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Thorium in Australia

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Executive summary

- Thorium is a radioactive element that can be used in a new generation of nuclear reactors as an alternative source of fuel for the generation of electricity.
- A thorium-based fuel cycle is more proliferation resistant than conventional uranium-based reactors though there is still a degree of risk.
- A thorium-based fuel cycle is less accident prone and is more energy efficient than conventional uranium-based reactors.
- Thorium-based fuel cycle waste products are not as long lived as those from conventional nuclear reactors.
- Thorium is abundant in Australia.
- There are technical issues still needing resolution before a thorium-based fuel cycle can become common.
- Even if the technical issues can be resolved there are still residual environmental concerns in the mining, handling and storage of radioactive materials.

Contents

Introduction

Thorium is a naturally-occurring radioactive element that can be used in a new generation of nuclear reactors as an alternative source of fuel for the generation of electricity.

Thorium has several advantages as a nuclear fuel:

- it produces less of the nuclear by-products normally used to make nuclear weapons and less of the long-lived radioactive products of conventional nuclear power
- its use in suitable nuclear reactors can reduce the hazard of nuclear accidents
- unlike natural uranium, its energy content can be used almost in its entirety, and
- thorium ore minerals are abundantly available in Australia.

There are, however, some technical issues to be resolved before thorium can be considered as a fuel for Australia's future. If these technical issues can be resolved, residual environmental concerns of mining, handling and storage of radioactive materials will still make the decision to use any thorium-based fuel cycle a political one.

This research paper discusses thorium and the implications of its use, particularly in the Australian context.

Thorium

Thorium is a naturally-occurring radioactive element.[1] It was discovered in 1828 by the Swedish chemist and mineralogist Jöns Jakob Berzelius who named the element after Thor, the Norse god of thunder.[2] In 1898 Gerhard Carl Schmidt and Marie Curie independently found that thorium was radioactive.[3]

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1. In simple terms, an element is a substance which cannot be changed into another substance by ordinary chemical processes. Iron and lead, for example, are elements. A *naturally-occurring* element is found in nature and has not been manufactured using nuclear processes. A *radioactive* element is an element that has an unstable atomic nucleus—this sort of element spontaneously and randomly alters the state of its atomic nucleus, emitting sub-atomic particles in the process. Sub-atomic particles are the building blocks of atoms. There are many different sub-atomic particles; those mentioned here are the *electron*, and the *proton* and the *neutron* which in combination make up an atomic nucleus.

2. James B Hedrick, 'Thorium', United States Geological Survey at http://minerals.usgs.gov/minerals/pubs/commodity/thorium/690798.pdf,

In its natural state thorium is composed almost entirely of an isotope called thorium-232. Isotopes of an element, although *chemically* the same as each other, have different nuclear structures.[4]

Thorium-232 has a half-life of 14 050 million years, meaning that half of any given mass will decay—disintegrate—into other nuclear products in that time; 14 050 million years is over three times the age of the earth. This means that thorium-232 is not particularly radioactive, although its decay products are. From its natural state, thorium-232 decays through a number of stages finishing with lead-208, which is stable.[5]

Thorium is used for some industrial purposes, including bringing the intense white colour to gas-lamp mantles. However, its principal modern interest is as a nuclear fuel.

Sources of thorium

Thorium is found in small quantities in the earth's upper crust where, at 6–10 parts per million, it is about three times more abundant than uranium.[6]

The main source of thorium in Australia and worldwide is the mineral monazite which is a reddish-brown rare-earth phosphate mineral.[7] Monazite contains 8–10 per cent thorium.[8]

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accessed 23 July 2007; and Uranium Information Centre, 'Thorium', *Briefing Paper*, no. 67, UIC, May 2007, http://www.uic.com.au/nip67.htm, accessed 23 July 2007.

[3] Encyclopaedia Britannica Online, 'Thorium' at http://www.britannica.com/eb/article-9072236/thorium, accessed 23 July 2007.

