The Potential of Thorium Deposits

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Abstract. Increased uranium prices are continuing to impact uranium resource totals. Many countries have developed ambitious programs for their future energy supply and the use of nuclear energy is regarded a secure option. A number of industrialized and rapidly developing countries lack major uranium resources and the use of thorium as an alternative in the fuel cycle is envisaged. Up to now thorium has had a limited market and there has been little incentive to explore or to develop detailed information on known thorium deposits. This paper presents new data on worldwide thorium resources and potential future use as nuclear fuel.

Thorium Occurrences and Characteristics

Thorium is much more abundant in nature than uranium. 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 6-7% in average and up to 12% thorium oxide. A second major source is (urano)thorianite, a suggested name for a mineral intermediate between uraninite and thorianite $(Th,U)O_2$). Monazite and uranothorianite are found in igneous and metamorphic rocks but the richest concentrations are in secondary placer deposits, concentrated by fluviatile, marine and aeolien processes with other heavy minerals. Large thorium enrichments occur in Precambrian metamorphic belts like in southern and eastern Africa, India, Australia and in Scandinavia. Major thorium deposit types include carbonatites, placers, vein-type deposits in metamorphic terranes, and deposits associated with intrusive alkaline rocks. Today, thorium is recovered mainly from monazite as a by-product of processing heavy mineral sand deposits for titanium-, zirconium- or tin-bearing minerals.

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 Resources

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 (Table 1). Thorium deposits are found in several countries around the world. The largest thorium reserves are expected to be found in Australia, India, USA, Norway, Canada, and in countries such as South Africa and Brazil. Reserves and additional resources total 6.078 Mio t Th. This number, however, excludes data from much of the world.

Thorium as a Nuclear Fuel

Thorium can be used as a nuclear fuel through breeding to uranium-233 (U-233). 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

Table 1. Estimated World thorium resources (RAR + Inferred to USD 80/kg Th) [a].

Country	Tonnes	%
Australia	452 000	17,6
USA	400 000	15,6
Turkey	344 000	13,4
India	319 000	12,4
Brazil	302 000	11,7
Venezuela	300 000	11,7
Norway	132 000	5,1
Egypt	100 000	3,9
Russia	75 000	2,9
Greenland	54 000	2,1
Canada	44 000	1,7
South Africa	18 000	0,7
Other Countries	33 000	1,3
Total	2 573 000	

[a] Uranium 2007: Resources, Production and Demand.

of these are short-lived and hence much more radioactive than Th-232, though on a mass basis they are negligible. 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. When the thorium fuel cycle is used, much less plutonium and other transuranic elements are produced, compared with uranium fuel cycles.

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). 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.

Several reactor concepts based on thorium fuel cycles are under consideration (e.g., the Light Water Breeder Reactor concept). 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. The breeder reactor concept 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.

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.

Worldwide, the highest activity on thorium as a nuclear energy source is found in India where the Kakrapar-1 and -2 power plants are loaded with 500 kg of thorium blanket. Kakrapar-1 was the first nuclear reactor in the world to use thorium in the blanket, rather than depleted uranium, to achieve power flattening across the reactor core. In addition, the use of thorium based fuel is planned in 4 reactors, which are currently under construction.

India has about 1 % of the world's uranium resources while the thorium resources are one of the largest in the world with about 300 000 tonnes. With about six times more thorium than uranium, India has made utilization of thorium for large-scale energy production a major goal in its nuclear power program, utilizing a three-stage approach:

1. Pressurized Heavy Water Reactors (PHWRs), elsewhere known as CANDUs (CANada Deuterium Uranium) fuelled by natural uranium and Light Water Reactors (LWRs) of the Boiling Water Reactor (BWR) and VVER types. In this stage plutonium is produced.
2. Fast Breeder Reactors (FBRs) that 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 plutonium) is produced as well as the U-233.
3. Advanced Heavy Water Reactors (AHWRs) that burn the U-233 and plutonium with thorium, getting about 75 % of their power from the thorium.

India's future program on thorium based nuclear power is important for India's long term energy security. Some research and development activities are also carried out on the Compact High Temperature Reactor (CHTR) and on the subcritical Accelerator Driven System (ADS) including the development of a high power proton accelerator.

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 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). The 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.

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.

Developing a Thorium-Based Fuel Cycle

The fact that thorium is much more abundant in nature than uranium and the progres in technology still attract countries with limited uranium resources but ambitious programs for the future use of nuclear power. Up to now, production of thorium has been limited due to a lack of demand. Thorium is largely a by-product of the separation of rare earth elements. The production of thorium is presently some hundred tonnes per year. The production reached about 1000 tonnes in the 1970s, and has decreased thereafter due to lack of demand. Owing to its chemical toxicity, radiotoxicity and pyrophoricity, adequate precautions are required in the mining and processing of thorium. However, as a result of the very long half-life of thorium, limited quantities of pure thorium-232 can easily be handled, while some shielding is required for large amounts. Preparation of thorium fuel is somewhat more complex and more expensive than for uranium. Thorium as a nuclear fuel is technically well established and behaves remarkably well in Light Water Reactors and High Temperature Reactors. It has demonstrated a very good neutron damage resistance due to its excellent chemical and metallographic stability. However, 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 include (i) the possibility of utilising a very abundant resource which has hitherto been of so little interest that it has never been quantified properly, (ii) the production of power with few long-lived transuranic elements in the waste, (iii) reduced radioactive wastes generally.

The problems include (i) 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); (ii) the similar problems in recycling thorium itself due to highly radioactive Th-228 (an alpha emitter with two-year half life) present; (iii) some weapons proliferation risk of U-233 (if it could be separated on its own); (iv) the technical problems in reprocessing solid fuels. However, these problems may 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. 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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