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Thorium as nuclear fuel: What, how and when?

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INTRODUCTION

Even though thorium is considered a sustainable fuel cycle option, due to the abundance of uranium and its relative ease of handling, serious attention has not been paid to develop a commercial thorium fuel cycle. Recently, the focus has been renewed toward thorium utilization because of the favourable aspects of thorium fuel [1]. Advantages of thorium include its relative abundance compared to uranium and its occurrence as a coproduct or byproduct from deposits mined for other minerals [2]. Other benefits of thorium include the better waste profile of the fuel cycle and non-proliferation advantages. For these reasons, research and development activities are currently being carried out on several types of advanced reactors that can use thorium.

THORIUM AS A FUEL

The thorium fuel cycle differs from the uranium fuel cycle in some ways. Natural thorium (Th) contains only trace amounts of fissile material, which are insufficient to initiate a nuclear chain reaction. In a Th-fueled reactor, 232Th absorbs neutrons to produce 233U eventually. The 233U either fissions in situ or is chemically separated from the used nuclear fuel and formed into new nuclear fuel. The sustained fission chain reaction could be started with existing 233U or some other fissile material such as 235U or 239Pu. Subsequently, a breeding cycle similar to, but more efficient than that with 238U-239Pu can be created [3, 4].

Thorium-based fuels exhibit several attractive nuclear properties relative to uranium-based fuels, such as efficient fertile conversion, and better neutron economy and breeding possibilities in thermal spectrum reactors. Thorium dioxide (ThO2) has a higher melting point, higher thermal conductivity, lower coefficient of thermal expansion, and higher chemical stability than U-Plutonium (Pu) fuel. In addition, thorium offers an advantage from the waste perspective. The production of Pu and minor actinides (neptunium, americium, curium), which are the major contributors to the radiotoxicity of the wastes in the uranium-plutonium cycle, is drastically reduced if actinides are recycled [5]. The 233U produced in thorium fuels is inevitably contaminated with 232U, a hard gamma emitter; therefore, heavily shielded facilities are required for handling it. As a result, thorium-based used nuclear fuels possess inherent proliferation resistance.

Some of the unique features of the thorium fuel cycle often prove to be the significant challenges in its application. Initial fissile requirements for 235U, 233U, or Pu make thorium unsuitable for rapid expansion of nuclear energy. Thorium introduction could be preferred after a good stock of fissile material (in the form of either Pu or 233U) has been built up [6]. If thorium is used in an open fuel cycle (i.e., utilizing 233U in situ), higher burnup is necessary to achieve a favourable neutron economy. If thorium is used in a closed fuel cycle in which 233U is recycled, remote handling is needed because of the high radiation dose resulting from the decay products of 232U.

PREVIOUS WORK ON THORIUM FUEL

Research toward utilizing thorium as a nuclear fuel has occurred for over 50 years. Basic research and development, as well as the operation of test reactors with thorium fuel, has been conducted in Canada, Germany, India, Japan, the Netherlands, Norway, the Russian Federation, Sweden, Switzerland, the United Kingdom, and the United States.

Light water reactors can be operated with thorium fuel. In the United States, thorium fuel was tested in pressurized water reactors (PWRs) at the Indian Point plant in New York initially (start up in 1962), but this reactor was later converted to a uranium fuel cycle. The Shippingport reactor in Pennsylvania, a "seed-blanket"PWR, operated with thorium fuel from 1977 to 1982. Boiling water reactors (BWR) offer design flexibility that can be optimized for thorium fuels. Thorium was used in a BWR at the Elk River Reactor in Minnesota, United States from 1963 to 1968. Thorium fuel was also tested at the 60 MWe BWR in Lingen, Germany until 1973.

Heavy water reactors could offer excellent neutron economy and faster neutron energy, so they are considered better for breeding 233U. Conceptual design studies have indicated that thorium and uranium fuel concepts have many common design characteristics and that the thorium cycle could be used in a plant designed for the uranium cycle without substantial performance penalties. In Canada, Atomic Energy Canada Limited has more than 50 years of experience with thorium-based fuels. India is continuing the use of ThO2 pellets in pressurized heavy water reactors, used for neutron flux flattening of the initial core after start-up.

There is no advantage in using thorium instead of depleted uranium as a fertile fuel matrix in fast breeder reactor (FBR) systems due to a higher fast fission rate for 238U and the fission contribution from residual 235U in this material. 232Th in the blanket can be advantageous in a mixed reactor scenario. India has a three-stage nuclear energy scenario in which FBRs play an important role. Thorium has been used in the blanket to breed 233U in a 40 MWt FBR test reactor near Kalpakkam, India. As a pilot study, the Kamini 30 kWt experimental neutron-source research reactor, adjacent to the FBR test reactor, uses 233U as fuel.