[4] The number that is part of the isotope name—here 232—is the isotope's atomic mass number. This mass number is the sum of the number of protons in the nucleus—here 90—and the number of neutrons in the nucleus—here 142. The isotope thorium-228 also occurs in the decay series of thorium-232, i.e. in the chain of nuclear products produced as thorium-232 disintegrates. Most of these are short-lived isotopes and hence more radioactive than thorium-232; they are negligible in mass. A diagram of the decay series follows in the next footnote. 'Thorium', World Nuclear Association at http://www.world-nuclear.org/info/inf62.htm, accessed 23 July 2007.

[5] *McGraw-Hill Encyclopedia of Science and Technology*, 9th edition, p. 414 and the web site http://environmentalchemistry.com/yogi/periodic. Thorium-232 with an atomic mass number of 232 eventually decays to lead-208 with an atomic mass number of 208.

[6] Nuclear Energy Agency/Organisation of Economic Co-operation and Development, *Forty years of uranium resources, production and demand in perspective: 'The Red Book retrospective'*, NEA/OECD, Paris, 2006, p. 135.

[7] A mineral is a naturally-occurring homogeneous solid that has a definite chemical composition and a highly ordered atomic structure. Rare-earth minerals are a group of elements once

Other minerals containing thorium include thorite (thorium silicate), a thorium–uranium mineral which is also an important ore of uranium and thorianite which contains around 70 per cent thorium dioxide.[9]

In Australia monazite is usually found as a component of heavy mineral sand deposits.[10] Because there is no market for the mineral, monazite is not extracted during mining for heavy mineral sands but dispersed back through the original host material when a mining site is returned to its agreed post-mining land use.[11] This dispersal of monazite is done to prevent concentrations of radioactivity in rehabilitated mine sites.[12]

Thorium resources

Because there has been little commercial demand for thorium there are few detailed records on Australia's, or the world's, thorium resources.[13]

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thought rare; the term is probably now a misnomer. See *McGraw-Hill Encyclopedia of Science and Technology*, 9th edition, pp. 188 and 212.

[8] Nuclear Energy Agency/Organisation of Economic Co-operation and Development, *loc. cit*. Interestingly, monazite contains significant amount of helium caused by the alpha decay of thorium and uranium; the helium can be extracted by heating. In alpha decay the nucleus of an atom emits two protons and two neutrons—this is identical to emitting a helium nucleus.

[9] *McGraw-Hill Encyclopedia of Science and Technology*, 9th edition, p. 414; and US Department of Energy, Argonne National Laboratory, Environmental Science Division, *Radiological and chemical fact sheets to support health risk analyses for contaminated areas: thorium*, August 2005, http://www.ead.anl.gov/pub/doc/ANL_ContaminantFactSheets_All_070418.pdf, accessed 30 July 2007.

[10] Geoscience Australia, *Australia's identified mineral resources 2007*, Geoscience Australia, Canberra, 2007. These mineral sands are often found in placer deposits which are accumulations of dense materials trapped by the flow of water. Placer materials are dense materials that because of their density fail to be carried along by water flow and are left behind and concentrated in hollows and bends.

[11] The minerals in mineral sands are extracted for their titanium and zirconium content.

[12] Geoscience Australia, *loc. cit*. Radiation is an occupational health issue in the mineral sands industry and heavy mineral sands production is managed under the *Code of Practice for Mining and Milling of Radioactive Ores*. Current performance data indicate that current radiation levels are well below the recently set *Commonwealth Radiation Protection Code* limit for occupational exposure.

[13] Geoscience Australia, *loc. cit*.

However, Geoscience Australia estimates that Australia's monazite resources amount to 5.2 million tonnes. At an estimated average thorium content of 7 per cent, this is calculated to mean thorium resources of around 364 000 tonnes from this source. In addition, Geoscience Australia notes that the resources at Nolans Bore, 135 kilometres northwest of Alice Springs, contain 60 600 tonnes of thorium dioxide amountint to 53 300 tonnes of thorium; another deposit, Toongi, 30 kilometres south of Dubbo in New South Wales contains about 35 000 tonnes of thorium.

