Energy Policy
Volume 60, September 2013, Pages 4-12

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

Marvin Baker Schaffer

Show more

Share Cite

https://doi.org/10.1016/j.enpol.2013.04.062
Get rights and content

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.

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.

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 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.

Section snippets

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: …

Reactor design configurations

A variety of thorium cycle design configurations exist. A convenient way to differentiate between them is by core type: molten salt, solid rod bundles, prismatic TRISO, and pebble bed TRISO. …

Summary of thorium fuel cycles

Table 1 summarizes the various thorium cycles considered. Organized by core type, they include molten salt, solid core bundled rods, prismatic TRISO, and pebble bed TRISO. …

Thorium wastes

When thorium-232 captures a neutron, it transmutes to thorium-233. It then spontaneously undergoes beta decay to become protactinium-233 followed by another beta decay to uranium-233. The total transmutation has a half-life of 27 days. Thus, after 9 months, what was originally thorium-232 is now 99.9% uranium-233. This is summarized byn+$^{232}Th_{90} \rightarrow {}^{233}Th_{90} - \beta^- \rightarrow {}^{233}Pa_{91} - \beta^- \rightarrow {}^{233}U_{92}$

Thorium fission cycles produce radioactive wastes consisting of actinides and lower atomic weight elements. According to …

Proliferation resistance

Uranium-233 as transmuted in the thorium fuel cycle is typically contaminated with uranium-232 and is not easily separated from it. Uranium-232 has several decay products that emit high-energy gamma radiation, a radiological hazard that necessitates the use of remote handling equipment. As long as that material is in a reactor, it is not a problem and is eventually burned while producing energy. However, if the uranium-233 is removed and used for producing a military bomb, the trace uranium-232 …

Availability, extraction and driving costs

Thorium ore is distributed widely throughout the world. Monazite containing 6–12% thorium phosphate is the primary source. Thorium is extracted from monazite through a complex multi-stage process. Monazite sand is first dissolved in hot concentrated sulfuric acid, and thorium is then extracted in an organic phase containing an amine. Next it is stripped in an aqueous ionic solution and finally thorium oxide is precipitated (Barghusan and Smutz, 1958).

Table 2 summarizes world thorium reserves. …

Why thorium

The principal arguments for thorium rather than uranium as fuel for nuclear reactors are the ones stated in the title: thorium is considerably more abundant than uranium; thorium reactors can be configured to minimize the waste storage issue; and thorium reactors are less conducive to proliferation of weapons grade materials. Thorium will be an attractive fuel in 3–4 decades for countries like the United States since it is abundant in both the raw material and the starter materials. The waste …

Summary

Thorium has a long history of use as a nuclear fuel. Thorium-232 is a fertile material that can be transmuted into uranium-233 for production of fissile energy in reactors. The process requires a source of neutrons either from a fissile starter or from an external source such as an energy activator. 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.

The …

Recommended articles

References (19)

Andrew C. Kadak, A Future for Nuclear Energy—Pebble Bed Reactors, Massachusetts Institute of Technology, April ,...

John Barghusan *et al.*
Processing of monazite sands
Industrial and Engineering Chemistry (1958)

Bhabba Atomic Research Centre, AHWR300-LEU advanced heavy water reactor with LEU-Th MOX fuel, Department of Atomic...

Carlo Rubbia, The Energy Amplifier—A Description for Non-Specialists, CERN/ET Internal Note 96-01,...

David Jackson,...

Ingersoll, D.T., Status of Physics and Safety Analysis for the Liquid-salt-Cooled Very High Temperature Reactor...

International Atomic Energy Agency, Assessment and Management of Aging Major Components Important to Safety: CANDU...

International Atomic Energy Agency, Thorium Fuel Cycle—Potential Benefits and Challenges, IAEA-TECDOC-1450, May...

Kiryushin, A., Kodochigov, N. GT-MHR Project, OKB Mechanical Engineering, Russian Federation,...

Cited by (72)

Re-examining the role of nuclear fusion in a renewables-based energy mix

2021, Energy Policy

Show abstract

Selective separation of thorium from rare earths and uranium in acidic solutions by phosphorodiamidate-functionalized silica

2020, Chemical Engineering Journal

Show abstract

Viability of thorium-based nuclear fuel cycle for the next generation nuclear reactor: Issues and prospects

2018, Renewable and Sustainable Energy Reviews

Show abstract

Nano and micro U<inf>1-x</inf>Th<inf>x</inf>O<inf>2</inf> solid solutions: From powders to pellets

2018, Journal of Nuclear Materials

> *Citation Excerpt :*
>
> …The thorium-uranium fuel cycle has some intriguing capabilities over the traditional one [1].…

Show abstract

The separation of Th(IV)/U(VI) via selective complexation with graphene oxide

2015, Chemical Engineering Journal

Show abstract

Comparing concentrating solar and nuclear power as baseload providers using the example of South Africa

2015, Energy

Show abstract

View all citing articles on Scopus ↗

View full text