Thorium

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- **Thorium is much more abundant in nature than uranium.**
- **Thorium can also be used as a nuclear fuel through breeding to uranium-233 (U-233).**
- **When this thorium fuel cycle is used, much less plutonium and other transuranic elements are produced, compared with uranium fuel cycles.**
- **Several reactor concepts based on thorium fuel cycles are under consideration.**

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 occurs in several minerals, the most common source being the rare earth-thorium-phosphate mineral, monazite, which contains up to about 12% thorium oxide, but average 6-7%. 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). Thorite is another common mineral. A large vein deposit of thorium and rare earths is in Idaho. Thorium-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.

Estimated World thorium resources

(RAR + Inferred to USD 80/kg Th):

Country	Tonnes	% of world
Australia	452 000	18
USA	400 000	16
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	2 573 000	

source: OECD/NEA Uranium 2007: Resources, Production and Demand (Red Book) 2008.

The 2007 IAEA-NEA "Red Book" gives a figure of 4.4 million tonnes of resources, but this excludes data from much of the world. Geoscience Australia estimates the above 452,000 tonne figure for Australia, but stresses that this is based on assumptions and surrogate data for mineral sands, not direct geological data in the same way as most mineral resources.

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.

Thorium as a nuclear fuel

Thorium, as well as uranium, can be used as a nuclear fuel. Although not fissile itself, thorium-232 (Th-232) will absorb slow neutrons to produce uranium-233 (U-233), which is fissile (and long-lived). Hence like uranium-238 (U-238) it is fertile.

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-235 or Pu-239), a breeding cycle similar to but more efficient than that with U-238 and plutonium (in normal, slow-neutron reactors) can be set up. However, there are also features of the neutron economy which counter this advantage. In particular Pa-233 is a neutron absorber which diminishes U-233 yield. The Th-232 absorbs a neutron to become Th-233 which quickly beta decays to protactinium-233 and then more slowly to U-233. 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.

Over the last 30 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 breeder reactors).

A major potential application for conventional PWRs involves fuel assemblies arranged so that a blanket of mainly thorium fuel rods surrounds a more-enriched seed element containing U-235 which supplies neutrons to the subcritical blanket. As U-233 is produced in the blanket it is burned there. This is the Light Water Breeder Reactor concept which was successfully demonstrated in the USA in the 1970s.
It is currently being developed in a more deliberately proliferation-resistant way. The central seed region of each fuel assembly will have uranium enriched to 20% U-235. The blanket will be thorium with some U-238, which means that any uranium chemically separated from it (for the U-233) is not useable for weapons. Spent blanket fuel also contains 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 Pu.

A variation of this is the use of whole homogeneous assembles arranged so that a set of them makes up a seed and blanket arrangement. If the seed fuel is metal uranium alloy instead of oxide, there is better heat conduction to cope with its higher temperatures. Seed fuel remains three years in the reactor, blanket fuel for up to 14 years.

Since the early 1990s Russia has had a program 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 involves the US company Thorium Power and US government funding to design fuel for Russian VVER-1000 reactors. Whereas normal fuel uses enriched uranium oxide, the new design has a demountable centre portion and blanket arrangement, with the plutonium in the centre and the thorium (with uranium) around it (More precisely: 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). The Th-232 becomes U-233, which is fissile - as is the core Pu-239. Blanket material remains in the reactor for 9 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 MOX: proliferation resistance, compatibility with existing reactors - which will need minimal modification to be able to burn it, and the fuel can be made in existing plants in Russia. In addition, a lot more plutonium can be put into a single fuel assembly than with MOX, 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 weapons plutonium in Russia, the thorium-plutonium project would not necessarily cut across existing plans to make MOX fuel.

In 2007 Thorium Power formed an alliance with Red Star nuclear design bureau in Russia which will take forward the program to demonstrate the technology in lead-test fuel assemblies in full-sized commercial reactors.

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 Julich, 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). Maximum 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 (HTGR) in the USA operated between 1967 and 1974 at 110 MWth, using high-enriched uranium with thorium.
- 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 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. Fuel fabrication was on an industrial scale.
- The **Fort 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 Pressurised Water Reactors (PWRs) was investigated at the **Shippingport** reactor in the USA using both U-235 and plutonium as the initial fissile material. It was concluded that thorium would not significantly affect operating strategies or core margins. The light water breeder reactor (LWBR) concept was also successfully tested here from 1977 to 1982 with thorium and U-233 fuel clad with Zircaloy using the 'seed/blanket' concept.
- The 60 MWe **Lingen** Boiling Water Reactor (BWR) in Germany utilised Th/Pu-based fuel test elements.