Summing these three figures yields an estimate for Australia's total identified thorium resources of 452 300 tonnes which Geoscience Australia estimates are extractable at less than US$80 per kilogram of thorium.[14]

Other countries with thorium resources include India, Norway, the USA and Canada.

Table 1 shows estimates of world thorium resources derived by Geoscience Australia.[15]

The identified resources in the table are those resources considered to be extractable at less than US$80 per kilogram. The figure for Australia is the Geoscience Australia estimate discussed above. The remaining figures are from the OECD's Nuclear Energy Agency (NEA) reproduced by Geoscience Australia.[16] 'Undiscovered resources' are resources which are believed to exist and to be exploitable using conventional mining techniques; they have not

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[14] Geoscience Australia, *op. cit.*, pp 71–2. The figure of US$80 per kilogram is conventionally taken as the cut-off point for measuring the quantity of extractable resources of uranium and thorium. It does not imply that extraction is economic at that level because extraction is only economic if the market price exceeds the extraction cost. In the case of thorium there is no market price. Also Yanis Miezitis, Geoscience Australia, personal communication, 31 August 2007 and 12 September 2007.

[15] Geoscience Australia, *op. cit.*, p.73 and Yanis Miezitis, Geoscience Australia, personal communication, 31 August 2007. Other figures for thorium resources are at U.S. Geological Survey (USGS), 'Thorium', *Mineral Commodity Summaries 2007*, United States Government Printing Office, Washington, 2007, pp. 170–1. The entire USGS publication is at http://minerals.usgs.gov/minerals/pubs/mcs/2007/mcs2007.pdf, accessed 30 July 2007; the thorium chapter can be viewed at http://minerals.usgs.gov/minerals/pubs/commodity/thorium/thorimcs07.pdf, accessed 30 July 2007. Note that estimates from different sources vary because of different assumptions underlying their compilation and different interpretations of the term 'reserves'.

[16] Nuclear Energy Agency/Organisation of Economic Co-operation and Development, *Forty years of uranium resources, production and demand in perspective: 'The Red Book retrospective'*, NEA/OECD, Paris, 2006, p. 136–8.

yet been physically confirmed. Data for China and for central and eastern Europe are not available.[17]

These figures show that Australian thorium resources are significant on a world scale.

Table 1. Estimates of thorium resources

	Geoscience Australia estimates		
Country	**Identified resources (thousand tonnes thorium)**	**Percentages of world total (%)**	**Undiscovered resources (thousand tonnes thorium)**
Australia	452	18.1	Not available
Brazil	221	8.9	329–700
Canada	44	1.8	128
Egypt	100	4.0	280
Greenland	54	2.2	32
India	319	12.8	Not available
Norway	132	5.3	132
Russian Federation	75	3.0	Not available
South Africa	18	0.7	130
Turkey	344	13.8	400–500
USA	400	16.1	274
Venezuela	300	12.0	Not available
Other countries	33	1.3	81
World total	2 492	100.0	1786–2257

Australia's identified mineral resources, Geoscience Australia, Canberra, 2006, p. 73.

Thorium as a nuclear fuel

Naturally-occurring thorium, thorium-232, although radioactive, is not capable of sustaining a nuclear chain reaction; the necessary basis for extracting energy from nuclear fuel is a controlled, self-sustaining nuclear chain reaction. Thorium-232 is, however, *fertile*. Being fertile means that thorium is capable of being converted into a *fissile* material, i.e. into a material that *is* capable of sustaining a nuclear chain reaction.

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[17] R. Price and J.R. Blaise, 'Nuclear fuel resources: enough to last?', *NEA News*, no. 20.2, Nuclear Energy Agency, 2002, pp. 10–13 available at http://www.nea.fr/html/pub/newsletter/2002/20-2-Nuclear_fuel_resources.pdf, accessed 1 August 2007.