High-temperature gas-cooled reactors (HTGRs) are thermal spectrum reactors moderated with graphite and cooled by helium. In Germany, reactors testing Th-based nuclear fuels have included the 15 MWe AVR (Arbeitsgemeinschaft Versuchsreaktor) and a 300 MWe Th high-temperature reactor. Other examples of experimental HTGRs using Th as fuel have included: (1) in the United States, the Peach Bottom high-temperature, graphite-moderated, helium-cooled reactor in Pennsylvania and the Fort St Vrain test reactor in Colorado; and (2) in the United Kingdom, the experimental 20 MWt Dragon reactor.

In April 2013, Thor Energy of Norway commenced a test of two thorium-based fuels in the Halden research reactor in Norway. Fuel irradiation is being tested to determine if a mixed Th-Pu ("MOX") fuel can be used in commercial nuclear power plants.

Molten salt reactors (MSRs) offer attractive concepts for thorium utilization. In 1954, scientists at the Oak Ridge National Laboratory in Tennessee, United States, designed a 2.5 MWt MSR nuclear reactor with the intent to attain a high-power density for use as an engine in a nuclear-powered aircraft [7]. The Pratt and Whitney Aircraft Reactor No. 1 (PWAR-1) was a zero power MSR that was tested in Oak Ridge in 1957; the reactor used NaF-ZrF4-UF4 as the primary fuel and coolant [8].

THORIUM RESOURCES

Thorium is part of the group of element referred to as the High Field Strength Elements (HFSE), which have a valence state greater than two (high charge) and small-to-medium-size ionic radii, thus producing a high electric field (high field strength). These attributes inhibit the ability of the HFSE, which include the rare earth elements (REEs), to achieve charge balance and fit into the structure of most common igneous minerals. As a result, thorium and other HFSE co-occur in anomalous concentrations in unusual rocks, such as carbonatites, alkaline igneous intrusive complexes and associated veins and (or) dykes, and massive magnetite-apatite bodies. Additionally, some moderate- to high-grade metamorphic rocks (amphibolite facies and higher) contain monazite, a REE-Th-phosphate mineral, as an accessory mineral. Monazite is the principal thorium mineral. Xenotime [YPO4] and thorite [(Th,U)SiO4] are other Th minerals in some REE-Th deposits, but are less common.
Carbonatites host large tonnage REE deposits and commonly have associated enrichments in thorium [9]. Thorium and the REEs have a strong genetic association with alkaline igneous processes, particularly peralkaline magmatism [9]. Alkaline rocks typically have higher enrichments in REEs and Th than most other igneous rocks. Thorium-rich veins of uncertain origin also exist. Most of these types of vein deposits are interpreted to be related to concealed alkaline magmatism. Massive iron-oxide deposits of magmatic-hydrothermal origin can contain elevated concentrations of Th and REEs, usually in relatively small amounts.

Heavy-mineral sands are sedimentary deposits of dense (heavy) minerals that accumulate with sand, silt, and clay in coastal and alluvial environments, locally forming economic concentrations of heavy minerals [10]. Expansive coastal deposits of heavy-mineral sands are the main source of titanium feedstock for the titanium dioxide (TiO2) pigments industry, through the recovery of the minerals ilmenite (Fe2TiO3), rutile (TiO2), and leucoxene (an alteration product of ilmenite). Heavy-mineral sands are also the principal source of zircon (ZrSiO4); it is often recovered as a coproduct. Other detrital heavy minerals produced as coproducts from some deposits are sillimanite/kyanite, staurolite, garnet, and monazite, as a source of REEs and thorium.

Globally, the important thorium resources occur as minor minerals within a variety of REE deposits and some heavy-mineral sands. Significant REE deposits of all deposit types also represent the largest thorium deposits. Actively mined REE ore deposits are economic by their REE production, not for their Th content. Heavy-mineral sands operations are economic based on their production of titanium minerals (ilmenite and rutile) and zircon, but they also can often provide detrital monazite as a by-product, and sometimes xenotime. Thus, if a market develops for thorium in the future, mineral deposits that are economic as sources of REEs, including specific types of crystalline rocks and many heavy-mineral sands, can be evaluated as sources of byproduct or co-product thorium [1, 2].

