

# The Thorium Fuel Cycle

## EXECUTIVE SUMMARY

The thorium fuel cycle provides an alternative source of nuclear energy to the uranium fuel cycle. It was extensively researched and developed in research and test reactors programs in the UK (Dragon), the USA (Peach Bottom) and Japan, Russia and France, in the first decades of nuclear energy. The research was largely abandoned by the mid-1970s (except in India which has operated a very significant program), primarily because the cost of further development of the thorium fuel cycle was not justified, given the plentiful, cheap supply of uranium and an established uranium fuel cycle.

The research programs did lead to Thorium-uranium mixed fuel being applied in commercial high temperature gas reactors, notably the THTR-300 MWe (Germany) which shut down in 1989 and Fort St Vrain (USA) - a 330MWe plant - also closed in 1989.

There has been renewed interest in the thorium fuel cycle in recent years, driven by:

- The potential for an alternative fuel cycle to reduce proliferation concerns;
- Waste management challenges associated with the uranium fuel cycle; and
- Holders of thorium resources seeking to create a market.

In India, the interest was motivated, until very recently, by their exclusion from global nuclear markets because of their refusal to adhere to the Non-Proliferation Treaty. Nevertheless, the thorium fuel cycle still requires considerable further development before it can be determined if it is commercially viable:

- 1) There are a range of reactor types to which this fuel cycle can be applied: all would require detailed engineering, licensing and operations phases before they could be widely adopted;
- 2) There would have to be re-investment in fuel development, qualification and characterisation; and
- 3) The limited data and the erosion of experience with thorium fuels would require substantial investments to ensure that both the front end and back end of (open and closed) thorium fuel cycles was predictable and satisfactory from a regulatory and safeguards perspective.

Given the significant resources which a thorium fuel cycle research program would require, any Australian role in research into the thorium fuel cycle would best be achieved through participation in the Generation IV International Forum (GIF).

## THE CONCEPT

Unlike uranium, none of the thorium isotopes is fissile.<sup>1</sup> Thorium does not require enrichment to be used in a fuel cycle. Irradiation of the material in a reactor, or with a neutron source such as an accelerator, is required before the material can be used as nuclear fuel. In a reactor, Th-232 (the major isotope of thorium found in nature) will absorb neutrons from the fission of the other nuclear material (such as U-233, U-235 or Pu-239) to produce Th-233, which decays to U-233, which is fissile. Alternatively, it is considered possible that the initial conversion to U-233 could be done by an accelerator, thus eliminating the need for irradiation in a reactor. During irradiation, the newly created U-233 starts to fission and produce neutrons to sustain the reaction. A notable feature of this mechanism is that no enrichment (of U) is required for thorium fuels in accelerator driven conceptual power system.

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<sup>1</sup> Capable of maintaining a chain reaction.

Potentially, all natural thorium can be converted to nuclear reactor usable U-233, whereas less than 10% of the natural uranium (the U-235 component and the Pu generated from U-238) is usable in conventional reactors<sup>2</sup>. This postulated high “burn-up” is a key developmental objective for nations/groups that develop the thorium fuel cycle and could be the basis of very attractive economics – high abundance and high burn-up imply low overall cost. As indicated above, a closed thorium fuel cycle (which produces driver isotopes) would also eliminate the need to enrich uranium.

## MINERAL RESERVES

Thorium is thought to be three to five times more abundant in nature than uranium, and Australia has extensive reserves of both<sup>3</sup>. Estimated world reserves of thorium can be found in the following table<sup>4</sup>:

Table 1: Thorium Reserves (Nuclear Energy Agency 2007)

<i>(Reasonably assured and inferred resources recoverable at up to US\$80/kg Th)</i>		
<b>Country</b>	<b>Tonnes</b>	<b>% of total</b>
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

## HISTORY

The use of thorium-based fuel cycles has been studied for over 40 years, but on a much smaller scale than uranium or uranium/plutonium cycles. Basic research and development was conducted in Germany, India, Japan, Russia, the UK and the USA, and thorium has been used (either on its own or in conjunction with highly enriched uranium) as a fuel in several power reactors in Germany, the USA, Russia and India.

Most thorium research programs had ceased by the early 1980s. Reasons for this include: the maturity and proven track record of the uranium fuel cycle, the acceptability of uranium prices and, in the case of Germany, because it was moving away from nuclear power altogether.

The major exception to this trend was India. Because of its status as a non-party to the NPT, India was excluded from international uranium markets between 1974 and 2008. India also lacks significant resources of uranium, but holds significant thorium reserves. For those reasons, India continued (and continues today) an active research program into the thorium fuel cycle. It remains to be seen what effect the recent agreements opening up nuclear (especially uranium) commerce with India will have on that research program over time.

<sup>2</sup> This advantage does not apply if fast neutron reactors are used for uranium.

<sup>3</sup> The Australian Mines Atlas (<http://www.australianminesatlas.gov.au>) lists 53 occurrences of thorium in deposits. The Atlas indicates that “There has been no widespread exploration for thorium in Australia apart from two exploration licences which have been reported as being primarily for thorium exploration in Qld.”

<sup>4</sup> Given that there is currently little use of and demand for thorium, relatively little exploration has taken place. These figures should therefore be treated with a degree of caution.