This conversion process is relatively straightforward. When the nucleus of a thorium-232 atom is bombarded with neutrons, it passes relatively quickly through two steps to produce uranium-233 which is fissile.[18]

To undertake this process and to produce a useable fuel source, it is necessary to devise a source of neutrons. This can be achieved by using neutrons from plutonium or from enriched uranium or from both as they undergo fission in a conventional reactor or in a *fast breeder reactor*, a reactor which is designed to produce more fissile material than it consumes.[19] Fission is the process whereby large atoms split into smaller atoms, releasing energy and subatomic particles in the process; some of these particles are neutrons.

Another way to produce neutrons is to use a device called a *particle accelerator*. When a heavy metallic target such as lead is irradiated with high energy protons (another type of subatomic particle) large numbers of neutrons are produced.

The thorium fuel cycle can be either a *closed fuel cycle*, or an *open fuel cycle* (also known as a *once-through fuel cycle*). [20]

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[18] Neutrons are sub-atomic particles typically found within the nucleus of atoms. Outside the nucleus, free neutrons can be fired at nuclear targets such as thorium-232 atoms. A slow neutron has low energy. When bombarded with a slow neutron, thorium-232 absorbs the neutron and hence becomes thorium-233. Thorium-233 has a half life of about 22 minutes decaying into protactinium-233. Protactinium-233 has a half-life of about 27 days decaying into uranium-233. Each of these radioactive decays happens by a process called *beta emission* or *beta decay*. With beta decay, within the nucleus a neutron spontaneously changes into a proton—which produces the new element—and ejects an electron and another sub-atomic particle called an anti-neutrino. The resulting uranium-233 is fissile, i.e. is capable of sustaining a nuclear chain reaction. Because of the additional proton, the thorium has become protactinium which has 91 protons compared to thorium's 90 and the protactinium in turn becomes uranium which has 92 protons.

[19] The fissile isotope uranium-235 is not sufficiently concentrated in uranium in its natural state for the uranium to be useful as a fuel. The natural occurrence of about 0.7 per cent uranium-235 needs to be increased—'enriched'—to around three per cent uranium-235. See Ian Clark and Barry Cook, 'Uranium', *Introduction to Australia's Minerals*, vol. 5, Uranium Information Centre, 2000, p. 12. Although the element plutonium is found in very small trace amounts as the isotope plutonium-244 in nature, plutonium is manufactured from uranium. See http://environmentalchemistry.com/yogi/periodic/Pu.html, accessed 2 August 2007. The thorium used in conventional nuclear reactors is used in the form of *mixed oxide fuel* where oxides of thorium and of uranium or plutonium are mixed in forming the fuel assembly. S R Hashemi-Nezhad, University of Sydney, personal communication, 4 September 2007.

[20] International Atomic Energy Agency, *Thorium fuel cycle—potential benefits and challenges*, IAEA-TECDOC-1450, IAEA, Vienna, May 2005, p. 10.

In a closed fuel cycle uranium-233 produced from thorium-232 as outlined above, as well as other fissile material in the spent fuel of a reactor are separated, and then used as fuel in the same or in another reactor. In the first stage in this process, uranium-233 is prepared as an almost pure isotope, which can be separated by chemical means.[21] This chemical separation is possible because the three elements involved in the conversion of thorium-232 to uranium-233—thorium, protactinium and uranium—have different chemical properties; they will all be present after the neutron bombardment of thorium-232.[22] The uranium-233 is then fabricated as part of fuel assemblies for the second stage where a reactor uses uranium-233 as a nuclear fuel.[23] The system is called 'closed' because ultimately the spent fuel from the power reactor needs to be re-processed.

In an open fuel cycle, or once-through fuel cycle, of which there are several practical variations, thorium-232 is placed with the fissile materials uranium or plutonium within a fuel assembly. The fission of the uranium or plutonium converts the thorium-232 to uranium-233, which in turn fissions, sustaining the process.

