the molten salt reactor (MSR), these problems are likely to largely disappear.

Much development work is still required before the thorium fuel cycle can be commercialised, and the effort required seems unlikely while (or where) abundant uranium is available. In this respect, recent international moves to bring India into the ambit of international trade might result in the country ceasing to persist with the thorium cycle, as it now has ready access to traded uranium and conventional reactor designs.

Nevertheless, the thorium fuel cycle, with its potential for breeding fuel without the need for fast neutron reactors, holds considerable potential in the long-term. It is a significant factor in the long-term sustainability of nuclear energy.

Further Information

Notes

a. Neutron absorption by Th-232 produces Th-233, which has a half-life of about 22 minutes. This undergoes beta decay to form Pa-233 (half-life 27 days), most of which forms U-233 by further beta decay. Around 11% of the U-233 is converted by further neutron absorption to U-235, which is the fissile isotope of uranium used in conventional nuclear reactors. [Back]

b. Thorium Power (now Lightbridge Corporation, www.ltbridge.com) was formed in 1992 to develop Radkowsky's nuclear fuel designs, which would not produce weapons suitable plutonium in nuclear waste. In April 2007 the company formed an alliance with Red Star nuclear design bureau in Russia which will take forward the programme to demonstrate the technology in lead-test fuel assemblies in full-sized commercial reactors. In December 2008, Thorium Power became the first US company to sign an agreement with an Indian company (engineering firm Punj Lloyd) following the finalization of the US-India nuclear trade agreement. The company changed its name to Lightbridge Corporation in September 2009. [Back]

c. A normal VVER-1000 fuel assembly has 331 rods each 9 mm diameter forming a hexagonal assembly 235 mm wide. Here, the centre portion of each assembly is 155 mm across and holds the seed material consisting of metallic Pu-Zr alloy (Pu is about 10% of alloy, and isotopically over 90% Pu-239) as 108 twisted tricorn-section rods 12.75 mm across with Zr-1%Nb cladding. The sub-critical blanket consists of U-Th oxide fuel pellets (1:9 U:Th, the U enriched up to almost 20%) in 228 Zr-1%Nb cladding tubes 8.4 mm diameter - four layers around the centre portion. The blanket material achieves 100 GWd/t burn-up. Together as one fuel assembly the seed and blanket have the same geometry as a normal VVER-100 fuel assembly. [Back]

d. Spallation is the process where nucleons are ejected from a heavy nucleus being hit by a high energy particle. In this case, a high-enery proton beam directed at a heavy target expels a number of spallation particles, including neutrons. [Back]

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Several papers and articles related to the Radkowsky thorium fuel concept are available on the Lightbridge (formerly Thorium Power) website (www.ltbridge.com)

Related information pages

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