India

In India, both **Kakrapar**-1 and -2 units are loaded with 500 kg of thorium fuel in order to improve their operation when newly-started. Kakrapar-1 was the first reactor in the world to use thorium, rather than depleted uranium, to achieve power flattening across the reactor core. In 1995, Kakrapar-1 achieved about 300 days of full power operation and Kakrapar-2 about 100 days utilising thorium fuel. The use of thorium-based fuel was planned in Kaiga-1 and -2 and Rajasthan-3 and -4 (Rawatbhata) reactors.

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 program, utilising a three-stage concept:

- Pressurised Heavy Water Reactors (PHWRs, elsewhere known as CANDUs) fuelled by natural uranium, plus light water reactors, produce plutonium.
- Fast Breeder Reactors (FBRs) use this 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 (ideally high-fissile Pu) is produced as well as the U-233. Then
- 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 program 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.

Another option for the third stage, while continuing with the PHWR and FBR programs, is the subcritical Accelerator-Driven Systems (ADS), - see below.

Emerging advanced reactor concepts

Concepts for advanced reactors based on thorium-fuel cycles include:

- Light Water Reactors - With fuel based on plutonium oxide (PuO_2), thorium oxide (ThO_2) and/or uranium oxide (UO_2) particles arranged in fuel rods.
- High-Temperature Gas-cooled Reactors (HTGR) of two kinds: pebble bed and with prismatic fuel elements.
  Gas Turbine-Modular Helium Reactor (GT-MHR) - Research on HTGRs in the USA led to a concept using a prismatic fuel. The use of helium as a coolant at high temperature, and the relatively small power output per module (600 MWth), permit direct coupling of the MHR to a gas turbine (a Brayton cycle), resulting in generation at almost 50% thermal efficiency. The GT-MHR core can accommodate a wide range of fuel options, including HEU/Th, U-233/Th and Pu/Th. The use of HEU/Th fuel was demonstrated in the Fort St Vrain reactor (see above).
  Pebble-Bed Modular reactor (PBMR) - Arising from German work the PBMR was conceived in South Africa and is now being developed by a multinational consortium. It can potentially use thorium in its fuel pebbles.
- Molten salt reactors (MSR) - This is an advanced breeder concept, in which the fuel is a molten mixture of lithium and beryllium fluoride salts with dissolved enriched uranium, thorium or U-233 fluorides. 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 on-line 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. In 2002 a Thorium MSR was designed in France with a fissile zone where most power would be produced and a surrounding fertile zone where most conversion of Th-232 to U-233 would occur.
- Advanced Heavy Water Reactor (AHWR) - India is working on this, and like the Canadian ACR the 300 MWe 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.
- 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 high burn-up and low power costs are indicated.
- Plutonium disposition - Today MOX (U,Pu) fuels are used in some conventional reactors, with Pu-239 providing the main fissile ingredient. An alternative is to use Th/Pu fuel, with plutonium being consumed and fissile U-233 bred. The remaining U-233 after separation could be used in a Th/U fuel cycle.

Use of thorium in Accelerator Driven Systems (ADS)

In an ADS system, high-energy neutrons are produced through the spallation 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 means that less actinides are produced in the ADS itself.

(see paper on Accelerator-Driven Nuclear Energy) .

Developing a thorium-based fuel cycle

Despite the thorium fuel cycle having a number of attractive features, development even on the scale of India's 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);
- the similar problems in recycling thorium itself due to highly radioactive Th-228 (an alpha emitter with two-year half life) present;
- some weapons proliferation risk of U-233 (if it could be separated on its own); and
- the technical problems (not yet satisfactorily solved) in reprocessing solid fuels.

However, these are likely to largely disappear if the fuel is used a Molten Salt Reactor.

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 international moves to bring India into the ambit of international trade will be critical. If India has ready access to traded uranium and conventional reactor designs, it may not persist with the thorium cycle.

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

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