## PROLIFERATION RESISTANCE

One of the primary attractions of the thorium fuel cycle is a reduction in the generation of plutonium and other trans-uranic elements compared to the uranium cycle. On the other hand:

- the uranium-233 produced in the thorium fuel cycle is fissile, and is therefore useable in a nuclear weapon (although there are practical problems with its handling which make it less attractive than uranium-235 or plutonium-239)<sup>5</sup>. U-233 is subject to the same IAEA controls as other weapons-useable material; and
- any initial “driver”<sup>6</sup>, other than an accelerator driven system, is also fissile and there would need to be safeguards in place to prevent diversion of such “drivers” to a weapons program.

The degree of proliferation resistance of a thorium fuel cycle incorporating fissile driver(s) will be dependent on a number of factors: what drivers are used, how the driver is incorporated in the core (e.g. is it incorporated as separate fuel rods/blocks/pebbles or mixed with thorium) and if and how driver-bearing fuel elements are re-processed. The use of an accelerator<sup>7</sup>, rather than plutonium or enriched uranium, as a driver to initiate fission would remove the need to apply safeguards to that part of the cycle.

Because plutonium is not bred in thorium-based fuels, thorium reactors could be utilised to dispose of excess weapons plutonium and long-lived highly active “waste” actinides.

## WASTE & RECYCLING ISSUES

The attraction of the thorium fuel cycle (as opposed to the uranium fuel cycle) with regard to waste is the absence of plutonium and the reduced amounts of long-lived minor actinides (Np, Am, and Cm) for at least the first few recycles, when compared to the open uranium cycle<sup>8</sup>. However, the generation of other radionuclides, particular to the thorium cycle, may complicate this picture. Specifically, Pa-231, Th-229 and Th-230 (with half lives of 32,500, 7,900 and 75,400 years respectively) have long-term radiological importance. The net result is that it is probable that a thorium fuel cycle would still require the creation of geological repositories for the management of long-lived waste products, as the uranium fuel cycle currently does<sup>9</sup>.

If the thorium cycle were to utilise a fissile driver to begin production of U-233 from Th-232, the waste products of the uranium cycle will also be generated in some quantity. In this scenario, the difference in terms of minimisation of long-lived wastes will have been greatly reduced.

Another major problem for the closed thorium cycle is the production of U-232 concurrently with the U-233. U-232 cannot be chemically separated from U-233 and has a relatively short half-life of 73.6 years. Its daughter products (the isotopes into which it decays) have high gamma activity. This dictates that the reprocessing and re-fabrication of thorium fuels (necessary for a closed cycle) must be performed with complex remotely operated plant. This contrasts with the uranium

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<sup>5</sup> U-232 is generated alongside the U-233. U-232 decays rapidly, and its daughters emit high energy gamma-rays. This makes handling very difficult and adds a high degree of self-shielding that has been regarded as protecting the U-233 from being made into a weapon.

<sup>6</sup> A driver is a fissile material (such as U-233, U-235 or Pu-239) used to generate the neutrons to convert Thorium to U-233.

<sup>7</sup> Accelerators which could be used for this purpose have not yet been developed, and are probably some decades away from deployment.

<sup>8</sup> This apparent comparative advantage is sometimes overstated because if the uranium cycle is closed, the plutonium is largely consumed, in the same way the <sup>233</sup>U would be in the thorium cycle.

<sup>9</sup> Although the waste volumes would be smaller, meaning that the repositories could also be smaller.

fuel cycle, where both uranium and plutonium (for MOX fuel) can be handled without significant shielding.

## REVIVAL OF INTEREST IN THE THORIUM FUEL CYCLE

Unlike current power reactors, some of the advanced reactors currently being developed under the auspices of the Generation IV International Forum (GIF) could be used in a thorium fuel cycle<sup>10</sup>. In particular:

- the thorium fuel cycle has already been demonstrated with High Temperature Gas Reactors;
- the molten salt reactor (MSR) is an advanced breeder concept first studied in depth in the 1960s, but now being revived because of the availability of advanced technology for the materials and components. The MSR could utilise either uranium or thorium, or a combination of both, as fuel. The Chinese Academy of Sciences announced in January 2011 that it will finance a program to develop a Thorium Fuelled Molten Salt Reactor. The goal is to complete the technological research needed in 20 years, and to be in a position to commercialise the reactor technology from 2030. A small 2 MW experimental molten salt reactor is planned within five years. This will be followed by the creation of a Thorium Molten Salt Reactor Nuclear Energy park, as a base for the national research effort and subsequent demonstration reactors. The Chinese research program covers materials development, fuel-manufacture, waste disposal as well as reactor technology. One of the companion initiatives is to develop an accelerator-driven system (ADS) for radioactive waste transmutation.

## FURTHER RESOURCES

A good, comparatively recent, authoritative international source with information on the Thorium Fuel Cycle is IAEA-TECDOC-1450: *Thorium fuel cycle — Potential benefits and challenges (May 2005)*.

A recent authoritative report on Thorium resources in Australia that contains references to the thorium fuel cycle: *A Review of the Geochemical Processes Controlling the Distribution of Thorium in the Earth's Crust and Australia's Thorium Resources*. Terrence P. Mernagh and Yanis Miezitis, *Geoscience Australia (2008)*.

The Parliamentary Library contains a paper covering the same theme with a list of recent references: *Research Paper no. 11 2007–08 Thorium in Australia*, Greg Baker, *Statistics and Mapping Section 17 September 2007*

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<sup>10</sup> [http://nuclear.energy.gov/genIV/documents/gen\\_iv\\_roadmap.pdf](http://nuclear.energy.gov/genIV/documents/gen_iv_roadmap.pdf).