Energy Policy 60 (2013) 4–12

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Abundant thorium as an alternative nuclear fuel Important waste disposal and weapon proliferation advantages

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HIGHLIGHTS

- Thorium is an abundant nuclear fuel that is well suited to three advanced reactor configurations.
- Important thorium reactor configurations include molten salt, CANDU, and TRISO systems.
- Thorium has important nuclear waste disposal advantages relative to pressurized water reactors.
- Thorium as a nuclear fuel has important advantages relative to weapon non-proliferation.

ARTICLE INFO

Article history:
Received 10 May 2012
Accepted 26 April 2013
Available online 30 May 2013

Keywords::
Thorium
Non-proliferation
Nuclear waste reduction

ABSTRACT

It has long been known that thorium-232 is a fertile radioactive material that can produce energy in nuclear reactors for conversion to electricity. Thorium-232 is well suited to a variety of reactor types including molten fluoride salt designs, heavy water CANDU configurations, and helium-cooled TRISO-fueled systems.

Among contentious commercial nuclear power issues are the questions of what to do with long-lived radioactive waste and how to minimize weapon proliferation dangers. The substitution of thorium for uranium as fuel in nuclear reactors has significant potential for minimizing both problems.

Thorium is three times more abundant in nature than uranium. Whereas uranium has to be imported, there is enough thorium in the United States alone to provide adequate grid power for many centuries. A well-designed thorium reactor could produce electricity less expensively than a next-generation coal-fired plant or a current-generation uranium-fueled nuclear reactor. Importantly, thorium reactors produce substantially less long-lived radioactive waste than uranium reactors.

Thorium-fueled reactors with molten salt configurations and very high temperature thorium-based TRISO-fueled reactors are both recommended for priority Generation IV funding in the 2030 time frame.
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1. Introduction

It has long been known that thorium-232 is a fertile radioactive material that after being irradiated with neutrons can produce energy in nuclear reactors for conversion to electricity. Thorium-232 performs this function by transmuting into uranium-233 permitting reactor energy by fission. As do other fertile materials, thorium-232 requires a source of neutrons for the transmutation to take place, from a fissile material (such as uranium-235 or plutonium 239) or from an external source such as spallation neutrons. Thorium-232 appears in nature unmixed with isotopes, does not require enrichment for use as reactor fuel, and only needs relatively inexpensive chemical separation from ore impurities.

The thorium-232/uranium-233 cycle is well suited to a variety of reactor types. They include molten fluoride salt designs, heavy water CANDU configurations, and helium-cooled TRISO-fueled systems. An additional concept in which neutrons are generated by an energy amplifier rather than from a radioactive source element has also been proposed.

Among contentious commercial nuclear power issues are questions of what to do with long-lived radioactive waste and how to minimize weapon proliferation dangers. The substitution of thorium for uranium as fuel in nuclear reactors has significant potential for minimizing (but not eliminating) both problems.

Adding to the advantages of thorium is the fact that it is 3–4 times more abundant in nature than uranium. Whereas uranium has to be imported, there is enough thorium in the United States to provide adequate grid power there for many centuries. Advocates claim moreover that a well-designed thorium reactor could produce electricity less expensively than a next-generation

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0301-4215/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2013.04.062

coal-fired plant or a current-generation uranium-fueled nuclear reactor. Importantly, thorium reactors produce substantially less long-lived radioactive waste than uranium reactors. In principle, thorium waste can be reduced to the radioactive levels of ordinary coal ash.

Thorium reactors are discussed herein from historical, radiological, and energy production perspectives. The focus is on long-term cost reduction, on substantial radioactive waste reduction, and on the minimization of the inherent dangers from the presence of materials needed for weapons.

Thorium fueled reactors with molten salt cores, and very high temperature thorium-based TRISO-fueled reactors are both recommended for priority Generation IV funding in the 2030 time frame. These reactor configurations have been demonstrated as prototypes and have substantial advantages related to safety, nuclear proliferation and waste disposal. Externally supplied spallation neutron sources for fertilizing thorium-232 is another technology worthy of support but it is not yet ready for prototyping. We recommend an intensive research activity that could lead to affordable spallation neutron sources that are of sufficient energy and power to substitute for fission-generated neutrons.

2. Historical perspective

Thorium was isolated in 1828 by the Swedish chemist Jons Berzelius who named it for the Norse god of thunder. Found by Marie Curie to be radioactive in 1898, Ernest Rutherford subsequently investigated its disintegration products and lifetime. Thorium was determined to be very stable, having existed in nature for more than four billion years.