FUTURE THORIUM UTILIZATION

China in collaboration with the USA has extensive ongoing research on thorium utilization in MSR designs. This is a dual program involving an early solid fuel stream and advanced liquid fuel stream. In 2011, the China Academy of Sciences launched a research and development program on a liquid-fluoride thorium reactor, called the thorium-breeding molten salt reactor.

Since 2008, CANDU Energy of Canada and the China National Nuclear Corporation have been cooperating in the development of thorium and recycled uranium as alternative fuels for new CANDU reactors. CANDU Energy (now part of SNC Lavalin) works on Advanced Fuel CANDU Reactor (AFCR) technology, which aims at thorium utilization. AFCR will be designed to use recycled uranium or thorium as fuel, thus reducing spent fuel inventories and significantly reducing fresh uranium requirements. Spent fuel from four conventional PWR reactors can fully supply one AFCR unit (as well as providing recycled plutonium for mixed oxide fuel (MOX)).

In India, research on thorium utilization has been carried out since the 1950s. A three-stage nuclear energy program with uranium-fueled pressurized heavy water reactors, plutonium-fueled FBRs, and thorium-233U-based advanced heavy water reactors has been proposed as the long-term plan. A 500 MWe prototype fast-breeder reactor is in the final stages of completion. Additional 500 MWe FBRs are planned for immediate deployment and beyond 2025; also, a series of 1000 MWe FBRs with metallic fuel, capable of high breeding potential is proposed. The large-scale deployment of thorium is expected to occur in three to four decades after the commercial operation of FBR, with short doubling time when thorium can be introduced to generate 233U.

REFERENCES

[1] Van Gosen, B.S., and Tulsidas, Harikrishnan, 2016, Thorium as a nuclear fuel (Chapter 10), in Hore-Lacy, Ian, ed., Uranium for nuclear power—Resources, mining and transformation to fuel: Amsterdam, Elsevier Ltd., Woodhead Publishing Series in Energy, Number 93, p. 253–296.
[2] Ault, Timothy, Van Gosen, Bradley, and Croff, Allen, 2016, Natural thorium resources and recovery—Options and impacts: Nuclear Technology, v. 194, no. 2, p. 136–151.
[3] International Atomic Energy Agency (IAEA), 2005, Thorium fuel cycle—Potential benefits and challenges. Vienna, Austria, International Atomic Energy Agency Technical Document IAEA-TECDOC- 1450, 105 p.
[4] World Nuclear Association (WNA), 2018, Thorium: World Nuclear Association. A accessed 29.03.18 at http://www.world-nuclear.org/information-library/current-and-future-generation/thorium.aspx
[5] David, Sylvain, Huffer, Elisabeth, and Nifenecker, Hervé, 2007, Revisiting the thorium-uranium nuclear fuel cycle: Europhysics News, v. 38, no. 2, p. 24–27.
[6] International Atomic Energy Agency (IAEA), 2012, Role of thorium to supplement fuel cycles of future nuclear energy systems: Vienna, Austria, International Atomic Energy Agency, IAEA Nuclear Energy Series NF-T-2.4, 157 p.
[7] Rosenthal, M.W., 2009, An account of Oak Ridge National Laboratory's thirteen nuclear reactors.:Oak Ridge National Laboratory Report ORNL/TM-2009/181, 80 p. Available at http://info.ornl.gov/sites/publications/Files/Pub20808.pdf.
[8] Scott, D., Alwang, G.W., Demski, E.F., Fader, W.J., Sandin, E.V., and Malenfant, R.E., 1958. A zero power reflector-moderated reactor experiment at elevated temperature: Oak Ridge National Laboratory Report ORNL-2536. Available at http://energyfromthorium.com/pdf/ORNL-2536.pdf
[9] Verplanck, P.L., Van Gosen, B.S., Seal, R.R, and McCafferty, A.E., 2014, A deposit model for carbonatite and peralkaline intrusion-related rare earth element deposits: U.S. Geological Survey Scientific Investigations Report 2010–5070-J, 58 p., http://dx.doi.org/10.3133/sir20105070J.
[10] Van Gosen, B.S., Fey, D.L., Shah, A.K., Verplanck, P.L., and Hoefen, T.M., 2014, Deposit model for heavy-mineral sands in coastal environments: U.S. Geological Survey Scientific Investigations Report 2010–5070–L, 51 p., http://dx.doi.org/10.3133/sir20105070L.

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Author: Mr TULSIDAS, Harikrishnan (UNECE)

Co-author: Mr VAN GOSEN, Bradley (U.S. Geological Survey)

Presenter: Mr TULSIDAS, Harikrishnan (UNECE)

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