The other approach to creating neutrons to bombard thorium-232 is to use a particle accelerator. Some people within the nuclear industry consider the use of particle accelerators as too expensive for the moment as a practical option for the generation of slow neutrons.[24] Other researchers believe that this has become a realistic option due to advances in computer and accelerator technology and work on what are called accelerator driven subcritical systems (ADS) is continuing in several laboratories across the world.[25]

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21. In practice the uranium-233 will not be pure and will be contaminated with small amounts of uranium-232. Uranium-232 is highly radioactive; its decay products such as thallium-208 and bismuth-212 emit strong gamma radiation with very short half lives. Uranium Information Centre, 'Thorium', *Briefing Paper*, no. 67, UIC, May 2007, http://www.uic.com.au/nip67.htm, accessed 31 July 2007 and http://environmentalchemistry.com/yogi/periodic, accessed 31 July 2007.

22. This process is in contrast to the enrichment of uranium which is needed for conventional nuclear power reactors. Enrichment is the process of concentrating particular isotopes of the uranium element which have the same chemical properties as each other and hence cannot be chemically separated. See also footnote 21.

23. Uranium Information Centre, 'Thorium', *Briefing Paper*, no. 67, UIC, May 2007, http://www.uic.com.au/nip67.htm, accessed 31 July 2007. Nuclear fuel formed into fuel assemblies are commonly used to build a nuclear reactor core.

24. Mujid S Kazimi, 'Thorium fuel for nuclear energy', *American Scientist*, vol. 91, no. 5, September–October 2003, p. 408.

25. S R Hashemi-Nezhad, 'Accelerator driven subcritical nuclear reactors for safe energy production and nuclear waste incineration', *Australian Physics*, vol. 43, no. 3, 2006, p. 91

In an ADS, a stream of protons—also subatomic particles—are fired at what is called a *spallation target*. The spallation target is made from a material like lead or bismuth. When struck by the protons, it releases large numbers of neutrons, among other subatomic particles, which can be directed to strike the thorium-232 fuel. The thorium-232 converts to uranium-233 which fissions *in situ* aided by the neutron stream from the accelerator. The advantage of this system, according to proponents, is that because the reactor is subcritical (not self-sustaining), it will simply stop if the accelerator is turned off.[26]

There have been many experiments in countries including Germany, India, Japan, Russia, the United Kingdom and the USA seeking ways in which thorium may be used as a nuclear fuel.[27] These experiments began soon after the Second World War and thorium-fuelled reactors were trialled in the late 1970s and early 1980s. There are no commercial scale thorium reactors yet in operation and thorium cannot be used directly in current generation uranium-fuelled reactors.[28]

The future of thorium in Australia

The future of thorium as a nuclear fuel in Australia has been canvassed in several recent reports. These include the House of Representatives Standing Committee on Industry and Resources' *Australia's uranium—greenhouse friendly fuel for an energy hungry world* and the so-called Switkowski report *Uranium mining, processing and nuclear energy—opportunities for Australia?* Within the context of the need to reduce Australia's greenhouse gas emissions, these reports refer to the advantages of thorium mentioned in the introduction above:

- thorium produces less of the nuclear by-products normally used to make nuclear weapons and less of the long-lived radioactive products of conventional nuclear power

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[26] S R Hashemi-Nezhad ibid. and Uranium Information Centre, 'Thorium', *Briefing Paper*, no. 67, UIC, May 2007, http://www.uic.com.au/nip67.htm, accessed 31 July 2007. Conventional nuclear reactors operate in a *critical* mode and need complex systems to slow and stop the reaction.

[27] Uranium Information Centre, *Thorium*, Briefing Paper no. 67, May 2007, http://www.uic.com.au/nip67.htm, accessed 31 July 2007. The main proponent of thorium nuclear power technology is India which is pursuing the thorium route principally because of its concerns for security of supply for its nuclear fuel. Two of India's nuclear power reactors are loaded with thorium fuel in order to improve their operation when newly-started. India plans to use thorium-based fuel in four reactors under construction.