The nuclear power industry has a long record of experimentation with thorium fuel cycles. That history encompasses several reactor configurations: high-temperature gas reactors (HTGR), pressurized water reactors (PWR), and molten salt reactors (MSR). A fourth configuration using an energy amplifier (EA) to produce spallation neutrons has more recently been proposed.

2.1. High temperature gas reactors

High temperature gas reactor designs using thorium fuel were proposed by the Oak Ridge National Laboratories in 1947. That research led to the Peach Bottom, PA 40-MW reactor that produced electricity from 1966 to 1974. A scaled up 300-MW version was then built and operated at Fort St Vrain, CO from 1976 to 1989. Those reactors, fueled with oxides and di-carbides of thorium-232 and uranium-235, were arrayed in prismatic graphite cores. The coolant was helium.

The German THTR-300 was the first commercial power station to operate almost entirely with thorium. It was a helium-cooled high-temperature pebble-bed reactor that produced electricity from 1983 to 1989. The fuel was TRISO (triple-coated isotropic) containing thorium kernels embedded in a graphite matrix. Intermixed in each kernel was uranium-235 acting as a driver for fertilizing the thorium. The kernels were packaged in baseball-sized spherical pebbles whose outer layer was graphite. The THTR-300 generated 300-MW of power and was scaled from an earlier 15-MW installation.

Japanese and Chinese agencies have both recently implemented domestic thorium-based TRISO-fueled reactors. The Japanese high temperature test reactor went on line in 1999 with a power of 30-MW. It contains a prismatic core configuration and has a high enough outlet temperature to dissociate hydrogen from water. The HTR-10 Chinese version was completed in 2003. It is a pebble bed design, has a power of 10-MW, and is intended as a prototype. The first two full-scale Chinese 250-MW designs are scheduled for 2013 commissioning.

An American-designed gas-cooled reactor, the high temperature teaching and test reactor using ceramic-coated thorium kernels is also under construction. That facility in Odessa, TX will have either a pebble-bed or prismatic-block core. The earliest operational date is 2015.

The United States-led Generation IV International Forum has identified very high temperature reactors (VHTR) among the candidates for hydrogen production, coal gasification, and desalination applications along with electricity production. Intended for commissioning by 2030, the nominal VHTR is a 600-MW gas turbine system with TRISO fuel.

2.2. Liquid water-cooled thorium reactors

A 100-MW pressurized light water reactor operated at Shippingport, PA from 1977 until 1982. The 285-MW Indian Point reactor in Buchanan, NY was commissioned in 1962 and ran until 1980. Both were fueled with thorium-232 oxide pellets and a lesser amount of uranium-235.

India, with about 25% of the world's natural thorium reserves, has begun testing critical components for the Advanced Heavy Water Reactor (AHWR300-LEU). It is a 300 MW, vertical, pressure-tube type, boiling light-water cooled, and heavy-water moderated reactor. The fuel for the reactor is 19.75% enriched uranium oxide and thorium oxide; on the average, 39% of the power is obtained from the thorium. The reactor has a number of passive safety features and a fuel cycle that has reduced environmental impact (Bhabba Atomic Research Centre). India plans to meet 30% of its total power requirements in 2050 by using thorium-fueled reactors.

2.3. Molten salt thorium reactors

The liquid fluoride thorium reactor (LFTR) is a thermal breeder that uses thorium fuel dissolved in molten salt to generate energy. It operates at high temperature and atmospheric pressure. First researched at Oak Ridge National Laboratories in the 1960s (Rosenthal et al., 1971), it has more recently been investigated by nuclear agencies in the United Kingdom, and by private companies in the United States and Australia. The United States-based Flibe Energy Co has recently proposed development of a small modular LFTR using liquid Li/Be fluoride eutectic salt mixtures (Kirk Sorensen, 2011). The Flibe LFTR objective is a 20–50-MW modular design to power military bases. Fielding of such a reactor is estimated to require at least 5–10 years of development.

Development thorium fuel programs using molten-salt technology have also been initiated in Japan and China. The Japanese Fuji molten salt reactor is a 200-MW thermal breeder that has support from the United States and Russia. It is characterized as inherently safe, chemically inert, and operates under low pressure to prevent explosions and toxic releases. The Fuji would require about 20 years at the current rate of development for an operating reactor. The Chinese molten salt project is in a similar time frame. The Chinese thorium-breeding molten-salt reactor is the largest national effort in the world using that technology.

2.4. Accelerator-driven nuclear energy

Neutrons to fertilize thorium need not be provided by a fissile source such as uranium or plutonium. Neutrons can instead be generated by energy amplifiers and impacted on the thorium for fertilization. Professor Carlo Rubbia at the European Council for Nuclear Research (CERN) has proposed such a neutron source both to generate electricity and heat, and to incinerate long-lived

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