[28] Uranium Information Centre, *Thorium*, Briefing Paper no. 67, May 2007, http://www.uic.com.au/nip67.htm, accessed 13 september 2007 and Yanis Miezitis, Geoscience Australia, personal communication 12 September 2007.

- thorium's use in nuclear reactors can reduce the hazard of nuclear accidents
- thorium's energy content can be used almost in its entirety and
- thorium is in relative abundance in Australia.[29]

Nuclear by-products

As noted above, using thorium as a nuclear fuel produces less of the nuclear by-products normally used to make nuclear weapons and less long-lived nuclear waste.

The uranium-233 produced from thorium-232 has a great advantage over uranium-235, the fuel of traditional nuclear power reactors—it does not produce plutonium which is the greatest nuclear weapons proliferation risk.[30] In addition, the thorium fuel cycle is *proliferation resistant* because of the presence of an isotope of uranium, uranium-232, and its highly radioactive and difficult-to-handle decay products.[31]

These advantages are true for thorium as a fuel whichever technology is chosen. However accelerator driven subcritical systems simply do not produce the plutonium-239 which is used in nuclear weapons and only produces small quantities of nuclear waste which needs storage for no more than 500 years. Using thorium in conventional or fast breeder reactors reduces the amount of weapons-useable material and reduces the amounts of very long-life radioactive material.[32]

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[29] Australia, House of Representatives, Standing Committee on Industry and Resources, *Australia's uranium—greenhouse friendly fuel for an energy hungry world*, 2006; and Department of Prime Minister and Cabinet, *Uranium mining, processing and nuclear energy—opportunities for Australia?*, Report to the Prime Minister by the Uranium Mining, Processing and Nuclear Energy Review Taskforce, 2006.

[30] The uranium-235 in traditional nuclear power reactors is never pure and will be mixed with over 90 per cent uranium-238 in the fuel rods made for traditional nuclear power reactors. The uranium-238 itself is fertile. When exposed to the neutron bombardment in a nuclear reactor, atoms of uranium-238 on absorbing a neutron become uranium-239. This is a short-lived isotope and decays with a half-life of about 23 minutes into neptunium-239. This neptunium-239 with a half-life of 2.4 days, decays in turn into plutonium-239. Plutonium-239 is highly radioactive with a half-life of 24 110 years. It is this waste plutonium-239 which presents the greatest nuclear weapons proliferation risk. See the uranium, neptunium and plutonium pages at http://environmentalchemistry.com/yogi/periodic, accessed 30 July 2007. A good general discussion of this is at Tim Dean, 'New age nuclear', *Cosmos*, issue no. 8, 2006, pp 44–5.

[31] International Atomic Energy Agency, *Thorium fuel cycle—potential benefits and challenges*, IAEA-TECDOC-1450, IAEA, Vienna, May 2005, pp. 79–84.

[32] S R Hashemi-Nezhad, personal communication, 4 September 2007.

Thorium-based accelerator driven subcritical systems can also be used to change highly radioactive waste from conventional nuclear reactors into more benign and shorter-lived radioisotopes.[33]

Risk of nuclear accidents

Using the thorium fuel cycle in conventional critical reactors has many benefits (as discussed above) but it does not reduce the risk of nuclear accidents.

However if the thorium fuel cycle is used in an accelerator driven subcritical system the possibility of nuclear accidents will be almost eliminated. An accelerator driven system by definition is a subcritical nuclear reactor and will remain operational as long as the neutrons from an external source are injected into the reactor.[34] An ADS system can simply be switched off, taking advantage of the subcritical nature of the thorium core. Such a reactor cannot *melt down*; a meltdown is a situation where the heat of a nuclear reaction cannot be contained and the reactor core melts.

In addition, the thorium used in nuclear reactors is used as the chemical thorium dioxide which at 3300 degrees Celsius has the highest melting point of any oxide. This provides far better thermal and physical properties than the uranium oxide used in conventional reactors.[35]

Energy used in its entirety

Depending on the fuel cycle used, the energy content of thorium can be used almost in its entirety. Virtually all natural thorium is thorium-232 and is potentially useable in a reactor compared to 0.7 per cent of natural uranium.[36]

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[33] Tim Dean, op. cit., pp. 46–7.

[34] S R Hashemi-Nezhad, ‘Accelerator driven subcritical nuclear reactors for safe energy production and nuclear waste incineration’, *Australian Physics*, vol. 43, no. 3, 2006, p. 91

[35] International Atomic Energy Agency, *Thorium fuel cycle—potential benefits and challenges*, IAEA-TECDOC-1450, IAEA, Vienna, May 2005.

[36] International Atomic Energy Agency, *Thorium fuel cycle—potential benefits and challenges*, IAEA-TECDOC-1450, IAEA, Vienna, May 2005, p. 12; and World Nuclear Association, *Thorium* at http://www.world-nuclear.org/info/inf62.htm, accessed 23 July 2007. There are, of course, losses in transforming this energy into electricity but this is true of any energy source.

Abundance of thorium

The ores of thorium are in abundance in Australia although they are geographically dispersed. With little change to current sand mining practices, monazite can be readily extracted for its thorium and rare earth mineral content, rather than being discarded.

Technical issues

Not all technical problems have yet been solved in the development of fuel cycles based on thorium. The World Nuclear Association, echoed by Australia's Uranium Information Centre, has highlighted four of these problems.[37]

Firstly, it is difficult and expensive to fabricate fuel for closed cycle thorium reactors. Uranium-233, chemically separated from irradiated thorium, is highly radioactive and hence hard to handle for fuel assembly fabrication. In addition, separated uranium-233 is always contaminated with uranium-232. Uranium-232 is radioactive, has a half life of 68.9 years and produces strong gamma emitters like thallium-208 as decay products.[38]

Secondly, there are technical difficulties in recycling thorium due to the high radioactivity of thorium-228 which is a decay product of the contaminant uranium-232.[39]

Thirdly, there is some nuclear proliferation risk with uranium-233 if it can be separated.

And fourthly, there are technical problems in reprocessing spent fuel from these reactors.

Were the technical difficulties to be resolved, it is by no means clear that Australia's environmental movement would accept a thorium-based nuclear future for Australia. Two states—New South Wales and Western Australia—have current bans on the mining of thorium and influential organisations such as the Australian Conservation Foundation (ACF) are opposed to any nuclear industry in Australia.[40] The ACF correctly points out that uranium-233 is still subject to the same safeguard requirements as uranium-235, the material

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37. World Nuclear Association, *Thorium* at http://www.world-nuclear.org/info/inf62.htm, accessed 23 July 2007; and Uranium Information Centre, 'Thorium', *Briefing Paper*, no. 67, UIC, May 2007, http://www.uic.com.au/nip67.htm, accessed 31 July 2007.
38. http://environmentalchemistry.com/yogi/periodic/U-pg2.html#233, accessed 24 July 2007.
39. http://environmentalchemistry.com/yogi/periodic/Th-pg2.html, accessed 2 August 2007.
40. Australian Conservation Foundation (ACF), *Nuclear power no solution to climate change*, ACF, September 2005, available at http://www.acfonline.org.au/uploads/res_nukesreportfull.pdf, accessed 1 August 2007.

used in conventional nuclear reactors, as is any uranium or plutonium used to make neutrons for the thorium cycle.[41]

Conclusion

There are several advantages for Australia in pursuing a thorium-based nuclear future in preference to the conventional uranium-based reactors that are now central to the nuclear and climate change debate.

However, with technical problems yet to be resolved, the current relative abundance of uranium, and an environmental movement opposed to any nuclear activities in Australia, a thorium-based nuclear future does not appear likely in the short to medium term.[42]

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[41] ibid. section 3.7.

[42] The opinion of the chief of the Australian Nuclear Science and Technology Organisation (ANSTO), Dr Ziggy Switkowski, is that this technology may be as far away as the middle of this century. See the ABC Television Lateline interview of Dr Switkowski by Tony Jones, 15 August 2007.

Glossary

accelerator driven subcritical system See ADS.

ADS An accelerator driven subcritical system. This is a subcritical reactor.

alpha decay Radioactive decay in which the nucleus of an atom emits two protons and two neutrons—this is identical to emitting a helium nucleus.

anti-neutrino A sub-atomic particle.

atom One of the building blocks of matter. In simple terms an atom comprises a nucleus and a number of electrons.

beta decay With beta decay, within the nucleus a neutron spontaneously changes into a proton—which produces the new element—and ejects an electron and another sub-atomic particle called an anti-neutrino.

closed fuel cycle A nuclear fuel cycle in which the nuclear fuel is re-processed after it leaves the reactor.

electron A sub-atomic particle.

element A substance which cannot be changed into another substance by ordinary chemical processes

fast breeder reactor A reactor which is designed to produce more fissile material than it consumes.

fertile A fertile element is capable of being converted into fissile material.

fissile A fissile material is one that is capable of sustaining a nuclear chain reaction.

gamma emission The radiation produced during some radioactive decay.

half-life The half-life of a radioactive element or isotope is the time that it takes for exactly half its mass to decay to other isotopes.

isotope Isotopes of an element, although chemically the same as each other, have different nuclear structures.

mineral A naturally-occurring homogeneous solid that has a definite chemical composition and a highly ordered atomic structure.

mixed oxide fuel Nuclear fuel which is a mixture of the oxides of several nuclear fuels including uranium, plutonium and thorium.

monazite A reddish-brown rare-earth phosphate mineral.

naturally-occurring element An element found in nature and which has not been manufactured using nuclear processes.

neutron A sub-atomic particle that is in the nucleus of all atoms except hydrogen.

nuclear chain reaction A controlled, self-sustaining nuclear chain reaction is the necessary basis for extracting energy from nuclear fuel.

nucleus The core of an atom. It contains protons and neutrons.

once-through fuel cycle See open fuel cycle.

open fuel cycle A nuclear fuel cycle in which the nuclear fuel is not re-processed after it leaves the reactor.

particle accelerator A device which accelerates charged particles such as protons and thus increases their energy.

proliferation resistant A process or product which is difficult to be used for the manufacture of nuclear weapons.

protactinium-233 An isotope of proactinium which is a decay product of thorium-233.

proton A sub-atomic particle that is in the nucleus of all atoms.

radioactive decay A process in which spontaneously and randomly the state of an atomic nucleus is altered and gamma or nuclear particles are emitted.

radioactive element An element that has an unstable atomic nucleus—this sort of element spontaneously and randomly alters the state of its atomic nucleus, emitting sub-atomic particles in the process.

rare-earth mineral A group of elements once thought rare and difficult to separate.

spallation target Material that produces neutrons when struck by a stream of protons.

sub-atomic particles The building blocks of atoms. There are many different sorts of sub-atomic particle including the electron, the proton and the neutron.

subcritical reactor A nuclear reactor which is not self-sustaining.

thorium A naturally-occurring radioactive element which can be used in nuclear reactors as an alternative source of fuel for the generation of electricity.

thorium-232 This is the naturally occurring form of the element thorium.

thorium-233 This isotope is produced when thorium-232 is bombarded with slow neutrons.

uranium-232 A highly radioactive contaminant of the process to produce uranium-233.

uranium-233 The fissile material produced from the bombardment of thorium-232 with neutrons.

uranium-235 The uranium isotope used in conventional nuclear power reactors.

uranium-238 The uranium isotope that forms the great bulk of naturally-occurring uranium.